Geo-information Science and Remote Sensing

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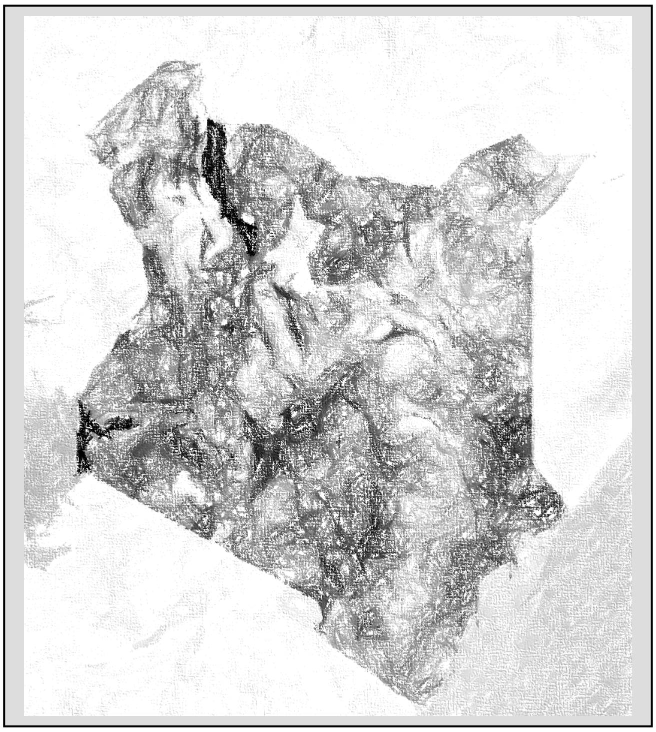
Assessing and understanding biomass change related to deforestation and forest degradation:

A case study in Kenya

Nadine Drigo



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Assessing and understanding biomass change related to deforestation and forest degradation:

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Acronyms

ABD	Aboveground biomass density
C	Carbon
°C	Degrees Celsius
CO^2	Carbon dioxide
FAO	Food and Agricolture Organization
h	Hours
HCC	High canopy cover
km	kilomiters
LCC	Low canopy cover
LU	Land use
MAI	Mean annual increment
masl	Meters above sea level
M	meters
mm	millimetres
Mt	Million of tonnes
REDD+	Reducing Emissions from Deforestation and Forest Degradation, as well as conservation, sustainable management of forests and enhancement of forest carbon stocks
TLU	Tropical livestock unit
t	Tonnes
UNFCCC	United Nations Framework Convention on Climate Change

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Abstract

Forests play an important role in the global carbon cycle as carbon sinks of terrestrial ecosystem. Human activities such as deforestation and forest degradation have a considerable impact on the ability of forests to sequester and store carbon. Pressure to convert and degrade forests continues to be high in developing countries such as Kenya, resulting in substantial emissions of carbon dioxide (CO_2). This research focuses on distinguishing emissions due to deforestation from the forest degradation in Kenya over the period 2003-2014, and to better understand the deforestation drivers. The main outcome of this study is that degradation is responsible for the 60% (-15.1 Mt) of the total change on biomass carbon with a rate of -2% of stock loss per year, while the main deforestation driver is pasture. The dominant role of degradation as source of carbon emissions sets important new light on land cover dynamics in Kenya and indicates the need for further research on the human activities leading to degradation to define specific and effective lines of interventions.
Possible solutions involve national policies such as improving sustainability practices and management of close and open forests, promotion of less forest dependent cattle breed at a national level and improving forage quality. At a global scale, the production of higher resolution carbon change maps would improve the quality of the analysis. Mapping carbon change represents a new and promising approach for the estimation of forest degradation. Advancing in this line of research, the production of higher resolution carbon change maps would allow to better monitor degradation and to undertake more consistent and detailed analyses.

1 Introduction

1.1 Problem statement

Nature's way of sequestering carbon from the atmosphere is a process of achieving balance of carbon dioxide levels and maintaining the global carbon cycle which has been an ongoing process for billions of years. However, the ability of the terrestrial biosphere to emit or remove carbon dioxide from the atmosphere has been compromised by human -induced activities such as combustion of fossil fuels and change in land-use patterns such as deforestation and forest degradation (Vashum et al., 2012). Forests play an important role in the global carbon cycle as carbon sinks of the terrestrial ecosystem. Forests sequester and store more carbon than any other terrestrial ecosystem and are an important natural 'brake' on climate change. Once cleared or degraded, their stored carbon is released into the atmosphere as carbon dioxide (CO^2).
The impact of tropical deforestation has been estimated to have released 1–2 billion tonnes of carbon per year during the 1990s, 15–25% of annual global greenhouse gas emissions (Gibbs et al., 2007)
Pressure to convert and degrade forests continues to be high in developing countries such as Kenya resulting in substantial emissions of carbon dioxide (Maukonen et al., 2016).
Parties of the United Nations Framework Convention on Climate Change (UNFCCC) have developed a mechanism for reducing emissions from deforestation and forest degradation, enhancing forest carbon stocks, sustainable management and conservation of forests (REDD+) in developing non-Annex I countries (De Sy, 2016; Agreements, 2010). The REDD+ concept is a proposal to provide financial incentives to help developing countries to reduce national deforestation and degradation rates and associated carbon emissions below a baseline (based either on a historical reference case or future projections). These emission reductions could simultaneously combat climate change, conserve biodiversity and protect other ecosystem goods and services. A better understanding is needed, not only for assessing the degree to which forests are changing, but also to identify the causes of change and to define effective policies, national REDD+ strategies and implementation plans (Boucher et al., 2011).

The vast majority of the country (80% of total land area) is covered of arid and semiarid lands with annual rainfall of less than 1000 mm and characterised by low and sparse population and settlement patterns, low vegetation richness with the main land use system being nomadic pastoralism. More than 75% of Kenya's population is concentrated in the high potential areas for plant growth, comprising only 20% of the land surface, where the annual rainfall exceeding 1000 mm the same areas where most closed canopy forests are located (Imo, 2012).
Kenyan forests cover a surface of around 7% of the total land (FAO, 2015), playing important roles and providing crucial services to the people living in the surroundings. While deforestation and forest degradation are significant contributors to climate change, they also result in numerous other problems: removal of forests leads to loss or reduction of many ecosystem services and functions such as soil stabilization, protection of water supply and fisheries, flood control, water retention and filtration, sustainable provision of timber and fibres, medicinal plants, food from the forest, pollination, cultural services and wildlife habitat(Maukonen et al., 2016; Akotsi and Gachanja, 2004; Lambrechts et al., 2003).
The loss of forest cover has been caused by several factors: expansion of agriculture, degradation, settlement (both legal and illegal), urbanization, unsustainable extraction of timber and forest products and lack of land use policy (Kenya Forest Working Group, 2005).

1.2 Scientific objectives

Research on deforestation is more developed as compared to research on forest degradation. As deforestation is the conversion of forest to other land use or the permanent reduction of the tree canopy cover below the minimum 10 percent threshold, while degradation implies changes in the structure of the forest and does not involve a change in land use, determining forest degradation and related forest carbon stock changes is more challenging (Herold et al., 2011). Forest area change is a response to the constant need of the local population: the need for land. Therefore, the main deforestation driver highlighted by many studies is agriculture (De Sy, 2016; Geist and Lambin, 2001). Degradation is a more complex process to monitor, compared to deforestation, where the quantity of carbon loss per hectare is smaller but constant in time: the degradation phenomena is characterised by the loss accumulating each year, while deforestation is characterised by the loss of all the stock (see Table 1.1 Definition Box). Degradation is the result of the need for wood material (mainly charcoal production and fuelwood harvesting, also timber and poles harvesting) by local people (Geist and Lambin, 2001). Degradation becomes a problem when it is not compensated by regrowth: when the fraction of carbon subtract to the forest is higher than what the stock is able to regrow; this is called non-renewable fraction, and that part is a threat to the forest (Drigo et al., 2015). Degradation is often a precursor to deforestation (Kleinschroth and Healey, 2017) and is a major source of emissions from forests (Baccini et al., 2017).

From a global point of view the scientific research on forest management and biomass estimation is enhancing thanks to publicly available datasets and satellites images. The continuous development of monitoring techniques and the increasing attention for the carbon cycle and related processes (for example REDD+), stimulates the production of new datasets. Various products that allow spatial analysis to have been produced in an ongoing process mostly from 2000 onward covering mainly the tropical zone, where the majority of the global forests are located. Hansen et al. (2013) produced a tree canopy cover of the year 2000 together with yearly updated deforestation and afforestation datasets at 30m resolution. Other research focuses on the forest stock available at various resolutions and referring to different years (Zarin et al., 2016; Baccini et al., 2012; Avitabile et al., 2016). Baccini et al., 2017 recently produced an aboveground live woody carbon density change at 400m resolution that monitor all carbon changes occurring on the land.

National studies have been recognised as essential to effectively reduce carbon emissions and find tailored solutions that can meet the needs of the population and forest ecosystems. Since then several studies have been produced with a special attention to the most urgent zones in Kenya (for example the five water towers). A Readiness Preparation Proposal in 2010 (Kenya, 2010) and a land use planning in 2016 (Maukonen et al., 2016) have been produced in line with the REDD+ guidelines. Understanding drivers of deforestation is fundamental for the development of policies and measures that aim to alter current trends in forest activities toward a more climate and biodiversity friendly outcome. Several possible solutions have already been identified focusing on the livestock and energy sectors, that are the most threatening for forests (Korir, 2016; Brandt et al., 2018; Drigo et al.,2015).

1.3 Research questions

Based on the scientific objectives these are the three objectives that will be carried out:

1. *What are the emissions related to deforestation and to forest degradation in Kenya over the period 2003 - 2014? Where are these processes more intense?*

To better understand how carbon changes in Kenya, the first objective aims to divide the two main carbon change forest related processes: forest area change (composed by the deforestation and afforestation component) and forest degradation (see Box for definition Table 1.1) and to spatially define it, over the period 2003 – 2014. This part of the research will be carried out for the whole of Kenya, identifying areas of different change intensities in relation with other strata (population distribution, livestock distribution and accessibility) (see section 2.1.4).

2. *What are the main deforestation drivers and related characteristics (deforestation speed, land management activities during deforestation process) recognisable in the 5 study areas in Western Kenya?*

Currently, there is a lot of research which focuses on calculating emissions from deforestation but the link with drivers is less well known (Achard et al., 2014; Harris et al., 2012; Hansen et al., 2013).
Five zoom-in zones in Western Kenya have been identified, where a land users survey was undertaken in November 2015 to better understand the process of deforestation. Our objective is to explain the deforestation process using information about deforestation drivers and related characteristics (deforestation speed, land management activities during deforestation process) derived from the survey.

3. *Is there a difference in carbon loss in each of the 5 study areas in Western Kenya?*

The third research question aims to integrate the quantitative information about carbon change derived from objective 1 with the qualitative information about deforestation drivers and land management activities carried out in the same period (objective 2). The quantity of carbon loss and the difference between forest area change and degradation will characterise the zone and help to understand better the drivers, also in light of the carbon emissions information.

Table 1.1: Definitions used in this research

Definition Box
Forests are defined as a surface area with a 25% or higher tree canopy cover (derived from Hansen et al.,2013)
Forest area change is composed of: – Deforestation is defined as "the conversion of forest to other land use or the permanent reduction of the tree canopy cover below the minimum 10 percent threshold" (FAO, 2012). – Afforestation: inverse of deforestation
Deforestation driver: land use following the deforestation process
Forest degradation is defined as the long term or permanent reduction of biomass in forest land remaining forest land. The expression ‘’long-term’’ is used in opposition to short-term/temporary degradation, which may be induced by individual disturbance and from which we can assume that the forest will be able to recover, thus, over time resulting in no net change to CO_2 in the atmosphere. Long-term degradation is understood as the result of recurrent disturbance with an impact above the recovery capacity of the forest, thus, resulting in emissions of CO_2 to the atmosphere which is not compensated by subsequent removals through post-harvest regrowth (Poudel et al., 2017).
Forest regrowth: is the inverse of degradation

2 Methods

First, we discuss the datasets and methods used to determine the carbon emissions (Objective 1). Secondly, the methodology used to analyse the five zoom-in zones (Objective 2) will be described. This will be followed by the Objective 3 where the findings of the two previous objectives are merged.

2.1 Carbon emissions (Objective 1)

This section will explain the methodology carried out to answer the first research question. It is divided in 6 sections: the first, illustrates the used datasets (Materials), the second, shows the pre-processing carried out on the datasets (Dataset pre-processing), the third, describes the analysis of the carbon change, and the fourth, explains the datasets and methodology used to characterise the change (stratification analysis). The last two define the correlation analysis and the carbon datasets inconsistency.

2.1.1 Materials

Table 2.1 shows an overview of the used datasets with a brief description.

Table 2.1: Overview of the used datasets

Dataset	Description
Aboveground live woody carbon density change (2003-2014) Hereafter referred as: total carbon change	The dataset represents total carbon change as a result of a time-series analysis over the period 2003-2014. The value of each pixel (463 x 463 m) represents the total net carbon density change (Mg/ha) (Baccini et al., 2017).
Aboveground live woody biomass density (2000) Hereafter ABD	The pantropical dataset produced at 30 m resolution represents the biomass stock for the year 2000 in (Mg/ha) (Zarin et al., 2016).
Year of gross forest cover loss event Hereafter referred as Hansen lossyear.	The dataset produced by Hansen et al. (2013) represents the forest loss surface and the year in which the event happened. The dataset covers the period 2000-2015.
Global forest cover gain (2000-2012) Hereafter: Hansen gain	The dataset produced by Hansen et al. (2013) represents the forest gain for the period 2000 – 2012.
Tree canopy cover (2000)	The tree canopy cover for the year 2000 is produced by Hansen et al., 2013 and represent the canopy closure for all vegetation taller than 5m in height.
Mean Annual Increment (MAI)	The Mean Annual Increment (MAI) values for each county were derived from the work of Drigo et al. (2015). The values represent the mean annual growth in each county have been calculated considering the information from plantation inventories and a simple equation relating biomass stock and MAI (as percent of stock).

2.1.2 Datasets pre-processing

The following actions have been applied to all datasets to make them comparable.

- Coordinate system: All datasets were projected on the coordinate system Arc 1960 UTM zone 37S. As the study area is Kenya, a national coordinate system would reduce the projection deformation.
- Spatial resolution (cell size): As not all datasets have the same spatial resolution, they have been harmonised at the highest spatial resolution (463.3 m) for the second part of the analysis, while in the first part the ABD map was resampled at a lower special resolution (27.8 m). Upon comparing the typology of data (surface of loss and biomass loss), we decided it was more important to rely on the exact surface of the loss and a resampled relative carbon stock instead of vice versa.
- Kenya borders: To avoid over/under estimation of the pixels close to the borders, a mask of Kenya at 463.3 m has been created based on the declaration of the administrative borders from the Kenyan government in 2009.

2.1.3 Carbon change

To determine the quantity of carbon that changed, the analysis was carried out in three parts:

1. The calculation of the carbon change due to forest area change (change on the area that the forest occupies)
2. The calculation of the carbon change due to change within the forest (degradation/regrowth)
3. The comparison between the carbon change described above and the carbon stock: Carbon loss fraction

2.1.3.1 Change of forest area (deforestation and afforestation)

The forest area change phenomenon is composed of two processes:

- Deforestation: area changed from forest to non-forest land cover
- Afforestation: forest regrowth in zones where the land cover was non-forest

The deforestation carbon impact was assessed using Hansen lossyear, selected for the period 2003-2014, to identify the deforestation surface, and ABD to assess the carbon loss for each deforested pixel.

The afforestation dataset was produced using Hansen gain to identify the afforestation surface and Mean Annual Increment (MAI) values per counties, multiplied by six. This was done to include an estimation of the carbon gain due to afforestation in the study period, as there is no information on when the zones started to gain carbon. Since the only information provided by Hansen, described the gain in forest area somewhere between 2000 and 2012, we assumed that allocating six years of carbon increment would be representative.

