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Implementation of a method and calculation of ecological indicators to assess the potential for natural regeneration in La Selva, Costa Rica.

I. Context and area study

In a global context where forest landscapes are increasingly degraded, natural regeneration has established itself as one of the relevant approaches to restore and reforest these degraded landscapes (Chazdon & Guariguata, 2016). Natural regeneration (or secondary succession) of tropical forests occurs naturally on degraded or deforested lands after abandonment of land uses such as agriculture or pasture for cattle production. Natural regeneration allows the recovery of many ecosystem services (pollination, seed dispersal, carbon storage, etc.) to gradually reach pre-disturbance level (or close-by) in terms of composition, structure and function (Guariguata & Ostertag, 2001). However the recovery of ecosystem services depends of many factors acting at two different scales. At a local scale, i.e. within forest site, natural regeneration success is strongly influenced by many factors such as climate, soils characteristics, repeated stand-level disturbances, prior land use, surrounding vegetation, and the regional species pool (Chazdon, 2014). At the landscape-level, i.e. within landscape surrounding forest site, natural regeneration success is influenced by close proximity to large forests patches, soil quality and seed dispersing fauna have a high importance (Pereira *et al.*, 2013 ; de Rezende *et al.*, 2015 ; Sloan & Sayer, 2015 ; Martínez-Ramos *et al.*, 2016). Chazdon & Guariguata presented a methodological approach for large-scale natural regeneration restoration and suggested indicators that can be used "to predict the capacity for natural regeneration within degraded or deforested tropical forest landscapes" (Chazdon & Guariguata, 2016). There are both internal (within local site) and external indicators (within surrounding landscape) (Table 1).

In Costa Rica there are studies that focused on certain ecosystem services (carbon stock, water quality) to evaluate the success of tropical forest restoration by natural regeneration in Costa Rica (Calvo-Alvarado *et al.*, 2009 ; Gilman *et al.*, 2016 ; Locatelli *et al.*, 2014). These studies did not take into consideration landscape indicators and did not generate any practical tool to predict the potential for natural forest regeneration. Here, we aim at taking into consideration both local and landscape indicators and designing a tool able to evaluate the natural regeneration recovery success illustrated by an ecosystem service (forest primary production) which will be evaluated by several variables of structure and composition. To achieve this objective, we will first gather the knowledge we have on land use dynamics in the study landscape (forest inventories, land use data, time series) in order to build ecological indicators of natural regeneration. Then we will design a tool allowing to characterise the natural regeneration potential in different forest areas. This work will be carried out in the San Juan La Selva Biological Corridor in Costa Rica (Figure 1).

The San Juan La Selva Biological Corridor, hereafter called "La Selva", is located in the northern zone of Costa Rica, in the provinces of Heredia and Alajuela, between the cantons of Sarapiqui and San Carlos. La Selva is covering an area of 244 618 ha with a wide altitudinal range, from 30 to 3000 m above sea level, ascending from the plains of San Carlos to the summits of the Central Volcanic Range. Looking at the land use map of La Selva, we can see that the landscape is dominated by mainly highly fragmented mature forest with some secondary forest, pastures and pineapple crops in the centre of the study area (Figure 2). La Selva was created in 2001, to maintain biological connectivity between larges patches of continuous forest in the protected areas of southeastern Nicaragua, the San Juan River, the system of protected areas of the Northern Arenal Huetar Conservation Area (ACAHN) and the Central Volcanic Cordillera Conservation Area (ACCVC) in Costa Rica. It is now part of the *Alianza Cinco Grandes Bosques de Mesoamérica* (the Five Great Forests of Mesoamerica Alliance). In La Selva, CATIE (*Centro Agronómico Tropical de Investigación y Enseñanza*) has established permanent plots in different types of forest systems: primary, production and secondary, in continuous or more fragmented matrices. These data will be used as the basis for calculating indicators to assess the regeneration potential of the forests of La Selva.

