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Agricultural Expansion and Intensification in the Foothills of Mount Kenya: A Landscape Perspective

Sandra Eckert [1,*], Boniface Kiteme [2], Evanson Njuguna [2] and Julie Gwendolin Zaehringer [1]

[1] Centre for Development and Environment, University of Bern, Hallerstrasse 10, 3012 Bern, Switzerland; julie.zaehringer@cde.unibe.ch
[2] Centre for Training and Integrated Research in ASAL Development, 10400 Nanyuki, Kenya; b.kiteme@africaonline.co.ke (B.K.); e.njuguna@cetrad.org (E.N.)
* Correspondence: sandra.eckert@cde.unibe.ch; Tel.: +41-31-631-5439

Received: 3 July 2017; Accepted: 28 July 2017; Published: 31 July 2017

Abstract: This study spatially assesses, quantifies, and visualizes the agricultural expansion and land use intensification in the northwestern foothills of Mount Kenya over the last 30 years: processes triggered by population growth, and, more recently, by large-scale commercial investments. We made use of Google Earth Engine to access the USGS Landsat data archive and to generate cloud-free seasonal composites. These enabled us to accurately differentiate between rainfed and irrigated cropland, which was important for assessing agricultural intensification. We developed three land cover and land use classifications using the random forest classifier, and assessed land cover and land use change by creating cross-tabulation matrices for the intervals from 1987 to 2002, 2002 to 2016, and 1987 to 2016 and calculating the net change. We then applied a landscape mosaic approach to each classification to identify landscape types categorized by land use intensity. We discuss the impacts of landscape changes on natural habitats, biodiversity, and water. Kappa accuracies for the three classifications lay between 78.3% and 82.1%. Our study confirms that rainfed and irrigated cropland expanded at the expense of natural habitats, including protected areas. Agricultural expansion took place mainly in the 1980s and 1990s, whereas agricultural intensification largely happened after 2000. Since then, not only large-scale producers, but also many smallholders have begun to practice irrigated farming. The spatial pattern of agricultural expansion and intensification in the study area is defined by water availability. Agricultural intensification and the expansion of horticulture agribusinesses increase pressure on water. Furthermore, the observed changes have heightened pressure on pasture and idle land due to the decrease in natural and agropastoral landscapes. Conflicts between pastoralists, smallholder farmers, large-scale ranches, and wildlife might further increase, particularly during the dry seasons and in years of extreme drought.

Keywords: land cover and land use change; landscape change; agricultural intensification; greenhouse cultivation; environmental impacts; remote sensing; Kenya

1. Introduction

Changes in land cover and land use worldwide have reached an unprecedented pace, magnitude, and spatial extent [1–5]. The changes affect and contribute to local, regional, and global aspects of earth system functioning [1–3,6]. In African landscapes, pastoralism, shifting cultivation, permanent or semi-permanent agriculture, and agroforestry have altered the environment to a point that the present landscape is the product of human-induced changes as much as natural variation in vegetation [7]. Over the last decades, anthropogenic impacts and competition over land have become issues of major concern [8,9]. Many areas in Africa are experiencing substantial human population growth, and, as a result, a shift away from extensive pastoral livestock-keeping to subsistence-oriented small-scale farming and agroforestry [10]. In addition, the last 10–15 years have also seen agricultural intensification. Triggered mainly by large-scale agricultural investments, it has become an additional important driver of land cover and land use change [8,10,11].

In Kenya, horticulture has grown faster over the last decade than any other industry in the agricultural sector [12,13]. In the Mount Kenya region, substantial agricultural expansion driven by population growth, in combination with recurring cycles of drought, has since the late 1990s been causing conflicts both between upstream and downstream water users and between pastoralists and farmers [12,14]. The more recent expansion of horticultural agribusinesses in the same area is further increasing pressure on limited natural resources, particularly water and land [15–17].

The livelihood systems of small-scale farmers in this region have been studied intensively for more than 20 years [18–23]. However, to date, there is only little spatially explicit quantitative information on agricultural expansion and land use intensification in the region, if any at all. It can only be estimated to which land covers' cost, and to what extent, land cover and land use changes related to agricultural expansion and intensification have shaped the Mount Kenya region's landscapes.

A growing body of literature focuses on the assessment of irrigated and rainfed cropland and related changes using multi-temporal or multi-sensor data [24–26]. However, many studies focus on the global or national scale, using multi-temporal MODIS satellite data that are too coarse to capture small-scale irrigated plots or regional changes [27–29]. More recently, scholars have begun to explore phenological profiles from Landsat time series, which has led to more accurate and more detailed cropland identification and change assessments [30–32]. Some studies have successfully assessed agricultural intensification in areas where it manifested itself in a change of land cover [33], a greater number of cropping cycles [34], or an increase in center-pivot irrigation areas [35]. However, most of these studies focus on pixel-level land cover and land use changes [32,36] rather than landscape-level changes towards more intense land use systems.

Land change science offers a strong conceptual framework to analyze transitions in land use systems dominated by smallholders [37]. It seeks to understand the dynamics of land cover and land use as a coupled human-environmental system [38]. These dynamics lead to distinct spatial land cover and land use patterns, creating mosaics of landscapes [39]. Landscape analysis is therefore considered a suitable approach for monitoring these distinct land cover and land use patterns, and transitions between them [2,40]. Geographical information sciences and remote sensing provide powerful tools to undertake such research [37,41,42].

Against this background, the aim of this study is to spatially assess and quantify agricultural expansion and land use intensification in the northwestern foothills of Mount Kenya over the last 30 years. Remote sensing-based land cover and land use classifications for three points in time provided the basis for extracting land use intensification. We present a landscape mosaic approach that enabled us, based on specific combinations of land cover and land use classes, to identify different landscape types categorized by land use intensity. Further, we differentiated landscape types according to the presence of woody biomass (e.g., trees, shrubs, and bushes). Focusing on the landscape scale has enabled us to assess and visualize changes in landscape type—including agricultural intensification—and to discuss their impacts on natural habitats, biodiversity, and water.

2. Materials and Methods

2.1. Study Area

The study area of 249,147 ha lies in the northwestern foothills of Mount Kenya, within the upper Ewaso Ng'iro basin, and includes parts of Laikipia, Meru, and Nyeri counties. The upper Ewaso Ng'iro basin encompasses steep ecological gradients, as it drops from 5199 m above sea level at the summit of the mountain to an average altitude of 1500 m above sea level in the northwest. Climatic conditions range from semi-humid (1000–1500 mm of rainfall annually) near Mount Kenya in the east to semi-arid (400–900 mm rainfall) and arid (about 350 mm rainfall) towards the west [43]. The farther away from Mount Kenya, the dryer the conditions.

