FOREFRONT

LAND USE CHANGE AND ECOSYSTEM SERVICES: LINKING SOCIAL AND ECOLOGICAL SYSTEMS ACROSS TIME

LUCAS DE CARVALHO GOMES

Propositions

1. Agroforestry systems are the solution for future coffee production in Brazil. (this thesis)

2. Quantification of ecosystem services allows to better plan the future of human landscapes. (this thesis)

3. Interdisciplinary research is challenging, but essential to plan a more sustainable future.

4. The rate of acquisition of scientific data exceeds the rate at which this information can be understood.

5. Creating public awareness is the most powerful weapon against deforestation in our connected world.

6. For a better future, scientists should convert their papers into children's books.

7. Raising a child during a PhD helps to put work related frustrations into perspective.

Propositions belonging to the thesis entitled
Land use change and ecosystem services: linking social and ecological systems across time
Lucas de Carvalho Gomes
Wageningen, 26 May 2020

Land use change and ecosystem services: linking social and ecological systems across time

Lucas de Carvalho Gomes

Thesis committee

Promotors

Prof. Dr R.P.O. Schulte
Professor of Farming Systems Ecology
Wageningen University & Research

Prof. Dr I.M. Cardoso
Professor at the Soil Science Department
Universidade Federal de Viçosa, Brazil

Co-promotors
Dr F.J.J.A. Bianchi
Associate Professor, Farming Systems Ecology Group
Wageningen University & Research

Prof. B.J.M. Arts
Personal chair, Forest and Nature Conservation Policy Group
Wageningen University & Research

Other members
Prof. Dr M.M. Bakker - Wageningen University & Research
Prof. Dr M.V.R. Ballester - Universidade de São Paulo, Brazil
Prof. Dr A.V. Griensven - Vrije Universiteit Brussel, Belgium & IHE-Delft, the Netherlands
Prof. Dr F.N.B. Simas - Universidade Federal de Viçosa, Brazil

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Land use change and ecosystem services: linking social and ecological systems across time

Lucas de Carvalho Gomes

Thesis

submitted in fulfilment of the requirements for the double degree of doctor between

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and

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Thesis Committee appointed by the Academic Boards of both universities

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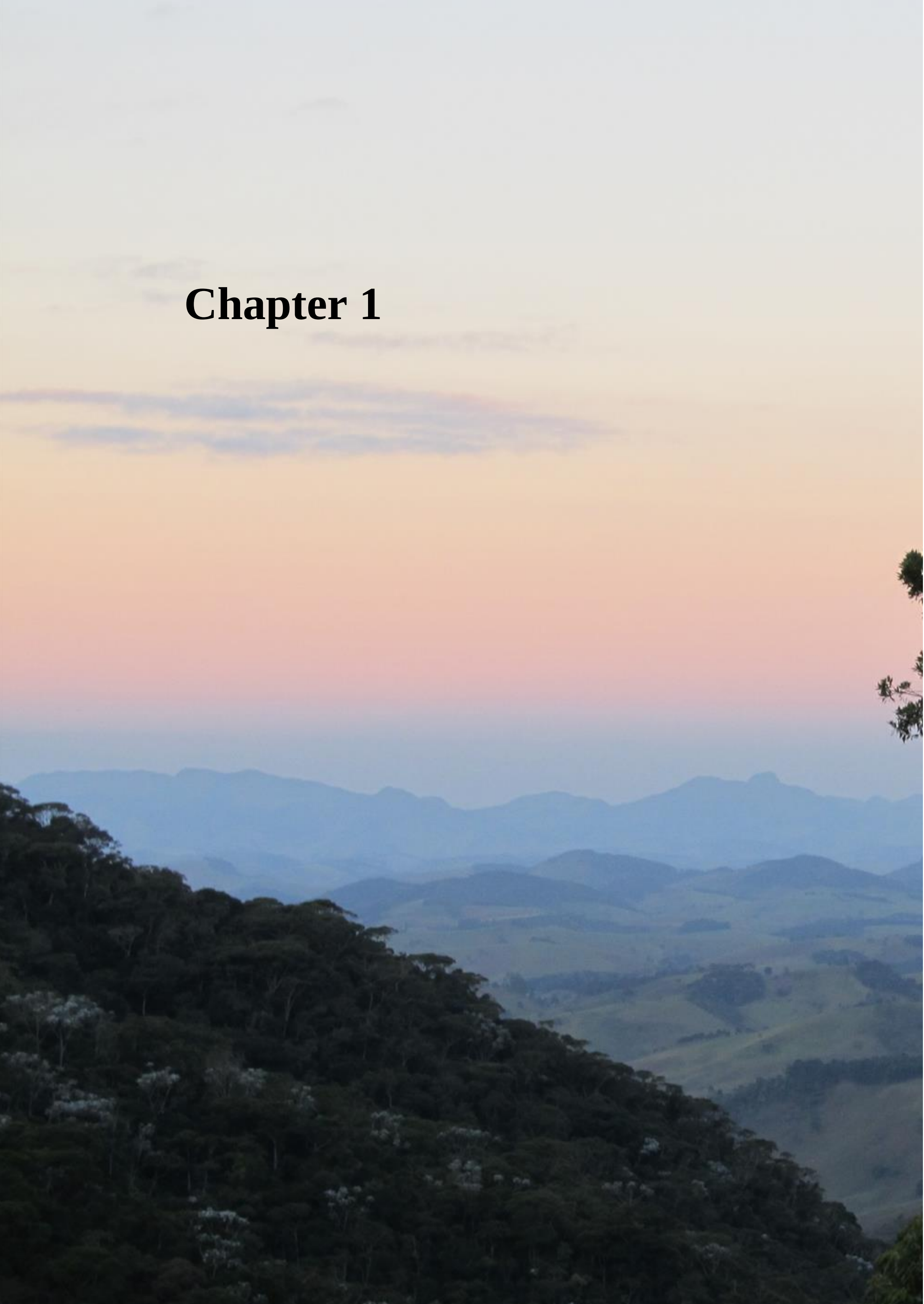
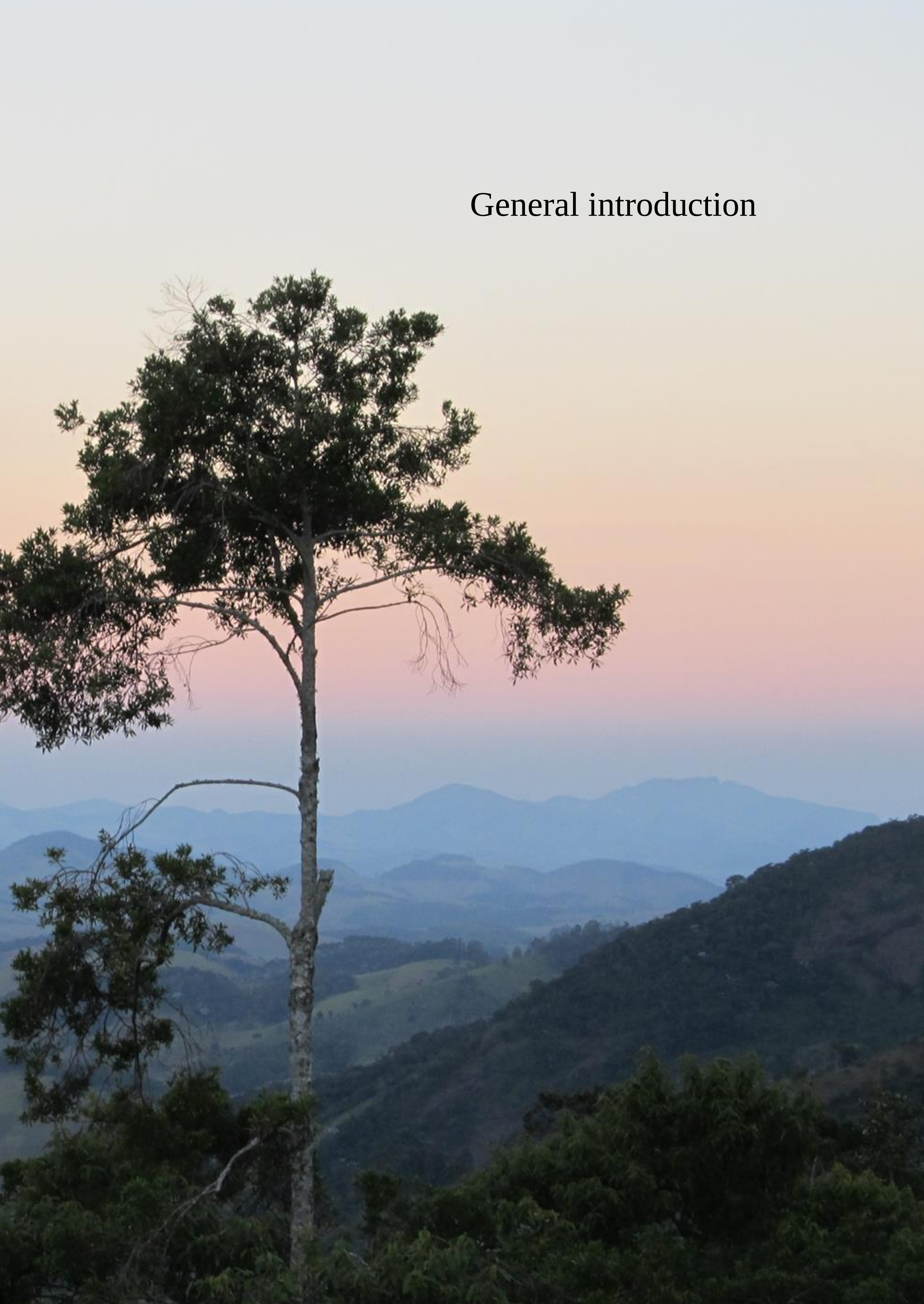
Chapter 1



General introduction



Land use and land cover (LULC) changes have impacted the functioning of (agro)ecosystems and their capacity to sustain the human needs (Borrelli et al., 2017; Foley et al., 2005). Human populated landscapes do not only comprise the biophysical structure of the environment, but can be considered socio-ecological systems resulting from complex interactions between social and ecological systems (Termorshuizen and Opdam, 2009; Vallés-Planells et al., 2014). Socio-ecological systems are dynamic, and over time, anthropogenic actions modify the biophysical environment, especially through LULC changes (Foley et al., 2005; Reyers et al., 2013). LULC changes can occur due to socioeconomic drivers and result in alterations of ecological processes (e.g., water cycling), which can affect the ability of landscapes to provide ecosystem services, which are essential for human wellbeing (Baral et al., 2013; Fu et al., 2015; Van der Sluis et al., 2018).

Ecosystem services are considered the benefits that humans receive from nature, and therefore ecosystems services constitute an important link between ecological and social systems (Costanza et al., 1997; Haines-Young and Potschin, 2010). In general, ecosystem services can be classified as supporting (e.g., nutrient cycling), provisioning (e.g., food production), regulating (e.g., flood regulation) and cultural services (e.g., aesthetics) (MA, 2005). Although ecosystem services research has made significant advances in the conceptualization, quantification and monetary valuation of ecosystem services in recent decades (Costanza et al., 2014; De Groot et al., 2012; Fisher and Turner, 2008; La Notte et al., 2017; Yi et al., 2018), we still have limited understanding about the main drivers of the provision and interactions of multiple ecosystem services in a socio-ecological context.

In Brazil, where intense LULC changes have been taking place and still are on-going, information about LULC changes and their socioeconomic drivers can give important insights about the socio-ecological drivers of multiple ecosystem services and inform future land use planning. The assessment of LULC changes can reveal the development of landscape dynamics and the associated interactions between social and ecological systems (Reyers et al., 2013). Although historic LULC changes maps are available for all Brazilian territory by MapBiomas initiative, these maps lack in information about crop types. The assessment of spatio-temporal variation of specific crops, which are local economically and culturally important, can help to better understand the local socio-ecological systems. Changes in LULC or in agricultural management are driven, among others, by public policies, social awareness and economic aspects (Meyfroidt et al., 2013; Rudel et al., 2009). Then, identifying how these socioeconomic drivers influence local LULC changes and, in turn, ecosystem services may provide insight that may be helpful for the development of more sustainable and resilient landscapes.

Anticipating the effects of future changes in climate and socioeconomic developments on landscape configuration and ecosystem services can also help to develop more sustainable and resilient landscapes. Scenario development is a useful tool to explore contrasting pathways of socio-economic developments and has been applied worldwide to build scenarios of LULC and ecosystem services (Carpenter et al., 2006; Oduro et al., 2014; Sleeter et al., 2012). The global Shared Socioeconomic Pathways scenarios describe future changes in human dynamics, economy, policies and institutions, technology, environment, and natural resources at the global level (O'Neill et al., 2017; Riahi et al., 2017). These qualitative scenarios have been used to explore the future global LULC changes (Popp et al., 2017). However, global and national scenarios have a coarse resolution, and the challenge remains to create LULC scenarios that reflect the local socioeconomic and environmental conditions. These local scenarios can better orient decision making on the management of landscapes and ecosystem services at regional and municipality levels, especially in areas where the environment configuration is sensitive to socio-economic changes.

Study area

The study area is located in the southeast of the Brazilian Atlantic Forest biome (Fig. 1.1), the 5th hotspot of biodiversity in the world (Myers et al., 2000), in which 70% of Brazilian population lives and about 12.4% of the original forest remains (Sosma, 2019). The altitude in the region varies from 27 to almost 2700 meters. The Zona da Mata region in Minas Gerais state is characterized by a mountainous environment, where the main LULC types are pasture, monoculture coffee plantations and forest fragments. The region is characterized by family farms that cultivate vegetables, coffee and raise cattle, with *Coffea arabica* the main cash crop. This region is considered a centre of agroecology in Brazil, resulting from social movements that has promoted and incentivised the development of agroecology. These social movements helped to implement and disseminate more sustainable agriculture practices. For instance, a group of family farmers aiming to decrease soil erosion and restore soil quality adopted agroforestry coffee systems, in which trees species are associated with coffee plants (Cardoso et al., 2001; Souza et al., 2010). In this region, altitudes higher than 1200 m are mainly occupied by two protected areas, the Serra do Brigadeiro State Park and the Caparaó National Park, which are important for tourism and recreation in this region.

This region is considered a complex socio-ecological system (Jackson et al., 2012), where LULC changes, public policies and society efforts shaped a unique and heterogeneous landscape. From several nature benefits, local farmers indicated that water regulation and agricultural production are the most important ecosystem services for them (Teixeira et al., 2018b). However, future socioeconomic developments and the projected changes in precipitation and temperature patterns can alter the landscape dynamics and affect the provision of water and coffee production, among other ecosystem services. For instance, the projected increase in temperature threatens the conditions for global coffee production (Ovalle-Rivera et al., 2015), which can have serious social and economic impacts in coffee production areas in Brazil. The analysis of scenarios that combine contrasting socioeconomic developments and changes in LULC or agricultural management can be a useful tool to explore possible future dynamics of ecosystem services. With a history of profound changes in LULC and complex socioeconomic relations, this region serves as a good case study for studying how these changes have influenced the provision of ecosystem services, and how these may unfold in the future under scenarios of climate change.

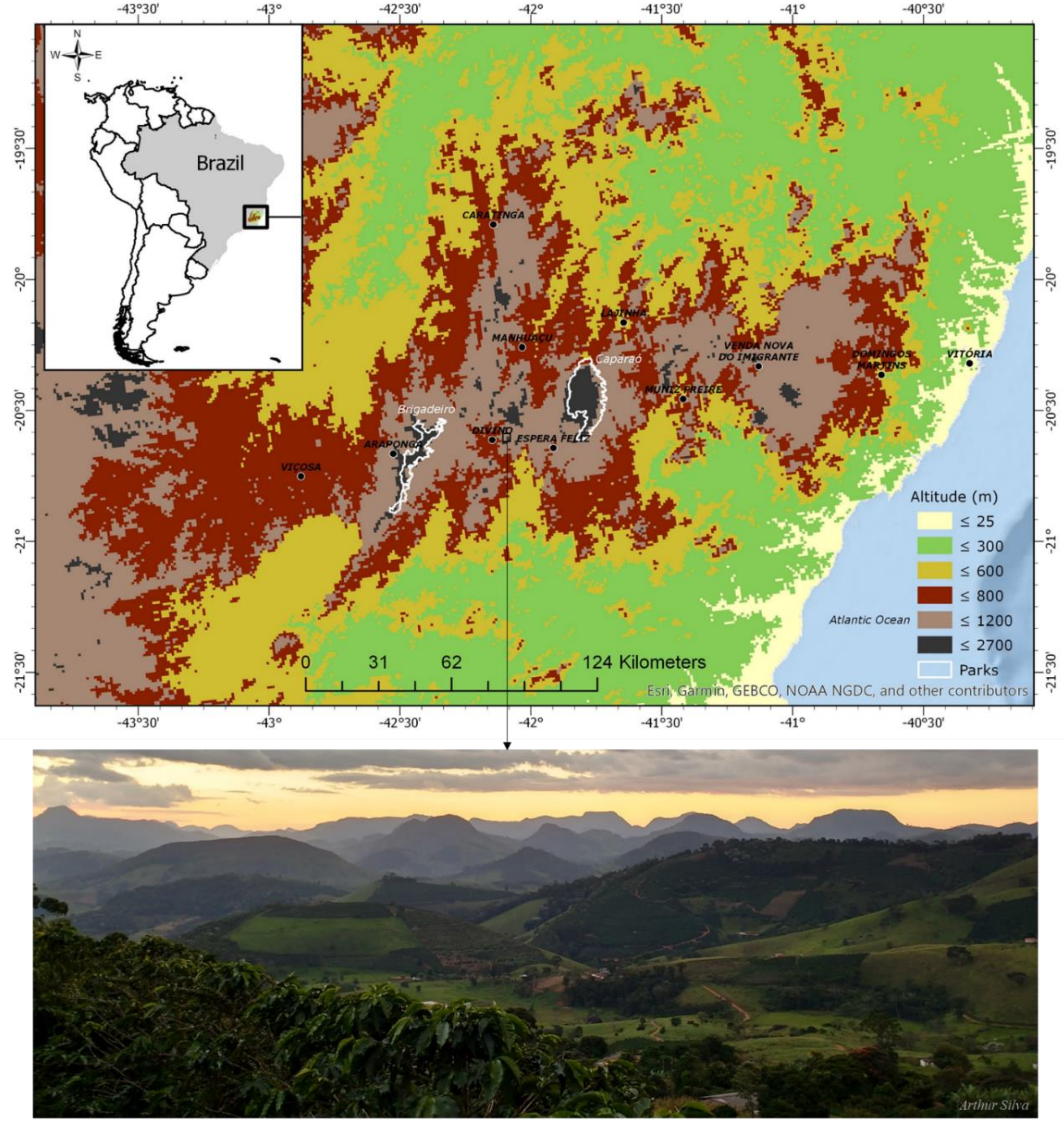


Figure 1.1. Southeast mountains of Atlantic Forest biome, Brazil, highlighting the altitude range and the protected areas (white lines).

The FOREFRONT Program

This PhD thesis forms part of the interdisciplinary and cross-country research program entitled FOREFRONT ("Nature's benefits in agro-forest frontiers: linking actor strategies, functional biodiversity and ecosystem services"). The program applies a landscape approach to agro-forest frontier areas, constituting dynamic borders between forested and agricultural land where both deforestation and reforestation can occur, in three sites of two Latin American countries, Brazil and Mexico. The three sites represent a diversity of social processes, institutions and practices shaping land use change and land use conflicts. The landscape approach entails an integrated vision of land use planning, policies, management decisions and relationships to maintain the resilience, productivity, biodiversity and sustainability of landscapes for the benefit of the people and nature (ecosystem services, nature's benefits to people). An integrated vision is crucially important to take into account the increasing complexity of land issues and the multiple and often competing claims on land. The program has three main objectives: (i) to identify and understand ecological and social drivers that shape agro-forest frontier landscapes and their ecosystem services; (ii) to explain temporal changes in the social-ecological system and their consequences for landscape configurations; and (iii) to design adaptive strategies to balance and optimise the supply of ecosystem services in changing landscapes.

The PhD candidates of the FOREFRONT program worked in collaboration, while each PhD candidate also developed and executed individual research projects, resulting in individual PhD theses. The collaboration process included international and local workshops attended by students and staff members, as well as frequent meetings among PhD candidates. The collaborative process allowed for the exchange of knowledge from different scientific disciplines. It also enabled the creation of complementary and synergetic links among the different projects, which together represent an interdisciplinary framework to assess the links between social actors, biodiversity, land use change and ecosystem services at multiple temporal and spatial scales.

Thesis objectives

The main objective of this thesis was to assess how historic changes in LULC have influenced the provision of ecosystem services in a context of socio-ecological systems, and to explore scenarios of LULC and climate change. Specifically, we addressed the following objectives:

1. To identify the temporal and spatial LULC changes and their main drivers from 1986 to 2015. Additionally, I aimed to project scenarios of LULC for the year 2045 under contrasting socioeconomic developments (Chapter 2).
2. To assess the spatio-temporal provision of several ecosystem services from 1986 with 2015 along an altitudinal gradient (Chapter 3).
3. To explore the effect of LULC changes and climate on historical water dynamics and under contrasting LULC scenarios to future scenarios under climate change (Chapter 4).
4. To identify the susceptibility of coffee production and the potential of agroforestry system management to mitigate the impacts of climate change in 2050 (Chapter 5).

Research methodology

In this research I used modelling approaches at the landscape level to assess LULC changes in the past and how this has influenced the provision of multiple ecosystem services relevant for coffee production and water dynamics. I complemented the assessment of historical dynamics of LULC and ecosystem services with explorations of how these dynamics may unfold in the future under scenarios of climate change (Fig. 1.2). In Chapter 2, I applied an interdisciplinary approach to assess the historical LULC changes and project future scenarios based on the Conversion of Land Use and its Effects (CLUE-S) modelling framework (e.g. Verburg et al. 2002, 2006, 2008). The interdisciplinary approach comprised three main steps. First, I assessed the LULC changes from 1986, 1995, 2007 and 2015 by combining data from satellite images at a resolution of 30 x 30 m and an automatic classification procedure using machine learning algorithms. Second, I identified the main drivers of LULC changes by conducting workshops with farmers and the analyses of secondary data. Finally, I combined information about LULC changes and the main drivers to forecast contrasting local LULC scenarios in the context of the global Shared Socioeconomic Pathway scenarios. In Chapter 3, I applied the spatially explicit InVEST model to map the spatio-temporal variation of multiple ecosystem services and assess the effect of LULC changes on the provision and interactions between ecosystem services. In Chapter 4, I applied the SWAT model to explore the effects of LULC changes and climate variability on water dynamics from 1990 towards 2045. For this, I used historical data on climate and river stream flow, as well as historical and future LULC maps developed in Chapter 2. In Chapter 5, I used the species distribution model MaxEnt to explore the effects of projected climate changes on coffee suitability for the study region. For this, I used historical climate data and future climate projections from 19 models from the WorldClim database. I also projected a scenario, where I estimated how the microclimate in agroforestry may affect the suitability for coffee production in 2050.

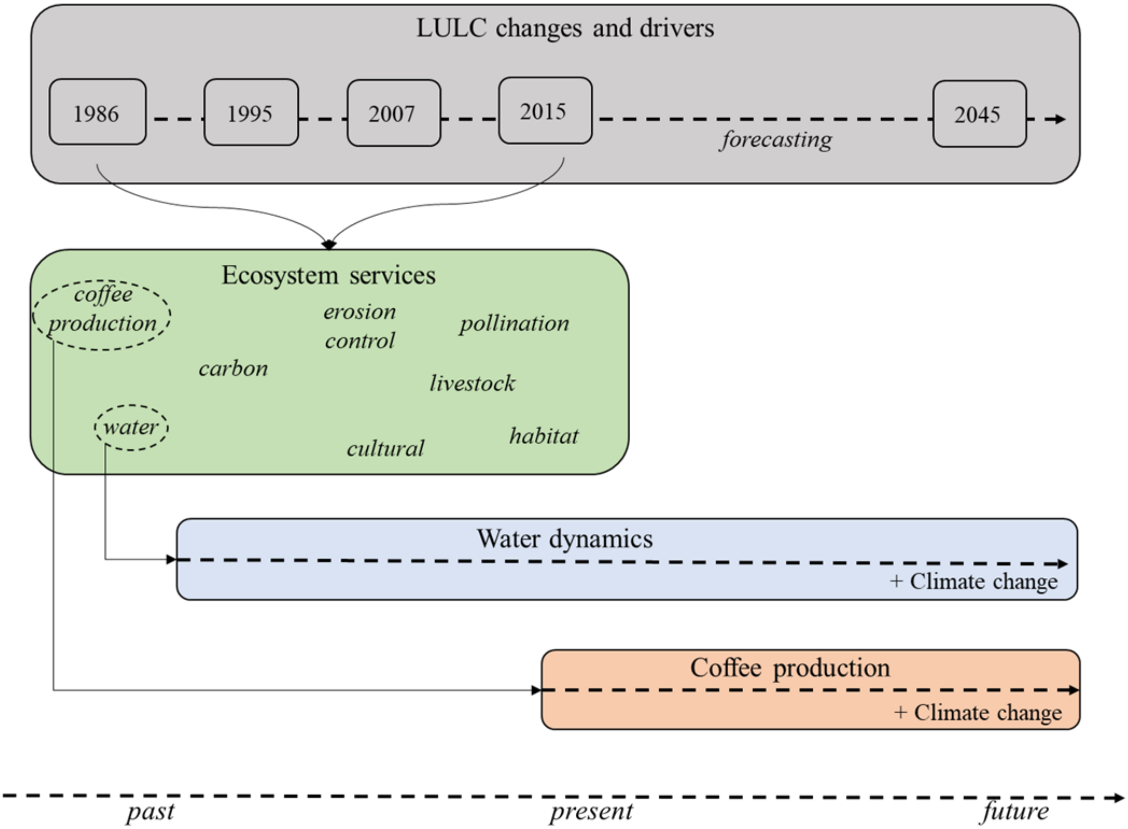


Figure 1.2. Structure of the PhD thesis indicating the analysis of LULC changes and their drivers (grey box), the spatio-temporal variation of ecosystem services (green box), the temporal analysis of water dynamic from past to future scenarios (blue box) and the suitability of coffee production from the current situation to the future (pink box).

Thesis outline

In **Chapter 2**, I mapped the LULC changes using satellite images from 1986 to 2015 and explored the main socioeconomic drivers of these changes, using historical data and workshops with farmers. Additionally, I simulated five LULC scenarios for 2045 under contrasting scenarios of socioeconomic development: Reference, Green Road, Rocky Road, Fossil Fuel and Inequality. For this, I applied an interdisciplinary approach building on the CLUE-S approach that combined LULC classification, scenarios development and forecasting modelling approaches.

LULC changes are the main factors involved in the alterations of the provision of ecosystem services. In **Chapter 3**, I explored the effect of LULC changes on eight ecosystems services and their trade-offs and synergies. Based on the LULC maps from 1986 and 2015, I mapped and analysed the changes in the following ecosystem services: carbon storage, pollination, habitat quality, erosion control, water regulation, coffee production, livestock and cultural service.

Changes in socioeconomic drivers can lead to changes in LULC, which in turn can influence the future provision of ecosystem services. However, this can also be influenced by climate change. In **Chapter 4**, I explored the effect of LULC on the water dynamics between 1986 and 2015 and analysed the impact of future changes in LULC and climate on the water dynamics.

In **Chapter 5**, I studied how future climate conditions can affect the suitability for coffee production in the study region in 2050. Additionally, I explored the potential of agroforestry systems to mitigate these impacts in a spatially explicitly way.

In **Chapter 6**, I integrated my chapters, exploring the provision of ecosystem services in a socio-ecological framework. I discussed my findings as components of the framework, and I analysed how this framework can contribute to anticipate the effect of socioeconomic changes on ecosystem services in the future. I also make recommendations for the application of the results and propose future research considerations.

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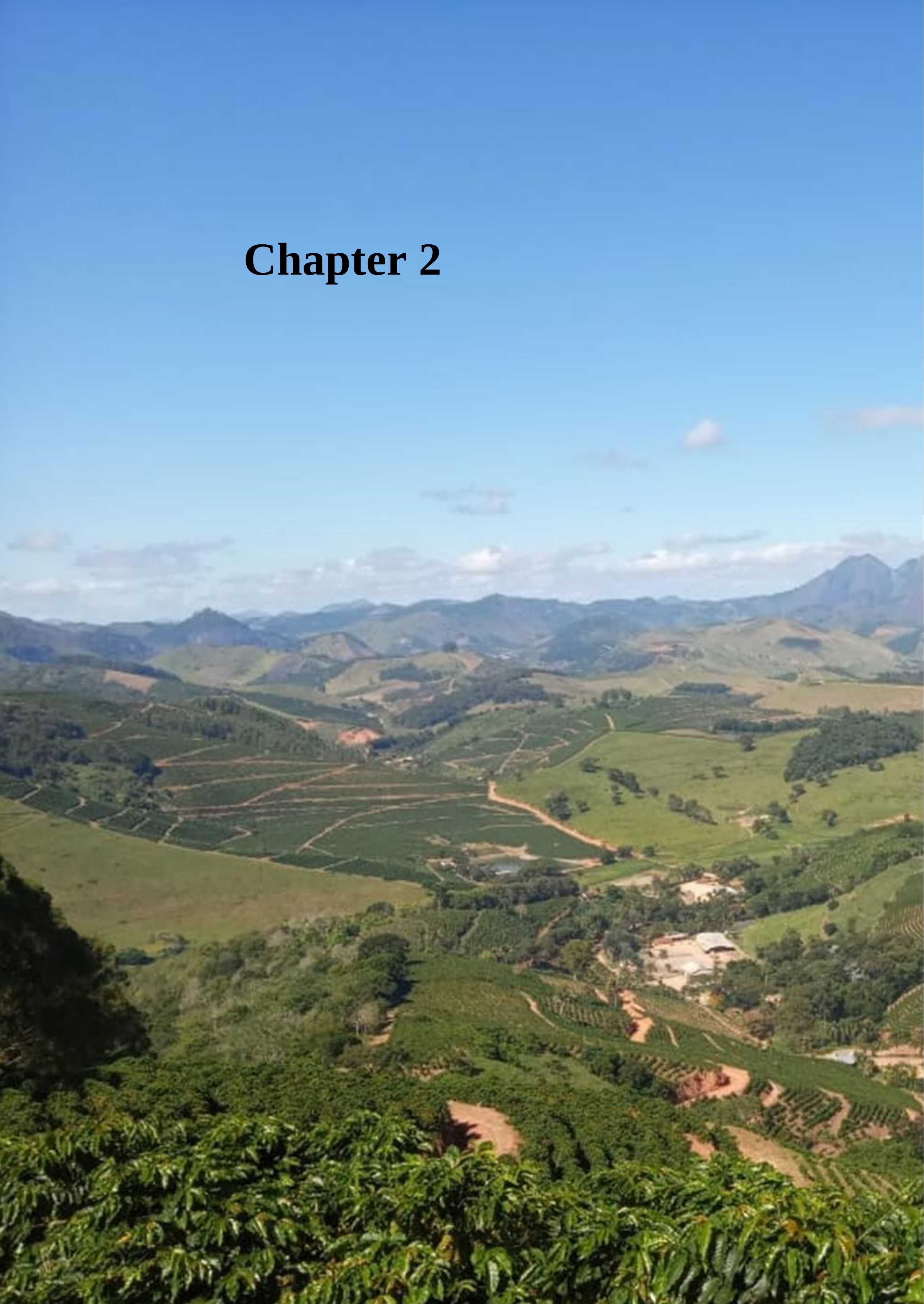
Chapter 2



Land use and land cover scenarios: an interdisciplinary approach integrating local conditions and the global shared socioeconomic pathways

Lucas C. Gomes
Felix J.J.A. Bianchi
Irene M. Cardoso
Rogier P.O. Schulte
Bas J.M. Arts
Elpídio I.F. Filho

Abstract

Land Use and Land Cover (LULC) changes have profound impacts on the functioning of (agro)ecosystems and have potential to mitigate global climate change. However, we still lack interdisciplinary methods to project future LULC scenarios at spatial scales that are relevant for decision making and future environmental assessments. Here we apply an interdisciplinary approach to develop spatially explicit projections of LULC at a resolution of 30 x 30 m informed by historic relationships between LULC and their key drivers, within the context of the four local qualitative scenarios in the context of global shared socioeconomic pathways. We apply this methodology to a case study in the Zona da Mata, Brazil, which has a history of major LULC changes. The analysis of LULC changes from 1986 to 2015 indicates that pasture area decreased from 76 to 58% of total area, while forest areas increased from 18 to 24%, and coffee from 3 to 11%. Environmental protection legislation, rural credit for smallholder farmers, and demand for agricultural and raw products were identified as main drivers of LULC changes. Projected LULC for 2045 strongly depends on the global socioeconomic pathway scenarios, and forest and coffee areas may increase substantially under strong government measures in the environmentally conscious Green Road scenario or decrease in the high consumption Rocky Road scenario. Our study shows that under the set of drivers during the past three decades reforestation can go hand in hand with increase of agricultural production, but that major and contrasting changes in LULC can be expected depending on the socioeconomic pathway that will be followed in the future. To guide this process, LULC scenarios at the local scale can inform the planning of local and regional development and forest conservation.

Introduction

Land Use and Land Cover (LULC) changes have profound impacts on the functioning of (agro)ecosystems and have potential to mitigate global climate change (Foley et al., 2005), but there is a lack of interdisciplinary methodological approaches to project future LULC scenarios at local scale based on global socioeconomic scenarios. Local LULC may change in response to economic drivers, social dynamics and environmental factors, and can have ecological, economic and social impacts at regional and even global scales (Lambin et al., 2001; Zhao et al., 2006). Exploring potential impacts of LULC changes on (agro)ecosystems by scenario analysis can inform decision making and supporting land use planning to strengthen socioeconomic development and nature conservation (Peterson et al., 2003).

Scenario analysis is widely used to explore pathways towards more sustainable land management (Duinker and Greig, 2007), and has been applied worldwide to build LULC scenarios in qualitative (Oduro et al., 2014; Wesche and Armitage, 2014) and quantitative terms (Han et al., 2015; Sleeter et al., 2012). Qualitative scenarios describe narratives or storylines of different socio-economic and/or environmental developments for the future (Tapinos, 2012). These scenarios are useful to engage with experts, land managers and policy makers to develop strategies to guide spatial planning and decision making at local and regional scales (Welp et al., 2006). However, the analysis of future scenarios of LULC can be enhanced when qualitative scenarios are coupled with quantitative modelling, resulting in a spatially explicit representation of LULC.

Spatially explicit modelling of LULC scenarios can inform how contrasting socioeconomic and environmental developments may play out in different landscape settings. A two-step process is often used for the projection of spatially explicit LULC scenarios: i) the assessment of future percentages of LULC classes, and ii) the allocation of LULC to landscape units (e.g., Verburg et al., 2002, 2006, 2009; Mas et al., 2014; Liu et al., 2017; Lin et al., 2011). The future LULC demand can be estimated by the story and simulation approach (Alcamo, 2008; Mallampalli et al., 2016), and spatial allocation of LULC types using models, such as the Conversion of Land Use and its Effect (CLUE-S) and Dynamics Land Systems (DLS) models (Verburg et al., 2002; Deng et al., 2008). LULC scenarios are often derived from global/regional qualitative or quantitative socioeconomic scenarios (e.g., IMAGE model; Global Europe 2050), which describe different trajectories of the economy, population, environment and agriculture of selected regions over time (Rounsevell et al., 2006; Sleeter et al., 2012). However, the coarse resolution of global LULC scenarios are not ideal for local applications.

Global narratives of socioeconomic and climate developments may be useful to inform the development of socioeconomic scenarios at the local scale, integrating local conditions in a global context (Nilsson et al., 2017). The global Shared Socioeconomic Pathways (SSPs) consist of five contrasting qualitative scenarios: Sustainability (Green Road), Regional Rivalry (Rocky Road), Inequality, Fossil-fueled Development, and Middle of the Road (Kriegler et al., 2012; O’Neill et al., 2014). These scenarios describe future changes in human dynamics, economy, policies and institutions, technology, environment, and natural resources at the global level (O’Neill et al., 2017;

Riahi et al., 2017). For instance, under the Green Road scenario there will be global cooperation, a limited growth of consumption, policies orientated toward sustainable development, and strong regulation of land use to avoid environmental externalities. On the other hand, under the Rocky Road scenario there will be a deglobalisation process, with weak governance and low priority for environment issues, and limited regulation of land use. While these scenarios allow a meaningful analysis of potential implications at global level, the relatively coarse resolution make these scenarios less suitable to study LULC changes at the regional scale and below (Doelman et al., 2018; Popp et al., 2014; Riahi et al., 2017). Therefore, there is a need for local plausible LULC scenarios, which reflect the local socioeconomic and environmental conditions, and are in accordance with global socioeconomic and climate projections.

Brazil is one of the world's biggest suppliers of agricultural products, such as coffee, soybeans, meat, and raw material as iron mineral, and has witnessed intense LULC changes. The Atlantic Forest biome is the fifth hotspot of biodiversity in the world (Myers et al., 2000). It supports 70% of the Brazilian population and, due to this anthropogenic pressure, the forested area has been reduced to only 12.4% of its original area (Sosma, 2019). In this biome, the region Zona da Mata of Minas Gerais was deforested in the 18th century. Over time, socioeconomic activities and public policies influenced the development of this region, which now consists of a mosaic of pastures, coffee fields and fragments of secondary forests, with a predominance of family farmers (Cardoso et al., 2001; Giovanini and Matos, 2004). The region is one of the three main areas of coffee production in Brazil and represents an interesting case study to analyse past socioeconomic development and to project future scenarios.

The aim of this study was to apply a methodological approach to project plausible spatially explicit LULC scenarios at relevant spatial scales to support land use policy making and future environmental assessments. Specifically, our objectives were (*i*) to assess LULC changes from 1986 to 2015, a period of profound changes in land use, in a selected area in the Zona da Mata region of Minas Gerais; (*ii*) to identify the main drivers of these changes, and, (*iii*) to create qualitative and quantitative socioeconomic scenarios and spatially explicitly projections of LULC for 2045 for the studied area in the context of SSPs scenarios.

Material and Methods

Study area

The study area covers 11,119 km^2 and is located in the Zona da Mata of Minas Gerais state. It borders the states of Espírito Santo and Rio de Janeiro in the Brazilian Atlantic Rainforest biome (Fig. 2.1). The study area includes the Caparaó National Park and the Serra do Brigadeiro State Park, which are protected areas for conservation and tourism. The climate is classified as humid subtropical, with hot and rainy summers and a well-defined dry season, and average annual precipitation of 1,300 mm (Alvares et al., 2013). The relief is hilly and mountainous, and the predominant soils are Ferrasols and Acrisols. The main LULCs in the region are pasture, forest, coffee, and since the 2000's eucalyptus plantations were introduced for wood biomass production. Forest areas consist typically of small and fragmented patches on hill tops. The pasture areas consist mostly by *Brachiaria spp*, to raise beef and dairy cattle in extensive systems. Coffee is mainly produced in monoculture/unshaded *Coffea arabica* systems, but there also some agroecologically managed agroforestry coffee systems (Souza et al., 2010).

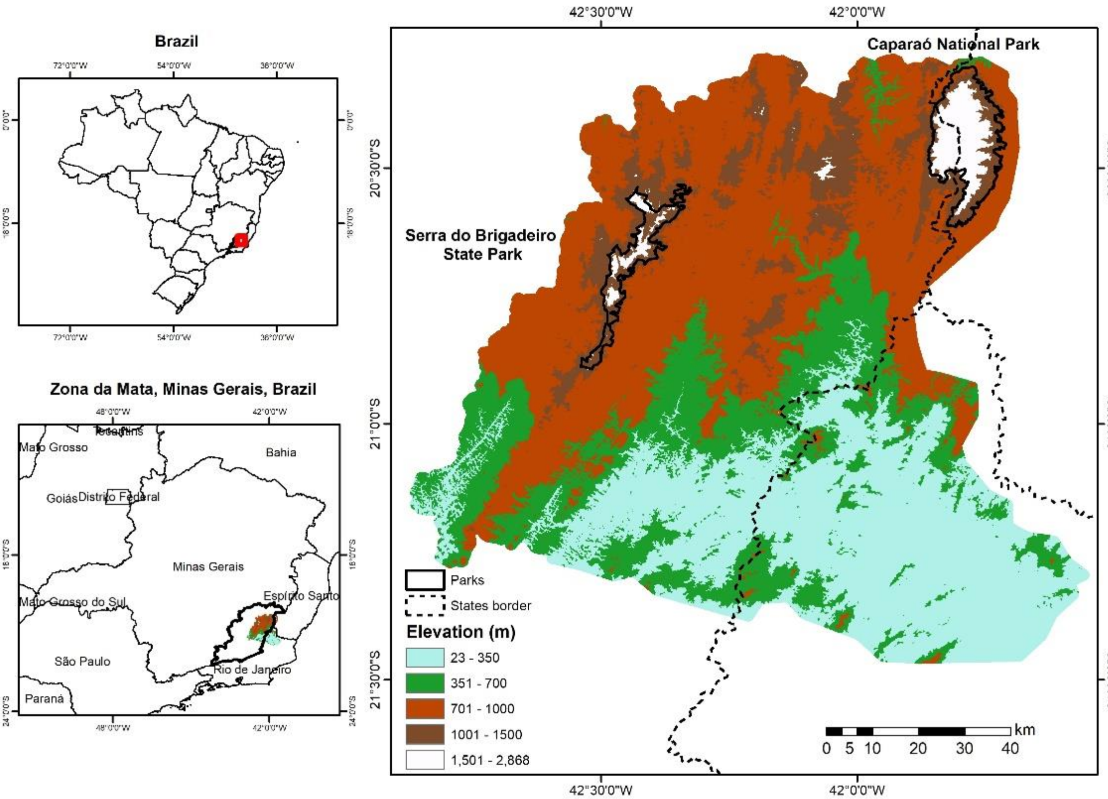


Figure 2.1. Zona da Mata, state of Minas Gerais, and its border with the states of Espírito Santo and Rio de Janeiro, Atlantic Forest Biome, Brazil.

The far majority of farmers in the study region are smallholders with 90 % of the farmers having less than 16 hectares of land (IBGE, 2018; Teixeira et al., 2018a). At the end of the 1980s the political and socioeconomic conditions had a negative impact on family farmer livelihoods and many farmers were struggling to maintain their agricultural activity (Cardoso and Ferrari, 2006). Since 2000, the national government has made efforts to financially support family farmers with the National Program for Strengthening Family Agriculture (Pronaf) and create a market for their produce with the Brazil's National School Feeding Program (Ghinoi et al., 2018; Valencia et al., 2019). In addition, over the last 30 years a strong social movement, integrating family farmers' organizations, has strived to implement agroecological practices, such as agroforestry systems, that reconcile nature conservation and agriculture production. In 1996, the 15,000 ha Serra do Brigadeiro State Park was created in a unique case of collaboration of social movements, non-governmental organizations (NGO), researchers and the state government.

Methodological framework

An interdisciplinary methodological approach was applied to generate spatially explicit scenarios of LULC for 2045 (Fig. 2.2, Verburg et al., 2006, 2008). First, we created maps of historic LULC (Section 2.3). Next, we identified the drivers of LULC changes through workshops with local stakeholders and historical data (Section 2.4) to build qualitative and quantitative scenarios (Section 2.5). Finally, we used a spatial allocation model to build maps of LULC for 2045 (Section 2.6). More specifically, the approach comprised five main steps: (1) map the LULC changes from 1986 to 2015; (2) identify the main socioeconomic drivers of these LULC changes in this period; (3) build and translate qualitative socioeconomic scenarios into quantitative estimates, with subsequent assessment of future LULC demands; (4) use biophysical variables to develop a predictive allocation model for the

LULC classes to landscape units; and (5) allocate LULC classes to landscape units by combining the future LULC area demand and the allocation model.

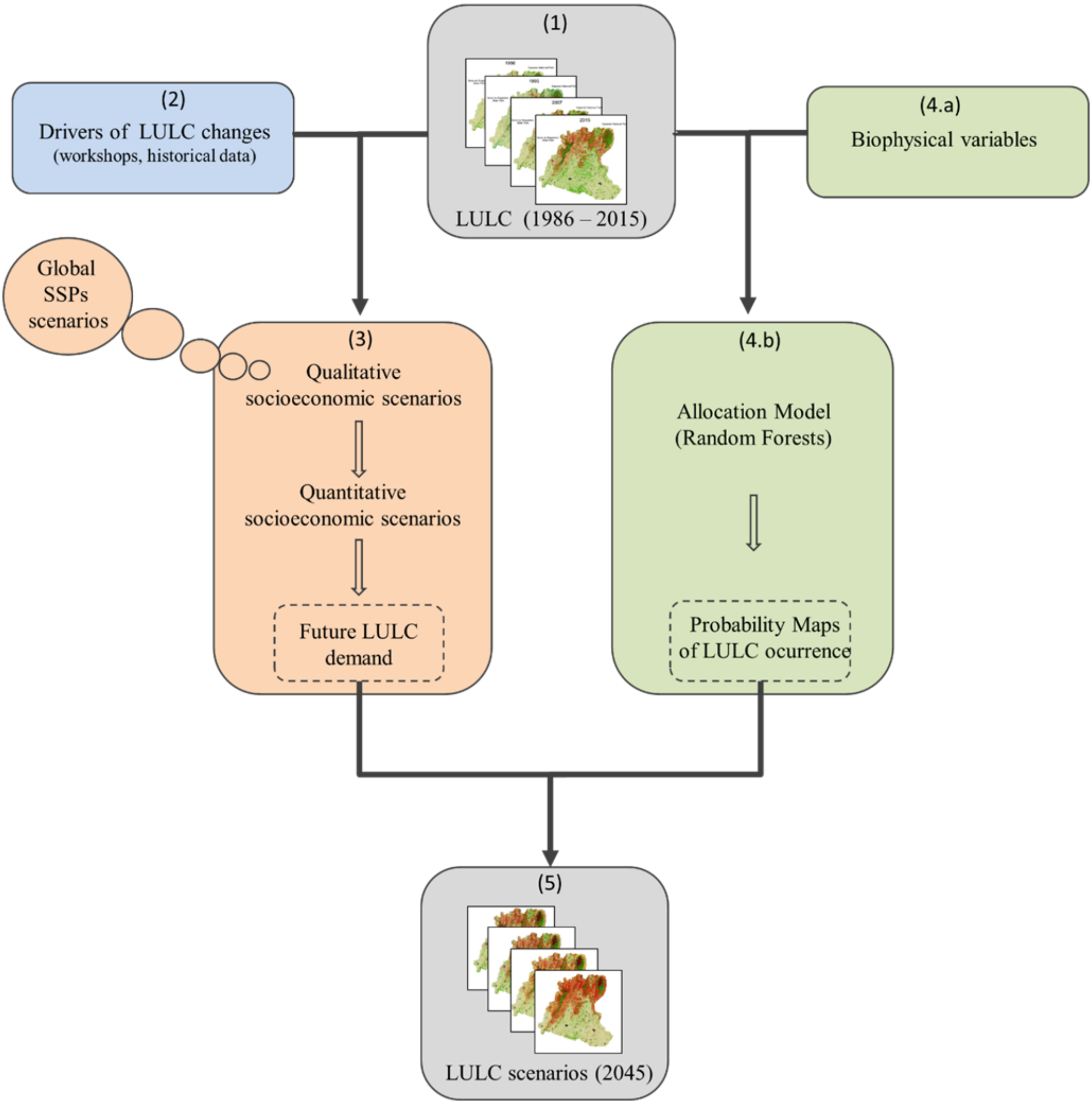


Figure 2.2. Methodological framework applied to build the spatially explicit future scenarios of Land Use and Land Cover (LULC).