The analysis of deforestation and afforestation was carried out separately at the spatial resolution of 27.8m, the carbon values where summed up using the focal statistics tool with a rectangular window of 463.3m and resampled using nearest neighbour. The carbon unit (kg) remained the same. The focal statistics introduce an error of overestimation that was corrected multiplying each cell for 0.962091 (for the deforestation) and 0.961690 (for the afforestation).

2.1.3.2 Change within the forest (degradation and regrowth)

Following a similar methodology applied by Baccini et al. (2017) to define the carbon change due to degradation, we subtracted the forest area change only for the pixels where the total change was assessed. The residual is the carbon change due to change within the forest (degradation/ regrowth).

The analysis was performed only on the pixel where the total change was assessed (change zones) because there is a significant difference between the resolution of the two components of the analysis (the total carbon change map and the Hansen forest loss surface and related carbon at approximatively 500 m and 30 m). Considering forest area change also in areas where the total carbon change was not detected would have led to an overestimation of the degradation component (especially in the regrowth part), as the degradation is the result of the total carbon change minus the carbon changed due to forest area change. For instance, if the total change in one pixel is 0 and the deforestation is -50, the degradation component would have been +50 to compensate. Therefore, we decided to limit the analysis to the pixel where the total change was assessed.

2.1.4 Characterisation of the change (Stratification analysis)

A literature review was used to identify strata which are expected to have differing rates of carbon change for both forest area change and degradation/regrowth. The datasets selected for the stratification are (1) accessibility was designated as public infrastructures (roads, railways) have been identified as direst drivers of deforestation (Maukonen et al.,2016). (2) Population distribution was selected considering that part of the wood fuel demand is not answered only by the commercial harvesting, but the rural population is collecting fuelwood in the nearby zones (Drigo et al., 2015). (3) Livestock distribution was chosen because of the increasing livestock production (Korir et al.,2016) and the importance of livestock impact on forests highlighted by many national reports in the past years (Lambrechts et al., 2003; Gathaara and Leakey, 1999) and tackled by recent studies (Brandt et al., 2018). The above listed datasets have been merged into a unique dataset with 54 classes (only 51 present in Kenya). In this way each pixel has the combined information about each dataset.

2.1.4.1 Description of the used strata

Datasets used to produce the strata map is a combination of datasets, each one divided in classes distributed to be visually represented in the high canopy cover area of Western Kenya. Details in table 2.2 and Appendix 7.1.

Table 2.2: Description of the classes for each dataset used for the stratification.

Strata	Description	
Accessibility	High:	zone reachable in 1 hour
	Medium:	zone reachable in 3 hours
	Low:	zone reachable in more than 3 hours
Tropical Livestock Unit (TLU)	Low density:	from 0 to 25 TLU per km^2
	Medium density:	from 26 to 75 TLU per km^2
	High density:	more than 75 TLU per km^2
Population density	Low:	from 0 to 100 persons per km^2
	Medium:	from 101 to 400 persons per km^2
	High:	more than 400 persons per km^2
Canopy cover	High	Tree cover >= 25% (Hansen et al., 2013).
	Low	Tree cover < 25% (Hansen et al., 2013).

2.1.4.1.1 Accessibility

The accessibility dataset is derived from the work of Drigo et al. (2015) and represents the estimated round-trip transport time to the nearest village or motorable road in hours. The map is the result of an accessibility model that considers the cost, or friction surface, based on terrain and land cover data. Classes are described in table 2.2 and map in Appendix 7.1, Figure 7.1.

2.1.4.1.2 Tropical Livestock Unit (TLU)

The Tropical Livestock Unit map is the results of the aggregated datasets of cattle, goats and sheep distribution. Each typology of animal has a TLU factor (see Table 2.3) indicating the impact on the land to aggregate them in one single livestock impact map indicating the density of the livestock in the surrounding 10 km[1]. The dataset was obtained applying the mean focal statistic tool with a circle of 22 cells diameter. Cattle, goats and sheep datasets are global datasets produced by Robinson et al. (2015). Classes are described in table 2.2 and map in Appendix 7.1 in Figure 7.2.

Table 2.3: Tropical Livestock Unit weight for cattle, goats and sheep

Class	TLU weigh
Cattle	0.7
Goat	0.1
Sheep	0.1

2.1.4.1.3 Population density (2009)

The population density dataset is derived from the work of Drigo et al. (2015) and represents the estimated distribution of the population at the level of administrative units (acquired from the data of the Census of 2009). Within each unit, the spatial distribution of the population is based on cartographic elements and attributes from the map of land cover that indicate population presence, such as built-up areas, farming areas, etc. Each cell represents the mean of the surrounding 10 km, obtained by applying the focal statistic tool with a circle of 22 cells diameter. Classes are described in table 2.2 and map in Appendix 7.1 in Figure 7.3.

2.1.4.1.4 Canopy cover

The land was divide in two classes based on the percent of tree canopy cover. The threshold is 25%, where high canopy cover is equal or greater 25%. In this study the surface of the high canopy cover was considered as forest mask.
To allocate the distribution of tree cover we referred to the country level forest estimation for the year 2000 (FAO, 2015; Kenya Forest Service, 2013). The forest surface in 2000 was estimated to be 3,557 thousand ha. The forest mask was deduced using the tree canopy cover dataset (Hansen et al., 2013). The percent of tree canopy cover that is closer to this surface is the 25% or higher with 3,960 thousand ha. Classes are described in table 2.2 and map in Appendix 7.1 in Figure 7.4.

[1] Selected based on an average of cattle walking distance derived from the study of Goopy at al. (2018)

2.1.5 Correlation analysis

We tested relations between each of the different stratification layers (see section2.1.4.1) and the two carbon change layers using the Spearman's rank correlation coefficient to investigate whether stratification layers could explain the carbon loss.

2.1.6 Carbon datasets inconsistency

The two carbon related datasets used in this research, the total carbon change (2006-2014) and the ABD (2000), represent the carbon stored or change in the same area. In order to produce meaningful results, the two datasets have to be consistent. To do so we assumed that the carbon change detected in the total carbon change dataset should not exceed the quantity of carbon stocked in the same area plus the MAI for 14 years.

Results reveal that inside the high canopy cover area the number of pixel with an error is 0.9% (see Table 2.4) of the pixel considered in the analysis, while outside the forest it is 3.5%. In total, the pixels with an error of less than 25 tonnes of carbon per ha represent the 85% (as shown in table 2.5).

Table 2.4: Pixels representing the inconsistency of the two carbon datasets (total carbon change and ABD) divided in classes of high and low canopy cover with the number of error pixel and the percent compared to the total number of pixels declaring loss

Class	Number of error pixels	% number error pixels compared to total number loss pixels
High canopy cover	953	0.9
Low canopy cover	3,692	3.5
	4,645	4.4

Table 2.5: Pixels representing the inconsistency of the two carbon datasets (total carbon change and ABD) divided in error classes with the number of pixels in each class and the percent

Classes of error (t of C per ha)	Number of pixels with error	% compared to the total number
-253; -100	5	0.1
-99; -50	119	2.6
-49; -25	576	12.4
-24; -1	3,945	84.9
	4,645	100.0

Therefore, we decided to not apply a correction factor as the error is relatively small for a country level analysis.

2.2 Zoom-in zones (Objective 2)

This section is divided in 3 chapters: the first, briefly describes survey data; the second, illustrates the datasets and assumptions used to characterise the 5 study areas and the third, explains how the survey data has been analysed.

2.2.1 Survey

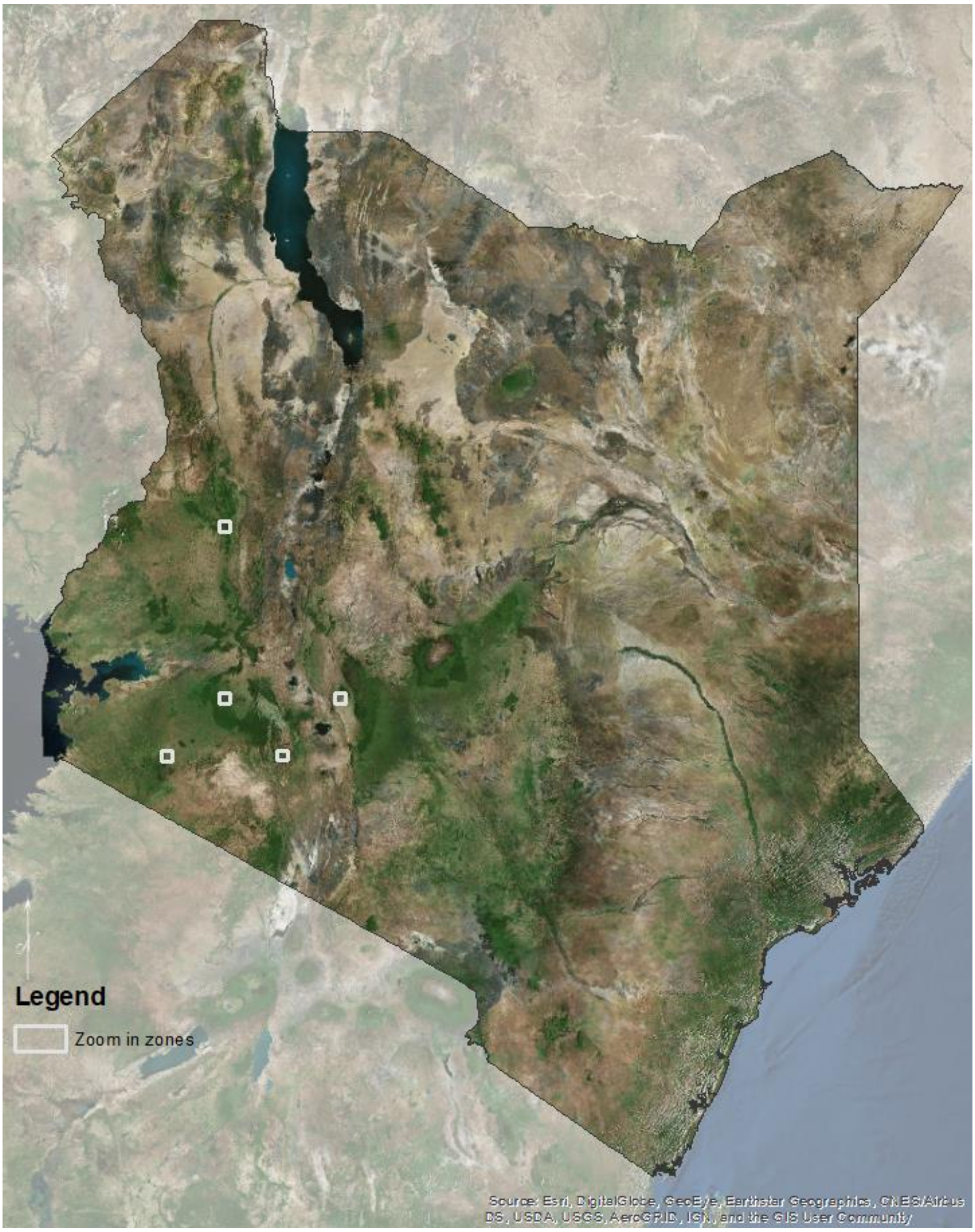


Figure 2.1: Kenya with the five zoom-in study areas in the Western part

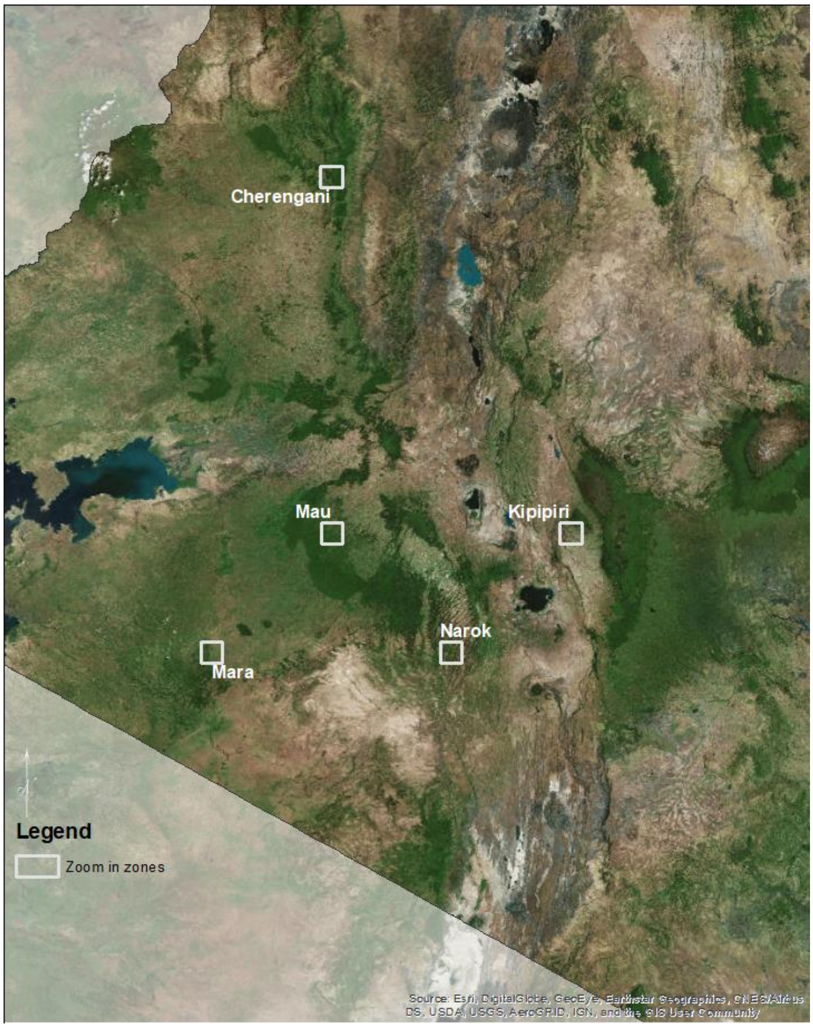


Figure 2.2: Detail of the zoom- in study areas

The data used in this research is derived from a survey undertaken in Kenya in November 2015 (see appendix 7.2 for details). Figure 2.1 and 2.2 show the five study areas covered by the survey in West Kenya. Each study area has a different number of samples that refer to plots that have been deforested between 1990 and 2015 (see Table 2.6). The owner of the plot was asked to describe the deforestation process.

Table 2.6: Distribution of sample numbers in each study area

Study area	Number of samples
Mara	37
Narok	38
Mau west	26
Kipipiri	25
Cherangani	16
Total	**142**

2.2.2 Study area descriptions

2.2.2.1 Material

For each of the 5 study areas general information are used to contextualise the areas. For details see table 2.7

Table 2.7: Overview of the information and related source of the study areas

Information	Source
General description zone, temperature (°C), moisture classification, annual rainfall (mm), vegetation, potential for plant growth	Sombroek et al. (1982)
Altitude (m)	ASTER GEDEM V2 30m resolution
High canopy cover 2000 %: percent of the total surface that is covered by tree canopy cover >= 25%	Tree canopy cover from Hansen et al. (2013)
Carbon stock 2000 (t): sum of the tonnes of carbon	Zarin et al. (2016)
Accessibility (hours): number of hours needed to reach a pixel. Mean and range (max-min)	Drigo et al. (2015)
Population density/km^2 (2009)	Drigo et al. (2015)
Tropical livestock Unit (TLU) (2006): density/km^2; % of cattle	Robinson et al. (2014)

2.2.2.2 Description

The five study areas are located in Western Kenya at an altitude ranging from 1,700 m to 2,600 m, with peaks of 3,000 masl. Based on the classification of Sombroek et al. (1982), the five study areas are in different moisture zones extending from humid (characterised with higher rates of rainfall and moist forest) to semi-humid (characterised by lower rates of rainfall and dry forest with moist woodlands). The moist forest in Kenya is the ecosystem with higher potential for plant growth that allows to stock high quantities of carbon. Among all parameters, the five study areas differ for canopy cover percent, population density, livestock density and carbon stock (see Table 2.8). The canopy cover percent is related to the carbon stock, the vegetation type and the climatic characteristics (rainfall, altitude, temperature).