Indicator	**Internal**	**External**
Presence of topsoil and soil organic matter	X	
Soil seed bank	X	
Presence of rootstocks	X	
Abundance and cover of shrubs	X	X
Abundance of remnant trees	X	X
Abundance of animal-dispersed trees	X	X
Living fences/hedgerows	X	X
Local avian abundance and diversity	X	X
Local mammal frugivore abundance and diversity	X	X
Remnant forest patches within 100 m		X
Riparian vegetation within 100 m		X
Large forest remnants or reserves within 200 m		X
Regional avian abundance and diversity		X
Regional mammal abundance and diversity		X

Table 1. Internal (local scale) and external (landscape scale) indicators suggested by Chazdon and Guariguata (2016) to predict natural regeneration potential in deforested and degraded tropical forest landscapes.

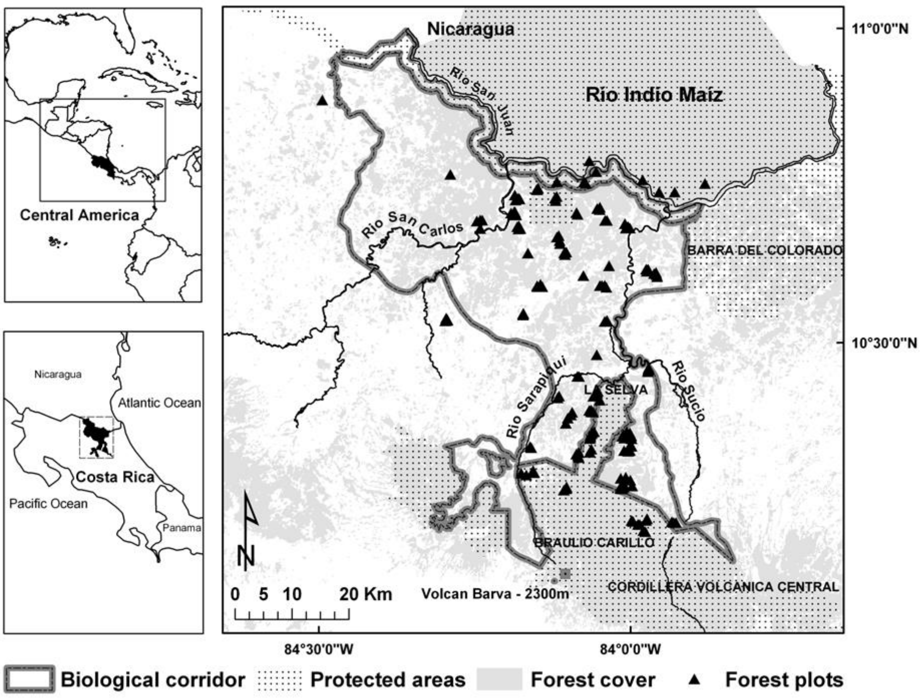

Figure 1. Map of San Juan La Selva Biological Corridor. This map is from Steven Sesnie thesis work (Sesnie, 2006).