Mapping past land use land cover

To assess LULC changes in the study area we used images of Landsat 5 and 8 from 1986, 1995, 2007 and 2015. We selected this period because major LULC changes took place in the study area and Landsat images with relatively little cloud cover were available for these years, allowing a meaningful assessment of the LULC changes across approximately a 30-year time period. The images were obtained from the United States Geological Survey Earth Resources Observation and Science Center with a resolution of 30 x 30 m (http://earthexplorer.usgs.gov/).

The images were processed using ArcGIS and were classified in six LULC classes: forest, coffee, pasture, urban areas, campo rupestre (scrub-grassy vegetation on rocks) and Eucalyptus. To classify the images, we collected sampling polygons (12 pixels each) for each LULC by visual interpretation of the Landsat images. The strategic sampling approach based on polygons allowed a better representation of the diversity of spectral characteristics from the same LULC type than an analysis based on a single pixel sample. This process created a database with about 2000 sampling polygons (24000 pixels), which reflects the area proportion of each LULC class in the study region. To separate the LULC classes we used the Landsat image bands (1 to 9), Normalized Digital Vegetation Index (NDVI) and Soil Adjusted Vegetation Index (SAVI) as predictor variables (Chakraborty et al., 2016). In addition, to further improve the separation of LULC classes in mountainous terrain we also included the distance from urban centre, the Digital Elevation Model (DEM), geomorphological variables derived from the DEM (e.g. slope, curvature) and solar radiation (Stathakis and Faraslis, 2014). The DEM was obtained from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) dataset with a resolution of 30 x 30m (http://earthexplorer.usgs.gov/). Then we extracted the values of explanatory variables for the location of pixel samples, generating a database of pixels with LULC types and associated explanatory variables. Next, we used the Random Forest algorithm to randomly select 75% of the data to train a predictive model, while keeping 25% of the data as an independent dataset to test the accuracy of the model using the Kappa index. LULC changes were assessed by the construction of a transition matrix of the images between 1986 and 2015, and an annual trend of each LULC was obtained by interpolation the data from the maps of 1986, 1995, 2007 and 2015.

Drivers of land use land cover change

To identify the main drivers that may have influenced these changes in LULC, we organized three workshops in the municipalities of Espera Feliz, Divino and Araponga that are representative for the study area in the Zona da Mata of Minas Gerais. The workshops were attended by 94 participants, which included family farmers, part-time farmers and the directors of the famer's union of the three municipalities. The workshops focussed on the identification of the historic development of LULC changes in the study region and their main drivers. Participants were asked to report their perceptions of changes in the percentage of forest, coffee, urban area and eucalyptus from 1986 to 2015 in a round table setting. This was followed by a discussion about the major socioeconomic and environmental drivers associated with the reported changes in LULC.

The identification of the main socioeconomic and environmental drivers of changes in LULC in the study region was informed by the outcomes of the workshop (Appendix 2.4). For instance, from the workshop it became clear that government measures to protect the environment, such as monitoring and high fines for deforestation, was an important driver for the changes in forest areas in the last decades. We used secondary data to triangulate and underpin the drivers that were identified in the workshop in a quantitative way. We used the annual deforestation rate data of the Atlantic Forest biome (Sosma, 2017) as a quantitative indicator for the effectiveness of government measures for forest protection (National Forest Code; Brasil, Lei 4771/1965). Likewise, to underpin drivers related to changes in the area of urban areas, coffee and pasture we used data on trends of rural and urban population densities from the Brazilian Institute of Geography and Statistics (IBGE, 2018) and from the population census of 1980, 1990, 2000 and 2010, data of the Rural Credit by the National Program to Strengthen Family Farming (PRONAF; Banco Central do Brasil, 2017), and coffee export data from the International Coffee Organization (ICO, 2017). National data on the production of coal and cellulose were derived from IBGE (2018). These socioeconomic and environmental data were interpolated to obtain a dataset with an annual resolution between 1986 and 2015.

The annual socioeconomic and environmental data from 1986 to 2015 were considered drivers for LULC change and used to explain changes in forest, coffee, eucalyptus and urban area LULC classes. We used multiple regression models with the annual percentage of each LULC class as the dependent variable and the drivers of LULC change (e.g., rural credit, urban population size) as independent variables (Appendix 2.3). These regression models were then used to predict the future LULC demands based on the future developments of the socioeconomic and environmental drivers (Reginster and Rounsevell, 2006).

Qualitative and quantitative scenarios

LULC changes are governed by local, regional and global drivers (Lambin et al., 2001). To develop qualitative scenarios that capture this diversity of drivers we combined a Scenario Development technique and the global socioeconomic SSP scenarios (O'Neill et al., 2014; Tapinos, 2012). This combination allows to create scenarios that capture local characteristics (e.g., national public policies, local population dynamics), but still align with the global SSP scenarios. Scenario Development involved three steps: (*i*) defining the scope of the scenario exercise, (*ii*) identifying the two most important drivers of LULC changes to define the dimensions for the scenarios (i.e. x and y axes in Fig. 2.6), and (*iii*) developing qualitative scenarios based on projected trajectories of the two main drivers. This approach resulted in four contrasting qualitative narratives (Fig. 2.6) as outlined below.

In the first step, we projected scenarios of LULC from 2015 to 2045, mirroring the temporal range of our 30-year historic dataset (1986 – 2015). In the second step, we analysed the results from the workshops and the secondary data to select the two key drivers that most influenced the changes in LULC. In the third step, we created a matrix of four contrasting local scenarios based on the two key drivers of LULC change (Wulf et al., 2010). For each of the four local scenarios we developed a storyline with qualitative descriptions of contrasting future socioeconomic and environmental developments. To build the four local scenarios in accordance with global future projections, we described the local socioeconomic and environmental developments following the assumptions of the four global SSPs scenarios (Green Road, Rocky Road, Inequality, Fossil-Fuel Development) (O'Neill et al., 2017). For instance, the Green Road SSP scenario describes a future development with low pressure on natural resources and effective international cooperation. Then, one of the four local scenarios was described in this context, with the socioeconomic and environmental developments focused on nature conservation and sustainable agricultural production. We applied the same process to develop the other three scenarios storylines. Specifically, the SSPs scenarios describe the future developments of public policies, socioeconomic and environmental factors in terms of relative scales (e.g., strong, weak, low, high, medium) (O'Neill et al., 2017). Based on the SSPs qualitative descriptions, we categorized the future tendencies to increase/decrease of each local socioeconomic and environmental driver in five classes: very low, low, moderate, high and very high. For instance, in the Rocky Road SSP scenario the global environment will be under "serious degradation" and land use will be "hardly any regulation; continued deforestation due to competition over land and rapid expansion of agriculture" (O'Neill et al., 2017). We used these global scenario assumptions to describe the socioeconomic and environmental factors in the local context (e.g., very high increase in deforestation rate), which enabled us to derive a local scenario in line with the global Rocky Road scenario.

To achieve the future demands of each LULC class (expressed in area units), we translated the socioeconomic qualitative scenarios into quantitative terms in a two steps process. First, we translated the future qualitative dynamic of each driver to quantitative estimates using Bayesian parameter estimation (Kemp-Benedict, 2010). Annual relative changes of each driver (e.g., rural credit) between 1986 and 2015 were assessed and rescaled to 5 class percentiles: very low (0.025); low (0.150); moderate (0.500); high (0.850) and very high (0.975) rates. Then we assigned relative driver rates (very low to very high) for each driver according to its description of future dynamics in the qualitative scenarios. Next, we extrapolated the future annual growth rate of each driver from the baseline year 2015 to 2045. For instance, a socioeconomic driver indexed as 100 in 2015 and has an annual growth rate of 1%, will amount 101 in 2016, 102.01 in 2017, and 134.78 in 2045. In the second step, we use these projected values of socioeconomic and environmental drivers in the multiple regression equations for each LULC class (section 2.4) to predict the future LULC demands in 2045 for forest, coffee, eucalyptus and urban area. For the area of Campo rupestre vegetation, which is not likely to change over time, we assumed that the area in 2045 will be the same as in 2015. Finally, we assumed that the percentage area that was not allocated to the above land use classes was pasture because in the workshop's farmers indicated even though pastures represent a major land use type, these are hardly managed and are not a priority in land use planning.

Spatial allocation of future LULC

The spatial allocation of future LULC was conducted using a predictive model (Verburg et al, 2002; Fuchs et al., 2013; Moulds et al., 2015) and involved four steps. First, we generated a transition matrix of the changes in LULC between 1986 and 2015. Second, we selected a set of spatially explicit socioeconomic and environmental variables (digital elevation model, slope, Euclidian distances from cities centres and rivers, precipitation and temperature from WorldClim database (Fick and Hijmans, 2017), which are plausible explanatory variables for the spatial distribution of LULC classes. Third, we selected a stratified random sample of 37800 pixels containing data from LULC classes and we used these to extract the respective values of explanatories variables corresponding to each LULC class. With the LULC class and associated explanatory variables as dependent and independent variables, respectively, we used the Random Forests algorithm to create a probability map of LULC based on the suitability of each pixel for the respective LULC classes. Fourth, the allocation algorithm was used to create a map of LULC based on the probability maps of LULC and the demand for the area per LULC class. The decision rules for LULC transitions in the allocation algorithm were based on the assumption that the transition matrix of LULC changes between 1986 and 2015 are representative for the period 2015-2045. We also assumed that new urban areas should expand only in the neighbourhood of existing urban areas and that areas currently protected may be subject to LULC changes in the future. The analysis was conducted using the LULCC package in R (Moulds et al., 2015; R Development Core Team, 2014).

To validate the allocation model, we created a predictive model from 1986 to 2007 and simulated the future LULC for 2015. The performance of the model was assessed by generating three-dimensional contingency tables, which compared the map of 1986, the simulated and actual map of 2015 (Pontius et al., 2011). This method allows to quantify and differentiate the allocation disagreement/agreement between observed and simulated maps within multiple resolutions. For instance, this method enables to separate agreement between maps due to persistence from agreement due to correctly simulated change. Here, we compared the model performance from 2 x 2 to 256 x 256 pixels resolutions. The agreement between the observed and simulated maps of 2015 was 67% at a 2 x 2 pixels resolution, consisting of the accurate prediction of 60% of all pixels with correctly simulated persistence of LULC and 7% of all pixels with correctly simulated change of LULC (Appendix 2.5). At a 256 x 256 pixels resolution the agreement increased to 92% (with an accurate prediction of 79 and 13% for correctly simulated persisting and changed pixels, respectively). This procedure strengthened our confidence that the performance of the model was satisfactory and that it can be used to make plausible projections of LULC in the study area. The model was used to generate LULC maps of 2045 for each of the four quantitative scenarios, and a reference scenario (RS), which was based on the extrapolation of LULC trends from 1986 to 2015 without scenario assumptions.

Results

Land use land cover classification and changes

The classification of past LULC change resulted in maps of the years 1986, 1995, 2007 and 2015 with a pixel resolution of 30 x 30 m with high accuracy (Kappa index > 0.81) (Fig. 2.3; Appendix 2.1). The covariates Digital Elevation Model, NDVI and SAVI indexes, satellite bands and solar radiation were selected as the most important predictors of LULC classes. The LULC maps indicated that the percentage pastures decreased from 76 to 58% between 1986 and 2015, while the forest area increased from 18 to 24%, coffee from 3 to 11%, and urban and eucalyptus increased in the same period (Fig. 2.3 and 2.4). The LULC changes from 1986 to 2015 were most profound for forest and coffee with 41.3% and 75.2% of the forest and coffee area in 2015 being converted from pasture. The majority of eucalyptus plantations (63%) were established in pasture, while 27% of eucalyptus replaced forest between 1986 and 2015 (Fig. 2.4; Appendix 2.2).

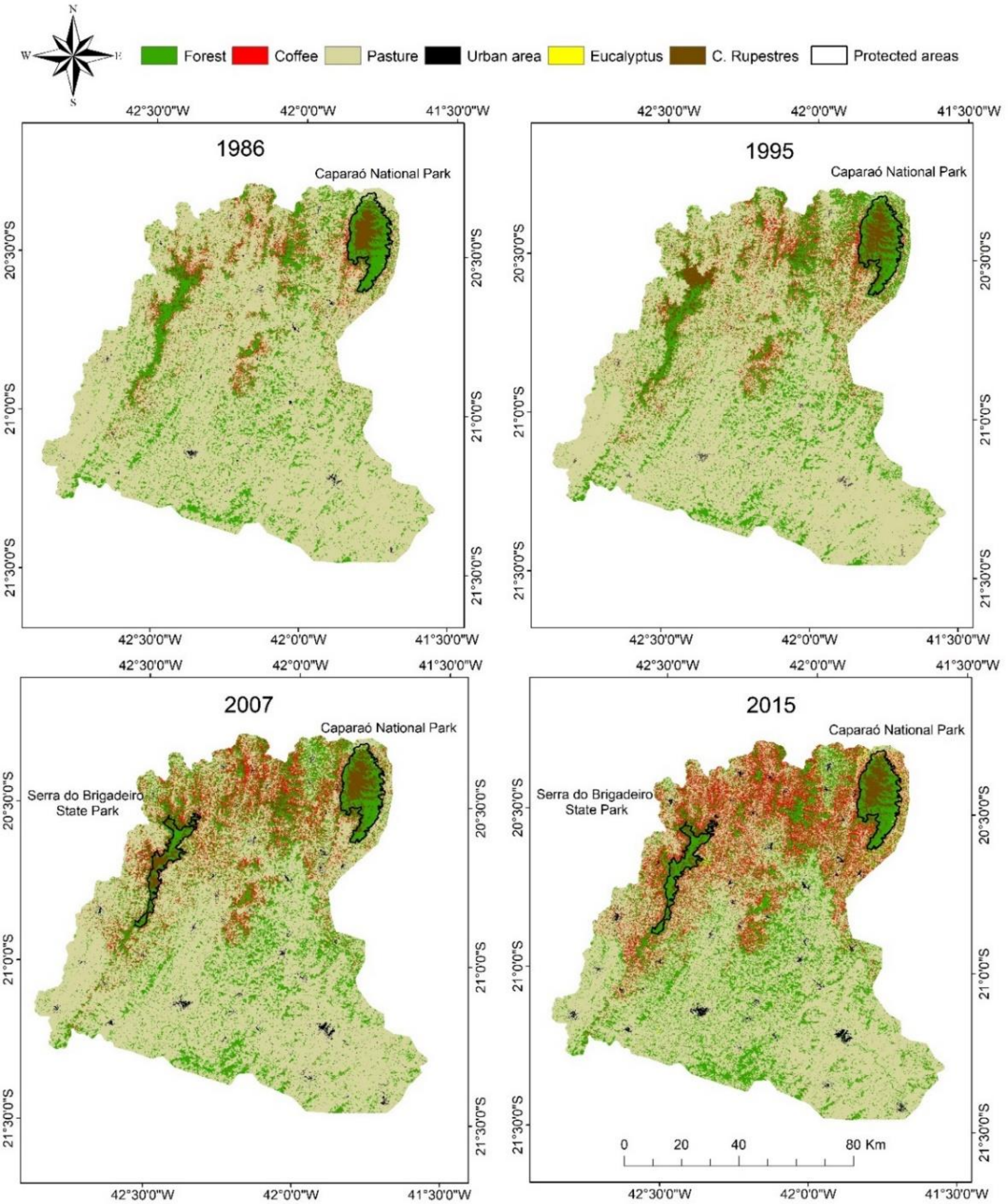


Figure 2.3. Land use and land cover maps in the Zona da Mata region, Brazil, of 1986, 1995, 2007 and 2015.

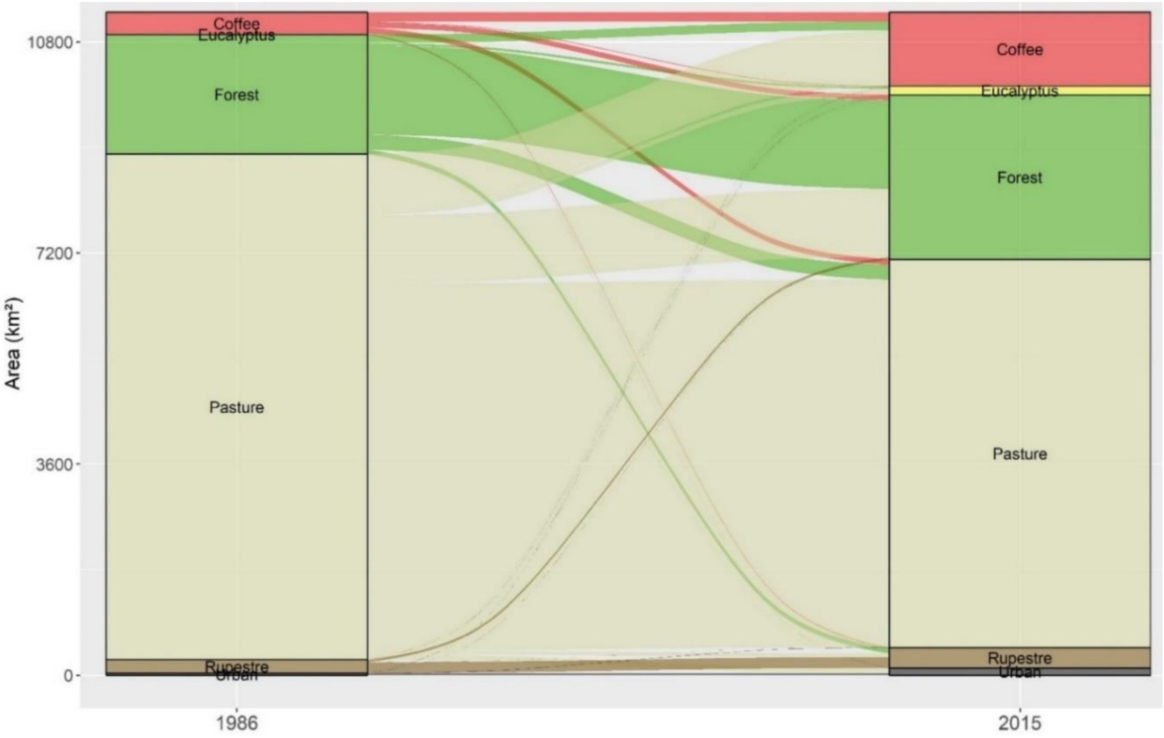


Figure 2.4. Transitions of land use and land cover for forest, coffee, pasture, urban, Eucalyptus and campos rupestres vegetation between 1986 and 2015. Each line represents one pixel (30 x 30 m) in the study area.

Drivers of land use land cover changes

A major outcome of the workshops was that participants perceived that government measures against deforestation (e.g., monitoring and surveillance), providing credit for family farmers, migration from rural areas to urban centers, and the founding of the Serra do Brigadeiro State Park were the main drivers of changes in LULC between 1986 and 2015. Deforestation rate of the Atlantic Rainforest biome decreased about 90% in this period, reflecting the effectiveness of the intensive monitoring programs by national environmental agencies. At the same time the rural population decreased from

50.2% to 25.1% of the total population (Fig. 2.5). Government credits for investment in the coffee production and livestock by family farmers increased steadily, amounting to almost 1 billion reais (Brazilian currency) per year in 2015. The export of coffee increased by approximately 380%, along with increases in the production of charcoal (265%) and cellulose (268%).

The temporal association of the socioeconomic and environmental drivers with the LULC classes resulted in multiple regressions that define the specific effect of each driver in each LULC class (Appendix 2.3). For instance, forest area was negatively associated with deforestation rates in the Atlantic Forest biome and public policies for rural credit for coffee and livestock production ($R^2 = 0.84$), while the coffee area was positively associated with rural credits for coffee production and annual rates of coffee exports ($R^2 = 0.94$). Urban area was positively associated with the increase of urban population ($R^2 = 0.84$), and the demand of charcoal and cellulose explained the establishment of eucalyptus plantations ($R^2 = 0.84$).

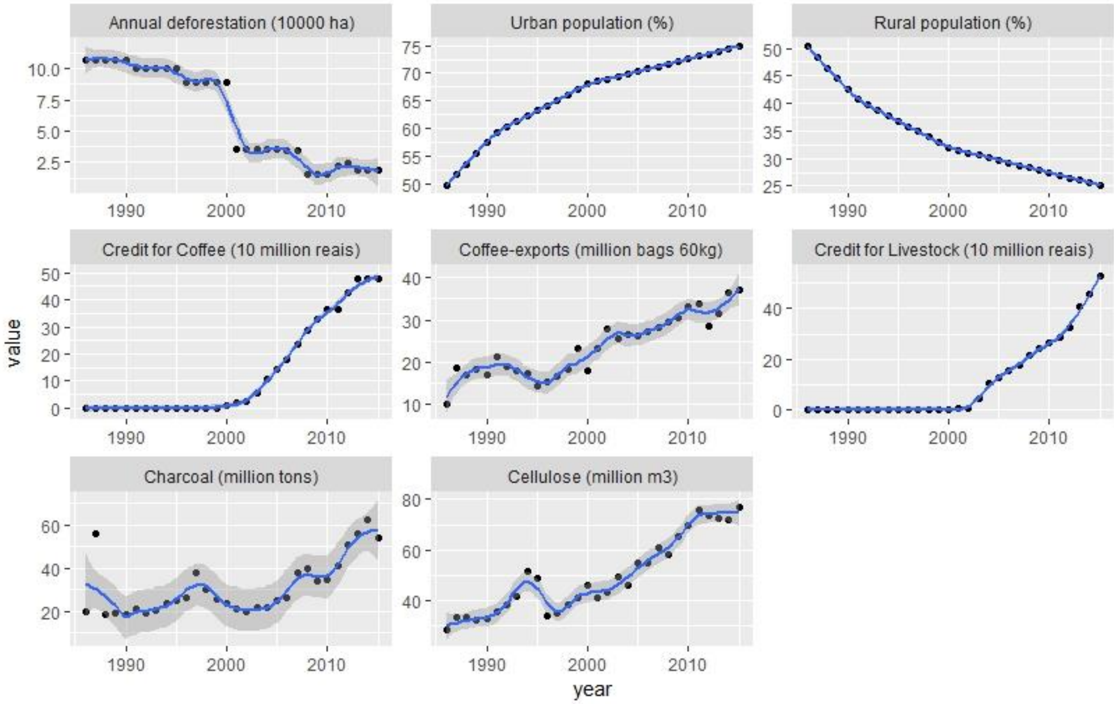


Figure 2.5. Trends of the main drivers of land use land cover changes from 1986 to 2015, with multi-annual trends indicated by the blue smoothing lines. Reais is the Brazilian currency.

Qualitative narratives and quantitative scenarios

Overall, the results from workshops and the analysis of historical data indicated that the government measures (e.g., credit for farmers) and the degree of environmental protection were the most influential drivers of the LULC changes. Based on these two main drivers we created four scenarios (Fossil Fuel, Green Road, Rocky Road, Inequality) in the context of SSP scenarios, with the vertical axis representing the high and low government measures and the horizontal axis representing low high and low environment protection (Fig. 2.6).

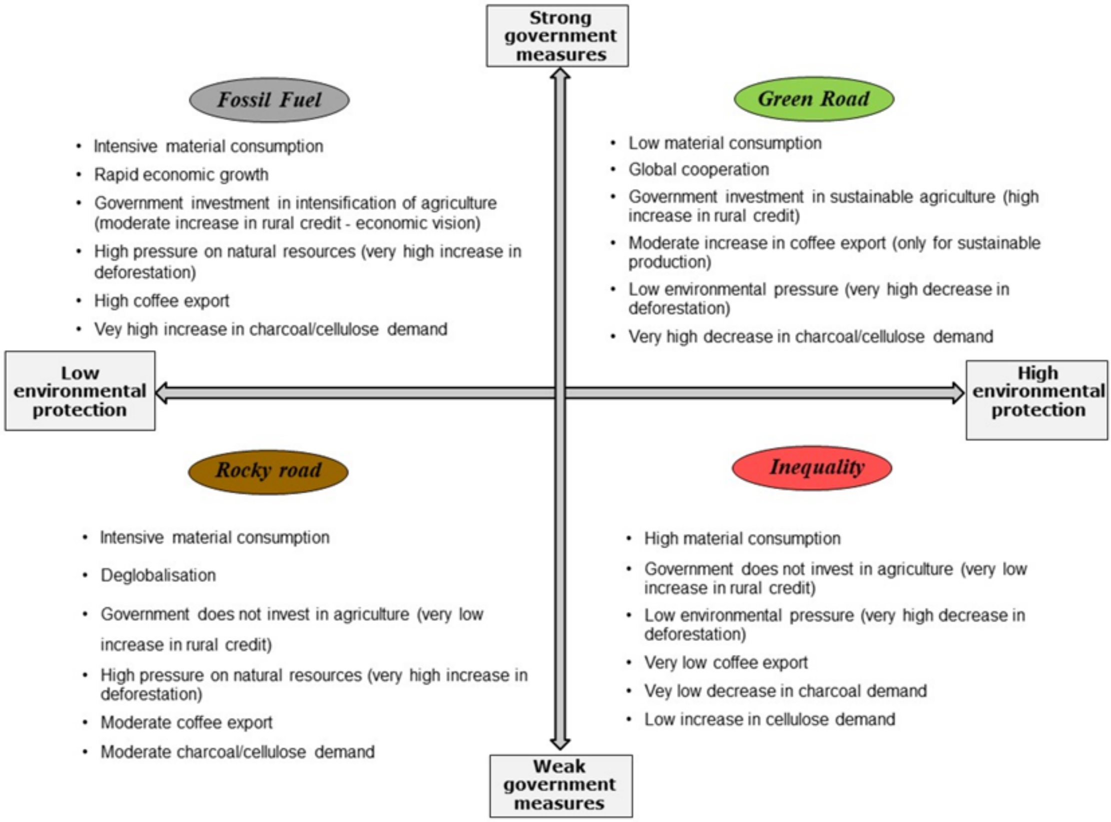


Figure 2.6. (Figure continued on next page)

The **Green road** scenario is characterized by **strong** government measures and by **high** environmental protection in a world with low material consumption and effective international cooperation. This implies that the coffee exports will increase, while the demand of charcoal and cellulose will decrease. The policy orientations will evolve towards sustainable development and will change from fossil fuel to renewable energy sources. There will be strong LULC regulations to avoid environmental trade-offs and improvements in agriculture productivity with rapid diffusion of best practices (e.g., agroforestry systems).
The **Fossil fuel** scenario is characterized by **strong** government measures and by **low** environmental protection in a strongly globalized world with focus on materialism and intensive consumption. This implies that the areas of coffee production and eucalyptus will increase in response to the growing world demand for coffee, steel and cellulose. In this scenario, policies will pay little attention to global environmental problems, focusing instead on highly managed and resource intensive agriculture. This process will be followed by a weakening of environmental legislation, which will result in high pressure on natural resources.
The **Rocky road** scenario is characterized by **weak** government measures and by **low** environmental protection in a world in a process of deglobalization, with intensive material consumption and weak international trade. This implies that the coffee exports will decrease, while eucalyptus plantations will increase to supply the demand for charcoal for the local industries. There will be weak government measures to protect the environment, with no regulations against deforestation and very low investment in agriculture.
The **Inequality** scenario is characterized by **weak** government measures and by **high** environmental protection in a world with high inequality between and within countries, moderate international trade and high consumption in developed countries and by rich people in developing countries. This implies that the policy orientation will benefit political and businesses elites, with increased agricultural production in large scale industrial farming, but not in small scale farming. This will lead to declines in the area of coffee and eucalyptus areas. The national government will not focus on sustainability. However, the local population and social organizations will be motivated to find local solutions for sustainability and nature conservation. The local farmers will use agroforestry systems to manage coffee and pastures, and famers organizations will mobilize the local society to conserve nature.

Figure 2.6. Qualitative future scenarios (Green Road, Fossil Fuel, Rocky Road and Inequality) of land use cover of 2045 in the context of shared socioeconomic pathways (SSPs).

The four qualitative scenarios (Green road, Fossil fuel, Rocky Road and Inequality) gave rise to different estimates of future annual rates for the socioeconomic and environmental drivers (Table 2.1). Adopting 2015 as a baseline, deforestation rates increases 8.9% per year in the scenarios Fossil Fuel and Rocky Road, and decrease 17.8% per year in the scenarios Green Road and Inequality. The investment in credit for coffee and livestock reaches the highest rate in the Green Road scenario (7.3% per year) and the lowest values for Rocky Road and Inequality with an annual decrease of -6.7% per year. Coffee export tends to increase in all scenarios, with the annual rate ranging from 4.46% (Fossil Fuel) to 0.3% (Inequality). The demand of charcoal and cellulose increases by about 3.6% per year in the scenarios Fossil Fuel and Rocky Road, and decreases about 2.3% per year in the Green Road and Inequality scenarios.

Table 2.1. Projected annual rates for the drivers of Land Use and Land Cover (LULC) changes derived from Bayesian analysis for four contrasting future scenarios.

LULC	Drivers of LULC	Annual growth rates (%) - Bayesian parameters			
		Fossil Fuel	Green Road	Rocky Road	Inequality
Forest	Deforestation	8.947	-17.754	8.947	-17.75
	Credit for livestock and coffee	1.175	7.317	-6.734	-6.734
Coffee	Credit for coffee	1.222	2.94	0.008	0.008
	Coffee export	4.46	2.97	0.5	0.3
Urban area	Urban population	0.669	0.669	0.669	0.614
Eucalyptus	Charcoal	3.902	-1.5	3.265	-1.5
	Cellulose	3.533	-2.918	3.533	-2.918

Predictive allocation model and future scenarios

The LULC demand for 2045 indicates that forest area is expected to increase by 52.4% in the environmental scenario Green Road, and decrease by 41.7% in the scenario Rocky Road compared to 2015 (Table 2.2; Fig. 2.7). On average the coffee area is expected to grow by 111% in the Green Road, Fossil Fuel, and Reference scenario, while decreasing by 3.6% in the Rocky Road and Inequality scenarios. In contrast to coffee area, pasture area tends to decrease on average by 32% in the Green Road, Fossil Fuel, and Reference scenarios, and increase 8% in the Rocky Road and Inequality scenarios. The area of eucalyptus is expected to increase by 257% in the Reference, Fossil

Fuel and Rocky Road scenarios, while decreasing by 99% in the Green Road and Inequality scenarios.

Table 2.2. Projected land use and land cover areas in the Reference, Green Road, Rocky Road, Fossil Fuel, and Inequality scenarios in 2045, and the percent change as compared to the base year 2015.

Land Use/Cover	Base year (2015)	Future scenarios (2045)				
		Reference	Fossil Fuel	Green Road	Rocky Road	Inequality
	Area*1000 ha (Gain/Loss %)					
Forest	280.8	368.6 (31.3)	188.2 (-32.9)	427.9 (52.4)	163.5 (-41.7)	270.4 (-3.6)
Coffee	125.7	310.2 (146.7)	247.6 (96.9)	239.5 (90.5)	123.4 (-1.8)	120.6 (-4.0)
Pasture	662.0	335.3 (-49.3)	590.6 (-10.7)	411.4 (-37.8)	743.0 (12.2)	688.3 (3.9)
Urban area	12.2	22.5 (84.2)	16.7 (35.9)	16.6 (35.9)	16.6 (35.9)	16.1 (31.5)
Eucalyptus	14.98	58.9 (293.1)	52.6 (251.4)	0.09 (-99.3)	49.0 (227.2)	0.09 (-99.3)
Rupestre	34.82	34.8 (0.0)	34.8 (0.0)	34.8 (0.0)	34.8 (0.0)	34.8 (0.0)

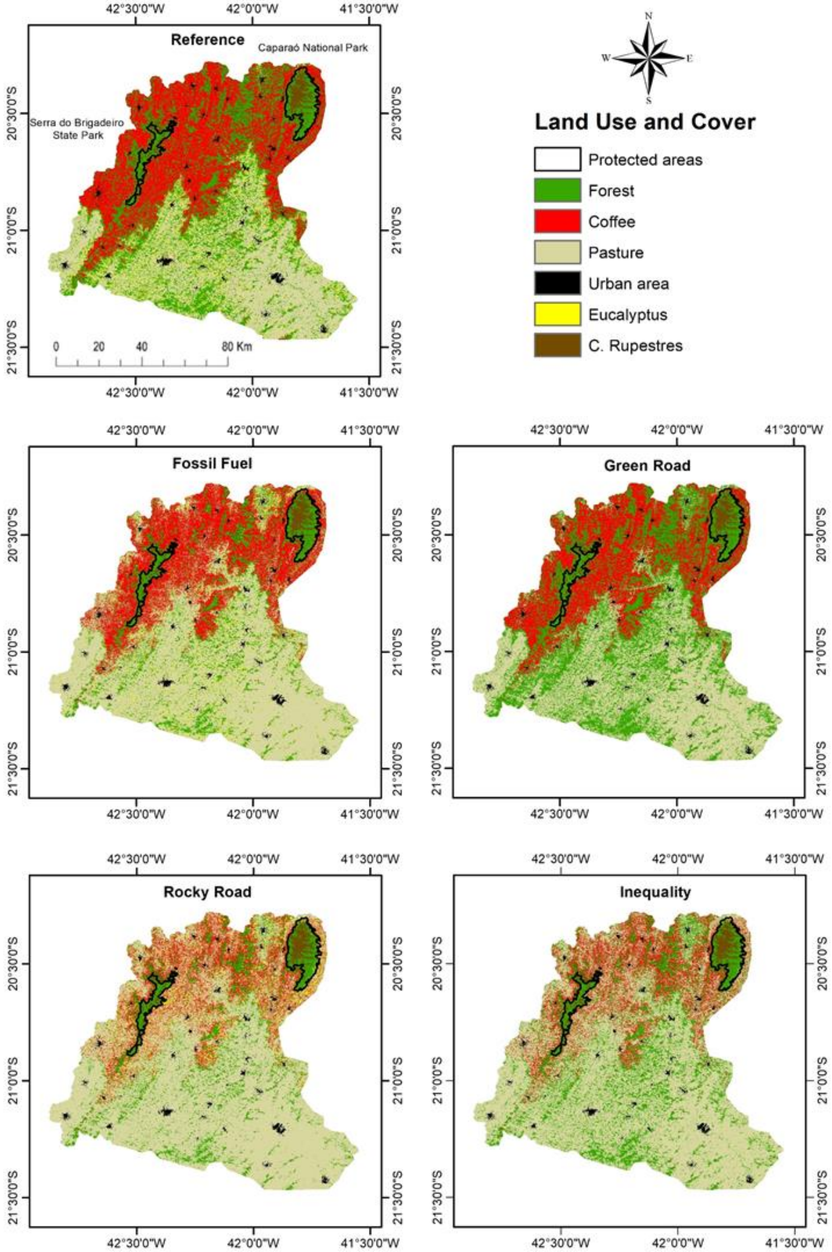


Figure 2.7. Projected land use and land cover of the Reference, Green Road, Rocky Road, Fossil Fuel, and Inequality scenarios in 2045, Zona da Mata of the Minas Gerais state, Brazil.

Discussion

Effects of drivers on LULC and future scenarios

Between 1986 and 2015 the area of forest, coffee, eucalyptus, and urban areas has increased in the Zona da Mata, which are likely driven by government measures and economic dynamics at local and global scales, among other drivers. However, these trends may change depending on the socioeconomic scenario that will unfold in the future. For instance, forest and agricultural areas may decrease in the Rocky Road scenario, and increase in the Green Road scenario.

Forest recovery was associated with government enforcement against deforestation and public policies, and the declining rural population. During the last two decades the policies have increasingly restricted deforestation, increasing the surveillance in the rural areas with real time monitoring, rural patrols and high fines. The effectiveness of public policies to decrease the deforestation has been reported as a key factor to protect the forest in Amazon biome (Arima et al., 2014). Another factor that contributed to decreasing the pressure on forest areas were the public policies for investments in agriculture, especially in coffee production and livestock (Fig. 2.5). The sustainable intensification of agriculture enables the increase of the productivity per unit area, reducing the need to convert forest into farmland (Garrett et al., 2018; Tilman et al., 2011). In the study region, the rural population decreased by 50% between 1986 and 2015 as a result of the large-scale migration of family farmers to urban centers in Brazil in the 1980' and 1990's, with the promise of jobs and a better life in the cities (Lobo, 2016).

The recovery of forest provides an inspiring example of how public policies against deforestation and financial support of farmers can be effective in reconciling agricultural production and environmental protection.

The 6% increase of forest area, after many years of deforestation, is an indication of a world phenomenon known as Forest Transition (Mather, 1992; Rudel, 1998). This phenomenon has been reported for developed countries, while in many developing countries the deforestation rates are still accelerating (Rudel et al., 2005). Our study is the first one to highlight, with satellite images, the forest recovery and suggest that a Forest Transition phenomenon is occurring in this region of the Atlantic Forest biome. However, should policies stop the protection of the environment and support for farmers, our scenarios project a decrease in forest area by 41.7% by 2045 in the Rocky Road scenario. On the other hand, in the Green Road scenario, forested areas are projected to increase by 52.4%, due to additional regulations to protect forests and increased investments in agriculture and livestock. Tropical forests are important sinks of carbon dioxide from atmosphere, but in most of these areas the drivers of forest dynamics are still unrevealed. The identification of the main drivers of forests dynamics at local scale and the analysis of future scenarios can orient local, regional and global measures to protect and expand forest.

Government investment in agriculture and livestock in the last two decades supported the increase of the area of coffee from 3 to 11%, and cattle stock from 600,000 to 830,000 animals from 1986 to 2015 in the study area (Statistical yearbooks-IBGE), despite an 18% decrease pasture area. Public policies (especially the Pronaf) that provide credit specifically for coffee production are one of the main reasons of the consistent increase of coffee area, making it possible for the small farmers to invest in machinery (e.g. brushcutter, coffee dryer, harvest machine - mechanical shakers), and management of the coffee plantations. Global demand for coffee increased over the last 30 years and this is projected to continue for the foreseeable future (OIC, 2017). The study region has ideal growing conditions for coffee production, and the introduction of agroforestry systems, already established in the region, has potential to maintain coffee production in the future (Souza et al., 2012a). The scenario analysis indicated (without accounting for impacts of climate change) that coffee areas may expand by almost 100% in the Fossil Fuel and Green Road scenarios due to public policies, while a 3.6% reduction is expected in absence of government measures in the Rocky Road scenario. Therefore, this region can contribute to supply the increase in the global demand for coffee under the Fossil Fuel and Green Road scenarios.

Land use changes are often driven by international commodity chains that support the global consumption (Lambin and Meyfroidt, 2011), highlighting the complexity and cross-scale interactions of drivers of local LULC. In our study area the global demand of iron mineral and cellulose in the last decades coincided with the increase of eucalyptus plantations. The fast growth of the economy of China in the early 2000's boosted the global demand for steel (Holloway et al., 2010) and fueled the export of iron ore from Brazil. Unlike other countries that use mineral charcoal to process iron minerals, in Brazil the charcoal from trees is mostly used, especially from eucalyptus. The world demand for steel therefore increased the value of eucalyptus wood and government agencies and private companies encouraged farmers to plant eucalyptus. Furthermore, the global decline of coffee prices in the 2000's, resulting from increased production in Brazil and Vietnam, also motivated farmers in the studied region to plant eucalyptus. Indeed, in the scenario of Fossil Fuel and Rocky Road with higher global demand of steel, an increase of eucalyptus area up to 251% may be anticipated. Our study suggests that the context of global drivers, such as expressed in SSPs scenarios, can have profound and case study specific impacts on local drivers of LULC and the associated LULC change.

Developing qualitative and quantitative socioeconomic and environmental scenarios at the local scale is important to detect local characteristics (e.g., specific crops), which are extremely important to local LULC changes, but may be overlooked when analysing at national or global level. Moreover, the advantage of creating future scenarios of LULC consistent with the global SSPs assumptions is the possibility to explore the future impact of LULC changes on ecosystem services (e.g., water availability) in line with well-established scenarios for environmental variables (e.g., temperature, precipitation).

Methodological considerations

We applied an interdisciplinary methodological approach to develop spatially explicitly scenarios at the local scale by integrating historic LULC changes, qualitative and quantitative socioeconomic scenarios inspired by global SSP scenarios, with subsequent estimation of LULC demand and the spatial allocation of LULC classes. Our interdisciplinary methodology follows the same steps as the multi-model CLUE-S approach (e.g. Verburg et al., 2002, 2006, 2008) that has been extensively applied worldwide to project LULC scenarios at different scales (Kucsicsa et al., 2019; Lin et al., 2007; Enríquez-Dole et al., 2018). In the CLUE-S methodology local LULC scenarios can be generated based on LULC maps and future socioeconomic scenarios (Verburg et al., 2006). However, this may pose a problem in situations where there is a scarcity of LULC data and socioeconomic scenarios at regional or local scales, such as in many developing countries. To overcome this information gap, we generated LULC scenarios at the local scale using open access methods and data. For instance, we used freely available Landsat images and the Random forest algorithm to classify past LULC trends. In addition, we applied a scenario development technique to develop local future narratives (Tapinos et al., 2012), and we used Bayesian regression analysis (Kemp-Benedict, 2010) to translate these qualitative socioeconomic scenarios into quantitative terms. This methodology has weaknesses and strengths, which will be discussed below.

The applied approach has several limitations. The first is that identification of LULC changes by contrasting two independently created maps can give rise to inaccuracies due to map error classification, and therefore resulting LULC maps need to be interpreted with care. Second, while our study demonstrates that combining local scenario development and global SSPs scenarios is a promise way to develop plausible local future scenarios consistent with global future projections, the translation of the implications of global scenarios to local drivers of LULC entails many uncertainties. The participation of farmers in the workshops was essential to identify and understand the drivers of historical LULC changes, since farmers are key actors that make land use decisions and have a good perception of their socioeconomic and environmental impacts (Ariti et al., 2015). The participatory component and on the ground impact of our methodology could still be further improved by discussing the outcomes of our analysis with relevant stakeholders, farmers, civil society and policy makers, and explore implications for future landscape planning and rural development (Nilsson et al., 2017; Palazzo et al., 2017; Häfner, et al., 2018; Gullino et al., 2018).

The estimation of the future LULC demands using the Bayesian regression analysis allows to translate qualitative scenarios to quantitative terms in a systematic way. Expert judgment is the most commonly used method to translate narratives to numerical values, but is dependent on expert knowledge (Mallampalli et al., 2016). Using Bayesian statistics, we derived annual future rates for the socioeconomic drivers without the subjectivity of a translation process. We linked quantitative estimates of drivers to LULC demand using regression analysis, which has been widely used to determine the effect of the driver in specific LULC classes, such as the built areas in Europe (Reginster and Rounsevell, 2006), and multiple LULC classes using dynamic system models (Liu et al., 2017). In our study we made the simplifying assumption that historic relationships between the main drivers and LULC changes will remain unchanged in the future. However, recent advances in non-stationary modeling of future LULC scenarios (McGarigal et al., 2018; Wang et al., 2019) open opportunities for accounting for the complexities of feedbacks and further improve land use models (Verburg et al., 2019). Yet, despite these technical advances, uncertainty about the interactions between drivers and wider developments in society in the future is a general yet unresolved issue in LULC scenarios studies, and therefore these need to be interpreted with care. The presented interdisciplinary methodology can be useful for scenario analysis in regions where historical LULC maps and future projections of socioeconomic and environmental developments are lacking. For future studies and depending on data availability, we also suggest including more assumptions of SSPs, related to demography, health and economy, which can further improve the quality of integrative future scenarios.

Conclusions

In this paper we show that in the past three decades forest and agriculture areas have expanded at the expense of pasture area in the Zona de Mata, Brazil, and that these LULC changes were likely be driven by government measures. The projected LULC for 2045 strongly depends on the global socioeconomic pathway scenarios. The Green Road scenario indicates that government measures to protect the environment, such strong regulations and monitoring, and agricultural credit for family farmers may contribute to balancing forest conservation and agricultural production. In contrast, the high consumption Rocky Road scenario may result in substantial deforestation. While the prediction of future LULC changes is fraught with uncertainties, LULC scenario analysis can assist in planning of socio-economic development and forest conservation efforts by providing quantitative estimates of the likely consequences of these efforts.

Appendix 2.1. Performance indicators for the LULC (kappa and accuracy) classification and best predictors.

Maps (year)	Kappa	Accuracy	Best predictors (order of importance)
1986	0.87	0.91	NDVI, SAVI, DEM and band 6 and 4
1995	0.86	0.89	DEM, SAVI, NDVI, solar radiation 1 and 2
2007	0.84	0.87	DEM, SAVI, NDVI, band 6 and 3
2015	0.94	0.95	band 5, DEM, band 4, band 3, band 7

band = satellite bands, NDVI = normalized difference vegetation index, SAVI = soil adjusted vegetation index and DEM = digital elevation model.

Appendix 2.2. Transition matrix of Land Use Land Cover (% of total area) from 1986 to 2015. The values in each column show the percentages of each LULC in 2015 that was converted from other LULC classes from 1986.

LULC		Forest	Coffee	Pasture	Urban	Rupestre	Eucalyptus
		2015					
Forest	1986	54.04	11.79	3.84	0.70	23.71	27.42
Coffee		3.24	12.76	1.42	1.26	5.17	8.70
Pasture		41.34	75.26	94.64	74.90	17.68	63.11
Urban		0.03	0.05	0.09	23.14	0.00	0.01
Rupestre		1.37	0.15	0.01	0.00	53.45	0.76
Eucalyptus		0.00	0.00	0.00	0.00	0.00	0.00

Appendix 2.3. Overview of regression analyses to quantify relationships between Land Use Land Cover (LULC) demand (response variables) and drivers of LULC (explanatory variables).

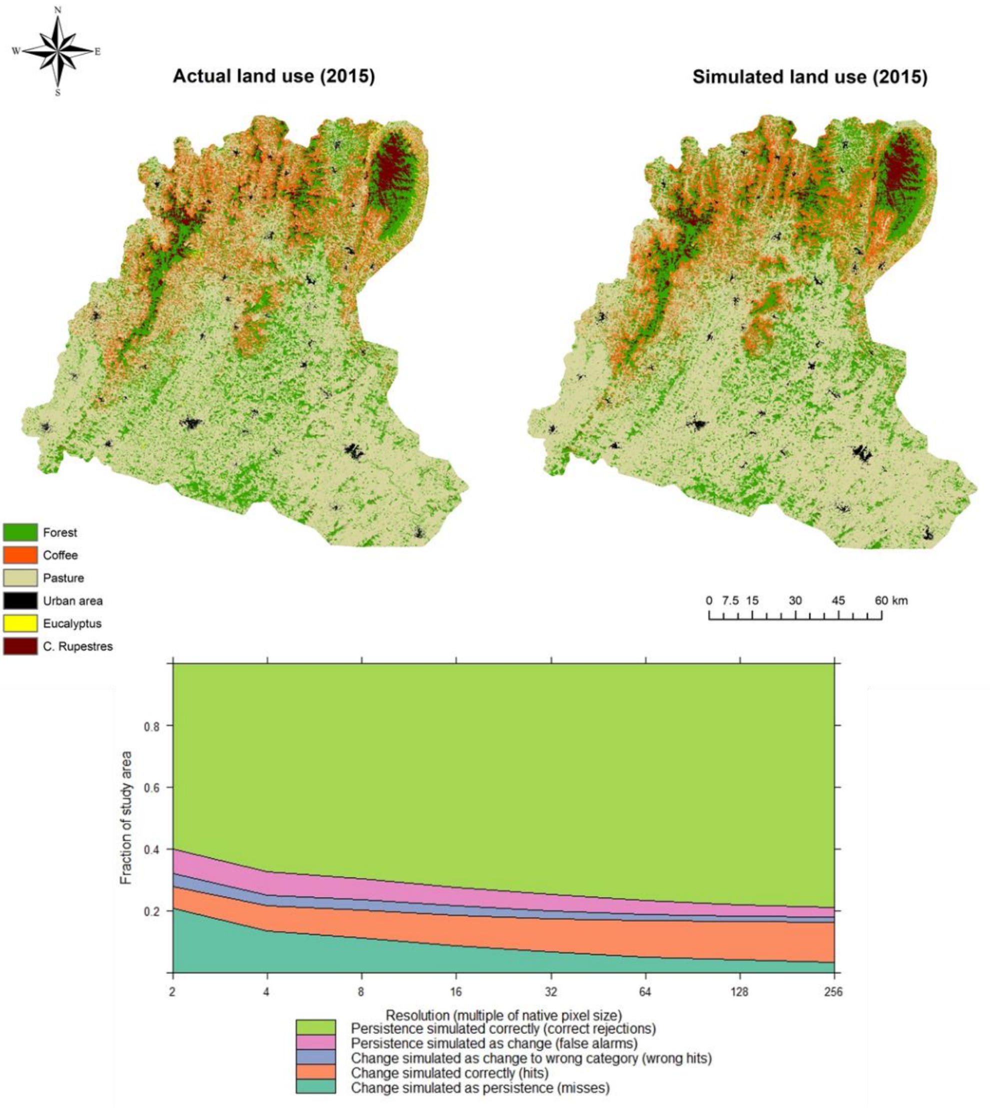
LULC	Drivers of LULC	Regression equation	R2	SE
Forest	Deforestation rate[1] (DF)*** Credit for Livestock and Coffee (CRLC)***	Y = 22.33 + 0.051*CRLC - 0.236*DF	0.84	0.740
Coffee	Credit for Coffee crop (CRC)*** Coffee export (CE)**	Y= 2.57 + 0.087*CRC + 0.097**CE	0.94	0.55
Urban	Urban Population (UP) ***	Y = -1.522 + 0.033*UP	0.84	0.105
Eucalyptus	Charcoal (CH) *** Cellulose (CE) ***	Y = -0.895 + 0.017*CH + 0.01*CE	0.88	0.145

***(p < 0.001), **(p < 0.01), [1] Deforestation rate is not a direct driver of LULC, but is a proxy for the governance effort of to protect the environment.