The study area with highest canopy cover in 2000 is the zone of Mau west, with 93% of the surface covered by high canopy cover, and a carbon stock of almost 1 million tonnes. The study area is located in the heart of the Mau complex (see Figure 2.2) and characterised of humid climate that leads to moist forest and very high potential for plant growth. The accessibility of the zone is the lowest of the five study areas with an average of 3.6 hours and a maximum of 6.9 hours, yet, the population and livestock are considerable if compared with the other study areas (153 inhabitants per km^2 and 57 TLU where cows represent 92% of the livestock).

Narok represents a completely different situation where the environment is characterised by a semi-humid zone (lower rainfall) leading to a dry forest and moist woodland vegetation type with a medium-high potential for plant growth. The high canopy cover surface covers 45% of the total surface and presents a carbon stock of around 300 thousand tonnes. The density of population and livestock is quite low (34 inhabitants per km^2 and 9 TLU where cows represent 67% of the livestock) and the accessibility is quite high (1.1 h in average with a maximum of 3.6 h).

In contrast Kipipiri has similar environmental characteristics, with a slightly greater elevation but the carbon stock is much higher, considering that the high tree canopy cover is covering only 28% of the surface. This is the most densely populated zone among the study areas, with 222 inhabitants per km^2 and 73 TLU where cows represent 99% of the livestock. The accessibility is the highest, with 0.4 hours on average and a maximum of 2.7 hours.

Table 2.8: Study areas environmental and socio-economic characteristics

Study area	**Mara**	**Narok**	**Mau west**	**Kipipiri**	**Cherangani**
General description zone	Lower Highlands, Middlelands	Lower Highlands	Lower Highlands	Lower Highlands	Upper Highlands
Altitude: average, min, max (m)	1,760 ; 1,708 ; 1,882 m	2,143 ; 1,955 ; 2,480 m	2,358 ; 2,204 ; 2,524 m	2,419 ; 2,145 ; 3,026 m	2,618 ; 2,301 ; 3,086 m
Temperature: annual mean (°C)	18 – 20 °C	14 – 16 °C	12 – 16 °C	(10) – 12 – 16 °C	10 – 14 °C
Moisture classification	Humid, sub-humid	Semi-humid	Humid	Semi-humid	Humid
Annual rainfall: average (mm)	1,000-1,600 mm	800 – 1,400 mm	1,100 – 2,700 mm	600 – 1,600 mm	1,000 – 2,700 mm
Vegetation	Moist and dry forest	Dry forest and moist woodland	Moist forest	Dry forest and moist woodlands, with parts of dry woodland and bushlands	Moist forest with parts of dry forest
High canopy cover (>= 25%) 2000 %	32%	45%	93%	28%	71%
Carbon stock 2000 (t)	353,996 t	338,570 t	945,212 t	343,039 t	1,161,221 t
Potential for plant growth	High	High to medium	Very high	High to medium	Very high
Accessibility (one way): mean, range (h)	1.2 ; 2.7 h	1.1 ; 3.6 h	3.6 ; 6.9 h	0.4 ; 2.7 h	2.1 ; 7.4 h
Population inhabitants per km^2	119 km^2	34 km^2	153 km^2	222 km^2	120 km^2
TLU per km^2, % of cattle	51; 94%	9; 67%	57; 92%	73; 99%	21; 81%

2.2.3 Study areas analysis

The samples were selected based on the following requirements:

(1) the plots were declared to be covered by forest when the owner moved into the plot;

(2) the deforestation process ended after 1990.

In this research, the comparison between two or more information (deforestation drivers, speed or land management) derived from the survey declaration are weighted on the surface of the deforested plot identified during the execution of the survey.

Table 2.9: Survey questions and answers used in this research

Code	Question	Possible answer
C.1	What year did you start using the land?	
D.3	What state was the land when you moved in/bought it/ started using it?	- Forest, including degraded/ secondary forest - Crops land - Pasture - Mixed agriculture
D.4	When did the forest start getting cut?	
D.6	Was the conversion of the forest a gradual process?	Yes/no
D.7	What was happening on the land during this conversion process?	- No activities - Mushrooms honey fruits (wild edibles) collection - Materials for construction of housing/furniture etc. (bamboo leaves etc.) - Materials for handicrafts - Materials for fuel (rewood /other materials for re making) - Charcoal production - Timber harvesting - Pole harvesting - Brick burning - Grazing cattle - Hunting animals
D.8	When did the trees stop getting cut?	
E.1	What is the plot currently used for?	- Food crops - Cash crops (i.e. sugar, tea, coffee,sesame, cotton) - Pasture - Agroforestry - Silvipasture - Fallow - Shrubs - Residential area/built-up/infrastructure, - Degraded / secondary forest - Natural / primary forest - Wetland - Plantation forest
G.1	Thinking back to the past, what was the land used or what was the cover during period 1[2]?	- Food crops - Cash crops (i.e. sugar, tea, coffee,sesame, cotton) - Pasture - Agroforestry - Silvipasture - Fallow - Shrubs - Residential area/built-up/infrastructure, - Degraded / secondary forest - Natural / primary forest - Wetland - Plantation forest

For each study area, the deforestation drivers were identified by question G.1 (Table 2.9) and represented as a chart. Additionally, land use evolution was further analysed comparing it with question E.1 to create a transition matrix. Not all farmers had a period 1 before the current period (2015), the one that did not change are counted both times with the same land use.

[2] Period 1 is the first period right after deforestation

For each deforestation driver a graph showing the speed of the deforestation process was created considering the number of years passed between the year when the deforestation process started and the year that it stopped (question D.8 – D.4 in Table 2.9) If both occurred in the same year, the deforestation speed was assumed to be 0 years (a fraction of the year).

For each driver, the percent of the land management activities performed during the deforestation process were divided in 3 main groups: grazing activities, food collection activities and wood collection activities (see table 2.10 for details). Wood collection activities were further divided by identifying the frequency of each sub activity for each study area. All information about land management were derived from the question D.7 of the survey (see Table 2.9).

Table 2.10: Land management activities groups and detailed sub-activities

Land management activity groups	Included sub-activities
Grazing	Cattle grazing in the plot
Food collection	– Mushrooms, honey, fruits (wild edibles) collection – Hunting animals
Wood collection	– Materials for fuel (firewood / other materials for fire making) – Charcoal production – Materials for construction of housing/furniture etc. (bamboo, leaves etc.) – Timber harvesting – Pole harvesting

2.3 Carbon emission for each zoom-in zone (Objective 3)

For each of the 5 study areas, the carbon values representing the four carbon change processes (degradation, regrowth, deforestation and afforestation) were extracted using the zonal statistics as a table tool in ArcGIS and plotted with the total carbon stock in 2000.

Zooming-in in the five study areas, the inconsistency error (see chapter 2.1.6) can have a higher impact especially in the zone of Narok (see Figure 2.3 and Table 2.11), therefore, we decide to correct the inconsistency by adding the difference to the carbon stock for the year 2000.

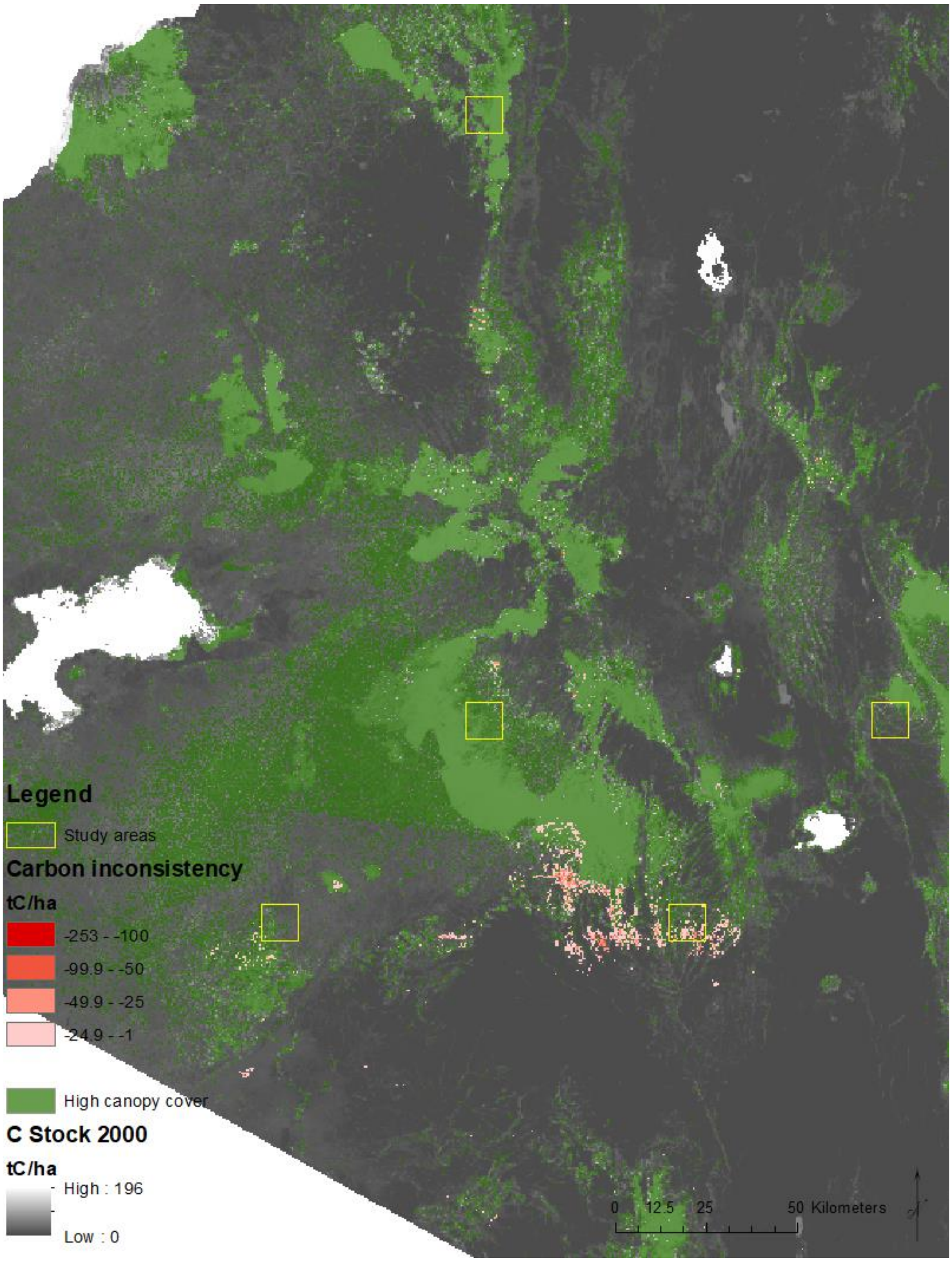


Figure 2.3: Inconsistency distribution over the study areas

Table 2.11: Inconsistency error in each study area

	Number of pixels	ha	error in tonnes
Mara	3	64	-279
Narok	96	2,061	-31,104
Mau west	0	0	0
Kipipiri	1	21	-429
Cherangani	1	21	-150

3 Results

This chapter is divided in three sub chapters: one, reports the results obtained by the analysis of the emissions for the whole of Kenya (objective 1), the second, focuses on the 5 study areas describing the deforestation process (objective 2) and the third, addresses the carbon emissions related to the 5 study areas (objective 3).

3.1 Carbon emissions (Kenya) (Objective 1)

All values represent carbon, the transformation to CO_2 can be made by multiplying for 3.67.

3.1.1 Carbon emissions

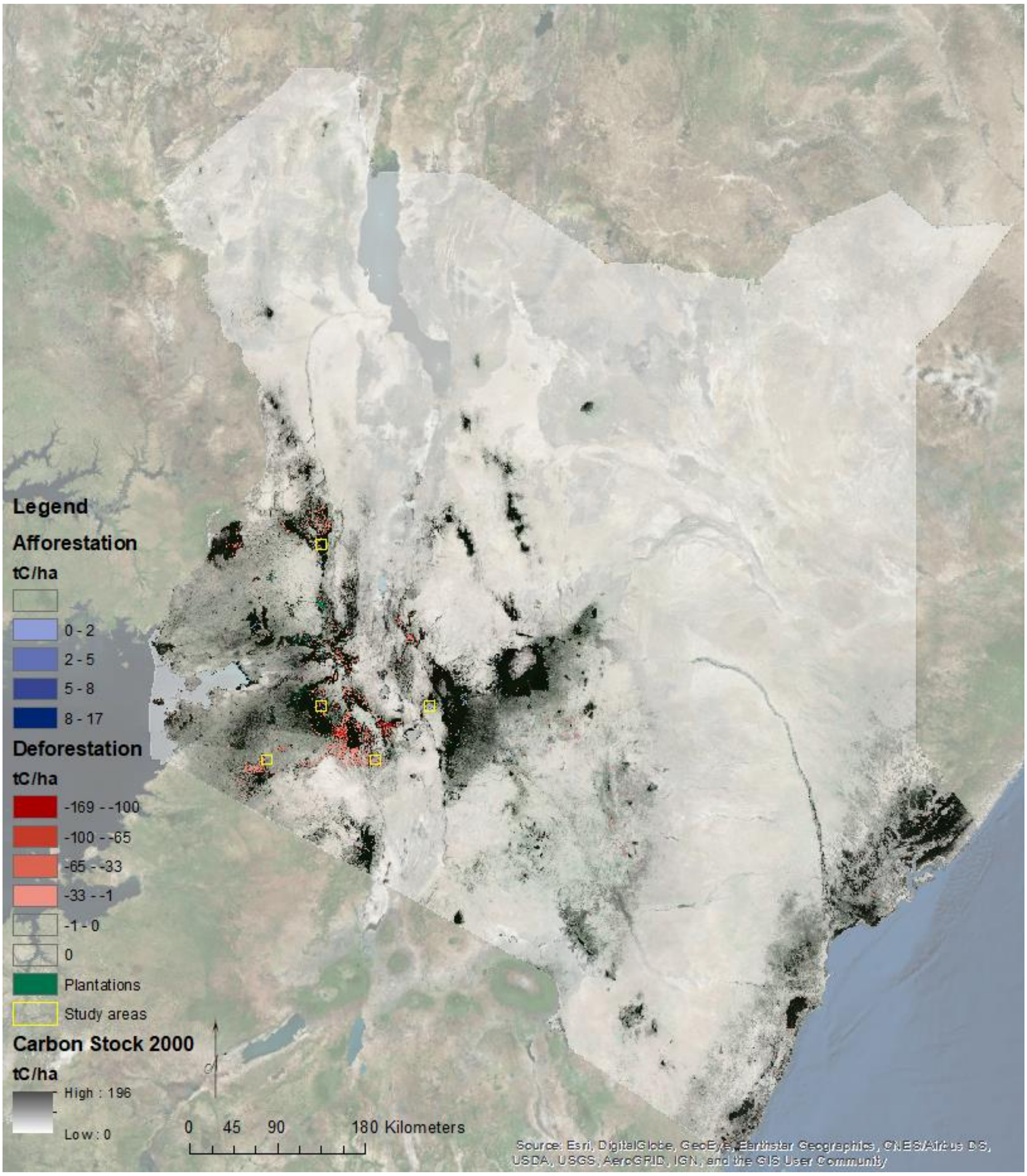


Figure 3.1: Deforestation and afforestation for the period 2003-2014 (in the Baccini et al., 2017 change zones)