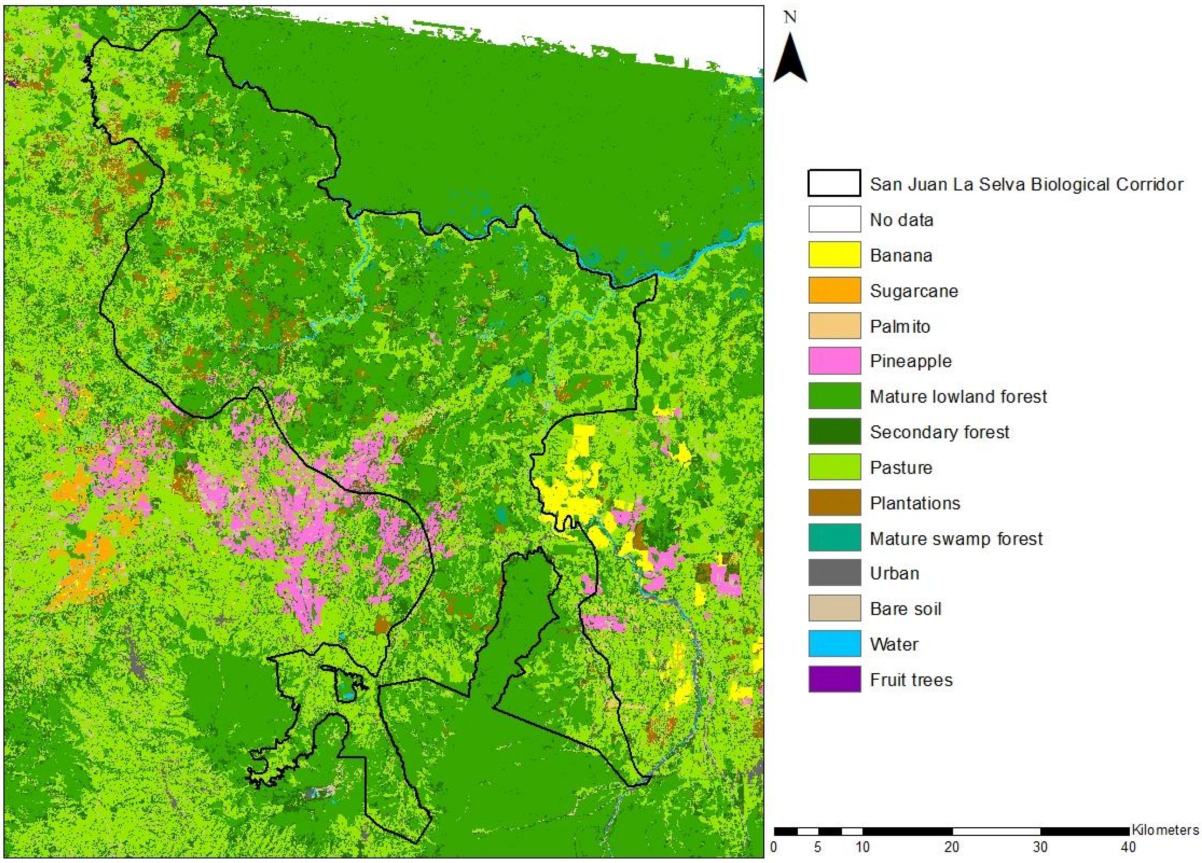

Figure 2. Land use map of the study area (outlined in black) in 2011. Land cover data are from (Fagan *et al.*, 2016).

II. Data available

1. Land use classifications

Three land use classifications are available at different dates (see Table 2) for La Selva. An example of each land use classification for the same year (2001) is given in **Appendix 1** to illustrate their differences.

Bibliographic reference	Classification year	Classes number	Characteristics
Sesnie, 2006	2001	32	Very accurate classes for crops and for forests based on composition, structure and dominant species
Fagan et al., 2013	1986, 1996, 2001, 2005, 2011	13	Distinction between different crops types and between tree plantations types (for wood or fruits)
Pedroni et al., 2015 (SINAC)	Every 5 years from 1986 to 2013	9	Classes are less specific (permanent or annual cultures) and presence of an "other land uses" class

Table 2. Land use classifications available in the literature and their characteristics.

2. Soil and climatic Data

Soil and climatic data for all Costa Rica are freely available online, on CIA (*Centro de Investigaciones Agronomicas*, http://www.cia.ucr.ac.cr/) for soil data and on CHELSA (http://chelsa-climate.org/) for climate data. There also is a soil database available from the FAO that we could use in addition (http://www.fao.org/soils-portal/soil-survey/en/). We also have access to two DEM (Digital Elevation Model) for Costa Rica at 10 and 30 meters of resolution. The one at 30 m of resolution is from SRTM (Shuttle Radar Topography Mission), and the one at 10 m of resolution was generated from Costa Rica's map elevation data, including Google Earth and 1:5000 mapping.