Appendix 2.4. Summary of outcomes of the group discussions on changes in Land Use Land Cover types during three workshops held in October and November 2017 in Espera Feliz, Divino and Araponga in the Zona da Mata of Minas Gerais state, Brazil.

LULC	LULC changes and main drivers discussed
Forest	• The farmers pointed out that the area of forest increased at the expense of pasture. • The high fines and the frequent inspection by governmental agencies decreased deforestation and other cutting of trees. • The forest on the highest part of the hills increased, because there is growing awareness that the presence of trees in these areas help water infiltration and, as a consequence, the maintenance of the springs all year. • Government subsidies to fences springs and the highest parts of the mountains, has helped to increase forest areas. • The creation of the “Serra do Brigadeiro state park” helped to conserve the forests and improved nature preservation awareness
Coffee	• The farmers indicated that the coffee area also increased at the expense of pasture. • The credit for family farmers to start new coffee fields or to manage old ones helped to increasing coffee fields. • To increase coffee fields does not mean to improve environmental issues, because it also increases the use of pesticide
Pasture	• The farmers pointed out that the area of pasture decreased. • Changes in the cattle management, for instance, increasing the feeding with concentrated soybean, decreased the pasture area needed for the cattle. However, the farmers criticised the dependency on genetically modified soybeans produced in other regions of Brazil, with intensive use of pesticides.
Urban area	• Unfortunately, the migration of many families from rural to urban areas also helped increasing forest. These families were searching for a better life, however, many of them were subjected to bad life conditions in the cities, due to low salaries, lack of good houses, etc.
Eucalyptus	• The low price of coffee in the early 2000s and the high price of eucalyptus wood influenced famers in the region to plant it. However, after two decades, farmers interest in cultivating eucalyptus decreased due to the high impact on water resources, low price of eucalyptus and difficulties in transportation of the wood.

Appendix 2.5. Actual Land Use Land Cover map (left) and the simulated map of 2015 (right) of Zona da Mata region, Atlantic Forest Biome, Brazil. The result of the agreement analysis is presented at the bottom panel.



Chapter 3

Land use change drives the spatio-temporal variation of ecosystem services and their interactions along an altitudinal gradient in Brazil

Lucas C. Gomes
Felix J.J.A. Bianchi
Irene M. Cardoso
Elpídio I. F. Filho
Rogier P.O. Schulte

Abstract

Land use and land cover (LULC) changes affect the provision of ecosystem services. However, little is known how LULC changes interact with biophysical conditions to govern the spatio-temporal variation in ecosystem service delivery in changing landscapes. Here we assessed the spatio-temporal variation of eight ecosystem services in an altitudinal gradient between 1986 and 2015, and quantified the effect of LULC transitions on the delivery and interactions of ecosystems services. We mapped eight ecosystem services (coffee production, tourism, livestock production, carbon storage, pollination, soil erosion control, water flow regulation and habitat quality) in an altitudinal gradient characterized by low (<600m), middle (600-1200) and high altitudes (>1200) in Zona da Mata, Brazil. We quantified changes in ecosystem services by contrasting ecosystem service maps between 1986 and 2015, and explored how four common LULC transitions affected the variation and the interactions between the eight ecosystem services. The spatio-temporal analysis indicated that six out of eight ecosystem services increased from 1986 to 2015, while soil erosion control and water flow regulation declined. In areas above 1200 m, regulating services dominated, while in areas below 1200 m provisioning service were most pronounced. LULC transitions from forest to agricultural areas, and vice versa, resulted in trade-offs between provisioning and regulating ecosystem services. LULC change drives the spatio-temporal variation of ecosystem services along contrasting biophysical conditions. Future management of ecosystem services in the landscapes should take into the account the biophysical context and the consequences of specific LULC transitions.

Introduction

Human inhabited landscapes are complex socio-ecological systems, and in the face of global changes, the future of human wellbeing will be shaped by our capability to manage these complex environments to provide bundles of ecosystem services that meet societal demands (Reyers et al., 2013; Vallés-Planells et al., 2014; WWDR 2018). Although ecosystem services research has made significant advances in the conceptualization, quantification and monetary valuation of ecosystem services in the last decades (De Groot et al., 2012; Costanza et al., 2014; Yi et al., 2018), we still have limited understanding of how patterns of multiple ecosystem services emerge and change in space and over time (Renard et al., 2015). Insight in the spatio-temporal dynamics of multiple ecosystem services in landscape settings with different biophysical conditions may direct more context specific management and planning of ecosystem services.

Spatio-temporal patterns of ecosystem services can be influenced by a range of abiotic and biotic factors (Pan and Blois 1999; La Notte et al., 2017; Mayor et al., 2017). Abiotic components may include highly dynamic variables, such as nitrogen availability in the soil and weather patterns, as well as variables that typically do not change across short time scales, such as relief, parent material and soil type. On the other hand, the rate of changes in biotic components of the landscape, such as crop and non-crop vegetation types, are often strongly dependent on the nature and intensity of human actions. Biophysical conditions, such as temperature, precipitation, evapotranspiration, soil type and ultimately vegetation types, can vary sharply along altitudinal gradients. As a consequence, mountainous areas may reflect a fine grained mosaic of contrasting ecosystems and land use types at relatively short distances, ultimately leading to heterogenous spatial patterns of bundles of ecosystem services (Körner 2003; Dieleman et al., 2013). Therefore, mountainous areas offer a unique opportunity to study how patterns of ecosystem services change over time in heterogenous environments with contrasting biophysical conditions.

With a projected need to increase global food production by 60% by 2050 to support a growing world population (PRB 2018; WWDR 2018) intense changes in LULC can be anticipated for the near future. This poses a challenge for farmers, scientists and policy makers to develop agricultural systems that produce sufficient and nutritious food, while also delivering other essential ecosystem services. Yet, our understanding of the way in which changes in LULC influence provision levels of different ecosystem services is still limited. In many parts of the world, agricultural policies and land managers have focussed on strengthening provisioning services, often resulting in a decrease of other ecosystem services, such as climate regulation and fresh water supply (MA 2005; Butchart et al., 2010). In Brazil, the deforestation in Amazon biome for food production and pasture land has decreased the capacity of ecosystems to sequester carbon, nutrient cycling, erosion control and water regulation (Portela and Rademacher 2001; Foley et al., 2007). Over the time, the loss in regulating services can have impacts at the local scale, such as reduced water supply, as well as at the national and global scale, for instance impacts on climate regulation. Understanding how LULC changes influence the associated delivery of ecosystem services can provide important insights relevant for the sustainable management of landscapes in the future.

LULC transitions may have specific impacts of different ecosystem services, which may unfold as synergies (win-win scenarios), trade-offs (win-lose scenarios), or, in case of lose-lose scenarios, as dis-synergies (Bennett et al., 2009). While interactions between ecosystem services have been reported at different spatial and temporal scales (Briner et al., 2013; Lang and Song 2018; Li et al., 2018; Qiu et al., 2018; Qiao et al., 2019), the consequences of LULC transitions for interactions between multiple ecosystem services are still relatively poorly understood (Valujeva et al., 2016). The assessment of interactions between multiple ecosystem services is challenging due to the context dependency and the overwhelming complexity of several possible pairwise interactions (Raudsepp-Hearne et al., 2010; Maes et al., 2012; Howe et al., 2014). Analysing the effect of specific LULC transitions on the provisioning levels of ecosystem services may offer a pathway to explore the interactions between multiple ecosystem services, and to identify management actions that lead to synergies between ecosystem services rather than trade-offs. Such practical information can guide spatial planning, land management and policy makers to sustainable management of ecosystem services in the future.

The aim of the study is to analyse the spatio-temporal variation of eight ecosystem services in an altitudinal gradient in the southeast region of the Atlantic Forest biome in Brazil, which has a historic of intense LULC changes. Specifically, we assess (i) how LULC changes impacted the provision of ecosystem services from 1986 to 2015, (ii) how the spatio-temporal provision of ecosystem services varies along an altitudinal gradient with different biophysical conditions, and (iii) how specific LULC transitions affect ecosystem services and their interactions.

Material and Methods

Study area

The study region covers an area of 11.300 km^2 and is for the largest part located in the Zona da Mata of Minas Gerais state and in the Brazilian Atlantic Forest biome, the fifth hotspot of biodiversity in the world (Myers et al. 2000; Fig. 3.1). This region can be considered as a complex socio-ecological system with the predominance of smallholder farmers, and have been subject to LULC changes in the last three decades (Cardoso et al., 2001; Jackson et al., 2012; Gomes et al., 2020). In contrast to many other tropical areas, in the last three decades, this region witnessed an increase in forest cover from 18 to 24%, an increase in the area of coffee plantations from 3 to 11%, and a decrease of pasture area from 76 to 58%. These changes have been fostered by governmental supported investments in agriculture and protection of the environment (Gomes et al., 2020). The region includes the Caparaó National and the Serra do Brigadeiro State parks, which are protected areas for nature conservation and used for tourism, recreation and natural history education. The study region has an altitudinal gradient ranging from 27 m to almost 2900 m above the sea level. This altitudinal gradient gives rise to a heterogenous landscape mosaic with strong gradients in temperature, precipitation, geomorphology and soil type at short distances (Fig. 3.1).

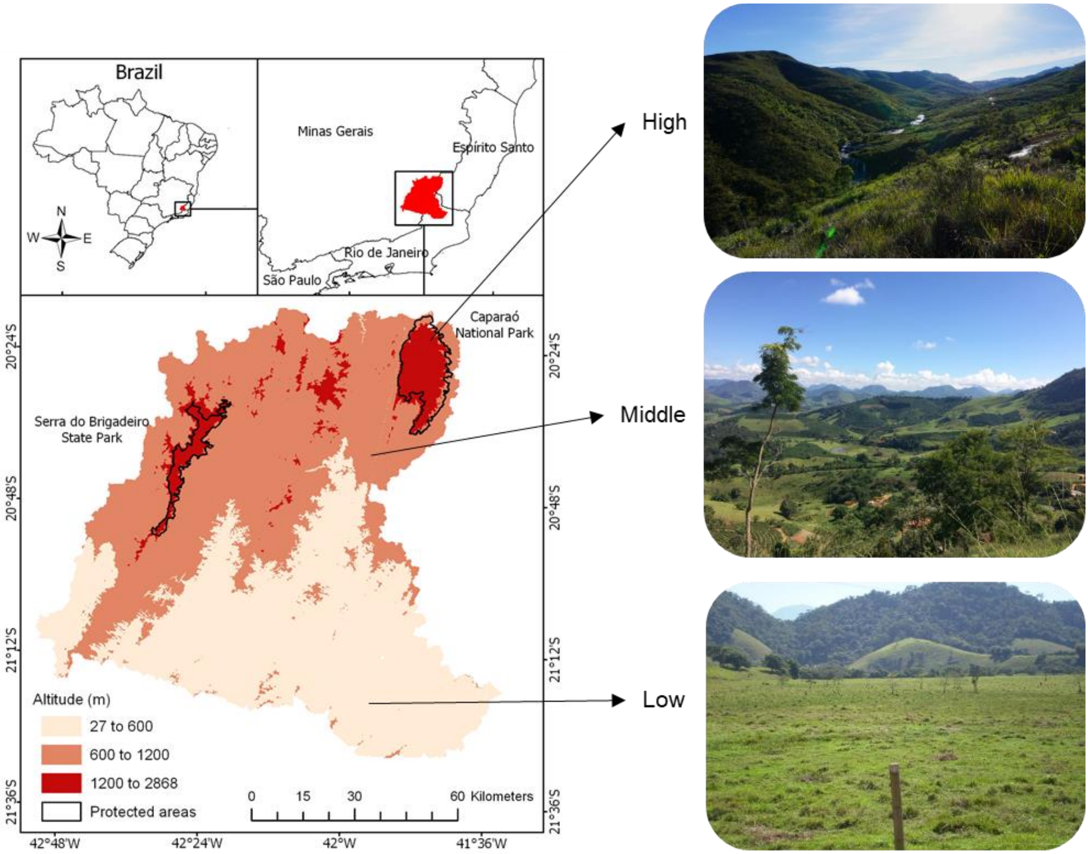


Figure 3.1. Study region highlighting three main altitudinal zones: Low (< 600 m), Middle (600-1200 m) and High (> 1200 m) in the Atlantic Forest Biome, Brazil.

We distinguished three altitudinal zones in the study region: Low (<600m), Middle (600-1200m) and High altitudes (>1200m) with contrasting biophysical characteristics. We chose these zones because the range between 600 and 1200 m offers optimal climatic conditions and soil types for coffee production, a key cash crop in the area, and protected natural areas prevail at 1200 m and higher. In the Low altitude zone, the mean annual temperature is about 22ºC, precipitation is 1242 mm and the potential evapotranspiration is

1515 mm. The main soil type is Acrisol, with large plains where the main rural activity is dairy farming and cattle ranging. The urban area increased from 20 to 62 persons per km^2 from 1980 to 2010. In the Middle altitude zone, the mean temperature is 19ºC, precipitation is 1333 mm and potential evapotranspiration 1410 mm. This Middle zone is characterized by the predominance of hills with deep valleys and deep weathered Ferralsols, and the dominant land use is coffee production and cattle ranging. The urban area increased from 15 to 65 km^2 from 1980 to 2010. In the High altitude zone, the mean temperature is 16ºC, precipitation is 1510 mm and potential evapotranspiration is 1245 mm. The area is characterized by shallow Regosol soils and rocky areas and Campos Rupestres at mountains top. This area is not permanently inhabited.

Assessing ecosystem services

We focussed on eight ecosystem services: coffee production, cultural service, livestock production, carbon storage, water flow regulation, soil erosion control, pollination and habitat quality. These ecosystem services were chosen because these are considered important by the local population (Teixeira et al., 2018b), and by data availability. The coffee production was informed by the area of coffee plantations (ha) and cultural services (e.g. tourism, recreation and natural history education) was based in the dimensions of protected natural areas (ha) in the region. We used cattle stocking rate (animals/ha) data obtained from the Brazilian bureau of statistic from 1986 to 2015 (IBGE, 2018) for each municipality in the study area as an indicator for livestock production. Carbon storage, water flow regulation, soil erosion control, pollination and habitat quality were assessed using the

InVEST model (Nelson et al., 2009; Sharp et al., 2018) and LULC maps from 1986 and 2015 at 30 x 30 m resolution (Gomes et al., 2020).

Carbon storage

Carbon storage was assessed using the LULC maps and the carbon density per LULC class, considering four carbon pools: above ground biomass, below ground biomass, soil and dead organic matter.

$$CA_x = PA\,.\,(C_A + C_B + C_S + C_D) \qquad \text{(Eq. 1)}$$

where carbon storage CA_x is the carbon stored in each pixel x (Mg). PA is the pixel area (30 x 30 m = 900 m^2 or 0.09 ha), C_A is the aboveground carbon density (Mg ha^{-1}); C_B is the belowground carbon density (Mg ha^{-1}); C_S is the soil carbon density (Mg ha^{-1}); and C_D is the dead mass carbon density (Mg ha^{-1}). We used carbon pool data from literature based on local studies for all LULC types (Appendix 3.1).

Water flow regulation

The water flow regulation was expressed by the water yield index, which is defined as the amount of water that runs off from each pixel in the landscape (Tallis 2011). The average annual water yield was calculated using a water balance based on precipitation and evapotranspiration data:

$$Y_x = P_x - AET_x \qquad \text{(Eq. 2)}$$

Where Y_x is the average annual water yield, Px is the average annual precipitation (mm), and AET is the annual actual evapotranspiration (mm) in pixel x (Sharp et al., 2018). We used spatial data of average annual precipitation of the study area from 1970 to 2000 from the WorldClim database (Fick and Hijmans 2017), the reference annual evapotranspiration from (Dias 2018) and the soil depth data from the Brazilian soil database (Cooper et al., 2005).

Soil erosion control

The soil erosion control was assessed by the average annual rate of soil loss (ARSL), which was calculated using the revised Universal Soil Loss Equation for each pixel x (Sonneveld and Nearing 2003) (Eq.3).

$$A_x = R_x \cdot K_x \cdot LS_x \cdot C_x \cdot P_x \qquad \text{(Eq. 3)}$$

where A_x is the annual rate of soil loss (tons $ha^{-1}yr^{-1}$) in pixel x, R_x is the rainfall erosivity (MJ mm $(ha\ hr)^{-1}$); K_x is the soil erodibility factor (ton ha hr $(MJ\ ha\ mm)^{-1}$); LS_x is the slope gradient (dimensionless); C_x is the crop management factor (dimensionless); and P_x is the support practice factor (dimensionless). We obtained the rainfall erosivity parameter R_x using a multivariate equation based in altitude, longitude and latitude developed for Brazilian territory (Mello et al., 2013). The soil erodibility parameter K_x was based in the soil class, and the LS_x factor using the equation from (Moore and Burch 1986). The crop management factor C_x and the support practice P_x for each LULC class derived from the literature (Appendix 3.2; 3.3).

Pollination

Coffee production is an important cash crop in the study region and there is a diversity of wild bees that pollinate the coffee plants, especially in agroforestry coffee systems (Ferreira 2008). Here, we focus on the unmanaged honey bee *Apis mellifera* and the wild bee *Trigona spinapis,* the most abundant bees species found in coffee plantations (Malerbo-Souza and Halak 2012; Ferreira, 2008). We assessed the potential pollination services provided by these two bee species using the InVEST pollination model. The procedure entails the scoring of land cover parcels for their potential to floral resources and nesting sites and generates an index of the relative abundance of pollinators. Species specific estimates for foraging distance, habitat for nesting and foraging likelihood in each land cover class were obtained from literature (Appendix 3.4, 3.5).

Habitat quality

Habitat quality refers to the ability of the ecosystem to provide suitable conditions for species population viability in terms of anthropogenic threat/disturbance levels. We considered four threats: agricultural areas, pastures, urban areas, and paved roads (Duarte et al., 2016; Appendix 3.6). Habitat quality is assessed based on the relative impact of threats, the sensitivity of the habitat to threats, and the distance between habitats and location of threats. The impact of a threat decreases with increasing distance from the location of the threat, and an impact map is generated by integrating the impact zones around the land use types considered as a threat. Habitat quality is then derived as a relative metric ranging between 0 and 1, with low values for high impact zones and high values for low impact zones.

Interactions between ecosystem services

We analysed the interactions for pairwise combinations of ecosystem services in the study region from 1986 (*T1*) to 2015 (*T2*) (Haase et al. 2012; Li et al. 2017) (Fig. 3.2). First, we created a map of temporal changes ($\Delta ES_j = ES1_{j,T2} - ES1_{j,T1}$) for each ecosystem service *j* in 1986 and 2015, using the raster calculator in ArcGIS 10 (Fig. 3.2A). Then, we normalized the ΔES maps values generating a new map with values ranging between -1 and 1 ($N\Delta ES_j$) (Fig. 3.2B). Next, we clipped the $N\Delta ES_j$ using a map mask of Land Use Transitions (LUT_j) that contained only the pixels that were converted from specific transitions between 1986 and 2015 (Fig. 3.2C). This resulted in a map ($ES_{j,LUT}$) representing the $N\Delta ES_j$ pixels values only for the areas where LULC transitions (LUT) took place between 1986 and 2015 (Fig. 3.2D). Finally, we visualised the interactions between ecosystem services by plotting the mean values of the map of ecosystem services (μESj_{LUT}) for each pairwise combination (Fig. 3.2E). We expressed the interactions between pairwise ecosystem services in terms of synergies (win–win), trade-offs (lose–win; win–lose), or dis-synergies (lose–lose) (Bennett et al. 2009; Haase et al. 2012). Here, we focused on four LULC transitions: “pasture to forest”, “forest to coffee”, “pasture to coffee” and “pasture to urban area”, which LULC types account for 95% of study region. This procedure was followed for each of the four LULC transitions.

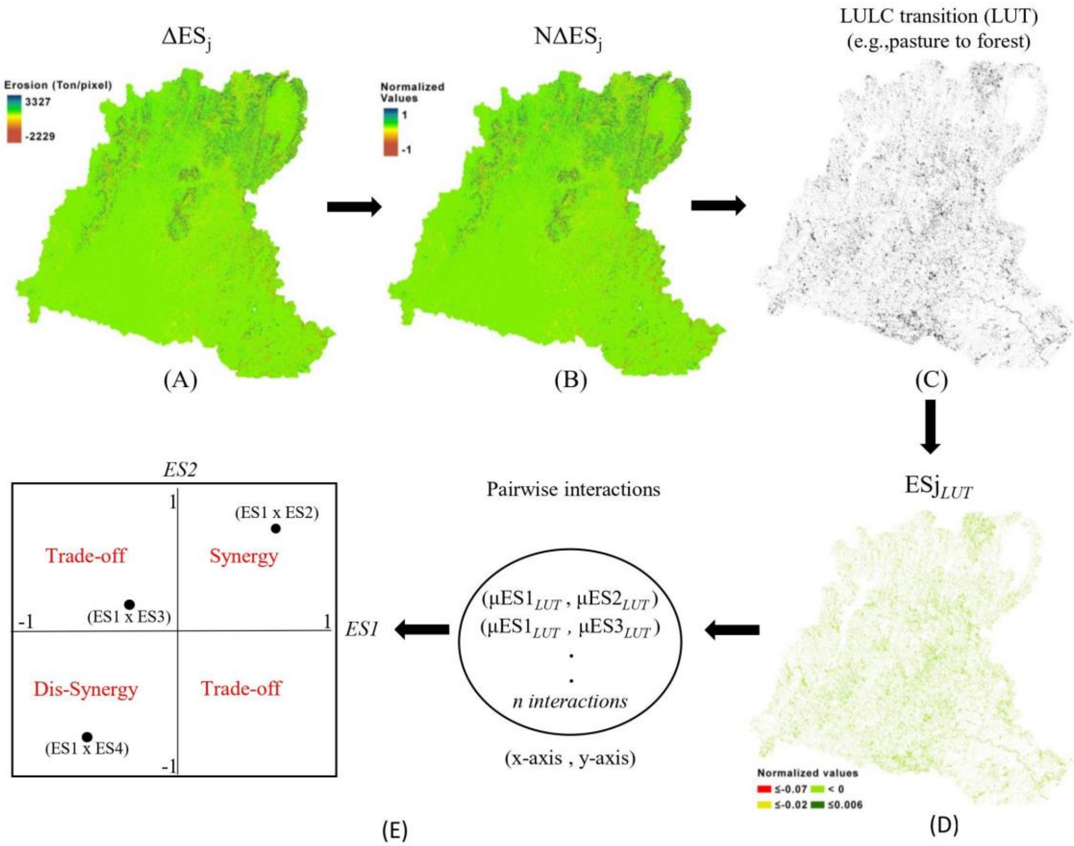


Figure 3.2. Schematic overview of the methodological approach to assess the impact of specific land use land cover transitions on multiple ecosystem services (ES) and their interactions. ΔESj: map of the changes of ecosystem service *j* from 1986 to 2015 (A); NΔESj: map with normalized values of the changes of ecosystem service *j* (B); ESj_{LUT}: map of ecosystem service *j* containing only the values in the pixels from specific LULC transitions (e.g., pasture to forest) (C, D); and μESj_{LUT}: the mean pixel value from the ESj_{LUT} map (E).

Results

Across the whole study region, six out of eight ecosystem services showed a positive trend between 1986 and 2015: coffee production (+266.6%), habitat quality (+40%), pollination (+29.2%), livestock stocking rates (+26.3%), carbon storage (+1.8%), and cultural service (+33.3%), while water flow regulation (-2.2%) and soil erosion control (-3.7%; Fig. 3.3) decreased.

The Low (<600 m) and Middle zones (600-1200 m) supported mostly provisioning services, such as coffee production and livestock raising, while the High zone (>1200 m) mainly consisting of protected areas, provided mostly regulating and cultural services, such as habitat quality, pollination and opportunities for recreation (Fig. 3.4). While the livestock stocking rate in the Low zone increased from 0.75 to 1.24 animals/ha between 1986 and 2015 (Fig. 3), the overall herd size in the study region decreased by 10% because pasture areas decreased from 76% in 1986 to 58% in 2015 (Fig. 3.3). On the other hand, the Low Zone showed a strong increase in habitat quality (+76%), water flow regulation (+60%), pollination (+54%) and soil erosion control (+27%) between 1986 and 2015. In the Middle zone the area for coffee production increased more than 260%, followed by an increase of habitat quality (+75%) and pollination (+45%) and a decrease in soil erosion control (-3.4%). In the High zone there was an increase in water flow from 0.3 in 1986 to 0.34 in 2015 (normalized values), and cultural services increased by 33.3% due to the establishment of the Serra do Brigadeiro state park. Habitat quality (+8.5%) and carbon storage (+0.4%) increased as well.

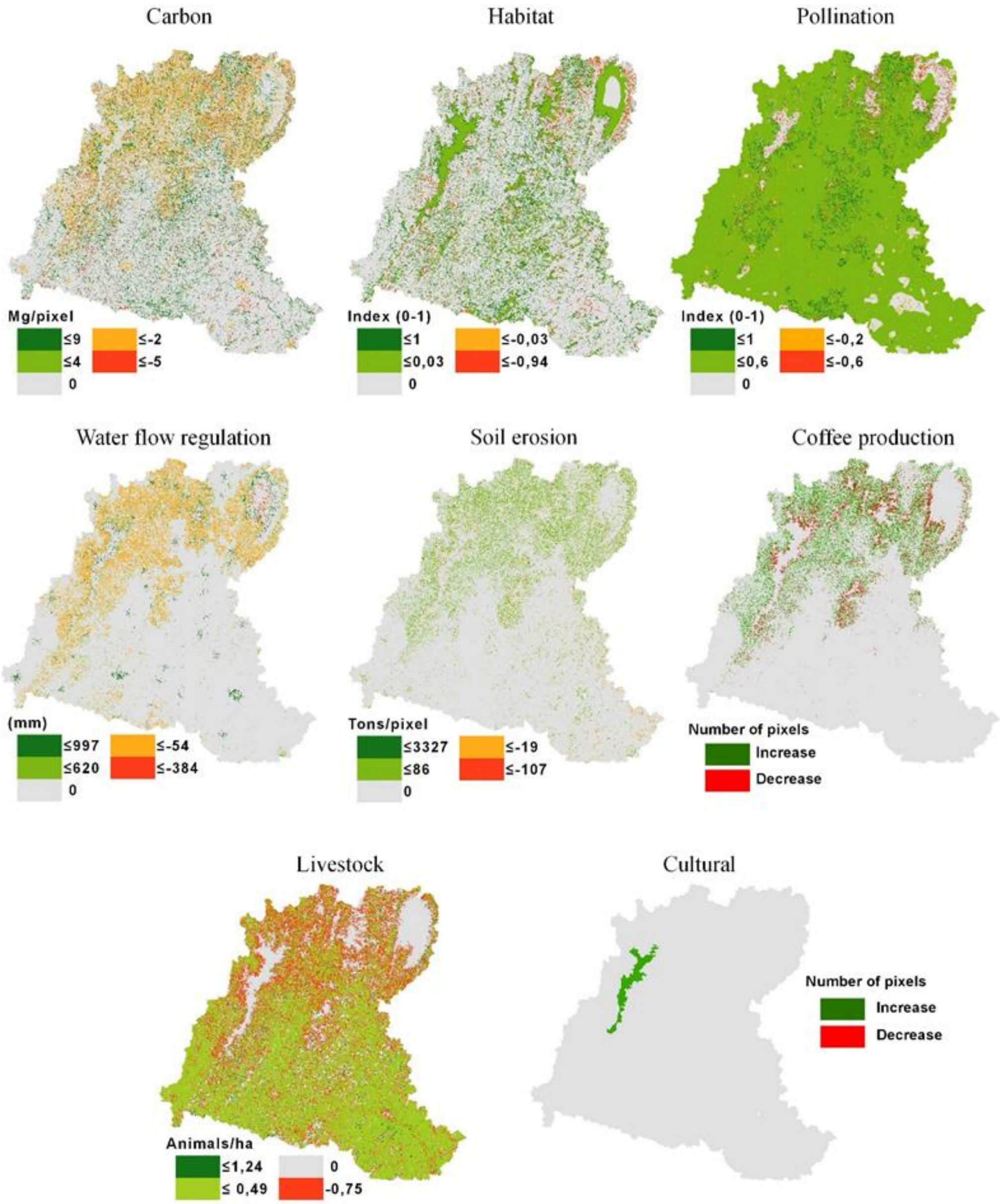


Figure 3.3. Maps of the spatio-temporal variation of eight ecosystem services (carbon, habitat, pollination, water flow regulation (water yield), soil erosion control, coffee production, livestock production and cultural services) in a study region in the Atlantic Forest Biome, Brazil, from 1986 to 2015.

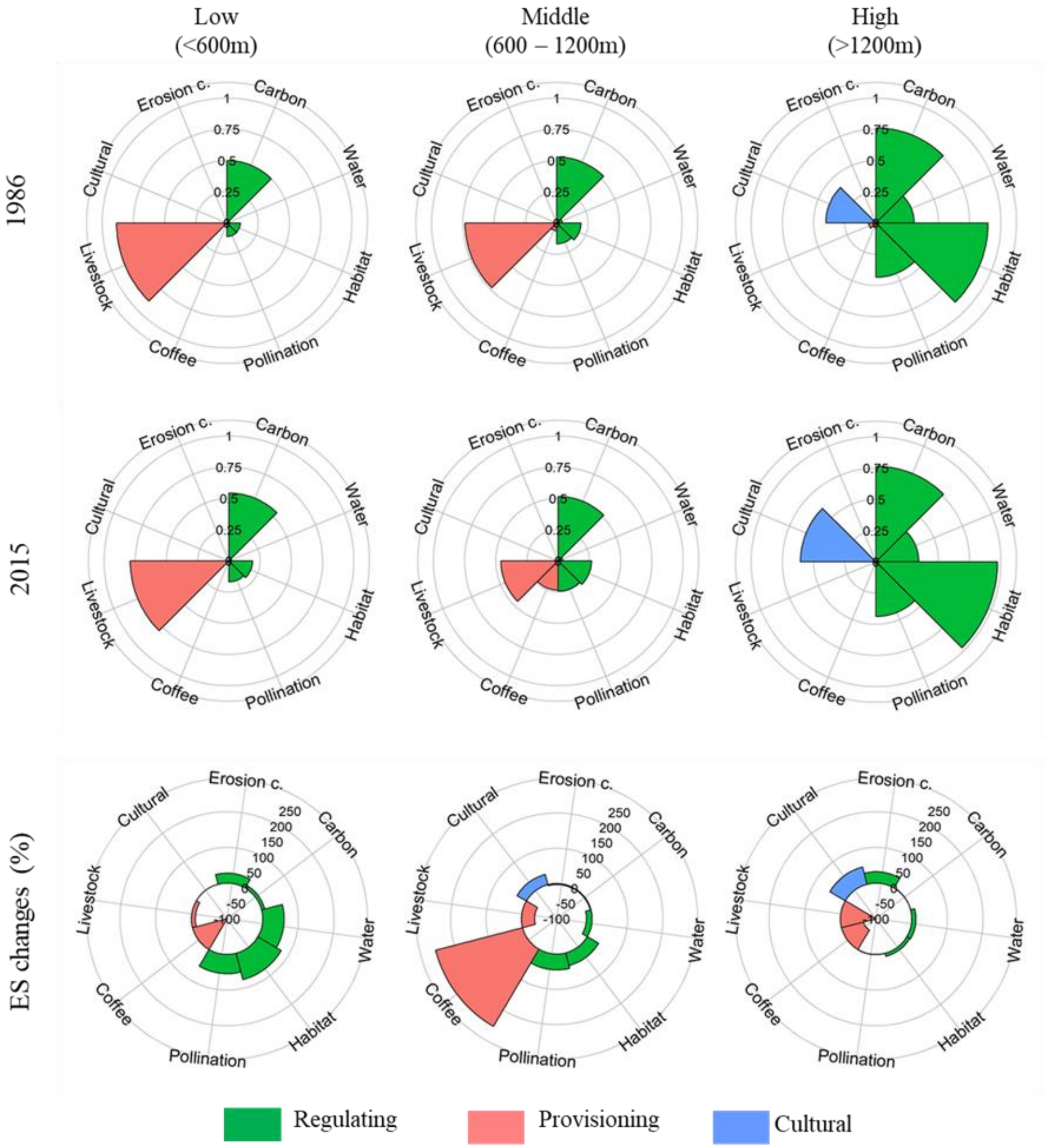
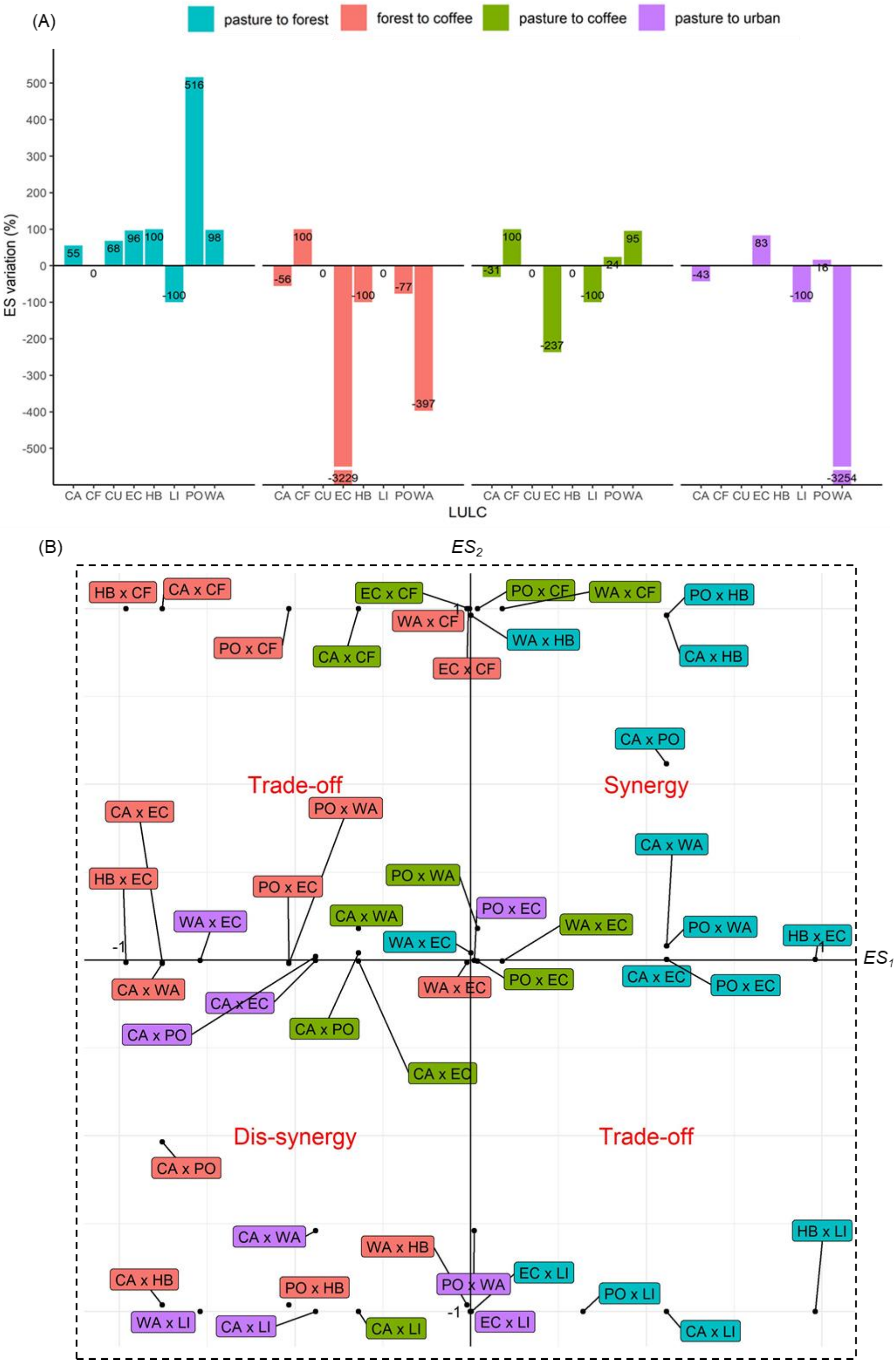


Figure 3.4. Provisioning levels of eight ecosystem services (ES; normalized mean values per pixel) in 1986 and 2015, and the change in provision levels between 2015 and 1986, for the Low (<600 m), Middle (600-1000 m), and High altitude zone (>1200 m).

The LULC transitions affected the provision of ecosystem services and their interactions in different ways (Fig. 3.5). The conversion of *pasture to forest* lead to an estimated 100% decrease of livestock production, but a 516% increase of pollination services, an approximate 98% increase of habitat quality and water flow regulation, a 55% increase of carbon storage (Fig. 3.5A). This LULC transition lead to joint increases for ten out of fourteen pairwise comparisons, with strong synergies for carbon storage and habitat quality (0.55 and 0.98, respectively) and a weaker synergy of water flow regulation and soil erosion control (0.04 and 0.002, respectively) (Fig. 3.5B). The conversion of *forest to coffee* had a positive impact on coffee production (+100 %) at the cost of the soil erosion control (-3229%), water flow regulation (-397%), habitat quality (-100%), carbon storage (-88%), and pollination services (-79%; Fig. 3.5A). This conversion led to ten dis-synergie and five trade-off responses between ecosystem services, with strong dis-synergies interactions of carbon storage and habitat quality (-0.88 and -0.98), carbon storage and pollination (-0.88 and -0.51), and habitat quality and pollination (-0.98 and -0.51; Fig 3.5B). The conversion of *pasture to coffee* led to a 95% and 100 % increase in water flow regulation and coffee production, respectively, and had a negative impact on livestock production (-100%), soil erosion control (-237%) and carbon storage (-32%; Fig. 3.5A). This conversion led mostly to weak dis-synergy and trade-off interactions (Fig. 3.5B). The conversion of *pasture to urban area* had a limited impact on most ecosystem services, but a strong negative impact on water flow regulation (-3254%), livestock production (-100%) and carbon storage (-43.7%), and a positive impact on soil erosion control (+83%; Fig. 3.5A).


(A)
pasture to forest
forest to coffee
pasture to coffee
pasture to urban
ES variation (%)
500
400
300
200
100
0
-100
-200
-300
-400
-500
55
0
68
96
100
-100
516
98
-56
100
0
-3229
-100
0
-77
-397
-31
100
0
-237
0
-100
24
95
-43
83
-100
16
-3254
CA CF CU EC HB LI PO WA
LULC
(B)
ES_2
ES_1
Trade-off
Synergy
Dis-synergy
Trade-off
HB x CF
CA x CF
PO x CF
EC x CF
CA x CF
WA x CF
EC x CF
PO x CF
WA x CF
WA x HB
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CA x HB
CA x PO
CA x EC
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1
-1

Figure 3.5. Effects of four land use and land cover transitions (pasture to forest, forest to coffee, pasture to coffee, and pasture to urban area) on the percentage of increase or decrease of ecosystem services (ES) values (A), and on pairwise interactions based on normalized values ranging between -1 and 1 between 1986 and 2015 (B). Eight ecosystem services are included: (CA) carbon storage; (CF) coffee production; (CU) cultural ecosystem services; (EC) soil erosion control; (HB) habitat quality; (LI) livestock production; (PO) pollination; and (WA) water flow regulation. (*left*)

Discussion

In this study we assessed the spatio-temporal variation of ecosystem services and the impact of four LULC transitions on eight ecosystem services and their interactions from 1986 to 2015 in a region of the Atlantic Forest biome, Brazil. Key findings of our study are that (i) overall, the provision of six out of eight ecosystem services increased in the study area, (ii) the spatio-temporal variation of ecosystem services showed contrasting responses in the three altitude zones due to different biophysical conditions, and (iii) conversion of forest to coffee or pasture has strong negative impacts on erosion control and water flow regulation, with mostly trade-offs and dis-synergies between ecosystem services. In contrast, conversion of pasture or coffee to forest has a positive impact on most ecosystem services, except livestock production and coffee production, with the predominance of synergies between regulating ecosystem services.

Our analysis indicates that between 1986 and 2015 there was an increase in the area used for coffee production (+266,6%), habitat quality (40%), pollination (29.2%) and carbon storage (1.8%) in the study region, which were associated with increases in forest cover and coffee production. While there is a worldwide tendency of expansion of agricultural areas for food, feed and raw material production, our study area reflects a different trend with the area under forest cover increasing from 18 to 24% and coffee production increasing from 3 to 11%, resulting in a joint increase in provisioning and many regulation services. The joint increase in coffee and forest areas is mainly due to public policies and environmental legislation, which increased the financial support for smallholder farmers to cultivate coffee and the surveillance measures to protect forest areas in the last three decades (Gomes et al., 2020). In parallel, the state government, NGO's and famer unions created the Serra do Brigadeiro State Park in 1996, a protected nature conservation area of about 11500 ha, which is used for recreation and educational programs for natural history and environmental protection. Indeed, public policies are considered important drivers of LULC changes and unintended influence the provision of ecosystem services (Rounsevell et al., 2012; Guerra et al., 2016). Here, analysis of the historic socio-economic trajectories, historical LULC changes and spatio-temporal provision of ecosystem services may generate new insights in the linkages between public policies and socio-economic drivers on the one hand, and ecosystem services on the other. As such, this approach may inform governmental/non-governmental actions to strengthen ecosystem services.

We found that the contrasting biophysical conditions along the altitudinal gradient gave rise to distinct spatio-temporal patterns of ecosystem service provision in the study region. The provision levels of regulating and cultural services, such as carbon storage, pollination, habitat quality and tourism, was higher in the High zone (>1200m) than at lower altitudes. Worldwide, the mountain regions are important areas for water supply, nature conservation and widely used for tourism (Beniston 2003; Catalan et al., 2017). The suitability of mountains for regulating services areas can in part be explained by their biophysical conditions, such as steep slopes, low temperatures, and shallow soil layers, which make these areas less suitable for provisioning services. Our study revealed that ecosystems service delivery levels are less dynamic in the High zone than lower zones, and that mountain regions can be expected to remain as sources of regulating ecosystem services in the future. In contrast, in the Middle zone there have been strong dynamics in provisioning and regulating ecosystem services due to intense LULC changes in the last three decades. This zone has favorable biophysical conditions to support agriculture, such as deep weathered soils with a high water holding capacity and excellent climate conditions for coffee production. Areas with favorable biophysical conditions for agricultural production are the most susceptible ecosystems for conversion to agricultural land (Ramankutty et al., 2002), and the associated changes in ecosystem services. The Low zone is mainly used for livestock raising and are not suitable for coffee production. Nevertheless, in the last decades this zone has seen an increase of pollination, habitat quality and carbon storage, which is associated with the increase of forest patches (Fig. 3). Therefore, the higher provision level and lower temporal variability of regulating services in the High zone compared with the Low and Middle zones, highlights that the contrasting biophysical conditions along an altitudinal gradient are key determinants to govern the spatio-temporal provision of ecosystem services. While variation in the spatio-temporal distribution of ecosystem services has been associated with differences in socio-ecological systems at municipality level (Raudsepp-

Hearne et al., 2010; Andersson et al., 2015; Queiroz et al., 2015), here we show that biophysical conditions can also influence the spatio-temporal distribution of ecosystem services at smaller spatial scales, either directly (e.g. less pollination at low temperatures) or indirectly through LULC changes. Accounting for biophysical conditions and associated LULC changes may be useful to better understand how ecosystem services may develop in the future under scenarios of climate change.

Our study explored the relationship between LULC change and ecosystem service provision levels, showing how specific LULC transitions affect the ecosystem services and their interactions. For instance, the conversion of pasture to forest may result in a 55% increase in carbon storage, while converting forest to coffee may lead to declines in habitat quality (-100%), carbon storage (-88%) and pollination (-79%; Fig. 3.5). These results are in accordance with previous studies showing that forest areas support more regulating services, while agricultural areas deliver more provisioning services (West et al., 2010; Baral et al., 2013). The conversion of pasture to coffee has increased the provision of provisioning and regulating services, but soil erosion is still a challenge in coffee cultivation. In the Zona da Mata the coffee plantations are mostly conventionally managed unshaded coffee systems, which are prone to soil erosion, and the intensive insecticide use to control pests might undermine essential pollination services by wild and managed pollinators (Goulson et al., 2015). In contrast, agroforestry coffee systems are less prone to water runoff (Cannavo et al., 2011) and have superior natural pest suppression (Rezende et al., 2014). While the effect of LULC changes on ecosystem services has been studied based on the association between temporal changes in the LULC and ecosystem services provision (Rodríguez-Echeverry et al., 2018), our analysis extends these findings by showing the consequences of four common LULC transitions on the complex interactions between ecosystem services. For instance, the conversion of forest to coffee areas had negative impacts on a suite of ecosystem services, with strong dis-synergies between carbon storage, habitat quality and pollination. Identifying the intensity of interactions between multiple ecosystem services can help to design and manage landscapes to provide a balanced set of ecosystem services (Gong et al., 2019). Earlier studies on trade-offs and synergies between ecosystem services mainly focused on the spatial or temporal variation of these interactions (Li et al., 2017; Sun et al., 2018). Analysing the quantitative effect of LULC transition on the ecosystem services and their interactions can be used to manage landscapes to achieve desired levels of ecosystem services in the future.

Appendix 3.1. Carbon density (Mg ha^{-1}) pools for each land use type (Amaro et al., 2013; Gatto et al., 2010; Silva et al., 2013; Ribeiro et al., 2010; Cunha et al., 2009).

LULC	Aboveground Biomass	Belowground Biomass	Soil Organic Carbon (40 cm)	Dead Organic Carbon
	Mg ha^{-1}			
Forest	68.2	16.41	74.8	5.6
Coffee	7.2	1.9	62.4	1.1
Pasture	2.9	7.7	94.6	1.1
Urban areas	15.0	3.8	41.0	0.0
Campo Rupestre	2.8	15.0	90.6	0.9
Eucalyptus	56.7	9.9	70.4	7.4

Amaro, M.A., Soares, C.P.B., de Souza, A.L., Leite, H.G., Silva, G.F., 2013. Estoque volumétrico, de biomassa e de carbono em uma Floresta Estacional Semidecidual em Viçosa, Minas Gerais. Rev Árvore 37,849–857.