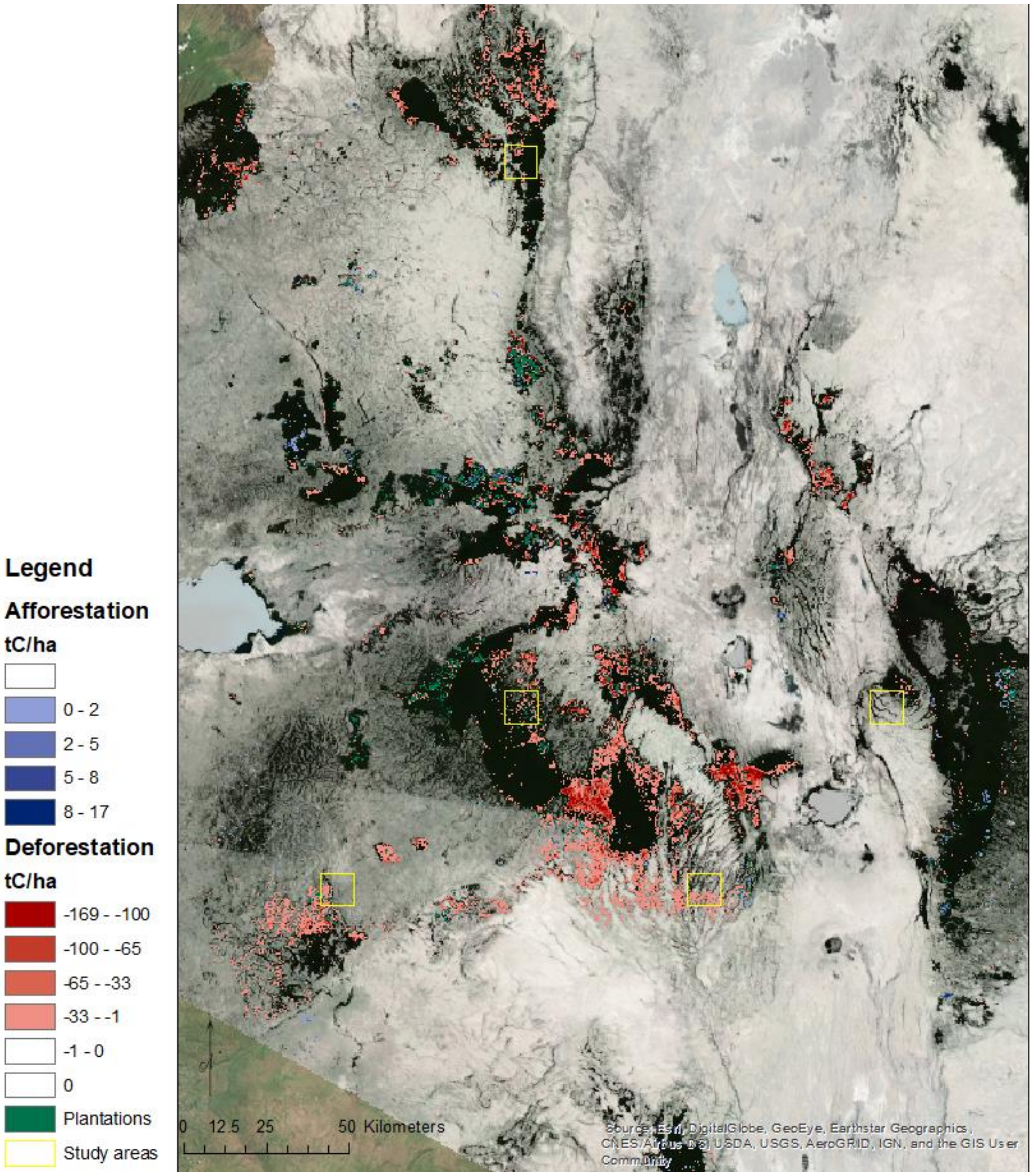


Figure 3.2: Deforestation and afforestation in Western Kenya for the period 2003-2014 (in the Baccini et al., 2017 change zones)

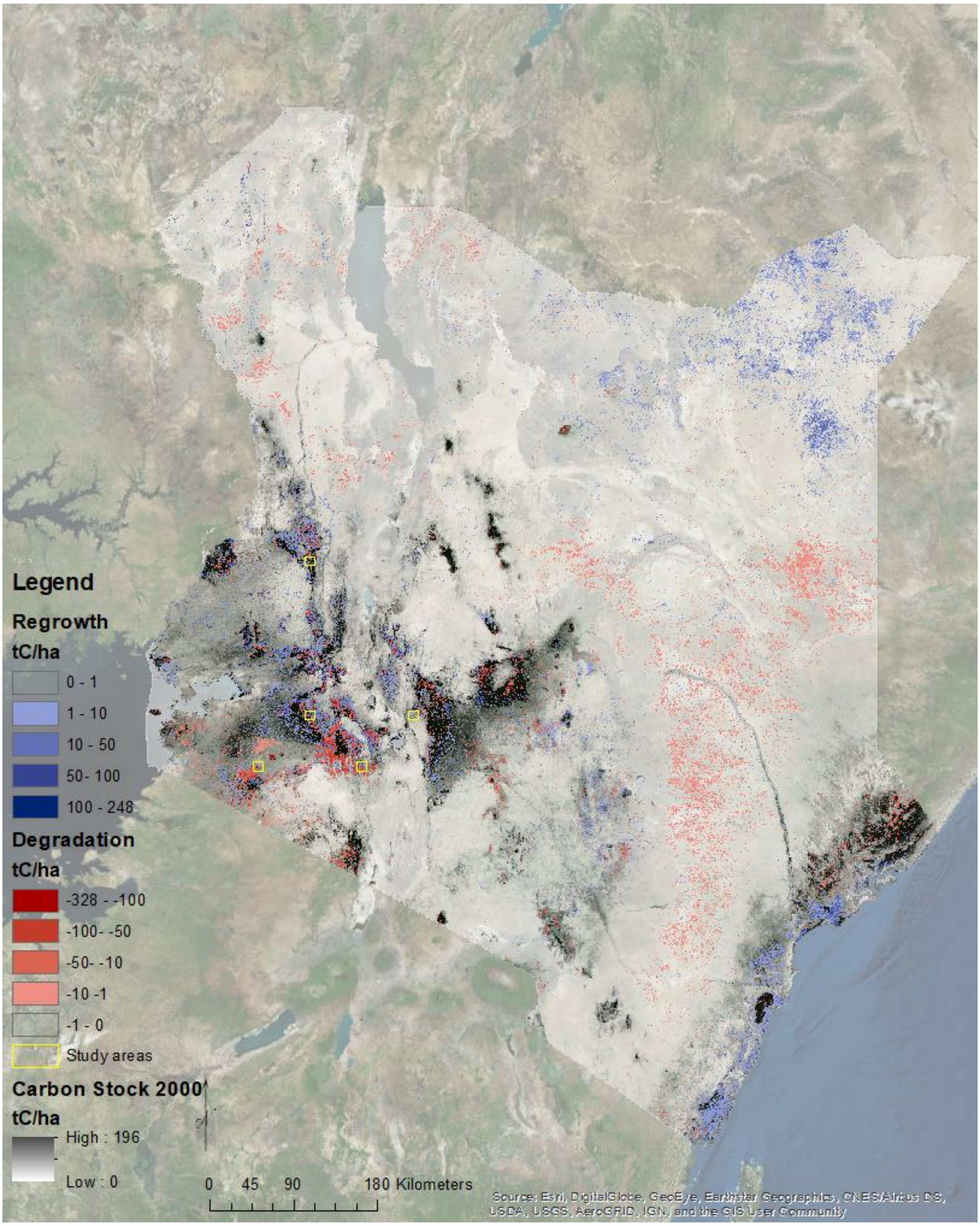


Figure 3.3: Degradation and regrowth in Kenya over the period 2003-2014

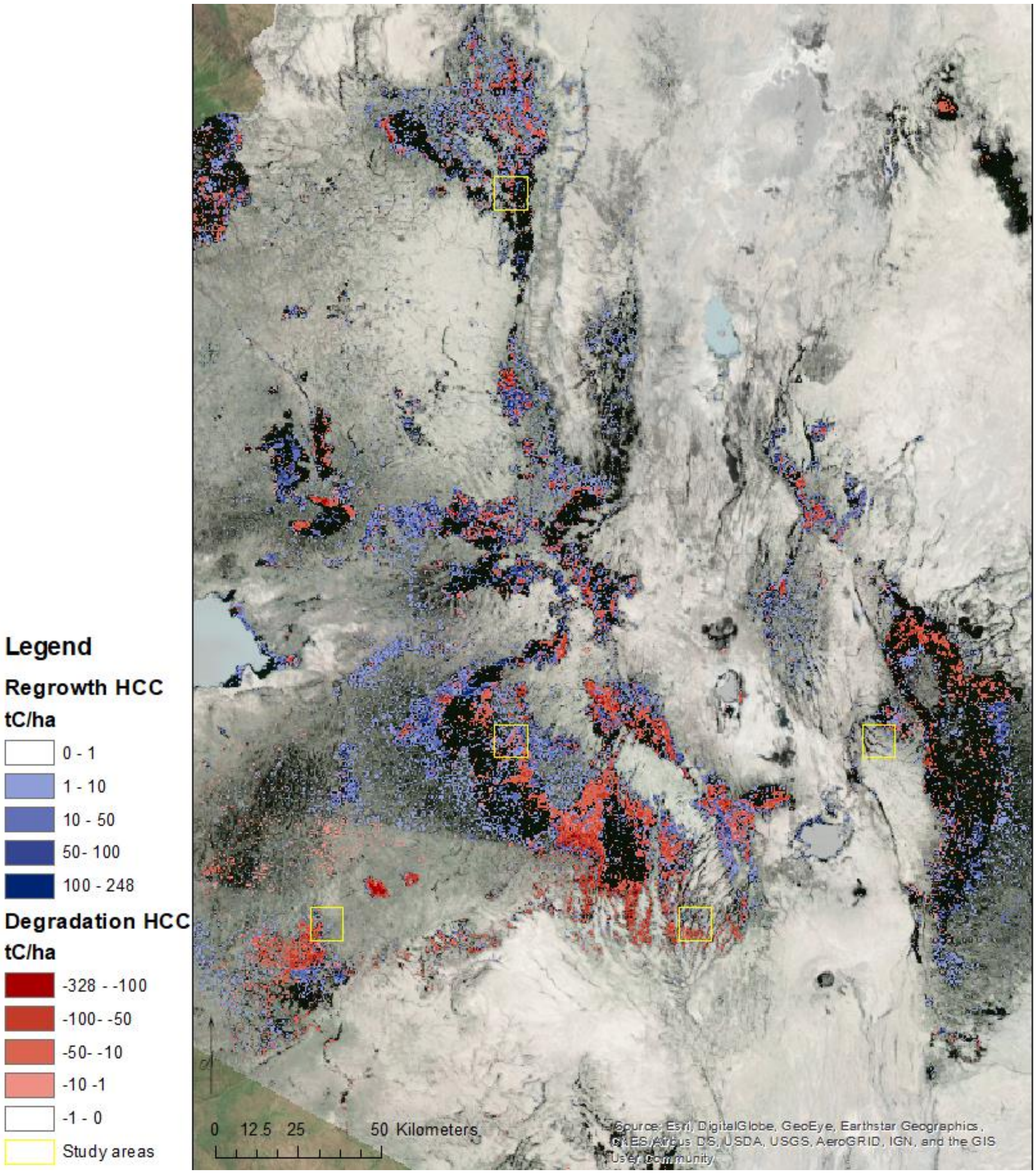


Figure 3.4: Degradation and regrowth in Kenya over the period 2003-2014 in Western Kenya

In Figure 3.1 is shown the distribution of the forest area change loss (deforestation) and gain (afforestation) detected by both Hansen et al. (2013) and Baccini et al. (2017).

Over the whole of Kenya, forest area change distributed mainly in the Western part, where the forests ecosystems are located (Figure 3.2). Degradation however is distributed over a larger surface (see Figure 3.3).

Table 3.1: Sum of carbon loss due to forest area change and degradation in millions of tonnes. The same loss is represented as percent of the carbon stock (2000)

	Sum Mt of C change		% C stock loss		% of C stock loss per year	
	Forest area change	Degradation/ Regrowth	Forest area change	Degradation/ Regrowth	Forest area change	Degradation/ Regrowth
Low Canopy cover (<25%)	-0.7	-4.5	-6.4	-38.8	-0.6	-3.5
High Canopy cover (>=25%)	-7.2	-10.6	-12.8	-19.0	-1.2	-1.7
Total	-7.9	-15.1	-11.7	-22.4	-1.1	-2.0

Majority of the loss is caused by degradation (-15.1 Mt) (Table 3.1) distributed as shown in Figure 3.3 and 3.4. In the high canopy cover, forest area change is responsible for a loss of -7.2 Mt loss, whereas degradation is responsible for a loss of -10.6 Mt. In the low canopy cover the degradation reduces the carbon stock of -38.8% in total, or -3.5% per year.

Overall, the forest area change has an impact on the aboveground carbon stock decrease of about -1% per year, while the degradation has a higher impact of around -2% per year.

Looking at the high canopy cover divided in classes (Table 3.2), the process of degradation shows an increase when the accessibility increases and population density decreases: low accessibility accounts for -4.6 Mt, while high accessibility for -1.7 Mt; in the low popultion density the degradation accounts for -8 Mt of carbon loss, while in the medium population for -2.7 Mt.

Deforestation shows a trend similar to degradation but less strong: deforestation decreases when the population density increase.

Table 3.2: Carbon loss due to forest area change and to degradation in millions of tonnes. The high canopy cover loss is also divided in accessibility, livestock or population classes

	Loss 2003-2014		Sum of stock at year 2000
	Forest area change	**Degradation/ Regrowth**	
	millions t of C	millions t of C	millions t of C
Low Canopy cover (<25%)	-0.7	-4.5	11.6
High Canopy cover (>=25%)	-7.2	-10.6	56.0
High accessibility	-2.4	-1.7	14.4
Medium accessibility	-2.9	-4.3	20.6
Low accessibility	-1.9	-4.6	21.0
Low livestock density	-0.8	-3.7	13.9
Medium livestock density	-3.8	-4.9	29.0
High livestock density	-2.5	-2.0	13.1
Low population density	-3.8	-8.0	30.6
Medium population density	-3.2	-2.7	23.7
High population density	-0.2	0.1	1.7
Total	-7.9	-15.1	67.6

3.1.1.1 *Correlation*

The results of the correlation analysis conducted using the Spearman's rank correlation coefficient (Table 3.3) reveals that livestock and population density are more correlated with carbon loss as compared to accessibility.

Table 3.3: Spearman rank correlation coefficients of the stratification layers (accessibility, popilation and livestock density) with the loss layers (Forest area change and Degradation/regrowth)

Sperman correlation coefficient	Forest area change	Degradation/ Regrowth
Accessibility	0.215	0.005
Livestock density	-0.370	-0.030
Population density	-0.372	-0.201

Therefore, a deeper analysis of the carbon change in relation with population and livestock has been performed (Table 3.4 and 3.7) revealing that forest area change (Table 3.4) (for the period 2003-2014) is principally composed by the deforestation process. Afforestation does not have a high impact (maximum +1% in the high livestock and high population density).

Deforestation increases with the increase of livestock density (looking at the total: -6% for the low livestock density, -13% for the medium and -20% for the high) while the population is stable with variations from -12% to -15%.

The fraction of carbon loss due to forest area change is higher where the livestock and/or the population are denser. The high population density class have a smaller surface (Table 3.5), compared to the others as it represents the zones where the population is higher than 400 inhabitants per km^2.

Table 3.4: Deforestation (loss, gain and net) represented as a fraction of the stock, divided in livestock and population classes

Deforestation carbon loss (stock fraction)				
%	Low livestock density	Medium livestock density	High livestock density	Total
Low population density	-3	-15	-22	-12
Medium population density	-14	-12	-18	-14
High population density	-4	-20	-7	-15
Total	-6	-13	-20	-13
Afforestation carbon gain (stock fraction)				
%	Low livestock density	Medium livestock density	High livestock density	Total
Low population density	0	0	0	0
Medium population density	0	0	1	0
High population density	0	1	1	1
Total	0	0	0	0
Net (deforestation and afforestation) carbon change (stock fraction)				
%	Low livestock density	Medium livestock density	High livestock density	Total
Low population density	-3	-15	-22	-12
Medium population density	-14	-12	-18	-13
High population density	-4	-19	-6	-13
Total	-6	-13	-19	-13

Table 3.5: Surface in thousands of ha of the livestock and population classes

Surface				
1000 ha	Low livestock density	Medium livestock density	High livestock density	Total
Low population density	138	122	58	318
Medium population density	34	129	58	221
High population density	2	14	10	26
Total	174	265	126	565

Table 3.6: Carbon stock (2000) in millions of tonnes for the livestock and population livestock

Carbon stock (2000)				
Million of tonnes	Low livestock density	Medium livestock density	High livestock density	Total
Low population density	10.2	13.9	6.5	30.6
Medium population density	3.7	14.1	5.9	23.7
High population density	0.1	1.0	0.6	1.7
Total	13.9	29.0	13.1	56.0

Degradation is a more balanced process as it is composed by a relatively high degradation (-35 to -21%) partly compensated by regrowth (+5 to +27%) (Table 3.7). Net carbon loss is higher in the low populated zones, as the regrowth is much lower, while in the highly populated zones the carbon change is balanced or even positive, as the regrowth is compensating the loss. The livestock presents a similar trend but the difference between the livestock classes are less strong: low livestock density presents a higher loss (-32%) and a lower regrowth (+6%), increasing the livestock density, the loss is slightly reducing (-24%) and the regrowth slightly increasing (+9%).

