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SPATIOTEMPORAL INTERVAL LOGIC FOR REASONING ABOUT LAND USE CHANGE DYNAMICS

Adeline Marinho Maciel

Doctorate Thesis of the Graduate Course in Applied Computing, guided by Drs. Lúbia Vinhas, and Gilberto Câmara, approved in december 12, 2017.

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São José dos Campos, 12 de dezembro de 2017

"Apparently the value of the raw iron is only what it costs to process it from the hill. Its greater value is determined by what is made of it. People are much the same as iron. You or I can remain nothing more than raw material, or we can be polished to a high degree. Our value is determined by what we make of ourselves".

Spencer W. Kimball
in *"On Cheating Yourself"*, *New Era*, Apr. 1972, 32

My parents ***Simões*** *and* ***Silvana***

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ABSTRACT

With the global population growth, the food production will need to rise, potentially causing extensive environmental damage. In Brazil, the demand for farmland is the key immediate driver of land use change, which has influence in public policies. For example, the soy and beef moratorium, that aim at reducing the advance of soybean cropping and pasture areas expansion over the Amazon biome. Currently, Earth observation satellites form part of a comprehensive Earth observation system due to their higher spatial, temporal and spectral resolutions, providing continuous and consistent information about Earth's surface. It is the era of *big Earth observation data*. It has been creating new perspectives in remote sensing data analysis that enable the development of land use and land cover maps at higher spatial resolution and with high temporal frequency. Given this scenery, this thesis introduces a spatiotemporal interval logic mechanism that can be used for reasoning about land use change dynamics, from big Earth observation data systems. The main contribution of this mechanism is to use the concept of events to reason about land use change. Building on this view this thesis extends Allen's interval temporal logic to the spatial context, resulting in a formal calculus that allows users to express queries about the land use dynamics. The calculus allows scientists to manipulate large sets of land use data in a flexible way, to understand the environmental and economic effects of land use change. The formalism was applied in three cases studies to identify and quantifying land use transitions in Mato Grosso state in Brazil.

Keywords: Events. Spatiotemporal. Logic formalism. Big Earth observation data. Land use change.

LÓGICA DE INTERVALO ESPAÇO-TEMPORAL PARA RACIOCINAR SOBRE DINÂMICA DE MUDANÇA DE USO DA TERRA

RESUMO

Com o crescimento da população mundial, a produção de alimentos precisará aumentar potencialmente causando grandes danos ambientais. No Brasil, a demanda por terras agrícolas é o principal condutor imediato da mudança de uso da terra, que influência políticas públicas. Por exemplo, a moratória da soja e da carne que visam reduzir o avanço da expansão de áreas de cultivo de soja e pastagem sobre o bioma Amazônia. Atualmente, satélites de observação da Terra fazem parte de um sistema abrangente de observação da Terra devido às suas maiores resoluções espaciais, temporais e espectrais, fornecendo informações contínuas e consistentes sobre a superfície terrestre. É a era dos grandes conjuntos de dados de observação da Terra. Isso tem criado novas perspectivas na análise de dados de sensoriamento remoto que permitem o desenvolvimento de mapas de uso e cobertura da terra com maior resolução espacial e com alta frequência temporal. Dado este cenário, esta tese introduz um mecanismo de lógica de intervalo espaço-temporal que pode ser usado para raciocinar sobre as dinâmicas de mudança de uso da terra, a partir de sistemas de grandes conjuntos de dados de observação da Terra. A principal contribuição deste mecanismo é usar o conceito de eventos para raciocinar sobre mudança de uso da terra. Com base nesta perspectiva, essa tese estende a lógica temporal de intervalos de Allen para o contexto espacial, resultando em um cálculo formal que permite usuários expressar consultas sobre a dinâmica de uso da terra. O cálculo permite aos cientistas manipular grandes conjuntos de dados de uso da terra de uma maneira flexível para entender os efeitos ambientais e econômicos da mudança de uso da terra. O formalismo foi aplicado em três estudos de casos para identificar e quantificar transições de uso da terra no estado de Mato Grosso, Brasil.

Palavras-chave: Eventos. Espaço-temporal. Formalismo lógico. Grandes conjuntos de dados de observação da Terra. Mudança de uso da terra.

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LIST OF ABBREVIATIONS

AI	–	Artificial Intelligence
CAGR	–	Compounded Annual Growth Rate
CRF	–	Cumulative Relative Frequency
DBMS	–	Database Management Systems
DC	–	Double Cropping
EVI	–	Enhanced Vegetation Index
EXP	–	Experiential perspective
F	–	Forest
FC	–	Forest Code
GIS	–	Geographic Information Systems
GR	–	Growth Rate
HIST	–	Historical perspective
IDE	–	Integrated Development Environment
INPE	–	National Institute for Space Research
LUC Calculus	–	Land Use Change Calculus
MODIS	–	Moderate Resolution Imaging Spectroradiometer
NDVI	–	Normalized Difference Vegetation Index
NIR	–	Near-infrared Reflectance
P	–	Pasture
PRODES	–	Program for the Estimation of Deforestation in the Brazilian Amazon
RF	–	Relative Frequency
SC	–	Single Cropping
SV	–	Secondary Vegetation
TWDTW	–	Time-Weighted Dynamic Time Warping
WTSS	–	Web Time Series Service

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1 INTRODUCTION

Humanity is changing rural and urban landscapes at an unprecedented pace. Global population will increase to around 8.5 billion by mid-century, driving crop and livestock demand and production. The growing demand for natural resources has caused major environmental impacts. From 1980 to 2000, 55% of the new agricultural land in the tropics came from intact forests, and another 28% came from disturbed forests (GIBBS et al., 2010). Assessing the impacts of global land use change is a challenge for researchers and developers of geospatial information technology.

Land use change is associated with biophysical changes as well as societal factors arising from different levels of the coupled human environmental system, observable at different scales. Brazil, more than any other country in the world faces the challenge of balancing agricultural production and environmental protection (GIL et al., 2015). Historically, forest conversion has begun with small-scale exploration, as subsistence agriculture, followed by consolidation within large-scale cattle ranching operations or abandonment to secondary forest. But, in the last decade, the expansion of large-scale mechanised agriculture at the forest frontier has introduced as a potential new pathway for loss of forest (MORTON et al., 2006). This has generated a debate over the impact of cropland expansion to deforestation and, consequently, on the economy (ARVOR et al., 2013). This work contributes to the scientific debate on the subject, as we propose methods for improving information in land use change.

Given a land use system, the term *transition* refers to changes from one stage to another, for example, when a forest is converted to cropland. *Trajectories* refers to a sequence of transitions observed in a given spatial unit of analysis (e.g. pixels or cells of is a partition). As transitions do not follow a fixed pattern a large variability of trajectories can appear when monitoring large areas (LAMBIN et al., 2003). To observe and monitoring land change the temporal component is also important. Chini et al. (2012) defines land use transitions as annual changes between land use states, where land use states are the fractions of each grid-cell occupied by different land uses in a given year. According to Zhou et al. (2008), the term *trajectory* refers to successions of land cover types, for example, forest, cropland, water, for a given sample unit over more than two observations (periods). For instance, land use change of *forest→pasture→cropland* on a pixel over three observations can be specified as trajectory, meaning that the land was found to be forest, pasture and cropland over the study period. This work takes Zhou et al. (2008)'s definition as a conceptual basis for developing a formalism for reasoning about land use trajectories.

1.1 The Challenges of Big Earth Observation Data

Remote sensing satellites provide consistent information about the Earth's land and oceans, since their sensors observe the same area many times, producing a continuous stream of data at local, regional, national or global level. The use of remote sensing satellite data is fundamental to monitor land use change in Brazil. For example, the Program for the Estimation of Deforestation in the Brazilian Amazon (PRODES) project, conducted by the National Institute for Space Research (INPE), has used Landsat images to map deforestation since 1988 to calculate the deforestation rate, wall to wall, for the Brazilian Legal Amazon forest, as well as yearly maps of clear cut areas in the Amazon biome (INPE, 2017).

For decades, access to most remote sensing images was restricted or available at a price. Since the mid 2000s, a big improvement has taken place: public space agencies have been providing open access to their archives. This is a legacy of times past when data was hard to get. Despite this unprecedented availability of data, most studies still take a snapshot approach to detect change. In this approach, researchers classify individual images and later compare them; the actual trajectories of change are not described (SKOLE; TUCKER, 1993; YANG; LO, 2002; ZHANG et al., 2002; MORTON et al., 2005; ABD EL-KAWY et al., 2011; RAWAT; KUMAR, 2015).

In this era of free data, in several domains, data repositories double its size every three years (GUO et al., 2017). In the twenty-first century the rapid advancement of computer networks and computation power has enabled the appearance of *big* data repositories with no spatial or temporal restrictions. The first Earth observation satellite was launched half a century ago, and currently there are more than 60 missions being flown specifically for multi-purpose land imaging, and at least 55 approved to be launched from 2018 on (CEOS, 2017). This satellites have higher spatial and spectral resolutions, storage capacity and have a global capacity of monitoring forming a comprehensive Earth observation system (GUO et al., 2017). Having now access to big Earth observation data sets the next goal for researchers in order to improve the understanding of how the planet is changing is to have access to new big data analytic for Earth observation (CÂMARA et al., 2016), as has been happening in application domains such as healthcare, entertainment, e-commerce and business (CHEN et al., 2014).

Long-term satellite image time series data are now available in global scale. Computing infrastructures can be built to manage this big data and make them available for use in an unprecedented way, leading to a new perspective in remote sensing data analysis. New technologies for Database Management Systems (DBMS) are most appropriate to deal with big Earth observation data. Recently, multidimensional array databases, such as SciDB, have been used as an efficient alternative to the relational and object-relational model (BROWN, 2010; STONEBRAKER et al., 2013). Since arrays are a natural data structure to store big Earth observations data researches can break the 'image as a snapshot' paradigm for remote sensing data applications.

An example of big Earth observation data analysis is the work by Hansen et al. (2013). Using more than 650,000 Landsat data at a 30 meter spatial resolution, the researchers compared data from 2000 to 2012 to produce annual global forest change maps using the computing power of the Google Earth Engine (GORELICK et al., 2017). The results documented a decade of global forest gains and losses over the entire global between the years 2000 and 2012.

Câmara et al. (2016) argued that using satellite image time series analysis researchers can better explore the high temporal data resolution to capture the most important and subtle land use changes, since the temporal autocorrelation of the data can be stronger than its spatial autocorrelation. Given data with adequate repeatability, a pixel will be more related to its temporal neighbours than to its spatial ones. In this case, *time-first, space-later* methods lead to better results than the *space-first, time-later* approach, as verified in the work by Maus et al. (2016). In this context, our work explores how logical formalisms can be used together with satellite image time series analysis.

1.2 Our Proposal

This thesis aims to contribute with spatiotemporal modelling, analysis tools and techniques to represent land use changes. This work explores the question: *How best to describe and reason about land use change using analysis on big Earth observation data sets?* Its core is an extension and improvement of Allen (1984)'s formalism to build a general calculus to reason about land use change events, so that one can model and capture changes and also reason about land use change trajectories. Including events as primitives in geospatial information systems increases their expressive power because they can represent both when change happens and which objects are affected by such changes.

The first contribution of the thesis is to formally model land use big Earth observation data as a set of events of change. Than it tackles the issue of *how to use concept of events to reasoning about land use change*. The hypothesis is that it is possible to reason about change events using a set of remote sensing images classified using data mining methods that process long-term time series data, and to develop a formalism to reasoning about it. For example, consider an area that was a studied during a period of seven years; during the first two years the area was covered by a pristine forest, with no signs of human interference. Then, this area was clear cut and used as pasture for cattle raising during two years. Finally, the same area use changed again to agriculture production for three years. The formalism should be able to express interesting questions about the land use change trajectory of this area during the time of monitoring.

The formalism is independent of programming language, it can be translated and implemented in different programming languages. In this work the formalism was implemented using the **R** programming language.

1.3 Document Structure

The content of this thesis comes from three papers (see Annex A and B for a copy of the published articles):

1) CAMARA, G.; MACIEL, A.; MAUS, V.; VINHAS, L.; SANCHEZ, A. *Using dynamic geospatial ontologies to support information extraction from big Earth observation data sets*. In: International Conference on GIScience Short Paper Proceedings. Montreal, CA, 2016. p. 41-44.

2) MACIEL, A. M.; VINHAS, L.; CAMARA, G.; MAUS, V. W.; ASSIS, L. F. F. G. *STILF - A spatiotemporal interval logic formalism for reasoning about events in remote sensing data*. In: BRAZILIAN SYMPOSIUM ON REMOTE SENSING, 18. (SBSR). Proceedings... São José dos Campos: National Institute for Space Research (INPE), 2017. p. 4558–4565.

3) MACIEL, A. M.; CAMARA, G.; VINHAS, L.; PICOLI, M. C. A.; BEGOTTI, R. A.; ASSIS, L. F. F. G. *An event calculus for reasoning about land use change using big Earth observation data sets*. (Submitted for review in July 2017 to the journal "International Journal of Geographical Information Science").

Chapter 2 provides an overview of the conceptual basis of the proposed formalism to reason about land use event. The approach draws from conceptions of events and processes in Philosophy of Language, Artificial Intelligence and GIScience. It considers the specific issue of defining land use events in big Earth observation data. This chapter also provides a review of the relevant literature pointing out the concepts that have been relevant to our proposal.

Chapter 3 describes the formalism to reasoning about land use changes from remote sensing data products. To describe land use changes, we take an approach based on a formalism built on time intervals. This work extends and improves the interval temporal logic from Allen (1984) to build a calculus for reasoning about land use change events, and also introduce a spatial version of the Allen's predicate to include locations.

Chapter 4 presents some use cases in which the formalist has been applied. We discus how the experiments were conducted and how the results can help experts to understand the main land use transitions occurred in the study areas. Chapter 5 presents the final discussions and future work.

2 DISTINCT PERSPECTIVES ON THE CONCEPT THAT DESCRIBE CHANGE

This thesis deals with a spatiotemporal logic capable of expressing the dynamics of land use change. Before presenting the proposed logic, it is useful to consider the concepts involving dynamics and action have been dealt with in the literature. This chapter presents some views on concepts involved in describing change, such as *events, states, actions.* We draw on references from Philosophy of Language, discussing concepts proposed by philosophers and linguists about verbs that express change. We also consider concepts about events in Artificial Intelligence and GIScience. Finally, we discuss how these ideas can be used in the domain of big Earth observation data reasoning.

2.1 Philosophy of Language

Philosophical work on dynamics of change dates back to Aristotle, who classifies verbs based on the kind of actions they describe (COHEN, 2016). Aristotle distinguishes cases where actions happens from those where a potential for action exists. Verbs such as 'build' and 'walk' describe performances where actual change happens, as in "Fred built a cottage". He uses the term *kinêsis* for such cases and contrasts them with verbs that express potential for producing change, which he calls *energeia*. Verbs such as 'want' and 'desire' describe situations with *energeia* as in "Fred wants to build a new house". Vendler (1957) expands Aristotle's idea to present a four-way classification for actions in natural language. His proposal has been influential in GIScience (WORBOYS, 2005; GALTON, 2008) and has been useful to clarify our design choices. Vendler considers four kinds of action, described below:

(A) *Activities* describe homogeneous eventualities[1]. Its sub-parts satisfy the same description as the activity itself; they have no natural finishing point or end result (CASATI; VARZI, 2015). Examples are 'run', 'walk', and 'swim', as in "Max walked for an hour".

(B) *Accomplishments* are eventualities that happen during a temporal interval; they have a logical endpoint and an end result. They may not be homogeneous. Examples are 'grow up', 'build', and 'climb' (a mountain) as in "Max built five houses in two months".

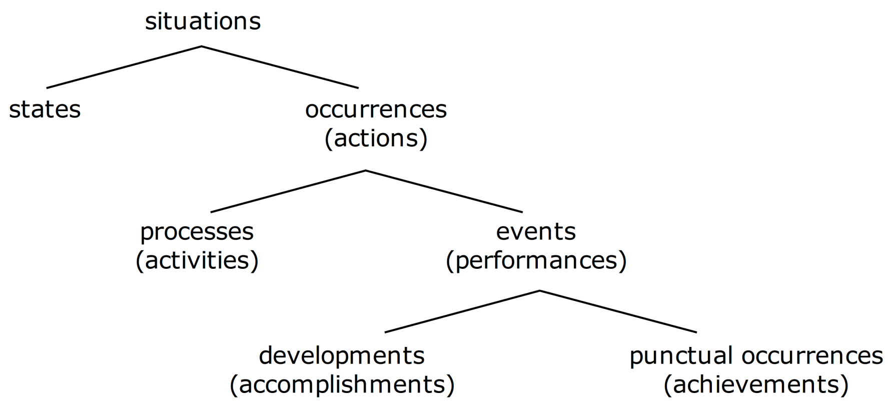
[1]Following Galton (2008), we use the term 'eventuality' to include both static and dynamic descriptions of actual and potential actions.

(C) *Achievements* are events which are considered instantaneous from the point of the view of the conversation being held. They occur at a single moment. Examples are 'win' (the race), 'find' (the treasure), 'reach' (the top), as in "Max found an old photograph".

(D) *States* are situations that do not involve immediate change and are not associated to an end result. They hold for some unspecified period of time. Examples are 'desire', 'want', 'love', 'know', as in "Max knows the answer".

Vendler's typology was extended by Mourelatos (1978) to distinguish between *states*, *processes*, and *events*. For Mourelatos, states are non-dynamic eventualities, while occurrences describe change. He divides occurrences in processes (activities in Vendler) that have no end point, and events with both a start and an end. Events thus imply completeness; they are further divided in *developments* (accomplishments in Vendler), if they occur over an interval, and *punctual occurrences* (achievements in Vendler), which happen instantaneously (Figure 2.1). We present examples of Mourelatos' classification below.

Figure 2.1 - A hierarchical classification of events.



SOURCE: Adapted from Mourelatos (1978).

(A) *State*: "The air smells of jasmine"

(B) *Process*: "It's snowing"

(C) *Development*: "The sun went down"

(D) *Punctual occurrence*: "The pebble hit the water"

When working with spatiotemporal data, Mourelatos's typology allows distinguishing between achievements (instantaneous events) such as "the fire engine entered the danger zone" from accomplishments (occurrences with known duration) such as "the area was used for crop production from 2008 until 2010". This distinction is relevant to our proposal. Land use change events are better represented as *accomplishments*, to which one can assign start and end points. Land use change events do not involve direct interaction between agents, which happens in location-based applications. Humans change the environment in stages. They first cut the forest; then, after clearing the land, they might use the land for agriculture. This view considers land use change as a sequence of occurrences with known duration. Therefore, a formalism for land use calculus needs to enable reasoning with accomplishments.

2.2 Event Reasoning in Artificial Intelligence

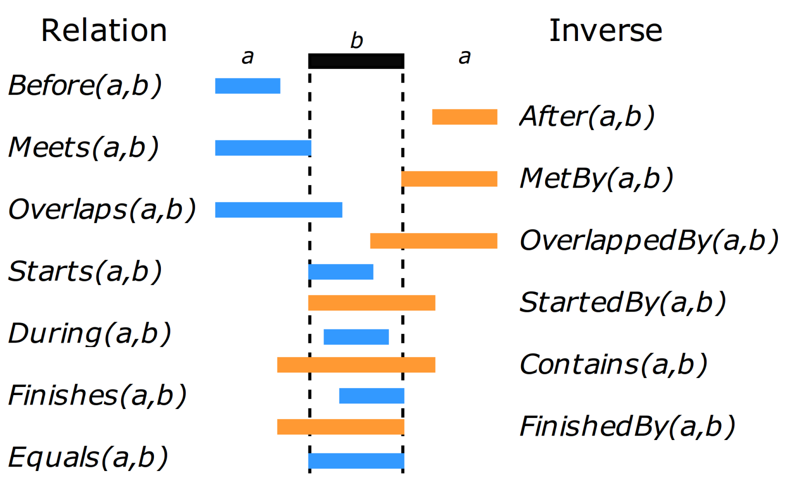
Artificial Intelligence (AI) researchers were the first Computer scientists to develop formalisms for temporal representation and reasoning about change. Regarding the reasoning about events, there are works which study different temporal, time and fuzzy representations and how they deal with events and imprecise, or uncertain, information over time (ALLEN, 1991; ALLEN; FERGUSON, 1994; DUBOIS et al., 2003). In our work, we are interested in logic formalisms. In this case, two of the more relevant proposals are the the Event Calculus (KOWALSKI; SERGOT, 1986) and the Interval Temporal Logic (ALLEN, 1983), discussed below.

As an alternative to logic-based reasoning, Worboys (2005) examines Process Calculus for expressing knowledge about location-based events. Worboys considers that process calculus is adequate for situations involving *concurrency* and *interaction*, which are typical of location-based problems. The reader should refer to Worboys (2005) for more details on Process Calculus applied to geospatial events.

The Event Calculus was introduced by Kowalski and Sergot (1986) and then extended by Shanahan (1999) for modelling and reasoning about narratives. Reasoning starts with generic rules ('an university career starts at the post of lecturer and moves to the status of professor'). Events, taken as punctual occurrences, add new information to the knowledge base. Suppose one gets new information: "Andrew was hired as a lecturer on 10 May 1979" and "Andrew was promoted from lecturer to professor on 1 June 1985". These events enable the knowledge base to deduce the information "Andrew was a lecturer from 10 May 1979 until 1 June 1985". To work in geospatial applications, the Event Calculus would need to be augmented with spatial predicates. Such augmented Event Calculus would be useful for GIScience problems where a knowledge base is enriched with information about occurrences in space-time. Consider real-time emergency situations. The knowledge base would have information on hospitals in a city, their specialities and their capacity. Given an accident, an emergency rescue team would update the knowledge base and get adequate information on the best route for response.

The Interval Temporal Logic was introduced by Allen (1983). The formalism consists of propositions about properties of the world and their temporal relations, shown in Figure 2.2. Propositions are assumed to be valid over a time interval. In Vendler's terminology, the Interval Temporal Logic works with *accomplishments*. Two such propositions are "Max was here last March" and "Fred visited us in April". One valid statement would be "Max visited us before Fred did". While the Event Calculus deals with an instantaneous actions, propositions in Interval Temporal Logic are expressed over intervals. Allen (1983) defines thirteen mutually exclusive primitive relations between temporal intervals. Each relation is a predicate over intervals: *before*, *meets*, *during*, *starts*, *finishes*, *overlap*, their inverses, and *equal*. Allen's relations work best with spatiotemporal data when events to be represented are *accomplishments*, to which one can assign start and end points. This is the case of land use change applications, as in "this was an area of native forest from 2001 until 2005". Therefore, the Interval Temporal Logic fits the needs of describing relationships between land use events.

Figure 2.2 - Allen's 13 temporal relations.



SOURCE: Adapted from Allen (1983).

2.3 Events on GIScience

There is a large body of GIScience literature on spatiotemporal data modelling and reasoning (PEUQUET; DUAN, 1995; CLARAMUNT; THERIAULT, 1996; HORNSBY; EGENHOFER, 2000; KUHN, 2001; BENNETT et al., 2002; GALTON, 2004; GOODCHILD et al., 2007). A leading research direction proposes to use the concepts of *events* and *processes* for representing change (YUAN, 2001; GRENON; SMITH, 2004; WORBOYS, 2005; GALTON, 2008; KUHN, 2012). In this thesis, we follow Galton (2008) who considers *processes* as unbounded activities (e.g., 'walking') in contrast with *events* that are bounded, discrete occurrences (e.g., 'John's walk from home to the station'). Events are thus complete entities on their respective time intervals; their lifetime is limited while objects persist in time and are complete in space (HACKER, 1982; WORBOYS, 2005; GALTON; MIZOGUCHI, 2009).

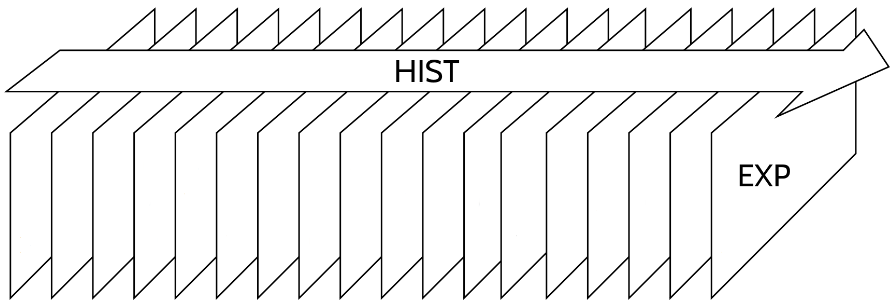
GIScience research draws from both the philosophical and the AI traditions to develop a theory of change for geospatial data. Drawing from Philosophy, Galton (2008) argues that real world phenomena can be divided into *continuants* and *occurrents*. *Continuants* (*endurants*) are entities to hold through time and exist over a period of time. Its properties may be different at each moment of their existence. When Cassius Clay changed his name to Muhammad Ali, he remained the same person. All his medals continued to belong to him after the name change. In contrast, *occurrents* (*perdurants*) include all things which happen, for example, a person's life, a fight, an eruption and a heartbeat. Continuants can undergo change and have spatial parts but not temporal parts. They are fully present at each moment of their existence. Occurrents cannot undergo change and have temporal parts. In much of GIScience literature, continuants are associated with objects and occurrents with events (WORBOYS, 2005; GALTON; MIZOGUCHI, 2009). In a nutshell, "objects exist, but events occur" (CRESSWELL, 1986).

The concept of event has been applied in location-based problems, which call for reasoning about the movement of objects (WORBOYS; DUCKHAM, 2006; HORNSBY; COLE, 2007). Hornsby and Cole (2007) model an event as the situation when a mobile object moves from one region to another. This would be the case when an ambulance crosses the five-minute perimeter from a hospital. In this view, events are instantaneous occurrences, a similar approach to the trajectory-based analysis of moving objects (SPACCAPIETRA et al., 2008).

In contrast to location-based problems, in land use change the observed locations are fixed. Change happens because of human or natural actions in these places (e.g., when farmers cut trees to make space for agriculture). Typical changes include the conversion of one land use into another, and the recurrence of previous events ("after five years of crop farming, the area was converted back to forest"). Modelling events as occurrences over intervals rather than instants fits the needs of land use change reasoning ("last year, we used the land for cattle-raising"). Therefore, to work with Earth observation data one needs a different approach to events than that applied to mobile objects.

A view directly relevant to our work is the EXP/HIST ontology by Galton (2008), sketched in Figure 2.3. The EXP (or experiential perspective) relates to the world as we experience it, which is constantly changing. The EXP entities represent the world as sequence of snapshots, which fits well with the data obtained by satellite observations. To reason about change, the EXP ontology is not enough, since it only allows comparison between two different states of the world. For proper temporal reasoning, we need to identify objects in the world, and describe how they change. To this end, we need the HIST ontology.

Figure 2.3 - Galton's view of events.



SOURCE: Adapted from Galton (2008).

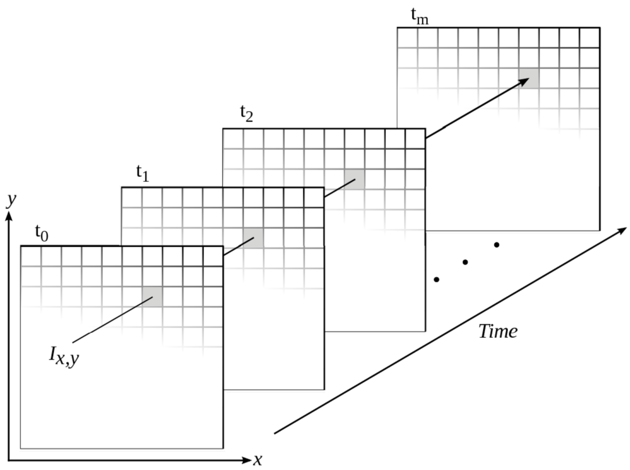
The HIST ontology (or historical perspective) relates to the historical record. It describes synoptic overviews that span a succession of EXP snapshots. It contains entities such as events that belong to the historical world and do not change themselves. The HIST entities can be built from the EXP measurements. A time-series of measurements of the same location in the surface of the Earth can be considered as a historical record. Combining the EXP and HIST perspectives breaks away from the limitations of snapshots. Changes on properties of individual objects are broken down in events, where each event spans one or more snapshots. In this way, we can infer which changes have taken place in each location.