There are two distinct rainy seasons per year. The long rains last from mid-March to mid-June (sowing and planting time). They are followed by a dry season from June to September or early October (harvesting time). A second, much shorter rainy season occurs in November. The two rainy seasons largely determine the cropping calendar in this semi-arid, water-scarce area, as most small-scale farmers rely on the seasonal rains. The rains are unreliable and unpredictable in terms of onset, duration, and termination [44]. This variability impacts greatly on all natural resources and particularly on water, which continues to become scarcer. The major river systems in the area show a significant decline in water even though there has been no significant change in the rainfall regime [18]. The growing number of water abstractions for irrigation, livestock, and domestic purposes has intensified competition for this scarce resource [45].

The study area has experienced substantial land use conversions since the beginning of the 20th century. Traditionally, the area was inhabited by the Maasai. At that time, much of the study area was covered with fire-modified acacia bushland and grassland [19], which the Maasai used as pasture. Subsequently, several major land use and socio-economic transitions occurred [14]. The dominant land use changed from pastoralism to extensive large-scale farming and ranching, which was reserved for European settlers [46]. After Kenya's independence, the land was distributed to immigrating small-scale subsistence farmers, shifting the dominant land use from extensive ranching to small-scale mixed farming [14], and leading to an increase in the population of Laikipia County from 60,000 in 1960 to over 400,000 in 2009 [47]. The past 15 to 20 years, finally, have seen the development of a highly technologized, export-oriented horticulture sector practicing greenhouse and high-input vegetable and flower production [48]. Today, the area's very fertile soils are used both by these high-input, large-scale commercial farms and by smallholders. The geospatial pattern of the different land use systems is largely determined by water availability. Closer to Mount Kenya, a dense population of smallholders practices small-scale farming; more recently, large-scale horticulture and greenhouse farms have been established in the area. In the drier areas farther away from Mount Kenya, land use is dominated by agropastoralism and pastoralism, interspersed with wildlife reserves and tourist lodges. The study area is depicted in Figure 1.

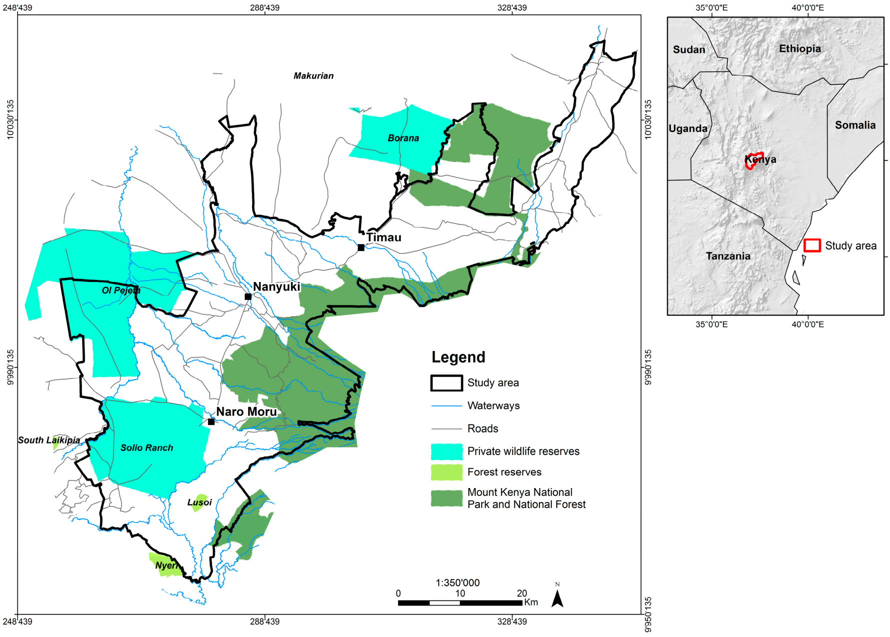


Figure 1. Overview of the study area located in the foothills of Mount Kenya (map projection of detailed study area map: UTM 37S).

2.2. Assessing Land Cover and Land Use Change since the Late 1980s

2.2.1. Satellite Data Preprocessing

For this study, we queried the USGS Landsat data archives for Landsat 5, Landsat 7, and Landsat 8 scenes using the Google Earth Engine (GEE) cloud computing environment. We worked with the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) surface reflectance products of Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI provided by USGS. These products are already geometrically coregistered, orthorectified, and atmospherically corrected. They are provided together with a cloud mask and a quality assessment (QA) band.

We generated three different image collections representing the situation in 1987, 2002, and 2016. In order to obtain cloud-free seasonal composites of surface reflectance we had to include several years of imagery for each point in time. For 1987, we used imagery acquired between 1984 and 1987; for 2002, we used data acquired between 1999 and 2002; and for 2016 we used data acquired between 2014 and 2016. Figure S1 in the Supplementary Materials provides an overview of the numbers of scenes that were available for each month and year, indicating which ones were used for this study. For all scenes acquired within these three time periods, we calculated the Normalized Difference Vegetation Index (NDVI). Then, we used the LEDAPS QA band to remove clouded pixels, resulting in a stack of cloud-free pixel values for each pixel location, which we then reduced to a monthly composite by choosing the median pixel value for each pixel and for each month. The use of the median pixel value ensures that outlier values (e.g., due to cloud shadows or clouds that were not previously removed by the QA band) are excluded. This was done for each optical Landsat band as well as the NDVI. Based on a visual check, we finally downloaded those monthly composites for the three time periods that (1) contained no or few no-data areas (due to masked clouded pixels), and (2) did not contain any cloud shadows. This resulted in three raster data stacks that contained three to four monthly composites representing the study area in one of the two dry seasons and at least one of the two wet seasons. Such seasonal composites representing key phenological time windows can be helpful for separating certain land cover and land use classes in a reliable way [49,50].

2.2.2. Land Cover and Land Use Classification and Change Analysis

The field reference data required for training and validating the classifier were collected during a field visit in February 2016. Additional reference data were digitized in Google Earth, which offered high-resolution data captured in 2001, 2003, 2013, and 2016. For the 1984–1987 composite, reference data were collected by inspecting the Landsat composites and delineating representative samples together with fellow researchers who have been working in the study area and following its development since the early 1980s, and have therefore acquired a great deal of local expertise [14,22,44,46,51].