Cunha, G.M, Gama-Rodrigues, A.C., Gama-Rodrigues, E.F., Velloso, A.C.X., 2009. Biomassa e estoque de carbono e nutrientes em florestas montanas da mata atlântica na região norte do estado do Rio de Janeiro. Rev Bras Ciência do Solo 33, 1175–1185.

Gatto, A., Barros, N.F., Novais, R.F., Silva, I.R., Leite, H.G., Leite, F.P., Villani, E.M.A., 2010. Estoques de carbono no solo e na biomassa em plantações de eucalipto. Rev Bras Ciência do Solo 34,1069–1080.

Ribeiro, S.C., Jacovine, L.A.G., Soares, C.P.B., Martins, S.V., Nardelli, A.M.B., Souza, A.L., 2010. Quantificação de biomassa e estimativa de estoque de carbono em uma capoeira da Zona da Mata Mineira. Rev Árvore 34, 495–504.

Silva, A.B., Mantovani, J.R., Moreira, A.L., Reis, R.L.N., 2013. Estoques de carbono no solo e em plantas de cafeeiro (*Coffea arabica* L.). Interciencia 38,286–291.

Appendix 3.2. Soil erodibility values (k factor) used in the Universal Soil Loss Equation (USLE) (Duarte et al., 2016).

Soil type	K
Argisol	0.04450
Cambisol	0.02314
Red Latosol	0.00962
Yellow-red Latosol	0.01717
Litholic Neosol	0.045

Appendix 3.3. Crop management factor (C) and the support practice factor (P) for the different land use land cover (LULC) types used in the Universal Soil Loss Equation (USLE; Duarte et al., 2016).

LULC	C	P
Forest	0.012	1
Coffee fields	0.18	0.4
Pasture	0.052	1
Urban areas	0.1	1
Campos rupestre	0.042	1
Eucalyptus	0.016	1

Duarte, G.T., Ribeiro, M.C., Paglia, A.P., 2016. Ecosystem services modeling as a tool for defining priority areas for conservation. PLoS One 11, e0154573.

Appendix 3.4. Biophysical characteristics of the different land use land cover types for nesting (N) suitability and floral resource availability (Lonsdorf et al., 2009).

LULC	N_cavity	N_ground	F_spring	F_summer
Forest	1	1	1	1
Coffee fields	0.2	0.2	0.8	0.2
Pasture	0.2	0.2	0.3	0.2
Urban areas	0.2	0.2	0.3	0.2
Campo Rupestre	0.1	0.1	0.1	0.1
Eucalyptus	0.3	0.3	0.3	0.3

Lonsdorf, E., Kremen, C., Ricketts, T., Winfree, R., Williams, N., Greenleaf, S., 2009. Modelling pollination services across agricultural landscapes. Ann. Bot. 103, 1589–1600.

Appendix 3.5. Guide table for the Bee species (Lonsdorf et al., 2009).

Species	N_cavity	N_ground	F_spring	F_summer	Alpha	Species weight
Apis melifera	1	1	1	1	1000	1
Trigona spinipes	0.2	0.2	0.8	0.2	500	0.5

The final output of the model is based on the following equation:

$$P_x\beta = N_j.\frac{\sum_{m=1}^{M} F_{jm} e^{\frac{-Dmx}{\alpha\beta}}}{\sum_{m=1}^{M} e^{\frac{-Dmx}{\alpha\beta}}}$$

where N_j is the suitability for nesting of land-use/land-cover (LULC) type *j*, F_j is the relative amount of floral resources LULC type *j* produces, Dmx is the Euclidean distance between cells m and x and αβ is the expected foraging distance of pollinator species β (Sharp et al., 2018).

Lonsdorf, E., Kremen, C., Ricketts, T., Winfree, R., Williams, N., Greenleaf, S., 2009. Modelling pollination services across agricultural landscapes. Ann. Bot. 103, 1589–1600.

Sharp, R., Tallis, H.T., Ricketts, T., Guerry, A.D., Wood, S.A., Chaplin-Kramer, R., Nelson, E., Ennaanay, D., Wolny, S., Olwero, N., Vigerstol, K., Pennington, D., Mendoza, G., Aukema, J., Foster, J., Forrest, J., Cameron, D., Arkema, K., Lonsdorf, E., Kennedy, C., Verutes, G., Kim, C.K., Guannel, G., Papenfus, M., Toft, J., Marsik, M., Bernhardt, J., Griffin, R., Glowinski, K., Chaumont, N., Perelman, A., Lacayo, M. Mandle, L., Hamel, P., Vogl, A.L., Rogers, L., Bierbower, W., Denu, D., and Douglass, J. 2018., InVEST 3.6.0 User's Guide. The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund.

Appendix 3.6. Parameters of the threats for the Habitat Quality model.

LULC	Intensity	Maximum Distance (Km)
Coffee fields	7.5	1
Eucalyptus	6.5	1
Pastures	7	1
Roads network	7	1
Urban areas	7.5	3

The intensity and maximum distance for each land use land cover class considered as threat; values obtained from specialist consultants (n=16; Duarte et al., 2016).

The impact in i_{rxy} of threat *r* from grid cell *y* on the habitat in grid cell *x* can be represented using the following equations:

$$i_{\mathrm{rxy}} = \exp\left(-\left(\frac{2.99}{d_{\mathrm{r\,max}}}\right) d_{\mathrm{xy}}\right)$$

where d_{xy} is the linear distance between grid cells *x* and *y* and $d_{r\mathrm{max}}$ is the maximum effective distance of the threat. The total threat level D_{xj} in a grid cell *x* with LULC *j* is calculated by:

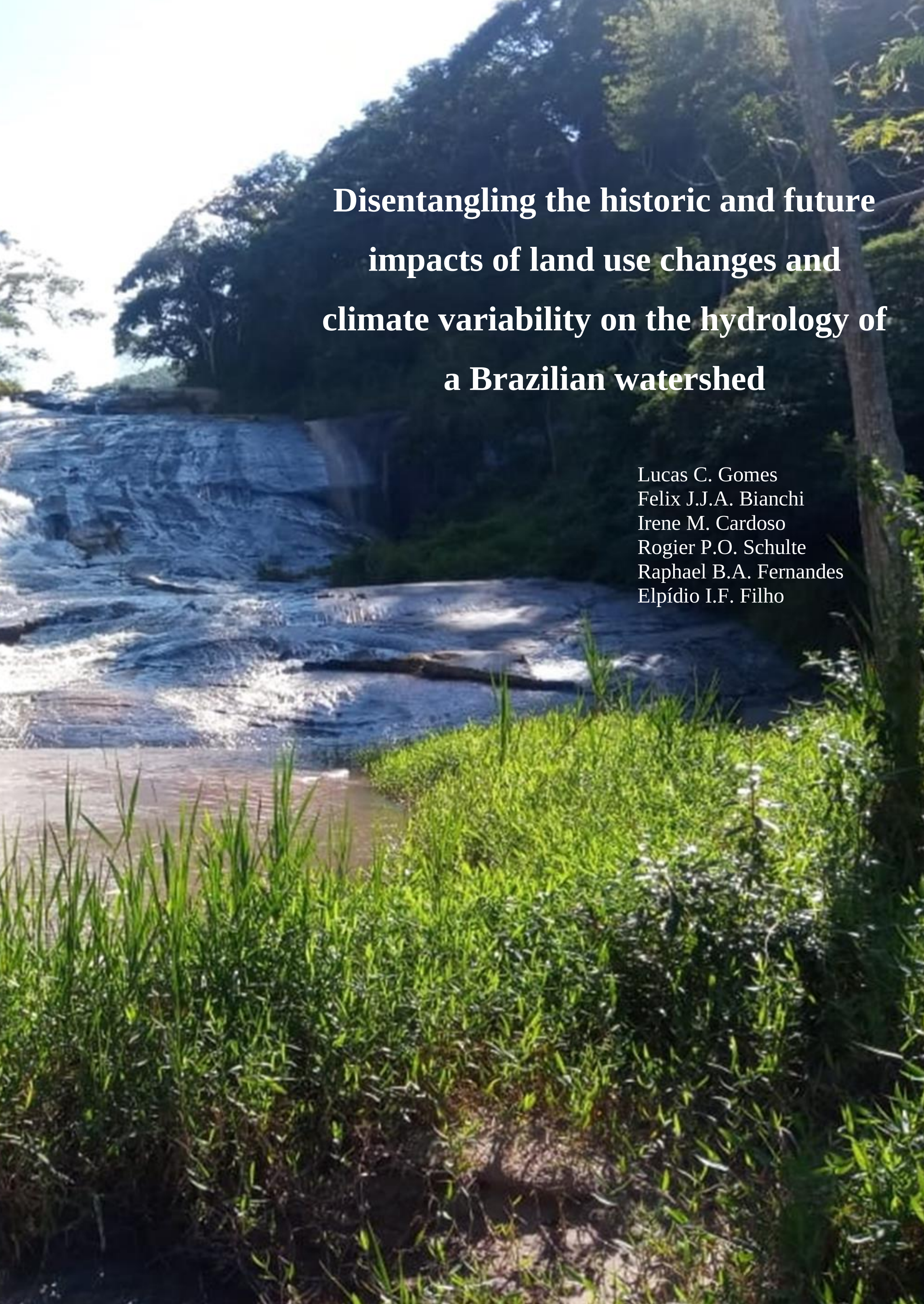
$$D_{xj} = \sum_{r=1}^{R} \sum_{y=1}^{Y_r} \left(\frac{Wr}{\sum_{r=1}^{R} Wr}\right) r_y i_{rxy} \beta_x S_{jr}$$

Finally, the habitat quality Q_{xj} of LULC j calculated by:

$$Q_{xj} = 1 - \left(\frac{D_{xj}}{D_{xj} + 0{,}5}\right)$$

Duarte, G.T., Ribeiro, M.C., Paglia, A.P., 2016. Ecosystem services modeling as a tool for defining priority areas for conservation. PLoS One 11, e0154573.

Chapter 4



Disentangling the historic and future impacts of land use changes and climate variability on the hydrology of a Brazilian watershed

Lucas C. Gomes
Felix J.J.A. Bianchi
Irene M. Cardoso
Rogier P.O. Schulte
Raphael B.A. Fernandes
Elpídio I.F. Filho

Abstract

Global changes in land use and land cover (LULC) and climate are expected to have profound impacts on water dynamics and the associated provision of water related ecosystem services, which are key for human wellbeing. However, we still lack understanding how changes in climate patterns and LULC are likely to interact and govern the hydrology at the watershed level in the future. Here we assessed the contribution of changes in weather patterns and LULC on the hydrology of a watershed in the southeast of Brazil between 1990 and 2015 using the SWAT model. In addition, we explored the likely impacts of two contrasting LULC scenarios (Green Road versus Fossil Fuel) on the hydrology in 2045 under the Representative Concentration Pathway 8.5. Between 1990-2004 and 2005-2015 the watershed witnessed an increase in precipitation and streamflow, in combination with an expansion of forest cover and coffee production. While surface runoff (+5.2 mm y^{-1}) and water yield (+252 mm y^{-1}) increased, soil water (-24.6 mm y^{-1}) and evapotranspiration (-15.7 mm y^{-1}) decreased. The analysis indicated that changes in climate patterns are the main drivers of historical water dynamics in the region. Compared with Fossil Fuel scenario, the increased forest area in the Green Road scenario will lead to a decrease in surface runoff and consequently in water yield, favouring water infiltration, mitigating soil erosion, and buffer against extreme precipitation events. Therefore, afforestation and the integration of trees on farms hold promise to improve water-related ecosystem services and enhance the resilience of watersheds under projected scenarios of climate change.

Introduction

In light of the projected changes in global population growth, land use and climate, the sustainable management of water resources to maintain ecosystem services functioning is a major challenge (Bangash et al., 2013). Water is essential for direct human needs, including drinking water and the production of feed, food and fibre, and is also a vital component of natural ecosystems (Falkenmark and Rockstrom, 2006). Understanding of the ways how climate and anthropogenic changes will affect water dynamics is crucial to manage and safeguard water provision in the future. Climatic patterns and land use land cover (LULC) changes are the most important drivers of water dynamics (Costa et al., 2003; Chien et al., 2013; Neupane and Kumar et al., 2015). Worldwide, these factors have been subject to changes over the last decades and most likely even more so in the coming decades (Foley et al., 2005; IPCC, 2018). LULC type may play a key role in the water dynamics, particularly in tropical mountain regions with steep slopes and intense precipitation events. However, quantitative information about the influence of LULC change and scenarios of climate change on water dynamics in tropical mountain regions is still scarce (Marhaento et al., 2018).

The southeast mountain region of Brazil witnessed intense LULC changes in the last decades and the decrease in precipitation patterns since 2012 has affected the water availability for millions of people in urban and rural areas (Soriano et al., 2016). However, in January 2020 heavy precipitations events up to 920 mm month lead to intense flooding and landslides (INMET, 2020). Impacts of weather extremes can be aggravated or buffered by LULC changes, which together may influence the water dynamics, such as infiltration, runoff and evapotranspiration (Brown et al., 2011). For instance, conversion of forest to pastures and the expansion of urban areas increases surface runoff, streamflow and flooding intensity (Huang et., 2008). Forest intercepts rain and limits the speed of water surface runoff on slopes, reducing soil erosion and enhancing water infiltration. While the benefits of forests on controlling surface runoff are well documented, the influence of increasing forest cover on water yield is less clear (Filoso et al., 2017). In tropical areas characterised by rainy seasons followed by dry seasons, insight into the impact of LULC changes on water dynamics is essential to inform management to reduce soil erosion in the rain season and sustain water availability in the dry season. Indeed, a recent study in the Zona da Mata of Minas Gerais in Brazil found that farmers perceived the provision of water as the main ecosystem service (Teixeira et al., 2018b). Therefore, a better understanding of the effects of changes in weather patterns and LULC on water dynamics can enhance water management.

Disentangling the effects of LULC changes and climate change on water dynamics is challenging, especially in heterogeneous and changing landscapes in tropical areas (Marhaento et al., 2017). Climate projections indicate that changes in temperature and precipitation can be anticipated across the globe (IPCC, 2018), which will have important implications for water dynamics and associated ecosystem services. While the monitoring and analysis of long-term hydrological data can provide important insights how LULC changes of the past have influenced streamflow (Zhang et al., 2014; Wang et al., 2018), modelling allows for the integration of environmental and climate variables, in order to predict water dynamics under scenarios of climate and LULC changes (López-Moreno et al., 2014; Giri et al., 2019). The SWAT model is used worldwide to model the hydrological dynamics in watersheds of varying size and contexts (Molina-Navarro et al., 2018; Tamm et al., 2018; Rani and Sreekesh et al., 2019) and to separate the individual effects of LULC changes and weather variables (Guo et al., 2016; Wang et al., 2014). Combining information about impacts of LULC changes on hydrology and projections of climate change allows the exploration of plausible scenarios for future water dynamics. While simulations of deforestation and reforestation shows that forest can reduce surface runoff and increase baseflow (Pereira et al., 2016; Oliveira et al., 2018), our understanding of the potential impacts of changes in multiple LULC and climate change on water dynamics is still scant.

The aim of this study is to assess the relationship between historical changes in LULC and climate patterns on water dynamics, and to explore impacts of future scenarios of LULC and climate changes on water dynamics in a watershed in the southeast of Brazil. Specifically, we aimed to: i) describe the historical trend of temperature, precipitation and streamflow between 1990 and 2015, ii) unravel the contributions of LULC and climate patterns on streamflow and water dynamics in this region, and iii) explore the impacts of contrasting scenarios of LULC under climate change on the water dynamics in 2045.

Material and Methods

Study area

The study was conducted in the Muriaé river basin covering an area of 5.717 km^2 in the southeast of the Atlantic Forest biome, Brazil (Fig. 4.1). The altitude of the studied basin ranges from 113 m to almost 2000 m. The climate is subtropical humid with mean temperature of 21ºC and annual precipitation of 1300 mm. The main soil types in the watershed are Ferrasols and Acrisols covering more than 80% of the area. The main LULC types are pasture, forest and coffee. The region has been subject to major changes in LULC in the last three decades. In contrast to many other tropical areas, during the period 1986-2015, the region witnessed a decrease of pasture area from 76 to 58% and an increase in forest cover from 18 to 24% and coffee area from 3 to 11% (Gomes et al., 2020). Climate data from six gauging and six precipitation stations were derived from Agência Nacional das Águas (ANA-Hidroweb), and from three meteorological stations in or near the study area, located in Viçosa (698 m), Caparaó (843 m) and Itaperuna (113 m) (Fig. 4.1).

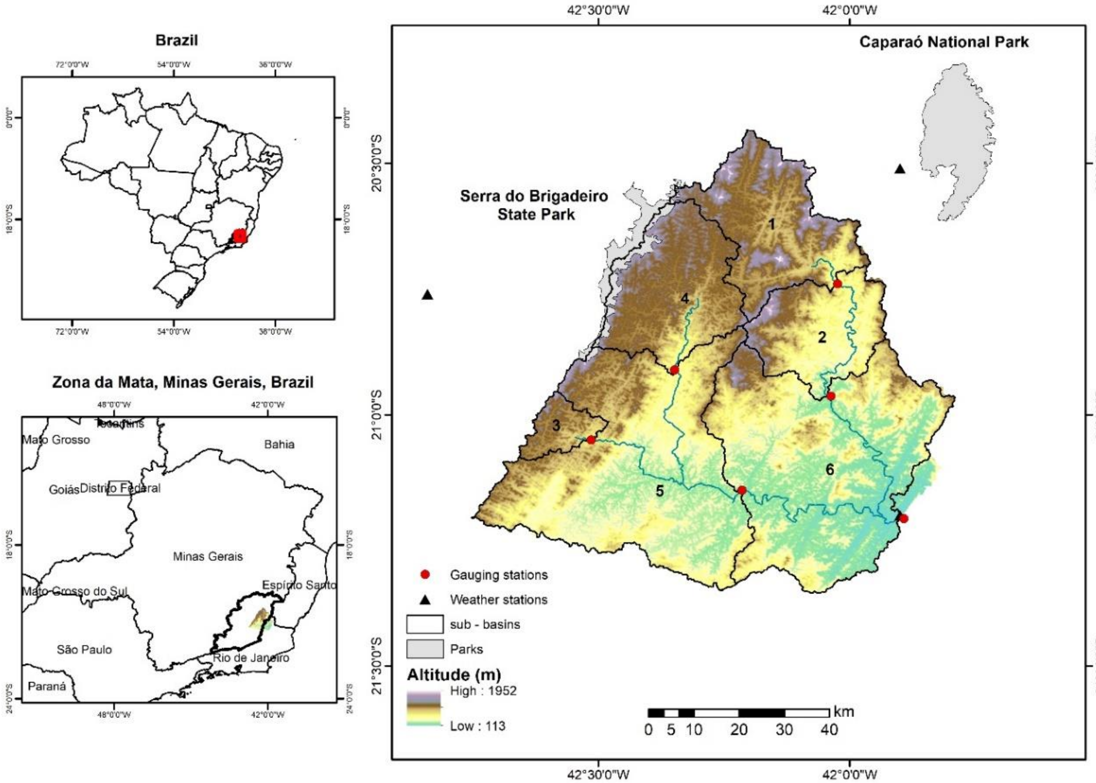


Figure 4.1. Location of the Muriaé river basin, Atlantic Forest Biome, Brazil, and elevation map of the study region with gauging and weather stations location indicated.

SWAT Model and input data

We used SWAT to analyse how changes in LULC and weather affect water dynamics in the Muriaé river basin. SWAT simulates the hydrology based on the water balance concept (Eq.1).

$$SW_t = SW + \sum(R_{day} - Q_i - E_a - P_i - QR_i) \quad \text{(Eq.1)}$$

where SW is soil water content (mm); t is time; R_{day} is the amount of precipitation (mm); Q_i is the amount of surface runoff (mm); E_a is the amount of evapotranspiration (mm); P_i is the amount of percolation (mm); and QR_i the amount of return flow (mm). For a detailed description of the components of the SWAT model we refer to (Neitsch et al., 2011). The timestep for the model was one month.

SWAT delineates sub-basins, which are further divided in hydrologic response units (HRUs). Each HRU represents a spatial unit with unique LULC, soil type and slope characteristics. We used maps of LULC of 1995 and 2015 with 30 x 30 m resolution to represent the dynamics of LULC change in the Muriaé river basin from 1990 to 2015 (Fig. 4.2A, B). The detailed LULC changes in quantitative terms in the sub basins are described in Appendix 4.1. We used the map of 1995 to represent the period between 1990 and 2004 (baseline period), while the LULC map from 2015 represented the period between 2005 and 2015. The LULC maps were developed by Gomes (2020) and contain six classes: forest, coffee, pasture, urban area, eucalyptus plantations and campos rupestres (scrub-grassy vegetation on rocks). The soil class map was derived from the soil maps from the states of Minas Gerais and Rio de Janeiro (Fig 4.2C; FEAM, 2010; Embrapa, 2016). The slope map was derived from the Digital Elevation Model using the ArcGIS software and was classified into five classes: 0 – 8, 8 – 15, 15 – 25, 25 – 45 and > 45% (Fig 4.2D). We used daily climatic records of precipitation, temperature, solar radiation, wind speed and relative humidity from three meteorological stations (Fig 4.1). However, data on solar radiation was only available for the station in Viçosa from 2005 to 2015. Therefore, we used the solar radiation data from 2005 to 2015 to derive a predictive model using the Random Forests algorithm and the maximum temperature, air humidity and daily daylight hours as explanatory variables to predict solar radiation for the three meteorological stations from 1990 to 2015 (Appendix 4.2).

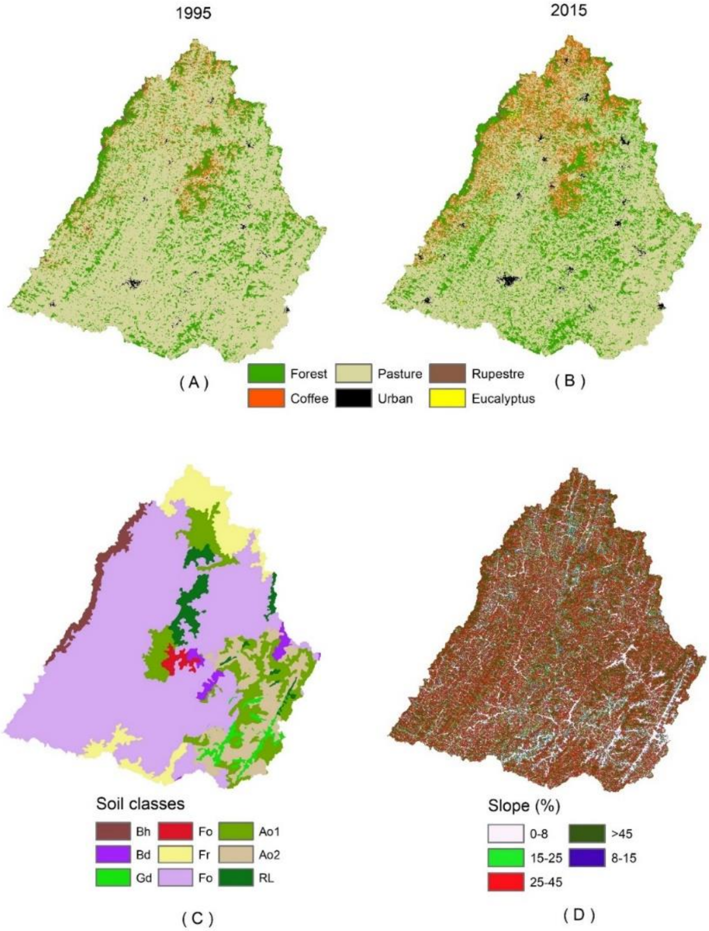


Figure 4.2. Land use Land cover maps of the Muriaé river basin, Brazil from 1995 (A) and 2015 (B), soil (C) and slope map (D). The maps served as input of the SWAT model to simulate hydrologic dynamics. Bh = Humic Cambisols; Bd = Dystric Cambisols; Gd = Dystric Gleysols; Fr = Rhodic Ferrasols; Fx = Xanthic Ferrasols; Fo = Orthic Ferrasols; Ao1 = Red Orthic Acrisols; Ao2 = Red-Yellow Orthic acrisol; and RL= Regosols.

SWAT calibration, validation and sensitivity analysis

We simulated the streamflow in the Muriaé river basin between 1990 and 2015. We calibrated the monthly streamflow for the period of 1990-1999 with the initial three years set as the model *spin-up* period (1990-1992) with the observed streamflow from the upstream gauging station number 4 (Fig. 4.3). We selected this gauging station since it is located upstream and is the most representative for the watershed. The *spin-up* period is an essential step to obtain a representative state of the model for the watershed hydrology (Kim et al., 2018). Next, we validated the model for the period 2000-2015. For model validation we used the Nash-Sutcliffe Efficiency (NSE; Nash and Sutcliffe, 1970) with the classification (0.75 < NSE < 1.00 very good; 0.65 < NSE < 0.75 good; 0.50 < NSE < 0.65 satisfactory; NSE < 0.50 unsatisfactory) and the performance indicators of the percent bias (PBIAS) with values lower than ±25% considered satisfactory (Moriasi et al., 2007). Aiming to improve the performance of the SWAT model, we conducted a global sensitivity analysis to identify the most important parameters that control the streamflow using p-value < 0.001. For this purpose, we used the SWAT-CUP with the Sequential Uncertainty Fitting version 2 (SUFI-2) algorithm for calibration and validation (Abbaspour et al., 2004).

The most sensitive parameters to changes in the historic streamflow were SOL_K, SOL_AWC, CN2, ALPHA_BF, RECHARGE_DP and GW_DELAY (Appendix 4.3). The observed and simulated monthly average streamflow of gauging station 4 in the calibration period (1993 to 1999) were 15.42 (± 11.02) and 16.04 (± 9.70) mm, respectively. The performance indicators of the SWAT model for this period were 0.72 for NSE and -3.3% for PBIAS. In the validation period (2000 – 2015) the measured and simulated average monthly streamflow were 18 (± 13.94) and 18.20 (± 11.25) mm, respectively, and the performance indicators were 0.71 for NSE and 20.4% for PBIAS. The performance of the SWAT model for calibration and validation was "good" according to the performance criteria of Moriasi (2007).

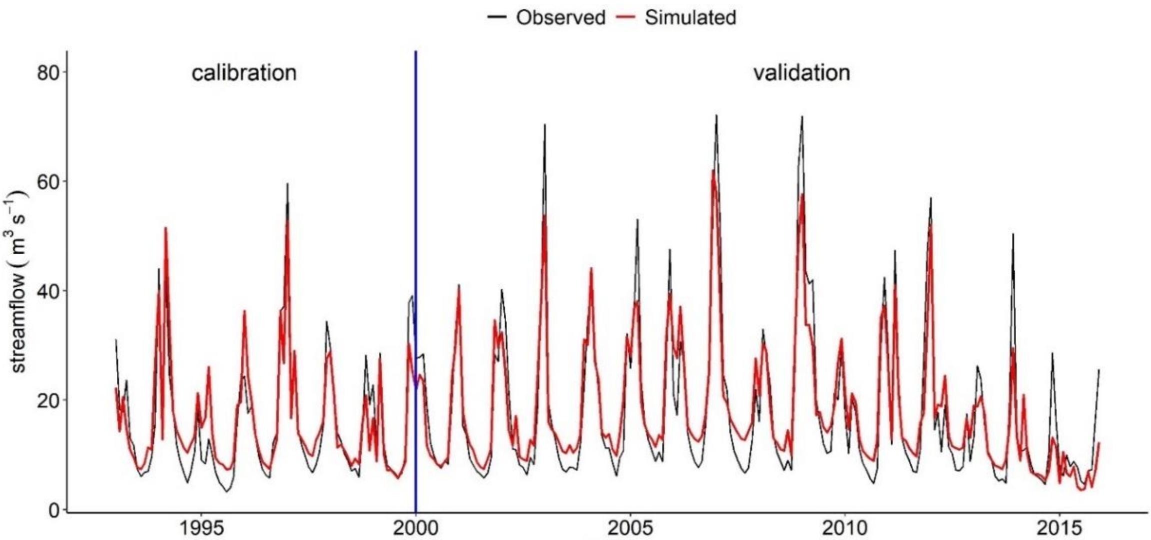


Figure 4.3. Monthly streamflow observed (black lines) and simulated (red lines) by SWAT model between 1990 and 2015 in the upstream sub-basin four, Muriaé river basin, Brazil. The blue line indicates the threshold between the calibrated period (1990 - 1999) and the validation period (2000 – 2015).

Historical trend analysis of hydro-climatic variables

We used the non-parametric Mann-Kendall test to identify significant trends in the annual time series of mean temperature, precipitation and streamflow from 1990 to 2015. This rank-based statistical method is extensively applied to series data and performs with robustness for non-normally distributed data

(Belle and Hughes, 1984; Guo et al., 2016). Here, we conducted an uncertainty analysis using a 95% confidence interval (i.e. ± 1.96 of the standard normal distribution).

Disentangling LULC and weather effects

We used the separation method to assess the relative contribution of changes in LULC and variation in weather variables on historical water yield, surface runoff, soil water and evapotranspiration (Dey and Mishra, 2017). We evaluated four simulations (S1, S2, S3 and S4) consisting of pairwise combinations of two contrasting LULC maps (1995 vs. 2015) and two climate data periods (1990-2004 vs. 2005-2015). The contrast between S3 and S1 reflects the effect of variation in climate on water dynamics, while the contrast between S4 and S3 indicated the effect of LULC change (Table 2). The difference between S4 and S1 represents the combined effect of changes in LULC and climate on water dynamics. The relative impact of changes in LULC was calculated as $EL = ((S3 - S1)/(S1 - S4)*100)$ and changes in climate as $EC = ((S4 - S3)/(S1 - S4))*100$).

Future LULC and climatic scenarios

To explore the effect of LULC changes and climate variability on hydrology for 2045 we developed three scenarios: the baseline, Fossil Fuel and Green Road. The baseline scenario was based on the LULC map of 2015, while the Green Road and Fossil Fuel were based on projected LULC maps for two contrasting local scenarios consistent with the global socioeconomic shared pathways (Gomes et al., 2020). The percentage forest area in the baseline LULC scenario is 24%, while in the Green Road scenario forest area will expand to 39%, and in the Fossil Fuel scenario the forest area will decrease to 18% and replaced mainly by pastures and coffee plantations (Fig 4.4; Table 4.1).

The three LULC scenarios were coupled with a climatic projection from 2020 to 2045, which was based on the global representative forcing pathway (RCP) 8.5 scenario of the HadGEM2-ES model. A limitation of RCP scenarios is that the temperature and precipitation data have a coarse spatial resolution and are unsuitable for the finer resolution of our study. Therefore, we used climate projections (bias corrected) from 2020 to 2045 combined with our historic daily database of temperature maximum, minimum and precipitation (Navarro-Racines and Tarapues, 2015). This process resulted in a database with daily values for maximum and minimum temperature and precipitation from 2020 to 2045. For the period 2035-2045, the mean temperature is expected to increase from 21.6ºC to 22.9ºC and precipitation will increase +42.43 mm y^{-1} compared with the period of 2005-2015.

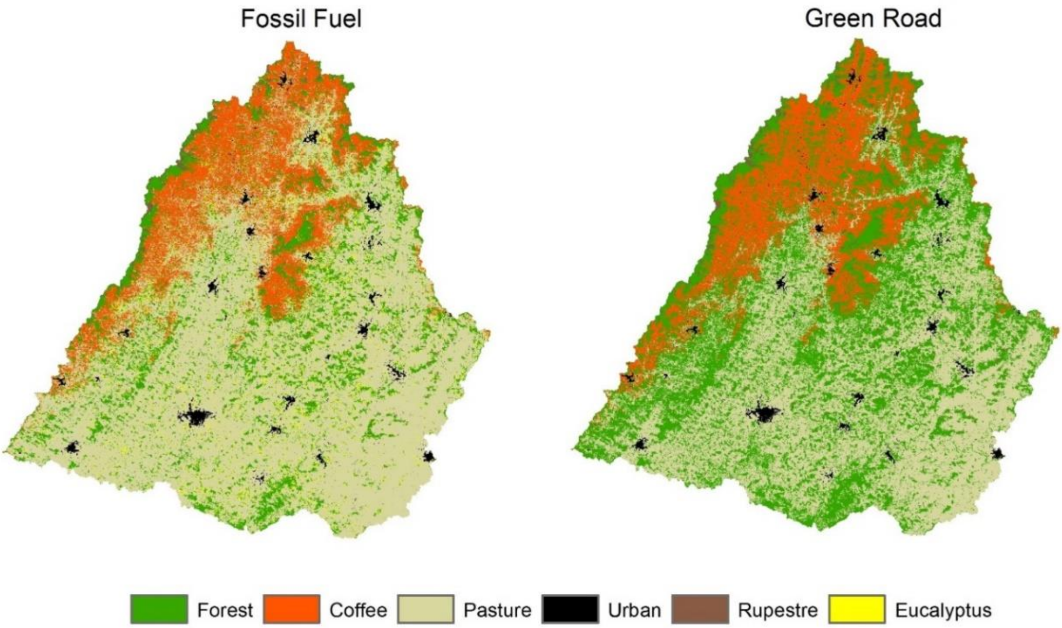


Fig. 4.4. Land Use and land Cover of the Fossil Fuel and Green Road scenarios for 2045 of the Muriaé river basin, Brazil. The Fossil Fuel scenario simulates a future with focus on economic returns and no protection to environment, while the Green Road simulates a future with high environment protection (Gomes et al., 2020).

Table 4.1. Absolute and relative changes in Land Use and Land cover (LULC) of the Fossil Fuel and Green Road scenario as compared to the baseline scenario (LULC 2015) for 2045 in six sub-basins of the Muriaé river basin, Brazil (Gomes et al., 2020).

	LULC changes in km^2 (% of sub-basin area)					
Sub-basins	1	2	3	4	5	6
			Fossil Fuel			
Forest	-58.5 (-7.7)	-57.3 (-10.6)	-11.5 (-8.2)	-65.1 (-8.8)	-158.8 (-9)	-182.2 (-10.3)
Coffee	160.4 (+21.1)	29.7 (+5.5)	17.1 (+12.2)	182.2 (+24.6)	33.5 (+1.9)	19.4 (+1.1)
Pasture	-130.7 (-17.2)	-5.9 (-1.1)	-13.2 (-9.4)	-142.9 (-19.3)	26.4 (+1.5)	65.4 (+3.7)
Urban	3 (+0.4)	3.2 (+0.6)	0.7 (+0.5)	2.9 (+0.4)	5.2 (+0.3)	5.3 (+0.3)
Eucalyptus	16.7 (+2.2)	35.1 (+6.5)	8.2 (+5.9)	16.2 (+2.2)	97 (+5.5)	91.9 (+5.2)
			Green Road			
Forest	126.9 (+16.7)	80.6 (+14.9)	27.4 (+19.5)	88.9 (+12)	298.3 (+16.9)	183.9 (+10.4)
Coffee	151.3 (+19.9)	25.9 (+4.8)	22.9 (+16.3)	228.9 (+30.9)	45.8 (+2.6)	10.6 (+0.6)
Pasture	-271.4 (-35.7)	-102.3 (-18.9)	-49.2 (-35)	-310.4 (-41.9)	-340.7 (-19.3)	-191 (-10.8)
Urban	3 (+0.4)	3.2 (+0.6)	0.7 (+0.5)	2.9 (+0.4)	5.2 (+0.3)	5.3 (+0.3)
Eucalyptus	-18.2 (-2.4)	-2.7 (-0.5)	-0.4 (-0.3)	-17 (-2.3)	-5.2 (-0.3)	-10.6 (-0.6)

Results

Historical trend analysis

Meteorological records from 1990 to 2015 indicate that the mean air temperature showed a significant increasing trend ($Z=2.81$, $p = 0.004$) from 1990 to 2015, while there was no significant trend in precipitation and streamflow in this period (precipitation: $Z= -0.48$, $p = 0.62$; streamflow $Z=0.06$, $p = 0.54$; Fig. 4.5). The mean air temperature varied from 21.6ºC ± 3.5 between 1990 - 2004 to 22.4ºC ± 2.9 between 2005 – 2015 (Fig. 4.5 and Appendix 4.4).

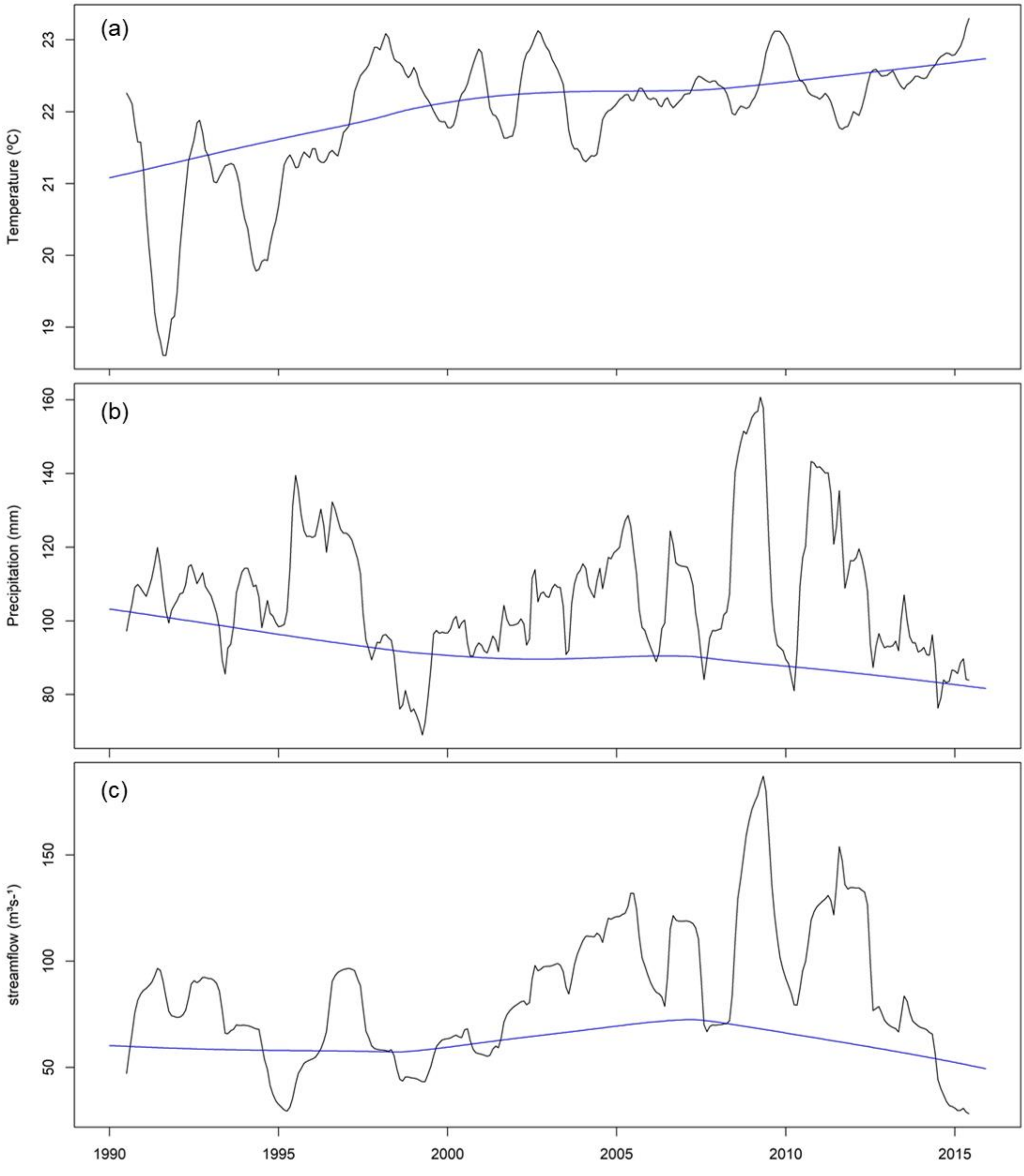


Figure 4.5. The inter-annual decomposed trend of mean temperature (a), precipitation (b) and streamflow (c) between 1990 and 2015 in the Muriaé river basin, Brazil (Appendix 4.4). The blue line was computed by a weighted regression.

Disentangling effects of LULC and climate on historical hydrological variables

The simulations S1 and S4 showed that the streamflow increased in average 15.8 m^3s^{-1} between 1990 and 2015 in the sub-basins (Table 4.2). Between 1990-2004 and 2005-2015 the simulated precipitation increased +348 mm y^{-1} in the sub-basins 1, 2 and 6, while no changes were observed for sub-basins 3, 4 and 5 (Appendix 4.5). At the watershed level, surface runoff of water increased by +5.2 mm y^{-1} as compared to the baseline period, with a relative contribution of 155% by climate and -55% by LULC changes (Fig. 4.6A). The drivers of surface runoff in sub-basins 1 and 2 showed contrasting patterns compared to sub-basin 3 and 4. The surface runoff in the sub-basins 1 and 2 were on average +8 mm y^{-1} higher than in the baseline period, as a result of climatic changes (155.1% contribution) and LULC changes (-55.1% contribution). On the other hand, in sub-basins 3 and 4, surface runoff increased by 3.6 mm y^{-1}, with contributions from changes in LULC of 71 and 14% in sub-basins 3 and 4, respectively.

Water yields in the impacted period (2005 – 2015) increased on average by 252 mm as compared to the baseline period (1990 – 2004) as result of climate variability (97%) and LULC changes (3%) (Fig. 4.6B). At the sub-basin level, the effect of LULC was positive in sub-basins 4 (+3.8%), 5 (+9.2%) and 6 (7.7%), and negative in sub-basins 1 (-0.6%), 2 (-0.3%) and 3 (-1.7%).

At the overall watershed level, the soil water content and evapotranspiration showed similar patterns with decreases of 24.6 and 15.7 mm y^{-1}, respectively (Fig. 4.6C, D). The change in soil water was due to climate variability

(605.5%) and LULC changes (-505.5%), while the climate and LULC contributed 59% and 41%, respectively, to the decrease in evapotranspiration. In contrast to the other sub-basins, sub-basin 1 showed an increase of 27.6 mm y^{-1} in soil water and 63.8% in evapotranspiration (Fig. 4.6C and D). On the other hand, in sub-basin 3, soil water decreased by 56.2 mm and evapotranspiration by 98.3 mm (Fig. 4.6C and D).

Table 4.2. Overview of four simulations (S) used to explore the effect of changes in Land Use Land Cover (LULC) and climate in the Muriaé river, Brazil. The simulated streamflow for the six sub-basins are presented.

Simulations	LULC	Climate	Sub-basins streamflow (m^3s^{-1})					
			1	2	3	4	5	6
S1	1995	1990-2004	10.8	7.7	4.7	21.5	60.6	96.8
S2	2015	1990-2004	13.5	9.9	3.8	20.2	65.3	124.1
S3	1995	2005-2015	22.0	15.3	5.2	24.3	74.3	140.2
S4	2015	2005-2015	23.4	17.0	4.0	21.2	71.4	159.9

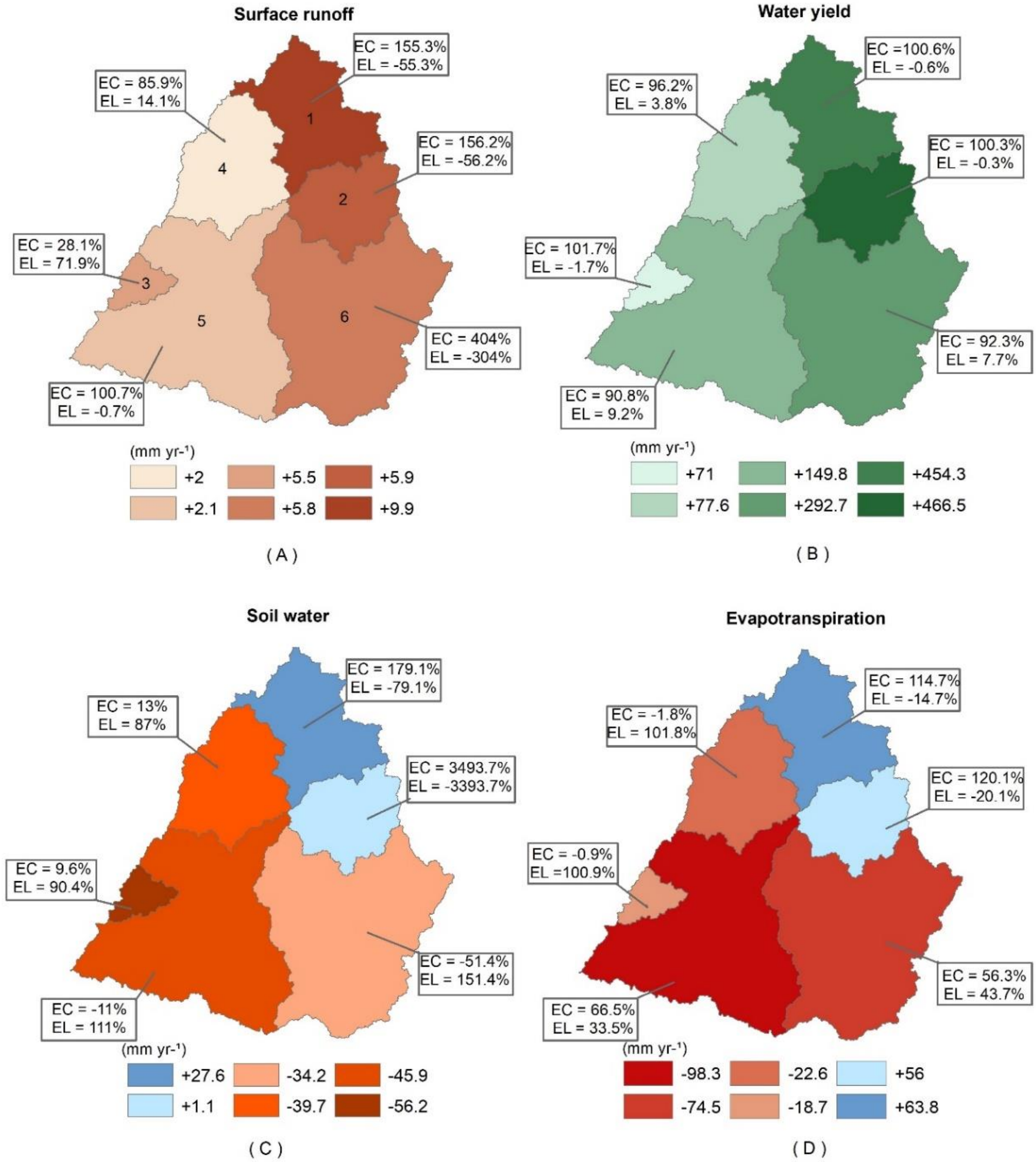


Figure 4.6. Mean annual changes of surface runoff (A), water yield (B), soil water (C) and evapotranspiration (D) between the 1990-2004 (baseline period) and 2005-2015 (impacted period). The partitioning of the contribution of variation in climate (EC) and LULC changes (EL) to the observed overall change is indicated as a percentage in the boxes.