There is few works in the GIScience literature dealing with change in Earth observation data. Chen et al. (2013) propose a representation for land use change using Allen's temporal logic. Ferreira et al. (2014) present an algebra for spatiotemporal data. Câmara et al. (2014) define the Field data type for big spatial data. Azeredo et al. (2016) proposes a redefinition of trajectory from the moving objects domain to the context of land cover change, and as case study he applies specifically to reason about the contents of a forest degradation database. These papers use algebraic specifications to model spatiotemporal data types but do not focus on the use of events as basic building blocks for reasoning about change.

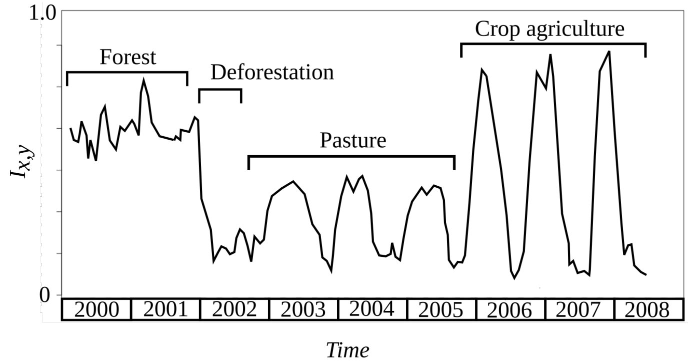
Big Earth observation data fits well within the EXP/HIST ontology. The availability of big Earth observation data allows researchers, in principle, to obtain a near-continuous record of observations about their areas of interest. Given a series of remote sensing snapshots (EXP entities), we can reorganise them into a set of time series (HIST entities). To do this, multiple satellite observations of an area are mapped into 3D arrays in space-time. A satellite image time series is obtained by taking measurements in the same pixel location (x, y) in consecutive times $t_1, ..., t_m$ (Figure 2.4(a)). Classification methods can then break an image time series into a set of intervals. We take each interval where the land use class is constant to be an 'accomplishment' (in Vendler's terms) and associate it to a land use event.

As an example, Figure 2.4(b) shows four events extracted from a remote sensing time series, expressed in terms of the their intervals. From 2000 to 2001 the area was a forest that was deforested in 2002. From 2003 to 2005 the area it was used for pasture and from 2005 to 2008, it was transformed into a cropland. This kind of classification is done by algorithms such as TWDTW (MAUS et al., 2016) that split a time series into a set of events. Combining the classification results with our formalism, scientists can explore the full depth of big remote sensing data archives.

Figure 2.4 - A 3-dimensional array of satellite data and a location land change events.



(a) Time series measures (e.g. EVI index) of a pixel location (x, y).



(b) Land change events associated to a pixel location (x, y).

SOURCE: Adapted from Maus et al. (2016).

3 THE LAND USE CHANGE CALCULUS

This chapter describes our proposal for a formalism to reasoning about land use change. Our motivation is that nowadays we have a set of remote sensing satellites which provide consistent information about Earth's land. These satellites observe the same area many times, producing a continuous stream of remote sensing data. Researchers would like to ask: *Which forest areas suffer none degradation, over 2000 to 2017? When certain single cropping practice arise in the study area? Which period the agricultural practice called double cropping turned dominant in the region? How different land use and land cover changes over time in a determined region?*.

3.1 Reasoning About Single Land Use Transitions

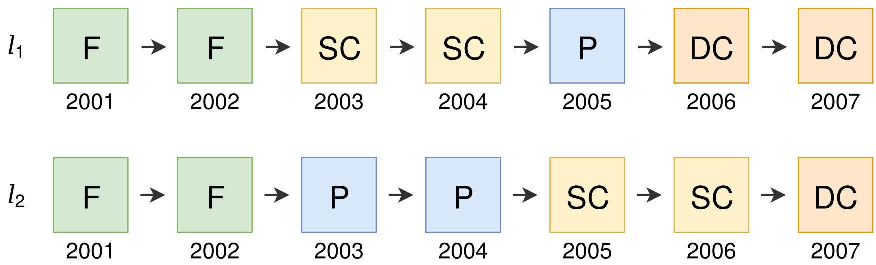
We propose a calculus for land use change that will be called *LUC Calculus* for short. LUC Calculus is a spatiotemporal calculus that takes an interval-based approach as its primitive time unit. The reason is that land use change transformations are not instantaneous. Clearing a forest for agriculture requires time and money. Given the effort required, after a human-induced transition has taken place the resulting land cover is likely to stay the same for years. These considerations led us to adopt Allen's interval temporal logic as one of the basic components of our formalism (ALLEN, 1984). We have extended Allen's proposal to spatial locations as part of a more general framework for reasoning about land use change. Our spatial locations correspond to pixels in remote sensing images. Therefore, the locations do not change, but the content of each location does.

Consistent with the EXP/HIST ontology (GALTON, 2008), we consider that geospatial locations are intrinsically tied to space, while events change their properties. We take locations as *continuants* and events of land use as *occurrents*. Locations hold through time and exist over a period of time; their properties may be different for each moment of their existence. An event is an accomplishment where a given location has a unique land use class with a defined beginning and end.

Considering the nature of remote sensing images, we do not have direct information about the events that cause change. Each image can be thought of a set of locations (pixels) whose values describe the state of the study area at a given time. Therefore, events are inferred from comparing different states of the same location, as when a pixel changes the value of its land use class.

As examples of land use change transitions, Figure 3.1 shows two locations with different sequences of land use classes for yearly intervals from 2001 to 2007. The letters stand for the land use classes *Forest* (F), *Pasture* (P), *Single Cropping* (SC) and *Double Cropping* (DC). Single cropping and double cropping are crop production systems (ARVOR et al., 2011); in the first, only one crop is planted during one agricultural year. Double cropping systems feature two crops are cultivated in one agricultural year (first and second harvest). In the lower part of Figure 3.1, the location l_2 was a forest from 2001 to 2002, pasture from 2003 to 2004 and used for agriculture from 2005 to 2007.

Figure 3.1 - Land change transitions in two distinct locations.



SOURCE: Author.

The LUC Calculus is based on the following building blocks:

- *a non-overlapping set of spatial locations* ($L = l_1, l_2, ..., l_n$), where each location is part of a region of study.
- *a mutually-exclusive set of properties* ($P = p_1, p_2, ..., p_n$). A typical set of properties would be $P =$ *Forest*, *Pasture*, *Single Cropping* and *Double Cropping*.
- *a set of non-overlapping and sequential time intervals* ($T = t_1, t_2, ..., t_n$) that represents the granularity of time.
- *the set of temporal predicates* defined by Allen (1983), as shown in Table 3.1, where *start_X* and *end_X* are the start date and the end date of a time interval X, the same logic for Y.
- *the usual logical connectives*, such as $\wedge$ for conjunction, $\vee$ for disjunction, $\implies$ for implication, $\Leftrightarrow$ for equivalence, and $\forall$ as the universal quantifier.

- *the additional predicates* IN, $FOLLOWS$ and $PRECEDES$ for comparing time intervals.

- *the predicate* $HOLDS$ used to assert some property of individual locations.

- *the predicates* $RECUR$, $CONVERT$ and $EVOLVE$ for reasoning on composition of land use transitions.

Table 3.1 - The interval comparison predicates.

Predicate	**Description**
BEFORE	$(end\_X < start\_Y)$
AFTER	$(start\_X > end\_Y)$
MEETS	$(end\_X == start\_Y)$
MET BY	$(end\_Y == start\_X)$
STARTS	$(start\_X == start\_Y) \wedge (end\_X < end\_Y)$
STARTED BY	$(start\_X == start\_Y) \wedge (end\_X > end\_Y)$
DURING	$(start\_X > start\_Y) \wedge (end\_X < end\_Y))$
CONTAINS	$(start\_X < start\_Y) \wedge (end\_X > end\_Y)$
FINISHES	$(start\_X > start\_Y) \wedge (end\_X == end\_Y)$
FINISHED BY	$(start\_X < start\_Y) \wedge (end\_X == end\_Y)$
EQUALS	$(start\_X == start\_Y) \wedge (end\_X == end\_Y)$

We use the predicate IN as originally proposed by Allen (1984) to express the case where one interval is inside another interval. We introduce the predicates $FOLLOWS$ to express the case in which one interval happens before another and $PRECEDES$ to capture the inverse relation, when one interval occurs after another interval. These predicates are formally defined in Table 3.2.

Table 3.2 - The predicates IN, FOLLOWS and PRECEDES.

$$\forall\ t_i, t_j \in T,\ \text{IN}(t_i, t_j) \Leftrightarrow \text{DURING}(t_i, t_j) \vee \text{STARTS}(t_i, t_j) \vee \text{FINISHES}(t_i, t_j)$$
$$\forall\ t_i, t_j \in T,\ \text{FOLLOWS}(t_i, t_j) \Leftrightarrow \text{MEETS}(t_i, t_j) \vee \text{BEFORE}(t_i, t_j)$$
$$\forall\ t_i, t_j \in T,\ \text{PRECEDES}(t_i, t_j) \Leftrightarrow \text{MET\_BY}(t_i, t_j) \vee \text{AFTER}(t_i, t_j)$$

In the LUC Calculus we use a spatial version of the Allen's predicate $HOLDS$, expressed as $HOLDS(l, p, t) \rightarrow bool$, to include the spatial location in the assertion. This predicate denotes a property p of a location l that is true over an entire time interval t. The statement "Maggie's farm was used for soybean crops from 2000 to 2010" would be expressed as $HOLDS(\text{“}Maggie'sfarm\text{”}, \text{“}soybeans\text{”}, [2000, 2010]) \rightarrow true$. From this definition, it follows that the current state of the farm hold in all of its subintervals. It also follows that two sequential subintervals with the same property can be combined. Table 3.3 describes the properties of the $HOLDS$ predicate.

Table 3.3 - The HOLDS predicate.

If a property holds in an interval, it holds inside all its subintervals
$\forall\ l \in L, t_i, t_j \in T$, $\text{HOLDS}(l, p, t_i) \wedge \text{IN}(t_i, t_j) \implies \text{HOLDS}(l, p, t_j)$
If a property holds in two consecutive intervals, it holds in their combination
$\forall\ l \in L, t_i, t_j \in T$, $\text{HOLDS}(l, p, t_i) \wedge \text{MEETS}(t_i, t_j)$ $\wedge\ \text{HOLDS}(l, p, t_j) \implies \text{HOLDS}(l, p, (t_i \cup t_j))$

To reason about land use transitions, we use expressions that combine the $HOLDS(l, p, t)$ predicate with interval comparison operators. For instance, consider the land use transitions shown in Figure 3.1. Table 3.4 shows some questions in natural language and how they can be translated to expressions in LUC Calculus. In expression a, we are interested in specific land use conversion. In this case, the $MEETS$ predicate captures the assertion for direct conversions, where "forest" was replaced immediately by "single cropping". In question b, we are interested in land use conversions that can occur immediately or later. This case requires the $FOLLOWS$ predicate. Applying these expressions in the example, we have that location l_1 satisfies the first expression and both locations l_1 and l_2 satisfy the second expression.

Table 3.4 - Examples of LUC Calculus expressions.

a) Search for all "forest" locations that have been directly replaced by "single cropping" $\forall\ l \in L, \forall\ t_i, t_j \in T$, HOLDS $(l, \text{"}Forest\text{"}, t_i) \wedge$ HOLDS$(l, \text{"}Single_Cropping\text{"}, t_j) \wedge$ MEETS(t_i, t_j)
b) Search for all "single cropping" locations that have became "double cropping" $\forall\ l \in L, \forall\ t_i, t_j \in T$, HOLDS$(l, \text{"}Single_Cropping\text{"}, t_i) \wedge$ HOLDS$(l, \text{"}Double_Cropping\text{"}, t_j) \wedge$ FOLLOWS(t_i, t_j)

3.2 Reasoning About Multiple Land Use Transitions

For reasoning about land use transitions, sometimes one needs to derive expressions that combine two occurrences. These expressions could be stated using only the $HOLDS$ predicate and the interval relations. However, these expressions can become complex to build. To simplify matters, the LUC Calculus provides predicates to include three typical combinations: *recurrence*, *conversion* and *evolution*. Recurrence happens when a location has the same property in a non-continuous way. For example, an area of mature forest may be cut for agriculture and later abandoned so the forest regrow. In this case, the land class 'forest' is associated to two distinct, non-consecutive intervals, denoting a case of *recurrence* of forest cover.

Conversion happens when one land use is directly converted to another. This allows scientists to study direct conversions that are very important, such as from forest to cropland or forest to pasture. Evolution happens when a conversion from land use A to B happens directly or interspersed by other use. For instance, scientists want to know the areas that are currently used for agriculture, but that sometime in the past were forest. Table 3.5 shows the definition of $RECUR$, $CONVERT$ and $EVOLVE$ predicates.

Table 3.5 - The predicates RECUR, CONVERT and EVOLVE.

$$\forall\ l \in L, \forall\ p, p_i, p_j \in P, p \neq p_i \neq p_j,\ \forall\ t_i, t_j, t_k \in T, t_i \neq t_j \neq t_k,$$

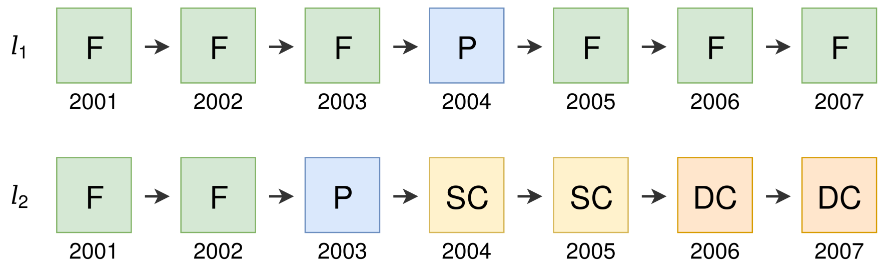
$$\text{RECUR}\ (l, p, t_i, t_j) \Leftrightarrow \text{HOLDS}(l, p, t_i) \wedge \text{HOLDS}(l, p, t_j) \wedge \text{BEFORE}(t_i, t_j)$$
$$\wedge \neg\ \text{HOLDS}(l, p, t_k) \wedge \text{MEETS}(t_i, t_k) \wedge \text{MEETS}(t_k, t_j)$$

$$\text{CONVERT}(l, p_i, t_i, p_j, t_j) \Leftrightarrow \text{HOLDS}(l, p_i, t_i) \wedge \text{HOLDS}(l, p_j, t_j) \wedge \text{MEETS}(t_i, t_j)$$

$$\text{EVOLVE}(l, p_i, t_i, p_j, t_j) \Leftrightarrow \text{HOLDS}(l, p_i, t_i) \wedge \text{HOLDS}(l, p_j, t_j) \wedge \text{FOLLOWS}(t_i, t_j)$$

The combined predicates help us to explore land use change trajectories (LAMBIN et al., 2003), or, the sequence of land use transitions that happens during the time interval of our data set. For example, we may want to know what land use has replaced the mature forest, or what other uses we had for an area before it became pasture, or we want to find out if the pasture area was abandoned later and a new forest has grown there. To exemplify this idea, consider the sequence of transitions associated to two different locations from 2001 to 2007 shown in Figure 3.2. Table 3.6 shows three questions in natural language and how they can be represented by expressions in the LUC Calculus. These expressions show the expressive power of the combined predicates.

Figure 3.2 - Sequence of change with three types of multiple transitions.



SOURCE: Author.

Table 3.6 - Examples of LUC Calculus with multiple transitions.

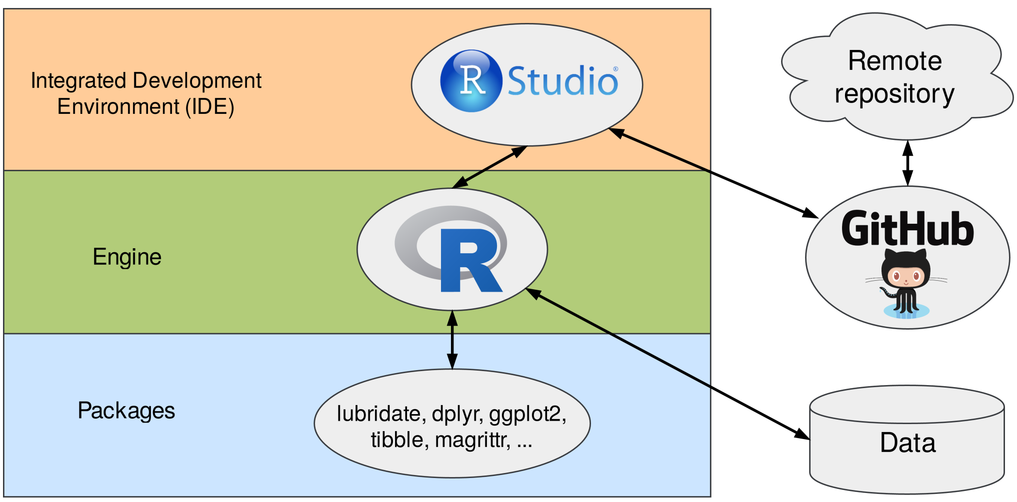
Search for all "forest" locations recurred in "forest"
$\forall\ l_1 \in L, \forall\ t_i, t_j \in T$, RECUR$(l_1, \text{"}Forest\text{"}, t_i, t_j)$
Search for all "forest" locations that have been converted into "pasture"
$\forall\ l_2 \in L, \forall\ t_i, t_j \in T$, CONVERT$(l_2, \text{"}Forest\text{"}, t_i, \text{"}Pasture\text{"}, t_j)$
Search for all "pasture" locations that have been evolved into "double cropping"
$\forall\ l_2 \in L, \forall\ t_i, t_j \in T$, EVOLVE$(l_2, \text{"}Pasture\text{"}, t_i, \text{"}Double_Cropping\text{"}, t_j)$

3.3 A LUC Calculus Implementation in R

To carry our case studies, we have implemented the LUC Calculus in **R**, a programming language and statistical environment (R CORE TEAM, 2015). We used **R** because besides being an open source language it provides a wide variety of statistical and graphical packages and is largely accepted in the scientific community.

The **lucC**[1] **R** package developed in this thesis is available in GitHub, web-based hosting service for open source software projects. In its initial version the **lucC** is able to process the time series of classified images in raster representation stored in GeoTIFF files. The predicates HOLDS, BEFORE, AFTER, MEETS and others as well as its combinations are implemented along with functions to visualise results in graphics or maps. Figure 3.3 shows the overall architecture for this implementation. We use RStudio as an integrated development environment (IDE) for **R**, integrated with the GitHub to version control system. RStudio has an open source edition and that can runs in different operational systems (RSTUDIO, 2017).

Figure 3.3 - Overview of the **R** implementation.



SOURCE: Author.

[1]https://github.com/ammaciel/lucC

4 REASONING ABOUT LAND USE CHANGE

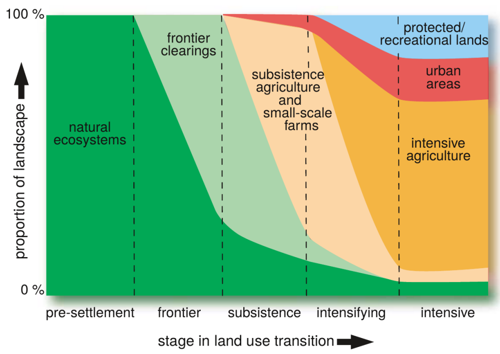
In this chapter we show how the LUC Calculus proposed in this thesis can be used to reason about land use changes. We have been motivated by the fact that Brazil can be considered unique worldwide in relation to land use. It has vast areas of forest and savannas that have been converted into farmland, but it still safeguards the largest tracts of native tropical vegetation on Earth, with high levels of biodiversity.

4.1 The Importance of Studying Land Use Change

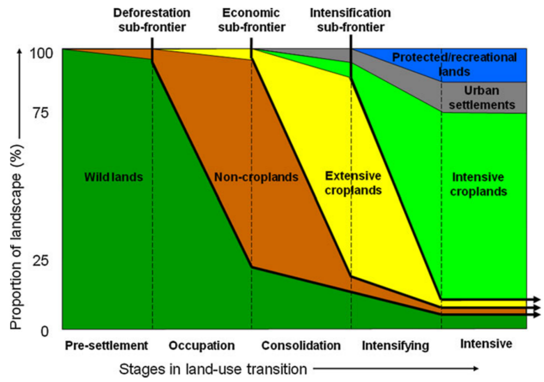
Although land use practices vary greatly across the world, their final outcome is generally the same: the acquisition and exploration of natural resources for immediate human needs, often at the expense of degrading environmental conditions. Despite of the fact that modern agriculture has been successful in increasing food production, it has caused extensive environmental damage. Foley et al. (2005) shows that land use is becoming a force of global importance. Changes in land use have transformed a large proportion of the planet's land surface. The expansion of global croplands, pastures, plantations, and urban areas in the last decades are accompanied by large increases in water, energy and fertiliser consumption, along with considerable losses of biodiversity. By clearing tropical forests, practising subsistence agriculture, intensifying farmland production or expanding urban areas, humans actions are changing the world's landscapes in pervasive ways.

Considering a land use system as a sequence of stages of uses, transitions refer to changes from one stage to another, for example, when a mature forest is converted to an area of annual crops. Transitions are non-linear in time and heterogeneous in space. There are two forces of different nature behind land use transitions, those associated with negative socio-ecological feedback as a result of a depletion of key resources. For example changes resulting from a severe degradation in ecosystem services caused by past land use practices. And there is also land use transitions caused by socio-economic changes and innovations that take place rather independently from the ecological system such as urbanisation, economic development or globalisation (LAMBIN; MEYFROIDT, 2010). In Figure 4.1(a) Foley et al. (2005) represents transitions in land-use activities that may be experienced within a given region over time. Arvor et al. (2013) uses land use transitions to highlight the dynamics of the soybean agricultural in Mato Grosso state in Brazil, using a frontier model adapted to the region (see Figure 4.1(b)). This model can be used to map the rapid agricultural changes in this area using remote sensing data, leading to the identification of three sub-frontiers. Land use transitions between the land use types are observed when wildlands are cleared, configuring a deforestation sub-frontier; cropped areas for commodities are expanding, or retracting, constitute an economic sub-frontier; and areas where agriculture practices are evolving to turn agriculture more profitable as intensification sub-frontier.

Figure 4.1 - Examples of land use transition representations.



(a) A global context.



(b) Soybean expansion in Mato Grosso.

SOURCE: (a) from Foley et al. (2005) and (b) from Arvor et al. (2013).

Brazil in particular faces an increasing challenge: balancing agricultural production and environmental protection. Studies show that deforestation, greenhouse gas emissions, agriculture and local/regional climate changes, such as changes in precipitation in the dry season, have been closely interconnected in Brazil (MORTON et al., 2006; FOLEY et al., 2007; MALHI et al., 2008; MEYFROIDT; LAMBIN, 2011; OMETTO et al., 2011; LAPOLA et al., 2014). Still, the demand for farmland is the key immediate driver of land use change in Brazil and there is little evidence that agriculture expansion is stopping, with increasing intensification and commoditization of Brazilian agriculture (LAPOLA et al., 2014).

The Amazon biome is an area of great concern regarding the loss of its forest with the expansion of pastures for cattle ranching and other different causes (ASNER et al., 2004; MORTON et al., 2006; ARIMA et al., 2011; OMETTO et al., 2011; HANSEN et al., 2013; LAPOLA et al., 2014). Such situation have influenced the creation of protected areas, land managements laws, and public services responsible for research and by education on natural resources management, as well as to market-driven enforcement of environmental laws (LAMBIN; MEYFROIDT, 2010; LAPOLA et al., 2014). A new Forest Code (FC) for Brazil was signed into law in 2012, preserving the legal reserve requirements tailored for each of the biomes, but also providing amnesty for landholders of 29 million hectares of illegal deforestation carried out before July 2008 (NEPSTAD et al., 2014; SOARES-FILHO et al., 2014).

The policy known as "Soy Moratorium" (RUDORFF et al., 2011; GIBBS et al., 2015), is a treat signed by major soybean traders, agreeing not to purchase soy grown on lands deforested after July 2006 in the Brazilian Amazon. The soy moratorium later changed the moratorium reference date from July 24, 2006 to July 22, 2008 to adapt to the new Forest Code of 2012 (ABIOVE, 2017). Farmers abiding by the soy moratorium agree not to *directly* replace forest by soybean plantations. However, the agreement does not preclude *indirect* land use changes, as when a farmer buys previously deforested land that is being used as a pasture. In this case, the cattle rancher may sell his land and move elsewhere, causing deforestation without violating the soy moratorium. Thus, it is necessary to identify not only *direct* land use changes, for example forest areas that were replaced by cropping areas, but also *indirect* land use changes that occurs when agricultural activities displaced from one region are reconstituted in another. Or deforestation at particular locations occurs partly due to events far away (LAPOLA et al., 2010; ARIMA et al., 2011).

Quantifying and studying land use change is crucial for the proposal of actions related to the decrease of the effects of deforestation and prevent its large expansion. To do that tools to carry precise analysis in timely manner are needed. The LUC Calculus proposed in this thesis is an example of such tools. For example, in Table 4.1 we exemplify how the LUC Calculus can be used to formally elicit direct and indirect land use change questions that are relevant to verify and analyse the effects of the soy moratorium policy.

Table 4.1 - Examples of LUC Calculus expressions to reason about the soy moratorium.

a) *Search for all forest areas that have been replaced by soybeans* $\forall\ l \in L, \forall\ t_1, t_2 \in T, HOLDS(l, \text{“}Forest\text{”}, t_1) \wedge HOLDS(l, \text{“}Soybean\text{”}, t_2) \wedge MEETS(t_1, t_2)$
b) *Search for all forest areas that have been replaced by pasture and later turned into soybean* $\forall\ l \in L, \forall\ t_1, t_2, t_3 \in T, HOLDS(l, \text{“}Forest\text{”}, t_1) \wedge HOLDS(l, \text{“}Pasture\text{”}, t_2) \wedge HOLDS(l, \text{“}Soybean\text{”}, t_3) \wedge MEETS(t_1, t_2) \wedge MEETS(t_2, t_3)$

4.2 The LUC Calculus

In this section we present a methodology to reason about land use changes using the LUC Calculus, in a pragmatic approach, as summarised in Figure 4.2. The presented methodology is open up to the point where the set of land use change trajectories are explicit. Different methods and classification algorithms could be used and are not the central contribution of this thesis. But aiming at comprehensibility, in this section we also provide some details about the classification algorithm used in our case studies.