3. Data on forest structure, composition and dynamics

In order to calculate the internal indicators suggested by Chazdon and Guariguata (2016) at local scale (within site), forest data for 215 plots studied in San Juan La Selva are available. Amongst these 215 plots, 71 are permanent plots of CATIE, established within primary, production, and secondary forests, and monitored for 30 years (from 1987 to 2017). The other 144 plots are not permanent and were sampled in 2004 by Steven Sesnie and used in several studies (Sesnie, 2006 ; Sesnie *et al.*, 2009 ; Chain-Guadarrama *et al.*, 2018). For all plots, values of Above Ground Biomass (AGB), Diameter at Breast Height (DBH), Basal Area (BA), or Wood Density (WD) have been measured or calculated in both database. These parameters will be used to estimate and calculate the natural regeneration variables to be explained (Table 4).

Variables to explain			**Database used**
Dynamic	Dendrometric	Growth rate, recruitment, mortality, biomass production	71 plots (CATIE)
	Floristic	Composition, diversity & abundance variation	
Punctual	Dendrometric	Biomass, carbon stock, tree density	144 plots (Sesnie) 71 plots (CATIE)
	Floristic	Composition, diversity, abundance	

Table 4. Forestry variables to be explained used in the model.

4. Bird and mammal Data

We also have access to bird and mammal occurrence data in La Selva, available on GBIF (https://www.gbif.org/), a free database where anyone can share one observation of biodiversity, it location and other information. We will use bird and mammal occurrences in La Selva as a proxy of diversity since we do not have access to inventory data as suggested in Chazdon & Guariguata (2016). From GBIF occurrence data available in La Selva region, we will look for occurrences of frugivorous bird and mammal species. From these data we will build Habitat Suitability Models (HSM) to have an indicator of avian presence in La Selva based on the quality of the habitat. HSM are quantitative tools useful to identify the potential spatial distribution of species. Based on the concept of ecological niche, HSM statistically analyse species-environment relationships and can be extrapolated to predict the geographical distribution of the focal species (Guisan & Zimmermann, 2000).

III. Methods

To achieve our objective, our work will be divided in three steps, summarized on Figure 3. The first step is to collect and homogenize databases. For spatial data, we will choose one of the three classifications available, and update it with more recent data (forest type data for 2012 and culture type/pasture data for 2017). Concerning forest data, the objective is to create one unique and identify which parameters can be used to build local indicators.

The second step is to identify and select response variables and explanatory variables at both scales. At local scale, we will use environmental and geographical factors (DEM, soil, and slope) as we don't have all data necessary to build all internal indicators suggested by Chazdon & Guariguata (2016), such as seed bank or abundance of remnant trees. At regional scale, i.e. within surrounding landscape, we will calculate temporal and spatial landscape metrics derived from land use time series and climate data. These metrics will be indicators of composition and configuration of the landscape.

The third step is to create a statistical model to analyse and evaluate natural regeneration potential of recovery of La Selva. This model will evaluate forest characteristics and dynamics with local and landscapes metrics. For this purpose we may use random forest regression (RF) or generalized linear model (GLM).

The fourth and final step of this project is to design a tool that we could use as a decision-making tool for managers, to identify areas where the potential of recovery with natural regeneration is optimal.