Table 3.7: Degradation (loss, gain and net) represented as a fraction of the stock, divided in livestock and population classes

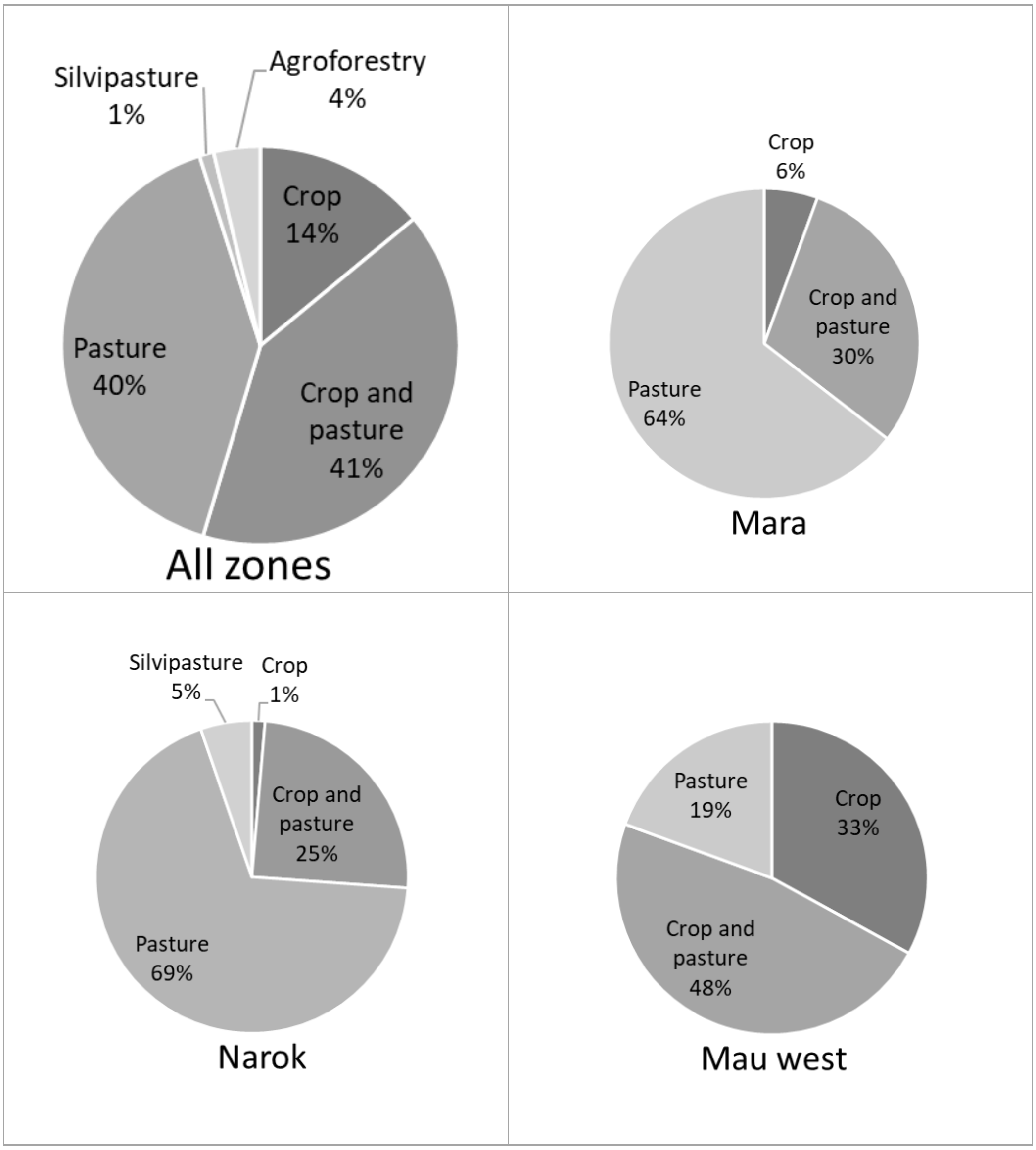
Degradation carbon loss (stock fraction)				
%	Low livestock density	Medium livestock density	High livestock density	Total
Low population density	-35	-28	-28	-30
Medium population density	-25	-21	-21	-22
High population density	-25	-24	-13	-20
Total	-32	-25	-24	-26
Regrowth carbon gain (stock fraction)				
%	Low livestock density	Medium livestock density	High livestock density	Total
Low population density	5	4	3	4
Medium population density	7	10	14	10
High population density	11	25	27	25
Total	6	7	9	7
Net (degradation and regrowth) carbon change (stock fraction)				
%	Low livestock density	Medium livestock density	High livestock density	Total
Low population density	-30	-24	-24	-26
Medium population density	-18	-11	-8	-11
High population density	-14	1	14	5
Total	-27	-17	-15	-19

3.2 Deforestation process: zoom-in study areas (Objective 2)

This subchapter is divided in 3 sections: deforestation driver, deforestation speed and land management activities performed during the deforestation process. All the information derived from the questionnaire are based on the number of samples described in section 2.2.1.

3.2.1 Deforestation driver

As shown in Figure 3.5, the overall main deforestation drivers are the mixture of crop and pasture (41%) together with pasture (40%). Mara and Narok present pasture as a main driver while Mau west, Kipipiri and Cherangani presents crop and pasture. Crop is generally less important apart for the zone of Mau west and Cherangani where it occupies around 30%.



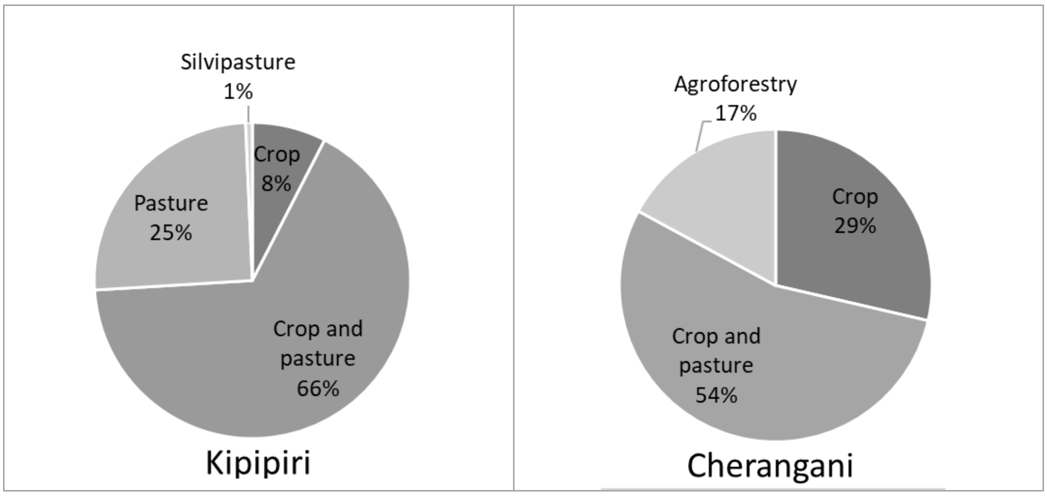


Figure 3.5: Deforestation driver in in all the study area together and in each one separately

3.2.1.1 Deforestation drivers transition matrix

In the study areas of Mara and Narok, the main deforestation drivers derived from the first land use are pasture (66%) (see Table 3.8) and crop and pasture (28%). Compared with 2015 land use, pasture is still the main driver (64%) but crop and pasture decreased to 6%. In Table 3.8 from the column of crop and pasture (First LU) we can see that 1.4 ha remained crop and pasture, but 8.2 ha became pasture and 4.2 crop. The overall trend shows that the land use changed in direction of increasing crop surface in disadvantage of the mixture of crop and pasture. Pasture remained stable. In Table 3.9, the number of observations used to calculate the transition matrix, are shown.

Table 3.8: Transition matrix of deforestation drivers of the study areas: Mara and Narok in hectares and percent

Study areas of: MARA and NAROK						
Surface in ha	**First LU**					
Current LU	**Crop**	**Crop and pasture**	**Pasture**	**Silvipasture**	**Current LU total**	**Current LU %**
Crop	1.8	4.2	5.1		11.1	22
Crop and pasture		1.4	1.9		3.3	6
Pasture	0.2	8.2	24.6		33.0	64
Silvipasture			1.0	1.1	2.1	4
Shrubs			0.2		0.2	0
Degraded		0.6	1.1		1.7	3
First LU total	2.0	14.3	34.0	1.1	51.4	100
First LU %	4	28	66	2	100	

Table 3.9: Transition matrix of deforestation drivers of the study areas: Mara and Narok. Number of observations used to calculate Table 3.8

Study areas of: MARA and NAROK					
Number of observations	**First LU**				
Current LU	**Crop**	**Crop and pasture**	**Pasture**	**Silvipasture**	**Current LU total**
Crop	2	7	6		15
Crop and pasture		5	3		8
Pasture	1	7	36		44
Silvipasture			1	3	4
Shrubs			1		1
Degraded		2	1		3
First LU total	3	21	48	3	75

In the study areas of Mau west, Kipipiri and Cherangani, the main deforestation driver derived from the first land use are crop and pasture (55%) (see Table 3.10) and crop (25%). Compared with 2015 land use, pasture became the main driver (47%), while crop and pasture decreased to 24%. In Table 3.10 from the column of crop and pasture (First LU) we can see that 10.0 ha remained crop and pasture, but 12.1 ha became pasture and 3.2 crop. In the crop column (First LU) we can see that 5.8 ha of crop remained crop, but 0.9 became crop and pasture and 4.9 became pasture. The overall trend shows that the land use changed in direction of increasing pasture surface in disadvantage of the mixture of crop and pasture, and crop.

Table 3.10: Transition matrix of deforestation drivers of the study areas: Mau west, Kipipiri and Cherangani in hectares and percent

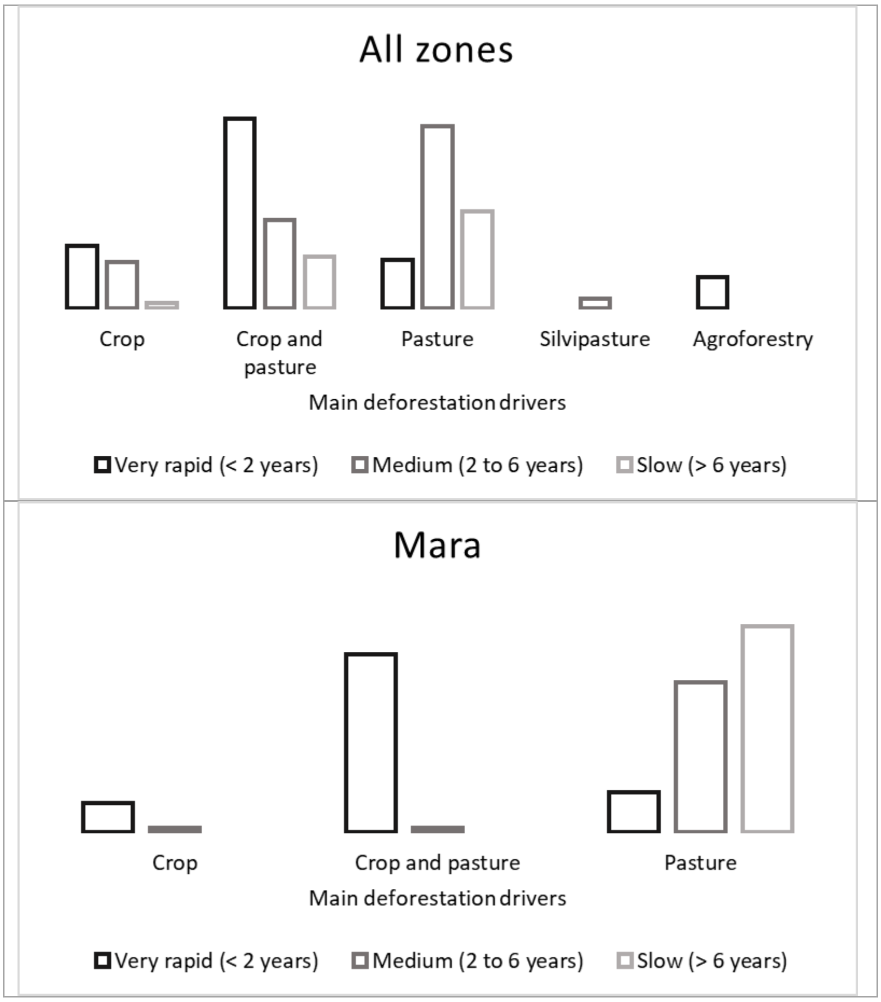
Study areas of: Mau west, Kipipiri and Cherangani							
Surface in ha	**First LU**						
Current LU	**Crop**	**Crop and pasture**	**Pasture**	**Agroforestry**	**Silvipastur e**	**Current LU total**	**Current LU %**
Crop	5.8	3.2	0.6			9.6	21
Crop and pasture	0.9	10.0	0.2			11.1	24
Pasture	4.9	12.1	4.5			21.5	47
Agroforestry				3.7		3.7	8
Silvipasture		0.1			0.1	0.1	0
First LU total	11.6	25.2	5.3	3.7	0.1	46.0	100
First LU %	25	55	12	8	0	100	

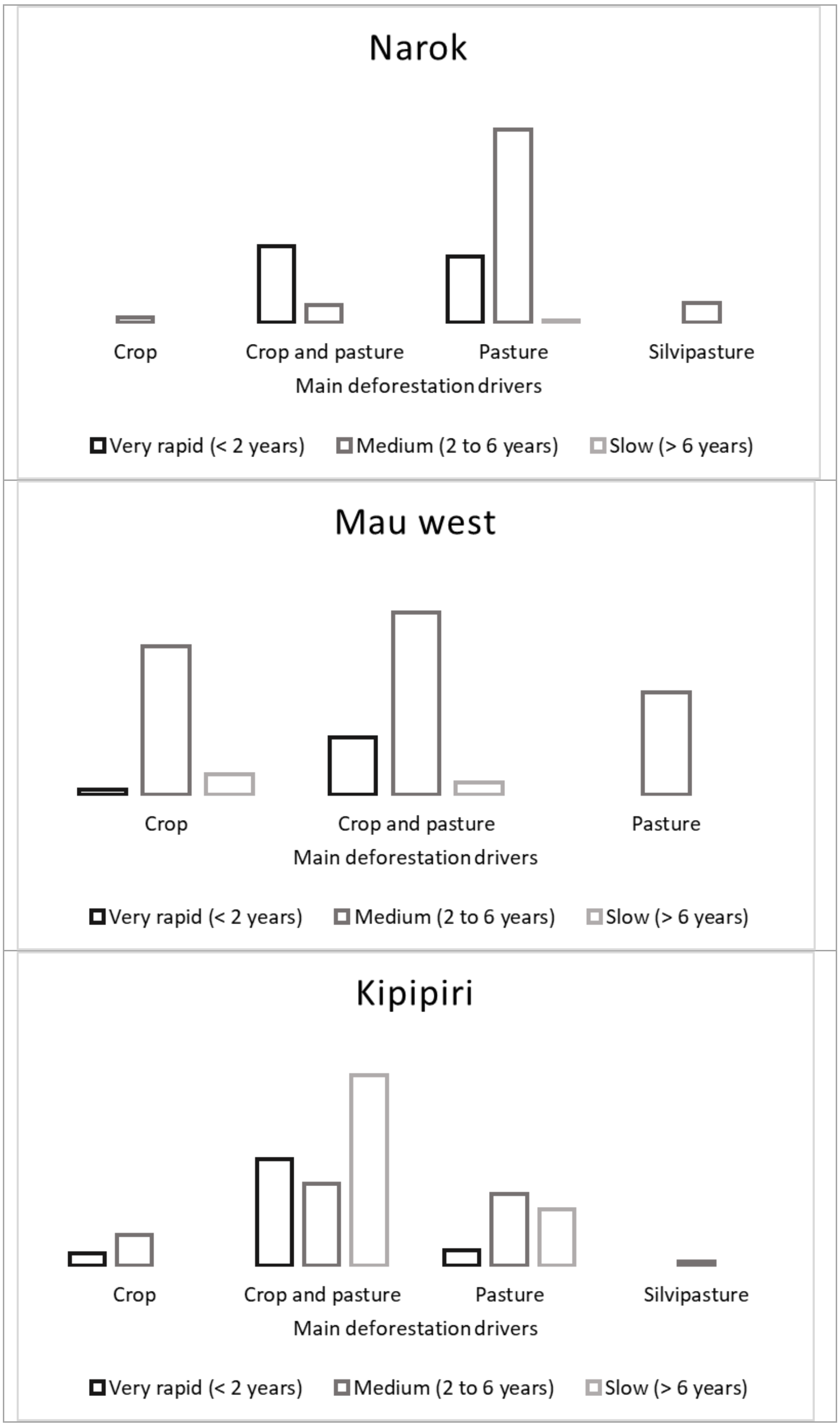
Table 3.11: Transition matrix of deforestation drivers of the study areas: Mau west, Kipipiri and Cherangani. Number of observations used to calculate Table 3.10