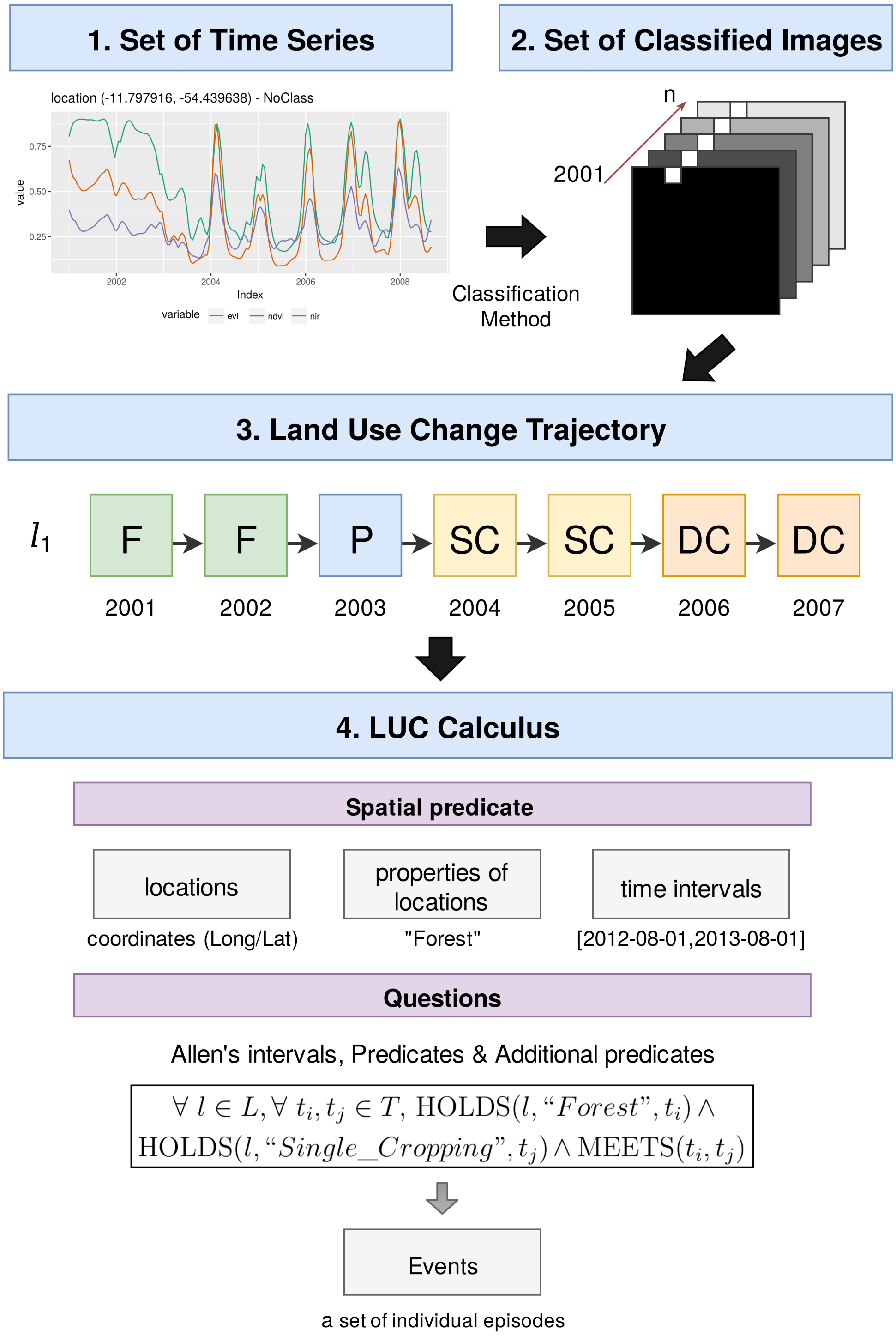
1) Our input data is a long-term repository of MODIS land products, including vegetation indexes, arranged in an array database. This repository is accessible using a web service interface known as the Web Time Series Service (WTSS) (VINHAS et al., 2016) that provides long-term time series.

2) We selected the Time-Weighted Dynamic Time Warping (TWDTW) method (MAUS et al., 2016) to classify each long-term time series in a sequence of land use classes by matching a known temporal patterns associated to the phenological cycle of vegetation cover classes with the data in time series of vegetation indexes and other radiometric parameters. The TWDTW method performs well when applied to MODIS land products data because it captures the seasonality characteristics of land use in cropping areas. The final result is a set of yearly classified imagery data where each pixel location is associated to a land use class as represented in stage 2 in Figure 4.2.

3) The yearly sequence of classified images is used to explicit the land use trajectories during the study period (stage 3 in Figure 4.2). Each land use trajectory is associated to a location and contains a set of land use classes over time. In our case studies we represented the set of land use trajectories as a table in which each row refers to location with its land use class from a start to an end date. Another possible way we could represent the set of land use trajectories would be as a multidimensional raster representation, with the raster elements representing the location and land use class and the time interval associated to this use are represented as bands.

4) The stage 4 in Figure 4.2 is the core of the methodology. It offers the spatial predicates (e.g. *HOLDS*), the locations, its properties and time intervals to be used to formally to reason about land use change in the study area.

Figure 4.2 - The LUC Calculus application methodology.



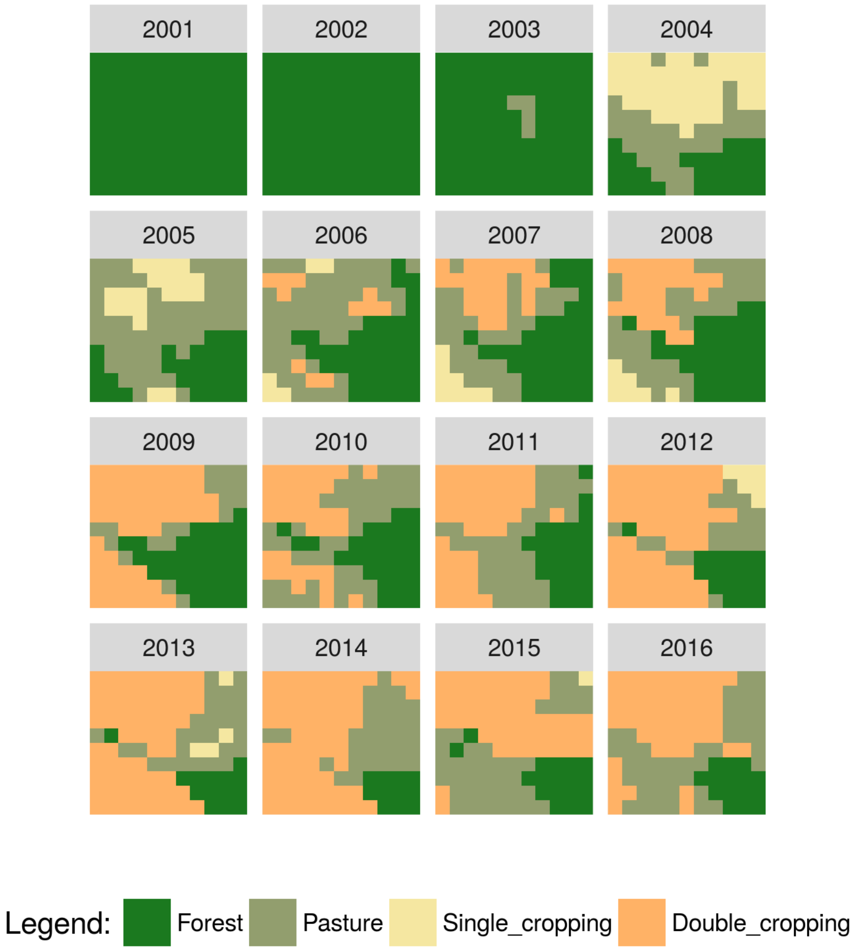
SOURCE: Author.

As argued previously, the LUC Calculus is not restricted to a particular classification method to generate a temporal sequence of classification data to a set of land uses. It can also consider different spatial unit of analysis (e.g. pixels or cells), as long as it can be distinguished by a two dimensional location.

4.3 Detecting Land Use Change Transitions in a Small Region

In this section we apply the LUC Calculus in a small region to show its effectiveness in reasoning about land use changes. We consider the set of annual classification of a small area in four land use classes, such as *Forest*, *Pasture*, *Single cropping* and *Double cropping* from 2001 to 2016 as shown in Figure 4.3.

Figure 4.3 - Yearly classified images in a sample region.



SOURCE: Author.

Table 4.2 shows the representation of the land use trajectories in the area in a tabular format.

Table 4.2 - Tabular format representation for land use trajectories.

state id	location id	longitude	latitude	start_date	end_date	land_use
1	1	-55.05274	-11.89287	2000-09-01	2001-09-01	Forest
2	1	-55.05274	-11.89287	2001-09-01	2002-09-01	Forest
3	1	-55.05274	-11.89287	2002-09-01	2003-09-01	Forest
4	1	-55.05274	-11.89287	2003-09-01	2004-09-01	Forest
...						
13	1	-55.05274	-11.89287	2012-09-01	2013-09-01	Double_cropping
14	1	-55.05274	-11.89287	2013-09-01	2014-09-01	Double_cropping
15	1	-55.05274	-11.89287	2014-09-01	2015-09-01	Double_cropping
16	1	-55.05274	-11.89287	2015-09-01	2016-09-01	Double_cropping
...						
972	61	-55.03997	-11.89287	2011-09-01	2012-09-01	Double_cropping
973	61	-55.03997	-11.89287	2012-09-01	2013-09-01	Double_cropping
974	61	-55.03997	-11.89287	2013-09-01	2014-09-01	Double_cropping
975	61	-55.03997	-11.89287	2014-09-01	2015-09-01	Pasture
976	61	-55.03997	-11.89287	2015-09-01	2016-09-01	Pasture
...						
1756	110	-55.02766	-11.87412	2011-09-01	2012-09-01	Single_cropping
1757	110	-55.02766	-11.87412	2012-09-01	2013-09-01	Pasture
1758	110	-55.02766	-11.87412	2013-09-01	2014-09-01	Double_cropping
1759	110	-55.02766	-11.87412	2014-09-01	2015-09-01	Single_cropping
1760	110	-55.02766	-11.87412	2015-09-01	2016-09-01	Pasture

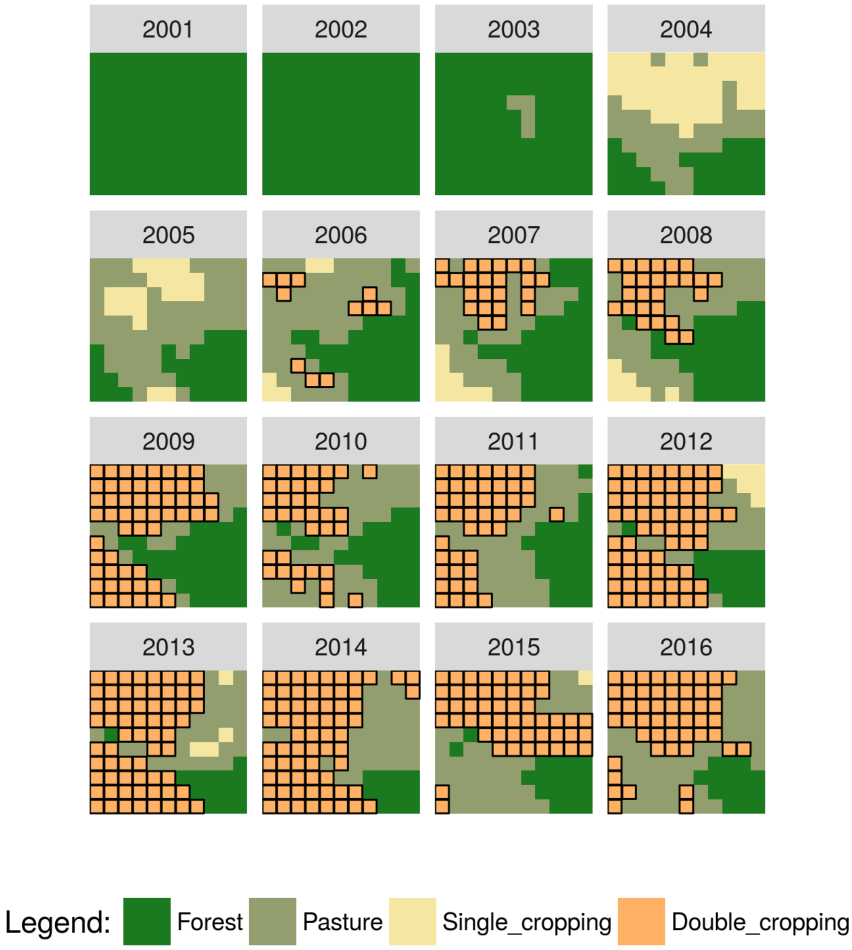
We want to analyse double cropping production in the area using the LUC Calculus to select the locations that used double cropping systems at any time during the study period, as shown in Table 4.3.

Table 4.3 - LUC Calculus expression to select double crop locations.

Searching for double cropping areas during the whole interval (2001 to 2016).
$\forall\ l \in L, \forall\ t_i \in T, HOLDS(l, \text{“}Double\_cropping\text{”}, t_i),\ where\ t_i = [2001, 2016]$

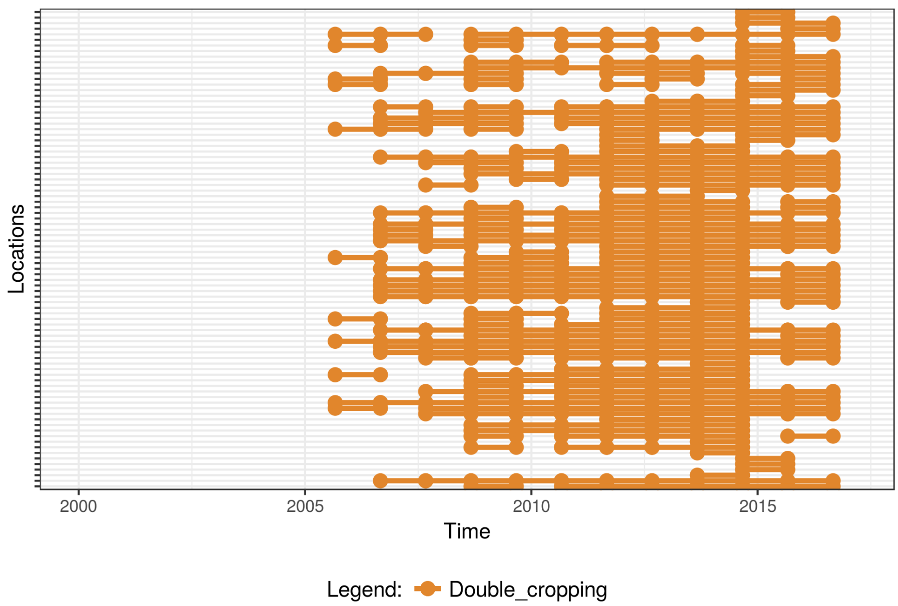
The result is shown Figure 4.4, were the selected locations are highlighted in black. Figure 4.5 shows the different locations with this use along the time, we can see that the transitions are not homogeneous in space and non-linear in time. Finally, in Figure 4.6 is shown the quantitative evolution of this use in the area. This example shows the effectiveness of the LUC Calculus quantitative and qualitative land use transitions analysis. This suggests that double cropping use emerged in the area after 2008, with a major expansion from 2010 until a decrease in 2015.

Figure 4.4 - Locations of double cropping (highlighted in black).



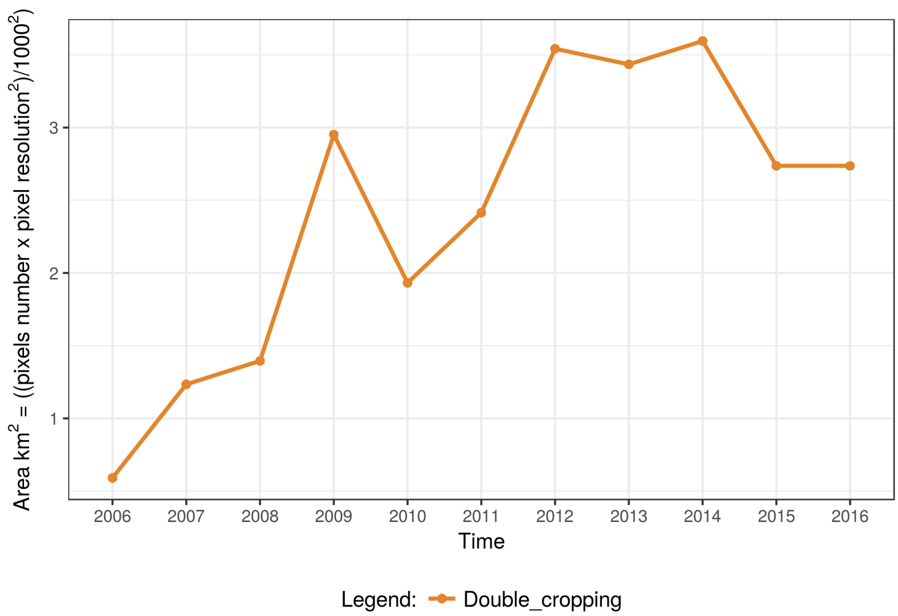
SOURCE: Author.

Figure 4.5 - Sequence of locations with double cropping.



SOURCE: Author.

Figure 4.6 - Double cropping along the years.



SOURCE: Author.

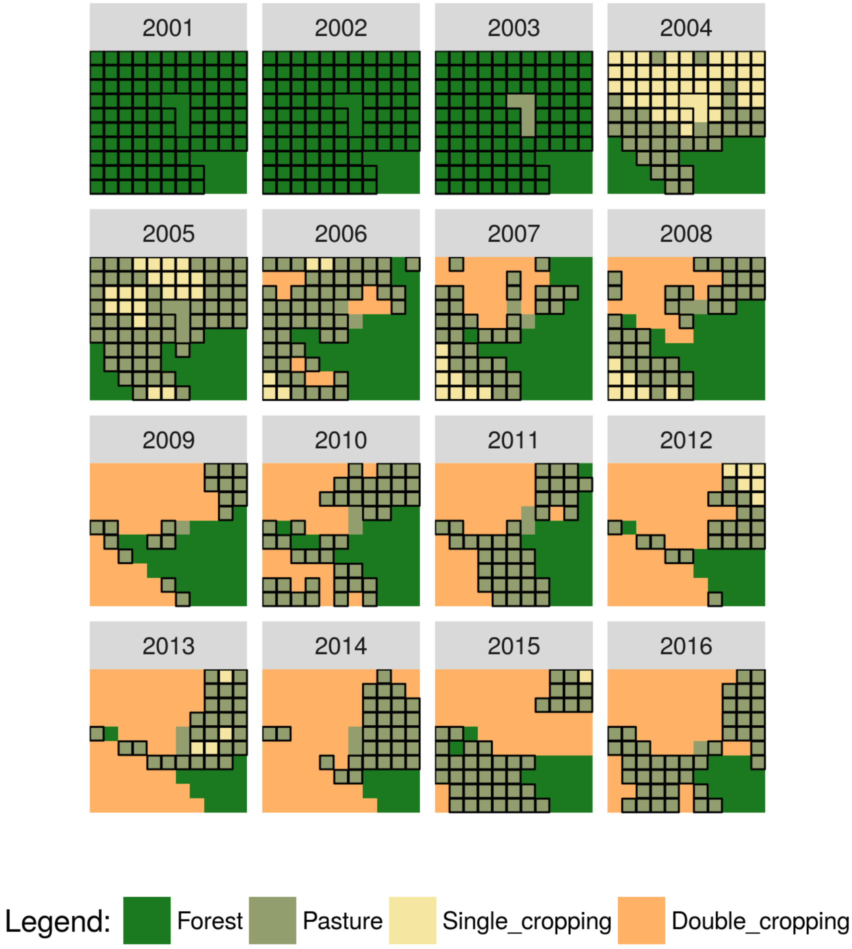
Now, we want to study forest areas converted into pasture or single cropping after the year 2003. In other words, finding the locations that until 2003 were forest areas that did not suffer any type of degradation, but from 2004 have been turned into other land uses, such as pasture or single cropping. Table 4.4 shows the LUC Calculus expression to select these locations. We use the FOLLOWS predicate because the transition of land change to pasture or single cropping can occur any time within the interval 2004 to 2016. Figure 4.7 shows the locations where LUC Calculus expression is evaluated as true (highlighted in black).

Table 4.4 - LUC Calculus expression to select a specific land use transition.

Search for all forest areas that have been replaced by pasture or single cropping after the year 2003. $\forall\ l \in L, \forall\ t_i, t_j \in T, HOLDS(l, \text{“}Forest\text{”}, t_i) \wedge (HOLDS(l, \text{“}Pasture\text{”}, t_j) \vee HOLDS(l, \text{“}Single\_cropping\text{”}, t_j)) \wedge FOLLOWS(t_i, t_j),$ $where\ t_i = [2001, 2003], t_j = [2004, 2016]$

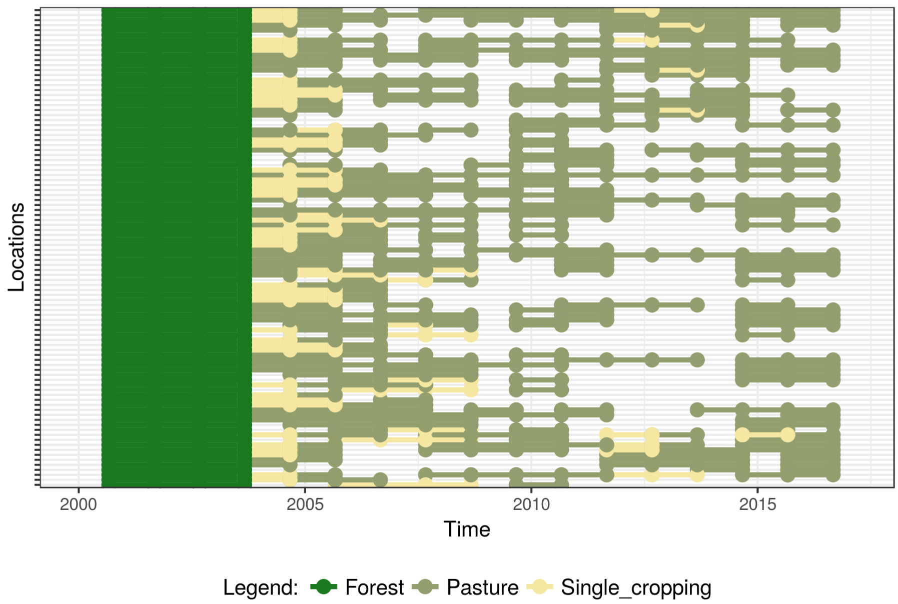
Analysing the locations that were deforested after 2003 (see expression in Table 4.4) we can see that the transitions are not sequential along the time, locations used for pasture are turned into single cropping and later become pasture again, as is represented in Figure 4.8. But we can quantify the area of each use along the years, see Figure 4.9. In the year 2004, most of them have been turned into annual single crops, and pasture became dominant from year 2005.

Figure 4.7 - Locations where forest turned into pasture or single cropping (highlighted in black).



SOURCE: Author.

Figure 4.8 - Sequence of land use transitions along the years.



SOURCE: Author.

Figure 4.9 - Quantifying the land use transitions.

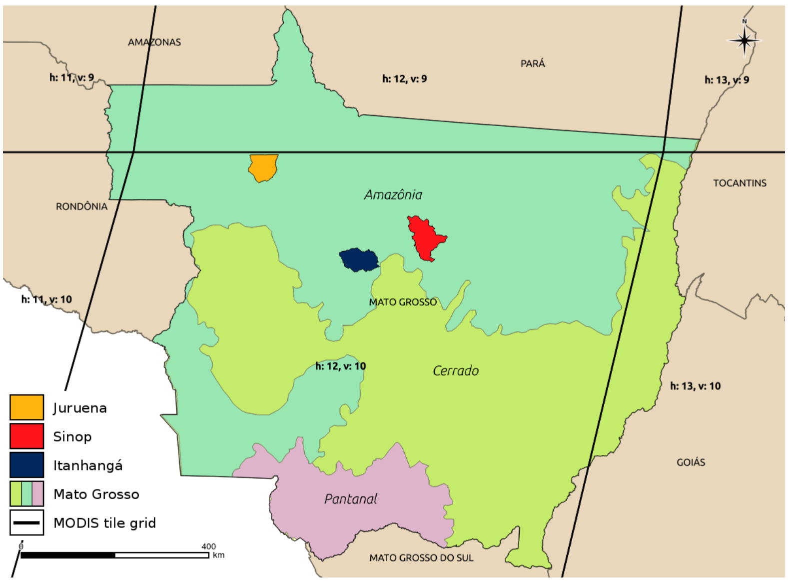
SOURCE: Author.

4.4 Land Use Change in the Amazon Biome

In this section we present three case studies of reasoning on land use change in the Brazilian Amazon biome. We intend to show how the LUC Calculus can be used to formally describe and identify land use transitions in this area.

This biome encompasses almost 50% of the Brazilian territory, it is covered mainly by rainforests and has the richest biodiversity in the world (RUDORFF et al., 2011). In recent years the area has been subject to an extensive removing of forested areas (ARIMA et al., 2011; KASCHUK et al., 2011; PINHEIRO et al., 2016). They have been replaced by pasture and crops such as soybean and maize (LAPOLA et al., 2010; ARVOR et al., 2013; LAPOLA et al., 2014). In particular, the Mato Grosso (MT) state is an interesting part of the Amazon biome because it has a heterogeneous landscape, explained by the presence of different natural conditions, populations and agricultural practices. It is the main area of expansion of cropland and pasture generating an increasing in forest loss (MORTON et al., 2006; ARVOR et al., 2011; BROWN et al., 2013; SPERA et al., 2014). We concentrate our case studies in three municipalities of MT, Juruena, situated in the north of the state, an area of pasture expansion; Itanhangá and Sinop, located in the border of the Amazon and Cerrado biomes. Figure 4.10 shows the study area.

Figure 4.10 - Location of the case studies.



SOURCE: Author.

4.4.1 The land use trajectories

In the section 4.2 we have shown the input to the LUC Calculus methodology is a set of land use trajectories. In our case studies we worked with a series of the Moderate Resolution Imaging Spectroradiometer (MODIS) data, during the period of 2001 to 2016. MODIS sensor have a revisit cycle of 16 days and produces images with a spatial resolution of 250 meters. We worked specifically with the MOD13Q1 product. This product grid consists of 4,800 x 4,800 pixels, includes the Normalized Difference Vegetation Index (NDVI), the Enhanced Vegetation Index (EVI) and the reflectance bands NIR, MIR, RED and Blue (DIDAN, 2015).