We defined land cover and land use classes that reflect the natural vegetation cover in the study area, as well as ones that reflect land covers and land uses that developed with increasing human activity in the study area (Table 1). Further, we distinguished “rainfed cropland” from “irrigated cropland”, and included a “greenhouses” land use class to identify and assess agricultural intensification in the study area.

Table 1. Land cover and land use classes characterizing the landscapes in the study area.

Land Cover and Land Use Class		**Description**
Bare land		Bare soil including dirt roads, rock outcrops, and sand
Cropland	Rainfed cropland	Plots of varying size covered with crops or ploughed
	Irrigated cropland	Plots showing a high amount of green vegetation cover during dry seasons
Savannah grassland		Grassland interspersed with bushes, shrubs, and trees at a low to medium density, and fallows with a vegetation cover
Bush- and shrubland		Areas with a bush and shrub cover of medium to high density and an understory that is bare or covered with grass or dry matter

Table 1. *Cont.*

Land Cover and Land Use Class	Description
Forest	Natural or plantation forests, including riparian forests, and very densely grown bush- and shrubland with a high amount of green vegetation
Waterbodies	Small and shallow natural waterbodies and larger artificial reservoirs for irrigation
Settlements	Settlements, large buildings, tarmac
Greenhouses	Glass or plastic greenhouses

The three data stacks representing typical dry- and wet-season conditions in 1987, 2002, and 2016 were split up into homogeneous subsets of predominantly natural habitats and predominantly cropland areas in order to avoid misclassifications between bush- and shrubland and rainfed cropland, which have very similar spectral characteristics.

All subsets were classified using random forest (RF), an ensemble method for supervised classification, and regression trees (CART), first developed by Breiman in [52]. RF is a high-performance machine learning algorithm based on an ensemble of decision trees. Even slight variations in training data cause CARTs to differ significantly in their structure. This characteristic of CARTs can be combined with bootstrap aggregation and random feature selection to create independent predictors [53]. It has many benefits compared to traditional classifiers [52,54,55]. RF is relatively insensitive to the number and multi-collinearity of input data, and makes no assumptions about distributions. Furthermore, it has been shown to provide reliable and stable classification results, outperforming other classifiers [56–59]. In our classification, we used 1000 trees for the RF model, and the number of selected features was set as the square root of all features. The Gini coefficient served as the impurity criterion. The accuracy of the resulting land cover and land use classifications was assessed using 40% (1987), 51% (2002), and 57% (2016) of the collected field reference data as independent validation points. We calculated overall accuracy, class-wise user's and producer's accuracies, as well as kappa and F1 accuracies [60]. The overall accuracies for 1987, 2002, and 2016 range between 83.8% and 86.7%. The kappa accuracies lie between 78.3% and 82.1%, and the average F1 accuracies between 83.6% and 87.8%. Detailed class accuracies are indicated in Table S1 in the Supplementary Materials.

We assessed land cover and land use change for each pixel of the study area by creating cross-tabulation matrices for the intervals from 1987 to 2002, from 2002 to 2016, and from 1987 to 2016, and by calculating net change. Furthermore, when analyzing class changes, we accounted for the spatial extent of the various land cover and land use classes, as this makes it possible to differentiate between random changes and systematic change processes [61,62].

2.2.3. A Landscape Mosaic Approach to Capture the Intensification of Agricultural Land Use

Land cover and land use change maps are of limited suitability for assessing land use intensification processes and landscape changes. This is because certain landscape types, as well as certain intensification processes and landscape changes, are hard to capture spatially by remote sensing. Doing so requires analyzing changes in the combinations of land covers and land uses in a certain context area. To address this problem, Messerli et al. [63] introduced an approach that interprets a pixel's land cover by taking into account human-environment interactions and the condition of neighboring pixels. The approach was successfully applied to distinguish shifting cultivation systems from permanent land use systems in Laos and Madagascar [64,65]. Arvor et al. [40] developed a similar approach to map and analyze the soybean agricultural frontier in Mato Grosso, Brazil. In the present study, we adapted the approach to the different land use systems found in Kenya in order to identify land use intensification and landscape changes. The following paragraphs describe how we proceeded.

First, we defined the size of the context area to be considered as a square of 2 × 2 km. This is large enough to contain the typical combinations of land cover and land use classes that define the different land use systems of varying land use intensity (e.g., greenhouses with outdoor irrigated cropland and irrigation water reservoirs). Once the size was defined, we used focal statistics to calculate class percentages per context area. Then, we developed a matrix of landscape types based on five categories of agricultural land use intensity and three categories of woody biomass cover, as well as a decision rule set for each category.

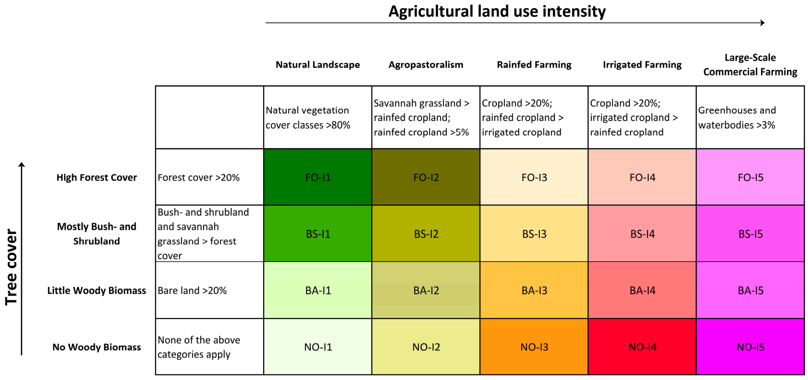
As a guideline for categorization, we used the conceptual model of frontier dynamics proposed by DeFries et al. [2]. The five agricultural land use intensity categories were defined based on (1) the share of natural land cover classes in the context area, and (2) the relation between rainfed cropland, irrigated cropland, and greenhouses. This resulted in the following intensity categories:

- Natural landscape: Natural vegetation cover classes (bare land, savannah grassland, bush- and shrubland, and forest) cover more than 80% of the context area (I1)
- Agropastoralism: Savannah grassland covers a greater share of the context area than rainfed cropland, but cropland covers at least 5% of the context area (I2)
- Rainfed farming: Rainfed cropland and irrigated cropland together cover more than 20% of the context area, but the share of rainfed cropland is larger than that of irrigated cropland (I3)
- Irrigated farming: Rainfed cropland and irrigated cropland together cover more than 20% of the context area, but the share of irrigated cropland is larger than that of rainfed cropland (I4)
- Large-scale commercial farming: Greenhouses and waterbodies together cover more than 3% of the context area (I5)

The four woody biomass categories were defined based on the amount and type of woody biomass present in the context area. This categorization makes it possible to capture change in forest and woodland areas, which is closely linked to biodiversity [66] as well as to agroforestry land use systems, in which tree crops play an important role. Agroforestry is considered to be an important sustainable farming system in Africa [67].