Study areas of: Mau west, Kipipiri and Cherangani						
Number of observations	**First LU**					
Current LU	**Crop**	**Crop and pasture**	**Pasture**	**Agroforestry**	**Silvipastur e**	**Current LU total**
Crop	11	7	2			20
Crop and pasture	4	14	1			19
Pasture	5	8	11			24
Agroforestry				2		2
Silvipasture		1			1	2
Grand Total	20	30	14	2	1	67

3.2.2 Deforestation speed

The highlighted overall trend shows that crop and a mixture of crop and pasture present mainly a fast deforestation that occurred in less than two years (see Figure 3.6, All zones), while pasture has a medium deforestation speed (between 2 and 6 years).
Comparing Mara and Narok (the two zones where the main deforestation driver is pasture) we can see a difference in the deforestation speed: Mara shows a slower deforestation (slow: in more than 6 years) while Narok is medium fast (less than 6 years).
A mixture of crop and pasture is the main deforestation driver of the other three study areas, but the situation is not homogeneous: in each study area the deforestation speed is different. Mau west is characterised by a medium deforestation speed, while Kipipiri is slow (more than 6 years) and Cherangani is rapid (less than two years).




Narok
Crop
Crop and pasture
Pasture
Silvipasture
Main deforestation drivers
Very rapid (< 2 years)
Medium (2 to 6 years)
Slow (> 6 years)
Mau west
Crop
Crop and pasture
Pasture
Main deforestation drivers
Very rapid (< 2 years)
Medium (2 to 6 years)
Slow (> 6 years)
Kipipiri
Crop
Crop and pasture
Pasture
Silvipasture
Main deforestation drivers
Very rapid (< 2 years)
Medium (2 to 6 years)
Slow (> 6 years)

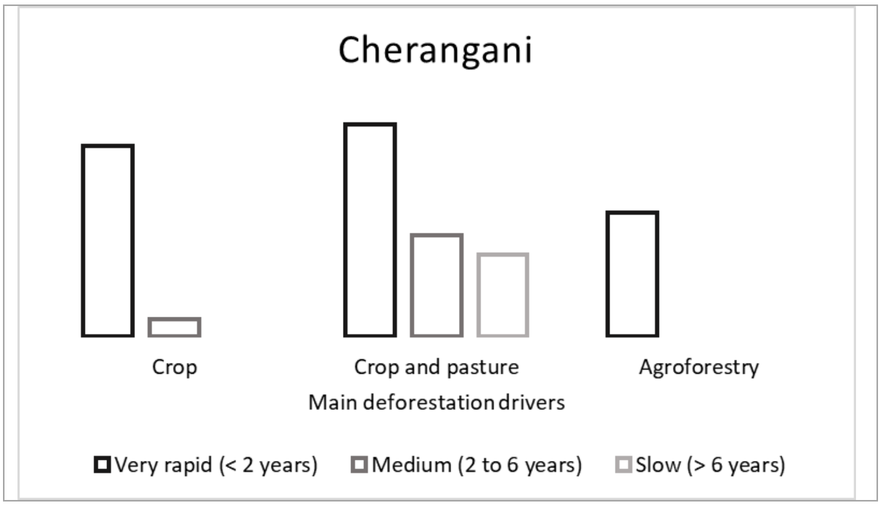


Figure 3.6: Deforestation speed of the main deforestation drivers for all zones together and for each one separately

3.2.3 Land management

Among the three type of land management activities performed during the deforestation (see Table 3.12) (grazing, food collection and wood collection), wood collection is the most represented: in all study areas, it has been performed in 80% of the surface. Grazing is also important (total 70% or more in three of the five study areas) especially in the south west zones where the driver is pasture or a mixture of crop and pasture. Food collection is the least performed.

Table 3.12: Land management activities performed during the deforestation process in each study area

DEFORESTATION DRIVERS		LAND MANAGEMENT ACTIVITIES PERFORMED DURING DEFORESTATION					
MARA		GRAZING %		FOOD COLLECTION %		WOOD COLLECTION %	
	%	Grazing	No grazing	Food	No food	Wood	No wood
Pasture	65	93	7	22	78	95	5
Crop and pasture	30	30	70	0	100	94	6
Crop	6	100	0	0	100	100	0
Tot	100	74	26	14	86	95	5
DEFORESTATION DRIVERS		LAND MANAGEMENT ACTIVITIES PERFORMED DURING DEFORESTATION					
NAROK		GRAZING %		FOOD COLLECTION %		WOOD COLLECTION %	
	%	Grazing	No grazing	Food	No food	Wood	No wood
Pasture	69	86	14	16	84	100	0
Crop and pasture	25	19	81	8	92	100	0
Silvipasture	5	100	0	87	13	100	0
Crop	1	100	0	0	100	100	0
Tot	100	70	30	17	83	100	0
DEFORESTATION DRIVERS		LAND MANAGEMENT ACTIVITIES PERFORMED DURING DEFORESTATION					
MAU WEST		GRAZING %		FOOD COLLECTION %		WOOD COLLECTION %	
	%	Grazing	No grazing	Food	No food	Wood	No wood
Crop and pasture	48	87	13	24	76	74	26
Crop	33	71	29	3	97	100	0
Pasture	19	100	0	42	58	100	0
Tot	100	84	16	21	79	88	12

DEFORESTATION DRIVERS		LAND MANAGEMENT ACTIVITIES PERFORMED DURING DEFORESTATION					
KIPIPIRI	%	GRAZING % Grazing	No grazing	FOOD COLLECTION % Food	No food	WOOD COLLECTION % Wood	No wood
Crop and pasture	66	5	95	0	100	100	0
Pasture	25	91	9	53	47	100	0
Crop	8	55	45	0	100	100	0
Silvipasture	1	100	0	100	0	100	0
Tot	100	31	69	14	86	100	0

DEFORESTATION DRIVERS		LAND MANAGEMENT ACTIVITIES PERFORMED DURING DEFORESTATION					
CHERANGANI	%	GRAZING % Grazing	No grazing	FOOD COLLECTION % Food	No food	WOOD COLLECTION % Wood	No wood
Crop and pasture	54	59	41	58	42	67	33
Crop	29	8	92	8	92	100	0
Agroforestry	17	0	100	0	100	100	0
Tot	100	35	65	34	66	82	18

3.2.3.1 *Wood related land management activities*

Among all the wood related land management activities performed during the deforestation process (see Table 3.13), fuelwood and charcoal, followed by construction material, are the activities with the highest frequency in almost each zone. The zones where fuelwood collection and charcoal making are more intense are: Narok (with 94% fuelwood and 100% charcoal) and Kipipiri. The zones that show a lower rate of wood collected for fuel (fuelwood and charcoal) are Mau west and Cherangani (see Table 3.12 and 3.13).

Table 3.13: Wood related land management activities for each study area divided for each driver

		WOOD COLLECTION RELATED ACTIVITIES %				
MARA	Driver %	Fuelwood	Charcoal	Construction material	Timber	Poles
Pasture	65	74	74	60	18	0
Crop and pasture	30	52	63	94	3	23
Crop	6	100	100	100	88	0
Tot	100	69	72	73	18	7

		WOOD COLLECTION RELATED ACTIVITIES %				
NAROK	Driver %	Fuelwood	Charcoal	Construction material	Timber	Poles
Pasture	69	94	100	73	46	0
Crop and pasture	25	93	100	92	31	0
Silvipasture	5	100	100	13	0	0
Crop	1	100	100	0	100	0
Tot	100	94	100	74	40	0

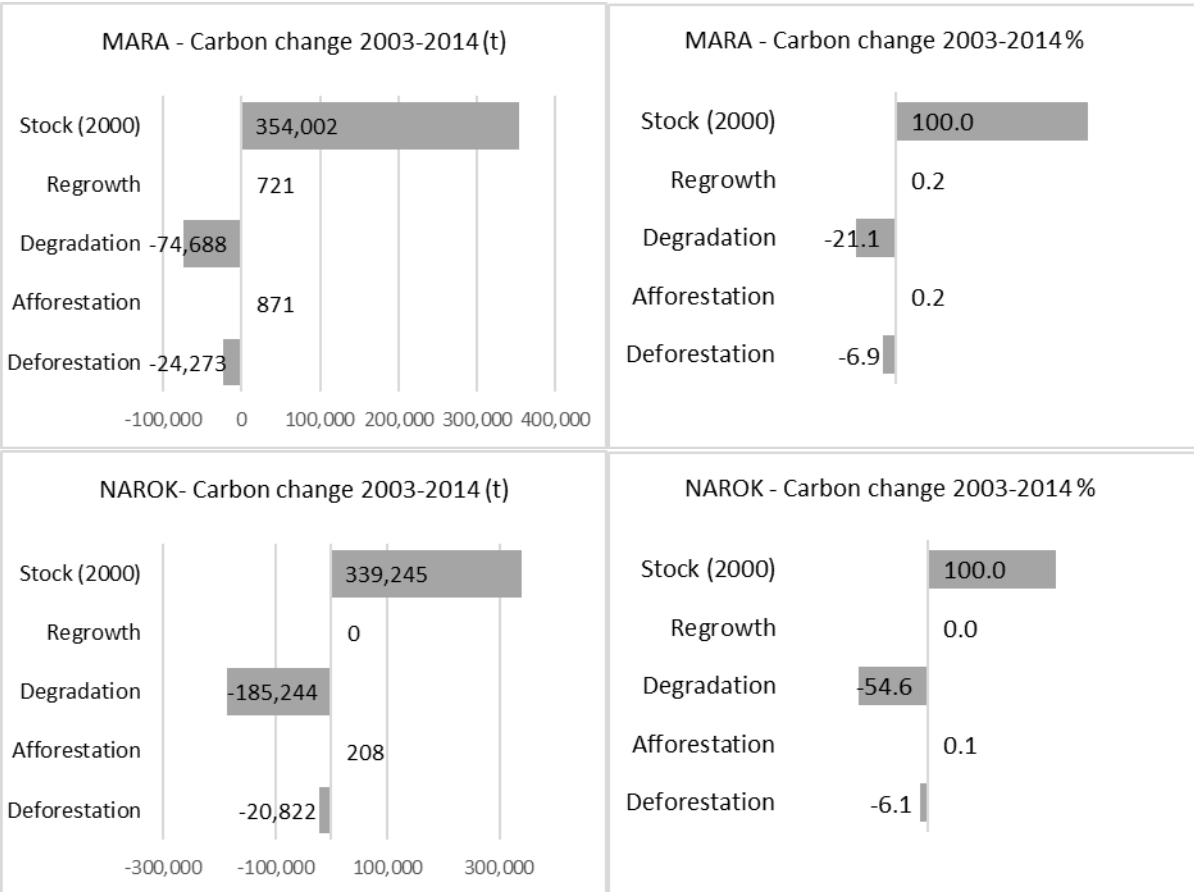
		WOOD COLLECTION RELATED ACTIVITIES %				
MAU WEST	Driver %	Fuelwood	Charcoal	Construction material	Timber	Poles
Crop and pasture	48	70	0	69	28	0
Crop	33	76	24	95	29	0
Pasture	19	0	58	17	42	0
Tot	100	58	19	68	31	0

WOOD COLLECTION RELATED ACTIVITIES %						
KIPIPIRI	Driver %	Fuelwood	Charcoal	Construction material	Timber	Poles
Crop and pasture	66	93	99	100	30	0
Pasture	25	61	49	64	91	0
Crop	8	100	71	100	0	16
Silvipasture	1	100	100	100	100	0
Tot	100	86	84	91	44	1

WOOD COLLECTION RELATED ACTIVITIES %						
CHERANGANI	Driver %	Fuelwood	Charcoal	Construction material	Timber	Poles
Crop and pasture	54	42	0	100	0	0
Crop	29	1	26	12	30	29
Agroforestry	17	6	1	92	10	66
Tot	100	9	14	50	20	35

3.3 Carbon change in the study areas (Objective 3)

Over the period 2003-2014 carbon change in each study area mainly due to forest degradation. The study areas with higher intensity of change are Narok and Mara (see Figure 3.7). Narok lost around 54% of the total stock: 185,244 tonnes of carbon due to degradation over the 339,245 tonnes of total stock. The zone with the highest carbon stock (1,161,224 tonnes) is Cherangani that has been subject to the lowest carbon loss due to degradation recorded (-26,564 tonnes, -2.3% of the stock).



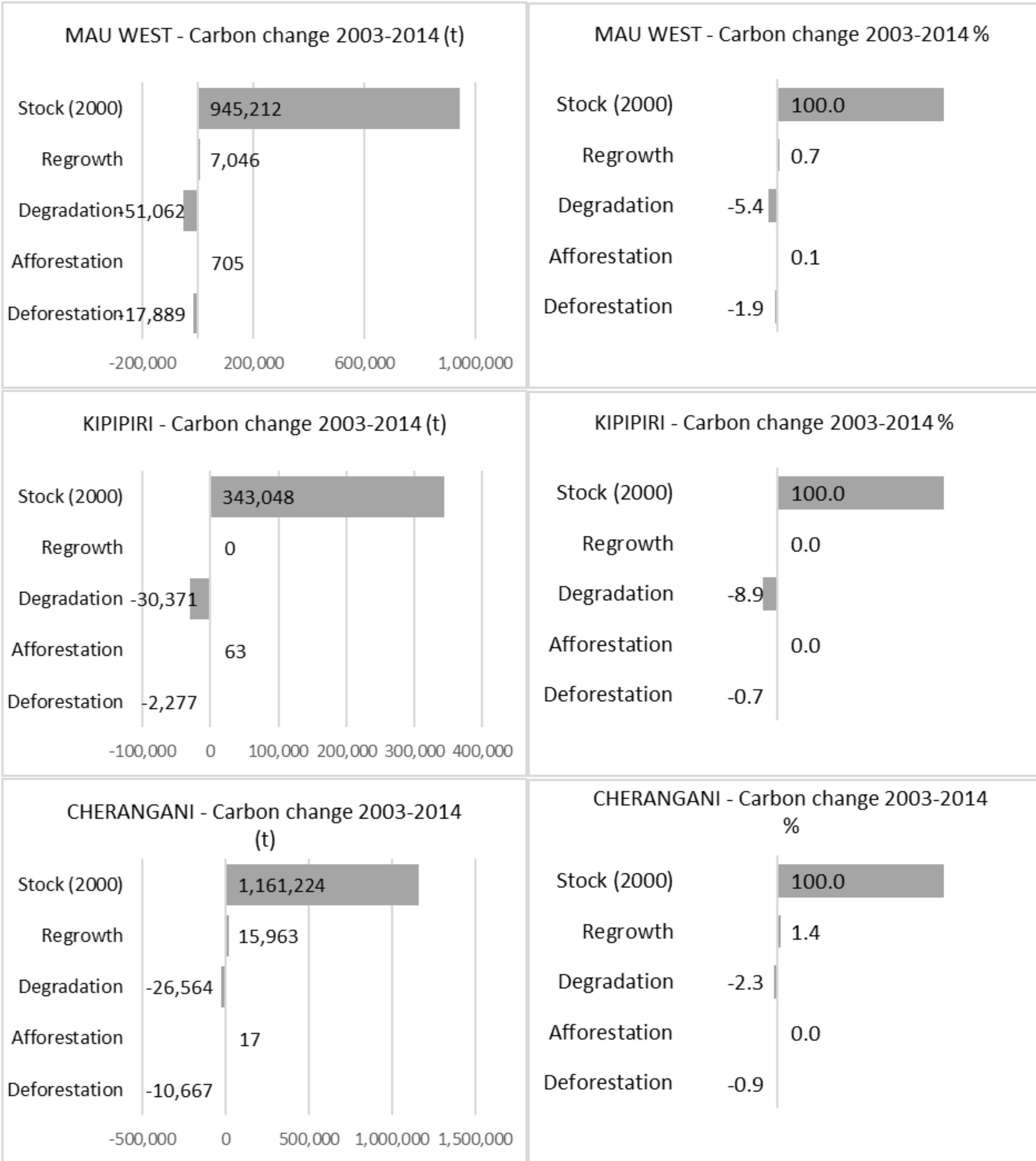


Figure 3.7: Carbon change in each of the study area (10x10km)

4 Discussion

This chapter is divided in two parts: the first will discuss the findings, the second will discuss the methodology applied.