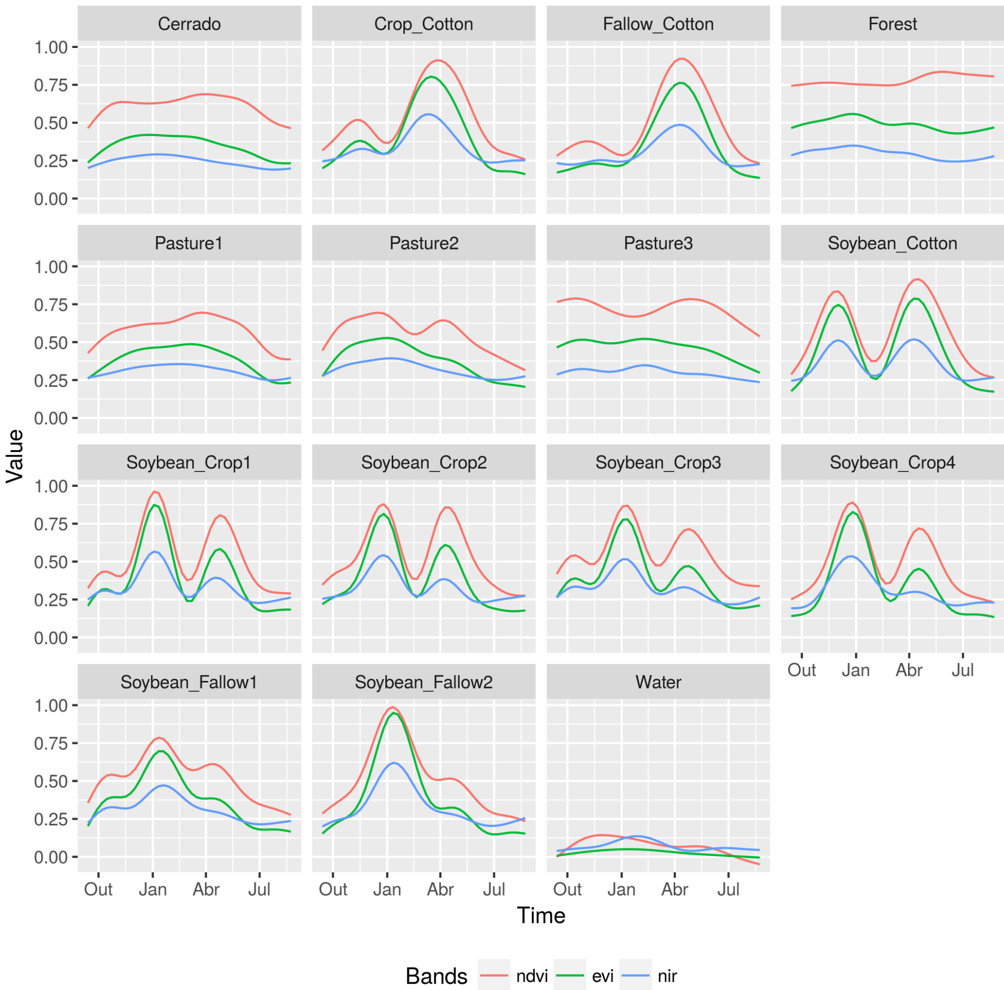
This data set was classified using the TWDTW method (MAUS et al., 2016). This method matches temporal patterns representative of the land uses to a long-term time series, and allows us to distinguish single cropping and double cropping systems, that cannot be distinguished when looking at a single time stamp. In our case studies 15 land use classes (temporal patterns) were defined by experts discriminated by two vegetation indexes (NDVI and EVI) and one reflectance band (NIR), shown in Figure 4.11. It is interesting to note that there are more than one type of pasture (*Pasture1*, *Pasture2* and *Pasture3*), *Soybean_Crop*, and *Soybean_Fallow*. This occurs because a same land use type can be characterised by its variability in relation of the vegetation indices and reflectance bands. As a result, 16 classified imagery were generated, with each pixel labelled with one of the 15 land use classes.

However, in our case studies we are interested in the general agricultural practices and not in the specific crops. Table 4.5 shows an aggregation of the 15 original land use classes in 6 classes of interest.

Table 4.5 - Land use classes aggregation.

Aggregated class	**Original classes**
Forest	Forest
Pasture	*Pasture1*, *Pasture2* and *Pasture3*
Cerrado	Cerrado
Single cropping (SC)	*Fallow_Cotton*, *Soybean_Fallow1* and *Soybean_Fallow2*
Double cropping (DC)	*Crop_Cotton*, *Soybean_Cotton*, *Soybean_Crop1*, *Soybean_Crop2*, *Soybean_Crop3* and *Soybean_Crop4*
Water	Water

Figure 4.11 - The use classes temporal patterns.



SOURCE: e-Sensing project (http://www.esensing.org).

4.5 Case Study 1: Land Use Changes in Itanhangá

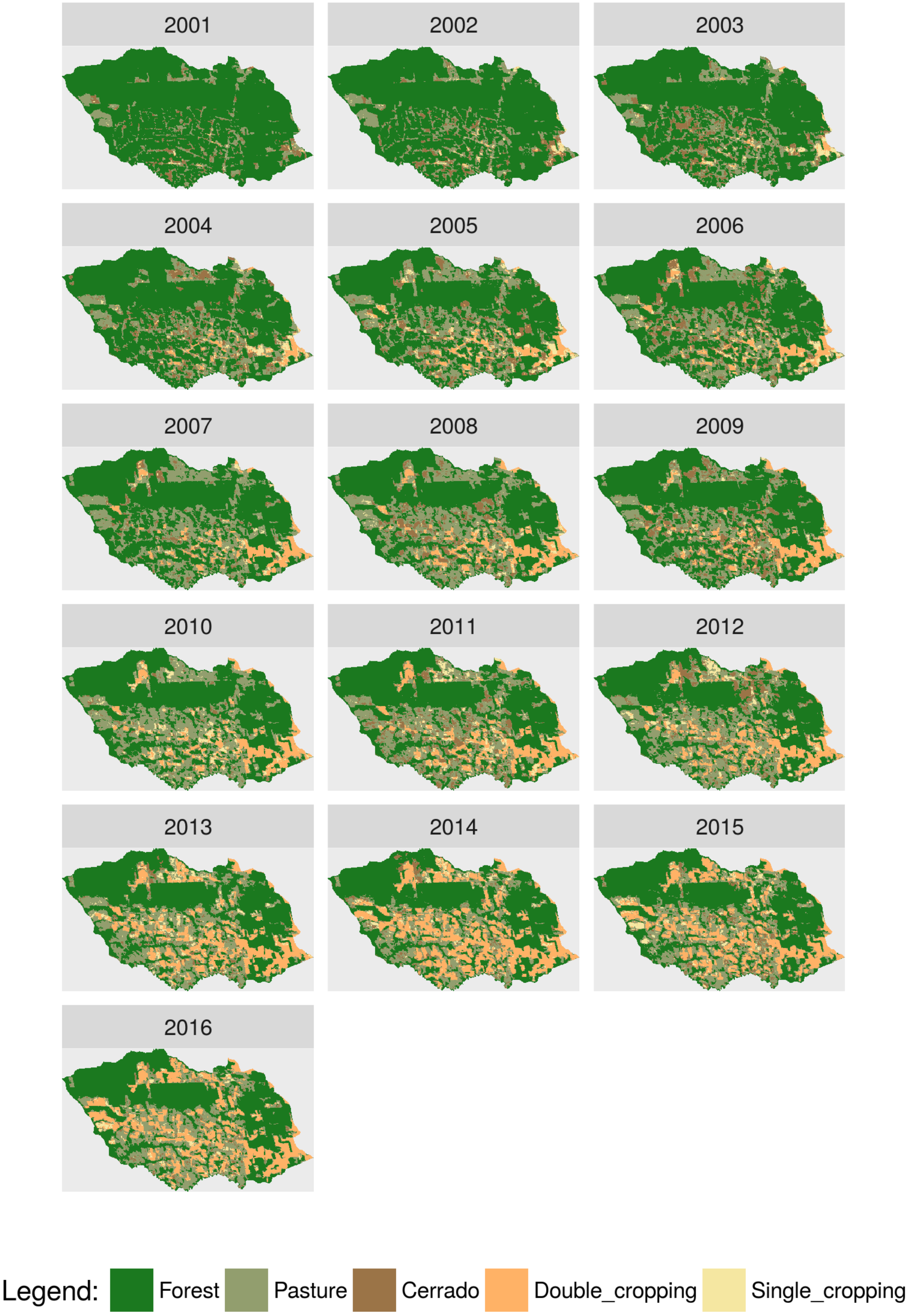
The first case study refers to the Itanhangá municipality. It has an area of 2,898 km^2 and had a population of 5,276 inhabitant in 2010 (IBGE, 2016). 54,698 image time series were processed to generate the land use trajectories (shown in Figure 4.12) in this area from 2001 to 2016. These images show a massive removal of the mature forest to be used for agriculture. It is visually clear that more than half of the municipality area has been cut since the early 2000s.

One of our interests is distinguish secondary vegetation from mature forest. Mature forests have high biomass and biodiversity and have not been affected by recent human actions. Secondary vegetation areas, or secondary forest, are places where the original forest was cut and the area was later abandoned. After a few years, these areas will appear in remote sensing images as forests. However, their biodiversity and biomass is much smaller than that of a mature forest (CHOKKALINGAM; JONG, 2001; PERZ; SKOLE, 2003).

The growth of the secondary vegetation is seen as an important mechanism to recuperate the regional ecosystem dynamic, for instance, hydrology, soil surface properties, energy balance and biodiversity, and also to mitigate historical emissions from deforestation (OMETTO et al., 2011; MÜLLER et al., 2016). Souza (2006) presents an overview of the processes that lead the transition of forested areas into degraded land and secondary growth in Brazilian Amazon, his proposal is summarised in Figure 4.13. In this case study we show that a LUC Calculus expression is able to identify areas that follow this proposal in a simple and precise way.

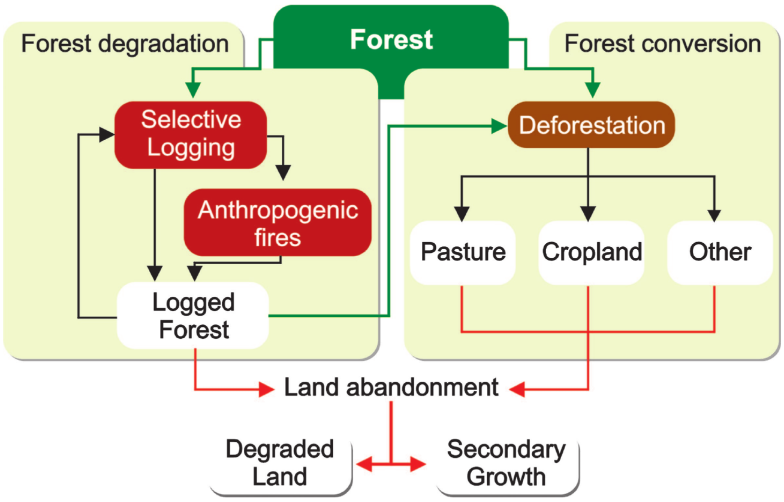
To single out secondary vegetation, we use the full history of the study area as a set of land use trajectories. For an area to be singled out as secondary vegetation, the location has to be associated to transitions of land use change in previous years. For example, an area which was forest from 2001 to 2005, then converted to pasture from 2006 to 2010, later abandoned and where forest regrew between 2010 and 2016, will be recognised as secondary vegetation of 2010 to 2016. Table 4.6 shows the expression used to uncover areas of secondary vegetation from the data set as can be seen in Figure 4.14. It should be noticed that the original maps do not have the class “secondary vegetation” explicitly. Using a LUC Calculus expression we were able to mine these locations.

Figure 4.12 - Land use in Itanhangá, MT, from 2001 to 2016.



SOURCE: Author.

Figure 4.13 - A process of transition of forest into degraded land and secondary vegetation.



SOURCE: Souza (2006).

Table 4.6 - LUC Calculus expression including areas of secondary vegetation.

Searching for all forest areas that have been replaced by pasture, *cerrado*, single cropping or double cropping and turned into forest areas again.

$\forall\ l \in L, t_1 = [2001, 2002], \forall\ t_i \in T, t_i \neq t_1,\ RECUR(l, \text{“}Forest\text{”}, t_1, t_i)\ \wedge$

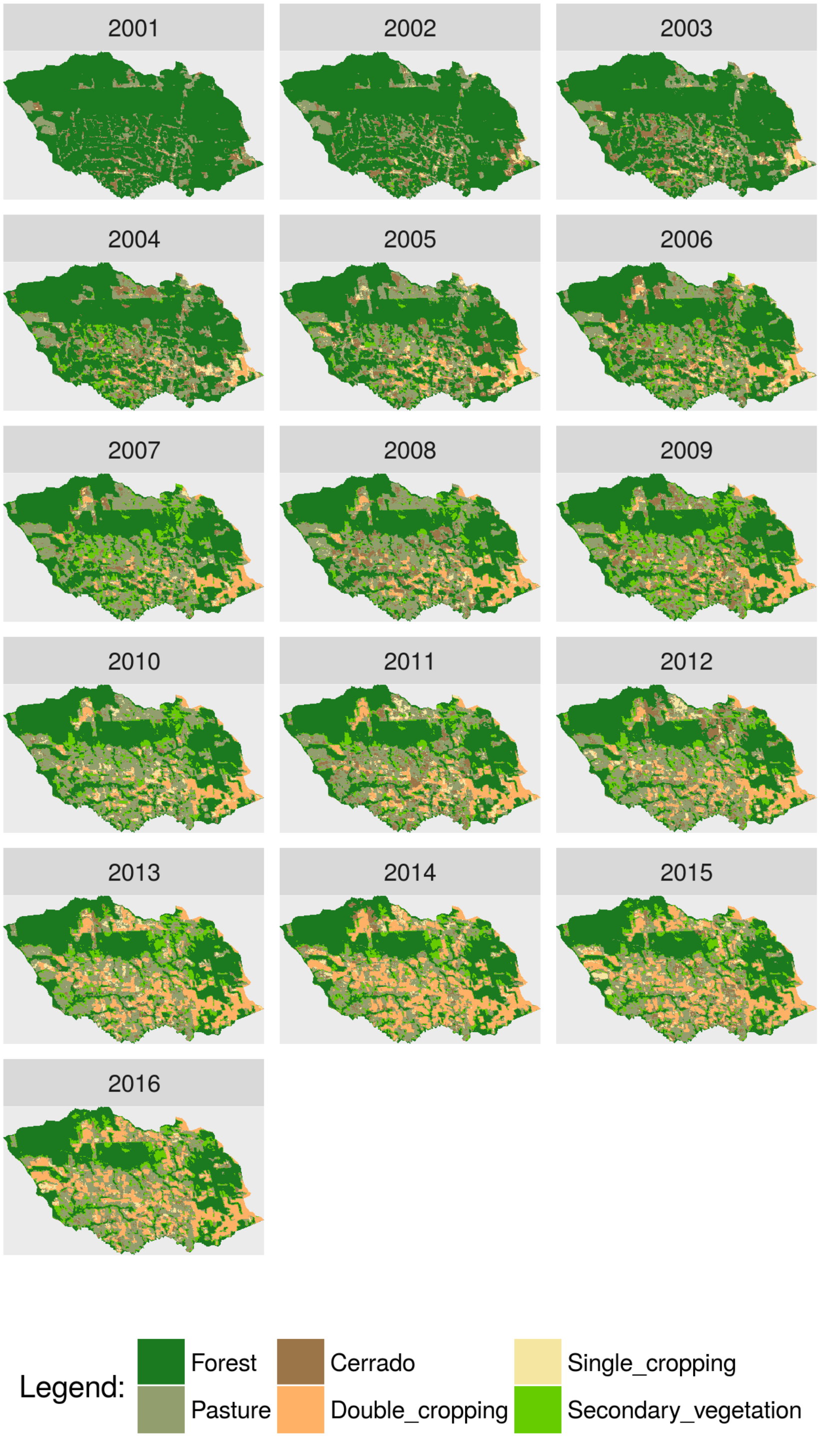
$(\ EVOLVE(l, \text{“}Pasture\text{”}, t_1, \text{“}Forest\text{”}, t_i)\ \vee$

$EVOLVE(l, \text{“}Cerrado\text{”}, t_1, \text{“}Forest\text{”}, t_i)\ \vee$

$EVOLVE(l, \text{“}Single\_cropping\text{”}, t_1, \text{“}Forest\text{”}, t_i)\ \vee$

$EVOLVE(l, \text{“}Double\_cropping\text{”}, t_1, \text{“}Forest\text{”}, t_i)\ )$

Figure 4.14 - Itanhangá from 2001 to 2016, reclassified with the new class secondary vegetation.



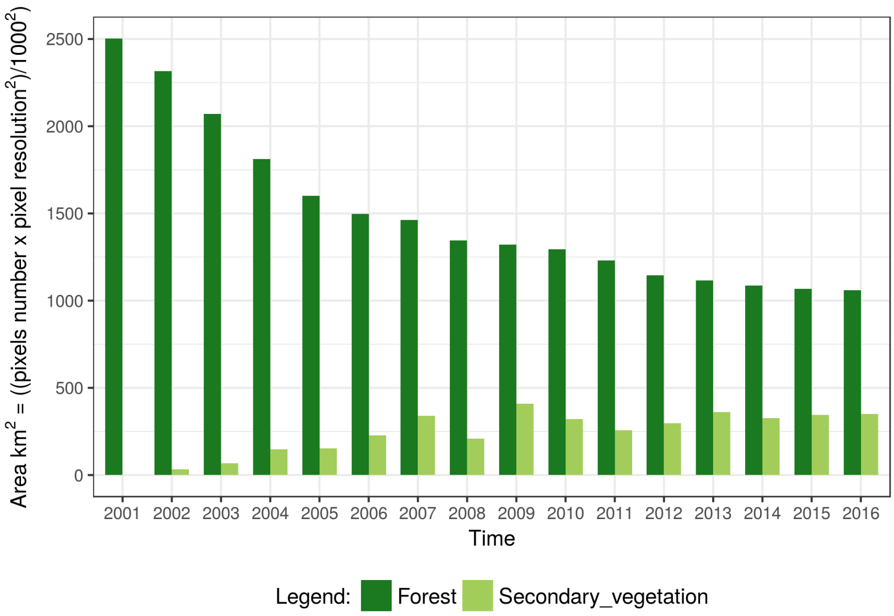
SOURCE: Author.

To quantify these land use changes we can also use a LUC Calculus expression. Table 4.7 shows the expression to discover locations classified as forest or secondary vegetation. Figure 4.15 presents the total area of secondary vegetation since 2002 and the amount of forest from 2001 to 2016.

Table 4.7 - LUC Calculus expression to select secondary vegetation and forest locations.

Search for all secondary vegetation locations. $\forall\ l \in L, \forall\ t_j \in T, HOLDS(l, \text{“}Secondary\_vegetation\text{”}, t_j)$ $where\ t_j = [2002, 2016]$
Search for all forest locations that weren't replaced by other land use. $\forall\ l \in L, \forall\ t_i \in T, HOLDS(l, \text{“}Forest\text{”}, t_i)\ where\ t_i = [2001, 2016]$

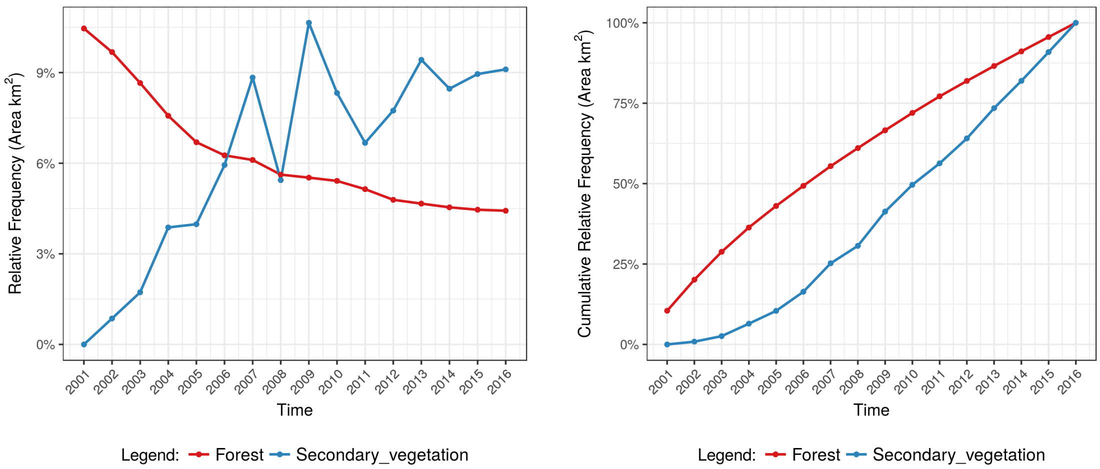
Figure 4.15 - Total area of forest and secondary vegetation in Itanhangá from 2001 to 2016.



SOURCE: Author.

These results show that a significant portion of the deforested areas were abandoned and started to regrow. To analyse statistically the results we can quantify the growth or decrease of a given land use class using the measures: Growth Rate (GR), Compound Annual Growth Rate (CAGR), Relative Frequency (RF) and Cumulative Relative Frequency (CRF) (as defined by the Appendix A). With these estimates we intend to describe differences due to change over time and trends. Figure 4.16 shows the RF and CRF for both land use forested area and secondary vegetation.

Figure 4.16 - Relative and cumulative frequency of forest and secondary vegetation in Itanhangá.



(a) Relative frequency.

(b) Cumulative relative frequency.

SOURCE: Author.

The Table 4.8 presents percentages that includes GR, CARG and CRF for forest from 2001 to 2016 and secondary vegetation from 2002 to 2016. The growth rate of locations of forested area between 2001 and 2008 decreased 46% and 20% more between 2009 to 2016. The CAGR provides a mean annual growth rate and revels that in the period from 2001 to 2008 forest decrease 8% per year. However, secondary vegetation GR between 2002 and 2008 is 532%, and constant growth in the first period. Considering the CRF until 2008, forest area lost 61% of natural hedge. The growth of secondary vegetation was slow in initial years of the study period, with a rapid growth from year 2007 on.

Table 4.8 - Quantification of loss and gain of forest and secondary vegetation in Itanhangá.

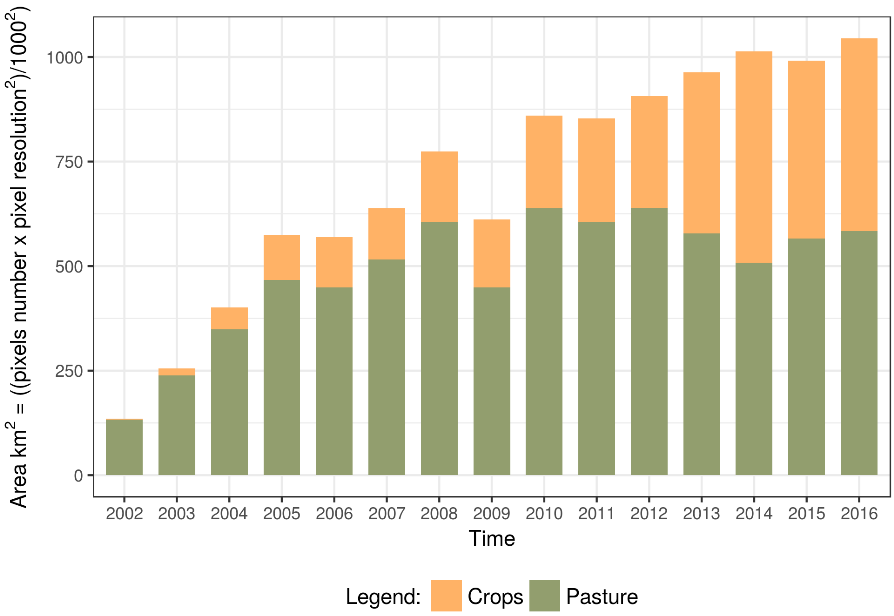
Period	Forest (%)			Secondary vegetation (%)		
	GR	CAGR	CRF	GR	CAGR	CRF
2001(2) – 2008	-46,25	-8,48	61,04	532,14	35,97	30,65
2009 – 2016	-19,84	-3,11	–	-14,48	-2,21	–
2001(2) – 2016	-57,68	-5,57	100,00	958,27	18,35	100,00

Using the data set which divides the forest areas into mature forest and the secondary vegetation, we can explore the transitions of deforested area. We use the LUC Calculus to find out locations that were converted from mature forest into pasture or crops after 2001. Table 4.9 shows the LUC Calculus expression to represent this question. Figure 4.17 presents the amount of mature forest converted to each major land use. As the results show, in the early 2000s the deforested areas were used for cattle raising and since the late 2000s, these pasture areas are being converted for crop production. Figure 4.18 shows the RF and CRF for pasture and crop area.

Table 4.9 - LUC Calculus expression to select forest areas turned into pasture or crops.

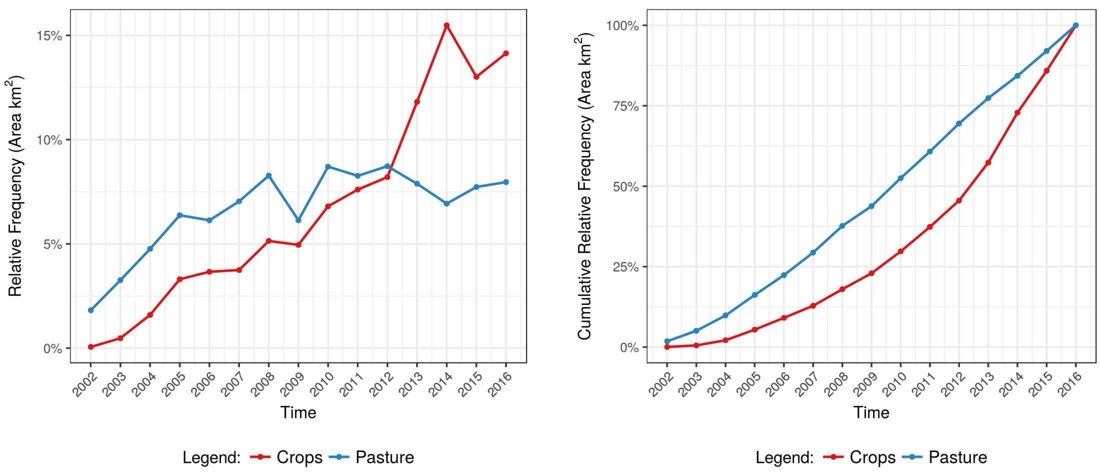
Search for all locations have been deforested after 2002 and turned into pasture or crops. $\forall\, l \in L, \forall\, t_i, t_j \in T, HOLDS(l, \text{“}Forest\text{”}, t_i) \wedge (HOLDS(l, \text{“}Pasture\text{”}, t_j) \vee HOLDS(l, \text{“}Crops\text{”}, t_j)) \wedge FOLLOWS(t_i, t_j)$ $where\ t_i = [2001, 2002], t_j = [2002, 2016]$

Figure 4.17 - Forest areas converted into pasture or crop in Itanhangá.



SOURCE: Author.

Figure 4.18 - Relative Frequency for pasture and crops in Itanhangá.



(a) Relative frequency.

(b) Cumulative relative frequency.

SOURCE: Author.

Table 4.10 presents percentages of crop and pasture transitions using GR, CARG and CRF, from 2002-2016 (15 periods) considering two land use crops and pasture. The compound annual growth rate (CAGR) from 2002-2016 to crop expansion was around 48%. This period can be divided in two intervals, 2002-2008 and 2009-2016, on basis of the soy moratorium. The period from 2002-2008 had 110% of growth, however, the interval 2009-2016 had 16% growth. These results show that most crops expansion happened in the first time interval when the municipality started the agriculture expansion. For pasture class was computed 11% annual growth in area for pasture expansion between 2002-2016. Desegregating this growth into two periods, for 2002-2008, the pasture expansion counted 28% of the growth. However, after year 2008 the growth production declined around 4%. It reveals a large amount of forest areas turned in pasture during 2002-2008, before the moratorium.

Table 4.10 - Quantification of gain of crops and pasture in Itanhangá.

Period	Crops (%)			Pasture (%)		
	GR	CAGR	CRF	GR	CAGR	CRF
2002 – 2008	8580,55	110,42	17,99	355,23	28,73	37,66
2009 – 2016	185,45	16,16	–	29,83	3,80	–
2002 – 2016	23775,0	47,86	100,00	338,19	11,13	100,00

4.5.1 Understanding Land Use Transitions in Itanhangá

Besides quantifying the amount of land uses, it is also important to understand the influences of land use change on different environment aspects such as climate variability, water resources and food production, in order to improve the management of these resources (ZHAO et al., 2016). To do that, it is relevant to study the sequence of land use transitions. For example, we might be interested in discover mature forest areas that have been converted into pasture in a time span of one year, we call these "direct transitions". In this case study we select the following direct transitions to be highlighted:

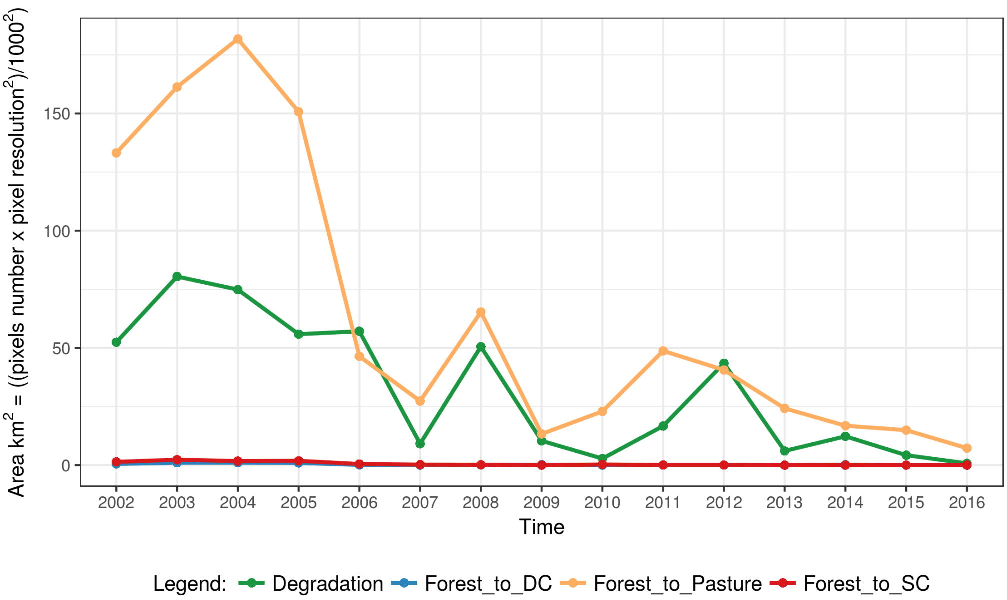
- forest to pasture;
- forest to *cerrado* (*Degradation*);
- forest to single cropping;
- forest to double cropping;
- pasture to single cropping;
- pasture to double cropping;
- pasture to secondary vegetation;
- single cropping to double cropping;
- secondary vegetation to single cropping;
- secondary vegetation to double cropping;
- secondary vegetation to pasture.