- High forest cover: Forest covers at least 20% of the context area (FO)
- Mostly bush- and shrubland: Bush- and shrubland and savannah grassland together cover a larger share of the context area than forest (BS)
- Little woody biomass: Bare land covers at least 20% of the context area (BA)
- No woody biomass: All areas that do not fall in one of the above categories, e.g., monoculture cropland (NO)

The resulting matrix of landscape types is presented in Figure 2.



		Natural Landscape	Agropastoralism	Rainfed Farming	Irrigated Farming	Large-Scale Commercial Farming
		Natural vegetation cover classes >80%	Savannah grassland > rainfed cropland; rainfed cropland >5%	Cropland >20%; rainfed cropland > irrigated cropland	Cropland >20%; irrigated cropland > rainfed cropland	Greenhouses and waterbodies >3%
High Forest Cover	Forest cover >20%	FO-I1	FO-I2	FO-I3	FO-I4	FO-I5
Mostly Bush- and Shrubland	Bush- and shrubland and savannah grassland > forest cover	BS-I1	BS-I2	BS-I3	BS-I4	BS-I5
Little Woody Biomass	Bare land >20%	BA-I1	BA-I2	BA-I3	BA-I4	BA-I5
No Woody Biomass	None of the above categories apply	NO-I1	NO-I2	NO-I3	NO-I4	NO-I5

Figure 2. Landscape types categorized by land use intensity and woody biomass cover (adapted from Zaehringer et al. [65]).

The five binary maps representing the five intensity categories are largely complementary, but some overlaps nonetheless exist. For this reason, we combined them according to their intensity levels, with the map showing the most intensive category at the top and the one showing the least intensive one at the bottom. The four binary maps representing woody biomass were processed analogously, with the map showing the category with the most woody biomass at the top and the one showing the category with the least woody biomass at the bottom. The resulting two categorical maps were then combined to produce a landscape mosaic map. This procedure was repeated for each of the three points in time.

The resulting three landscape mosaic maps depict aggregated land use information at the landscape level for the three points in time studied. This makes it possible to detect changes that affect entire land use systems, as well as to assess intensification processes [65]. In order to analyze landscape change and quantify the intensification of agricultural land use, we cross-tabulated the landscape mosaic statistics for the three points in time.

The landscape mosaic maps were evaluated based on visual inspection and local expertise. A quantitative assessment at the landscape level is not feasible based on the available field reference data. Furthermore, single pixel classification errors in the land cover maps have little influence on the landscape-level mosaic maps.

3. Results

3.1. Land Cover and Land Use Changes in the Study Area

Table 2 shows the net changes in area that occurred in each land cover and land use class over the last 30 years, split up into two time intervals. A look at the changes over the entire 30 years shows strikingly that massive changes between 1987 and 2016 occurred mainly in four classes: while savannah grassland and bush- and shrubland decreased by 46,105 ha and 11,837 ha, respectively, cropland (rainfed and irrigated) increased by 47,752 ha. This change is also clearly visible in Figure 3.

A look at the two partial intervals shows that the transition to cropland first occurred on the northwestern slopes and foothills closer to Mount Kenya, followed by areas farther away from the mountain and areas near rivers. Smaller amounts of savannah grassland were converted to forest, bush- and shrubland, and irrigated cropland. While the increase in rainfed cropland is much smaller during the second interval (0.85%), irrigated cropland continues to increase at a similar rate as during the first interval (3.87%). The conversion to irrigated cropland mainly happened near Mount Kenya, near greenhouses or irrigation water reservoirs, or along rivers, where riparian forests and wetlands were converted to irrigated or rainfed cropland.

A number of forest plantations were established during the first interval, increasing the forest area by 8509 ha. During the second interval, the total forest area shrank again (by 605 ha) due to the harvesting of trees from plantations and the conversion of riparian and other small forest patches to irrigated and rainfed cropland. Class changes between savannah grassland, bush- and shrubland, and forest were also observed. These can partly be attributed to natural succession and tree harvesting, but in part they are also caused by variability in green vegetation cover between the three points in time investigated due to rainfall variability.

Table 2. Net area changes for each land cover and land use class within the study area in hectares (ha) and percent (%) of the total area analyzed between 1987 and 2002, between 2002 and 2016, and across the entire time interval from 1987 to 2016.

Net Changes	1987–2002		2002–2016		1987–2016	
	ha	%	ha	%	ha	%
Rainfed cropland	28,740	11.6	2079	0.8	29,438	11.9
Bare land	228	0.1	1026	0.4	3351	1.4
Waterbodies	24	0.0	73	0.0	97	0.0
Irrigated cropland	8882	3.6	9515	3.9	18,315	7.4
Savannah grassland	−41,023	−16.6	−6030	−2.5	−46,105	−18.7
Forest	8509	3.4	−605	−0.2	7816	3.2
Settlements	306	0.1	31	0.0	322	0.1
Greenhouses	21	0.0	604	0.2	624	0.3
Bush- and shrubland	−5689	−2.3	−6693	−2.7	−11,837	−4.8