Exploring future water dynamic scenarios

The Green Road and Fossil Fuel scenarios under the RCP 8.5 climate scenario resulted in contrasting hydrology outcomes in 2045 compared with the baseline scenario (Fig. 4.7). In the Fossil Fuel scenario, increases in water yield (+1.5%), surface runoff (+10.7%), soil water (+1.2%), and a decrease in evapotranspiration (-1.9%) are expected. In contrast, in the Green Road scenario decreases in water yield (-3%) and soil water (-3.6%) and increases in surface runoff (+3.8%) and evapotranspiration (+4.2%) may be anticipated. The water yield tends to increase in all sub-basin under the Fossil Fuel scenarios in 2045 with increases up to 2.4% in sub-basin 6 (Fig. 4.7A). By contrast, in the Green Road scenario the water yield decreased by -4.4% in sub-basin 5 (Fig. 4.7B). Surface runoff is expected to increase in all sub-basins for the Fossil Fuel scenario, up to 15% in sub-basins 2 and 3 (Fig. 4.7C). In the Green Road scenario surface runoff increased by up to 9.3% in sub-basins 2, 3, 4 and 5, and decreased in sub-basins 1 (-2.5%) and 6 (-1.7%; Fig. 4.7D). Soil water increased by up to 2.5% in the Fossil Fuel scenario (Fig. 4.7E) and decreased by -6.3% in the Green Road scenario (Fig. 4.7F). Evapotranspiration showed a contrasting trend compared to soil water: evaporation decreased by as much as 3.3% in the Fossil Fuel scenario (Fig. 4.7G) and increased by as much as 5.6% in the Green Road scenario (Fig. 4.7H).

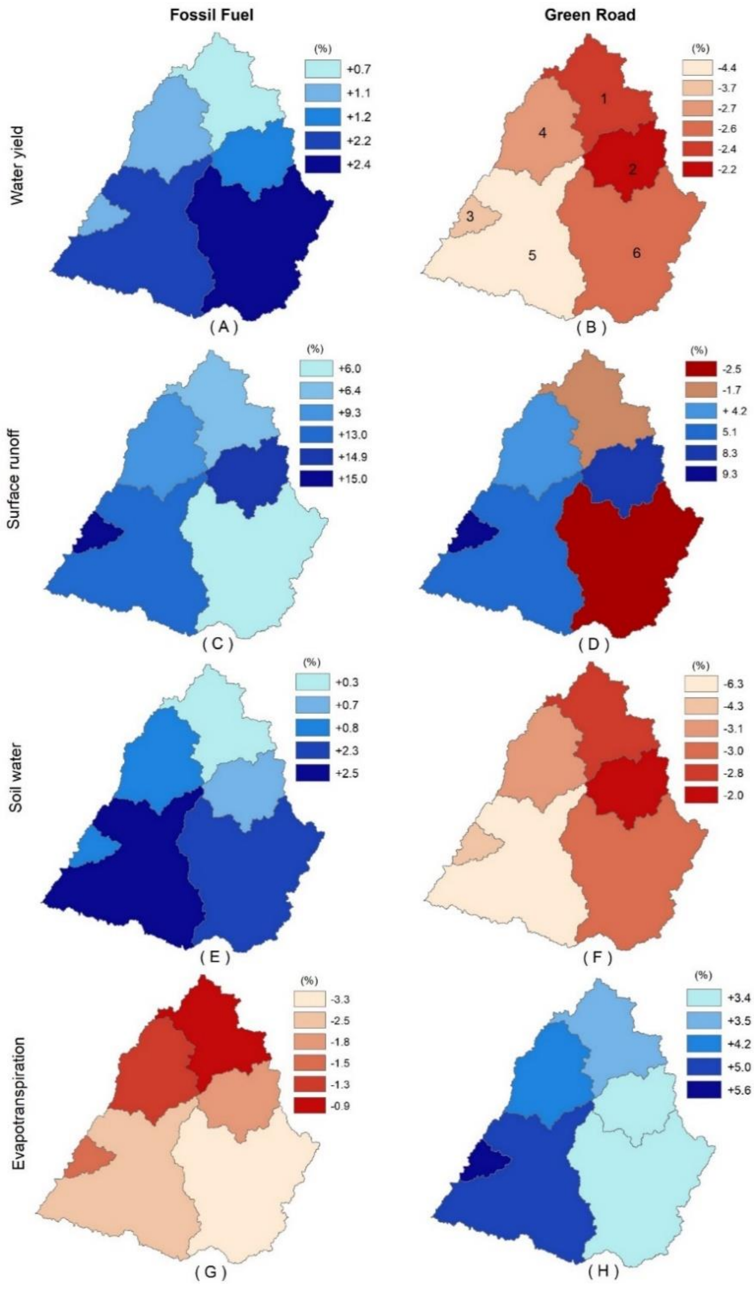


Figure 4.7. Relative changes in water yield (A, B), surface runoff (C, D), soil water (E, F) and evapotranspiration (G, H) in the Fossil Fuel and Green Road as compared with the baseline scenario between 2035 and 2045 in the Muriaé river basin, Brazil.

Discussion

In this study we explored the effect of historic LULC changes on the hydrology in a sub-tropical watershed between 1990 and 2015 and explored the potential consequences of future scenarios of LULC changes and climate for hydrological dynamics in 2045. Our key messages are: (i) the simulated river streamflow increased by 60% from 1990-2004 to 2005-2015, which was mostly explained by changes in climate patterns, ii) the contribution of LULC on the hydrology at the sub-basin level depends strongly on climate conditions, and (iii) scenarios for 2045 indicate that LULC changes can have a strong impact on water dynamics.

The simulated increase in river streamflow (+15.8 m^3s^{-1}) between 1990-2004 and 2005-2015 was mainly attributed to the increase in the annual precipitation (+348 mm) rather than LULC changes. It is difficult to determine which LULC changes (Appendix 4.1) contributed to the changes in the streamflow in this study. For instance, while the increase in forest area tend to decrease surface runoff and increase evapotranspiration, expansion of urban areas is associated with increased surface runoff and decreased evapotranspiration. In general, forests can increase the water infiltration and groundwater recharge (Lopes et al., 2020; Ouyang et al., 2019), and afforestation has been associated with reduced water yield and river streamflow due to increased evapotranspiration (Filoso et al., 2017). In the last decades water management has focussed on present in rivers and lakes. However, it is important to also consider soil water and the water flow by evapotranspiration, which are essential to maintain the ecosystem functioning

(Falkenmark and Rockström, 2006). When forests area expands, higher rates of evapotranspiration and photosynthesis can increase the frequency of precipitation and improve human health by pollution removal from the air (Ellison et al., 2012; Nowak et al., 2014). Therefore, the analysis of water-mediated ecosystem services should go beyond streamflow or water yield and also include ecosystem services related to natural process and functions, such as climate regulation and water purification, which can have a major impact on human wellbeing (Schulte et al., 2019).

The analysis of the water balance at the sub-basin level shows that the contribution of LULC on key hydrological variables depends on the actual weather conditions. In cases of increased precipitation, about +436 mm y^{-1} in sub-basins 1 and 2, the climate was the most important driver of the increase in surface runoff, soil water and evapotranspiration, while LULC changes were associated with a decrease of surface runoff, soil water and evapotranspiration (Fig. 4.6). In contrast, when there were no significant changes in precipitation, LULC changes were the most important driver of increases of surface runoff and of decreases of soil water and evapotranspiration (sub-basins 3 and 4). Our findings align with those of (Li et al., 2016, 2009; Shang et al., 2019) who also identified changes in climate as main drivers of hydrology in various contexts. LULC changes can be considered as a moderator of water dynamics, which is strongly related to the quantity of precipitation in the environment. Global studies show that afforestation in drier areas has a stronger negative effect on water yield than in humid regions (Jackson et al., 2005; Zhang et al., 2017). Therefore, to improve the management of future water resources we should take in consideration contrasting simulations for a specific LULC type combined with future projections of climate changes.

The Fossil Fuel and Green Road scenarios indicated contrasting outcomes for the hydrological dynamics in 2045. Compared with the baseline scenario, the Fossil Fuel scenario with 18% less forest is expected to result in increased water yields, surface runoff and soil water contents, and decreased evapotranspiration. By contrast, in the Green Road scenario, which entails an increase of forest cover to 39% of the total area, may lead to decreased water yields, reduced surface runoff in sub-basins 1 and 6, and increased evapotranspiration. Although the Fossil Fuel and Green Road scenarios involve changes in multiple LULC types as compared to the baseline scenario, the most pronounced changes involve forest area (Table 4.2). This allowed us to explore the effect of forest on hydrology variables. In general, the Green Road scenario was associated with higher evapotranspiration and lower surface runoff, water yield and soil water content compared to the Fossil Fuel scenario. Forest canopies can intercept about 20% of precipitation (Sari et al., 2016). Yet, understand the water dynamics inside forests is needed to fully understand the role of forests on water cycle. LULC scenarios developed with the Distributed Hydrology Soil Vegetation Model in the same region as our study supported our finding that increases in forest areas are associated with increased evapotranspiration and decreased surface runoff, soil water and water yields (Alvarenga et al., 2016). For instance, our analysis indicated that forest areas provide other water related ecosystem services, such as the reduction of surface runoff, which can improve water infiltration and reduce soil erosion, and therefore land degradation (Didoné et al., 2015).

Forests may also mitigate impacts of extreme climatic events that are predicted to happen more often in the future (IPCC, 2018), such as the precipitation up to 920 mm recorded in January 2020 causing severe flooding and landslides in some parts of our study region (INMET, 2020). Therefore, the expansion of forests and the integration of trees on farmland, such as in agroforestry systems, offer potential to manage water dynamics in the future.

We encountered several challenges and limitations in our attempts to separate the effects of climate and LULC change on historic water dynamics and to explore hydrological dynamics in the future, based on combined LULC and climate change scenarios. First, we lacked historical records of solar radiation and addressed this issue by estimating these data using the Random Forests algorithm. Second, we used only one climate model (HadGEM2-ES) for exploring the future climatic conditions. We identified that climate was the main driver of water dynamics between 1990 and 2015, and for future studies we recommend using multiple climatic models to explore the effects of different projections of precipitations patterns on the hydrology. Third, our study did not explore the monthly dynamics of the streamflow. In the same region of our study, (Cecílio et al., 2019) found that increasing forest cover in the upper areas of a basin can increase the minimum streamflow, while the afforestation close to watercourses might reduce the minimum streamflow. Therefore, we recommend that future studies explore the monthly dynamics of hydrological variables to improve our understanding of the effects of LULC changes on water dynamics in the region.

Conclusions

In this study we disentangled the effects of climate and LULC changes on historic water dynamics. This analysis revealed that changes in climate patterns are the main drivers of historical water dynamics in the region. Furthermore, the Green Road and Fossil Fuel scenarios allows to anticipate the impacts of LULC changes and climate on hydrology. The analysis of these scenarios indicated that an increase in forest area is expected to decrease surface runoff and the associated water yield, favouring other water related ecosystem services. For instance, reducing surface runoff can increase water infiltration and decrease soil erosion, and mitigate the negative impacts of climate extremes, such as intensive precipitation events. Therefore, incentives that stimulate the expansion of forests and the on-farm planting of trees can improve the provision of water-related ecosystem services and strengthen the resilience of (agro)ecosystems.

Appendix 4.1. Land Use and Land cover changes (%) from 1990 to 2015 in the six sub-basins in the Muriaé river basin, Brazil.

	LULC changes (1990 - 2015)					
Sub-basins	1	2	3	4	5	6
LULC	km^2 (% of sub - basin area)					
Forest	25.9 (+3.4)	37.4 (+6.9)	11.8 (+8.4)	17 (+2.3)	176.5 (+10)	116.8 (+6.6)
Coffee	104.9 (+13.8)	-2.7 (-0.5)	11.8 (+8.4)	88.2 (+11.9)	17.7 (+1)	8.8 (+0.5)
Pasture	-151.3 (-19.9)	-47.1 (-8.7)	-27.3 (-19.4)	-118.5 (-16)	-215.4 (-12.2)	-148.6 (-8.4)
Urban	6.1 (+0.8)	4.3 (+0.8)	1.7 (+1.2)	5.2 (+0.7)	8.8 (+0.5)	7.1 (+0.4)
Eucalyptus	10.6 (+1.4)	7.6 (+1.4)	1.8 (+1.3)	10.4 (+1.4)	10.6 (+0.6)	10.6 (+0.6)

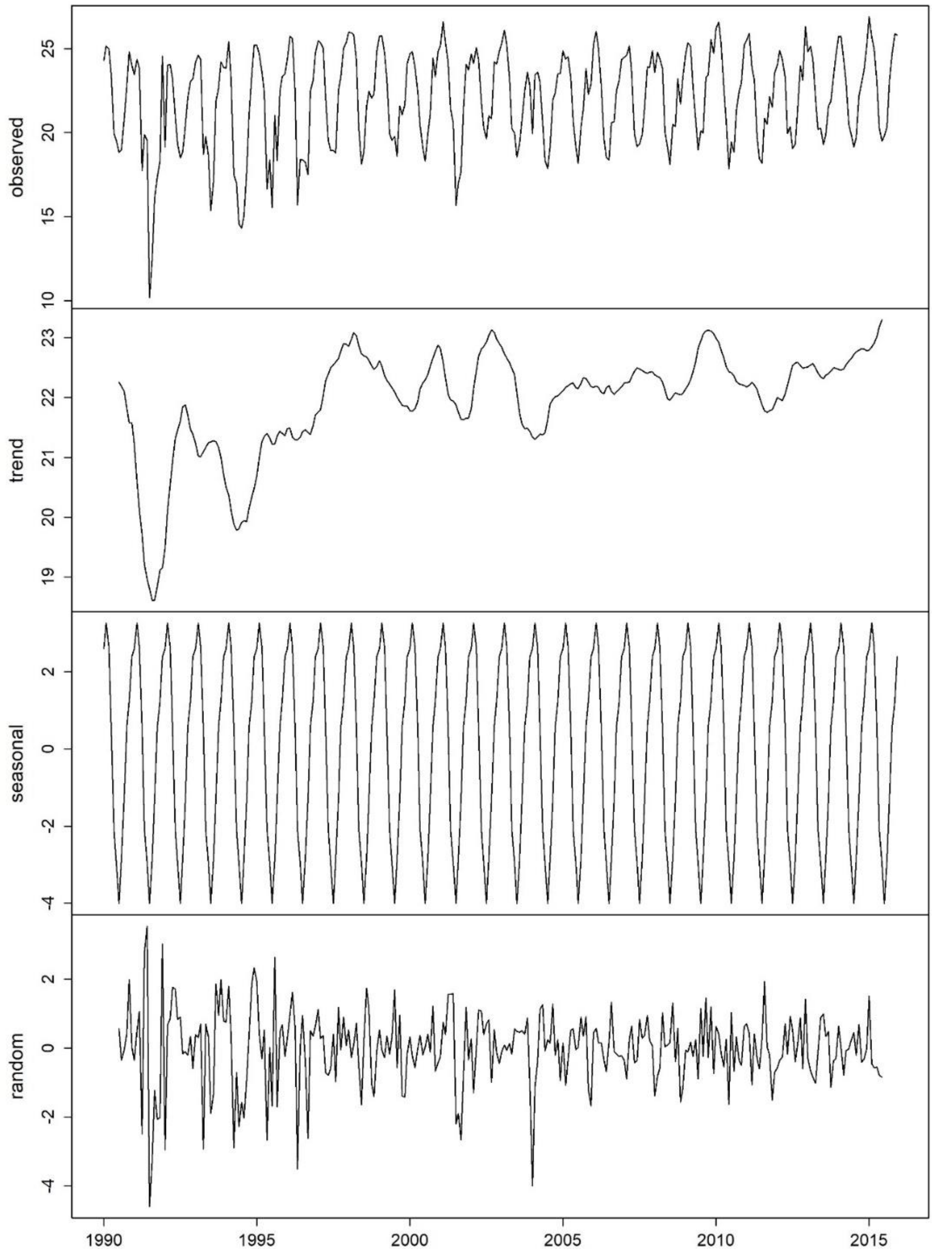
Appendix 4.2. Observed and predicted mean solar radiation values by Random Forest algorithm from the Viçosa weather station from 2005 to 2015.

Month	Solar radiation (kj/day)	
	observed	predicted
January	17506.5	18062
February	18456	18987.1
March	15208.7	16429.3
April	14174.2	14330
May	12152.8	12519.3
June	11494.6	12014.8
July	12556	13031.8
August	15089.7	15027.7
September	16326.6	16448
October	16441.6	16557.4
November	16066.4	16052.4
December	17286.6	17191

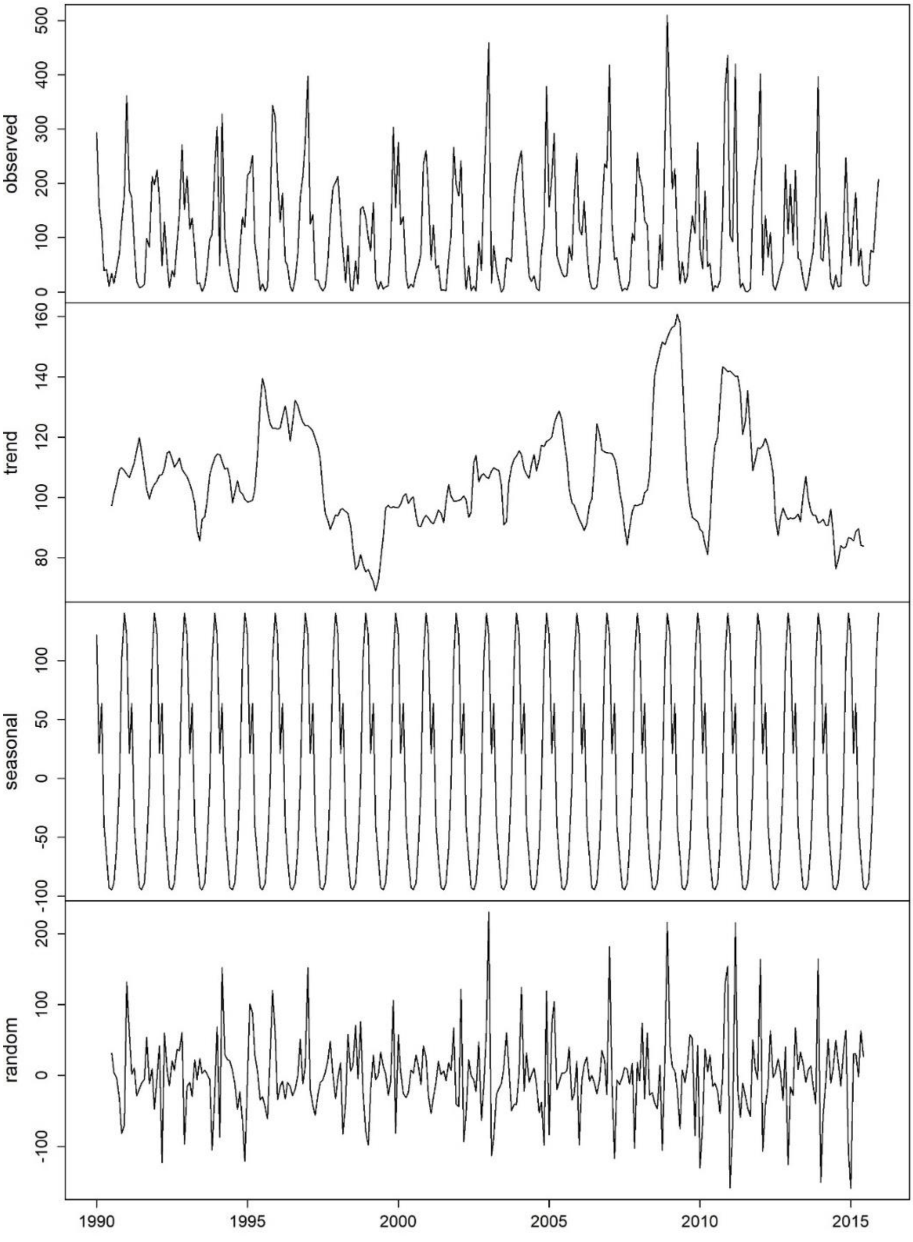
Appendix 4.3. Parameters used in the sensitivity analysis and calibration of the SWAT model. The minimum and maximum of possible values (range), p-value, rank of the parameter and optimized value for the statistically significant parameters that were used in the analysis are presented.

Parameter	Description	Range	P-Value	Rank	Optimal value
r_SOL K	Soil conductivity (mm/h)	(-0.5)-5	< 0.001	1	0.166
r_SOL AWC	Available water capacity of the soil layer (mm/mm soil)	(-0.5)-5	< 0.001	2	1.222
r_CN2	Soil conservation service run-off curve number for moisture II	(-0.2)-0.2	< 0.001	3	0.712
v_ALPHA BF	Baseflow alpha factor (days)	0 - 1	< 0.001	4	0.171
v_GW DELAY	Groundwater delay (days)	30 - 450	< 0.001	5	445.17
v_RCHRG DP	Deep aquifer percolation fraction	0 - 1	< 0.001	6	0.98
v_CH K2	Hydraulic conductivity in main channel (mm/h)	0 - 130	0.003	7	-
r_SOL ALB	Soil albedo	(-0.25) - 0.25	0.036	8	-
v_REVAPMN	Threshold depth of water in the shallow aquifer required for revap to occur (mm)	0 - 5000	0.040	9	-
v_EPCO	Plant evaporation compensation factor	0.01 - 1	0.381	10	-
v_ESCO	Soil evaporation factor	0.01 - 1	0.555	11	-
v_SURLAG	Surface runoff lag time (days)	1 - 24	0.569	12	-
v_GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	0 - 2	0.658	13	-

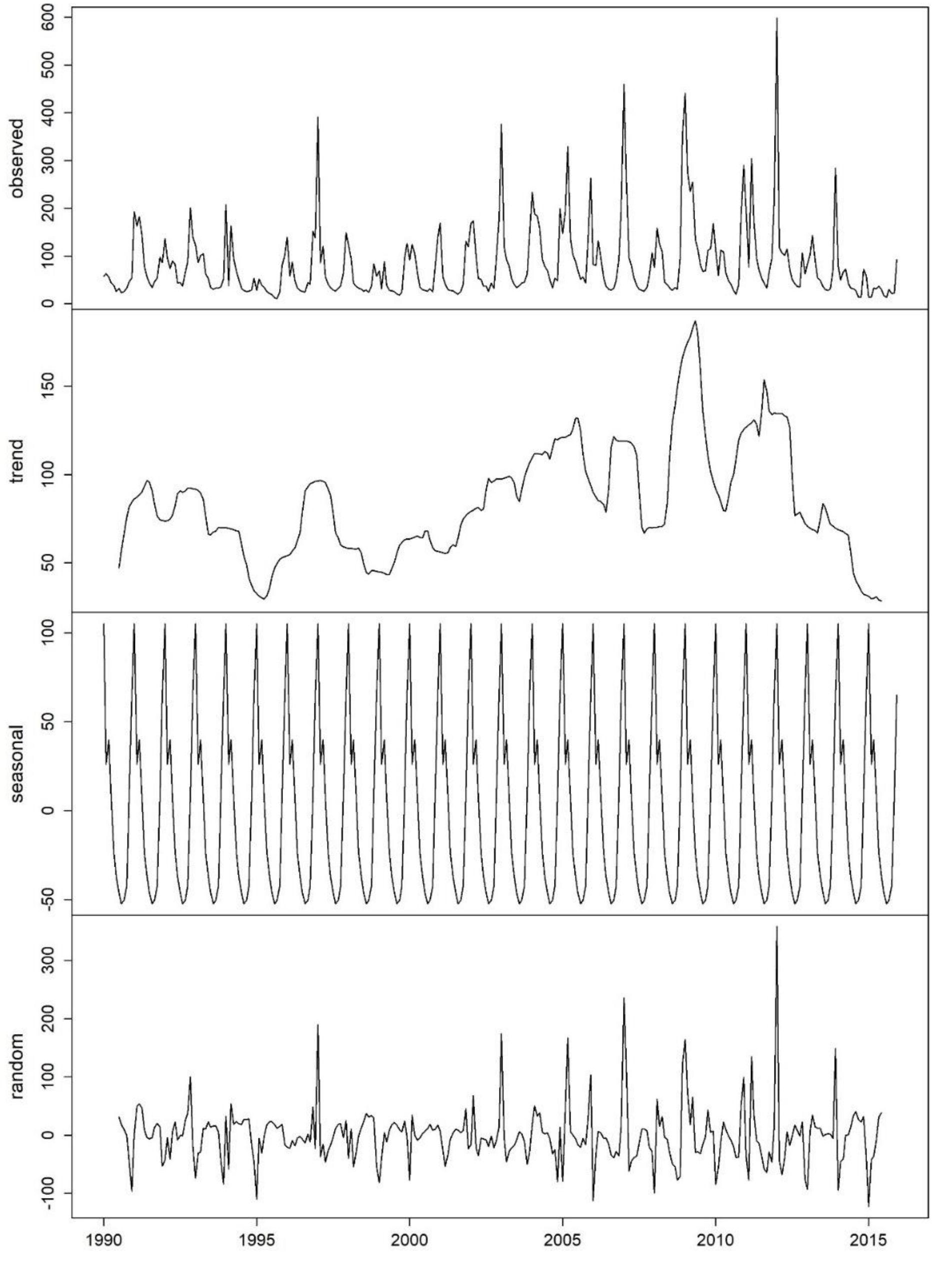
Appendix 4.4A. Decomposed factors of mean air temperature variation between 1990 and 2015.



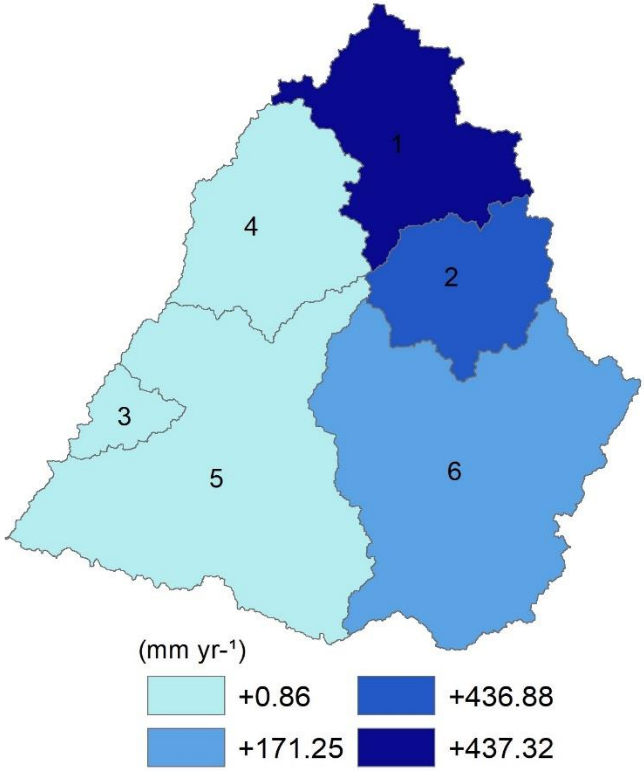
Appendix 4.4B. Decomposed factors of precipitation (mm) variation between 1990 and 2015.



Appendix 4.4.C. Decomposed factors of streamflow variation between 1990 and 2015.



Appendix 4.5. Changes in precipitation simulated by SWAT model in the six sub-basins between the baseline period (1990 – 2004) and the impacted period (2005 – 2015) for the Muriaé river basin, Brazil.



Chapter 5

Agroforestry systems can mitigate the impacts of climate change on coffee production: a spatially explicit assessment in Brazil

Lucas C.Gomes, Felix J.J.A.Bianchi, Irene M.Cardoso, Raphael B.A.Fernandes, Elpídio I.F.Filho, Rogier P.O.Schulte, 2020.
Agriculture Ecosystem and Environment 294, 106858

Abstract

Climate change may impose severe challenges to farmers to maintain agricultural production levels in the future. In this study we analysed the effect of projected changes in climate on the area suitable for coffee production in 2050, and the potential of agroforestry systems to mitigate these effects in a major coffee production region in southeast Brazil. We conducted a spatially explicit analysis with the bioclimatic model MaxEnt to explore the area that is suitable for coffee production in 2050 when coffee is grown in unshaded plantations and in agroforestry systems. The projected climate in 2050 was assessed using 19 global circulation models, and we accounted for the altered microclimate in agroforestry systems by adjusting the maximum and minimum air temperature. The climate models indicated that the annual mean air temperature is expected to increase 1.7ºC ± 0.3 in the study region, which will lead to almost 60% reduction in the area suitable for coffee production in unshaded plantations by 2050. However, the adoption of agroforestry systems with 50% shade cover can reduce the mean temperatures and maintain 75% of the area suitable for coffee production in 2050, especially between 600 and 800 m altitude. Our study indicates that major shifts in areas suitable for coffee production may take place within three decades, potentially leading to land conflicts for coffee production and nature conservation. Incentives that contribute to the development of coffee agroforestry systems at appropriate locations may be essential to safeguard coffee production in the southeast of Brazil.

Introduction

Climate change is expected to impose severe challenges to farmers to maintain agricultural production levels in the future (IPCC, 2019; Schroth et al. 2009). This is particularly the case for producers of coffee, which is an important cash crop for approximately 25 million smallholder farmers and 100 million livelihoods in many countries in Africa, Mesoamerica, and South America (Pendergrast, 2010; Waller et al., 2007). *Coffea arabica* is highly sensitive to changes in climate and global projections indicate a reduction in the area that is suitable for coffee production due to changing temperature and precipitation regimes (DaMatta, 2004; DaMatta and Cochicho Ramalho, 2006; Ovalle-Rivera et al., 2015). This may force coffee production to move to other regions with more favourable climatic conditions. Alternatively, farmers may adapt by switching to coffee varieties that are better adjusted to future climate conditions or by changing the management of coffee systems to mitigate the effects of climate change (Baca et al., 2014; Schroth et al., 2009). Relocation of production areas, switching coffee varieties or to other crops types are challenging, and entail many complexities, including the availability of suitable areas, availability of new *C. arabica* varieties resistant to higher temperatures and cultural adaptation to another crop species (Eskes and Leroy, 2009). On the other hand, changing coffee management systems may be easier to implement. For instance, agroforestry management systems have been identified as a promising way to maintain coffee production in the future under scenarios of climate change (Lin 2007; IPCC, 2014).

Agroforestry coffee systems consist of coffee plants intercropped with shade trees, which can increase nutrient cycling, biodiversity, carbon storage, and provide a moderate microclimate (Bhagwat et al., 2008; Duarte et al., 2013; Nair, 1997; Soto-Pinto et al., 2009). The microclimate created by the trees results in lower mean air temperatures and higher soil moisture in coffee agroforestry systems than in unshaded coffee systems (Lin, 2010; Moreira et al., 2018; Souza et al., 2012a). However, increasing shade can also affect the physiology of coffee plants, stimulating the vegetative growth instead of flower buds, reducing the number of nodes per branch and coffee yield (Cannell, 1976). While shade levels above 50% in coffee plantations are associated with a decrease in coffee productivity, shade levels below 50% do not seem to compromise yield (Moreira et al., 2018). In unshaded systems, the coffee flowering shows strong yearly fluctuations, resulting in a biennial production pattern with alternating years with high and low productivity (DaMatta, 2004). These fluctuations can compromise income security for farmers and decrease the lifespan of coffee plants due to exhaustion during heavy production years. In contrast, the productivity of coffee under shade tends to be more stable across years than in unshaded coffee systems (DaMatta, 2004). Therefore, agroforestry coffee systems, when properly managed, may alleviate the effects of projected climate change by modifying the microclimate without decreasing coffee productivity. Yet, although several studies have shown the benefits of agroforestry systems on microclimate at specific locations, the effectiveness of agroforestry systems to mitigate the effects of climate change may differ along geographic location and altitude (Akpo et al., 2005; Lin, 2007; Souza et al., 2012a). Therefore, the assessment of areas where agroforestry systems may have most potential to mitigate climate change can inform climate adaptation management to safeguard future coffee production.

Brazil is the world's largest producer of coffee, with mostly unshaded coffee systems and only limited agroforestry coffee systems. The dominance of unshaded coffee systems makes coffee production in Brazil vulnerable for impacts of climate change with potential serious socio-economic repercussions. There are three main regions of coffee production in Brazil: Savannah areas in the Minas Gerais (Cerrado), south of Minas Gerais (Sul de Minas) and the Southeast Mountains (Matas de Minas Gerais and Montanhas do Espírito Santo). These regions have contrasting characteristics. Savannah areas in the Minas Gerais are characterized by flat areas and mechanized and irrigated sun coffee systems, while the south of Minas Gerais and the Southeast Mountains are mountainous areas. The Southeast Mountains cover almost one-third of all coffee production areas in Brazil, being managed mainly by smallholder family farmers. In this region, a group of family farmers in partnership with a non-governmental organization and the Federal University of Viçosa implemented agroforestry systems following participatory methodologies, aiming to restore soil quality and biodiversity in the 1990's (Cardoso et al., 2001). From this experience, the family farmers and researchers identified the criteria to identify best trees species for intercropping with coffee (Souza et al., 2010). They also indicated several tree species to be intercropped and several benefits associated to these trees (Souza et al., 2010), including natural pest suppression (Rezende et al., 2014), increased soil quality and biodiversity (Duarte et al., 2013; Souza et al., 2012a), diversification of agricultural production (Souza et al., 2012b) and climate regulation (Gomes et al., 2016). These findings underline the potential of coffee agroforestry systems in the Southeast Mountains region in Brazil.

Because of its mountainous terrain and heterogeneous landscapes, the projected changes in temperature and precipitation regimes may vary locally in Southeast Mountains, potentially impacting coffee production differentially in distinct locations. While field experiments in the Southeast Mountains show that agroforestry systems can reduce the daily maximum temperatures by up to 5ºC (Souza et al., 2012a), it is not clear how this will play out in different locations and what the implications are for coffee production. The identification of areas with high to low risk can inform spatial planning and management actions to mitigate effects of climate change. This study aimed to explore potential effects of climate change on the area suitable for coffee production, and the potential of agroforestry system to mitigate impacts of climate change at the regional scale. More specifically, the study aimed to (i) assess the projected monthly temperature and precipitation in the Southeast Mountains for 2050, (ii) assess how these climate conditions may affect the suitability for coffee production, and (iii) identify the potential of agroforestry systems to mitigate the impacts of climate change.

Material and Methods

Study area

The Southeast Mountains region (40.5ºW, 43.3ºW, 19.15S, 21.30S) is located in the southeast of Brazil, and is part of the Atlantic Forest Biome, which is an important biodiversity hotspot (Fig. 5.1; Myers et al. 2000). The main part of this area is characterized by mountains with elevations varying between 400 to 2700 meters above sea level. The region covers 31,700 km^2 and includes 107 municipalities, where approximately 383,000 ha consists of coffee plantations, producing on average 484,000 tons coffee per year, corresponding to almost 22% of the total *C. arabica* production in Brazil (IBGE, 2019). The areas over 1200 m altitude are mainly located in the Caparaó National Park and the Serra do Brigadeiro State Park, which are protected areas for nature conservation and tourism.

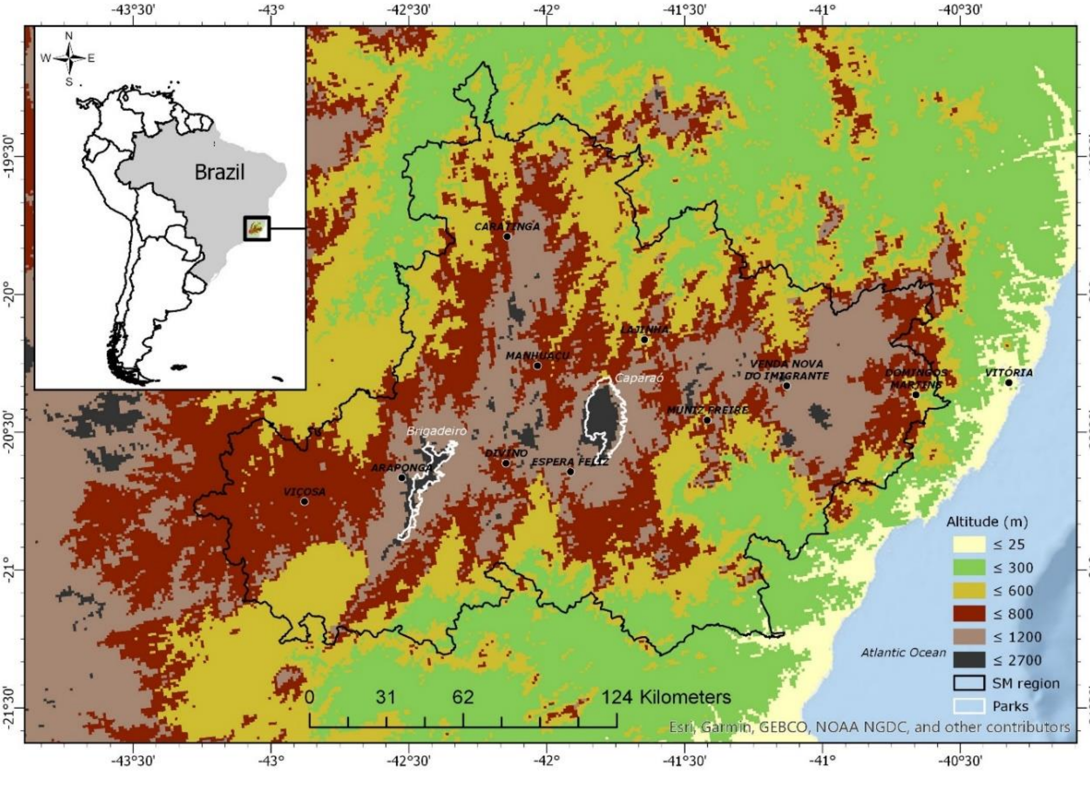


Figure 5.1. The Southeast Mountains region (SM) and the digital elevation model (m) in the Atlantic Forest Biome, Brazil. The borders of the National Caparaó Park (Caparaó) and the Serra do Brigadeiro State Park (Brigadeiro) are represented in white.

Coffee production areas and climate data

The current coffee production areas in the Southeast Mountains region were identified by the analysis of land use maps, annual yearbooks of statistical agricultural production from the municipalities (IBGE, 2019), and by checking Google Earth maps. First, we selected 3000 random sample points with coffee production from a land use map (Gomes et al., 2020) and 2000 additional sampling points from Google Earth maps in the municipalities that currently produce coffee, resulting in 5000 sampling points in total. Then, we checked each sampling point to confirm the presence of *C. arabica* and for overlapping sampling points, which reduced the number of suitable sampling points to 4200 (Appendix 5.1, Supplementary material). To assess the historical climate data in the study region between 1960-1990 and the projected climate in 2050 we used the WorldClim database version 1.4, which contains maps of monthly precipitation and mean, minimum and maximum temperatures at a spatial resolution of approximately 1x1 km (Hijmans et al., 2005). The WorldClim database 1.4 also includes maps of historic and projections of 19 bioclimatic variables (Table 5.1) that represent annual trends of temperature and precipitation, seasonality, and crop growth limiting factors, such as temperature of the coldest and warmest month, and precipitation during the wettest and driest month (Hijmans et al., 2005).

To study the changes in the spatial distribution of areas suitable for coffee production in the Southeast Mountains in 2050, we used projections of precipitation, temperature and bioclimatic variables from 19 different Global Circulation Models (GCMs) for the Representative Concentration Pathway

4.5 scenario for 2050 (RCP 4.5), which is considered the reference and therefore the most plausible climate scenario (Hijmans et al. 2005).

Coffee suitability analysis

We used the MaxEnt model (Phillips, Dudík and Schapire, 2019) to predict the current and the future coffee suitability in 2050 under the RCP 4.5 scenario climate change. The MaxEnt model has been applied for species distribution/environmental modelling (Merow et al., 2013; Phillips et al., 2006), and has been used to analyse the impact of climate change on coffee suitability from regional to global scales (Bunn et al., 2015; Läderach et al., 2017; Ovalle-Rivera et al., 2015). In MaxEnt we used the actual location of the 4200 coffee plantations as input data and the bioclimatic variables as environmental predictors. To avoid model-overfitting, we applied a Pearson correlation analysis ($r < 0.8$) on the 19 maps of bioclimatic variables and this resulted in six relatively uncorrelated bioclimatic variables (Bio 3, 4, 10, 12, 13 and 19), which were used for further analysis. We restricted the analysis to bioclimatic variables as predictor variables because no soil data at sufficiently fine resolution are available for the study region. We applied a multiple logistic regression in MaxEnt to create a predictive model for the probability of the presence of coffee plantations in each pixel with values ranging from zero to one (Ovalle-Rivera et al., 2015). In order to assess the changes in the percentage of area suitable for coffee production from current situation to 2050, we used a coffee suitability threshold of 0.25, which corresponds with the coffee suitability of marginal areas for current coffee production (Fig. 3a).

We split the 4200 locations in datasets for model training and validation. Eighty percent of the data were randomly assigned for model training and the remaining twenty percent was used for validation using the default setting in MaxEnt (Läderach et al., 2017). We used a fixed background area from which we drew 10,000 random locations for pseudo-absences of coffee (Läderach et al., 2017; VanDerWal et al., 2009). Then we ran the MaxEnt 25 times to map the current coffee suitability and also for each of the 19 GCMs, resulting in a total of 25 suitability maps for the current situation, and 475 suitability maps for 2050. For each of the 25 replicate runs new random training and validation datasets were drawn. To assess the uncertainty of the MaxEnt estimations and the predictions of the GCMs, we generated maps with the mean and coefficient of variation of the suitability predictions for 2050 of the 19 GCMs. The accuracy of the model to predict the suitability for coffee production was assessed using the Area Under the Curve (AUC) index (Peterson et al., 2008; Schroth et al., 2015). The model presented median AUC values of 0.77 for training and validation indicating satisfactory performance (Appendix 5.2).

Potential of agroforestry systems to mitigate the effects of climate changes

Shade trees affects the maximum and minimum daily temperature, and can decrease the mean daily temperature by up to 4ºC (Beer et al., 1998). More specifically, shade levels of 50% can decrease the mean daily temperature by 2-3ºC (Barradas and Fanjul, 1986; Rahn et al., 2018; Van Oijen et al., 2010), decrease the maximum air temperature by 3ºC, and increase the minimum temperature by 1ºC without compromising coffee yield (Moreira et al., 2018; Souza et al., 2012). To assess the spatial distribution of areas suitable for coffee production under agroforestry systems in 2050, we adjusted the maps of monthly minimum and maximum temperature from the RCP 4.5 scenario. First, we derived maps of the averages of the 19 GCMs for minimum and maximum temperature maps for each month in 2050. This resulted in twelve maps of monthly minimum and maximum temperatures in 2050. Then we subtracted 3ºC from the monthly maximum temperature maps and added 1ºC for monthly minimum temperature maps to mimic the effect of shade on the microclimate in coffee agroforestry systems. With the adjusted maps of temperature we recalculated new bioclimatic variables (BIO 3, 4, and 10) that account for shade effects (Appendix 5.3; O'Donnell and Ignizio 2012), which were used as input for MaxEnt (Section 2.3) to explore the spatial distribution of areas suitable for coffee production in agroforestry systems.

Results

Projected climate changes

The 19 global circulation models show a trend of increasing temperature and decreasing precipitation for 2050 in coffee production areas in the Southeast Mountains, Brazil (Fig. 5.2 and Table 5.1). The mean annual temperature is projected to increase 1.71 ± 0.3 ºC, with the highest increase from October to December, when the temperature can increase by up to 2.3 ºC. The total annual precipitation is projected to decrease from 1257 to 1199 mm, with the largest decrease from September to December.

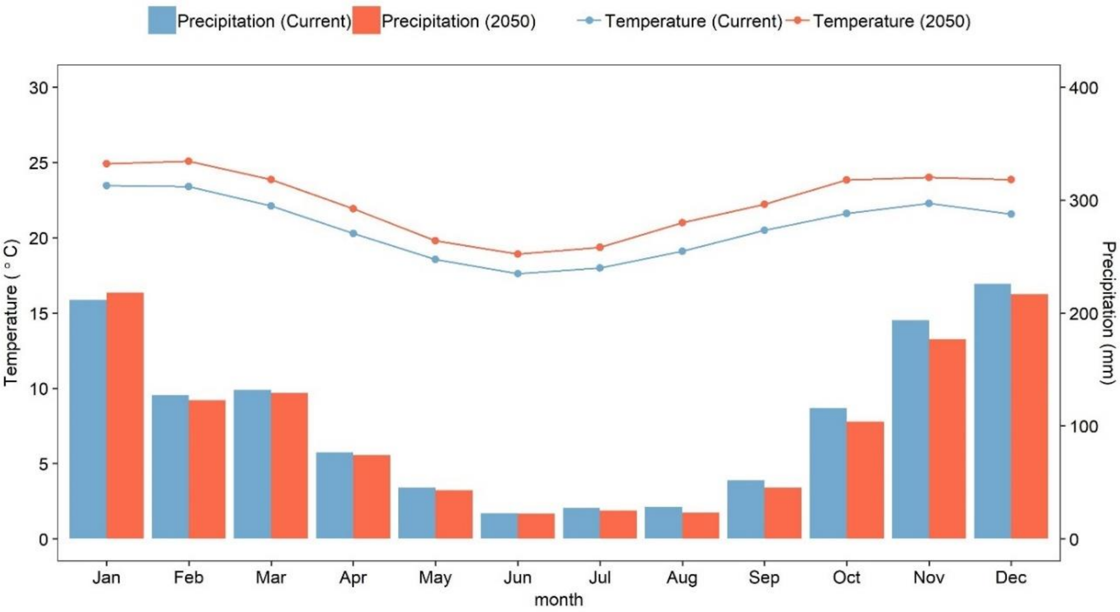


Figure 5.2. Annual variation of temperature (lines) and precipitation (bars) between 1960 and 1990 (Current, blue) and projected for 2050 (red) for coffee production areas in the Southeast Mountains region, Brazil. Projections for 2050 are based on the average of 19 Global Circulation Models for the Representative Concentration Pathways 4.5 scenario (RCP 4.5) from the Intergovernmental Panel on Climate Change (IPCC).

Table 5.1. Overview of values of bioclimatic variables (BIO) for 4200 locations with coffee production in the Southeast Mountains region in Brazil for the period between 1960 and 1990, and projected for 2050. The data for 2050 are generated with 19 Global Circular Models under the Representative Concentration Pathway 4.5 scenario (RCP 4.5). Variables Bio 3, 4, 10, 12, 13 and 19 were used for the MaxEnt modelling. Means and standard deviation are presented.

Code	Bioclimatic variables	Current	2050
BIO1	Annual Mean Temperature	19.61 ± 1.15	21.35 ± 1.13
BIO2	Mean Diurnal Range (Mean of monthly (max temp - min temp))	12.39 ± 0.70	12.5 ± 0.70
BIO3	Isothermality (BIO2/BIO7) (x 100)	64.84 ± 0.90	65.24 ± 0.87
BIO4	Temperature Seasonality (standard deviation *100)	193.1 ± 8.99	197 ± 8.64
BIO5	Max Temperature of Warmest Month	28.38 ± 1.10	30.17 ± 1.08
BIO6	Min Temperature of Coldest Month	9.43 ± 1.48	11.04 ± 1.43
BIO7	Temperature Annual Range (BIO5-BIO6)	18.95 ± 0.93	19.1 ± 1.10
BIO8	Mean Temperature of Wettest Quarter	21.29 ± 1.14	23.06 ± 1.13
BIO9	Mean Temperature of Driest Quarter	17.19 ± 1.17	18.88 ± 1.14
BIO10	Mean Temperature of Warmest Quarter	21.77 ± 1.17	23.40 ± 1.15
BIO11	Mean Temperature of Coldest Quarter	16.91 ± 1.17	18.59 ± 1.14
BIO12	Annual Precipitation	1296 ± 59.20	1235 ± 58.42
BIO13	Precipitation of Wettest Month	230.48 ± 12.69	239.2 ± 15.35
BIO14	Precipitation of Driest Month	21.10 ± 5.46	19.42 ± 4.88
BIO15	Precipitation Seasonality (Coefficient of Variation)	68.10 ± 5.81	72.16 ± 5.96
BIO16	Precipitation of Wettest Quarter	651.46 ± 35.35	634.2 ± 38.98
BIO17	Precipitation of Driest Quarter	80.29 ± 18.98	73.74 ± 13.36
BIO18	Precipitation of Warmest Quarter	492.52 ± 37.27	494.6 ± 38.11
BIO19	Precipitation of Coldest Quarter	96.40 20.21	90.9 ± 18.72

Environmental factors and coffee suitability

Temperature of wettest quarter (Bio 10) explained 63.2% and precipitation of the coldest quarter (Bio 19) explained 21.4% of the variation in suitability for coffee production (Appendix 5.4). Under the current conditions, the highest suitability for coffee production occurred between altitudes of 800 and 1200 m, with an average of 0.50 and maximum values of up to 0.66 (at a scale ranging from 0 to 1; Fig. 5.3a). Areas at altitudes between 600 and 800 m had a mean of 0.39 for suitability for coffee production, while the areas under 600 m had the lowest values with a mean of 0.13. The area suitable for coffee production in 2050 is expected to decrease by 60% when using the criterion that suitable coffee production areas should have a higher suitability than 0.25. For 2050, the maximum suitability values were 0.46 and occurred in the regions between 800 and 1200 m (Fig. 5.3b). The strongest reduction in suitability for coffee production is expected to occur between 600 and 800 m, with a decrease in coffee suitability of up to -0.48 (Fig. 5.3d). However, the suitability for coffee production is projected to increase slightly in an area covering approximately 1069 km^2, located mainly between 1200 and 1800 m (Fig. 5.3d).