Table 4.11 shows a part of the LUC Calculus expression used to highlight a set of direct land use transitions. Than we quantified the total of area of each direct transition per year, as shown in Figure 4.19. It is possible to see that there was an intense deforestation in early 2000's mainly to be converted to pasture and *cerrado* (degradation). Between 2002 to 2007 the reduction in forested areas was around of 79%. This data also suggests that *Cerrado* land use class, in this study area, is an intermediate use before being used for pasture, and not the vegetation characteristic of the Cerrado biome. For this reason, the land use transition "Forest to Cerrado" was renamed to *Degradation* and represents a heavy forest degradation. In other words, we can indicate that deforestation in the initial years of the study period is due to an extensive pasture expansion for cattle production.

Table 4.11 - LUC Calculus expression to select land use sequential transitions in Itanhangá, from 2001 to 2016.

Search for all land use class converted by other over the years since 2001
$\forall\ l \in L, \forall\ t_i = [t_{2001}..t_{2015}], t_j = [t_{2002}..t_{2016}] \in T,$
$CONVERT(l, \text{“}Forest\text{”}, t_i, \text{“}Pasture\text{”}, t_j)$
...
$\forall\ l \in L, \forall\ t_i = [t_{2001}..t_{2015}], t_j = [t_{2002}..t_{2016}] \in T,$
$CONVERT(l, \text{“}Secondary\_vegetation\text{”}, t_i, \text{“}Pasture\text{”}, t_j)$

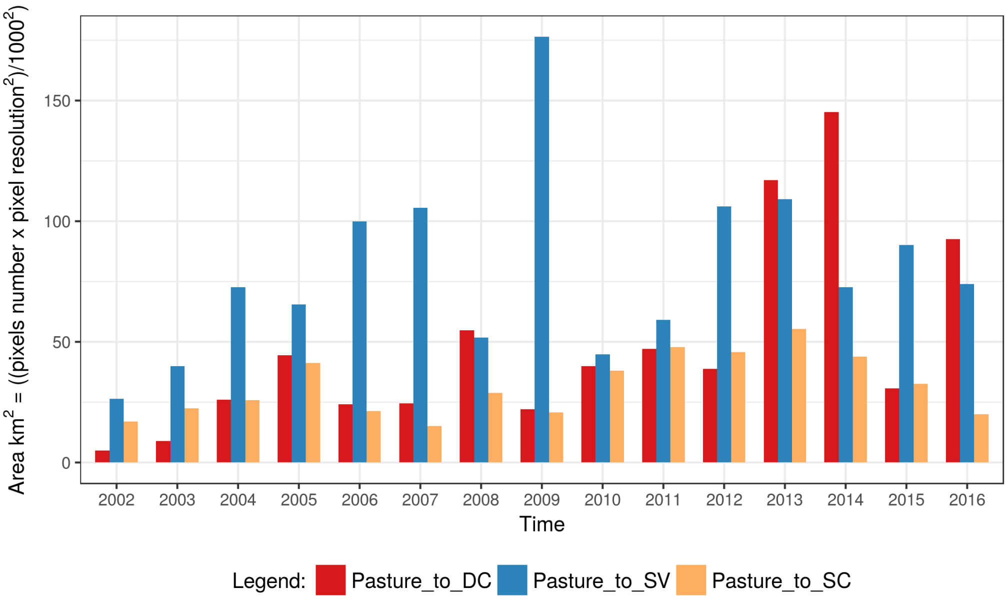
Figure 4.19 - Deforestation in Itanhangá.



SOURCE: Author.

Similarly, in Figure 4.20 we quantify the direct transition of pasture areas to single cropping (SC), double cropping (DC) and secondary vegetation (SV). It indicates that a large portion of pasture areas begun to regenerate to natural vegetation, mainly in the periods of 2006, 2007, 2009, 2012 and 2013. As for the direct transition of pasture to croplands, in early 2000's we can see the introduction of double cropping immediately after being used for pasture, which is not the usual practice when deforestation is carried on in small farms. This process remains stable until 2012, from 2013 on it becomes more strong.

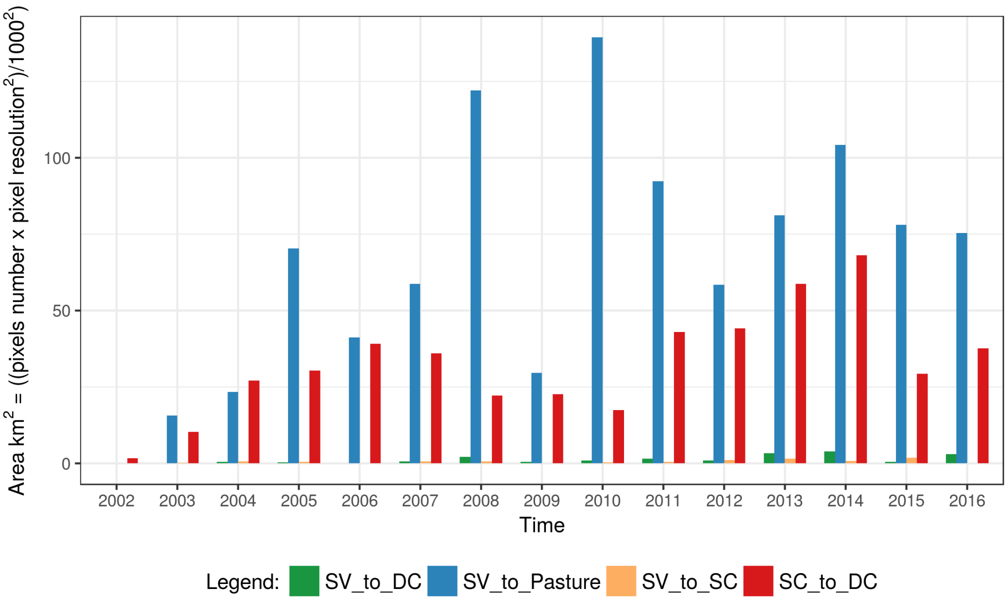
Figure 4.20 - Pasture transitions in Itanhangá.



SOURCE: Author.

Figure 4.21 shows the direct transitions of secondary vegetation to pasture, single cropping and double cropping. It also shows the transition from single cropping to double cropping. In this case, we want to highlight secondary vegetation areas that in some period of time had recovered their natural vegetation, but then soon were converted to cropping or pasture. Until 2010 we notice a growing tendency in secondary vegetation areas that have been directly converted to pasture. After this process seems to become more stable. This result also shows that secondary vegetation areas that had been converted into single cropping or double cropping are not as significant. Single cropping areas converted into double cropping had variations during the study period, with a growth acceleration from 2011 on.

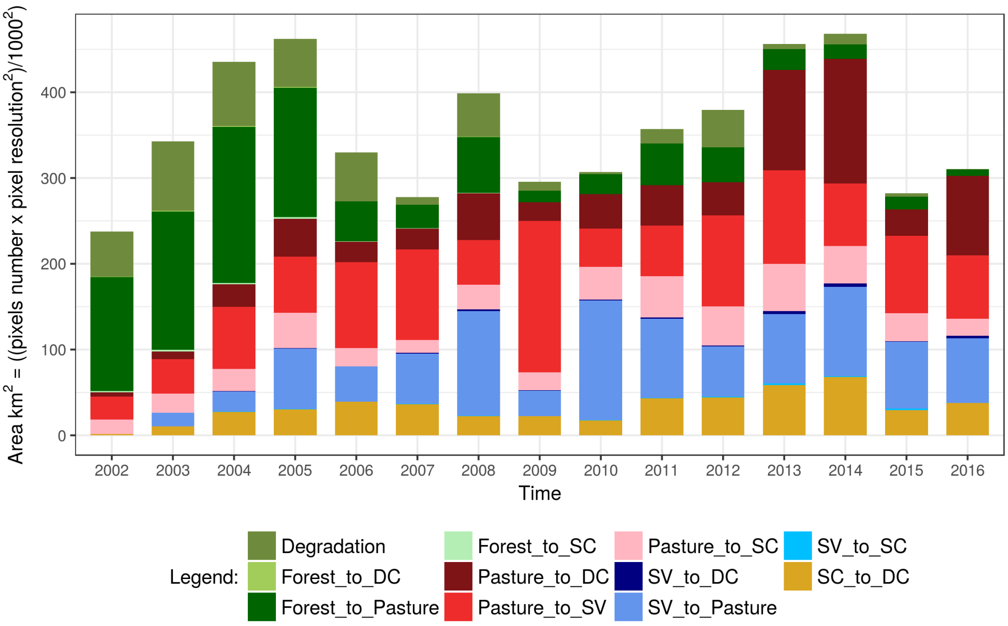
Figure 4.21 - Secondary vegetation and crop transitions in Itanhangá.



SOURCE: Author.

We also show all the transitions in a single chart in Figure 4.22. We can see that in initial years of the study period forest areas were converted in pasture, from 2008 to 2013, on many secondary vegetation areas were converted in pasture, and from 2013, on pasture areas were converted to double cropping. An interesting fact that can be observed is a decreasing of forest areas converted to pasture over the years, this is probably due to policies such as the soy moratorium.

Figure 4.22 - Direct land transitions in Itanhangá.

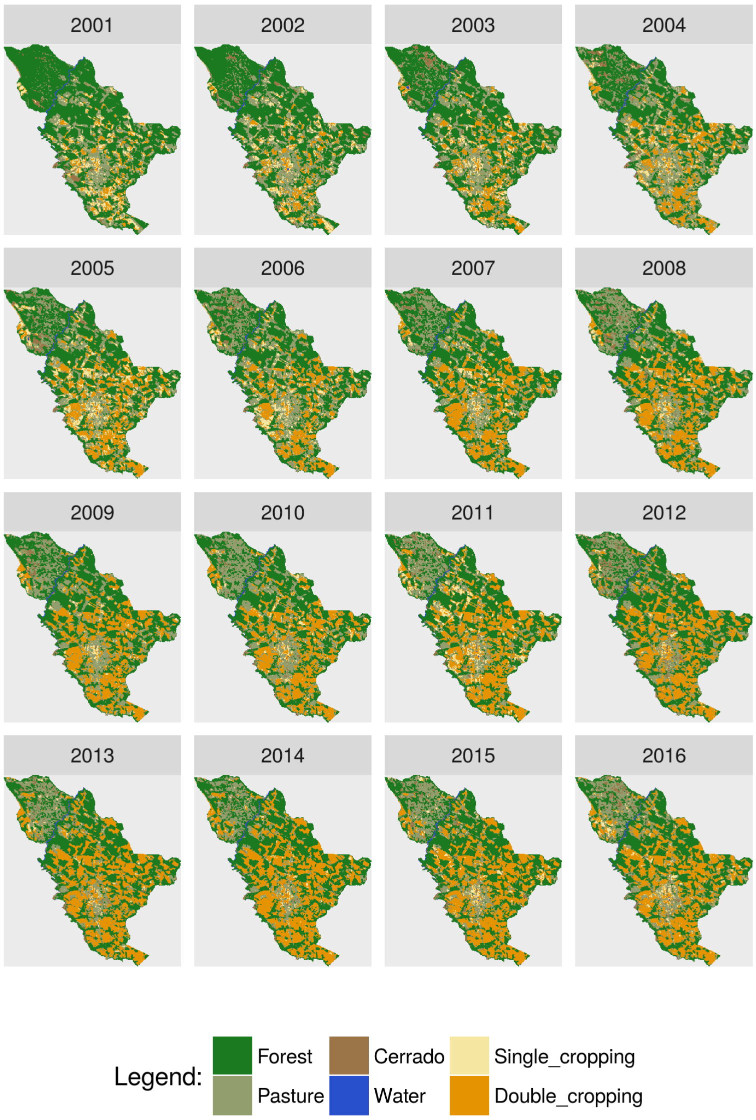


SOURCE: Author.

4.6 Case Study 2: Land Use Changes in Sinop

The second case study is the municipality of Sinop. It has an area of 3,942 km^2 and had a population of 113,099 inhabitant in 2010 (IBGE, 2016). 73,784 time series were classified to generate the land use trajectories for the period from 2001 to 2016, see Figure 4.23.

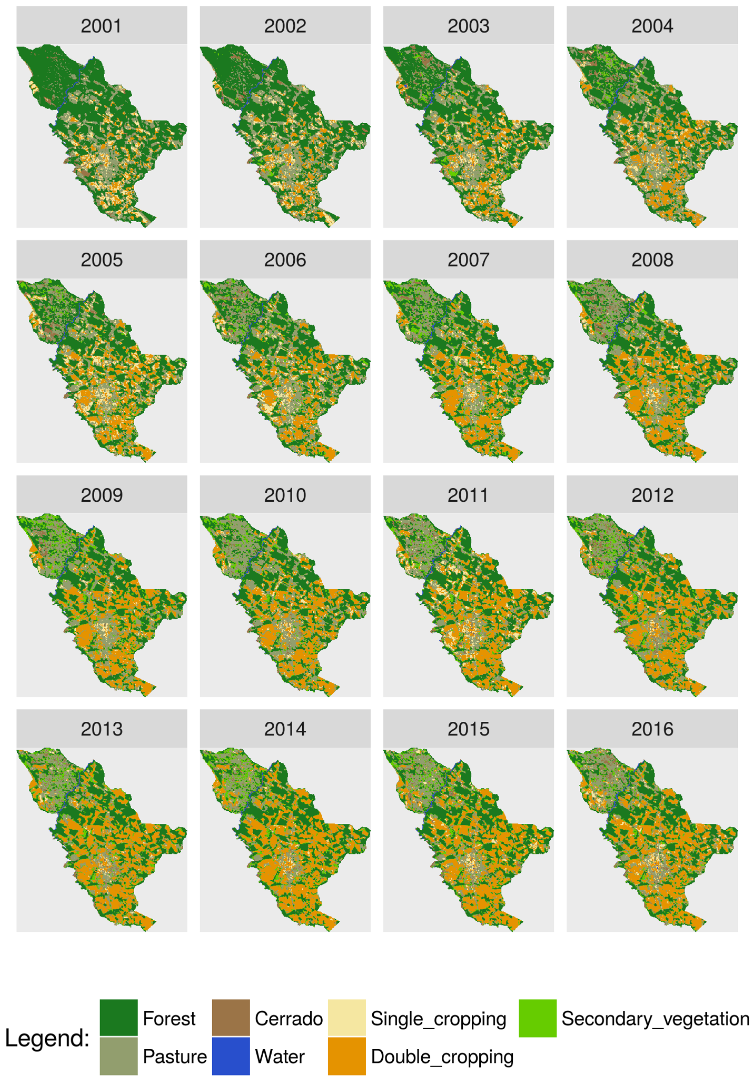
Figure 4.23 - Land use in Sinop, MT, from 2001 to 2016.



SOURCE: Author.

Differently from Itanhangá, that in 2000 showed the beginning of the pasture and croplands expansions, in Sinop we can see the existence of crops early in the study period. Sinop is one of the centres of crop production along the Cuiabá-Santarém highway (BR-163) in central Mato Grosso state (MORTON et al., 2006; BROWN et al., 2013). A massive removal of the mature forest was performed in the last decade. We applied a LUC Calculus expression to distinguish between mature forest and secondary vegetation, see Figure 4.24.

Figure 4.24 - Sinop from 2001 to 2016, reclassified with the new class secondary vegetation.



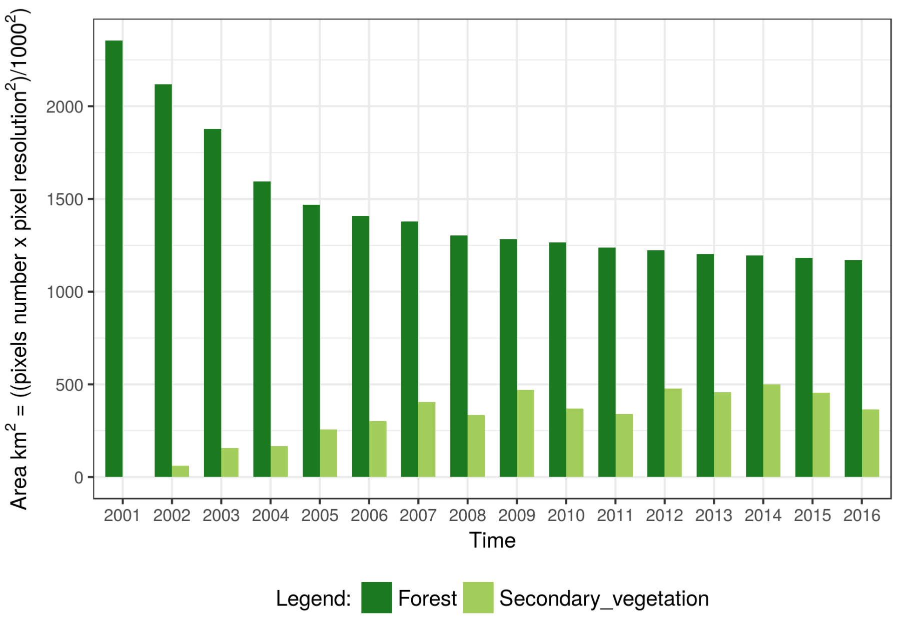
SOURCE: Author.

Using the data set that differentiate mature forest from secondary vegetation we applied the LUC Calculus to quantify forest and secondary vegetation areas, Table 4.12 and Figure 4.25 show the result of this expression. We can see that the majority of deforestation occurred from 2001 to 2006, after the year 2006 the deforestation has reached stable point due to control of forest loss policies, while secondary vegetation presents an increasing tendency due to farmland abandonment, fallow periods or unsuitable topography can result in the establishment of secondary vegetation on pastures and cropping areas (MÜLLER et al., 2016). Figure 4.26 shows the proportion (in percentage terms) of the two classes.

Table 4.12 - LUC Calculus expression to select secondary vegetation and forest locations.

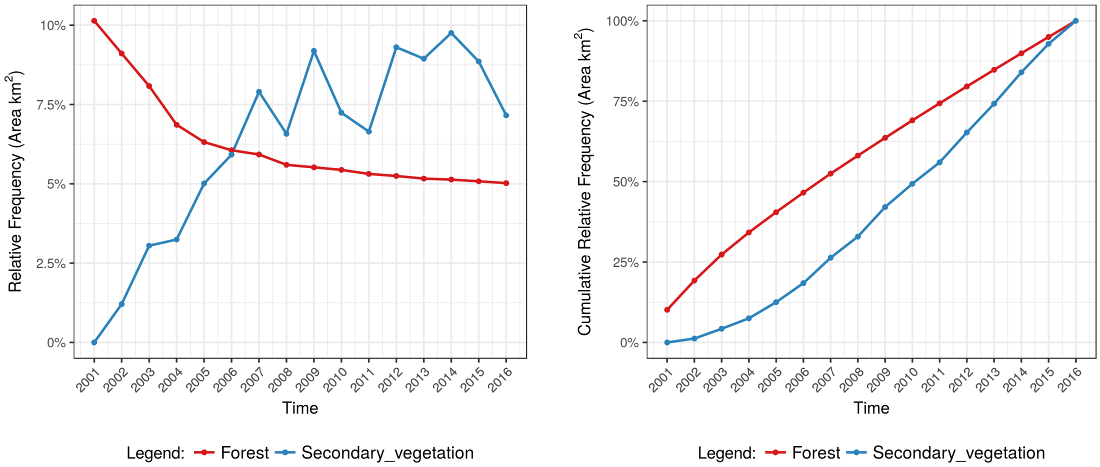
Search for all forest and secondary vegetation areas hold during the study period.
$\forall\ l \in L, \forall\ t_i \in T, HOLDS(l, \text{“}Forest\text{”}, t_i)\ \vee$
$HOLDS(l, \text{“}Secondary\_vegetation\text{”}, t_i),\ where\ t_i = [2001, 2016]$

Figure 4.25 - Total area of forest and secondary vegetation in Sinop from 2001 to 2016.



SOURCE: Author.

Figure 4.26 - Relative and cumulative frequency of forest and secondary vegetation in Sinop.



(a) Relative frequency.

(b) Cumulative relative frequency.

SOURCE: Author.

The Table 4.13 quantify the estimators used to analyse our results (GR, CARG and CRF) for forested areas from 2001 to 2016 and secondary vegetation from 2002 to 2016. In this result we see a considerable area of mature forest was deforested between 2001 to 2008 with 44% of the original covered by other land use with a annual rate around 8% per year, and growth rate of more 9% in second period. Considering all complete study period (between 2001 and 2016), lost was approximately 50% of the forest cover in Sinop. Secondary vegetation shows a slow growth during the years. The CAGR from 2002 to 2016 shows a growth rate of 492% of secondary vegetation area, with an annual rate of 13%. The most growth occurred during the first period from 2002 to 2008.

Table 4.13 - Quantification of loss and gain of forest and secondary vegetation in Sinop.

Period	Forest (%)			Secondary vegetation (%)		
	GR	CAGR	CRF	GR	CAGR	CRF
2001(2) – 2008	-44,78	-8,13	58,08	444,12	32,62	32,90
2009 – 2016	-9,01	-1,34	–	-22,10	-3,50	–
2001(2) – 2016	-50,46	-4,57	100,00	492,44	13,55	100,00

Considering that Sinop already have a large portion of its territory deforested we focused our study to discover single and double cropping agricultural systems that succeeded pasture in the year 2001. Table 4.14 expresses this question using the LUC Calculus. Figure 4.27 quantify the amount of pasture area have been turned into each type of agricultural practice during the years. The results show a large portion of pasture areas were transformed in double cropping during the period from 2002 to 2016. From 2005 on the double cropping increased its expansion, and became the dominant agriculture system in Sinop while single cropping system decreased. Figure 4.28 shows the relative and cumulative frequencies, it is possible to see the expansion of double cropping over the years.

Table 4.14 - LUC Calculus expression to select pasture areas turned into crops.

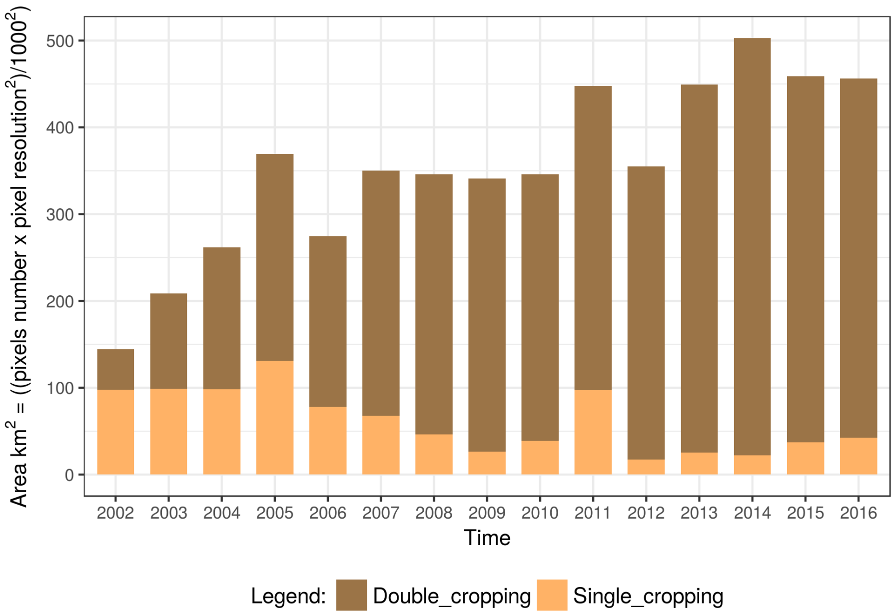
Search for all locations of pasture areas have been turned into single or double cropping from 2002.
$\forall\ l \in L, \forall\ t_i = [2001, 2002], t_j = [2002, 2016] \in T,$
$EVOLVE(l, \text{“}Pasture\text{”}, t_i, \text{“}Single\_cropping\text{”}, t_j) \vee$
$EVOLVE(l, \text{“}Pasture\text{”}, t_i, \text{“}Double\_cropping\text{”}, t_j)$

Table 4.15 quantify some measures for the study period. The CAGR from 2002 to 2016 shows a decreasing in single cropping practices (-5,74%) whereas double cropping has grown 543 percent between 2002 and 2008.

Table 4.15 - Quantification of gain and loss of single and double cropping in Sinop.

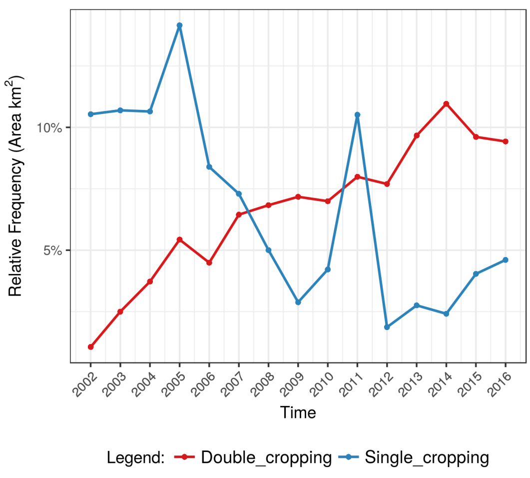
Period	Single cropping (%)			Double cropping (%)		
	GR	CAGR	CRF	GR	CAGR	CRF
2002 – 2008	-52,50	-11,66	66,71	543,31	36,37	30,48
2009 – 2016	59,75	6,92	–	31,40	3,97	–
2002 – 2016	-56,30	-5,74	100,00	787,44	16,87	100,00

Figure 4.27 - Pasture areas converted into crops in Sinop.

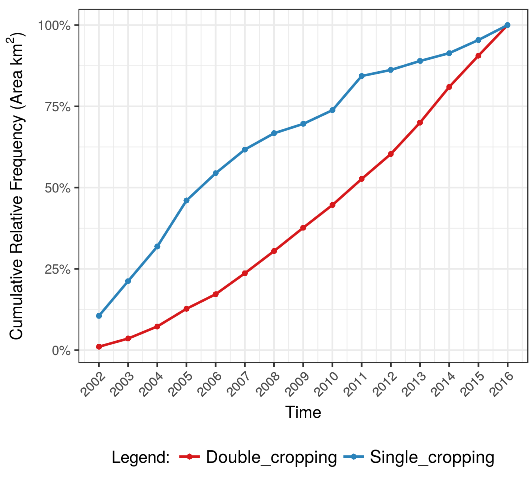


SOURCE: Author.

Figure 4.28 - Relative Frequency for single and double cropping in Sinop.



(a) Relative frequency.