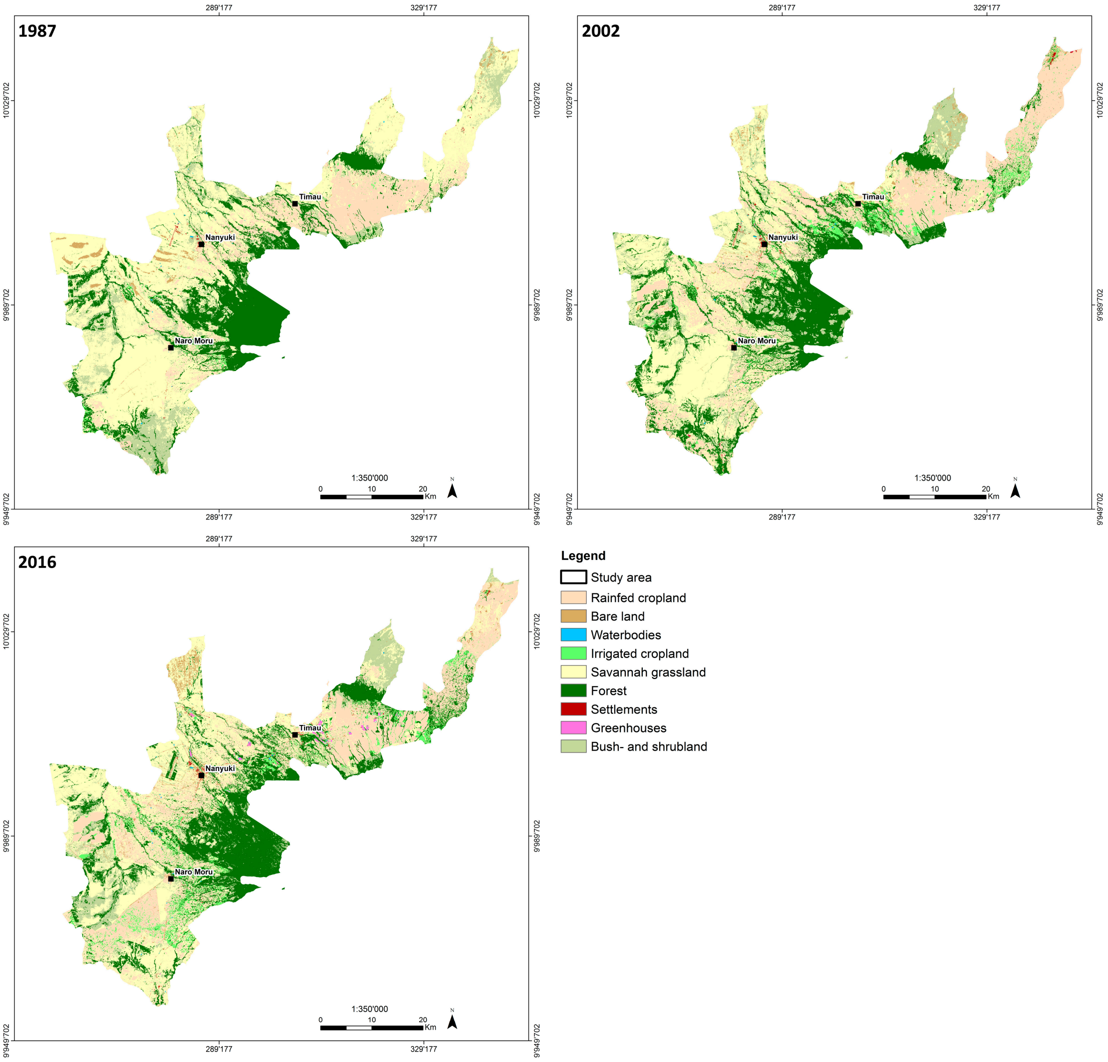


Figure 3. Land cover and land use classification maps of the study area around 1987, 2002, and 2016 (map projection: UTM 37S).

Settlements grew considerably during the first interval, while waterbodies and greenhouses expanded mostly during the second interval. Between 1987 and 2016, greenhouses increased by 624 ha and waterbodies by 97 ha. The appearance of greenhouses surrounded by small water reservoirs can be observed particularly along the main road connecting Nairobi with the towns of Naro Moru, Nanyuki, and Timau. Figure 4A shows this impressive development east of Timau, while Figure 4B shows the conversion of savannah grassland, wetlands, as well as riparian and other small forests to rainfed and irrigated cropland northwest of Naro Moru, along the Naro Moru and Burguret rivers.

Areas cultivated by large-scale investors are mostly used for highly technologized commercial floriculture or horticulture. Floriculture farms are typically characterized by greenhouses and water storage reservoirs, while horticulture farms are generally surrounded by irrigated cropland.

Areas classified as greenhouses in 2016 were formerly either used as rainfed cropland (297 ha) or converted from savannah grassland (239 ha), bush- and shrubland (37 ha), and forest (25 ha). Detailed land cover and land use class change matrices for the two time intervals are provided in Tables S2 and S3 in the Supplementary Materials.