4.1 Results

Carbon change

In Kenya, over the period 2003-2014, the net change of biomass carbon is negative. Forests are dynamic ecosystems that continuously stock and release carbon. For keeping the balance, it is essential that the carbon stocked compensate the lost, otherwise the result is an increasing carbon emission in the atmosphere (CO_2) and consequent contribution to the climate change phenomenon.
The two main processes responsible are deforestation and forest degradation, two different processes by definition (Table 1.1: Definition Box) but strictly linked one another: for instance, the land management activities performed during deforestation can degrade the surrounding land; or forest patches can be so strongly degraded to lead to outright deforestation.
Land management activities performed during deforestation show the important role of wood products, especially fuelwood and charcoal and, as national studies highlight, the need for wood is great in Kenya and is a major driver of forest degradation (Drigo et al., 2015; Gathaara and Leakey, 1999; Lambrechts et al., 2003; Kenya Forest Working Group, 2005).

Degradation, which is defined as a loss of stock and density in areas remaining forest, is the process mainly responsible for biomass related carbon emissions in Kenya: over the period 2003-2014 the total net biomass carbon change is -23Mt, 66% of which (-15.1 Mt) is attributed to degradation.
The results are in line with the recent findings of Baccini et al. (2017) that estimate pantropical degradation to account for the 68.9% of total change. The pantropical study of Bailis et al. (2015) locate Kenya between “highest per capita wood fuel consumption” and “highest rate of non-renewable biomass use”, thus degradation represents a real problem causing wood resources to be exploited more than their maximum renewable potential, damaging and reducing the stock with a trend of -2% of the non-renewable stock every year (Drigo et al., 2015).
The zones most involved in the degradation process are where the population density is lower and livestock density is medium-low. In the high populated areas, the situation is more stable as the carbon gain due to vegetation re-growth compensate the loss. This can be explained by the colonization wave: high population density shows a more “stable” situation where forest has already been reduced in the past: here the deforestation process covers only a small surface or none, and what is left is sustainably managed.
In the newly colonized zones the situation is the opposite: there is a low population density and high forest surface and stock. When population density increases, forest surface and stock is reduced to give space and wood products to the increasing population. This phase is characterised by high rate of deforestation and degradation, as is happening in the southern study areas of Narok, where the population and livestock density is modest, but the degradation loss is important. In different measures this phenomenon is visible in the other study areas. The most stable zone is Kipipiri, where the forest is covering only 28% of the surface, the population and livestock density is higher than in the other zones and the total carbon loss accounts for less than 10% of the stock. While in Narok forest cover 45% but the total carbon loss is around 60% of the stock (54% degradation and 6% deforestation).
Such a big difference in loss can also be explained by the fact that some study areas fall within zones better monitored by government. For instance, national studies highlighted the importance of protecting the ecosystem of the five water towers in more than one occasion in the past (Kenya, 2010;

Akotsi and Gachanja, 2004). Therefore, there is greater attention on protecting certain zones more than others, especially the densely forested. This difference on the attention and protection of different areas can explain the significant differences in carbon loss.
However, one third of the loss due to degradation is happening in the low canopy cover zones, to reduce the carbon emissions from biomass, is needed to include the low canopy cover zones in order to find tailored policies to reduce the loss.

Degradation hasn't been yet defined and agreed at an international level therefore, there is still a lot of effort that have to be made in order to effectively incorporate it in the REDD+ program.
It is necessary to understand the drivers causing degradation not only to create appropriate REDD+ strategies and policies, but also to define suitable methods for measuring and monitoring it. Moreover, different degradation processes are present within one country, and have different effects on the forest (carbon) (Herold et al., 2011).

The changes in forest area (deforestation and afforestation) have been responsible for the net loss of 7.9 Mt of biomass carbon over the period 2003-2014, which is approximately half of the loss due to degradation. The positive impact of the afforestation component of the forest area change is much lower than that of deforestation partly because good part of the latter represents a permanent change (conversion to agriculture, mainly) and part because afforestation or re-growth after clearing is a process that takes longer compared to the quick loss of carbon due to deforestation.
Deforestation has been studied and monitored for longer and in more depth than degradation, as since the 1990 the Intergovernmental Panel on Climate Change (IPCC) indicated the urgent need to reduce deforestation (and degradation) to decrease the climate change effect. Deforestation is also a relatively easy phenomenon to monitor if compared to degradation, as it shows as a sudden and high gradient transition in terms of biomass stock (and radiometric signal) while degradation represents a slight and progressive reduction of tree density and biomass stock in forest remaining forest, which is far more challenging to detect and measure (Herold et al., 2011). Therefore, several solutions have already been identified and put into action concerning deforestation, an example is represented by the case of Mt Kenya, where the afforestation surface is higher than deforestation surface (Gathaara and Leakey, 1999), while forest degradation remained undefined and poorly understood.
In fact, the dominant role of degradation as source of carbon emissions resulting from this study sets important new light on land cover dynamics in Kenya and indicates the need for further research on the human activities leading to degradation in order to define specific and effective lines of interventions.

Drivers of deforestation

The two main drivers of deforestation standing out from this research are pasture in the southern part of West Kenya, and a mixture of crop and pasture in the northern part. The climatic, morphological and vegetative characteristics of these zones can provide a possible explanation for this distinction: the south is characterised by a dry montane forest zone with lower rainfall, less suitable for crops, while in the north the forest tends to be moister and denser due to the higher rainfall, therefore more suitable for crops and settlement (Imo, 2012).
However, the definition of driver has a great impact on the results of the research on drivers. Looking at the deforestation driver transition matrix (section 3.2.1.1), where the transition matrix was performed between the land use declared to follow the forest cover right after the deforestation process and the current land use (at the date when the survey was undertaken), we can see that in the southern areas the land use after deforestation is changing in favour of crop. This change in the land use can be due to the colonization wave where settlements and crops are increasing as a result of the

increase population density. Besides, pasture is increasing in the northern study areas with the decrease of the mixture of crop and pasture, this can be justified by the increasing livestock production that is expanding in the whole East Africa (Robinson et al., 2014).

Livestock as a deforestation driver have already been identified by national studies (Imo, 2012; Korir et al., 2016; Lambrechts et al., 2003; Gathaara and Leakey, 1999) and the findings of this study highlight the possible relation between the increase of the fraction of carbon loss due to deforestation with the increase of livestock density. The livestock datasets used in this research refer to 2006, while overall livestock number of animals have been increasing of almost 80% from 2006 to 2014 (Korir et al., 2016); therefore, we expect an increase of deforestation and degradation surface in the next coming years.
Recently, several studies focused on the possible solution for mitigation: improving forage quality by increasing the use of Napier grass (Brandt et al., 2018) or to improve dairy breeds in order to reduce the number of livestock in the forest. These breeds have high productivity and are less tolerant of harsh forest conditions hence it discourages them from grazing in the forest. (Korir et al., 2016)

Several possible solutions have been found to lower deforestation and forest degradation, but "initiatives to reduce deforestation implemented in the forest sector alone, will not reduce deforestation" (Carter, 2018). There is great need of cooperation between different sectors to reach an effective solution, for example the principal sectors are the energy, agriculture and forestry. Practical points have been identified from the REDD+ Kenya planning (Maukonen et al., 2016): implementing biofuel, promoting fast growing fuelwood plantations, introducing woodlands management guide-lines including establishing and enforcing sustainable harvesting, implementing agroforestry. Other solutions have been carried out by other international actors, as the Global Alliance for Clean Cookstoves (GACC) that promotes clean and efficient cooking technologies which meet the needs of users and producers. The traditional production of charcoal has serious environmental impacts and improving the efficiency of charcoal stoves is one of the ways to minimize these impacts (Bailis et al.,2015).
Socio economic studies (Imo, 2012) together with the REDD+ Kenya planning (Maukonen et al., 2016) agreed upon the importance of involving local communities in the process of solving these problems. National experts are also important figure in the management context for the creation of efficient national and local policies. Workshops[3] have been organized worldwide by the GOFC-GOLD (Global Observation of Forest Cover and Land Dynamics) where REDD+ experts have been involved in training local expert to effectively monitor and manage their own land.

Each study area presents characteristics that show different local dynamics: an example is the deforestation speed of the same driver. Mixture of crop and pasture is the main driver of three of the study areas, but in each area the speed is different. This can be explained by different factors (population and livestock increment, governmental laws in the zone, climatic conditions) but indicates that a standard global policy may not respond to the different needs of people and to the local circumstances. Locally tailored policies are likely to protect the carbon stock more effectively in a way that is sustainably used and has the time to re-grow.

[3] Material available at http://www.gofcgold.wur.nl/redd/training-materials/about/

4.2 Methodology and future research

It is important to consider the results of this research keeping in mind that the used datasets are mainly global, and that Kenya presents fragmented and scattered forest ecosystems and the majority of the country is covered by low density formations ranging from dry woodlands to desert shrubs. This type of vegetation is subject to strong seasonality and with a high variation of reflectance between the wet and dry season. This can lead to errors on biomass estimation from satellite images.
The total carbon change dataset used as the basis of this research is the result of a global analysis and has a spatial resolution of around 500m being based on MODIS satellite images: a relatively coarse resolution to study the dynamics at national level. In addition, some inconsistencies may derive from the combination of this data with 30m resolution data on carbon stock and on forest area change, which were used to estimate the carbon change due to deforestation and to degradation separately (section 2.1.6).
To reduce inconsistencies due to resolution of analysis it would be beneficial to monitor the carbon change at a finer scale, which would also allow more detailed analysis at a country level. The use of medium-high resolution data such as Landsat may also support the analysis of carbon change history over the last 30 years. Baccini and his work group at the Wood Hole Research Center are currently working on the production of a carbon change map using Landsat that would enable higher resolution analysis.
One possible limitation on the production of a Landsat-based carbon change map is the temporal resolution of the Landsat satellite images and the lack of historical field data, as the MODIS-based carbon change map relies on the high temporal resolution of MODIS (Baccini et al., 2017). Sentinel is a newly lunched satellite at medium-high temporal resolution and high spatial resolution but is lacking the historical images that Landsat provides. For future research it would be valuable to consider Sentinel to produce annual carbon density maps from now onward and Landsat to provide historical data.

In this research, the stratification analysis could be improved using other strata to have a better correlation. The accessibility and population density have been found to be weak deforestation or degradation indicators, even if are both datasets produced at country level, which may be explained by the lack of updated information. The accessibility and population density should represent the population colonization, but the speed of mapping new roads is not so fast, and demographic censuses are carried out on a 10-years basis, which make them inadequate in depictive the dynamic fronts of expansion. Livestock, on the other hand, is a global dataset, not specifically produced for Kenya.
For next studies suitable indicators to consider should include specific parameters related to population and livestock density increment and infrastructure expansion, if feasible.

Although results about deforestation drivers found in this research seem to be in line with the general findings most of the forest threats are made by illegal activities: illegal settlement, illegal charcoal production and logging, illegal livestock grazing in the forest and marijuana field cultivation (Kenya Forests Working Group, 2005; Lambrechts et al., 2003). Illegal activities are not easily admitted during a survey; therefore, anonymous survey may have more chances of capturing the reality of the activities as the respondent would feel more comfortable to declare the real activities knowing that there will be no consequences. On the other hand, it’s always difficult to establish if qualitative information are reliable and to which extent.
Other limitations about the survey analysis are related to the small amount samples on which the analysis is based and the samples distribution. There are several zones where deforestation is found to be important, but the survey is not covering.

5 Conclusions

The main conclusions of this study are based on policy issues and methodological issues.

5.1 Policy issues:

Emissions due to degradation are far greater than those due to deforestation, which means that from a carbon perspective the change within the remaining forests is greater than expected and should be studied with much greater attention, although more challenging to asses compared to deforestation, and the specific drivers of forest degradation clearly defined (fuelwood and charcoal production; industrial roundwood; feed and fodder; grazing, etc.). If from one side deforestation interest mainly the high canopy cover zones, degradation is found to be consistent also in the low canopy cover zones. Therefore, there is urgent need to identify and implement lines of interventions to reduce forest degradation especially in the less dense forest areas. Such interventions should aim at (i) improving the sustainability of the supply of the needed goods and products and, at the same time, (ii) reducing the demand for such products.

Interventions on the supply side may include encouraging inter-sectors cooperation, training of local expert and involving local community for more efficient solutions. Promote and implement sustainable forest management practices, such as rotational harvesting practices with coppicing or replanting and effective protection during the establishment/initial re-growth phases. Develop improved, efficient and legal charcoal production practices linked to sustainable harvesting concessions and increase the fodder supplement by planting specific grass types.

Interventions on the demand side may include adopting fuel-efficient fuelwood and charcoal stoves, switch to alternative fuels and sustainable energy options (biofuel). Reduce the impact of grazing and increase milk production by upgrading the present stock with a more productive breed less dependent on forest grazing.

5.2 Methodological issues

The main methodological issues concern assessing forest degradation rates. It has always been a difficult and challenging task, to the extent that degradation rates are generally omitted from national REDD+ reference emission levels and national/international forestry statistics. The high relevance of degradation processes evidenced by this study call for more research specifically focused on assessing such processes and identifying the main drivers of degradation, possibly at a regional or country level. Mapping carbon change represents a new and promising approach for the estimation of forest degradation. Advancing in this line of research, the production of higher resolution carbon change maps would allow to better monitor degradation and to undertake more consistent and detailed analyses.