(b) Cumulative relative frequency.

SOURCE: Author.

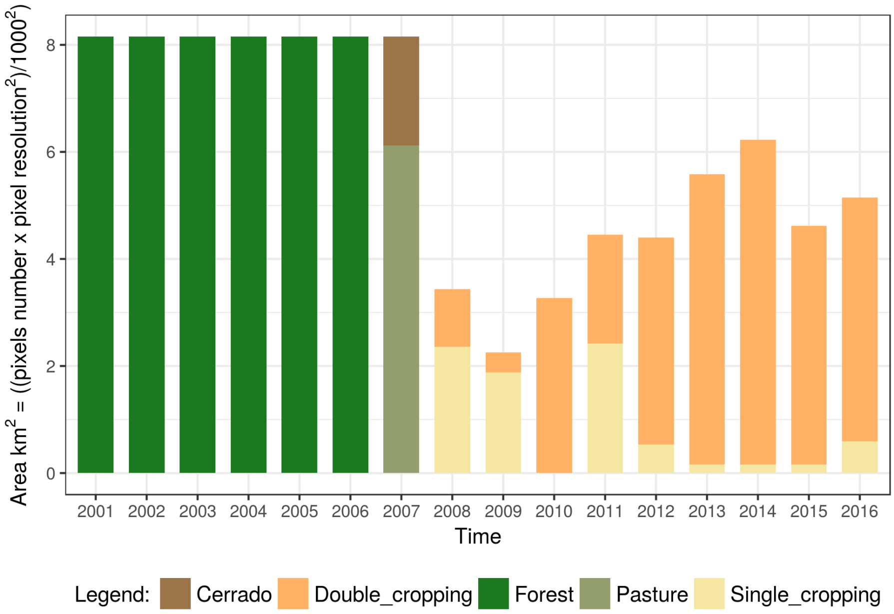
Other interesting question is about crops that had been arisen after pasture or *cerrado* areas, since the pasture or *cerrado* areas had been initially forested areas. To express this question we consider three time intervals: from 2001 to 2006 to identify forest areas, from 2006 to 2007 forested locations converted to pasture or *cerrado* areas, and from 2007 to 2016 crops evolved of pasture or *cerrado* areas.

Table 4.16 expresses this question in terms of the LUC Calculus, and Figure 4.29(a) quantify the total of land use that satisfy this expression. Figure 4.29(b) shows different locations with this land use along the time, and the transitions are not homogeneous in space and non-linear in time. Based on this result we note that single cropping is the agricultural system selected for use in areas previously occupied by pasture or *cerrado* lands, then double cropping system turned more significant.

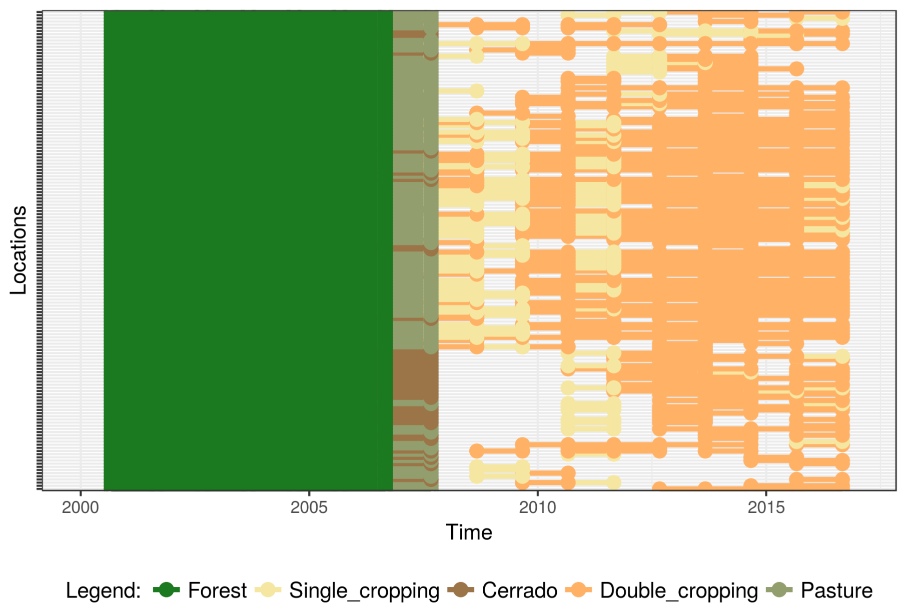
Table 4.16 - LUC Calculus expression to select crops evolved from forest in Sinop.

Search for all forest areas have been converted into pasture or *cerrado*,
and after evolved to single or double cropping after the year 2007.
$\forall\ l \in L, \forall\ t_i = [2001, 2006], t_j = [2006, 2007], t_k = [2007, 2016] \in T,$
$HOLDS(l, \text{“}Forest\text{”}, t_i)\ \wedge$
$(CONVERT(l, \text{“}Forest\text{”}, t_i, \text{“}Pasture\text{”}, t_j)\ \vee$
$CONVERT(l, \text{“}Forest\text{”}, t_i, \text{“}Cerrado\text{”}, t_j))\ \wedge$
$(EVOLVE(l, \text{“}Pasture\text{”}, t_j, \text{“}Single\_cropping\text{”}, t_k)\ \vee$
$EVOLVE(l, \text{“}Pasture\text{”}, t_j, \text{“}Double\_cropping\text{”}, t_k))\ \wedge$
$(EVOLVE(l, \text{“}Cerrado\text{”}, t_j, \text{“}Single\_cropping\text{”}, t_k)\ \vee$
$EVOLVE(l, \text{“}Cerrado\text{”}, t_j, \text{“}Double\_cropping\text{”}, t_k))$

Figure 4.29 - Direct transition of forest to pasture or *cerrado*, and also indirect transition from forest to crops.



(a) Transitions from forest to crops.



(b) Sequence of locations with forest evolved in crops along time.

SOURCE: Author.

4.6.1 Understanding Land Use Transitions in Sinop

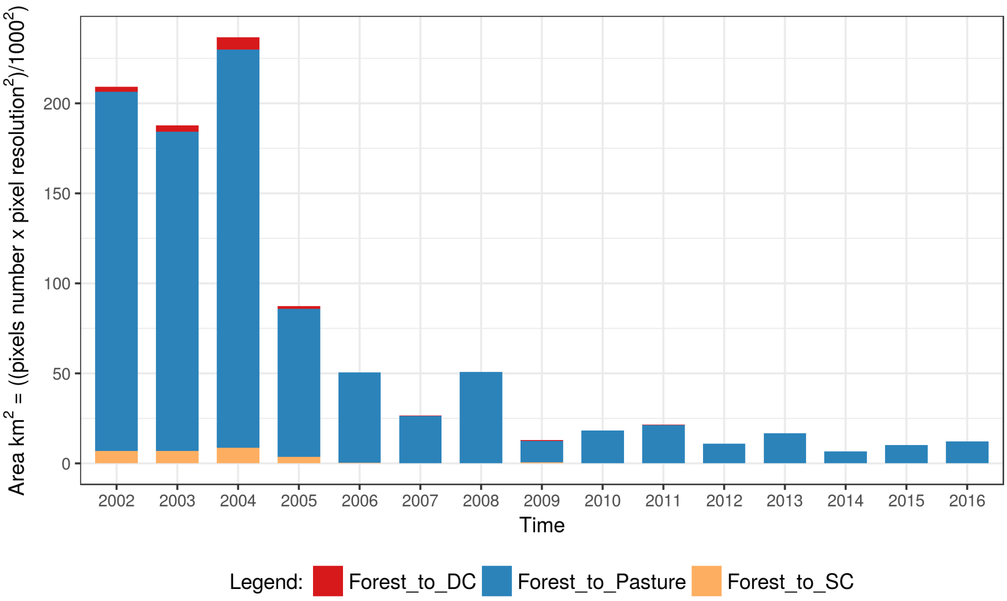
Following the same line of reasoning applied in the previous study case, we apply the LUC Calculus expression (presented in the Table 4.11) in order to identify a sequence of land use transitions. Specifically for this case study, our main interest is to highlight direct transitions involving crop and pasture expansion:

- forest to pasture;
- forest to single cropping;
- forest to double cropping;
- pasture to single cropping;
- pasture to double cropping;
- pasture to secondary vegetation;
- single cropping to double cropping;
- secondary vegetation to single cropping;
- secondary vegetation to double cropping;
- secondary vegetation to pasture.

Figure 4.30 shows the amount of forest converted into pasture, single cropping and double cropping. Based on this result we note that in the early years a large portion of forest was direct converted into pasture, mainly during the period of 2002 to 2004. After these years there was a sharp decline in deforestation expansion until it became stable. Direct conversion of forest to croplands occurred only in the initial years, but in terms of area are not significant.

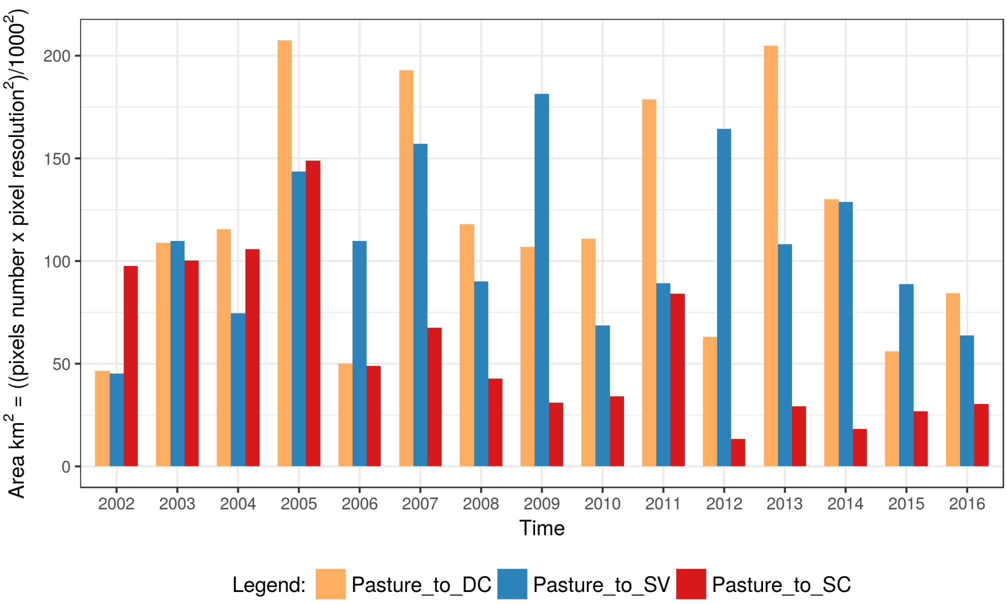
Figure 4.31 shows the land use transitions from pasture to single cropping, double cropping and secondary vegetation. The direct transitions of pasture to double cropping happened mainly in the years 2005, 2007, 2011 and 2013. The transitions of pasture to single cropping remains low in comparison with the pasture to double cropping. It is possible see a significant number of pasture areas converted to secondary vegetation.

Figure 4.30 - Deforestation in Sinop.



SOURCE: Author.

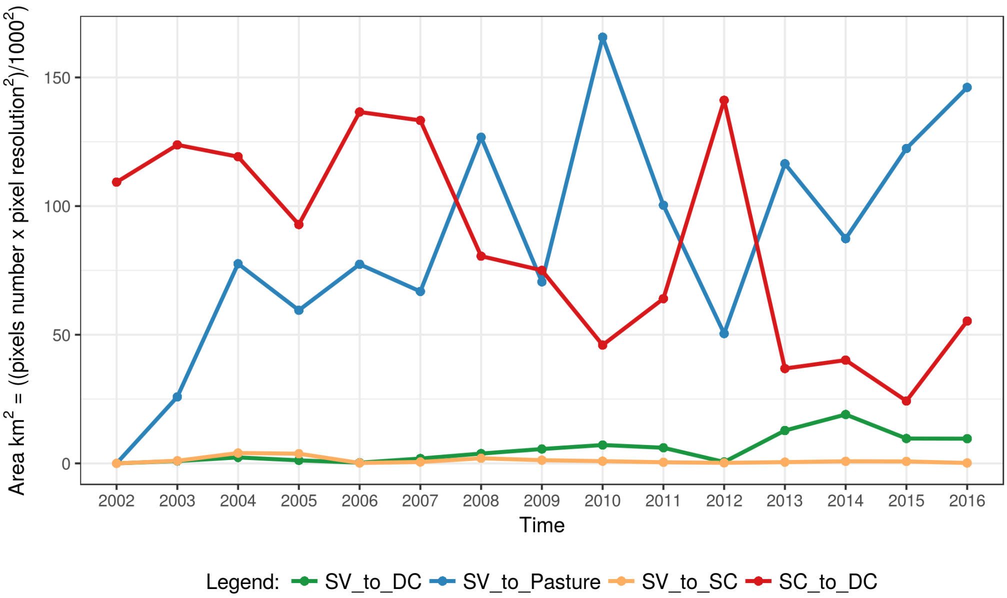
Figure 4.31 - Pasture transitions in Sinop.



SOURCE: Author.

Figure 4.32 is associated with transition of secondary vegetation turned into pasture, single cropping and double cropping, and also transition between single to double cropping. The direct transition from secondary vegetation to pasture presented a major growth over the years. However, the transition from single cropping to double cropping has a large number of areas changed from 2002 to 2007, after this period some variations occurred during the years. The transitions from secondary vegetation to double cropping have happened with more frequency after 2012.

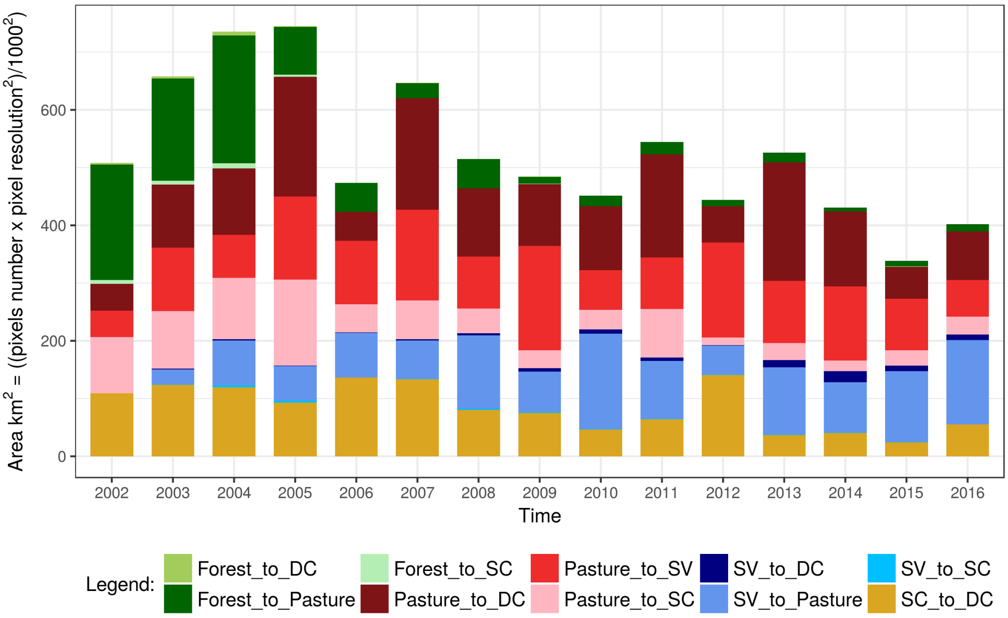
Figure 4.32 - Secondary vegetation and crop transitions in Sinop.



SOURCE: Author.

Figure 4.33 shows an overview that include all direct transitions presented previously. We see that a large number of transitions from pasture to croplands, in special to double cropping. The establishment of secondary vegetation on pasture areas is also significant. In this study area we can also observe the main direct land use transitions concentrate from pasture to crops or secondary vegetation to pasture.

Figure 4.33 - Direct land transitions in Sinop.

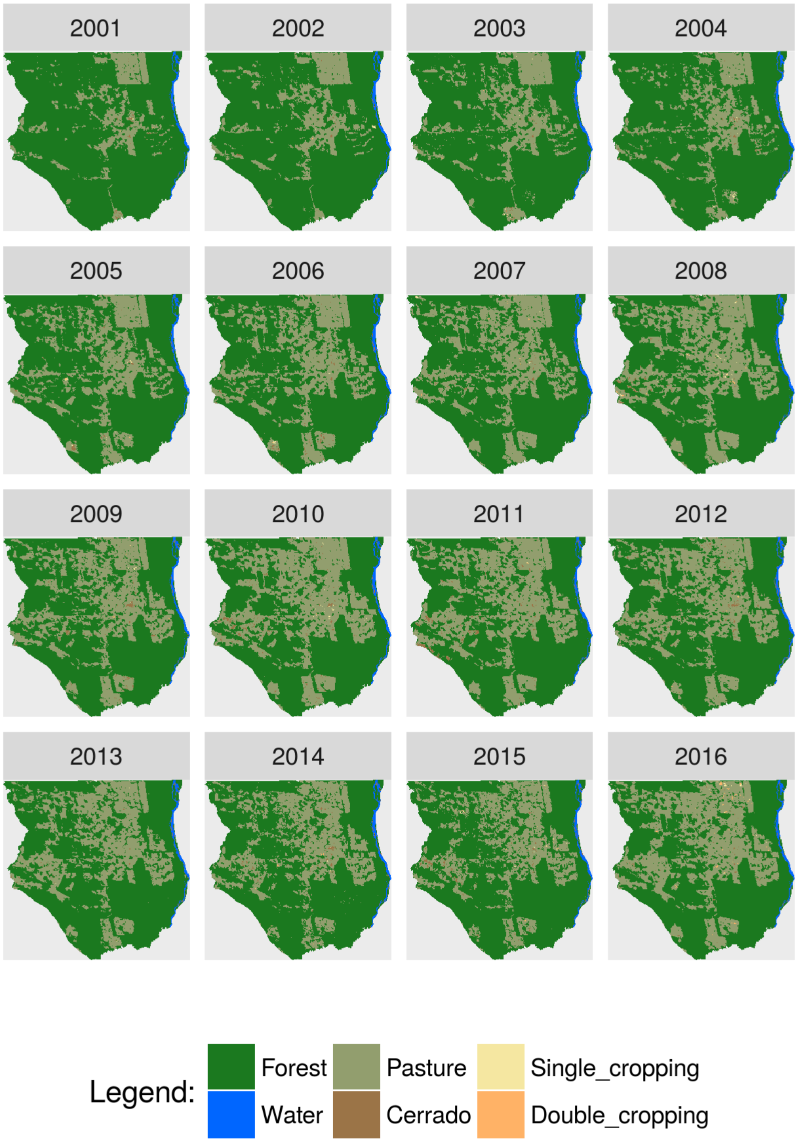


SOURCE: Author.

4.7 Case Study 3: Land Use Changes in Juruena

The third case study is the municipality of Juruena. It has an area of 2,778 km^2 and population of 11,201 inhabitant in 2010 (IBGE, 2016). 51,964 long-term time series were classified to generate the land use trajectories for the period from 2001 to 2016, as shown in Figure 4.34.

Figure 4.34 - Land use in Juruena, MT, from 2001 to 2016.



SOURCE: Author.

We can observe a massive conversion of forest areas to pasture during the study period with almost half of the forest totally removed. Studies show that deforestation for cattle pasture predominated in the northern portion of the Mato Grosso state, where Juruena is located (MORTON et al., 2006; ARVOR et al., 2013; PARENTE et al., 2017). The deforested areas turned into pasture expansion, small-scale agriculture and some forest regeneration. The first LUC Calculus expression is used to distinguish between mature forest and secondary vegetation (see Figure 4.35).

In Table 4.17 we show the LUC Calculus expression to quantify mature forest and secondary vegetation areas, with the results shown in Figure 4.36. In the Figure 4.37 we notice that the deforestation rate remained between 9% and 5% during the study period, but secondary vegetation rate increased 431% between 2002 and 2008 (Table 4.18). These results highlights the pasture expansion and a rapid rate of forest loss during the study period in this area.

Table 4.17 - LUC Calculus expression to select secondary vegetation and forest locations in Juruena.

Search for all forest and secondary vegetation areas hold from 2001 to 2016.

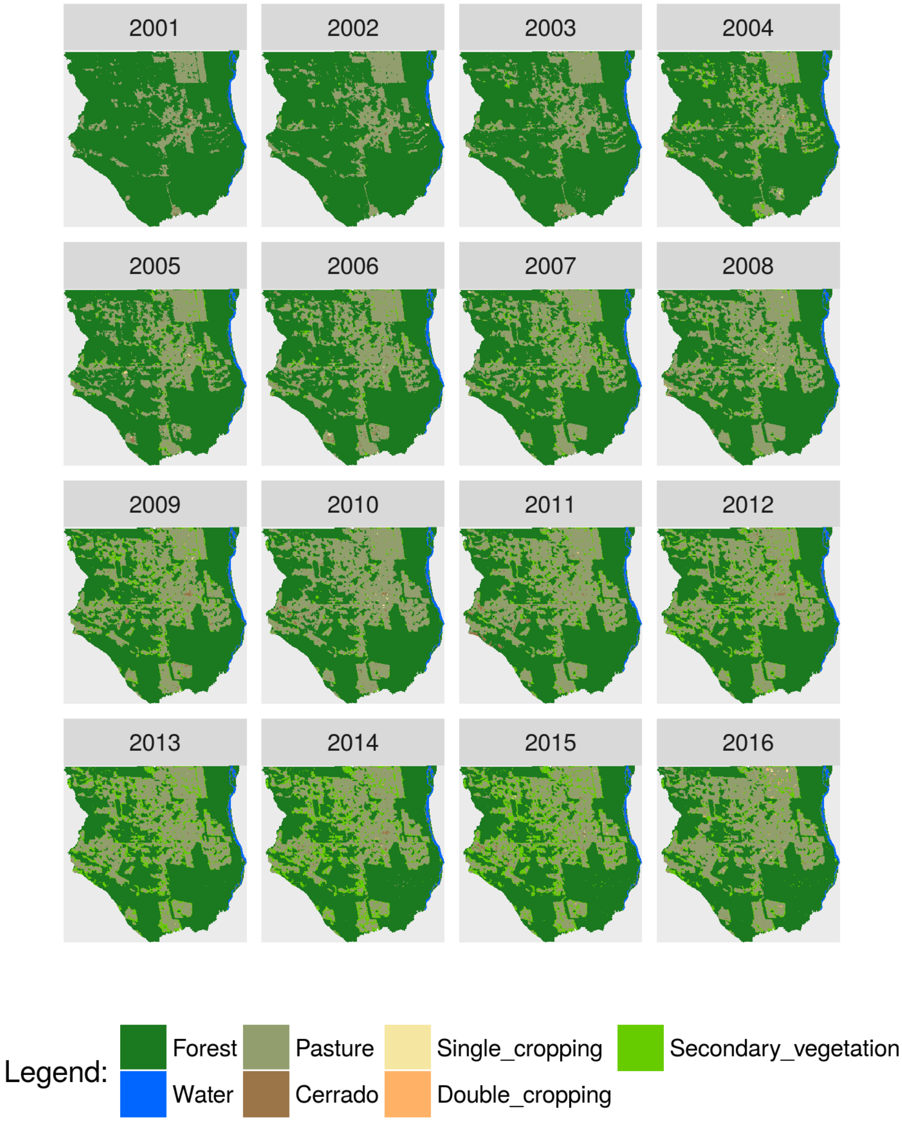
$\forall\ l \in L, \forall\ t_j \in T, HOLDS(l, \text{“}Forest\text{”}, t_j) \vee$

$HOLDS(l, \text{“}Secondary\_vegetation\text{”}, t_j),\ where\ t_j = [2001, 2016]$

Table 4.18 - Quantification of loss and gain of forest and secondary vegetation in Juruena.

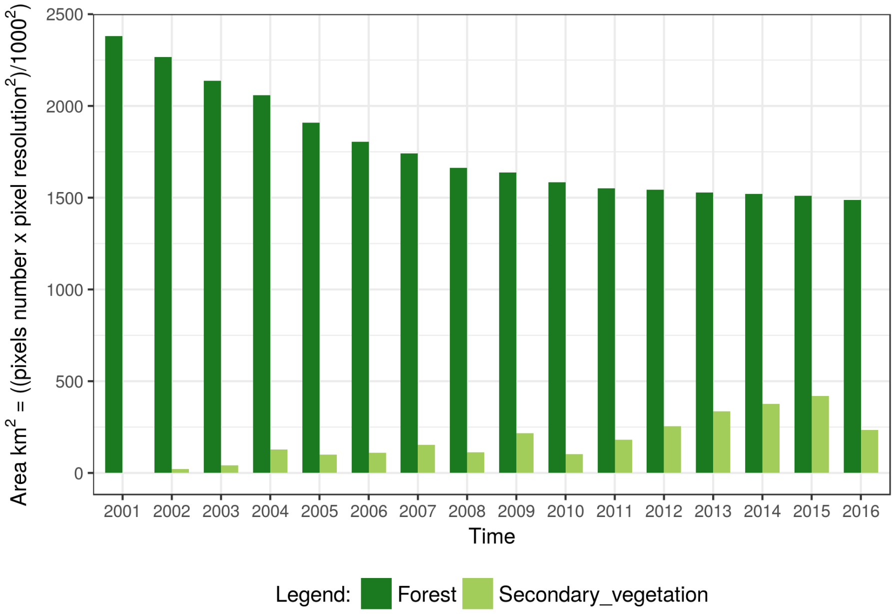
Period	Forest (%)			Secondary vegetation (%)		
	GR	CAGR	CRF	GR	CAGR	CRF
2001(2) – 2008	-30,20	-5,00	56,34	431,63	32,10	23,86
2009 – 2016	-9,09	-1,35	–	7,81	1,08	–
2001(2) – 2016	-37,47	-3,08	100,00	1008,16	18,74	100,00

Figure 4.35 - Juruena from 2001 to 2016, reclassified with the new class secondary vegetation.



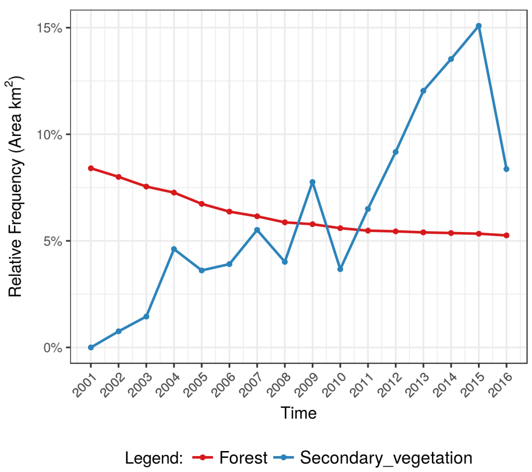
SOURCE: Author.

Figure 4.36 - Total area of forest and secondary vegetation in Juruena from 2001 to 2016.

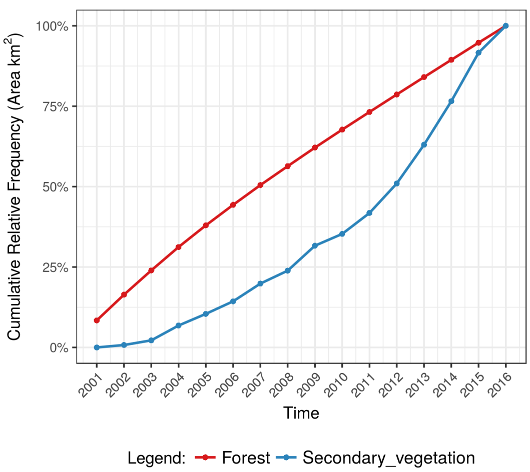


SOURCE: Author.

Figure 4.37 - Relative and cumulative frequency of forest and secondary vegetation in Juruena.



(a) Relative frequency.



(b) Cumulative relative frequency.