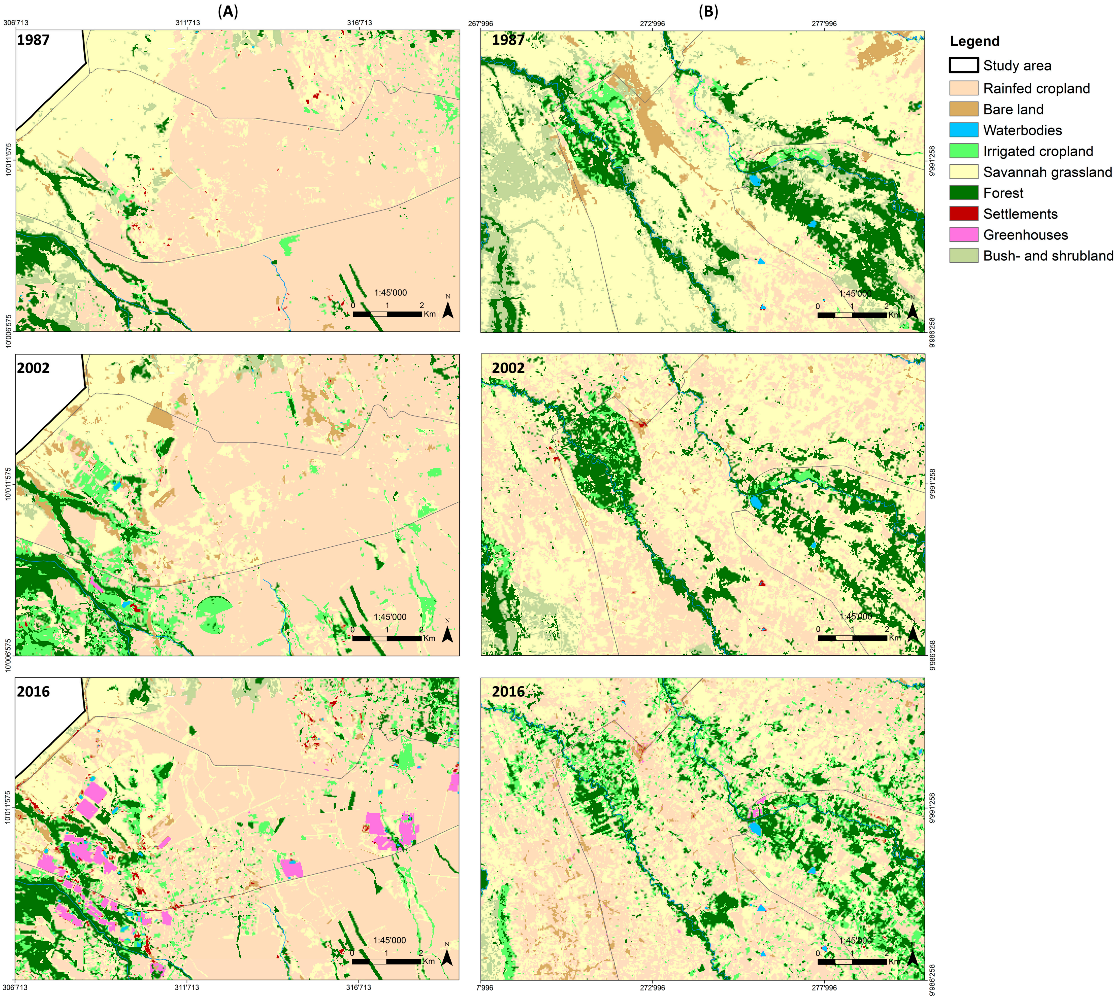
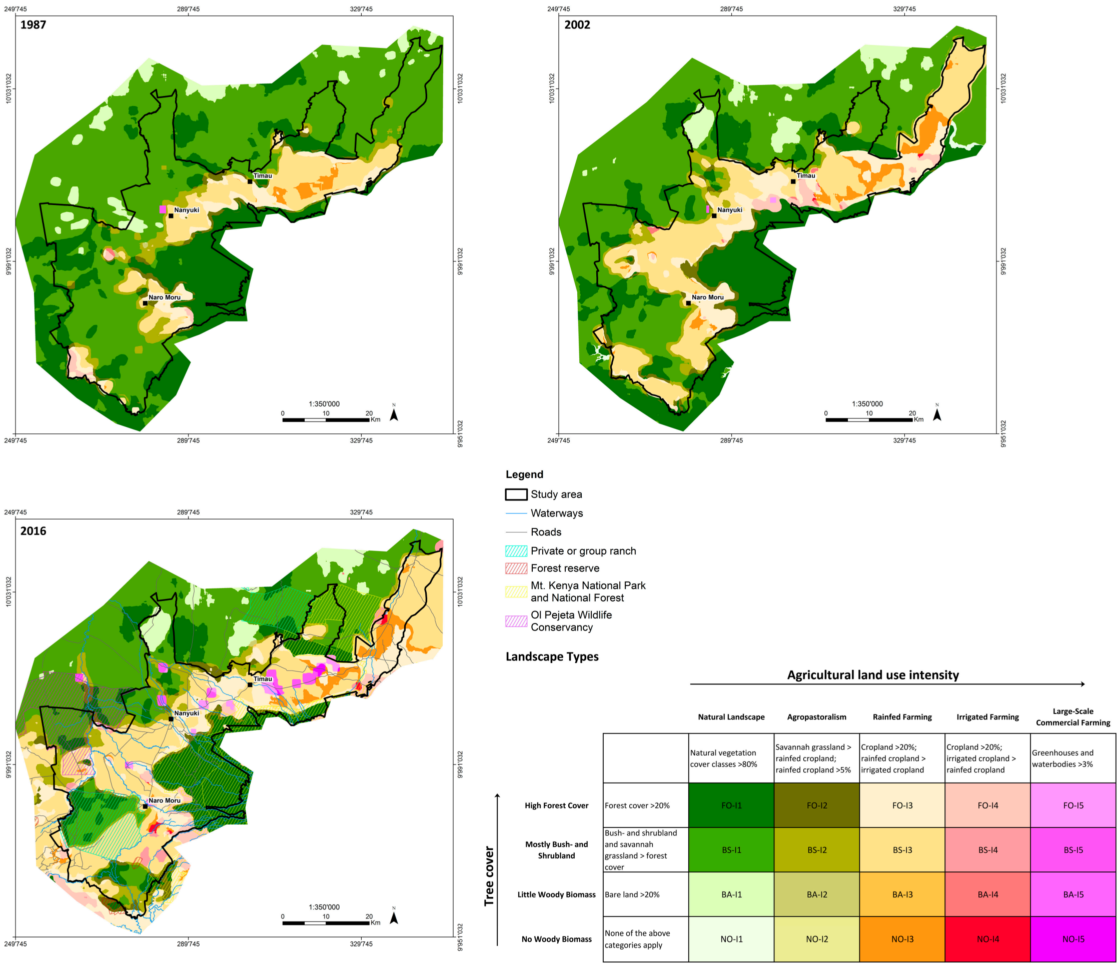


Figure 4. Two subsets of the land cover and land use classifications for 1987, 2002, and 2016 showing (**A**) the development of greenhouses and irrigation water reservoirs east of Timau, and (**B**) the conversion of savannah grassland, forests mostly along rivers, and wetlands northwest of Naro Moru, along the Naro Moru and Burguret rivers to rainfed and irrigated cropland (map projection: UTM 37S).

3.2. Landscape Changes in the Study Area

The availability of aggregated land use information at the landscape level makes it possible to detect changes that affect entire land use systems, as well as to assess and visualize processes of cropland expansion and use intensification (Figure 5).

In 1987, the study area was dominated by natural vegetation and agropastoral land use systems, which together covered around 75% of the study area. In 2016, this was no longer the case, with these landscape types now covering only 45% of study area (Figures 6 and 7). This reduction happened at the expense of landscapes characterized by natural vegetation (forest, bush- and shrubland, grassland; −22%). Such areas were converted, mostly during the first interval, in the vicinity of Mount Kenya, where rainfall in those years was comparably reliable; during the second interval, the change affected natural landscapes in the lower, more arid plains farther away from Mount Kenya but near rivers and wetlands. Most of these landscapes were converted to smallholder farmland (23%) dominated by rainfed, low-input agriculture (BS-I3, BA-I3). One exception is an area northeast of Timau, where large-scale cereal cultivation in monoculture (NO-I3) was practiced already before 1987. Here, there was little change over the past 30 years, except in some plots that were given to smallholder farmers practicing multicropping and agroforestry, resulting in a conversion from NO-I3 to FO-I3 or FO-I4. Throughout the study area, an increase in tree cover—mostly due to the adoption of agroforestry systems—occurred particularly in areas with sufficient water availability, that is, in the semi-humid areas near Mount Kenya or along perennial rivers. Since 2002, agroforestry has expanded along rivers, where riparian forests and wetlands were converted mainly to irrigated cropland. Agroforestry is also increasingly found at higher elevations near the boundaries of the Mount Kenya National Park and National Forest, where water is more readily available.