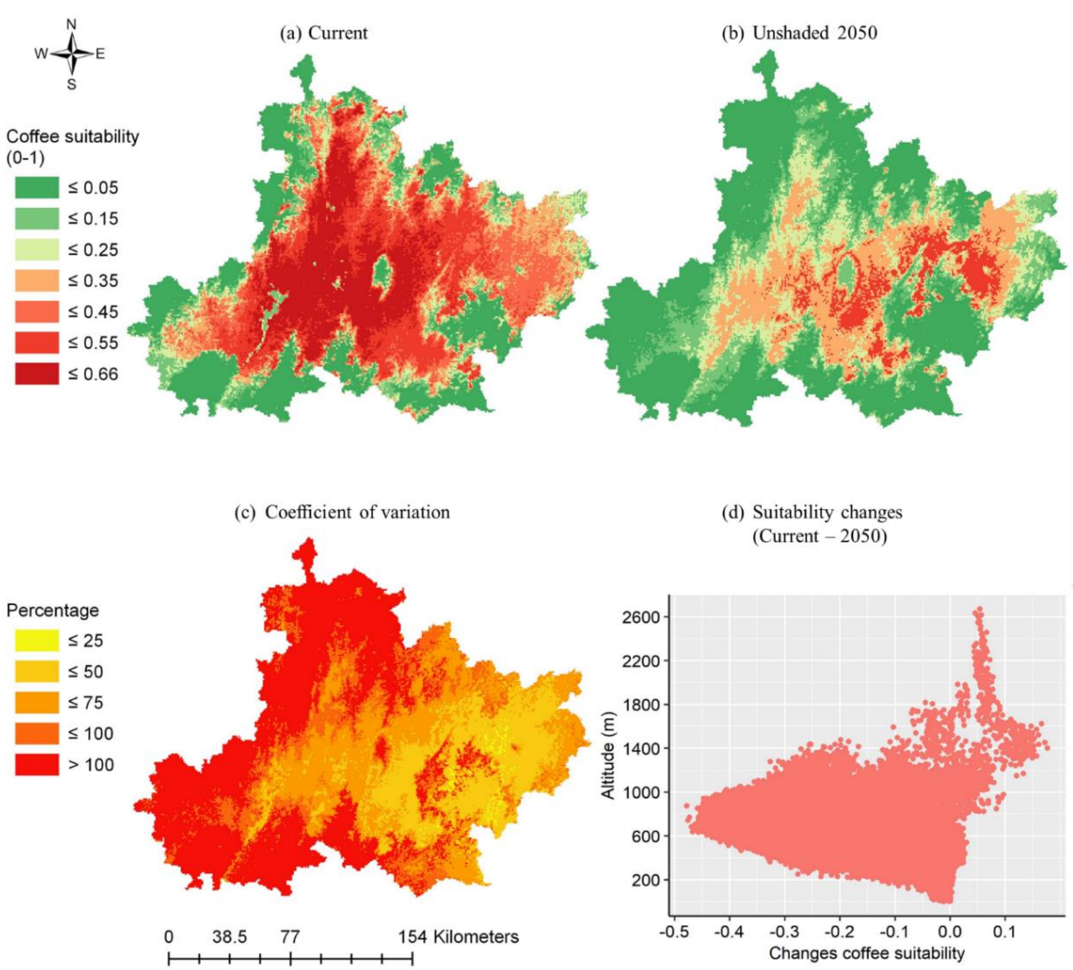


Figure 5.3. Suitability for coffee production for the current situation (a) and for 2050 under unshaded coffee management systems based on the Representative Concentration Pathways scenario 4.5 from 19 Global Circulation Models (b). Model uncertainty is indicated by the coefficient of variation (%) based on 475 suitability maps for 2050 (19 models x 25 replications) (c). Relationship between altitude and the change in suitability for coffee production from the current situation and 2050 (d).

Potential of agroforestry systems

MaxEnt simulations show that agroforestry systems have potential to partly mitigate the impact of climate change on coffee suitability for the Southeast Mountains region in 2050 (Fig. 5.4). Under the agroforestry systems scenario with 50% shade cover, 75% of the currently suitable area for coffee production will remain suitable for coffee production in 2050 with suitability values ranging from 0.25 to 0.59 (Fig. 5.4a, c). Yet, the potential of agroforestry systems to mitigate the effects of climate change depends strongly on altitude: in areas between 600 and 800 m, agroforestry systems have the potential to increase coffee suitability by up to +0.45 in 2050 compared to unshaded coffee systems, especially in the region of the Caparaó National park (Fig. 5.4b). In areas between 800 and 1200 m, agroforestry systems with 50% shade cover are expected to have a similar positive effect of up to +0.45, but can also have negative effects of up to -0.29 (Fig. 5.4b).

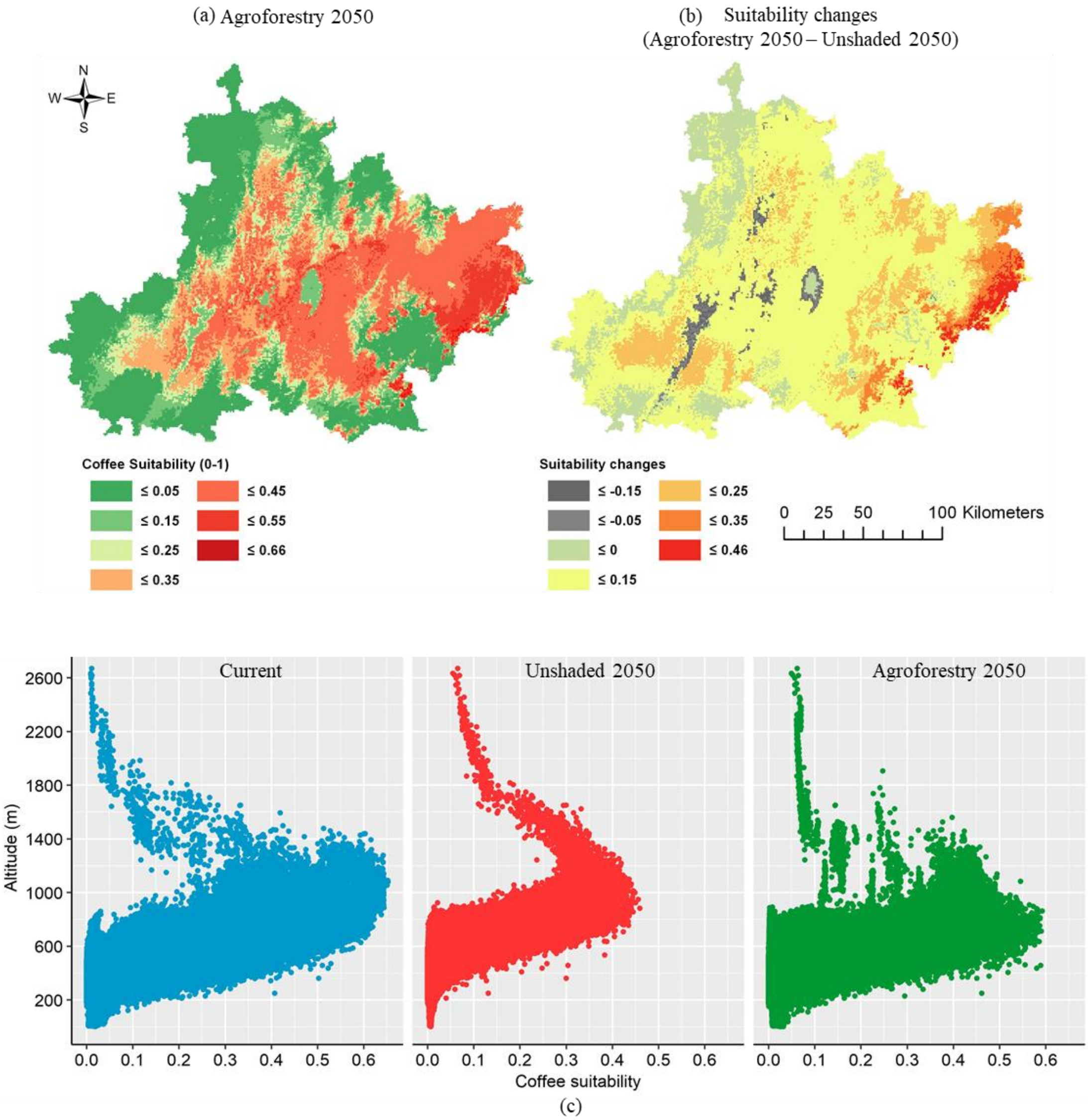


Figure 5.4. Changes in coffee suitability from the current situation as compared to 2050 under unshaded and agroforestry coffee systems in the Southeast Mountains region, Brazil. Maps show the coffee suitability in the agroforestry (shaded coffee) scenario for 2050 (a), and the changes in coffee suitability between the Agroforestry and Unshaded scenario in 2050 (b). The bottom panels show the relation between altitude and suitability for coffee production for the current situation (left), unshaded coffee for 2050 (middle), and agroforestry coffee for 2050 (right).

Discussion

We explored the impact of climate change on coffee suitability in the Southeast Mountains region in Brazil using a bioclimatic modelling approach. We found that i) substantial increases in the temperature and changes in precipitation regimes may be anticipated throughout the year in 2050; ii) the projected changes in temperature and precipitation may lead to a strong decrease in the suitability for coffee production in this region, and iii) agroforestry systems can mitigate some of the impacts of these changes in climate on the suitability for coffee production.

The projected changes in the annual mean temperature (+1.7°C) and changes in precipitation regimes (almost 60 mm less) under the RCP 4.5 scenario can affect the physiology of coffee plants and the associated coffee yields. In the coldest months (April to July), the projected temperature is expected to increase by about 1.3°C, while in the warmest months (October to November) the mean temperature may increase by 2.1ºC followed by decrease in precipitation of almost 60 mm (Fig. 5.2). The changes in temperature and precipitation vary across the year, which deviates from projections for other countries in Mesoamerica, where temperature is expected to consistently increase throughout the year (Läderach et al., 2017). The predicted increase of temperature from October to November combined with the decrease in precipitation will increase the potential evapotranspiration and decrease the water availability, resulting in a longer dry season. Since the seasonal water cycle influences the growth and development of coffee plants, including the flowering and fruiting stages (Carr, 2001), the projected changes in

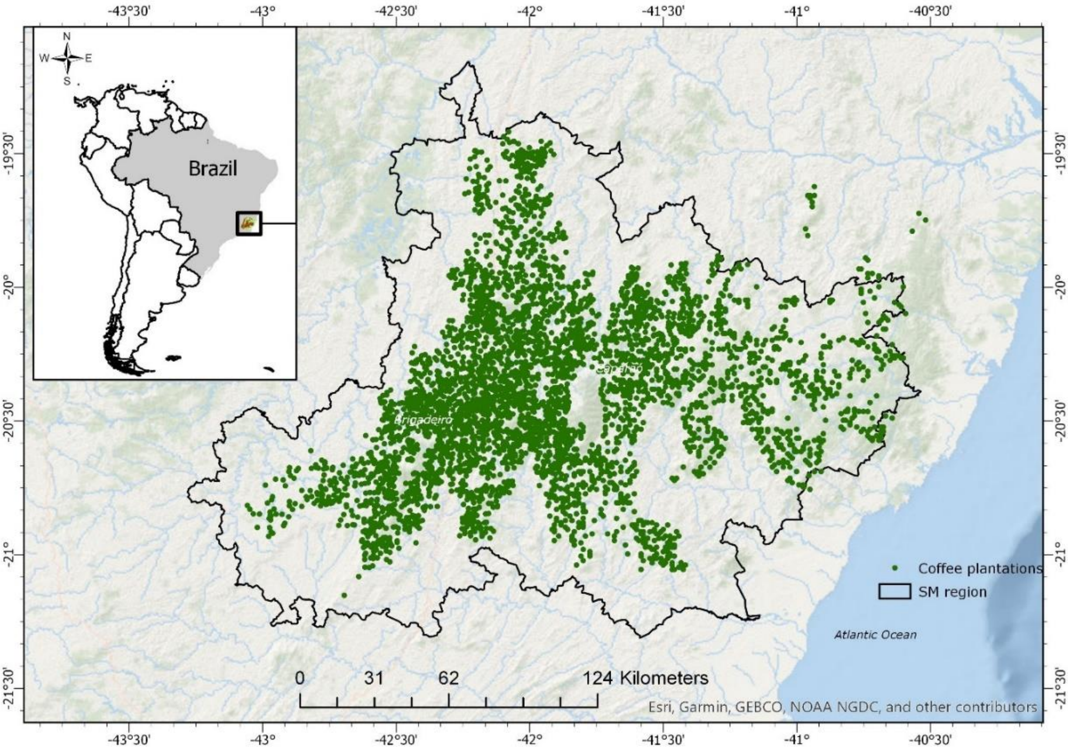
temperature and precipitation may reduce coffee productivity. Indeed, the increase of temperature associated with a prolongated dry season can alter coffee plant photosynthesis, cause abortion of flowers, thus compromising coffee yields (Camargo, 1985; DaMatta and Cochicho Ramalho, 2006).
The projected change in climate in the study area in 2050 may lead to an 60% decrease in the area suitable for coffee production, particularly affecting coffee plantations in altitudes ranging from 600 to 800 m. Currently, the areas suitable for coffee production range from 600 to 1200 m, but due to climate change, these areas are expected to be restricted to altitudes higher than 800 m by 2050 (Fig. 3). The decline and shifts in areas suitable for coffee production have also been reported in global and regional studies. In Nicaragua, the area suitable for coffee production is expected to decrease by 90% in 2050 (Bunn et al., 2015; Läderach et al., 2017; Ovalle-Rivera et al., 2015). Similar to our findings, a global study identified that coffee production will need to be relocated to higher elevations, where the climate will become suitable for coffee production in the future (Magrach and Ghazoul, 2015). However, in our study region the land at elevated areas consist of national parks, which could potentially lead to competing claims for land use for coffee production and nature conservation. However, such potential conflict could be limited or avoided with adapted climate management with agroforestry coffee systems.

Our study shows that the adoption of agroforestry coffee systems is a promising strategy to mitigate the negative impact of climate change and maintain 75% of current area that is suitable for coffee production in the study region in 2050. Agroforestry systems with 50% shade cover can especially mitigate the impact of climate change at altitudes between 600 and 800 m (Fig. 4). This altitude range covers a large area of coffee production, where the coffee suitability can decrease by -0.48, but with agroforestry systems the coffee suitability could increase up to +0.45 under the projected climate change scenario for 2050. Farmers may further mitigate of climate change impacts on coffee production by increasing the shade cover of agroforestry systems to more than 50%. This will require tailored shade management throughout the year, with reduced shade cover after harvesting (Souza et al., 2010), when the coffee plants need more solar energy to develop the nodes. In contrast, coffee plants at altitudes exceeding 1000 m may benefit from higher temperatures in the future, and coffee agroforestry systems at this altitude should have shade levels below 50%. The incorporation of shade trees in coffee systems may influence the productivity of coffee plants in different ways. Positive effects include reduced temperatures under shade that slow down the maturation of fruit, leading to larger coffee beans of better quality (Muschler et al., 2001; Bote and Struik, 2011). In addition, the presence of trees in coffee systems can lead to more birds and bees, which contribute to pollination and pest control (Chain-Guadarrama et al., 2019). On the other hand, increasing shade cover in coffee systems may favour diseases, such as coffee leaf rust (López-Bravo et al., 2012), and increase competition for water and nutrients, which reduce coffee yield (DaMatta, 2004).

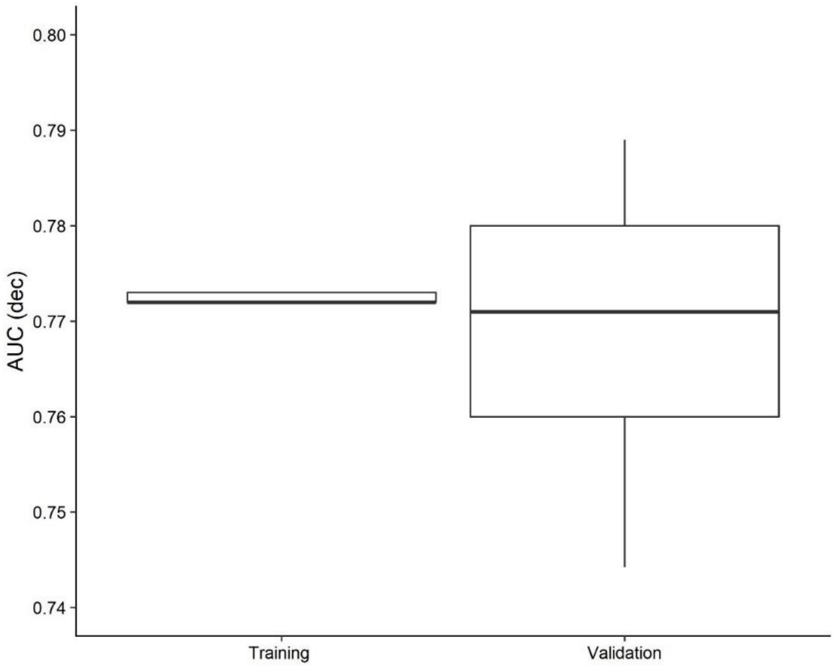
Careful selection of shade trees and tailored pruning management may limit the competition between coffee plants and shade trees (Souza et al., 2010). This is particularly relevant for competition for water, nutrient and light, limiting factors for coffee production. Compared with unshaded coffee, agroforestry coffee systems may maintain higher levels of soil water content due to decreased soil evaporation (Lin et al., 2010), but on the other hand shade trees also take up soil water (Padovan et al., 2018). Due to the complex interactions between tree species, coffee plants and the soil, the selection of shade trees species for agroforestry must consider several factors, including canopy structure, rooting pattern and depth, and leaf phenology (e.g., evergreen or deciduous). A list of suitable shade tree species for agroforestry coffee systems for the study region has been developed by a group of family farmer with more than 30 years of experience with agroforestry systems (Souza et al., 2010). The list includes, among others, *Aegiphila sellowiana* Cham. (papagaio), *Persea americana* Mill. (abacate) and *Solanum mauritianum* Scop. (capoeira-branca) (Appendix E). These shade tree species have rooting systems that limit the competition with coffee plants for water and nutrients and, moreover, improve recycling important nutrients such as P, Ca, Mg and N via litter fall (Duarte et al., 2013; Souza et al., 2010). The agroforestry systems have been successfully used in the region by some farmers (Cardoso et al., 2001; Souza et al., 2010; Souza et al., 2012a,b) and may be a viable option to mitigate the negative impact of climate change (Geertsema et al., 2016). However, the expansion of agroforestry systems in the region needs a joint effort of scientists and family farmers to improve the understanding about the effect of climate change and trees on coffee suitability. We recommend for future studies to integrate species distribution models, water balance and solar interception modelling for selected trees species under contrasting shade levels according to seasons and altitude ranges (Rahn et al., 2018). This could result in context-specific recommendations for the successful development of agroforestry coffee systems.

Our study indicates that a decline of 60% in the area suitable for coffee production may be expected in the Southeast Mountains, which can impact millions of livelihoods. Yet, recent studies suggest that the projected negative impacts of increase of temperature and changes in precipitation patterns on coffee production can be compensated up to 13-21% by the CO_2 fertilization effect associated with the emission of greenhouse gasses (Rahn et al., 2018; Ramalho et al., 2018). However, this beneficial effect of CO_2 fertilization is linked with highly intensified coffee systems, which may be not realistic for family farmers in mountainous areas (Rahn et al., 2018). In this context, the implementation of shade trees may be a more promising alternative for smallholder farmers. Moreover, agroforestry systems may reconcile coffee production with conservation of nature, and act as a frontier buffer between more intensively managed agricultural areas and nature conservation areas. Since coffee production is at the heart of social, economic and cultural development in the region, smallholder farmers, government, NGOs, scientific community and policy makers should join forces to implement agroforestry systems in the region to counteract the threat posed by climate change and safeguard the future of coffee production in the Southeast Mountains. Our assessment of the impacts of climate change on the area suitable for coffee production may be useful for identifying coffee production areas that are vulnerable to climate change and may benefit from direct targeted management actions.

Appendix 5.1. Geographical location of the current coffee plantations used to model the coffee suitability in the Southeast Mountains region (SM), Brazil. The geographical coordinates from each coffee plantation are presented in the supplementary material.



Appendix 5.2. Performance of the MaxEnt model from 25 repetitions for the training and validation data. The whiskers show 5–95% of the distributions, the box shows the quartiles and the black horizontal line shows the median.



Appendix 5.3. Overview of mean and standard deviation of bioclimatic variables values in 2050 for 4200 locations for unshaded coffee (RCP 4.5 scenario 2050) and shaded coffee (Agroforestry 2050) in the Southeast Mountains, Brazil.

Code	Bioclimatic variables	2050	Agroforestry 2050
BIO1	Annual Mean Temperature	21.35 ± 1.13	20.33 ± 1.14
BIO2	Mean Diurnal Range (Mean of monthly (max temp - min temp))	12.5 ± 0.70	8.73 ± 0.70
BIO3	Isothermality (BIO2/BIO7) (x 100)	65.24 ± 0.87	54.27 ± 1.68
BIO4	Temperature Seasonality (standard deviation *100)	197 ± 86.49	212 ± 104.7
BIO5	Max Temperature of Warmest Month	30.17 ± 1.08	27.36 ± 1.14
BIO6	Min Temperature of Coldest Month	11.04 ± 1.43	12.08 ± 1.44
BIO7	Temperature Annual Range (BIO5-BIO6)	19.1 ± 1.10	15.28 ± 0.99
BIO8	Mean Temperature of Wettest Quarter	23.06 ± 1.13	22.24 ± 1.13
BIO9	Mean Temperature of Driest Quarter	18.88 ± 1.14	17.25 ± 1.16
BIO10	Mean Temperature of Warmest Quarter	23.40 ± 1.15	22.24 ± 1.13
BIO11	Mean Temperature of Coldest Quarter	18.59 ± 1.14	17.25 ± 1.16
BIO12	Annual Precipitation	1235 ± 58.42	1235 ± 58.42
BIO13	Precipitation of Wettest Month	239.2 ± 15.35	239.2 ± 15.35
BIO14	Precipitation of Driest Month	19.42 ± 4.88	19.42 ± 4.88
BIO15	Precipitation Seasonality (Coefficient of Variation)	72.16 ± 5.96	72.16 ± 5.96
BIO16	Precipitation of Wettest Quarter	634.2 ± 38.98	634.2 ± 38.98
BIO17	Precipitation of Driest Quarter	73.74 ± 13.36	73.74 ± 13.36
BIO18	Precipitation of Warmest Quarter	494.6 ± 38.11	494.6 ± 38.11
BIO19	Precipitation of Coldest Quarter	90.9 ± 18.72	90.9 ± 18.72

Appendix 5.4. Explained variance (%) of bioclimatic variables (BIO) used to predict the coffee suitability using the MaxEnt model in the Southeast Mountains, Brazil.

Code	Bioclimatic variables	Contribution (%)
BIO3	Isothermality (BIO2/BIO7) (* 100)	6.76
BIO4	Temperature Seasonality (standard deviation *100)	5.90
BIO10	Mean Temperature of Warmest Quarter	63.24
BIO12	Annual Precipitation	0.08
BIO13	Precipitation of Wettest Month	2.59
BIO19	Precipitation of Coldest Quarter	21.41

Appendix 5.5. Family, species and common Portuguese names of tree species used in agroforestry systems in the Zona da Mata, Minas Gerais, Atlantic Coastal Rainforest, Brazil (Adapted from Souza et al, 2010). Origin specifies whether tree species is native (N) or exotic (E) and the classification as Fruit is also highlighted. Local source (Yes) indicates whether tree species are present in nearby forest fragments (up to hundreds of metres).

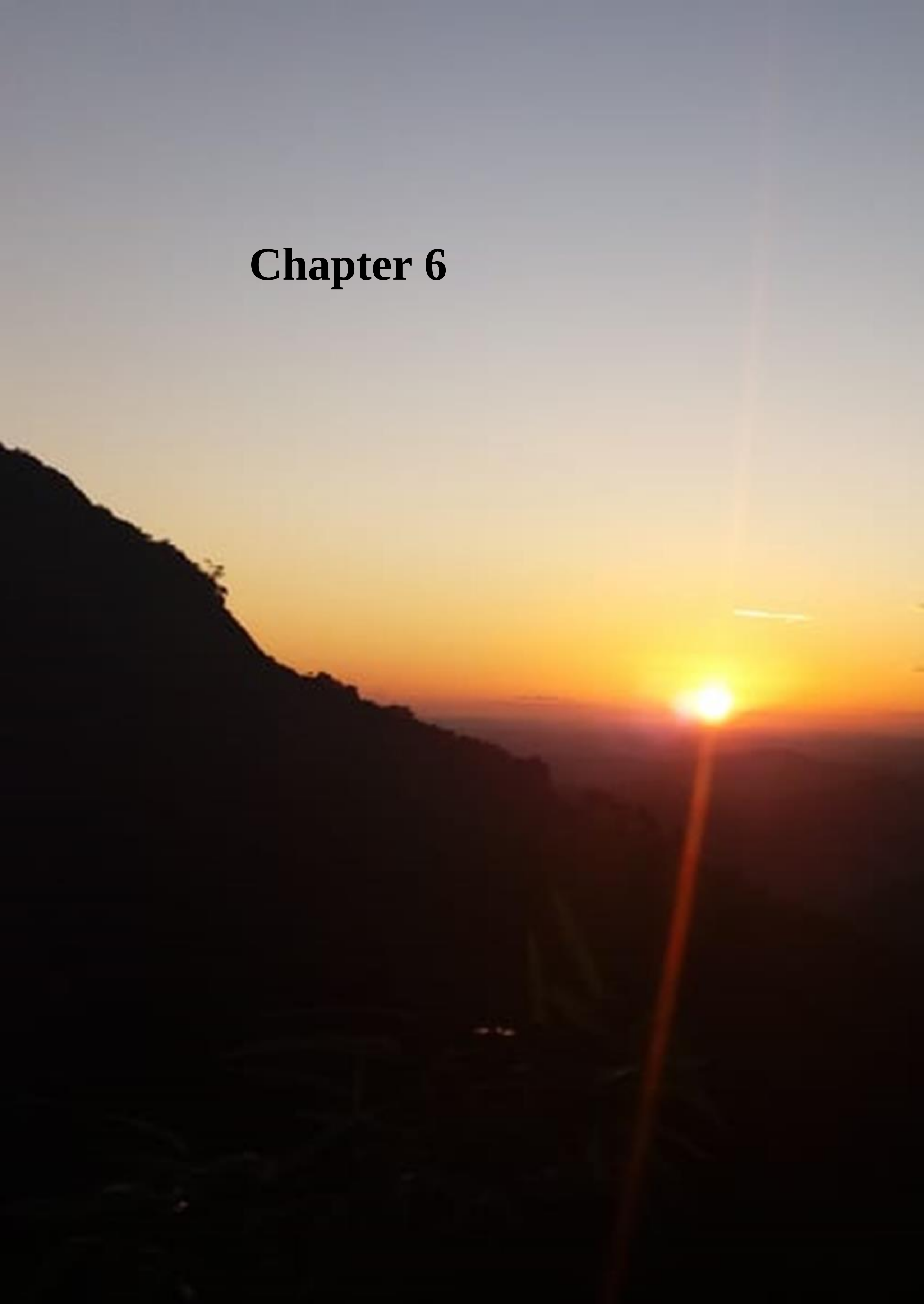
Family	**Species (common names)**	**Origin**	**Fruit**	**Local source**
Anacardiaceae	*Mangifera indica* L. (manga)	E	x	
	Schinus terebinthifolia Raddi (aroeirinha)	N		Yes
	Spondias lutea L. (cajá manga)	E	x	
Annonaceae	*Annona muricata* L. (graviola)	E	x	
	Annona squamosa L. (fruta-do-conde)	E	x	
	Rollinia dolabripetala A.St.-Hil. (araticum)	N	x	Yes
Apocynaceae	*Aspidosperma polyneuron* Müll. (guatambu)	N		Yes
Araucariaceae	*Araucaria angustifolia* (Bertol.) Kuntze (pinheiro-brasileiro)	N		
Arecaceae	*Bactris gasipaes* Kunth (pupunha)	E		
	Cocos nucifera L. (coco-da-bahia)	E	x	
	Euterpe edulis Mart. (palmito-jussara)	N		Yes
	Syagrus romanzoffiana (Cham.) Glassman (coco-babão)	N		Yes
Asteraceae	*Eremanthus erythropappus* (DC.) MacLeish (candeia)	N		Yes
Bignoniaceae	*Jacaranda macrantha* Cham. (caroba)	N		Yes
	Sparattosperma sp. (cinco-folhas)	N		
	Tabebuia impetiginosa (Mart. *ex* DC.) Standl. (ipê-roxo)	N		Yes
	Tabebuia chrysotricha (Mart. *ex* A. DC.) Standl. (ipê-mulato)	N		Yes

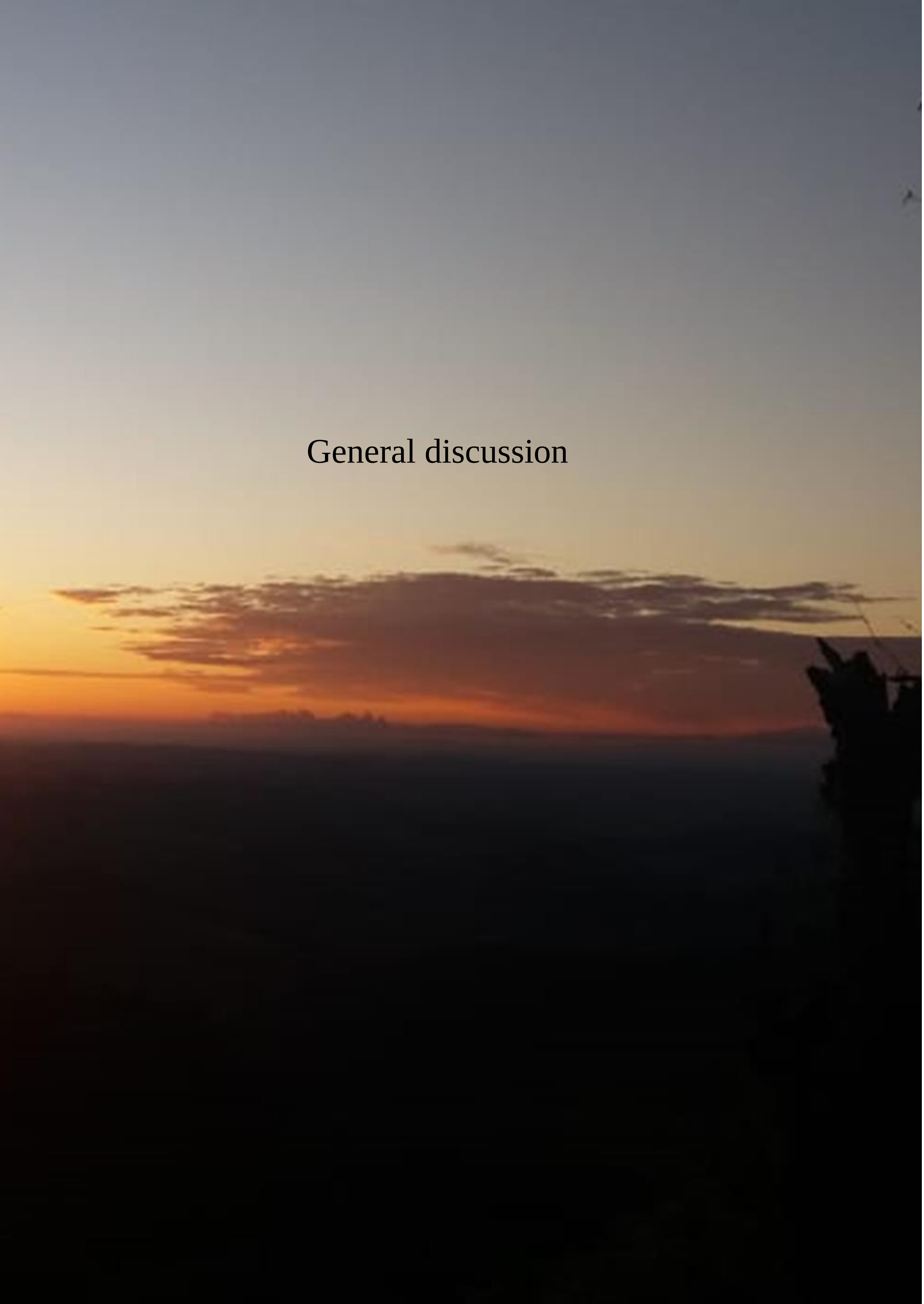
	Tabebuia serratifolia (Vahl) G. Nicholson (ipê-amarelo)	N		Yes
	Zeyheria tuberculosa (Vell.) Bureau (ipê-preto)	N		Yes
Bixaceae	*Bixa orellana* L. (urucum)	N		
Cannabaceae	*Trema micrantha* (L.) Blume. (crindiúva)	N		Yes
Caricaceae	*Carica papaya* L. (mamão)	E	x	
Casuarinaceae	*Casuarina equisetifolia* L. (casuarinas)	E		
Ebenaceae	*Diospyros kaki* L. f. (caqui)	E	x	
Elaeocarpaceae	*Muntingia calabura* L. (calabura)	E		
Euphorbiaceae	*Alchornea triplinervia* (Spreng.) Müll. Arg. (pau-de-bolo)	N		Yes
	Croton urucurana Baill. (adrago)	N		Yes
	Joannesia princeps Vell. (cotieira)	N		
	Hyeronima alchorneoides Allemao (liquerana)	N		Yes
	Mabea fistulifera Mart. (canudo-de-pito)	N		Yes
Lamiaceae	*Aegiphila sellowiana* Cham. (papagaio)	N		Yes
	Vitex montevidensis Cham. (maria-preta)	N		
Lauraceae	*Persea americana* Mill. (abacate)	E	x	
Leguminosae	*Anadenanthera peregrina* (L.) Speg. (angico-vermelho)	N		Yes
	Calliandra houstoniana (Mill.) Standl. (caleandra)	E		
	Caesalpinia pluviosa DC. (sibipiruna)	N		
	Cassia ferruginea (Schrad.) DC. (canafístula)	N		Yes
	*Erythrina verna*Vell. (pau-abóbora)	N		
	Erythrina speciosa Andrews (mulungu)	N		
	Hymenaea courbaril L. (jatobá)	N		

	Inga edulis Mart. (ingá)	N		Yes
	Dalbergia nigra (Vell.) Benth. (jacaranda-caviúna)	N		Yes
	Enterolobium contortisiliquum (Vell.) Morong (orelha-de-macaco)	N		Yes
	Machaerium stipitatum (DC.) Vogel (canela-de-velho)	N		Yes
	Machaerium nyctitans (Vell.) Benth. (jacarandá-bico-de-pato)	N		Yes
	Piptadenia gonoacantha (Mart.) J.F. Macbr. (jacaré)	N		Yes
	Schizolobium parahyba (Vell.) S.F. Blake (breu)	N		Yes
	Senna macranthera (Collad.) H.S. Irwin and Barneby (fedegoso)	N		Yes
Malpighiaceae	*Byrsonima sericea* DC. (massaranduva)	N		Yes
Malvaceae	*Bombax marginatum* (A. St.-Hil., Juss. and Cambess.) K. Schum. (castanha-mineira)	E	x	
	Ceiba speciosa (A. St.-Hil.) Ravenna (paineira)	N		Yes
	Luehea grandiflora Mart. (açoita-cavalo)	N		Yes
Melastomataceae	*Tibouchina granulosa* (Desr.) Cogn. (quaresmeira)	N		Yes
Meliaceae	*Cedrela fissilis* Vell. (cedro)	N		Yes
	Melia azedarach L. (cinamomo)	E		
	Toona ciliata M. Roem. (cedro-australiano)	E		
Moraceae	*Artocarpus heterophyllus* Lam. (jaca)	E	x	
	Morus nigra L. (amora)	E		
Moringaceae	*Moringa oleifera* Lam. (moringa)	E		
Musaceae	*Musa paradisiaca* L. (banana)	E	x	
Myrsinaceae	*Rapanea ferruginea* (Ruiz and Pav.) Mez (pororoca)	N		Yes
Myrtaceae	*Campomanesia xanthocarpa* (Mart.) O. Berg (gabiroba)	N	x	Yes

	Eugenia malaccensis L. (jamelão)	N	x	
	Eugenia uniflora L. (pitanga)	N	x	
	Myrciaria jaboticaba (Vell.) O. Berg (jaboticaba)	N	x	
	Psidium araca Raddi (araçá)	N	x	
	Psidium guajava L. (goiaba)	N	x	
	Syzygium jambos (L.) Alston (jambo)	E		
Pinaceae	*Pinus* sp. (pinus)	E		
Rhamnaceae	*Hovenia dulcis* Thunb. (ovenia)	E	x	
	Colubrina glandulosa Perkins (só-brasil)	N		Yes
Rosaceae	*Moquilea tomentosa* Benth. (oiti)	N		
	Eriobotrya japonica (Thunb.) Lindl. (ameixa)	E	x	
	Pyrus communis L. (pêra)	E	x	
	Prunus persica (L.) Batsch (pêssego)	E	x	
Rutaceae	*Citrus* sp. (limão-cravo)	E	x	
	Citrus sp. (mexerica)	E	x	
	Citrus sinensis (L.) Osbeck (laranja)	E	x	
	Citrus sp. (turanga)	E	x	
	Dictyoloma vandellianum A.H.L. Juss. (brauninha)	N		Yes
Sapindaceae	*Litchi chinensis* Sonn. (lichia)	E	x	
Solanaceae	*Solanum lycocarpum* A. St.-Hil. (lobeira)	N		Yes
	Solanum mauritianum Scop. (capoeira-branca)	N		Yes
Urticaceae	*Cecropia* sp. (embaúba)	N		Yes
Verbenaceae	*Citharexylum myrianthum* Cham. (pau-de-viola)	N		

Chapter 6





General discussion

Worldwide, anthropogenic activities have influenced the potential of ecosystems to deliver ecosystem services, and a major challenge for the future is to develop multifunctional landscapes that combine environmental protection and the provision of ecosystem services. Landscapes are complex socio-ecological systems, in which LULC changes and ecosystem services are the links between the social and ecological components (Fig. 6.1; Haines-Young and Potschin, 2010; Reyers et al., 2013). Changes in LULC are the main anthropogenic pressure on environment, leading to changes in the biophysical structure of the environment and consequently in the provision of ecosystem services that are the direct and indirect benefits that humans receive from nature (Fu et al., 2015; Metzger et al., 2006; Milheiras and Mace, 2019; Quintas-Soriano et al., 2016). Although the effect of LULC changes on ecosystem services have been intensely studied in the last decade, analyses of the spatio-temporal provision of ecosystem services in an integrated socio-ecological approach are still scarce (Kelble et al., 2013; Nassl and Löffler, 2015). Apart from the advances in the frameworks and approaches to integrate socio and ecological systems up to now, the complexity of these interactions requires the development of frameworks that clearly integrate and display more components of the socio and ecological systems and their interactions. The integrated analysis of historical LULC changes, the main socio-economic drivers and the associated ecosystem services can give important insights about the functioning of socio-ecological system, and enable more plausible simulations of the impact of contrasting socio-economic developments on the future provision ecosystem services.

In the following subsections, I will link and discuss my findings of the individual chapters in a proposed framework that combines the DPSIR (Drivers, Pressure, State, Impacts and Response) concept and the ecosystem services cascade framework (Fig. 6.1). First, I will describe the proposed socio-ecological system framework, and describe its components and their relationships. Second, I discuss the importance of the assessment of LULC changes and the identification of their main drivers. Third, I demonstrate the effects of LULC changes on the different types of ecosystem services in a socio-ecological context. Finally, I explore how simulated changes in the social and ecological systems can affect the provision of ecosystem services and discuss its importance to guide public policies concerning the future management of ecosystem services.

Framework design

The proposed framework is designed in a circular form to convey the message that socio-ecological systems are dynamic (circles in movement – shown by the arrows) and many changes in social system result in modifications in the ecological system (Fig. 1). The ecological system is presented in the upper half of the circle and the social system in the lower half. These systems are linked by human activities on one side, here represented by the changes in LULC or management and by ecosystem services on the other side, representing the benefits the humans receive from nature. The **DPSIR** framework is projected around the circle with the different colours representing each component (Drivers, Pressure, State, Impacts, Response). Inside the circle, the ecosystem service cascade framework is represented by the grey figures and is allocated mainly in the ecological system. We can read the framework in this way: **Drivers** are presented in the social subsystem and are directly or indirectly responsible for the LULC or management changes. LULC changes are the active linkage between the social and ecological system and represent the human **Pressure** on the environment. This pressure will result in changes in the **State** of environment, here represented by the biophysical structure, which is the first step of the cascade ecosystem service approach. Changes in the biophysical structure will have ecological **Impacts** in the full chain of ecosystem services, where trade-offs and synergies occur between multiple ecosystem services. Changes in ecosystem services will lead also to social **Impacts** related to perceived and/or economic values of ecosystem services by people. The social **Impacts** can lead to changes in the **Drivers** of LULC or management, closing the loop in the socio-ecological framework. During a complete loop in this framework, **Responses** from local, regional or global scales can occur in all steps of the framework, especially due to changes in the **State** of environment that results in social and ecological **Impacts**. These **Responses** can influence changes in the **Driver**s that will affect the **Pressures** on environment and so on, resulting in modifications of the socio-ecological system and in the provision of ecosystem services.

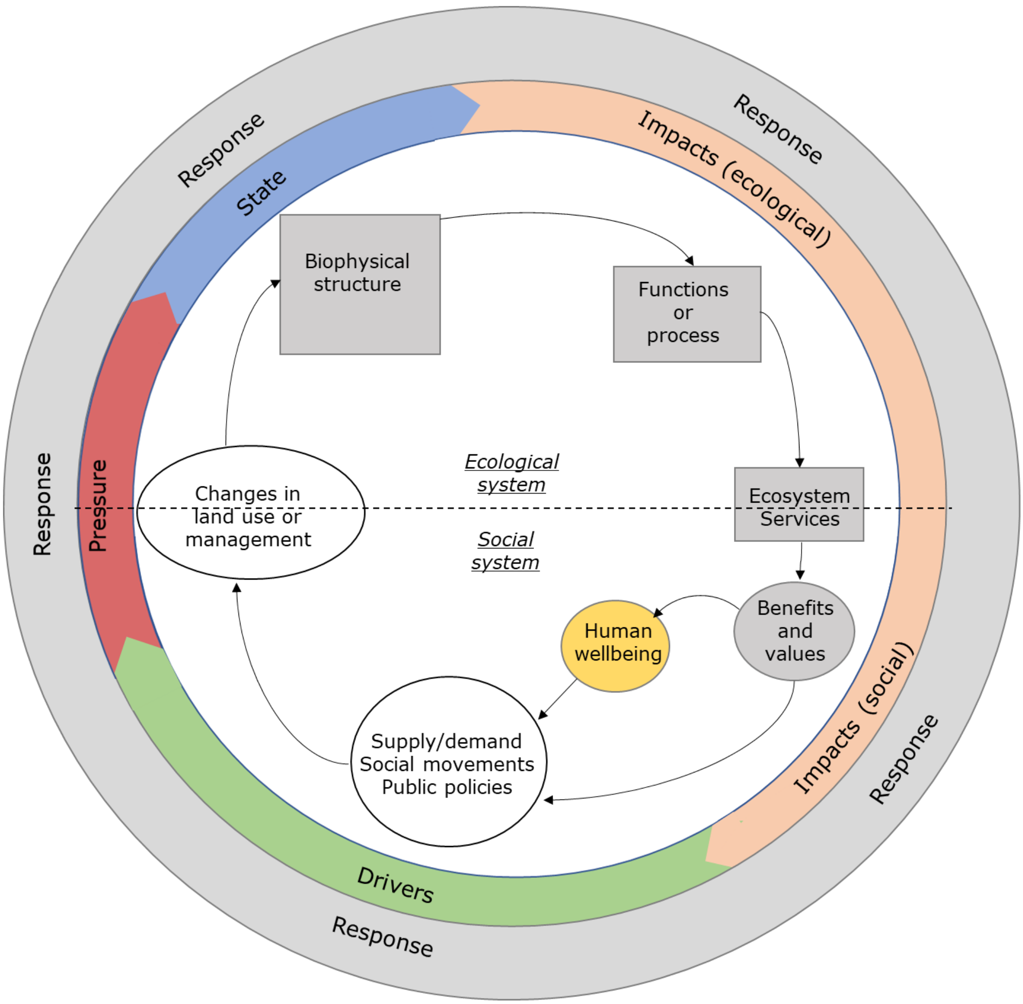


Figure 6.1: Conceptual framework to analyse ecosystem services in a context of socio-ecological systems. The proposed framework integrates the social (circles) and ecological systems (boxes) using the **DRPSI** concept (**D**rivers, **P**ressure, **S**tate, **I**mpacts, **R**esponse) represented by the colours in the outside circles and by the ecosystem services cascade framework (grey figures) inside the circle.

Assessment of land use changes and their drivers: the first step to understand socio-ecological systems at landscape level

In chapter 2, I argue that combining LULC assessment and the identification of socioeconomic drivers is a useful approach to understand the temporal and spatial changes in the environment. In this section, I will discuss my findings as an example for future studies, especially for developing countries, of how drivers from different scales can alter local ecosystems. In chapter 2, I mapped the spatial and temporal LULC changes from 1986 to 2015. In general, I found that the forest and coffee areas increased at the expense of pasture areas in the study region. My finding deviates from the worldwide LULC trends, in which pasture and crops have expanded in the last decades, covering about 38% of terrestrial ecosystem (Foley et al., 2011; Ramankutty et al., 2008). The increase of forest cover in the last decades highlights that my study area is the recovering phase in the forest transition process after five centuries of deforestation. The forest transition process describes the temporal changes in forest areas and point out that the forest areas quickly reach the lowest levels in history and then increase slowly after (Mather, 1992; Rudel, 1998). While European countries passed through this process, Brazil is still in the descendent curve with accelerating deforestation (Rudel et al., 2005). However, my research in the Zona da Mata of Minas Gerais and Calaboni (2018) in São Paulo suggest that there is a forest recovery in these areas of the Atlantic Forest biome. Nevertheless, in the Brazilian biomes Amazon and Cerrado that are frontiers of large-scale agricultural production, deforestation rates are still increasing (Escobar, 2019). Understanding the drivers of afforestation in the Atlantic Forest can guide policy makers to bend the deforestation curve before forest cover reaches very low levels in the Amazon and Cerrado.