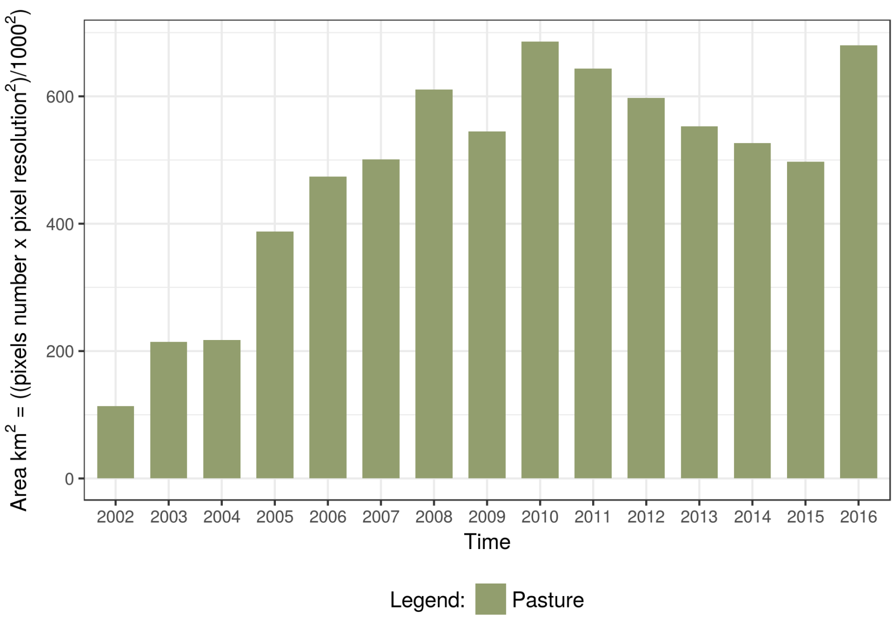
SOURCE: Author.

In this case study a particular emphasis is given on pasture expansion. Our next question searches for pasture areas that have been emerged after 2001. Table 4.19 expresses the LUC Calculus and Figure 4.38 quantify the pasture areas in km^2. We can observe the pasture areas expanded, from 2005 to 2010 is possible to see a rapid growth of pasture expansion. Between 2002 and 2008 the growth rate was 439,5% whereas between 2009 and 2016 the growth rate was 24,83%. CARGs from 2002 to 2008 and from 2009 to 2016 were 34,32 per cent and 3,21 per cent respectively. For entire study period, between 2002 and 2016, the growth rate was 500,61%.

Table 4.19 - LUC Calculus expression to select pasture areas evolved from forest in Juruena.

Search for all locations of forest areas have been turned into pasture after of the year 2002.
$\forall\ l \in L, \forall\ t_i = [2001, 2002], t_j = [2002, 2016] \in T,$
$EVOLVE(l, \text{``}Forest\text{''}, t_i, \text{``}Pasture\text{''}, t_j)$

Figure 4.38 - The area of pasture evolved from forest in Juruena.



SOURCE: Author.

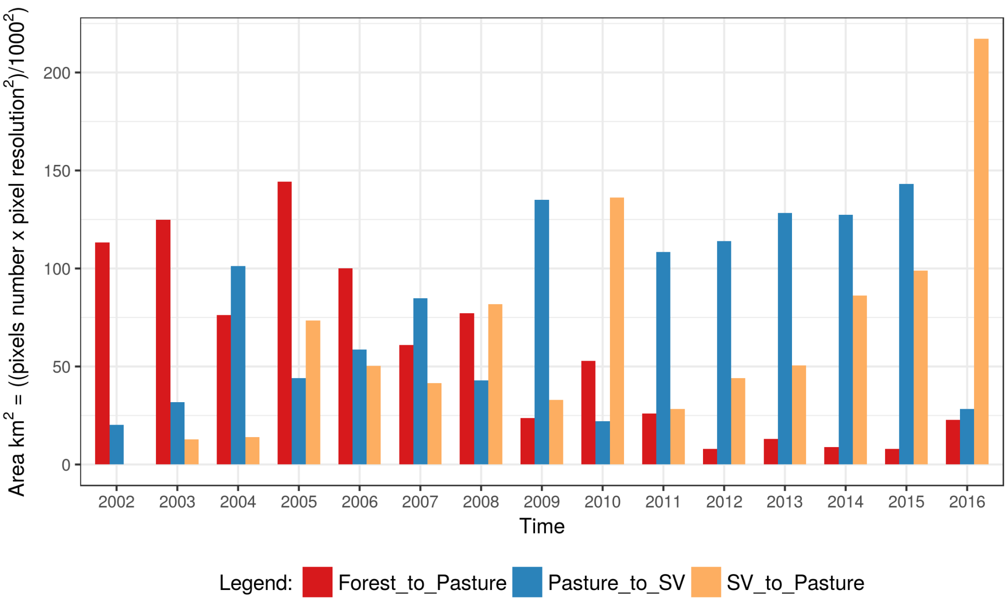
4.7.1 Understanding Land Use Transitions in Juruena

In this study area we investigate direct transitions trends associated with deforestation that has been caused by pasture expansion. We followed the same formalism built in the LUC Calculus expression showed in the Table 4.11. We focused mainly on land use transitions:

- forest to pasture;
- pasture to secondary vegetation;
- secondary vegetation to pasture.

Figure 4.39 shows the land use transitions of forest areas that has been direct converted to pasture, pasture to secondary vegetation, and its inverse transition. We can observe that the conversion of forest to pasture was the main transition that occurred in the initial eight-year period. While the direct conversion of pasture to secondary vegetation occurred more frequently from 2004, with a considerable expansion until 2015, except by the year of the 2010. Significant conversion of secondary vegetation to pasture occurred in 2010 and 2016.

Figure 4.39 - Direct land transitions in Juruena.



SOURCE: Author.

4.8 Soy Moratorium Effects in Sinop and Itanhangá

For this analysis we reorganised our original land use classes (see Figure 4.11) in order to identify the effects of soy moratorium (RUDORFF et al., 2011; GIBBS et al., 2015) in Sinop and Itanhangá municipalities. In this study we are interested in mining the only soybean crops reduction or expansion over deforested areas before and after 2006. We expand the idea of Maus (2016), who proposed a rule for detecting soy moratorium effects in the Amazon biome region of the Mato Grosso state. Table 4.20 shows a re-aggregation of the 15 original land use classes in 6 classes of interest. All soybean crops, regardless of agricultural practices, are grouped in a single class "soybean".

Table 4.20 - Land use classes re-aggregated to emphasise soybean crops.

Aggregated class	Original classes
Forest	Forest
Pasture	*Pasture1*, *Pasture2* and *Pasture3*
Cerrado	Cerrado
Crops	*Fallow_Cotton* and *Crop_Cotton*
Soybean	*Soybean_Cotton*, *Soybean_Crop1*, *Soybean_Crop2*, *Soybean_Crop3*, *Soybean_Crop4*, *Soybean_Fallow1* and *Soybean_Fallow2*
Water	Water

We derived the LUC Calculus expression to represent three data sets of interest: *1)* search for all locations of forest directly converted to pasture; *2)* search all locations of forest directly converted to soybean; *3)* search for all locations of soybean crop that: *a)* at any moment in the past were pasture areas, and *b)* these locations were deforested before or after 2006. There are two results for the third questions, one with all soybean crop areas that have emerged from deforested occurred before 2006 and another with soybean areas emerged from deforested areas after 2006. Table 4.21 shows these expressions.

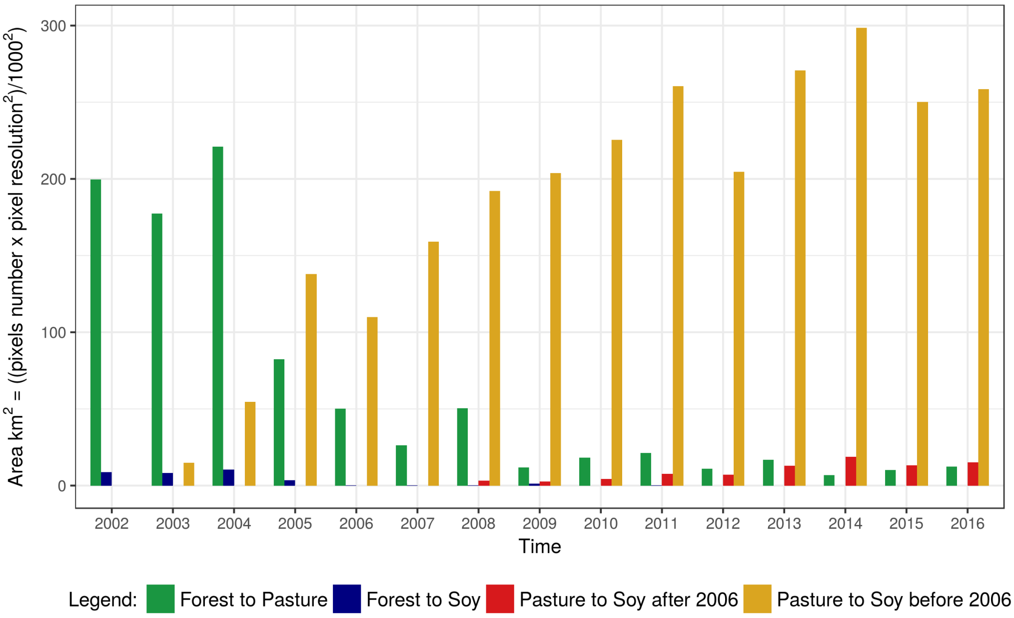
Table 4.21 - LUC Calculus expressions to select land use transitions relevant to study soy moratorium effects.

Search for all locations where its land use class changed from forest to pasture or soybean since 2001.
$\forall\ l \in L, \forall\ t_i = [t_{2001}..t_{2015}], t_j = [t_{2002}..t_{2016}] \in T,$
$CONVERT(l, \text{"}Forest\text{"}, t_i, \text{"}Pasture\text{"}, t_j)$
...
$\forall\ l \in L, \forall\ t_i = [t_{2001}..t_{2015}], t_j = [t_{2002}..t_{2016}] \in T,$
$CONVERT(l, \text{"}Forest\text{"}, t_i, \text{"}Soybean\text{"}, t_j)$
Search for all soybean locations that have been converted from pasture and deforested before or after 2006.
Forest → Pasture, occurred before 2006, → Soybean
$\forall\ l \in L, \forall\ t_i = [t_{2003}..t_{2016}], t_j = [t_{2001}..t_{2006}] \in T, HOLDS(l, \text{"}Soybean\text{"}, t_i) \wedge$
$HOLDS(l, \text{"}Pasture\text{"}, t_j) \wedge HOLDS(l, \text{"}Forest\text{"}, t_j) \wedge PRECEDES(t_i, t_j)$
Forest → Pasture, occurred after 2006, → Soybean
$\forall\ l \in L, \forall\ t_i = [t_{2008}..t_{2016}], t_j = [t_{2006}..t_{2015}] \in T, HOLDS(l, \text{"}Soybean\text{"}, t_i) \wedge$
$HOLDS(l, \text{"}Pasture\text{"}, t_j) \wedge HOLDS(l, \text{"}Forest\text{"}, t_j) \wedge PRECEDES(t_i, t_j)$

In Figure 4.40 we observe that in Sinop a large quantity of soybean crops emerged in areas deforested before 2006, suggesting that the soy moratorium had a positive impact in Sinop to reduce deforestation.

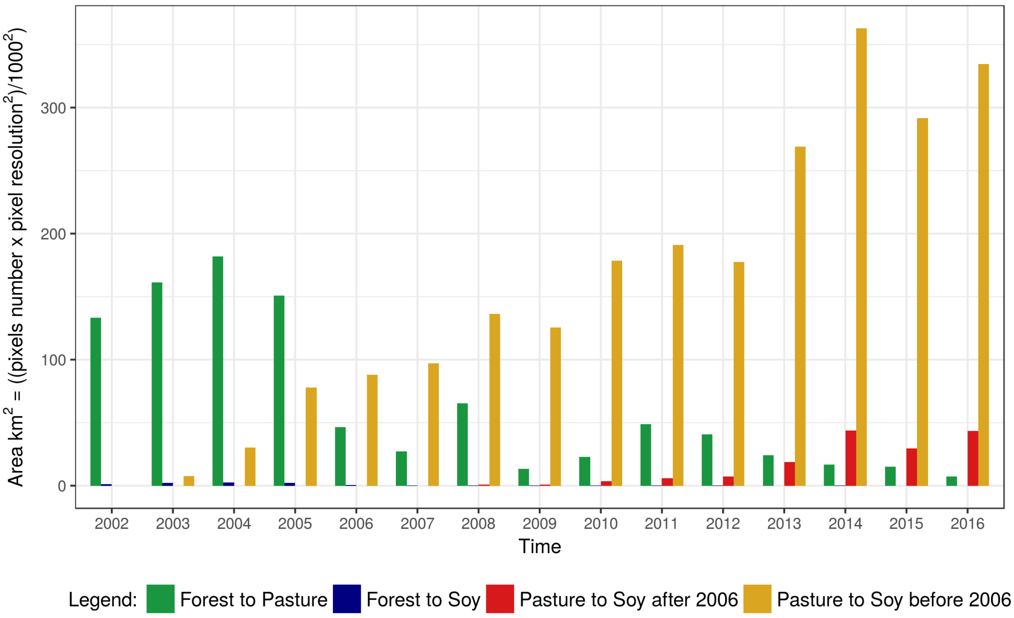
Figure 4.41 summarises the resulting data sets in terms of the area associated with each transitions along the years in Itanhangá. From 2006 on there is a significant reduction of the amount of area deforested to be used as pasture. The majority of the soybean crops has emerged from pasture areas that followed deforestation before 2006, i.e. they do not break the terms of the moratorium. However, from the year 2013 on we can note soybean crops appearing in areas that were deforested after 2006.

Figure 4.40 - Land use transitions from 2002 to 2016 in Sinop.



SOURCE: Author.

Figure 4.41 - Land use transitions from 2002 to 2016 in Itanhangá.



SOURCE: Author.

4.9 Discussion

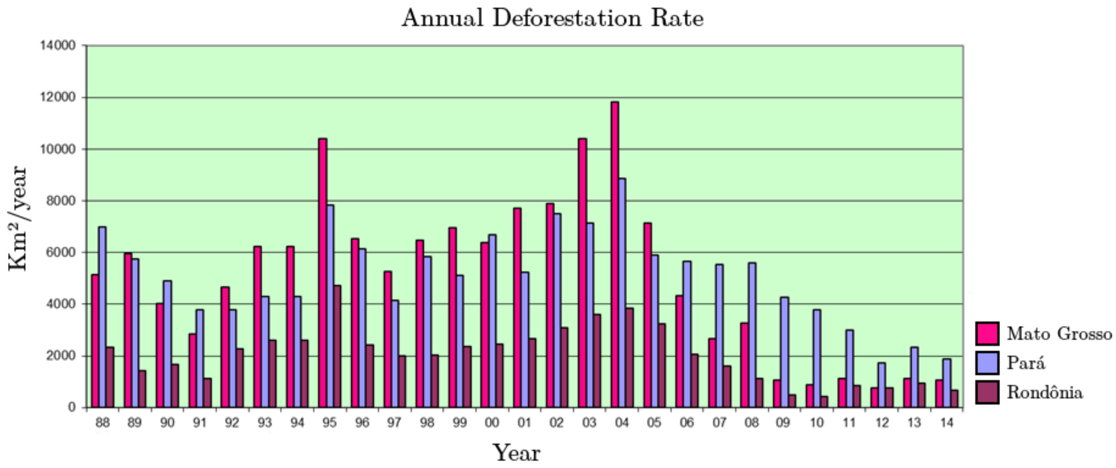
In the three case studies presented in this Chapter we show how the LUC Calculus can be flexible and efficient to study land use changes. It allows scientists to easily express questions about particular transitions, quantify results or highlight scenarios. In our case studies we reason about land use trajectories derived from classified images generated from the analysis of MOD13Q1 product time series. As the case studies were conducted in areas situated in the Mato Grosso state, it was possible to highlight the extent and rapidity of the expansion of agriculture and pasture from 2001 to 2016.

The human activity expansion over the study areas caused the environmental impacts of land use in the Amazon biome. Our results show that the major influence of deforestation was caused by pasture expansion for cattle raising and later the use these pasture lands to agricultural expansion as can be observed in Figures 4.14 and 4.24. Although changes in deforestation can be attributed to a wide range of factors, for instance, macroeconomic impacts to the Brazilian economy and international exchange rates, land tenure arrangements and policy failures are also significant factors (OMETTO et al., 2011). Some studies argued that cattle ranching is the most important land use after deforestation in the Amazon region (SOUZA, 2006), and that the expansion of soybean crops in this biome is considered as the last economic cycle involving new migrations to still unexplored areas (ARVOR et al., 2013).

The use of LUC Calculus expressions to distinguish between secondary vegetation and mature forest allows the confirmation that the decreasing in deforestation coincided with the beginning of the soy moratorium in 2006 and in 2008 when it was renewed with the Brazilian government as an additional signatory. Our results show the reduction in annual deforestation rate occurred after implementation of the initiative to reduce the deforestation of the Amazon, this decreased has been reported by Boucher et al. (2013), DeFries et al. (2013) and Kastens et al. (2017), and also has been confirmed by PRODES for entire Mato Grosso state (see Figure 4.42).

However, our results also indicate that deforestation is still happening after soy moratorium initiative. In the results shown in section 4.8 we observe the existence of soybean crop emerged in areas deforested after 2006, mainly from the year 2013 on for both Sinop and Itanhangá municipalities. These results show that although policies such as the soy moratorium has been reached impacts on soybean and deforestation dynamics in the study areas, government efforts to monitor properties where there are soybean crops derived from illegal land clearing are needed.

Figure 4.42 - The evolution of clear-cut deforestation from 1988 to 2014.



SOURCE: Adapted from INPE (2017).

When we analyse our results considering two perspectives of time intervals, one from 2001/2002 to 2008 and another from 2009 to 2016, before and after soy moratorium renewed respectively, we can see that the growth period with more impact over forest is from 2001/2002 to 2008, which shows severe forest loss over the study areas.

Our results are in line with the works of Perz and Skole (2003), Sampaio et al. (2007) and Müller et al. (2016), which discusses about secondary vegetation had been occurred in degraded or abandoned pasture, and also occurs due to fallow land use periods or farmland abandonment. Using the LUC Calculus as support to reasoning about land use changes, our results revel that many pasture areas have been converted to secondary vegetation, corroborating with previous studies (PERZ; SKOLE, 2003; SPERA et al., 2014).

Arvor et al. (2013) reports that Mato Grosso is mainly characterised by the adoption of double cropping system. Our results show this trend in both municipalities localised in the south of Amazon biome, where is evident the selectivity for double cropping system is more pronounced that the selectivity for single cropping system (SPERA et al., 2014). Our results show, considering the study period, that in the early years there is a adoption for single cropping agricultural system, but years after, the intensive use of double cropping becomes the main agricultural system.

Our results are in accordance with studies that show spatial distribution of large clearings from 2002 to 2005 the gradual advance of deforestation into municipalities in northwest of Mato Grosso state (MORTON et al., 2006; PARENTE et al., 2017). Juruena municipality presented this type of trend. As well as, that the southern regions of Mato Grosso have been more affected by deforestation than northern areas. This is justified by the historical occupation of the state that first began with the colonisation of the Cerrado biome, located in the southern part of the state and easier to clear than forest (ARVOR et al., 2013).

4.9.1 Summary points

- Even though the deforestation was caused mainly by pasture expansion. Initiatives as soy moratorium, accomplished its objective to reduce the deforestation and has been inhibited the planting in recent deforested areas of the Amazon biome.
- Land use transitions occurred through different pathways, land use trajectories, that are necessary *a priori* knowledge about local historical and economics issues. In this work we apply only a few generic pathways of land use transitions that can be identified.
- The satisfactory application of the LUC Calculus depends on *a)* a set of key questions that can be properly performed, bring results, *b)* the properties of locations that will be identified in the data set, *c)* a combination of spatial predicates and interval predicates, and *d)* the data set with locations of different land use types.

The LUC Calculus has been proved as a useful tool to carry other studies and hypothesis about land use transitions in different study areas and classes of use.

5 CONCLUSION

This thesis introduced a spatiotemporal interval logic mechanism for reasoning about land use change dynamics, extended from Allen (1984) proposal. The approach of the formalism intents to capture the nature of transitions in big Earth observation data sets. We consider discrete transitions where one land use class is replaced by another to allow the reasoning about land use trajectories in regional and global areas. We implemented the spatiotemporal interval logic formalism using **R**, an open source programming language and a statistical environment with a big community of contributors of statistical and graphical packages. We demonstrated the potential of the formalism in 3 case studies for extracting land use transitions in the Mato Grosso state, an agricultural and pasture expansion in Brazil.

The spatiotemporal interval logic formalism is flexible. It allows scientists to express interesting questions, confirm scenarios and hypothesis and mining specific data of interest. Its new elements, such as the concept of locations and extended predicates, are useful to account for land use changes types in a long-term time series of classified imagery.

Although the formalism proposed it be independent of different methods, algorithms and techniques for time series classification from remote sensing data, our approach needs to be supported by a set of consistent and sequential land use trajectories. The quality the input classified data set, given the land use trajectories, is the main factor to the success of results of the formalism application. Thus, considerable efforts were spent to improve the classification process and its results, before we investigated the events in the data set.

A current limitation of the LUC Calculus is its reliance on a simple definition of land use events. It assumes that a land use event is defined by a single property (the label of the land use). In the more general case, it would be useful to associate different properties to events. The properties could be numerical values, ranges of values, or probabilities. Another restriction is that the current version of the LUC Calculus does not consider the events associated to the spatial neighbours of a location.

5.1 Future Work

Based on our case studies and the results of this thesis, we describe specific points for future works:

- The definition of new spatial predicates and multiple transitions for reasoning about land use change dynamic that will be able to capture more information about land use change dynamics, in the simplest way possible.
- The formalism is a local approach, where one location is analysed in time independently of its spatial context. As a future work we intend to study how to extract focal neighbourhoods to capture local spatial effects.
- In our case studies, we used only land use trajectories extracted from MODIS product MOD13Q1 data, in an annual resolution. As a future work, we intend to explore the LUC Calculus in different time granularities such as biannual or biennial, and using classified images data sets with higher spatial resolution, for example, images of Landsat satellites.
- We also intend to apply the LUC Calculus to reason about land use dynamics in national and regional scales. To include the variability of different biomes and capture interesting properties of different land use types.
- Finally, we intent to improve the **R** package to handle with spatiotemporal data set using this logic formalism. The package aims to provide a user-friendly set of functions for land use change analysis using information extracted from classified remote sensing data sets.

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APPENDIX A - STATISTICAL MEASURES

This appendix defines the four statistical measures to estimate growth rates and frequency of the results during the years, used to analyse the land use transitions in Chapter 4. With these estimates, we describe differences due to change over time and trends:

- Growth Rate (GR) (Equation A.1) - it computes the percent change from one period to another.

$$GR(t_0, t_n) = \frac{V(t_n) - V(t_0)}{V(t_0)} \tag{A.1}$$

  where:

  t_0 = first year
  t_n = last year
  $V(t_0)$ = initial value (or past value)
  $V(t_n)$ = final value (or present value)

- Compound Annual Growth Rate (CAGR) (Equation A.2), is a measure that applies a predetermined growth rate over multiple time periods.

$$CAGR(t_0, t_n) = \left(\frac{V(t_n)}{V(t_0)}\right)^{\frac{1}{t_n - t_0}} - 1 \tag{A.2}$$

  where:

  t_0 = first year
  t_n = last year
  $V(t_0)$ = initial value (or past value)
  $V(t_n)$ = final value (or present value)
  $t_n - t_0$ = number of years

- Relative Frequency (RF), is the proportion, or fraction, of the total values.
- Cumulative Relative Frequency (CRF) is the accumulation of all the relative frequencies.

ANNEX A - USING DYNAMIC GEOSPATIAL ONTOLOGIES TO SUPPORT INFORMATION EXTRACTION FROM BIG EARTH OBSERVATION DATA SETS

This annex presents a paper published in the *International Conference on GIScience Short Paper Proceedings* – GIScience 2016 (CÂMARA et al., 2016):

Using dynamic geospatial ontologies to support information extraction from big Earth observation data sets

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Abstract

This paper presents the spatiotemporal interval logic formalism and shows how to use it for reasoning about land use change using big Earth observation data. This formalism improves our ability to extract information from large land remote sensing data sets.

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Abstract

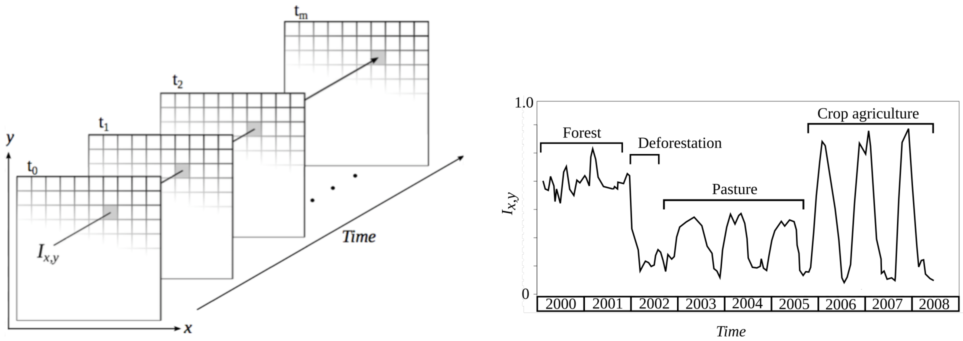
This paper presents the spatiotemporal interval logic formalism and shows how to use it for reasoning about land use change using big Earth observation data. This formalism improves our ability to extract information from large land remote sensing data sets.

1 Events as key concepts for describing land use change

Remote sensing satellites are the only source that provides consistent data about the Earth's land and oceans. The open availability of big Earth observation data has led to an opportunity to improve information on land changes in the planet. However, most studies that use remote sensing images to detect change still adopt a *snapshot* approach. Image from a sequence are classified one by one; results are compared to account for change. There is no actual representation of the occurrences of change, but only of their effects. Two land areas with different change trajectories whose initial and final states are the same cannot be distinguished. With access to big data sets, researchers need better ways to describe and understand change. The challenge is to make best use of big Earth observation data sets to represent change.

This paper uses the concept of *'events'* from dynamic spatial ontologies to describe land use change. Events are complete entities on their respective time intervals; their lifetime is limited while objects persist in time and are complete in space (Galton and Mizoguchi, 2009; Worboys, 2005; Hacker, 1982). Since events are intrinsically related to the objects they modify, a geospatial event calculus should specify not only what happens, but also which objects are affected by such changes. We present an event calculus formalism for reasoning about land use change. The formalism is general enough to be applied in other geospatial domains.

To define events in big Earth observation data sets, multiple satellite observations of an area are mapped to 3D arrays in space-time. A pixel location (x, y) in consecutive times $t_1, ..., t_m$ makes up a satellite image time series (Figure 1a). One can extract land use change information for each pixel, considered as an atomic ‘land object’. Data mining techniques such as Time-Weighted Dynamic Time Warping (Maus et al., 2016) match temporal patterns of events to their actual occurrence in remote sensing time series (Figure 1b). The results are the temporal boundaries of events associated to a land object. For example, Figure 1b shows four major events extracted from a remote sensing time series, expressed in terms of the intervals they happen. From 2000 to 2001 the area was a forest that was deforested in 2002. From 2003 to 2005 the area it was used for pasture and from 2005 to 2008, as cropland. Since classifying all pixels in a space-time array produces a large set of events, we need an event reasoning formalism to extract information.



(a) Time series measures (e.g. EVI index) of a pixel location (x, y)

(b) Land-use/cover change events associated to a pixel location (x, y)

Figure 1: A 3-dimensional array of satellite data and events describing change at a particular location. Adapted from Maus et al. (2016).