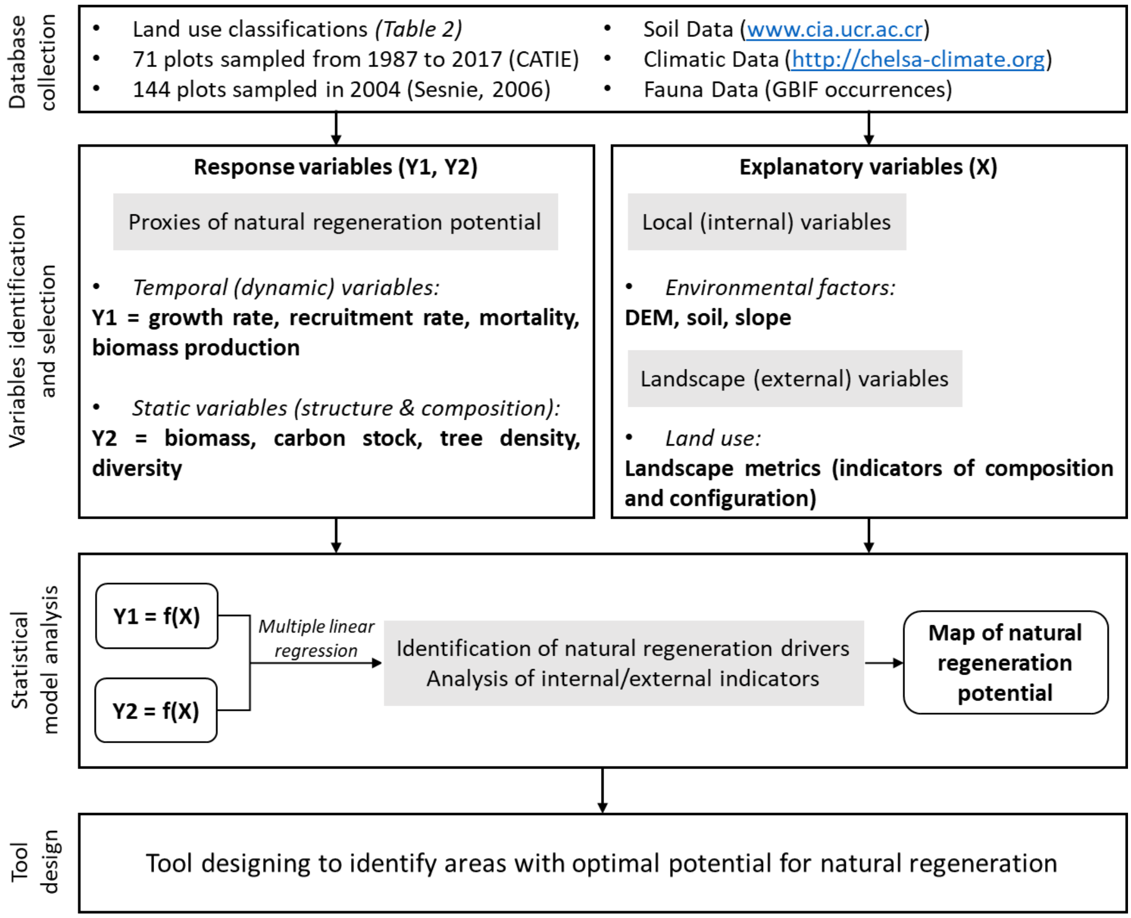

Figure 3. Workflow of the method used to build indicators to assess forest natural regeneration potential in La Selva, at both local and landscape scale.