In Chapter 2, I identified that public policies played a key role in past LULC changes in the studied region between 1986 and 2015. The identification of the main drivers was derived from the narratives of family farmers in workshops. Farmers identified government environmental monitoring programs and inspections as the main drivers for the observed increase in forest cover in the region. In addition, the creation of the Serra do Brigadeiro park in 1996 further contributed to the increase forest cover. The agroecological movement in the region played a key role in establishing the park, and, over the last decades, also in promoting nature conservation and more sustainable agriculture practices, such as the use of agroforestry systems. Migration from the countryside to cities was also an important reason for the increase in forest area. The PRONAF (National Program of Family Faming) supporting financial credit for coffee farmers and cattle raising was an important driver of the increase in the area of coffee production and the decrease in pasture areas. However, the family farmers also indicated that the increase in coffee area was accompanied with intensive use of chemicals. They also addressed that the increase of the stocking rate of livestock in smaller pasture areas was facilitated by the supplementary feed made of genetically modified plants cultivated with pesticides.

Although the main drivers of LULC changes operated at the local or national level, global drives can also influence local LULC changes. Global demand for coffee and iron ore were associated with the increase in the area of coffee and eucalyptus plantations in the region. The same trend is observed for other commodities worldwide. For instance, the increase in the world demand for palm oil and beef led to a high expansion rate of palm plantations in Southeast Asia, South America and Mesoamerica (Vijay et al., 2016) and pasture for beef production in Brazil (McAlpine et al., 2009), which can result in negative impacts on biodiversity (Fitzherbert et al., 2008; Fujisaka et al., 1998). While the changes in the environment are local, their effects on ecosystem services can have impacts at local, regional or global levels (Defries and Bounoua, 2004; Findell et al., 2017). The current impacts of climatic extremes and the projected impacts of climate change for the near future have increased the societal awareness for the need to protect the environment. Then, identification of on-going LULC changes and its drivers can induce quick responses from policy from local to global levels in the form of economic measures and political actions, but also by civil society that can influence consumer attitudes towards agricultural products originating from areas that do not preserve the environment (Kehoe et al., 2019). Therefore, the assessment of local LULC changes and their main drivers can be a valuable tool for policy makers and civil society to develop more sustainable landscapes in the future.

Provision of ecosystem services in a socio-ecological context

Worldwide, ecosystems are changing fast and the provision of ecosystems services are no longer only the benefits of nature, but can be considered ecological impacts of the human pressure on the environment. The analysis of the multiple ecosystem services in a socio-ecological context can give important insights for future developments and management of landscapes. As proposed by the framework (Fig. 1), I found in Chapter 2 that socio-economic drivers are responsible for the spatial and temporal LULC changes, which modify the biophysical structure of landscapes, leading to changes in the provision of ecosystem services (Chapter 3). In Chapter 2, I found that the main LULC transitions in the study area were the conversion of pasture to forest and coffee fields. Based on these main LULC transitions, I will analyse the socio-ecological context of regulating, provisioning and cultural ecosystem services.

The increase of regulating ecosystem services in the study region, which included carbon sequestration and pollination, was strongly associated with the increase of forest cover between 1986 and 2015 (Chapter 3). Forest cover increased mainly as a result of public policies (Chapter 2), and we can assume that the public policies helped in an indirect way to increase the provision of regulating ecosystem services. Therefore, the protection of the environment by strict monitoring and fining in case of offenses (Chapter 2) led to increased habitat quality, potential pollination and carbon sequestration (Chapter 3). The replacement of pasture by forest changed the state of environment, modifying the biophysical structures and resulting in ecological and social impacts (Fig. 1). The increase in forest area resulted in increased carbon sequestration (Chapter 3), decreased surface runoff and increased evapotranspiration (Chapter 4), what lead to improvements of water and air quality (Ellison et al., 2017; Nowak et al., 2014). In turn, these enhanced levels of ecosystem services had a positive impact on society. For instance, family farmers in the study region value trees because they contribute to a better air quality, support wildlife and water regulation (Teixeira et al., 2018b). These perceived values about the importance of nature have strengthened the social agroecological movement, which can be a driver to influence other farmers to change agricultural management and favour the provision of ecosystem services. Therefore, public policies and social movements that promote forest conservation and protection can result in regulating ecosystem services that improve the human wellbeing.

Increasing provisioning ecosystem services, such as food production, is one of the main purposes of the human interventions in ecosystems. I found that the increase in credit for smallholder farmers by public policies was the main driver for the increase in livestock stocking rates and coffee production areas (Chapter 2 and 3). The increase in livestock stocking rates led to a decrease in the demand for pasture areas, which fostered the conversion of pasture to forest and coffee plantations. The replacement of pasture with coffee plants and forest changed the biophysical structure of the landscape, specifically the covering of soil surface. While soil cover increases under forest, it decreases under monoculture coffee fields, resulting in increases of soil erosion (Chapter 3), probably due to the increase in soil surface runoff (Chapter 4). Coffee production is the main cash crop in the region and has high economic value for the local economy, but the adopted monoculture cultivation system has led to declines in regulating ecosystem services (Chapter 3). Therefore, the adoption of more diversified coffee systems, such as agroforestry systems, could reduce the trade-offs between provisioning and regulating ecosystem services.

Cultural services can have important and direct social benefits for human wellbeing. I found that the creation of the Serra do Brigadeiro State Park (Chapter 2) had increased the provision of cultural ecosystem services in the region (Chapter 3). Unlike regulating and provisioning services that depend of ecological processes, cultural services are more related to social drivers and perceptions. The implementation of areas for recreation and tourism can increase the options for people to gather together with nature. Accessibility to natural areas have been pointed out as one of the main reasons for improving quality of life and health (Bratman et al., 2019; Pedersen et al., 2019). Indeed, protected areas can serve educational purposes to increase awareness for the importance of natural process and the importance to protect nature. Societal awareness about the benefits of cultural services can also be a strong driver to require and guide public policies to preserve the environment.

In general, the increase in forest and coffee areas improved the delivery of regulating and provisioning services in the study region, but the declines in erosion control and water flow regulation remain a concern. The increase in coffee monoculture plantations was the main factor responsible for the decline in erosion control, while the associated increase in urban areas led to a decline in water flow regulation (Chapter 3). An alternative to mitigate the trade-off between ecosystem services in coffee production is the adoption of agroforestry systems. In agroforestry systems, shade trees are interspersed among coffee plants, which can increase soil cover and has potential to decrease water surface runoff and erosion (Zhu et al., 2019). Increasing parks in cities and avoiding impermeable surfaces in gardens can further help to support water infiltration (Nickel et al., 2014) and contribute to cultural services provision (Ngulani and Shackleton, 2019; Pulighe et al., 2016). These findings highlight that, for the balanced portfolio of ecosystem services in future, increased forest cover in the region should be combined with changes in management in agricultural coffee fields, and more sustainable practices and regreening of our cities.

Scenarios of ecosystem services in anticipation of future challenges

In the face of climate change, the maintaining ecosystem services at desired levels and the protection of nature is a major challenge. The development of scenarios of ecosystem services appears to be a pivotal option to capture the socio-ecological dynamics and guide policy makers towards the development of sustainable landscapes (IPBES, 2016). However, developing scenarios of ecosystem services in the context of socio-ecological systems is challenging, due to the specific context of each environment and the complexity of social-ecological systems (Kok et al., 2017). In this section, I will explore how changes in the socio-ecological systems can impact the provision of ecosystem services. I will demonstrate how future scenarios with contrasting socioeconomic developments (Chapter 2) can affect the provision of bundles of ecosystem services. Next, I will explore how changes in LULC and climate can affect the water dynamics (Chapter 4) and how the changes in coffee management can mitigate the climate change impacts on coffee production (Chapter 5).

The management of future LULC changes can improve carbon storage and mitigate climate change more than previously indicated (Searchinger et al., 2018). In Chapter 2, I developed four scenarios with contrasting socio-economic developments for 2045 that resulted in different LULC pathways. In the Green Road scenario, the forest area and coffee plantation are expected to increase due to measures taken by the government to protect the environment and support family farmers with financial credit. Forest areas can increase regulating ecosystem services (Chapter 3) and we can expect an increase in habitat quality, pollination, carbon sequestration and soil erosion control under the Green Road scenario in 2045. In contrast, the socioeconomic development in the Fossil Fuel scenario, which projects a decline in environmental protection and focuses on rapid economic development, there will be a decline in forest areas, leading to a loss of regulating services. These simulations show how changes in the socio-ecological systems may affect the provision of ecosystem services. The quantification of the effects of specific LULC changes (e.g., pasture to forest) on the provision and interactions of multiple ecosystem services provides useful information to support the design of sustainable landscapes in the future. For instance, information on the percentage of forest increase in the future could be used to make quantitative estimations of the consequences for the delivery of multiple ecosystem services. This can be used by policy and decision makers to anticipate the consequences of certain public policies and, thus, better plan the future provision of ecosystem services. However, to project more plausible scenarios for the provision of ecosystem services, we must also integrate the projections of climate change.

Water provision and agricultural production, including coffee, are the two most important ecosystem services as perceived by local farmers in the study region (Teixeira et al., 2018b). I projected contrasting future scenarios of water dynamics, taking in consideration LULC scenarios integrated with a climate projection for 2045 (Chapter 4). The results show that under the Green Road scenario, there will be a decrease in water surface runoff and an increase in evapotranspiration as compared with the Fossil Fuel scenario. The decrease in water surface runoff can mitigate the erosion (Mohammad and Adam, 2010), while the increase in evapotranspiration can improve microclimate quality in the future (Bright et al., 2017). The projected increase in temperature is expected to decrease the area suitable for coffee production in the study region by 60% (Chapter 5). Nevertheless, changing the management of coffee cultivation through the introduction of trees in the coffee system can reduce air temperatures and reduce the negative impacts of climate change for 2050 by 25%. These scenarios for water and coffee production indicate that changes in LULC and climate can have important consequences for these ecosystem services. I hope that this information can guide society and policy makers in future environmental planning.

Conclusions

In this thesis, I explored the spatio-temporal dynamics of the provision of ecosystems services in a socio-ecological system context from the past to the future. For this, I investigated how LULC changes and socioeconomic drivers affect the provision of multiple ecosystem services and specifically the water and coffee production under climate change.

In the study region, the historical socioeconomic developments led to increases in forest and coffee area over the last three decades, showing that it is possible to combine nature preservation and agricultural production. Government measures to protect the environment and support family farmers were the main drivers behind these observed LULC changes. This makes this region an interesting example of socio-ecological development for other regions of Brazil where deforestation is still ongoing.

The historical LULC changes, mainly the transition of pasture to forest and coffee plantations, increased the provision of ecosystem services. However, coffee monocultures can give rise to soil erosion. This represents a clear trade-off between provisioning and regulating ecosystem services that can be mitigated using management systems that focus more on conservation, without necessarily decreasing production, such as agroforestry coffee systems.

The development of the landscapes in the study region in the future is likely to be strongly affected by social developments and climate change. The contrasting future scenarios of LULC for 2045 indicate that government measures to protect the environment and support family farmer will lead to a more sustainable future in the Green Road scenario, in which forest and coffee areas will increase, and consequently the provision of ecosystem services. In contrast, a lack of government measures to promote nature conservation and finance support for family farmers can result in the materialisation of the Fossil Fuel scenario, with low levels of forest areas, resulting in a decline of regulating ecosystem services. Moreover, the projected changes in precipitation and temperature can also affect the provision of ecosystem services in future, including coffee production. Specifically, the Green Road LULC scenario under projected climate change for 2045 shows that a higher forest cover can mitigate surface water flow and consequently soil erosion, compared with the Fossil Fuel scenario. The projected climate changes are also expected to decrease the suitability for coffee production in the study region. However, the use of agroforestry coffee systems has potential to mitigate the negative impacts of climate changes on coffee production areas.

Analysing the provision of ecosystem services in a socio-ecological context can be a useful tool to identify the main drivers and anticipate the effect of LULC changes. For future studies, I recommend to specifically study more components of the proposed framework in an interdisciplinary research setting, and involve famers more closely in the development of the research. For instance, to analyse how the benefits and values (perceived or economic) affect human wellbeing and consequently the drivers of LULC changes or management. Moreover, farmers should also be involved in the process of scenario development. Therefore, the socio-ecological analysis of ecosystem services can bring together farmers, researchers from different fields, civil society and policy makers to join forces and plan more sustainable and resilient landscapes for the future.

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References

Abbaspour, K.C., Johnson, C.A., Van Genuchten, M.T., 2004. Estimating uncertain flow and transport parameters using a sequential uncertainty fitting procedure. Vadose Zo. J. 3, 1340–1352.

Akpo, L.E., Goudiaby, V.A., Grouzis, M., Le Houerou, H.N., 2005. Tree shade effects on soils and environmental factors in a savanna of Senegal. West African J. Appl. Ecol. 7, 41–52.

Alcamo, J., 2008. The SAS approach: combining qualitative and quantitative knowledge in environmental scenarios. In: Alcamo, J. (Ed.), Environmental Futures: The practice of environmental scenario analysis. Elsevier, Amsterdam, 123–150.

Alvarenga, L.A., de Mello, C.R., Colombo, A., Cuartas, L.A., Bowling, L.C., 2016. Assessment of land cover change on the hydrology of a Brazilian headwater watershed using the Distributed Hydrology-Soil-Vegetation Model. Catena 143, 7–17. https://doi.org/10.1016/j.catena.2016.04.001

Alvares, C.A., Stape, J.L., Sentelhas, P.C., De Moraes Gonçalves, J.L., Sparovek, G., 2013. Köppen's climate classification map for Brazil. Meteorol. Zeitschrift. 22, 711–728. https://doi.org/10.1127/0941-2948/2013/0507

Andersson, E., Tengö, M., McPhearson, T., Kremer, P., 2015. Cultural ecosystem services as a gateway for improving urban sustainability. Ecosyst. Serv. 12, 165–168. https://doi.org/10.1016/j.ecoser.2014.08.002

Arima, E.Y., Barreto, P., Araújo, E., Soares-Filho, B., 2014. Public policies can reduce tropical deforestation: Lessons and challenges from Brazil. Land Use Policy 41, 465–473. https://doi.org/10.1016/j.landusepol.2014.06.026

Ariti, A.T., van Vliet, J., Verburg, P.H., 2015. Land-use and land-cover changes in the Central Rift Valley of Ethiopia: Assessment of perception and adaptation of stakeholders. Appl. Geogr. 65, 28–37.

Baca, M., Läderach, P., Haggar, J., Schroth, G., Ovalle, O., 2014. An integrated framework for assessing vulnerability to climate change and developing adaptation strategies for coffee growing families in mesoamerica. PLoS One 9, e88463 https://doi.org/10.1371/journal.pone.0088463

Banco Central do Brasil. Anuário estatístico do Crédito Rural 1999-2015. https://www.bcb.gov.br/?RELRURAL

Bangash, R.F., Passuello, A., Sanchez-Canales, M., Terrado, M., López, A., Elorza, F.J., Ziv, G., Acuña, V., Schuhmacher, M., 2013. Ecosystem services in Mediterranean river basin: Climate change impact on water provisioning and erosion control. Sci. Total Environ. 458–460, 246–255. https://doi.org/10.1016/j.scitotenv.2013.04.025

Baral, H., Keenan, R.J., Fox, J.C., Stork, N.E., Kasel, S., 2013. Spatial assessment of ecosystem goods and services in complex production landscapes: A case study from south-eastern Australia. Ecol. Complex. 13, 35–45. https://doi.org/10.1016/J.ECOCOM.2012.11.001

Barradas, V.L., Fanjul, L., 1986. Microclimatic chacterization of shaded and open-grown coffee (*Coffea arabica* L.) plantations in Mexico. Agric. For. Meteorol. 38, 101–112.

Beer, J., Muschler, R., Kass, D., Somarriba, E., 1998. Shade management in coffee and cacao plantations. Agrofor. Syst. 38, 139–164. https://doi.org/10.1007/978-94-015-9008-2_6

Beniston, M., 2003. Climatic change in mountain regions: A review of possible impacts, in: Climate Variability and Change in High Elevation Regions: Past, Present & Future. Springer, pp. 5–31.

Bennett, E.M., Peterson, G.D., Gordon, L.J., 2009. Understanding relationships among multiple ecosystem services. Ecol. Lett. 12, 1394–1404. https://doi.org/10.1111/j.1461-0248.2009.01387.x

Bhagwat, S.A., Willis, K.J., Birks, H.J.B., Whittaker, R.J., 2008. Agroforestry: a refuge for tropical biodiversity? Trends Ecol. Evol. 23, 261–267. https://doi.org/10.1016/j.tree.2008.01.005

Borrelli, P., Robinson, D.A., Fleischer, L.R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schütt, B., Ferro, V., Bagarello, V., Oost, K. Van, Montanarella, L., Panagos, P., 2017. An assessment of the global impact of 21st century land use change on soil erosion. Nat. Commun. 8, 2013. https://doi.org/10.1038/s41467-017-02142-7

Bote, A. D., Struik, P. C., 2011. Effects of shade on growth, production and quality of coffee (Coffea arabica) in Ethiopia. J. Hortic. For., 11, 336–341.

BRASIL. Lei 4771/1965. Código Florestal Brasileiro. http://www.planalto.gov.br/ccivil03/leis/L4771.htm.

Bratman, G.N., Anderson, C.B., Berman, M.G., Cochran, B., de Vries, S., Flanders, J., Folke, C., Frumkin, H., Gross, J.J., Hartig, T., Kahn, P.H., Kuo, M., Lawler, J.J., Levin, P.S., Lindahl, T., Meyer-Lindenberg, A., Mitchell, R., Ouyang, Z., Roe, J., Scarlett, L., Smith, J.R., van den Bosch, M., Wheeler, B.W., White, M.P., Zheng, H., Daily, G.C., 2019. Nature and mental health: An ecosystem service perspective. Sci. Adv. 5. https://doi.org/10.1126/sciadv.aax0903

Bright, R.M., Davin, E., Halloran, T.O., Pongratz, J., Zhao, K., Cescatti, A., 2017.

Local temperature response to land cover and management change driven by non-radiative processes. Nat. Clim. Chang. 7, 296–302. https://doi.org/10.1038/nclimate3250

Briner, S., Huber, R., Bebi, P., Elkin, C., Schmatz, D.R., Grêt-Regamey, A., 2013. Trade-offs between ecosystem services in a mountain region. Ecol. Soc. 18. https://doi.org/10.5751/ES-05576-180335

Brown, I., Poggio, L., Gimona, A., & Castellazzi, M., 2011. Climate change, drought risk and land capability for agriculture: Implications for land use in Scotland. Reg. Env. Change, 11, 503-518.

Bunn, C., Läderach, P., Ovalle Rivera, O., Kirschke, D., 2015. A bitter cup: Climate change profile of global production of Arabica and Robusta coffee. Clim. Change 129, 89–101. https://doi.org/10.1007/s10584-014-1306-x

Butchart, S.H.M., Walpole, M., Collen, B., Van Strien, A., Scharlemann, J.P.W., Almond, R.E.A., Baillie, J.E.M., Bomhard, B., Brown, C., Bruno, J., 2010. Global biodiversity: Indicators of recent declines. Science 328, 1164–1168.

Calaboni, A., Tambosi, L.R., Igari, A.T., Farinaci, J.S., Metzger, J.P., Uriarte, M., 2018. The forest transition in São Paulo, Brazil: Historical patterns and potential drivers. Ecol. Soc. 23, 7. https://doi.org/10.5751/ES-10270-230407

Camargo, A.P. de, 1985. O clima e a cafeicultura no Brasil. Inf. Agropec 11, 13–26.

Cannavo, P., Sansoulet, J., Harmand, J.-M., Siles, P., Dreyer, E., Vaast, P., 2011. Agroforestry associating coffee and *Inga densiflora* results in complementarity for water uptake and decreases deep drainage in Costa Rica. Agric. Ecosyst. Environ. 140, 1–13. https://doi.org/10.1016/j.agee.2010.11.005

Cannell, M.G, 1976. Crop physiological aspects of coffee bean yield a review. Kenya Coffee 41, 245-253.

Cardoso I. M., Ferrari E.A., 2006. Construindo o conhecimento agroecológico: trajetória de interação entre ONG, universidade e organizações de agricultores. Revista Agriculturas, 28–32. http://agriculturas.leisa.info.

Cardoso, I.M., Guijt, I., Franco, F.S., Carvalho, A.F., Ferreira Neto, P.S., 2001. Continual learning for agroforestry system design: University, NGO and farmer partnership in Minas Gerais, Brazil. Agric. Syst. 69, 235–257. https://doi.org/10.1016/S0308-521X(01)00028-2

Carpenter, S.R., Bennett, E.M., Peterson, G.D., 2006. Scenarios for Ecosystem Services. Ecol. Soc. 11, 29.

Carr, M.K.V, 2001. The water relations and irrigation requirements of coffee. Exp. Agric. 37, 1–36.

Catalan, J., Ninot, J.M., Aniz, M.M., 2017. The high mountain conservation in a changing world. Adv. Glob. Chang. Res. 62, 3–36. https://doi.org/10.1007/978-3-319-55982-7_1

Cecílio, R.A., Pimentel, S.M., Zanetti, S.S., 2019. Modeling the influence of forest cover on streamflows by different approaches. Catena 178, 49–58. https://doi.org/10.1016/j.catena.2019.03.006

Chain-Guadarrama, A., Martínez-Salinas, A., Aristizábal, N., Ricketts, T.H., 2019. Ecosystem services by birds and bees to coffee in a changing climate: A review of coffee berry borer control and pollination. Agric. Ecosyst. Environ. 280, 53–67. https://doi.org/10.1016/j.agee.2019.04.011

Chakraborty, A., Sachdeva, K., Joshi, P.K., 2016. Mapping long-term land use and land cover change in the central Himalayan region using a tree-based ensemble classification approach. Appl. Geogr. 74, 136–150. https://doi.org/10.1016/j.apgeog.2016.07.008

Chien, H., Yeh, P.J.-F., Knouft, J.H., 2013. Modeling the potential impacts of climate change on streamflow in agricultural watersheds of the Midwestern United States. J. Hydrol. 491, 73–88. https://doi.org/10.1016/j.jhydrol.2013.03.026

Cooper, M., Mendes, L.M.S., Silva, W.L.C., Sparovek, G., 2005. A national soil profile database for Brazil available to international scientists. Soil Sci. Soc. Am. J. 69, 649–652.

Costa, M.H., Botta, A., Cardille, J.A., 2003. Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia. J. Hydrol. 283, 206–217. https://doi.org/10.1016/S0022-1694(03)00267-1

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R. V, Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260. https://doi.org/10.1038/387253a0

Costanza, R., de Groot, R., Sutton, P., Van der Ploeg, S., Anderson, S.J., Kubiszewski, I., Farber, S., Turner, R.K., 2014. Changes in the global value of ecosystem services. Glob. Environ. Change. 26, 152–158.

DaMatta, F.M., 2004. Ecophysiological constraints on the production of shaded and unshaded coffee: A review. F. Crop. Res. 86, 99–114. https://doi.org/10.1016/j.fcr.2003.09.001

DaMatta, F.M., Cochicho Ramalho, J.D., 2006. Impacts of drought and temperature stress on coffee physiology and production: A review. Brazilian J. Plant Physiol. 18, 55–81. https://doi.org/10.1590/S1677-04202006000100006

De Groot, R., Brander, L., Van Der Ploeg, S., Costanza, R., Bernard, F., Braat, L., Christie, M., Crossman, N., Ghermandi, A., Hein, L., 2012. Global estimates of the value of ecosystems and their services in monetary units. Ecosyst. Serv. 1, 50–61.

Defries, R., Bounoua, L., 2004. Consequences of land use change for ecosystem services: A future unlike the past. GeoJournal, 61, 345–351.

Deng, X., Su, H., Zhan, J., 2008. Integration of multiple data sources to simulate the dynamics of land systems. Sensors 8, 620–634. https://doi.org/10.3390/s8020620

Dey, P., Mishra, A., 2017. Separating the impacts of climate change and human activities on streamflow: A review of methodologies and critical assumptions. J. Hydrol. 548, 278–290.

Dias, S.H.B., 2018. Evapotranspiração de referência para projeto de irrigação no Brasil utilizando o produto MOD16. Universidade Federal de Viçosa. Master Dissertation. Available in: https://www.locus.ufv.br/handle/123456789/20513

Didoné, E.J., Minella, J.P.G., Merten, G.H., 2015. Quantifying soil erosion and sediment yield in a catchment in southern Brazil and implications for land conservation. J. Soils Sediments 15, 2334–2346. https://doi.org/10.1007/s11368-015-1160-0

Dieleman, W.I.J., Venter, M., Ramachandra, A., Krockenberger, A.K., Bird, M.I., 2013. Soil carbon stocks vary predictably with altitude in tropical forests: Implications for soil carbon storage. Geoderma 204–205, 59–67. https://doi.org/10.1016/J.GEODERMA.2013.04.005

Doelman, J.C., Stehfest, E., Tabeau, A., van Meijl, H., Lassaletta, L., Gernaat, D.E.H.J., Neumann-Hermans, K., Harmsen, M., Daioglou, V., Biemans, H., van der Sluis, S., van Vuuren, D.P., 2018. Exploring SSP land-use dynamics using the IMAGE model: Regional and gridded scenarios of land-use change and land-based climate change mitigation. Glob. Environ. Change. 48, 119-135. https://doi.org/10.1016/j.gloenvcha.2017.11.014

Duarte, E.M.G., Cardoso, I.M., Stijnen, T., Mendonça, M.A.F.C., Coelho, M.S., Cantarutti, R.B., Kuyper, T.W., Villani, E.M.A., Mendonça, E.S., 2013. Decomposition and nutrient release in leaves of Atlantic Rainforest tree species used in agroforestry systems. Agrofor. Syst. 87, 835–847. https://doi.org/10.1007/s10457-013-9600-6

Duarte, G.T., Ribeiro, M.C., Paglia, A.P., 2016. Ecosystem services modeling as a tool for defining priority areas for conservation. PLoS One 11, e0154573.

Duinker, P.N., Greig, L.A., 2007. Scenario analysis in environmental impact assessment: Improving explorations of the future. Environ. Impact Assess. Rev.

27, 206–219. https://doi.org/10.1016/j.eiar.2006.11.001

Ellison, D., Morris, C.E., Locatelli, B., Sheil, D., Cohen, J., Murdiyarso, D., Gutierrez, V., van Noordwijk, M., Creed, I.F., Pokorny, J., Gaveau, D., Spracklen, D. V, Tobella, A.B., Ilstedt, U., Teuling, A.J., Gebrehiwot, S.G., Sands, D.C., Muys, B., Verbist, B., Springgay, E., Sugandi, Y., Sullivan, C.A., 2017. Trees, forests and water: Cool insights for a hot world. Glob. Environ. Change. 43, 51–61. https://doi.org/10.1016/j.gloenvcha.2017.01.002

Ellison, D., N. Futter, M., Bishop, K., 2012. On the forest cover–water yield debate: From demand to supply side thinking. Glob. Chang. Biol. 18, 806–820. https:/3/doi.org/10.1111/j.1365-2486.2011.02589.x

Embrapa, 2016. Mapa de solo do Estado do Rio de Janeiro. Rio de Janeiro. http://geoinfo.cnps.embrapa.br/maps/461.

Escobar, H., 2019. Amazon fires clearly linked to deforestation, scientists say. Science 365, 853. https://doi.org/10.1126/science.365.6456.853

Eskes, A., Leroy, T., 2009. Coffee: growing, processing, sustainable production. A guidebook for growers, processors, traders and researchers, in: Wintgens, J. N. (Editor.), Coffee selection and breeding. Wiley-VCH , Weinheim - Germany, pp. 61–90.

Falkenmark, M., Rockström, J., 2006. The new blue and green water paradigm: Breaking new ground for water resources planning and management. J. Water Resour. Plan. Manage. 132, 129–132.

FEAM, 2010. Mapa de Solos de Minas Gerais. Belo Horizonte, 2010. 49p.

Ferreira, F.M.C., 2008. A polinização como um serviço do ecossistema: uma estratégia econômica para a conservação. PhD thesis, Univeridade Federal de Minas Gerais.

Fick, S.E., Hijmans, R.J., 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. Int. J. Climatol. 37, 4302–4315.

Filoso, S., Bezerra, M.O., Weiss, K.C.B., Palmer, M.A., 2017. Impacts of forest restoration on water yield: A systematic review. PLoS One 12, 1–26. https://doi.org/10.1371/journal.pone.0183210

Findell, K.L., Berg, A., Gentine, P., Krasting, J.P., Lintner, B.R., Santanello, J.A., Shevliakova, E., Malyshev, S., 2017. The impact of anthropogenic land use and land cover change on regional climate extremes. Nat Commun 8, 989. https://doi.org/10.1038/s41467-017-01038-w

Fisher, B., Turner, R.K., 2008. Ecosystem services: Classification for valuation. Biol. Conserv. 141, 1167–1169. https://doi.org/10.1016/j.biocon.2008.02.019

Fitzherbert, E.B., Struebig, M.J., Morel, A., Danielsen, F., Brühl, C.A., Donald, P.F., Phalan, B., 2008. How will oil palm expansion affect biodiversity? Trends Ecol. Evol. 23, 538–545.

Foley, J.A., Asner, G.P., Costa, M.H., Coe, M.T., DeFries, R., Gibbs, H.K., Howard, E.A., Olson, S., Patz, J., Ramankutty, N., 2007. Amazonia revealed: Forest degradation and loss of ecosystem goods and services in the Amazon Basin. Front. Ecol. Environ. 5, 25–32.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., 2005. Global consequences of land use. Science 309, 570–574. https://www.doi.org/10.1126/science.1111772

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., Connell, C.O., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Sheehan, J., Siebert, S., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockstro, J., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478, 337-342 https://doi.org/10.1038/nature10452

Fu, B., Zhang, L., Xu, Z., Zhao, Y., Wei, Y., Skinner, D., 2015. Ecosystem services in changing land use. J. Soils Sediments 15, 833–843.

Fuchs, R., Herold, M., Verburg, P.H., Clevers, J.G.P.W., 2013. A high-resolution and harmonized model approach for reconstructing and analysing historic land changes in Europe. Biogeosciences 10, 1543–1559. https://doi.org/10.5194/bg-10-1543-2013

Fujisaka, S., Castilla, C., Escobar, G., Rodrigues, V., Veneklaas, E.J., Thomas, R., Fisher, M., 1998. The effects of forest conversion on annual crops and pastures: Estimates of carbon emissions and plant species loss in a Brazilian Amazon colony. Agric. Ecosyst. Environ. 69, 17–26. https://doi.org/10.1016/S0167-8809(98)00091-7

Garrett, R.D., Koh, I., Lambin, E.F., le Polain de Waroux, Y., Kastens, J.H., Brown, J.C., 2018. Intensification in agriculture-forest frontiers: Land use responses to development and conservation policies in Brazil. Glob. Environ. Change. 53, 233–243. https://doi.org/10.1016/j.gloenvcha.2018.09.011

Geertsema, W., Rossing, W.A., Landis, D.A., Bianchi, F.J.J.A., Van Rijn, P.C., Schaminée, J.H., Tscharntke, T., Van Der Werf, W., 2016. Actionable knowledge for ecological intensification of agriculture. Front. Ecol. Environ. 14, 209–216. https://doi.org/10.1002/fee.1258

Ghinoi, S., Junior, V.J.W., Piras, S., 2018. Political debates and agricultural policies: Discourse coalitions behind the creation of Brazil’s Pronaf. Land Use Policy 76, 68–80. https://doi.org/10.1016/j.landusepol.2018.04.039

Giri, S., Arbab, N.N., Lathrop, R.G., 2019. Assessing the potential impacts of climate and land use change on water fluxes and sediment transport in a loosely coupled system. J. Hydrol., 577, 123955. https://doi.org/10.1016/j.jhydrol.2019.123955

Giovanini, R.R., Matos, R.E.S., 2004. Geohistória econômica da Zona da Mata mineira. In: Seminário sobre a economia mineira, 11. Diamantina. Anais. Belo Horizonte: CEDEPLAR / UFMG, 2004.

Gomes, L.C., Cardoso, I.M., Mendonça, E.S., Fernandes, R.B.A., Lopes, V.S., Oliveira, T.S., 2016. Trees modify the dynamics of soil CO_2 efflux in coffee agroforestry systems. Agric. For. Meteorol. 224, 30–39. https://doi.org/10.1016/j.agrformet.2016.05.001

Gomes, L.C., Bianchi, F.J.J.A., Cardoso, I.M., Schulte R.P.O., Arts, B.J.M., Fernandes Filho, E.I, 2020. Land use and land cover scenarios: an interdisciplinary approach integrating local conditions and the global shared socioeconomic pathways. Accepted for publication in Land Use Policy, https://doi.org/10.1016/j.landusepol.2020.104723

Gullino, P., Devecchi, M., Larcher, F., 2018. How can different stakeholders contribute to rural landscape planning policy? The case study of Pralormo municipality (Italy). J. Rural Stud. 57, 99–109.

Gong, J., Liu, D., Zhang, J., Xie, Y., Cao, E., Li, H., 2019. Tradeoffs/synergies of multiple ecosystem services based on land use simulation in a mountain-basin area, western China. Ecol. Indic. 99, 283–293. https://doi.org/10.1016/j.ecolind.2018.12.027

Goulson, D., Nicholls, E., Botías, C., Rotheray, E.L., 2015. Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. Science 347, 1255957.

Guerra, C.A., Metzger, M.J., Maes, J., Pinto-Correia, T., 2016. Policy impacts on regulating ecosystem services: looking at the implications of 60 years of landscape change on soil erosion prevention in a Mediterranean silvo-pastoral system. Landsc. Ecol. 31, 271–290. https://doi.org/10.1007/s10980-015-0241-1

Guo, J., Su, X., Singh, V.P., Jin, J., 2016. Impacts of climate and land use / cover change on streamflow using SWAT and a separation method for the Xiying River basin in northwestern China. Water 8, 192. https://doi.org/10.3390/w8050192

Häfner, K., Zasada, I., van Zanten, B.T., Ungaro, F., Koetse, M., Piorr, A., 2018. Assessing landscape preferences: A visual choice experiment in the agricultural region of Märkische Schweiz, Germany. Landsc. Res. 43, 846–861.

Haase, D., Schwarz, N., Strohbach, M., Kroll, F., Seppelt, R., 2012. Synergies, trade-offs, and losses of ecosystem services in urban regions: An integrated multiscale framework applied to the leipzig-halle region, Germany. Ecol. Soc. 17. https://doi.org/10.5751/ES-04853-170322

Haines-Young, R., Potschin, M., 2010. The links between biodiversity, ecosystem services and human well-being. Ecosyst. Ecol. a new Synth. 1, 110–139.

Han, H., Yang, C., Song, J., 2015. Scenario simulation and the prediction of land use and land cover change in Beijing, China. Sustain. 7, 4260–4279. https://doi.org/10.3390/su7044260

Henríquez-Dole, L., Usón, T.J., Vicuña, S., Henríquez, C., Gironás, J., Meza, F., 2018. Integrating strategic land use planning in the construction of future land use scenarios and its performance: The Maipo River Basin, Chile. Land Use Policy 78, 353–366. https://doi.org/10.1016/j.landusepol.2018.06.045

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. Int. J. Climatol. 25, 1965–1978.

Holloway, J., Roberts, I., Rush, A., 2010. China's steel industry'. RBA Bull. December 19–25.

Howe, C., Suich, H., Vira, B., Mace, G.M., 2014. Creating win-wins from trade-offs? Ecosystem services for human well-being: A meta-analysis of ecosystem service trade-offs and synergies in the real world. Glob. Environ. Change. 28, 263–275. https://doi.org/10.1016/J.GLOENVCHA.2014.07.005

Huang, H., Cheng, S., Wen, J., Lee, J., 2008. Effect of growing watershed imperviousness on hydrograph parameters and peak discharge. Hydrol. Process. An Int. J. 22, 2075–2085.

IBGE, 2018. Instituto Brasileiro de Geografia e Estatística. Sistema IBGE de Recuperação Automática- SIDRA. http://www.sidra.gov.br/bda

IBGE, 2019. Censos Agropecuários (2012 - 2017): Fundação Instituto Brasileiro de Geografia e Estatística. Rio de Janeiro, RJ, Brasil. https://sidra.ibge.gov.br/home/pms/brasil. Accessed August 3, 2019

ICO, 2017. International Coffee Organization. http://www.ico.org/new_historical.asp

INMET, 2020. Instituto Nacional de Meteorologia (INMET). http://www.inmet.gov.br/portal/

IPCC, 2014: Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press Cambridge, United Kingdom and New York, NY, USA (2014).

IPCC, 2018. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.). https://www.ipcc.ch/sr15/

IPCC, 2019. Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. https://www.ipcc.ch/report/srccl/. Accessed August 9, 2019.

Jackson, L.E., Pulleman, M.M., Brussaard, L., Bawa, K.S., Brown, G.G., Cardoso, I.M., de Ruiter, P.C., García-Barrios, L., Hollander, A.D., Lavelle, P., Ouédraogo, E., Pascual, U., Setty, S., Smukler, S.M., Tscharntke, T., Van Noordwijk, M., 2012. Social-ecological and regional adaptation of agrobiodiversity management across a global set of research regions. Glob. Environ. Change. 22, 623–639. https://doi.org/10.1016/j.gloenvcha.2012.05.002

Jackson, R.B., Jobbágy, E.G., Avissar, R., Roy, S.B., Barrett, D.J., Cook, C.W., Farley, K.A., le Maitre, D.C., McCarl, B.A., Murray, B.C., 2005. Trading water for carbon with biological carbon sequestration. Science 310, 1944–1947. https://doi.org/10.1126/science.1119282

Kehoe, L., Reis, T., Virah-Sawmy, M., Balmford, A., Kuemmerle, T., Knohl, A., Antonelli, A., Hochkirch, A., Vira, B., Massa, B., 2019. Make EU trade with Brazil sustainable. Science 364, 341.

Kelble, C.R., Loomis, D.K., Lovelace, S., Nuttle, W.K., Ortner, P.B., Fletcher, P., Cook, G.S., Lorenz, J.J., Boyer, J.N., 2013. The EBM-DPSER conceptual model: integrating ecosystem services into the DPSIR framework. PLoS One 8, e70766. https://doi.org/10.1371/journal.pone.0070766

Kemp-Benedict, E., 2010. Converting qualitative assessments to quantitative assumptions: Bayes' rule and the pundit's wager. Technol. Forecast. Soc. Change 77, 167–171. https://doi.org/10.1016/j.techfore.2009.06.008

Kim, K.B., Kwon, H.-H., Han, D., 2018. Exploration of warm-up period in conceptual hydrological modelling. J. Hydrol. 556, 194–210.

Kok, M.T.J., Kok, K., Peterson, G.D., Hill, R., Agard, J., Carpenter, S.R., 2017. Biodiversity and ecosystem services require IPBES to take novel approach to scenarios. Sustain. Sci. 12, 177–181. https://doi.org/10.1007/s11625-016-0354-8

Körner, C., 2003. Alpine plant life: functional plant ecology of high mountain ecosystems. Springer Science & Business Media.

Kriegler, E., O'Neill, B.C., Hallegatte, S., Kram, T., Lempert, R.J., Moss, R.H., Wilbanks, T., 2012. The need for and use of socio-economic scenarios for climate change analysis: A new approach based on shared socio-economic pathways. Glob. Environ. Change. 22, 807–822. https://doi.org/10.1016/j.gloenvcha.2012.05.005

Kucsicsa, G., Popovici, E. A., Bălteanu, D., Grigorescu, I., Dumitraşcu, M., Mitrică, B., 2019. Future land use/cover changes in Romania: regional simulations based on CLUE-S model and CORINE land cover database. Landsc. Ecol. Eng. 15, 75–90. https://doi.org/10.1007/s11355-018-0362-1

La Notte, A., D'Amato, D., Mäkinen, H., Paracchini, M.L., Liquete, C., Egoh, B., Geneletti, D., Crossman, N.D., 2017. Ecosystem services classification: A systems ecology perspective of the cascade framework. Ecol. Indic. 74, 392–402. https://doi.org/10.1016/j.ecolind.2016.11.030

Läderach, P., Ramirez–Villegas, J., Navarro-Racines, C., Zelaya, C., Martinez–Valle, A., Jarvis, A., 2017. Climate change adaptation of coffee production in space and time. Clim. Change 141, 47–62. https://doi.org/10.1007/s10584-016-1788-9

Lambin, E.F., Meyfroidt, P., 2011. Global land use change, economic globalization, and the looming land scarcity. Proc. Natl. Acad. Sci. 108, 3465–3472. https://doi.org/10.1073/pnas.1100480108

Lambin, E.F., Turner, B.L., Geist, H.J., Agbola, S.B., Angelsen, A., Bruce, J.W., Coomes, O.T., Dirzo, R., Fischer, G., Folke, C., George, P.S., Homewood, K., Imbernon, J., Leemans, R., Li, X., Moran, E.F., Mortimore, M., Ramakrishnan, P.S., Richards, J.F., Skånes, H., Steffen, W., Stone, G.D., Svedin, U., Veldkamp, T.A., Vogel, C., Xu, J., 2001. The causes of land-use and land-cover change: Moving beyond the myths. Glob. Environ. Change. 11, 261–269. https://doi.org/10.1016/S0959-3780(01)00007-3

Lang, Y., Song, W., 2018. Trade-off analysis of ecosystem services in a mountainous karst area, China. Water 10, 300.

Levy, M.C., Lopes, A. V, Cohn, A., Larsen, L.G., Thompson, S.E., 2018. Land use change increases streamflow across the arc of deforestation in Brazil. Geophys.

Res. Lett. 45, 3520–3530. https://doi.org/10.1002/2017GL076526

Li, B., Chen, N., Wang, Y., Wang, W., 2018. Spatio-temporal quantification of the trade-offs and synergies among ecosystem services based on grid-cells: A case study of Guanzhong Basin, NW China. Ecol. Indic. 94, 246–253. https://doi.org/10.1016/j.ecolind.2018.06.069

Li, Y., He, D., Li, X., Zhang, Y., Yang, L., 2016. Contributions of climate variability and human activities to runoff changes in the upper catchment of the Red River Basin, China. Water 8, 414.

Li, Y., Zhang, L., Qiu, J., Yan, J., Wan, L., Wang, P., Hu, N., Cheng, W., Fu, B., 2017. Spatially explicit quantification of the interactions among ecosystem services. Landsc. Ecol. 32, 1181–1199. https://doi.org/10.1007/s10980-017-0527-6

Li, Z., Liu, W., Zhang, X., Zheng, F., 2009. Impacts of land use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China. J. Hydrol. 377, 35–42. https://doi.org/10.1016/j.jhydrol.2009.08.007

Lin, B.B., 2007. Agroforestry management as an adaptive strategy against potential microclimate extremes in coffee agriculture. Agric. For. Meteorol. 144, 85–94. https://doi.org/10.1016/j.agrformet.2006.12.009

Lin, B.B., 2010. The role of agroforestry in reducing water loss through soil evaporation and crop transpiration in coffee agroecosystems. Agric. For. Meteorol. 150, 510–518. https://doi.org/10.1016/j.agrformet.2009.11.010

Lin, Y.P., Chu, H.J., Wu, C.F., Verburg, P.H., 2011. Predictive ability of logistic regression, auto-logistic regression and neural network models in empirical land-use change modeling - a case study. Int. J. Geogr. Inf. Sci. 25, 65-87.

Lin, Y.P., Hong, N.M., Wu, P.J., Wu, C.F., Verburg, P.H., 2007. Impacts of land use change scenarios on hydrology and land use patterns in the Wu-Tu watershed in Northern Taiwan. Landsc. Urban Plan. 80, 111–126. https://doi.org/10.1016/j.landurbplan.2006.06.007

Liu, X., Liang, X., Li, X., Xu, X., Ou, J., Chen, Y., Li, S., Wang, S., Pei, F., 2017. A future land use simulation model (FLUS) for simulating multiple land use scenarios by coupling human and natural effects. Landsc. Urban Plan. 168, 94–116. https://doi.org/10.1016/j.landurbplan.2017.09.019

Lobo, C., 2016. Dispersão espacial da população no Brasil. Mercator-Revista de Geografia da UFC 15.3. https://www.redalyc.org/html/2736/273647136003/

Lonsdorf, E., Kremen, C., Ricketts, T., Winfree, R., Williams, N., Greenleaf, S., 2009. Modelling pollination services across agricultural landscapes. Ann. Bot. 103, 1589–1600.

Lopes, V.S., Cardoso, I.M., Fernandes, O.R., Rocha, G.C., Simas, F.N.B., de Melo Moura, W., Santana, F.C., Veloso, G.V., da Luz, J.M.R., 2020. The establishment of a secondary forest in a degraded pasture to improve hydraulic properties of the soil. Soil Tillage Res. 198, 104538. https://doi.org/10.1016/j.still.2019.104538

López-Bravo, D.F., Virginio-Filho, E.D.M., Avelino, J., 2012. Shade is conducive to coffee rust as compared to full sun exposure under standardized fruit load conditions. Crop Prot. 38, 21–29. https://doi.org/10.1016/j.cropro.2012.03.011

López-Moreno, J.I., Zabalza, J., Vicente-Serrano, S.M., Revuelto, J., Gilaberte, M., Azorin-Molina, C., 2014. Impact of climate and land use change on water availability and reservoir management: Scenarios in the Upper Aragón River, Spanish Pyrenees. Sci. Total Environ. 493, 1222–1231. https://doi.org/10.1016/j.scitotenv.2013.09.031

Maes, J., Paracchini, M.L., Zulian, G., Dunbar, M.B., Alkemade, R., 2012. Synergies and trade-offs between ecosystem service supply, biodiversity, and habitat conservation status in Europe. Biol. Conserv. 155, 1–12. https://doi.org/10.1016/j.biocon.2012.06.016

Magrach, A., Ghazoul, J., 2015. Climate and pest-driven geographic shifts in global coffee production: Implications for forest cover, biodiversity and carbon storage. PLoS One 10, 1–15. https://doi.org/10.1371/journal.pone.0133071

Malerbo-Souza, D.T., Halak, A.L., 2012. Agentes polinizadores e produção de grãos em cultura de café arábica cv."Catuaí Vermelho". Científica 40, 1–11.

Mallampalli, V.R., Mavrommati, G., Thompson, J., Duveneck, M., Meyer, S., Ligmann-Zielinska, A., Druschke, C.G., Hychka, K., Kenney, M.A., Kok, K., Borsuk, M.E., 2016. Methods for translating narrative scenarios into quantitative assessments of land use change. Environ. Model. Softw. 82, 7–20. https://doi.org/10.1016/j.envsoft.2016.04.011

Marhaento, H., Booij, M.J., Hoekstra, A.Y., 2018. Hydrological response to future land-use change and climate change in a tropical catchment. Hydrol. Sci. J. 63, 1368–1385. https://doi.org/10.1080/02626667.2018.1511054

Marhaento, H., Booij, M.J., Rientjes, T.H.M., Hoekstra, A.Y., 2017. Attribution of changes in the water balance of a tropical catchment to land use change using the SWAT model. Hydrol. Process. 31, 2029–2040. https://doi.org/10.1002/hyp.11167

Mas, J.F., Kolb, M., Paegelow, M., Camacho Olmedo, M.T., Houet, T., 2014. Inductive pattern-based land use/cover change models: A comparison of four software packages. Environ. Model. Softw. 51, 94–111.

Mather, A.S., 1992. The forest transition. Area 367–379.