2 The spatiotemporal interval logic

The main elements of a temporal reasoning formalism include the primitive time unit (*instants or intervals?*) and the granularity (*is time continuous or a sequence of discrete elements?*). For describing land use change trajectories from remote sensing data, we consider that an interval-based approach with discrete granularity is better than instant-based formalisms such as the Event Calculus (Kowalski and Sergot, 1989). Thus, we propose to extend Allen’s interval temporal logic (Allen, 1984) to build a general framework to reason about events. Allen (1983) defines a set of mutually exclusive primitive relations between temporal intervals. Each of these is a predicate over intervals: *during*, *starts*, *finishes*, *before*, *overlap*, *meets*, and *equal*. These predicates have become widely used in many areas of computing.

In this work, we propose a spatiotemporal interval logic that includes geospatial objects explicitly. Geo-objects are intrinsically tied to space, and events change their properties. The elements of the formalism are a set of *discrete geo-objects* ($O = o_1, o_2, ..., o_n$), *discrete time intervals* ($T = t_1, t_2, ..., t_n$), and *properties of objects* ($P = p_1, p_2, ..., p_n$). Extending the ideas from Allen (1984), we introduce the predicate $holds(o, p, t) \rightarrow bool$, to denote the assertion that the property p of geo-object o holds over interval t. We also introduce the predicate $occur(o, p, T_e) \rightarrow bool$ to denote that, given an interval $T_e \subset T$, the property p of geo-object o is true over the whole subset T_e. Some of the basic axioms of our spatiotemporal interval logic are presented in Table 1. In these axioms, we use the notation $T_e \subset T$ to denote a temporally connected proper subset of T.

Table 1: Basic axioms of spatiotemporal interval logic

Events happen over a given interval $\forall o \in O, occur(o, p, T_e) \wedge in(T'_e, T_e) \implies \neg occur(o, p, T'_e)$ *where* $in(T'_e, T_e) \Leftrightarrow during(T'_e, T_e) \vee starts(T'_e, T_e) \vee finishes(T'_e, T_e)$
Events do not change over an interval $\forall o \in O, occur(o, p, T_e) \implies \forall t \in T_e, holds(o, p, t)$
Events are unique $\forall o \in O, occur(o, p, T_e) \wedge meets(T_e, T'_e) \wedge occur(o, p', T'_e) \implies p \neq p'$

3 Reasoning about land use change

While the full development of the spatiotemporal interval logical applied to land classification is beyond the scope of this paper, we show some queries useful to reason about *land use trajectories*. Informally, a *land use trajectory* is a path from one land use state to another, for example when a forest area is converted to pasture. Formally land use trajectories are expressed as logical expressions over an event data set.

As an example, consider a study that investigates the agreement known as the Brazil's Soy Moratorium, signed by major commodity traders agreeing not to purchase soybeans grown on lands deforested after July 2006 in the Brazilian Amazonia (Gibbs et al. (2015)). Farmers abiding by the Soy Moratorium agree not to directly replace forest by soybean plantations. However, the agreement does not preclude indirect land use changes, as when a farmer buys land previously deforested that is being used as pasture. In this case, the cattle rancher may sell his land and move elsewhere, causing deforestation without violating the Soy Moratorium. Thus, we want to discover not only direct land use changes, where forest is replaced by soybeans, but also indirect land use changes. The queries in Table 2 point out how to elicit both direct and indirect land use change caused by soybeans in Amazonia.

Table 2: Using the spatiotemporal interval logic to map land use change trajectories in Brazil

Which forest areas have been replaced by soybeans? $occur(o, \text{"}forest\text{"}, t_1) \wedge meets(t_1, t_2) \wedge occur(o, \text{"}deforestation\text{"}, t_2)$ $\wedge\, meets(t_2, t_3) \wedge occur(o, \text{"}soy\text{"}, t_3)$
Which forest areas have been replaced by pasture and later turned into soybean? $occur(o, \text{"}forest\text{"}, t_1) \wedge meets(t_1, t_2) \wedge occur(o, \text{"}deforestation\text{"}, t_2) \wedge meets(t_2, t_3)$ $\wedge\, occur(o, \text{"}pasture\text{"}, t_3) \wedge meets(t_3, t_4) \wedge occur(o, \text{"}soy\text{"}, t_4)$

4 Conclusions

This paper presents the spatiotemporal interval logic, which is a spatial extensions of the temporal interval logic proposed by Allen (1984). The formalism considers the nature of events detectable using Earth observation data, which are discrete transitions where one land cover type is replaced by another. The proposed logic allows reasoning about land use trajectories in regional and global areas. To be useful, this formalism needs to be supported by efficient data mining techniques, capable of extracting event data sets from big data. When such event data be available, the spatiotemporal interval logic improves information extraction from large remote sensing data sets.

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ANNEX B - STILF - A SPATIOTEMPORAL INTERVAL LOGIC FORMALISM FOR REASONING ABOUT EVENTS IN REMOTE SENSING DATA

This annex presents a paper published in the *XVIII Brazilian Symposium on Remote Sensing* – XVIII SBSR 2017 (MACIEL et al., 2017):

STILF - A spatiotemporal interval logic formalism for reasoning about events in remote sensing data

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Abstract. Although several studies perform time series analysis using remote sensing data provided by Earth observation satellites, few have been explored concerning the reasoning about land use change using these data. Besides, exists the challenge of make the best use of big Earth observation data sets to represent change. In this context, this work presents a new formalism - STILF (Spatiotemporal Interval Logic Formalism), and shows how to use it for reasoning about land use change using big Earth observation data. Extending the ideas from Allen's interval temporal logic, we introduce predicates $holds(o, p, t)$ and $occur(o, p, T_e)$ to build a general framework to reason about events. Events can be defined as complete entities on their respective time intervals and their lifetime is limited while objects persist in time, with a defined begin and end. Since events are intrinsically related to the objects they modify, a geospatial event formalism should specify not only what happens, but also which objects are affected by such changes. The formalism proposed and predicates extended from Allen's ideas can model and capture changes using big Earth observation data, and also allows reasoning about land use trajectories in regional or global areas. Examples for tropical forest area application is presented to better

understand our proposal using STILF. For the future, the proposed formalism will be include other temporal analysis tools to thinking about events related the land use and cover change.

Keywords: land use and land cover, spatiotemporal representation, Allen's interval, events, logic formalism, remote sensing

STILF - A spatiotemporal interval logic formalism for reasoning about events in remote sensing data

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Keywords: land use and land cover, spatiotemporal representation, Allen's interval, events, logic formalis, remote sensing

1. Introduction

One of the recent trends in applications of remote sensing data is the use of big data sets for obtaining information about land use and land cover. Using long-term time series, scientists can obtain new information to understand how mankind is using natural resources. Satellite image time series data provides a new perspective in remote sensing data analysis (CAMARA et al., 2016a).

An example of big Earth Observation data analysis is the work by Hansen et al. (2013). Using more than 650,000 LANDSAT images and processing more than 140 billion pixels, the authors compared data from 2000 to 2010 to produce maps of global forest loss. The results for 2000 and 2010 were compared to account for forest loss during the 2000-2010 decade. The method classifies each 2D image one by one.

By contrast, methods such as the time-weighted dynamic time warping (TWDTW) (MAUS et al., 2016) and TIMESTAT (JöNSSON; EKLUNDH, 2004) work on remote sensing time series to extract long-term information for each pixel. These algorithms work on individual time series and combine the results for selected periods to generate classified maps.

The benefits of remote sensing time series analysis arise when the temporal resolution of the big data set is able to capture the most important changes. Here, the temporal autocorrelation of the data can be stronger than the spatial autocorrelation. Given data with adequate repeatability, a pixel will be more related to its temporal neighbours than to its spatial ones. In this case, *time-first, space-later* methods lead to better results than the *space-first, time-later* approach (CAMARA et al., 2016a).

Given the possible new results that can be obtained with big remote sensing data, the scientific challenge is how to best represent and detect change. Issues about representation, reasoning, modelling of changes have been researched in GIScience (PEUQUET; DUAN, 1995; GALTON, 2004). In general, these studies show the usefulness of using the concept of "events" to represent changes in spatiotemporal data. The objective of this paper is to apply the concept of "events" for representing change in big remote sensing data sets, following the ideas from Galton (2015). Additionally, we extend the interval temporal logic proposed by Allen (1984) to build a logic formalism which allows reasoning about events of change in land use and land cover data. This paper extends and improves on earlier work by our research group (CAMARA et al., 2016b).

2. A Spatiotemporal Interval Logic Formalism - STILF

To describe land use and land cover changes, we consider an approach based in time intervals. We extend the interval temporal logic from Allen (1984) to build a logic formalism for reasoning about events. Allen (1983) defines a set of thirteen relationships between two time intervals: *before*, *meets*, *during*, *starts*, *finishes*, *overlap*, with inverse relationship, and *equal*.

To extend the predicates from Allen (1984) to spatiotemporal data, we aggregate the notion of geo-objects, which are related to space. This way, the formalism is composed for a set of elements: (1) discrete geo-objects ($O = o_1, o_2, ..., o_n$); (2) properties of geo-objectos ($P = p_1, p_2, ..., p_n$); and (3) time intervals ($T = t_1, t_2, ..., t_n$). We also use the predicates: (1) $holds(o, p, t) \rightarrow bool$, which asserts that a properties p from geo-object o holds during a interval t; and (2) $occur(o, p, t_e) \rightarrow bool$, given a interval $T_e \subset T$, the properties p from geo-object o will be true during all sub-interval T_e.

The start point of the spatiotemporal interval logic formalism (STILF) is a set of time series data classified from remote sensing images. This images were previously classified by means of data mining algorithm, such as TWDTW (MAUS et al., 2016), and stored in a array database. This is a important stage for the application of the formalism, once allows that Earth observation data were stored in a database which support a large amount of remote sensing data, and subsequently, can will be used for different applications. Next, this data set will be processed, for extraction of the set of elements. Each element is composed of a discrete geo-object, its properties of geo-object and time intervals for which these properties hold.

The set of elements will be used as input data for our formalism. Combining the $holds(o, p, t)$ and $occur(o, p, t_e)$ predicates with Allen's relations, we can ask questions about trajectories of land use and land cover change. The answers will be data sets with the events that have occurred during the whole interval for which we have data. In the last stage, individual events will be combined in terms of their characteristics into recurring events or transition events. Figure 1 shows a overview of our proposed formalism.

3. Application: Examples of Reasoning About Events from Classified Land Use and Land Cover Time Series

In this section we show three examples of application using remote sensing data. The formalism presented was developed in a R programming language and applied on sample

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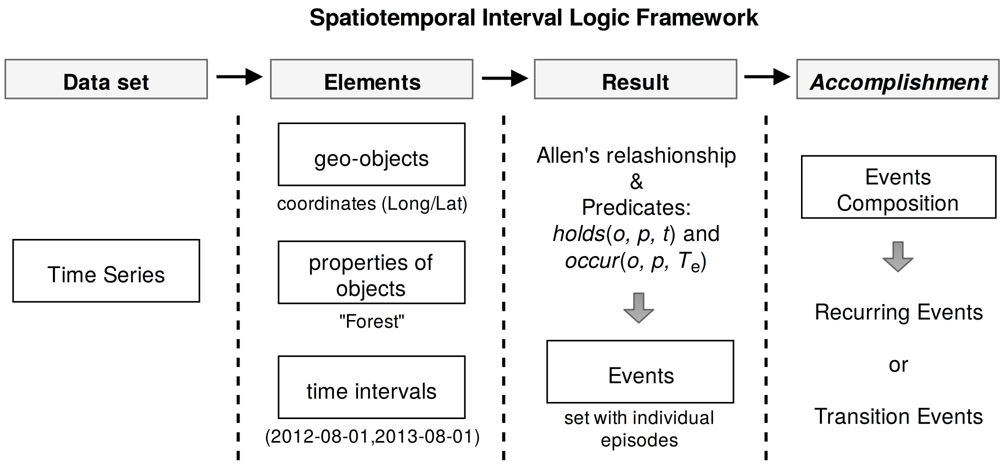

Figure 1: Spatiotemporal interval logic formalism (STILF) design

regions. The input data is composed for a set of time series classified to the municipality of Porto dos Gaúchos, located in northwest Mato Grosso (MT) state, Brazil. With territorial area 6,862.118 km^2, geographical coordinates, latitude 11° 31' 31" South and longitude 57° 24' 50" West and population of 5,400 inhabitant in 2010, according to IBGE statistics (IBGE, 2016). Porto dos Gaúchos is an area into Amazon biome.

Figure 2: Municipality of Porto dos Gaúchos with highlight for three sample regions selected to application of the formalism.

We extracted information from each sample region to discover what events had happened. These events allow us to establish the trajectories of land use and land cover. For example, the results may indicate the increase of deforestation in the municipality after earlier expansion of areas. We can also detect the conversions from pasture to soybean and from soybean to double cropping (soybean-corn or soybean-cotton).

After we classify the time series, we apply a post-processing rule to distinguish natural, intact forests from areas that had been deforested and then were allowed to regrow. This is required to be able to differentiate primary forest, without degradation, from secondary vegetation, forest areas that happened after other land use or land cover classes. The new classes generated after this stage were called "Secondary vegetation".

In the first sample region, with an area of 50.23 km^2, located in Northeast of the

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municipality, we explored the ability of the formalism to detect events composition. Our query searched for events preceding and following the year of 2008, associated to the "Soybean-Millet" crop areas Question 1. The result were three graphics with information for analysing land use trajectories: (1) a custom map that highlights events that show the transition from "Pasture" to"Soybean-Millet", Figure 3; (2) a bar graph which counts the total area (km^2) for each event by year; and (3) a graph which represents the temporal sequence of the events for each pixel in the time. This type of graph show what pasture areas were transformed into crop areas (Figure 4(b)).

Question 1: Example of application of the spatiotemporal interval logic formalism for mapping of changes in land use and cover for the first sample region

a) *Which "Pasture" areas before 2008 have been turned in "Soybean-Millet" cropping areas?*

$$\forall o \in O, occur(o, \text{"}Pasture\text{"}, t_1) \wedge occur(o, \text{"}Soybean - Millet\text{"}, t_2) \wedge$$
$$occur(o, \text{"}Soybean - Millet\text{"}, t_3) \wedge$$
$$preceding(t_2, t_1) \Leftrightarrow (metBy(t_1, t_2) \vee after(t_1, t_2)) \wedge$$
$$next(t_2, t_3) \Leftrightarrow (meets(t_1, t_2) \vee before(t_1, t_2))$$
$$\textit{where } t_1 = \{2000, ..., 2007\}, t_2 = 2008, t_3 = \{2009, ..., 2015\}$$

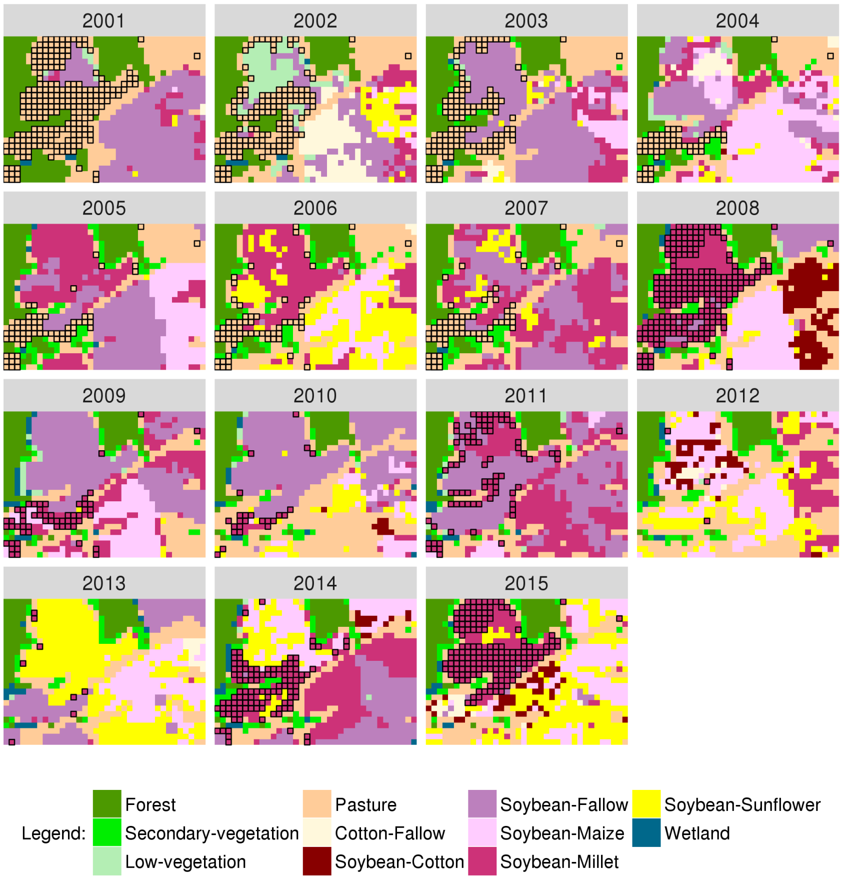

Figure 3: Sample region 1, events highlighted.

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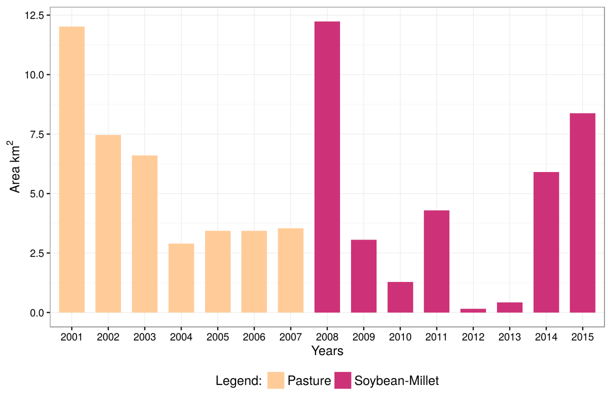
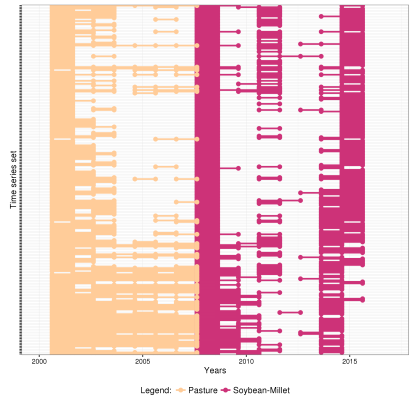


(a) Area in (km^2) with "Pasture" events turned into "Soybean-Millet" from 2008.



(b) Temporal sequence of the events.

Figure 4: Graphics to analyses of events composition - sample region 1

In the second sample region, located to the south of the municipality and area of 59.568 km^2, we investigated which "Forest" areas that have been turned into "Pasture" or " Low vegetation (a second type of pasture)" after 2001. The formal representation of the question is shown in Question 2. Three output plots were generated with information about events: a map that highlights events that happened yearly, Figure 5; a bar graph with total area for each event by year (Figure 6(a)), and a temporal representation for each pixel over time, which shows the transitions from forest to pasture (Figure 6(b)).

Question 2: Example of application of the STILF for mapping of changes in land use and cover for the second sample region

b) *Which "Forest" areas have been turned into "Pasture" or "Low-vegetation" after the year of 2001?*

$$\forall o \in O, occur(o, \text{“}Forest'', t_1) \wedge$$
$$(occur(o, \text{“}Pasture\text{”}, t_2) \vee occur(o, \text{“}Low-vegetation'', t_2)) \wedge$$
$$next(t_1, t_2) \text{ where } t_1 = 2001, t_2 = \{2002, ..., 2015\}$$

In a third sample region, located northwest of Porto dos Gaúchos municipality and area of 101.963 km^2, we wanted to know which "Forest" areas have not undergone degradation over years (Question 3) In a similar way to the PRODES system, forest areas that from regrowth after fire or deforestation are called "Secondary vegetation" by our post-processing rule and are not computed. Figure 7 shows a map that highlights the events. Figure 8 displays the amount of forest grouped by year. We can see the expansion of deforestation until 2006, when there was a significant reduction.

Question 3: Example of application of the STILF for mapping of changes in land use and cover for the third sample region

c) *Which "Forest" areas have not undergone degradation during interval of 15 years?*

$$\forall o \in O, occur(o, \text{“}Forest\text{”}, t_1) \text{ where } t_1 = \{2001, ..., 2015\}$$

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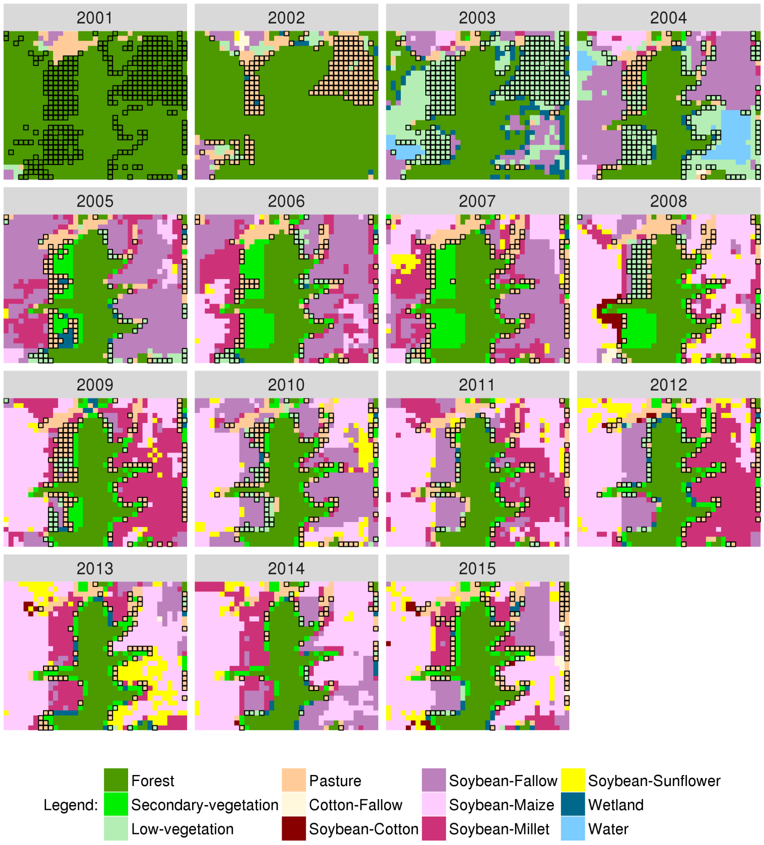
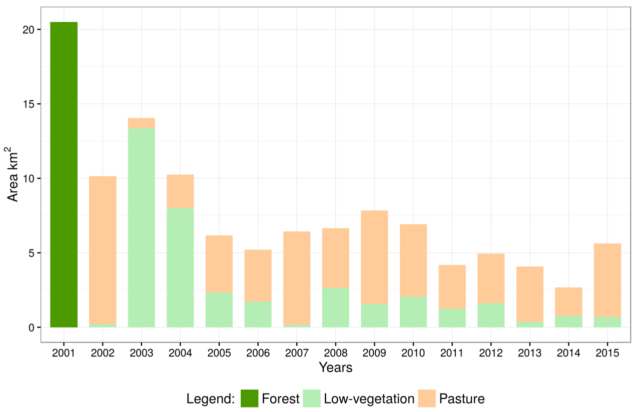
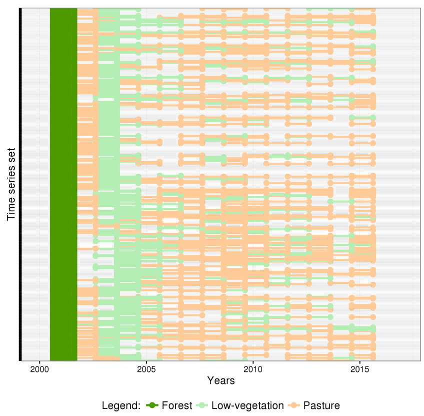


Figure 5: Sample region 2, events highlighted



(a) Area in (km^2) with “Forest” events turned into “Pasture” and/or “Low-vegetation” from 2001.



(b) Temporal sequence of the events to second sample region.

Figure 6: Graphics to analyses of events composition - sample region 2

This spatiotemporal interval logic formalism makes it easy to build questions in a logic representation in order to reason about changes in land use and land cover. We can show the trajectories of change in different perspectives. This makes it easier to understand changes in an environment. The formalism is robust. It allow different logical queries combining Allen’s relations and also predicates of geo-objects.

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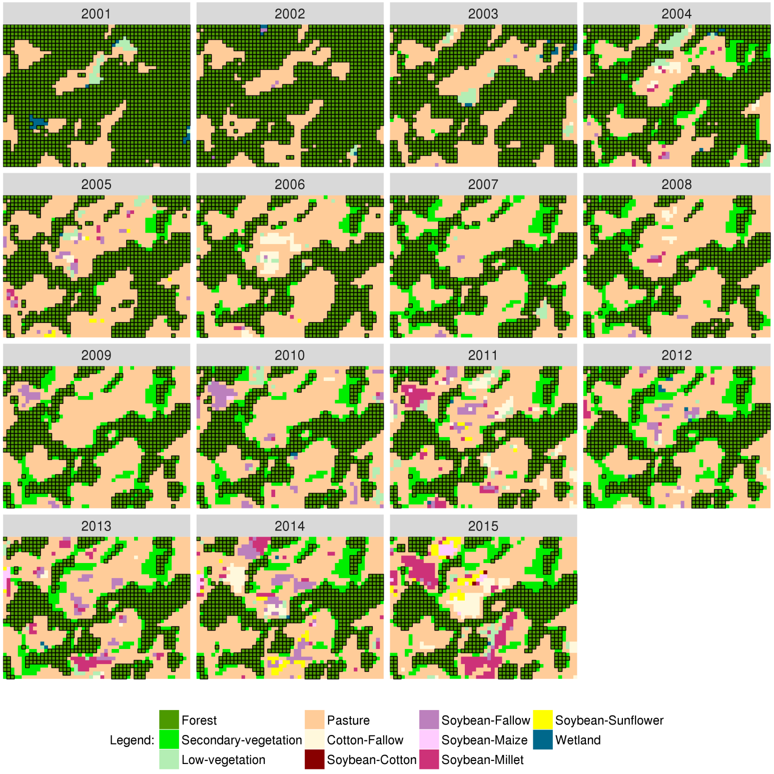

Figure 7: Sample region 3, with events highlighted

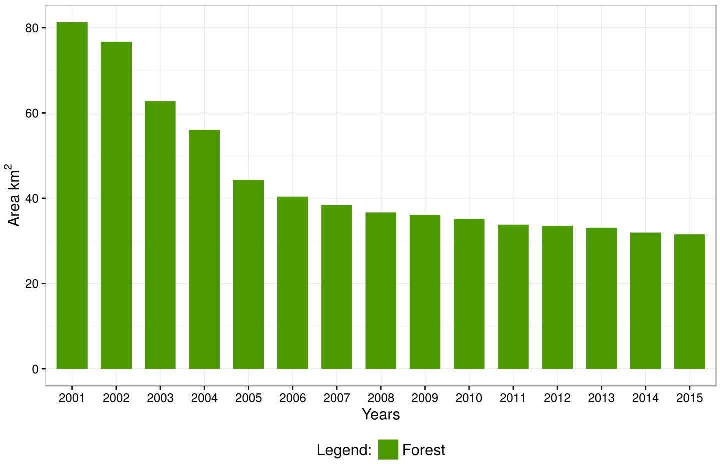

Figure 8: Area in (km^2) with "Forest" events which have not undergone degradation during the period of 15 years.

4. Final Considerations

A spatiotemporal interval logic formalism to reasoning about changes in land use and land cover was presented in this paper. This formalism is an extension from predicates defined by Allen (1984). We introduce geo-objects as new elements for analyses involving spatial data. We show three examples of application where the formalism was implemented in a programming language, take advantaging of the resources for data visualisation and results.

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