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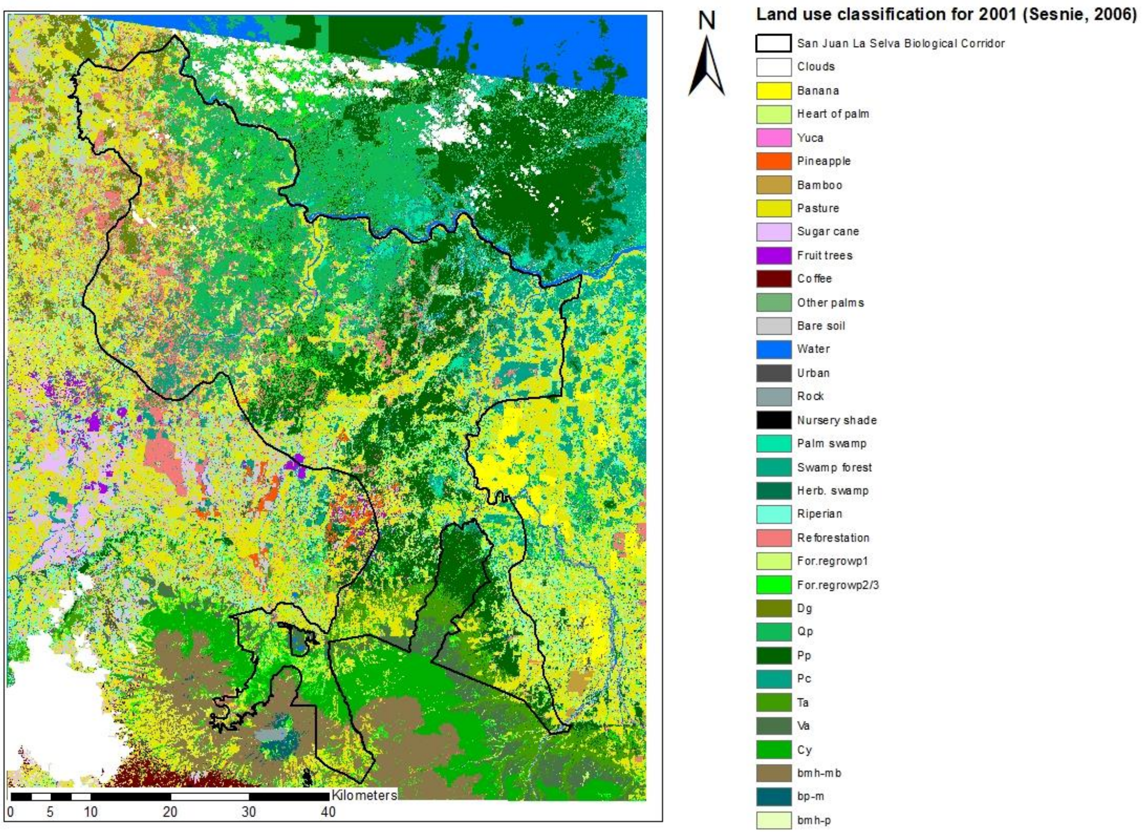
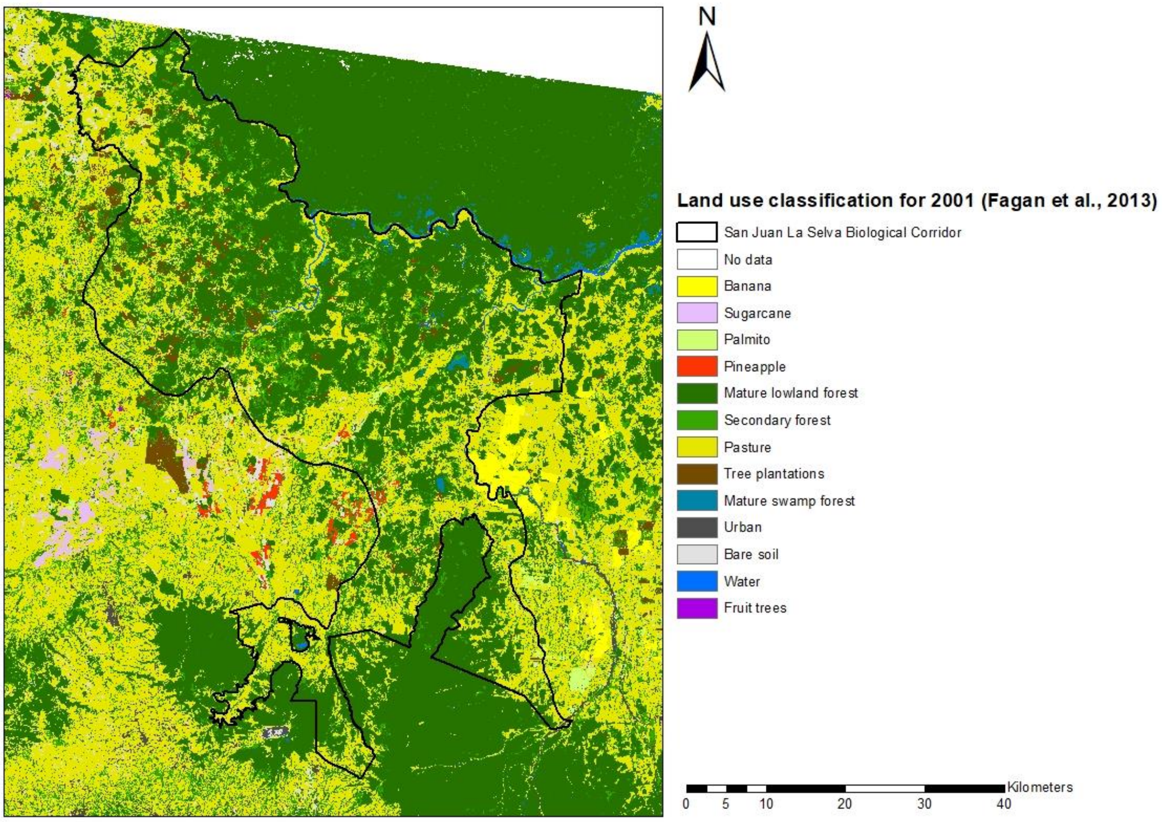
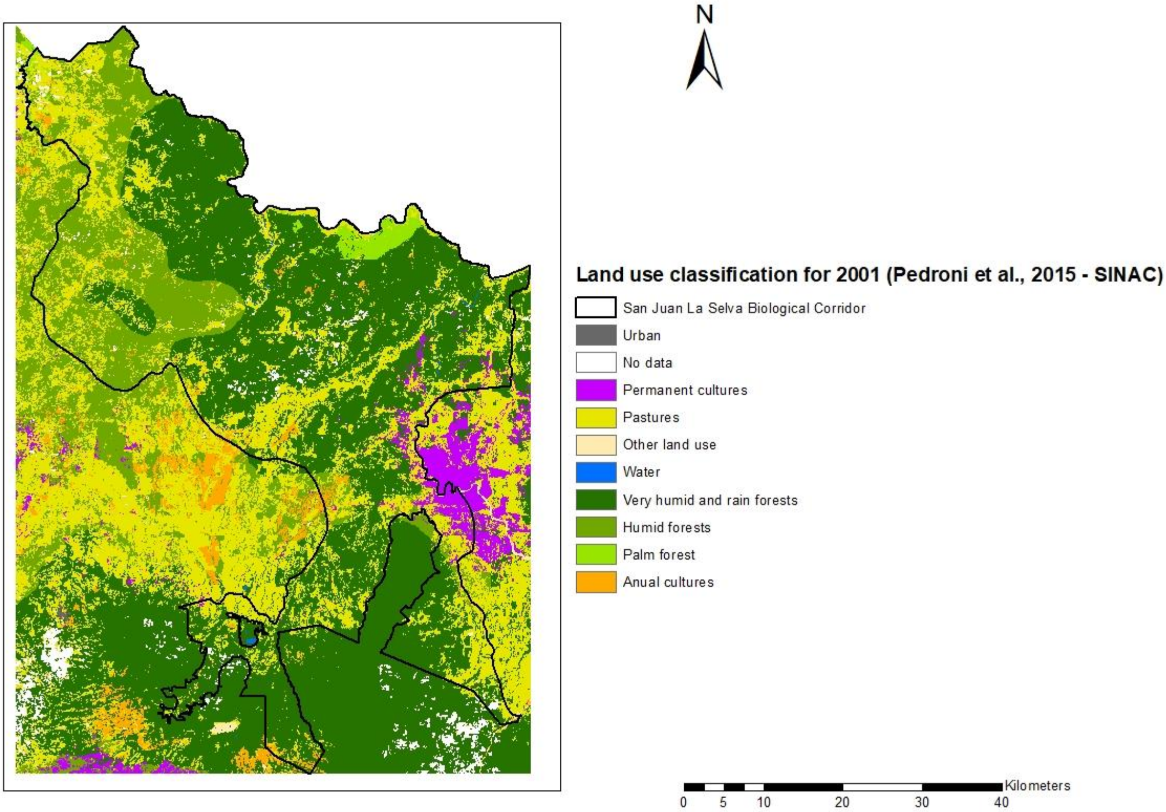
Appendix 1. The three land use classifications available for 2001



a. Data from Sesnie, 2006 (thesis): Dg, Qp, Pp, Pc, Ta, Va and Cy are forests classes dominated by one particular species.



b. Data from Fagan et al., 2013.



c. Data from Pedroni et al., 2015 (SINAC).