Mayor, J.R., Sanders, N.J., Classen, A.T., Bardgett, R.D., Clément, J.C., Fajardo, A., Lavorel, S., Sundqvist, M.K., Bahn, M., Chisholm, C., Cieraad, E., Gedalof, Z., Grigulis, K., Kudo, G., Oberski, D.L., Wardle, D.A., 2017. Elevation alters ecosystem properties across temperate treelines globally. Nature 542, 91–95. https://doi.org/10.1038/nature21027

McAlpine, C.A., Etter, A., Fearnside, P.M., Seabrook, L., Laurance, W.F., 2009. Increasing world consumption of beef as a driver of regional and global change: A call for policy action based on evidence from Queensland (Australia), Colombia and Brazil. Glob. Environ. Change. 19, 21–33. https://doi.org/10.1016/j.gloenvcha.2008.10.008

McGarigal, K., Plunkett, E.B., Willey, L.L., Compton, B.W., DeLuca, W. V, Grand, J., 2018. Modeling non-stationary urban growth: The SPRAWL model and the ecological impacts of development. Landsc. Urban Plan. 177, 178–190.

Mello, C.R. de, Viola, M.R., Beskow, S., Norton, L.D., 2013. Multivariate models for annual rainfall erosivity in Brazil. Geoderma 202, 88–102.

Merow, C., Smith, M.J., Silander, J.A., 2013. A practical guide to MaxEnt for modeling species distributions: What it does, and why inputs and settings matter. Ecography 36, 1058–1069. https://doi.org/10.1111/j.1600-0587.2013.07872.x

Metzger, M.J., Rounsevell, M.D.A., Acosta-Michlik, L., Leemans, R., Schröter, D., 2006. The vulnerability of ecosystem services to land use change. Agric. Ecosyst. Environ. 114, 69–85. https://doi.org/10.1016/j.agee.2005.11.025

Meyfroidt, P., Lambin, E.F., Erb, K.H., Hertel, T.W., 2013. Globalization of land use: distant drivers of land change and geographic displacement of land use. Curr. Opin. Environ. Sustain. 5, 438–444. https://doi.org/10.1016/j.cosust.2013.04.003

Milheiras, S.G., Mace, G.M., 2019. Assessing ecosystem service provision in a tropical region with high forest cover: Spatial overlap and the impact of land use change in Amapá, Brazil. Ecol. Indic. 99, 12–18. https://doi.org/10.1016/j.ecolind.2018.12.013

Millenium Ecosystem Assessment (MA), 2005. Ecosystems and human well-being. Island press Washington, D.C.

Mohammad, A.G., Adam, M.A., 2010. The impact of vegetative cover type on runoff and soil erosion under different land uses. Catena 81, 97–103. https://doi.org/10.1016/j.catena.2010.01.008

Molina-Navarro, E., Andersen, H.E., Nielsen, A., Thodsen, H., Trolle, D., 2018.

Quantifying the combined effects of land use and climate changes on stream flow and nutrient loads: A modelling approach in the Odense Fjord catchment (Denmark). Sci. Total Environ. 621, 253–264. https://doi.org/10.1016/j.scitotenv.2017.11.251

Moore, I.D., Burch, G.J., 1986. Modelling erosion and deposition: Topographic effects. Trans. ASAE 29, 1624–1630.

Moreira, S.L.S., Pires, C. V., Marcatti, G.E., Santos, R.H.S., Imbuzeiro, H.M.A., Fernandes, R.B.A., 2018. Intercropping of coffee with the palm tree, macauba, can mitigate climate change effects. Agric. For. Meteorol. 256, 379–390. https://doi.org/10.1016/j.agrformet.2018.03.026

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. ASABE 50, 885–900.

Moulds, S., Buytaert, W., Mijic, A., 2015. An open and extensible framework for spatially explicit land use change modelling: The lulcc R package. Geosci. Model Dev. 8, 3215–3229. https://doi.org/10.5194/gmd-8-3215-2015

Muschler, R.G., 2001. Shade improves coffee quality in sub-optimal coffee zone of Costa Rica. Agroforest Syst. 51, 131-139. https://doi.org/10.1023/A:1010603320653

Myers, N., Mittermeler, R.A., Mittermeler, C.G., Da Fonseca, G.A.B., Kent, J., 2000. Biodiversity hotspots for conservation priorities. Nature 403, 853 https://doi.org/10.1038/35002501

Nair, P.K.R., 1997. Directions in tropical agroforestry research: past, present, and future. Agrofor. Syst. 38, 223–245. https://doi.org/10.1023/A:1005943729654

Nash, J.E., Sutcliffe, J. V, 1970. River flow forecasting through conceptual models part I–A discussion of principles. J. Hydrol. 10, 282–290.

Nassl, M., Löffler, J., 2015. Ecosystem services in coupled social–ecological systems: Closing the cycle of service provision and societal feedback. Ambio 44, 737–749. https://doi.org/10.1007/s13280-015-0651-y

Navarro-Racines, C.E., Tarapues, J.E., 2015. Bias-correction in the CCAFS-Climate Portal: A description of methodologies. Decision and Policy Analysis (DAPA) Research Area. Cali, Colombia: International Center for Tropical Agriculture (CIAT). https://hdl.handle.net/10568/76609

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2011. Soil and water assessment tool theoretical documentation version 2009. Texas Water Resources Institute. https://swat.tamu.edu/media/99192/swat2009-theory.pdf

Nelson, E., Mendoza, G., Regetz, J., Polasky, S., Tallis, H., Cameron, Dr., Chan, K.M.A., Daily, G.C., Goldstein, J., Kareiva, P.M., 2009. Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. Front. Ecol. Environ. 7, 4–11.

Neupane, R.P., Kumar, S., 2015. Estimating the effects of potential climate and land use changes on hydrologic processes of a large agriculture dominated watershed. J. Hydrol. 529, 418–429. https://doi.org/10.1016/j.jhydrol.2015.07.050

Ngulani, T., Shackleton, C.M., 2019. Use of public urban green spaces for spiritual services in Bulawayo, Zimbabwe. Urban For. Urban Green. 38, 97–104. https://doi.org/10.1016/j.ufug.2018.11.009

Nickel, D., Schoenfelder, W., Medearis, D., Dolowitz, D.P., Keeley, M., Shuster, W., Nickel, D., Schoenfelder, W., Medearis, D., Dolowitz, D.P., 2014. German experience in managing stormwater with green infrastructure. J. Environ. Plan. Manage. 57, 403–423, https://doi.org/10.1080/09640568.2012.748652

Nilsson, A.E., Bay-Larsen, I., Carlsen, H., van Oort, B., Bjørkan, M., Jylhä, K., Klyuchnikova, E., Masloboev, V., van der Watt, L.M., 2017. Towards extended shared socioeconomic pathways: A combined participatory bottom-up and top-down methodology with results from the Barents region. Glob. Environ. Change. 45, 124-132 https://doi.org/10.1016/j.gloenvcha.2017.06.001

Nowak, D.J., Hirabayashi, S., Bodine, A., Green, E., 2014. Tree and forest effects on air quality and human health in the United States. Environ. Pollut., 193, 119-129. https://doi.org/10.1016/j.envpol.2014.05.028

O'Donnell, M.S., Ignizio, D.A., 2012. Bioclimatic predictors for supporting ecological applications in the conterminous United States. US Geol. Surv. Data Ser. 691.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W., 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Change. https://doi.org/10.1016/j.gloenvcha.2015.01.004

O'Neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., Mathur, R., van Vuuren, D.P., 2014. A new scenario framework for climate change research: The concept of shared socioeconomic pathways. Clim. Change 122, 387–400. https://doi.org/10.1007/s10584-013-0905-2

Oduro, K.A., Arts, B., Hoogstra-Klein, M.A., Kyereh, B., Mohren, G.M.J., 2014. Exploring the future of timber resources in the high forest zone of Ghana. Int. For. Rev. 16, 573–585 https://doi.org/10.1505/146554814814095320

Oliveira, V.A. Mello, C.R., Viola, M.R., Srinivasan, R., 2018. Land-use change impacts on the hydrology of the upper Grande River basin, Brazil. Cerne 24, 334–343.

Ouyang, Y., Jin, W., Grace, J.M., Obalum, S.E., Zipperer, W.C., Huang, X., 2019. Estimating impact of forest land on groundwater recharge in a humid subtropical watershed of the Lower Mississippi River Alluvial Valley. J. Hydrol. Reg. Stud. 26, 100631. https://doi.org/10.1016/j.ejrh.2019.100631

Ovalle-Rivera, O., Läderach, P., Bunn, C., Obersteiner, M., Schroth, G., 2015. Projected shifts in Coffea arabica suitability among major global producing regions due to climate change. PLoS One 10, 1–13. https://doi.org/10.1371/journal.pone.0124155

Padovan, M.P., Brook, R.M., Barrios, M., Cruz-Castillo, J.B., Vilchez-Mendoza, S.J., 2018. Water loss by transpiration and soil evaporation in coffee shaded by Tabebuia rosea Bertol. and Simarouba glauca dc. compared to unshaded coffee in sub-optimal environmental conditions. Agric. For. Meteorol. 248, 1–14. https://doi.org/10.1016/j.agrformet.2017.08.036

Palazzo, A., Vervoort, J.M., Mason-D’Croz, D., Rutting, L., Havlík, P., Islam, S., Bayala, J., Valin, H., Kadi Kadi, H.A., Thornton, P., Zougmore, R., 2017. Linking regional stakeholder scenarios and shared socioeconomic pathways: Quantified west African food and climate futures in a global context. Glob. Environ. Change. 45, 227-242 https://doi.org/10.1016/j.gloenvcha.2016.12.002

Pan, D., Domon, G., De Blois, S., & Bouchard, A., 1999. Temporal (1958–1993) and spatial patterns of land use changes in Haut-Saint-Laurent (Quebec, Canada) and their relation to landscape physical attributes. Landsc. Ecol. 14, 35-52.

Pedersen, E., Weisner, S.E.B., Johansson, M., 2019. Wetland areas’ direct contributions to residents’ well-being entitle them to high cultural ecosystem values. Sci. Total Environ. 646, 1315–1326. https://doi.org/10.1016/j.scitotenv.2018.07.236

Pendergrast, M., 2010. Uncommon grounds: the history of coffee and how it transformed our world (revised edition). Basic Books. New York.

Pereira, R., Martinez, M.A., Pruski, F.F., Demetrius, D., 2016. Hydrological simulation in a basin of typical tropical climate and soil using the SWAT model part I : Calibration and validation tests. J. Hydrol. Reg. Stud. 7, 14–37.

Peterson, A.T., Papeş, M., Soberón, J., 2008. Rethinking receiver operating characteristic analysis applications in ecological niche modeling. Ecol. Modell.

213, 63–72. https://doi.org/10.1016/j.ecolmodel.2007.11.008
Peterson, G.D., Cumming, G.S., Carpenter, S.R., 2003. Scenario Planning: a tool for conservation in an uncertain world. Conserv. Biol. 17, 358–366. https://doi.org/10.1046/j.1523-1739.2003.01491.x
Phillips, S.J., Anderson, R.P., Schapire, R.E., 2006. Maximum entropy modeling of species geographic distributions. Ecol. Modell. 190, 231–259. https://doi.org/10.1016/j.ecolmodel.2005.03.026
Phillips, S.J., Dudík, M., Robert E. Schapire, R.E., 2019. Maxent software for modeling species niches and distributions (Version 3.4.1). Available from: http://biodiversityinformatics.amnh.org/open_source/maxent/. Accessed on 20-01-2019.
Pontius, R.G., Peethambaram, S., Castella, J.C., 2011. Comparison of tree maps at multiple resolutions: A case study of land change simulation in Cho Don district, Vietnam. Ann. Assoc. Am. Geogr. 101, 45–62. https://doi.org/10.1080/00045608.2010.517742
Popp, A., Calvin, K., Fujimori, S., Havlik, P., Humpenöder, F., Stehfest, E., Bodirsky, B.L., Dietrich, J.P., Doelmann, J.C., Gusti, M., Hasegawa, T., Kyle, P., Obersteiner, M., Tabeau, A., Takahashi, K., Valin, H., Waldhoff, S., Weindl, I., Wise, M., Kriegler, E., Lotze-Campen, H., Fricko, O., Riahi, K., van Vuuren, D.P., 2017. Land-use futures in the shared socio-economic pathways. Glob. Environ. Change. 42, 331–345. https://doi.org/10.1016/j.gloenvcha.2016.10.002
Popp, A., Humpenöder, F., Weindl, I., Bodirsky, B.L., Bonsch, M., Lotze-Campen, H., Müller, C., Biewald, A., Rolinski, S., Stevanovic, M., Dietrich, J.P., 2014. Land-use protection for climate change mitigation. Nat. Clim. Chang. 4, 1095–1098. https://doi.org/10.1038/nclimate2444
Portela, R., Rademacher, I., 2001. A dynamic model of patterns of deforestation and their effect on the ability of the Brazilian Amazonia to provide ecosystem services. Ecol. Modell. 143, 115–146.
PRB, 2018. World population data sheet. Population Reference Bureau. https://www.prb.org/wp-content/uploads/2018/08/2018_WPDS.pdf.
Pulighe, G., Fava, F., Lupia, F., 2016. Insights and opportunities from mapping ecosystem services of urban green spaces and potentials in planning. Ecosyst. Serv. 22, 1–10. https://doi.org/10.1016/j.ecoser.2016.09.004
Qiao, X., Gu, Y., Zou, C., Xu, D., Wang, L., Ye, X., Yang, Y., Huang, X., 2019. Temporal variation and spatial scale dependency of the trade-offs and synergies among multiple ecosystem services in the Taihu Lake Basin of China. Sci.

Total Environ. 651, 218–229. https://doi.org/10.1016/j.scitotenv.2018.09.135
Qiu, J., Booth, E., Carpenter, S.R., Kucharik, C., Loheide II, S.P., Motew, M., Zipper, S.C., Turner, M.G., 2018. Understanding relationships among ecosystem services across spatial scales and over time. Environ. Res. Lett. 13, 054020. https://doi.org/10.1088/1748-9326/aabb87
Queiroz, C., Meacham, M., Richter, K., Norström, A. V., Andersson, E., Norberg, J., Peterson, G., 2015. Mapping bundles of ecosystem services reveals distinct types of multifunctionality within a Swedish landscape. Ambio 44, 89–101. https://doi.org/10.1007/s13280-014-0601-0
Quintas-Soriano, C., Castro, A.J., Castro, H., García-Llorente, M., 2016. Impacts of land use change on ecosystem services and implications for human well-being in Spanish drylands. Land Use Policy 54, 534–548. https://doi.org/10.1016/j.landusepol.2016.03.011
R Development Core Team, 2014. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org
Rahn, E., Vaast, P., Läderach, P., van Asten, P., Jassogne, L., Ghazoul, J., 2018. Exploring adaptation strategies of coffee production to climate change using a process-based model. Ecol. Modell. 371, 76–89. https://doi.org/10.1016/j.ecolmodel.2018.01.009
Ramalho, J.C., DaMatta, F.M., Rahn, E., Ghini, R., Läderach, P., 2018. Why could the coffee crop endure climate change and global warming to a greater extent than previously estimated? Clim. Change 152, 167–178. https://doi.org/10.1007/s10584-018-2346-4
Ramankutty, N., Foley, J.A., Norman, J., McSweeney, K., 2002. The global distribution of cultivable lands: current patterns and sensitivity to possible climate change. Glob. Ecol. Biogeogr. 11, 377–392.
Ramankutty, N., Foley, J.A., Olejniczak, N.J., 2008. Land-use change and global food production. In: Land Use and Soil Resources. Braimoh, A. K., and Vlek, P. L. G., Eds., Springer, Dordrecht, Netherlands pp. 23–40.
Rani, S., Sreekesh, S., 2019. Evaluating the responses of streamflow under future climate change scenarios in a western Indian Himalaya watershed. Environ. Process. 6, 155–174. https://doi.org/10.1007/s40710-019-00361-2
Raudsepp-Hearne, C., Peterson, G.D., Bennett, E.M., 2010. Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. Proc. Natl. Acad. Sci. 107, 5242–5247. https://doi.org/10.1073/pnas.0907284107
Reginster, I., Rounsevell, M., 2006. Scenarios of future urban land use in Europe.

Environ. Plan. B Plan. Des. 33, 619–636. https://doi.org/10.1068/b31079

Renard, D., Rhemtulla, J.M., Bennett, E.M., 2015. Historical dynamics in ecosystem service bundles. Proc. Natl. Acad. Sci. 112, 13411–13416. https://doi.org/10.1073/pnas.1502565112

Reyers, B., Biggs, R., Cumming, G.S., Elmqvist, T., Hejnowicz, A.P., Polasky, S., 2013. Getting the measure of ecosystem services: a social – ecological approach. Front. Ecol. Environ. 11, 268–273. https://doi.org/10.1890/120144

Rezende, M.Q., Venzon, M., Perez, A.L., Cardoso, I.M., Janssen, A., 2014. Extrafloral nectaries of associated trees can enhance natural pest control. Agric. Ecosyst. Environ. 188, 198–203. https://doi.org/10.1016/j.agee.2014.02.024

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J.C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L.A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J.C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., Tavoni, M., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Glob. Environ. Change. 42, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Rodríguez-Echeverry, J., Echeverría, C., Oyarzún, C., Morales, L., 2018. Impact of land-use change on biodiversity and ecosystem services in the Chilean temperate forests. Landsc. Ecol. 33, 439–453. https://doi.org/10.1007/s10980-018-0612-5

Rounsevell, M.D.A., Pedroli, B., Erb, K.H., Gramberger, M., Busck, A.G., Haberl, H., Kristensen, S., Kuemmerle, T., Lavorel, S., Lindner, M., Lotze-Campen, H., Metzger, M.J., Murray-Rust, D., Popp, A., Pérez-Soba, M., Reenberg, A., Vadineanu, A., Verburg, P.H., Wolfslehner, B., 2012. Challenges for land system science. Land Use Policy 29, 899–910. https://doi.org/10.1016/j.landusepol.2012.01.007

Rounsevell, M.D.A., Reginster, I., Araújo, M.B., Carter, T.R., Dendoncker, N., Ewert, F., House, J.I., Kankaanpää, S., Leemans, R., Metzger, M.J., Schmit, C., Smith, P., Tuck, G., 2006. A coherent set of future land use change scenarios for Europe. Agric. Ecosyst. Environ. 114, 57–68. https://doi.org/10.1016/j.agee.2005.11.027

Rudel, T., 1998. Is There a Forest Transition ? Sociol. J. Br. Sociol. Assoc. 63, 533–

552.

Rudel, T.K., Coomes, O.T., Moran, E., Achard, F., Angelsen, A., Xu, J., Lambin, E., 2005. Forest transitions: Towards a global understanding of land use change. Glob. Environ. Change. 15, 23–31. https://doi.org/10.1016/j.gloenvcha.2004.11.001

Rudel, T.K., DeFries, R., Asner, G.P., Laurance, W.F., 2009. Changing drivers of deforestation and new opportunities for conservation. Conserv. Biol. 23, 1396–1405. https://doi.org/10.1111/j.1523-1739.2009.01332.x

Sari, V., Paiva, E.M.C.D. de, Paiva, J.B.D. de, 2016. Interceptação da chuva em diferentes formações florestais na região sul do Brasil. RBRH 21, 65–79.

Schroth, G., Läderach, P., Blackburn Cuero, D.S., Neilson, J., Bunn, C., 2015. Winner or loser of climate change? A modeling study of current and future climatic suitability of Arabica coffee in Indonesia. Reg. Environ. Chang. 15, 1473–1482. https://doi.org/10.1007/s10113-014-0713-x

Schroth, G., Laderach, P., Dempewolf, J., Philpott, S., Haggar, J., Eakin, H., Castillejos, T., Moreno, J.G., Pinto, L.S., Hernandez, R., Eitzinger, A., Ramirez-Villegas, J., 2009. Towards a climate change adaptation strategy for coffee communities and ecosystems in the Sierra Madre de Chiapas, Mexico. Mitig. Adapt. Strateg. Glob. Chang. 14, 605–625. https://doi.org/10.1007/s11027-009-9186-5

Schulte, R.P.O., O'Sullivan, L., Vrebos, D., Bampa, F., Jones, A., Staes, J., 2019. Demands on land: Mapping competing societal expectations for the functionality of agricultural soils in Europe. Environ. Sci. Policy 100, 113–125. https://doi.org/10.1016/j.envsci.2019.06.011

Searchinger, T.D., Wirsenius, S., Beringer, T., Dumas, P., 2018. Assessing the efficiency of changes in land use for mitigating climate change. Nature 564, 249–253. https://doi.org/10.1038/s41586-018-0757-z

Shang, X., Jiang, X., Jia, R., 2019. Land use and climate change effects on surface runoff variations in the upper Heihe River basin. Water 11, 344. https://doi.org/10.3390/w11020344

Sharp, R., Tallis, H.T., Ricketts, T., Guerry, A.D., Wood, S.A., Chaplin-Kramer, R., Nelson, E., Ennaanay, D., Wolny, S., Olwero, N., Vigerstol, K., Pennington, D., Mendoza, G., Aukema, J., Foster, J., Forrest, J., Cameron, D., Arkema, K., Lonsdorf, E., Kennedy, C., Verutes, G., Kim, C.K., Guannel, G., Papenfus, M., Toft, J., Marsik, M., Bernhardt, J., Griffin, R., Glowinski, K., Chaumont, N., Perelman, A., Lacayo, M. Mandle, L., Hamel, P., Vogl, A.L., Rogers, L., Bierbower, W., Denu, D., and Douglass, J., 2018. InVEST 3.6.0 User's Guide.

The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund.

Sleeter, B.M., Sohl, T.L., Bouchard, M.A., Reker, R.R., Soulard, C.E., Acevedo, W., Griffith, G.E., Sleeter, R.R., Auch, R.F., Sayler, K.L., Prisley, S., Zhu, Z., 2012. Scenarios of land use and land cover change in the conterminous United States: Utilizing the special report on emission scenarios at ecoregional scales. Glob. Environ. Change. 22, 896–914. https://doi.org/10.1016/j.gloenvcha.2012.03.008

Sonneveld, B., Nearing, M.A., 2003. A nonparametric/parametric analysis of the Universal Soil Loss Equation. Catena 52, 9–21.

Soriano, É., Londe, L.R., Gregorio, L.T. Di, Coutinho, M.P., Santos, L.B.L., 2016. Water crisis in São Paulo evaluated under the disaster's point of view. Ambiente & Sociedade 19, 21–42.

Sosma, S.M.A. and INPE, 2019. Atlas dos Remanescentes Florestais da Mata Atlântica período 2017-2018. Available in: https://www.sosma.org.br/wp-content/uploads/2019/05/Atlas-mata-atlantica_17-18.pdf

Sosma, S.M.A., 2017. Relatório Anual de Atividades 2017. https://www.sosma.org.br/wp-content/uploads/2018/10/AF_RA_SOSMA_2017_web.pdf

Soto-Pinto, L., Anzueto, M., Mendoza, J., Ferrer, G.J., de Jong, B., 2009. Carbon sequestration through agroforestry in indigenous communities of Chiapas, Mexico. Agrofor. Syst. 78, 39–51. https://doi.org/10.1007/s10457-009-9247-5

Souza, H.N., Cardoso, I.M., Fernandes, J.M., Garcia, F.C.P., Bonfim, V.R., Santos, A.C., Carvalho, A.F., Mendonça, E.S., 2010. Selection of native trees for intercropping with coffee in the Atlantic Rainforest biome. Agrofor. Syst. 80, 1–16. https://doi.org/10.1007/s10457-010-9340-9

Souza, H.N., de Goede, R.G.M., Brussaard, L., Cardoso, I.M., Duarte, E.M.G., Fernandes, R.B.A., Gomes, L.C., Pulleman, M.M., 2012a. Protective shade, tree diversity and soil properties in coffee agroforestry systems in the Atlantic Rainforest biome. Agric. Ecosyst. Environ. 146, 179–196. https://doi.org/10.1016/j.agee.2011.11.007

Souza, H.N., de Graaff, J., Pulleman, M.M., 2012b. Strategies and economics of farming systems with coffee in the Atlantic Rainforest Biome. Agrofor. Syst. 84, 227–242. https://doi.org/10.1007/s10457-011-9452-x

Stathakis, D., Faraslis, I., 2014. Monitoring urban sprawl using simulated PROBA-V data. Int. J. Remote Sens. 35, 2731–2743.

Sun, X., Lu, Z., Li, F., Crittenden, J.C., 2018. Analyzing spatio-temporal changes and trade-offs to support the supply of multiple ecosystem services in Beijing, China. Ecol. Indic. 94, 117–129. https://doi.org/10.1016/j.ecolind.2018.06.049

Tallis, H., 2011. Natural capital: theory and practice of mapping ecosystem services. Oxford University Press.

Tamm, O., Maasikamäe, S., Padari, A., Tamm, T., 2018. Catena Modelling the effects of land use and climate change on the water resources in the eastern Baltic Sea region using the SWAT model. Catena 167, 78–89. https://doi.org/10.1016/j.catena.2018.04.029

Tapinos, E., 2012. Perceived environmental uncertainty in scenario planning. Futures 44, 338–345. https://doi.org/10.1016/j.futures.2011.11.002

Teixeira, H.M., Berg, L. Van Den, Cardoso, I.M., Vermue, A.J., Bianchi, F.J.J.A., Peña-claros, M., Tittonell, P., 2018a. Understanding Farm Diversity to Promote Agroecological Transitions. Sustainability 10, 4337. https://doi.org/10.3390/su10124337

Teixeira, H.M., Vermue, A.J., Cardoso, I.M., Peña Claros, M., Bianchi, F.J.J.A., 2018b. Farmers show complex and contrasting perceptions on ecosystem services and their management. Ecosyst. Serv. 33, 44–58. https://doi.org/10.1016/j.ecoser.2018.08.006

Termorshuizen, J.W., Opdam, P., 2009. Landscape services as a bridge between landscape ecology and sustainable development. Landsc. Ecol. 24, 1037–1052. https://doi.org/10.1007/s10980-008-9314-8

Tilman, D., Balzer, C., Hill, J., Befort, B.L., 2011. Global food demand and the sustainable intensification of agriculture. Proc. Natl. Acad. Sci. 108, 20260–20264. https://doi.org/10.1073/pnas.1116437108

Valencia, V., Wittman, H., Blesh, J., 2019. Structuring markets for resilient farming systems. Agron. Sustain. Dev. 39, 25. https://doi.org/10.1007/s13593-019-0572-4

Vallés-Planells, M., Galiana, F., Van Eetvelde, V., 2014. A classification of landscape services to support local landscape planning. Ecol. Soc. 19, 44.

Valujeva, K., O'Sullivan, L., Gutzler, C., Fealy, R., Schulte, R.P.O., 2016. The challenge of managing soil functions at multiple scales: An optimisation study of the synergistic and antagonistic trade-offs between soil functions in Ireland. Land Use Policy 58, 335–347. https://doi.org/10.1016/j.landusepol.2016.07.028

Van Belle, G., Hughes, J.P., 1984. Nonparametric tests for trend in water quality. Water Resour. Res. 20, 127–136.

Van der Sluis, T., Pedroli, B., Frederiksen, P., Kristensen, S.B.P., Busck, A.G., Pavlis, V., Cosor, G.L., 2018. The impact of European landscape transitions on the provision of landscape services: An explorative study using six cases of rural land change. Landsc. Ecol. 34, 307–323. https://doi.org/10.1007/s10980-018-0765-2

Van Der Wal, J., Shoo, L.P., Graham, C., Williams, S.E., 2009. Selecting pseudo-absence data for presence-only distribution modeling: How far should you stray from what you know? Ecol. Modell. 220, 589–594. https://doi.org/10.1016/j.ecolmodel.2008.11.010

Van Oijen, M., Dauzat, J., Harmand, J.M., Lawson, G., Vaast, P., 2010.Coffee agroforestry systems in Central America: II. Development of a simple process-based model and preliminary results. Agrofor. Syst. 80, 361–378. https://doi.org/10.1007/s10457-010-9291

Verburg, P.H., Alexander, P., Evans, T., Magliocca, N.R., Malek, Z., Rounsevell, M.D.A., van Vliet, J., 2019. Beyond land cover change: Towards a new generation of land use models. Curr. Opin. Environ. Sustain. 38, 77–85. https://doi.org/10.1016/j.cosust.2019.05.002

Verburg, P.H., Eickhout, B., van Meijl, H., 2008. A multi-scale, multi-model approach for analyzing the future dynamics of European land use. Ann. Reg. Sci. 42, 57–77. https://doi.org/10.1007/s00168-007-0136-4

Verburg, P.H., Overmars, K.P., 2009. Combining top-down and bottom-up dynamics in land use modeling: Exploring the future of abandoned farmlands in Europe with the Dyna-CLUE model. Landsc. Ecol. 24, 1167-1181.

Verburg, P.H., Schulp, C.J.E., Witte, N., Veldkamp, A., 2006. Downscaling of land use change scenarios to assess the dynamics of European landscapes. Agric. Ecosyst. Environ. 114, 39–56. https://doi.org/10.1016/j.agee.2005.11.024

Verburg, P.H., Soepboer, W., Veldkamp, A., Limpiada, R., Espaldon, V., Mastura, S.S.A., 2002. Modeling the spatial dynamics of regional land use: The CLUE-S model. Environ. Manage. 30, 391–405. https://doi.org/10.1007/s00267-002-2630-x

Vijay, V., Pimm, S.L., Jenkins, C.N., Smith, S.J., 2016. The impacts of oil palm on recent deforestation and biodiversity loss. PLoS One 11, e0159668

Waller, J.M., Bigger, M., Hillocks, R.J., 2007. Coffee pests, diseases and their management. Cab International, Oxfordshire.

Wang, H., Stephenson, S.R., Qu, S., 2019. Modeling spatially non-stationary land use/cover change in the lower Connecticut River Basin by combining geographically weighted logistic regression and the CA-Markov model. Int. J. Geogr. Inf. Sci. 33, 1313–1334.

https://doi.org/10.1080/13658816.2019.1591416

Wang, R., Kalin, L., Kuang, W., Tian, H., 2016. Individual and combined effects of land use / cover and climate change on Wolf Bay watershed stream flow in southern Alabama. Hydrol. Process. 28, 5530-5546. https://doi.org/10.1002/hyp.10057

Welp, M., de la Vega-Leinert, A., Stoll-Kleemann, S., Jaeger, C.C., 2006. Science-based stakeholder dialogues: Theories and tools. Glob. Environ. Change. 16, 170–181. https://doi.org/10.1016/j.gloenvcha.2005.12.002

Wesche, S.D., Armitage, D.R., 2014. Using qualitative scenarios to understand regional environmental change in the Canadian North. Reg. Environ. Chang. 14, 1095–1108. https://doi.org/10.1007/s10113-013-0537-0

West, P.C., Gibbs, H.K., Monfreda, C., Wagner, J., Barford, C.C., Carpenter, S.R., Foley, J.A., 2010. Trading carbon for food: Global comparison of carbon stocks vs. crop yields on agricultural land. Proc. Natl. Acad. Sci. 107, 19645–19648. https://doi.org/10.1073/pnas.1011078107

Wulf, T., Meissner, P., Stubner, S., 2010. A Scenario-based approach to strategic planning: tool description - scenario matrix. Working Paper 4/2010. HHL - Leipzig Graduate School of Management Center for Scenario Planning - Roland Berger Research Unit. Leipzig, Germany.

WWDR, 2018. The United Nations world water development report 2018: Nature-based solutions for water. UNESCO Paris.

Yi, H., Güneralp, B., Kreuter, U.P., Güneralp, İ., Filippi, A.M., 2018. Spatial and temporal changes in biodiversity and ecosystem services in the San Antonio River Basin, Texas, from 1984 to 2010. Sci. Total Environ. 619–620, 1259–1271. https://doi.org/10.1016/j.scitotenv.2017.10.302

Zhang, L., Nan, Z., Yu, W., Zhao, Y., Xu, Y., 2018. Comparison of baseline period choices for separating climate and land use/land cover change impacts on watershed hydrology using distributed hydrological models. Sci. Total Environ. 622–623, 1016–1028. https://doi.org/10.1016/j.scitotenv.2017.12.055

Zhang, M., Liu, N., Harper, R., Li, Q., Liu, K., Wei, X., Ning, D., Hou, Y., Liu, S., 2017. A global review on hydrological responses to forest change across multiple spatial scales: Importance of scale, climate, forest type and hydrological regime. J. Hydrol. 546, 44–59.

Zhang, Y., Guan, D., Jin, C., Wang, A., Wu, J., Yuan, F., 2014. Impacts of climate change and land use change on runoff of forest catchment in northeast China. Hydrol. Process. 28, 186–196. https://doi.org/10.1002/hyp.9564

Zhao, S., Peng, C., Jiang, H., Tian, D., Lei, X., Zhou, X., 2006. Land use change in Asia and the ecological consequences. Ecol. Res. 21, 890–896. https://doi.org/10.1007/s11284-006-0048-2

Zhu, X., Liu, W., Chen, J., Bruijnzeel, L.A., Mao, Z., Yang, X., Cardinael, R., Meng, F.R., Sidle, R.C., Seitz, S., Nair, V.D., Nanko, K., Zou, X., Chen, C., Jiang, X.J., 2019. Reductions in water, soil and nutrient losses and pesticide pollution in agroforestry practices: A review of evidence and processes. Plant Soil, 1–42. https://doi.org/10.1007/s11104-019-04377-3

Summary

In light of the projected climate change for the coming decades, there is an urgent need for multifunctional landscapes that are capable to provide a diversity of ecosystem services. This requires a better understanding of social and ecological factors that influence how these landscapes are managed and how this, in turn, influences the provision of ecosystem services. Land Use Land Cover (LULC) changes are one of the main factors that lead to spatio-temporal changes of ecosystems services. As such, the identification of the main socioeconomic drivers of LULC can give important insights about the drivers of ecosystem services. However, the analysis of ecosystem services in a context of socio-ecological systems is still underdeveloped. Brazil has witnessed intense changes in LULC in the last five centuries, which may have influenced the provision of ecosystem services at local, regional and global scales. In the southeast mountain area of the Atlantic Forest biome, the Zona da Mata de Minas Gerais is characterized by a heterogeneous landscape mosaic composed of pasture and coffee fields intermingled with forest fragments, which are predominantly inhabited and managed by family farmers. The Zona da Mata is considered a complex socio-ecological system and is an interesting case to study the spatio-temporal provision of ecosystem services. In Chapter 2, I assessed the LULC changes from 1986 to 2015 and their main socioeconomic drivers. By combining data obtained from satellite images, workshops and secondary data, I showed that forest and coffee areas increased, and pasture decreased. These changes were associated with government measures to protect the environment, financial support of family farmers, migration to cities and the agroecological movement. A scenarios analysis of contrasting socio-economic narratives indicated that sustainable measures taken by the government to protect the environment and support family farmers with financial credit will lead to increase forest and coffee areas in the Green Road scenario. In contrast, the socioeconomic development in the Fossil Fuel scenario, which projects a decline in environmental protection and focuses on rapid economic development, there will be a decline in forest areas. In Chapter 3, I explored the spatial variation of ecosystem services from 1986 to 2015 and the impacts of LULC changes on ecosystem services provision levels and their interactions. To map the spatio-variation of ecosystem services, I used the LULC maps from 1986 and 2015 (Chapter 2) and the InVEST model. This analysis indicated that the conversion of forest to pasture has strong negative impacts on soil erosion control and water flow regulation, manifesting mostly as trade-offs and dis-synergies between ecosystem services. In Chapter 4, I investigated the separate effects of LULC changes and climate on water dynamics from 1990 to 2015, and explored scenarios of LULC change and climate change for 2045. For this purpose, I used the SWAT model and climate data combined with historical and future LULC maps developed in Chapter 2. I found that the variation in climate variables was the main factor for the observed increase in the river streamflow in the study period and that forest can buffer extreme precipitation events. The exploration of future scenarios indicated that the increase in forest cover under the Green Road scenario is expected to decrease the surface runoff water and increase evapotranspiration as compared to the Fossil Fuel scenario, mitigating the impacts of soil erosion and climatic extremes in the region. Projected changes in precipitation and temperature are expected to have negative impacts for agriculture in the future. In Chapter 5,

I assessed the impact of climate change on the suitability of *Coffea arabica* production in the study region and the potential of agroforestry systems to mitigate these impacts. For this, I combined the species distribution model MaxEnt with current and future climate projections. Agroforestry system have the potential to reduce air temperatures under the canopy of trees. I explored the effect of the altered the microclimate in agroforestry systems on the suitability for coffee production by adjusting future climate data to reflect conditions in agroforestry systems. I found that the area suitability for coffee production from the current monoculture coffee systems will decline by 60% under the projected climatic changes. However, the implementation of coffee agroforestry systems can mitigate these negative impacts of climatic change and maintain 75% of the area suitable for coffee production in 2050. Combining social and ecological systems in an interdisciplinary framework, generated insights in the relationships between climate and LULC change, and how this influences several ecosystem services. This framework connects different research fields and allows different stakeholders to work together to find effective ways to work towards multifunctional landscapes that promote the sustainable use of ecosystem services.

Sumário

Diante das mudanças climáticas projetadas para as próximas décadas, há uma necessidade urgente de paisagens multifuncionais capazes de fornecer diversos serviços ecossistêmicos, que são os benefícios da natureza como água e alimentos. Isso requer melhor compreensão dos fatores sociais e ecológicos que influenciam o manejo destas paisagens e, por sua vez, influenciam a prestação de serviços ecossistêmicos. As mudanças na cobertura do uso da terra são um dos principais fatores influenciam a provisão serviços dos ecossistemas no tempo e espaço. Dessa forma, a identificação dos principais fatores socioeconômicos responsáveis pelas mudanças no uso da terra pode fornecer importantes informações sobre os fatores que impulsionam os serviços ecossistêmicos. No entanto, a análise dos serviços ecossistêmicos em um contexto de sistemas socioecológicos ainda está incipiente. O Brasil testemunhou intensas mudanças no uso da terra nos últimos cinco séculos, o que pode ter influenciado a prestação de serviços ecossistêmicos nas escalas local, regional e global. Localizada na região montanhosa do sudeste da Mata Atlântica, a Zona da Mata de Minas Gerais é caracterizada por um mosaico heterogêneo de paisagens composto por fragmentos florestais, pastagens e cafezais, predominantemente manejados por agricultores familiares. A Zona da Mata é considerada um sistema socioecológico complexo e por isso é um caso interessante para estudar a provisão espaço-temporal de serviços ecossistêmicos. No capítulo 2, mapeei as modificações no uso da terra de 1986 a 2015 e os principais fatores socioeconômicos associados. Combinando dados obtidos a partir de imagens de satélite, workshops e dados da literatura, mostrei que as áreas de floresta e

café aumentaram e as pastagens diminuíram no período estudado. Essas mudanças foram associadas a medidas governamentais de proteção ao meio ambiente, apoio financeiro a agricultores familiares, migração para cidades e ao movimento agroecológico na região. A análise de diferentes cenários socioeconômicos indicou que medidas sustentáveis tomadas pelo governo para proteger o meio ambiente e apoiar os agricultores familiares com crédito financeiro levarão ao aumento das áreas florestais e de café no cenário Caminho Verde (Green Road) para 2045. Por outro lado, o desenvolvimento socioeconômico no cenário Combustíveis Fósseis (Fossil Fuel), que projeta um declínio na proteção ambiental e é caracterizado pelo rápido desenvolvimento econômico, haverá um declínio nas áreas florestais. No capítulo 3, explorei a variação espacial dos serviços ecossistêmicos de 1986 a 2015 e os impactos das mudanças no uso da terra nos níveis de prestação de serviços ecossistêmicos e suas interações. Para mapear a variação espacial dos serviços ecossistêmicos, usei os mapas de uso da terra de 1986 e 2015 (capítulo 2) e o modelo InVEST. Essa análise indicou que a conversão de floresta em pastagem tem fortes impactos negativos no controle da erosão do solo e na regulação do fluxo de água, manifestando-se principalmente como trade-offs e de-sinergias entre os serviços do ecossistema. No capítulo 4, investiguei os efeitos separados das mudanças de uso da terra e do clima na dinâmica da água de 1990 a 2015 e explorei cenários de mudanças de uso da terra e mudanças climáticas para 2045. Para esse propósito, usei o modelo SWAT e dados climáticos combinados com dados históricos e futuros mapas LULC desenvolvidos no Capítulo 2. Identifiquei que a variações climáticas foram o principal fator para o aumento observado no fluxo do rio no período do estudo e que a floresta pode amortecer eventos extremos de precipitação.

A exploração de cenários futuros indicou que o aumento da cobertura florestal no cenário Caminho Verde deverá diminuir a água do escoamento superficial e aumentar a evapotranspiração em comparação com o cenário Combustível Fóssil, mitigando os impactos da erosão do solo e extremos climáticos na região. Em todo o mundo, projeções de mudanças na precipitação e na temperatura podem causar impactos negativos para a agricultura no futuro. No capítulo 5, avaliei o impacto das mudanças climáticas nas áreas aptas para produção de *Coffea arabica* nas regiões Matas de Minas e Montanhas do Sudeste e o potencial dos sistemas agroflorestais para mitigar esses impactos. Para isso, utilizei o modelo de distribuição de espécies MaxEnt e as projeções climáticas atuais e futuras. O sistema agroflorestal tem o potencial de reduzir a temperatura do ar sob o dossel das árvores. Eu explorei este efeito dos sistemas agroflorestais no microclima, ajustando dados climáticos futuros para refletir as condições caso os sistemas agroflorestais fossem adotados no futuro. Os resultados indicaram que diante das projeções climáticas, a área apta para produção de café nos atuais sistemas de monocultura será de apenas 40% da área total atual em 2050. No entanto, a implementação de sistemas agroflorestais de café pode mitigar esses impactos negativos das mudanças climáticas e manter 75% da área adequada para a produção de café em 2050. A combinação de sistemas sociais e ecológicos em uma estrutura interdisciplinar gerou importantes informações sobre as relações entre a sociedade, mudanças no uso da terra e clima e como isso influencia vários serviços ecossistêmicos. Essa estrutura conecta diferentes áreas de pesquisa e permite que diferentes partes interessadas trabalhem juntas para manejar paisagens multifuncionais que promovam o uso sustentável dos serviços ecossistêmicos.

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About the author

Lucas de Carvalho Gomes was born on 15 August 1987 in Lajinha on a family farm, located in the Zona da Mata region, Minas Gerais state, Brazil. After completing the high school education in Lajinha he enrolled at the Agronomy program of the Universidade Federal de Viçosa in 2006. From the first year in university he was involved in scientific research focussing on the benefits of agroforestry systems for soil quality.

In 2010, with one semester to complete the BSc, Lucas decided to go to Denmark in an internship program. He worked as trainee on the farm of Jesper Jensen in Odense. In this period, he met his future wife Olesia. Lucas returned to Brazil in 2012 to finish the BSc degree and after that he continued with a two years Soil Plant Nutrition MSc program. In 2014, Lucas finished the MSc and decided to go back to Denmark again. He married Olesia and started to work in the same farm in Odense.

In the middle of 2015, they moved back to Brazil and in 2016 Lucas started the PhD at the Universidade Federal de Viçosa. In the same week that he started the PhD, his daughter Sofia was born. The PhD was part of a double degree program between the Universidade Federal de Viçosa and Wageningen University within the framework of the FOREFRONT program. Lucas had the opportunity to spend 10 months in Wageningen between 2018 and 2019.

Publications

Peer reviewed journal articles

Gomes, L.C., Bianchi, F.J.J.A., Cardoso, I.M., Schulte R.P.O., Arts, B.J.M., Fernandes Filho, E.I, 2020. Land use and land cover scenarios: an interdisciplinary approach integrating local conditions and the global shared socioeconomic pathways. *Accepted for publication in Land Use Policy*, https://doi.org/10.1016/j.landusepol.2020.104723

Gomes, L.C., Bianchi, F.J.J.A., Cardoso, I.M., Fernandes, R.B.A., Fernandes Filho, E.I, Schulte R.P.O., 2020. Agroforestry systems can mitigate the impacts of climate change on coffee production: a spatially explicit assessment in Brazil. Agric. Ecosyst. Environ. 294, 106858. https://doi.org/10.1016/j.agee.2020.106858

Gomes, L.C., Faria, R.M., de Souza, E., Veloso, G.V., Schaefer, C.E.G.R., Filho, E.I.F., 2019. Modelling and mapping soil organic carbon stocks in Brazil. Geoderma 340, 337–350. https://doi.org/10.1016/j.geoderma.2019.01.007

Lopes, V.S., Cardoso, I.M., Fernandes, O.R., Fernandes, R.B.A., Cecon, P.R., **Gomes, L.C.,** Luz, J.M.R., 2019. Terraced Pasture Changes the Soil Moisture Dynamics. J. Agric. Sci. 11, 96–107. https://doi.org/10.5539/jas.v11n14p96

Gomes, L.C., Cardoso, I.M., Mendonça, E.S., Fernandes, R.B.A., Lopes, V.S., Oliveira, T.S., 2016. Trees modify the dynamics of soil CO2 efflux in coffee agroforestry systems. Agric. For. Meteorol. 224, 30–39. https://doi.org/10.1016/j.agrformet.2016.05.001

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Atlantic Rainforest biome. Agric. Ecosyst. Environ. 146, 179-196. https://doi.org/10.1016/j.agee.2011.11.007

Submitted

Gomes, L.C., Bianchi, F.J.J.A., Cardoso, I.M., Fernandes Filho, E.I., Schulte R.P.O., Land use change drives the spatio-temporal variation of ecosystem services and their interactions along an altitudinal gradient in Brazil. Landscape Ecology, *revised version submitted*.

Gomes, L.C., Bianchi, F.J.J.A., Cardoso, I.M., Fernandes Filho, E.I., Schulte R.P.O., Disentangling the historic and future impacts of land use changes and climate variability on the hydrology of a Brazilian watershed.

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (4.5 ECTS)

- A review on the effects of Land use change to the provision of ecosystem services (2017)

Writing of Project proposal (4.5 ECTS)

- Land use change and ecosystem services across time: learning from the past and projecting sustainable future

Post-graduate courses (13.8 ECTS)

- Land use in the tropics; Universidade Federal de Viçosa, Brazil - UFV (2016)
- Soil fertility; UFV, Brazil (2016)
- Geoprocessing applied to pedology; UFV, Brazil (2016)
- Pedogeomorphology; UFV, Brazil (2016)
- Social development and agroecological transitions; UFV, Brazil (2016)
- Application of R programing in soil science UFV, Brazil (2016)
- Hands-on Digital soil mapping; SRIC, Wageningen, the Netherlands (2019)

Invited review of (unpublished) journal manuscript (1 ECTS)

- Climate Change: coffee production under high levels of CO_2 (2018)

Competence strengthening / skills courses (2.3 ECTS)

- Writing scientific papers; UFV, Brazil (2016)
- Scientific writing; WGS, Wageningen, the Netherlands (2018)

Scientific integrity / ethics in science activity (0.3 ECTS)

- Ethics in plant and environmental sciences; WGS, Wageningen, the Netherlands (2019)

PE&RC Annual meetings, seminars and the PE&RC weekend (0.9 ECTS)

- PE&RC Last year weekend (2019)
- Plant-soil feedback: linkages between root traits and soil biota (2019)

Discussion groups / local seminars / other scientific meetings (5.3 ECTS)

- Soil Department seminars; UFV, Brazil (2016)
- International workshop of the FOREFRONT program; Zona da Mata region, Minas Gerais state, Brazil (2017)
- International workshop of the FOREFRONT program; Morelia, Mexico (2018)
-

International symposia, workshops and conferences (3.5 ECTS)

- 8th IOBC-WPRS Landscape management for functional biodiversity; oral presentation; Wageningen, the Netherlands (2015)
- Netherlands Annual Ecology meeting; poster presentation; the Netherlands (2019)

Lecturing / supervision of practicals / tutorials (17.4 ECTS)

Gênese do Solo (soil genesis); Soil Department, UFV, Brazil (2017-2018)

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