		Natural Landscape	Agropastoralism	Rainfed Farming	Irrigated Farming	Large-Scale Commercial Farming
		Natural vegetation cover classes >80%	Savannah grassland > rainfed cropland; rainfed cropland >5%	Cropland >20%; rainfed cropland > irrigated cropland	Cropland >20%; irrigated cropland > rainfed cropland	Greenhouses and waterbodies >3%
High Forest Cover	Forest cover >20%	FO-I1	FO-I2	FO-I3	FO-I4	FO-I5
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Figure 5. Landscape mosaic maps for 1987, 2002, and 2016, overlaid with waterways (map projection: UTM 37S). The map for 2016 additionally shows different types of protected or managed areas and the road network. Land use intensity increases with the color gradient changing from dark green towards dark pink. The darker and more intense the green and olive colors, the more woody biomass there is. The more intense the orange, red, and pink colors, the less woody biomass there is and the more intensively the land is used.

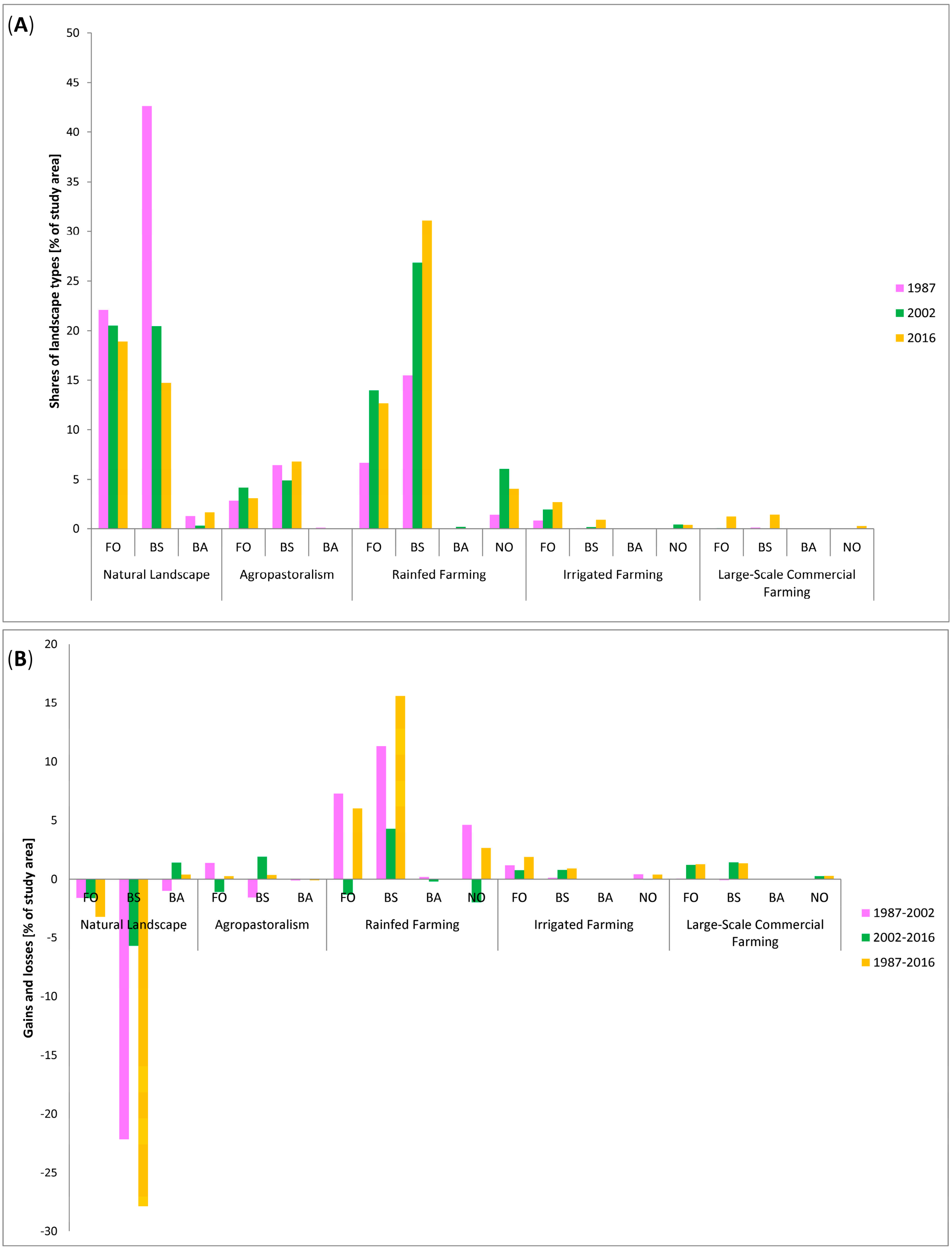

Figure 6. (**A**) Shares of landscape types in the total study area in percent for 1987, 2002, and 2016, and (**B**) gains and losses in each landscape type expressed as percentages of the total study area for the three intervals from 1987 to 2002, from 2002 to 2016, and from 1987 to 2016. FO = high forest cover, BS = mostly bush- and shrubland, BA = little woody biomass, NO = no woody biomass.