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7 Appendices

7.1 Appendix: Stratification maps

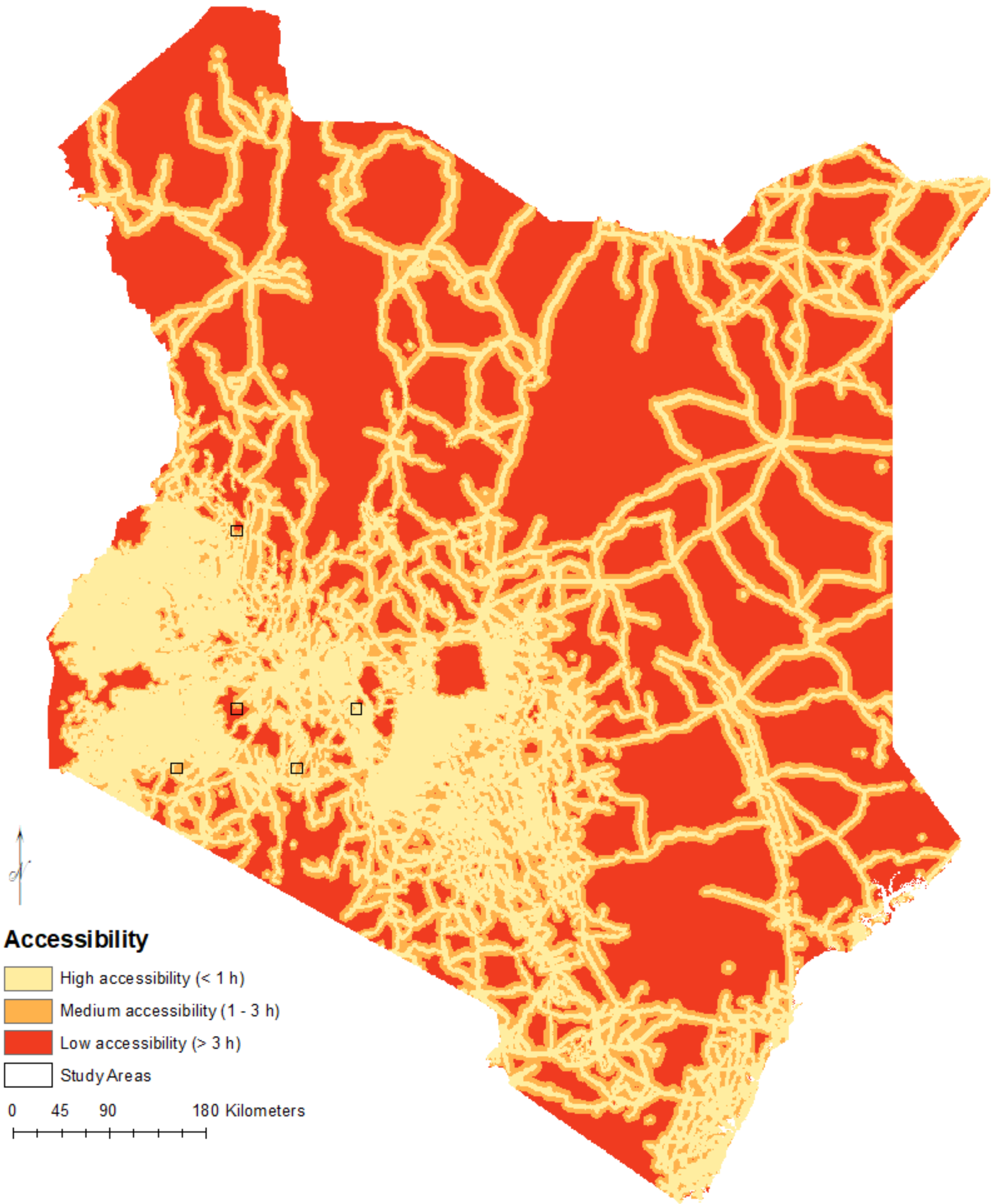

Figure 7.1: Accessibility map

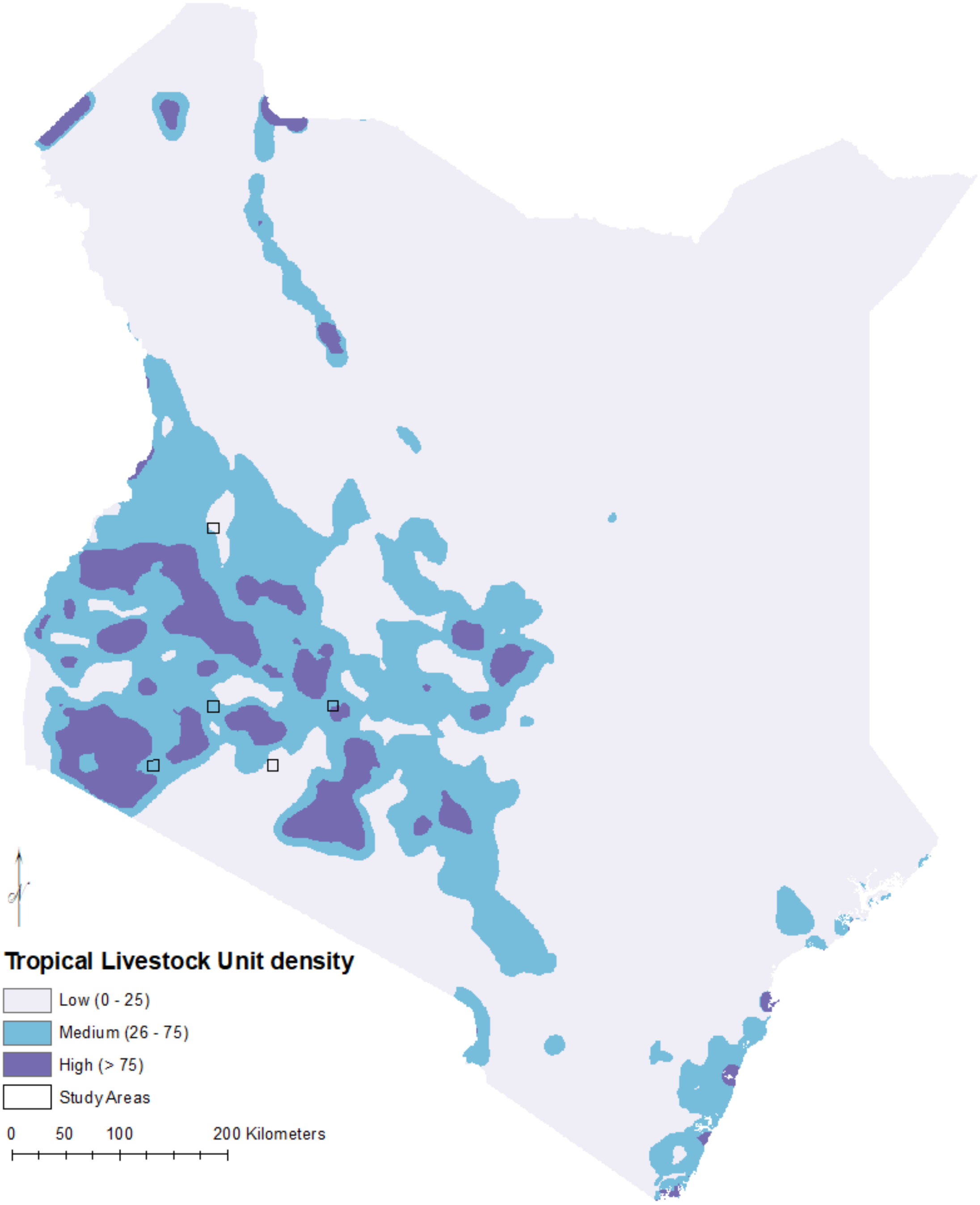

Figure 7.2: Tropical Livestock Unit density map

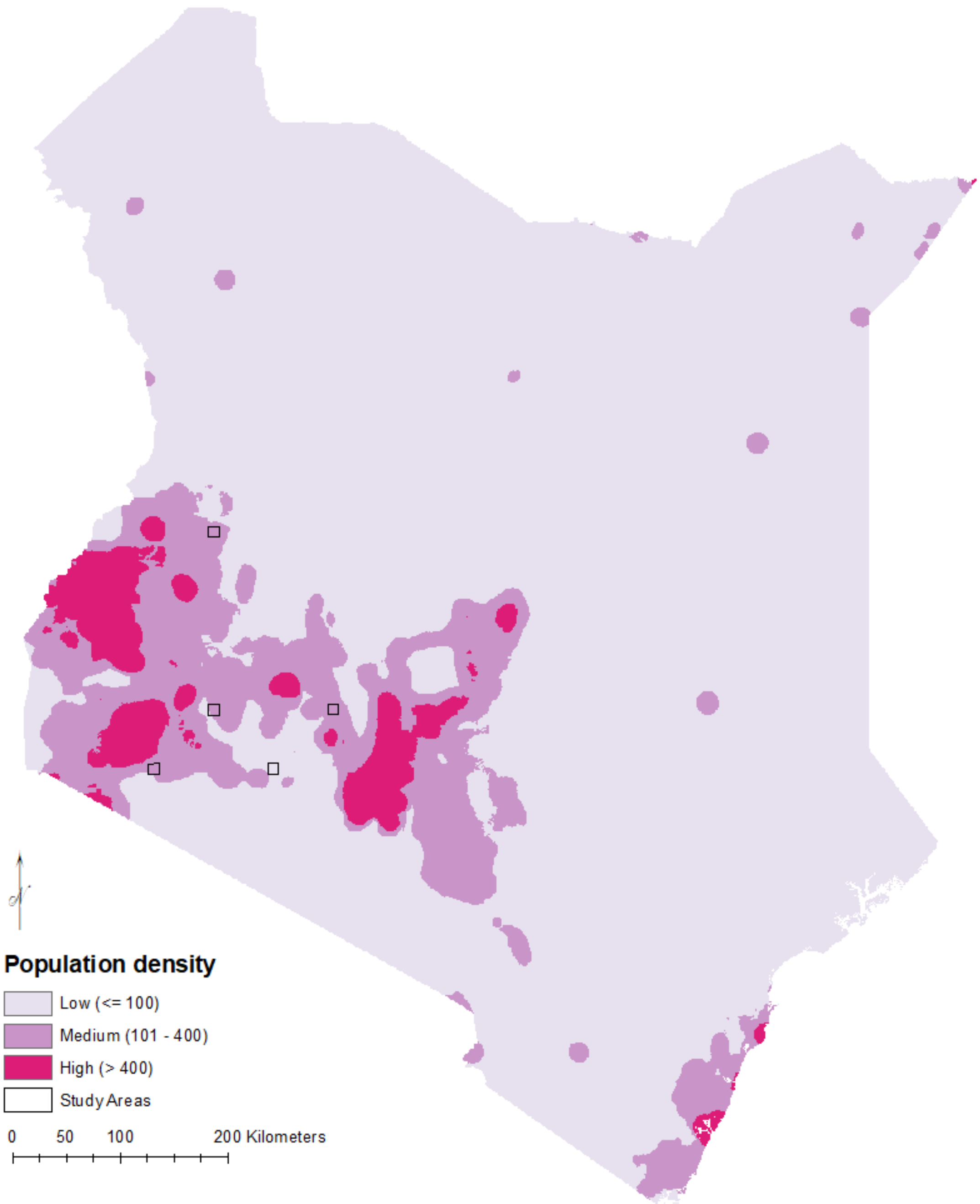

Figure 7.3: Population density map

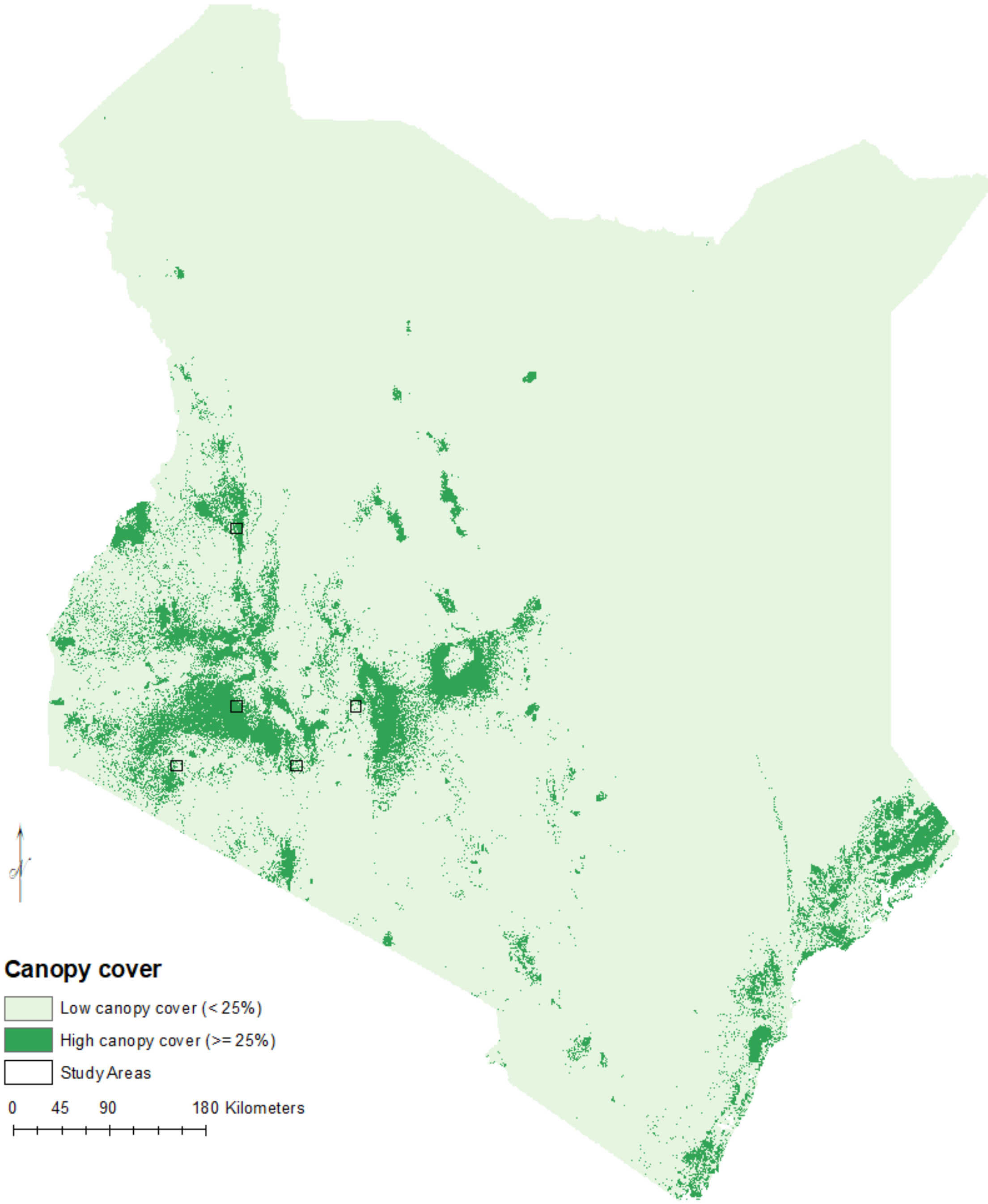

Figure 7.4: Canopy cover map

7.2 Appendix: Survey

The survey was undertaken in Western Kenya in 5 study areas (10x10 km square) characterised by recent deforestation processes, distributed over systematic grid of half-degree apart. To select the study areas different references have been used: TREES dataset (Achard et al., 2014), Forest Resources Assessment Remote Sensing Survey (FRA RSS) (Lindquist et al., 2012) (D'annunzio et al., 2014) and Hansen datasets (Hansen et al., 2013).

The FRA RSS dataset provides forest change between 1990 and 2010 in sample sites of 10 km x 10 km at each degree of longitude and latitude around the globe. Landsat images around the years 1990, 2000, 2005 and 2010 were used to segment images, and changes from forest land-use to another land-use were identified. Data from 1990-2005 show land-use change, but the 2010 data provided were land-cover change. In order to merge the two FRS RSS datasets, the definition of deforestation have been harmonized according to a land use and a land cover definition.

Five 10 x 10 km sample squares were selected using the following criteria:

(1) at least 50 deforestation polygons >0.5 ha

(2) in dairy region of Western Kenya

Where there were more than 50 deforestation polygons above 0.5 ha within one sample square, between 50 and 75 of these to sample were randomly selected. In each site, as many of the selected deforestation areas were surveyed as possible. Points which were inaccessible, or which could not be surveyed were excluded. In some cases, points could not be surveyed, as the land user did not want to be interviewed, or the land was cleared but was not being actively used so a land user could not be found to interview.

A total of 190 interviews were realized and distributed in the 5 study areas (Table 7.1). Farmers using land which was subject to deforestation during the period 1990 to 2010 were asked to describe the deforestation process and the land-use activities conducted in the past and currently.

Land user interviews were conducted during November 2015 using ODK software. (Pratihast et al., 2012). Surveys were carried out regarding the land parcel at the centre point of each deforestation polygon, and the questionnaire gathered information about the land user, and the use of the plot where the centre point fell.

The enumerator mapped out the area (by taking a point at each of the four corners) of the plot where the centre point fell using the GPS device on the mobile phone. This was used to define the area of interest.

Table 7.1: Number of samples in each zone

Zone	Number of samples
Mara	42
Narok	45
Mau west	36
Kipipiri	47
Cherangani	20
Total	**190**