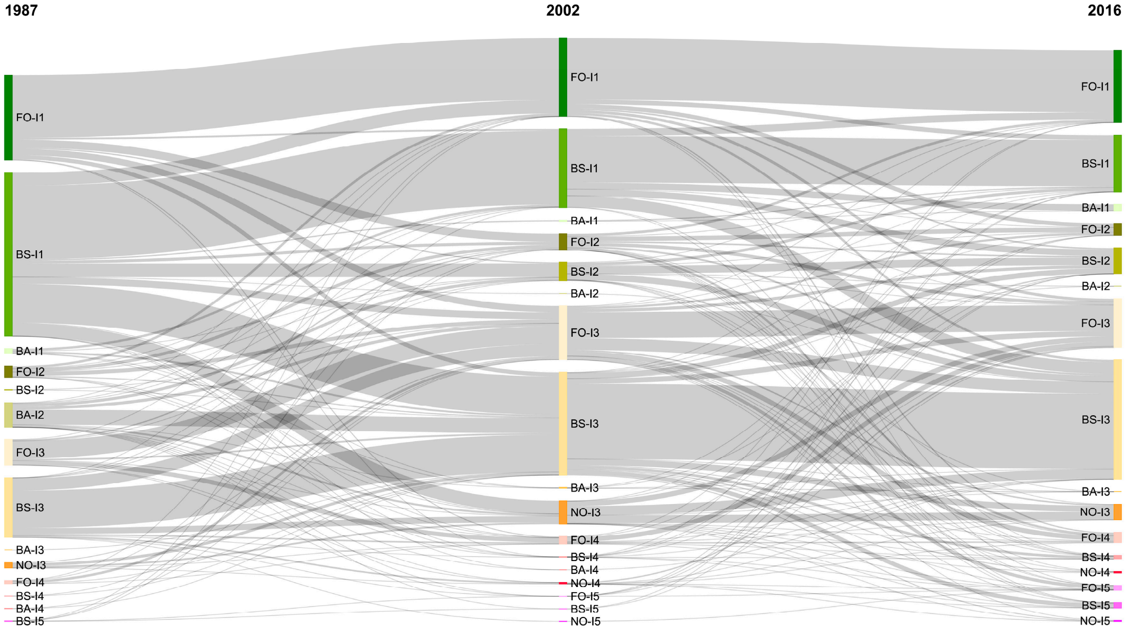

Figure 7. Sankey plot showing changes from one landscape type to another between 1987, 2002, and 2016. The colors and labels follow the scheme shown in Figure 2.

Mixed agropastoral landscape types remained fairly stable in size, but shifted farther away from Mount Kenya towards more arid areas. Irrigated farming was still rare in 1987 (<1% of study area), but became more prominent and appeared on the landscape mosaic map in 2002 (2.5%); in 2016, finally, it covered 4% of the study area. As mentioned above, it is mainly practiced by horticulture farms along the main road from Nanyuki to Timau, as well as by small-scale farmers, who mostly practice it in conjunction with agroforestry and have reliable access to irrigation water (FO-I4 and BS-I4). Another feature that first appears in the 2002 landscape mosaic map is the horticulture and floriculture hotspot area (FO-I4 and FO-I5) between Nanyuki and Timau. At that time, there were no greenhouses in the study area, and flowers were grown in open fields. However, greenhouses are needed for the production of high-value, high-quality flowers [68], which the floriculture sector started investing in around 2002 [69,70]. In 2016, landscapes characterized by such high-intensity agriculture already covered 3% of the study area. Most of them are located along rivers and along or only a short distance away from the main road.

3.3. Changes in Tree Cover and Woody Biomass

Landscapes with a high amount of woody biomass (FO and BS) experienced an increase between 1987 and 2002, followed by a slight decrease until 2016 (see Figure 8). The increase is mainly due to an expansion of riparian forests, and, even more so, of bush- and shrubland west to northwest of Naro Moru. By 2016, the area covered by these landscapes shrank again; the establishment of several tree plantations east of Nanyuki was unable to compensate for the loss of natural, forest-dominated landscapes that occurred, for example, north of Timau as well as south and southwest of Naro Moru, where large tracts of natural landscape were converted to rainfed farmland (clearly visible in the 2016 landscape mosaic map). Landscapes with little woody biomass have increased slightly since 1987, but at a low level. Landscapes without woody biomass show an overall increase since 1987, but have been on the decline since 2002.

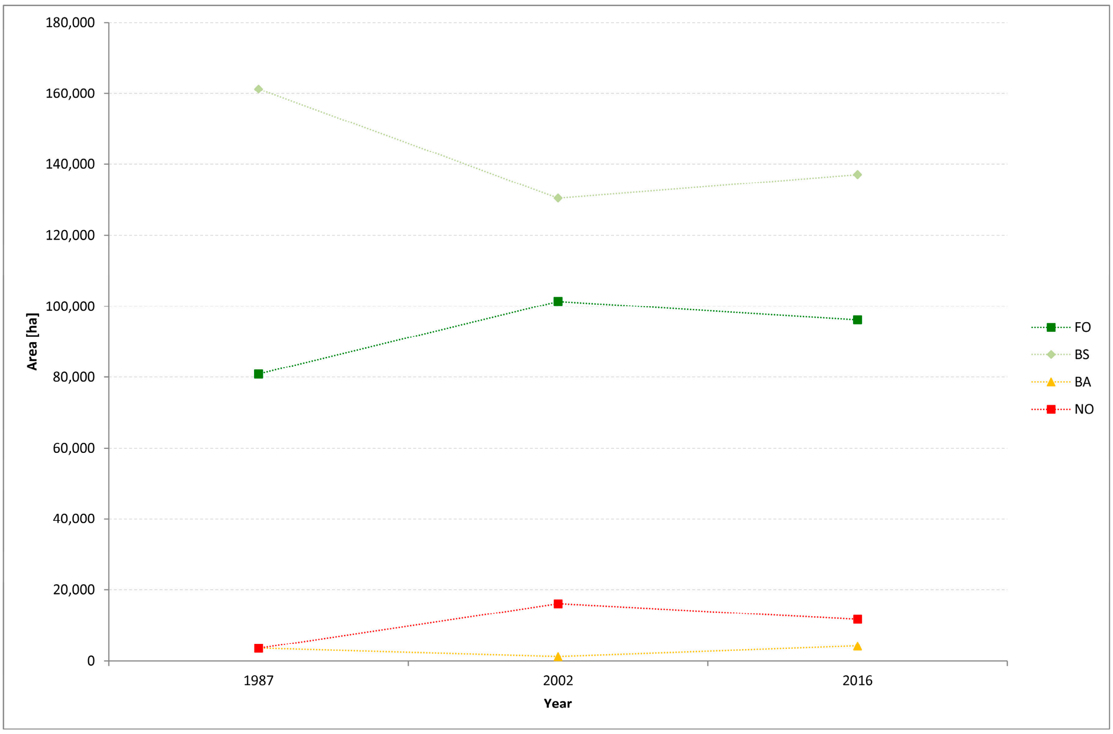

Figure 8. Area (ha) covered by each of the four woody biomass categories in 1987, 2002, and 2016. FO = high forest cover, BS = mostly bush- and shrubland, BA = little woody biomass, NO = no woody biomass.

3.4. Landscape Changes in Protected Areas

Most larger natural landscapes that have remained stable in the study area are protected areas where land uses other than conservation are restricted. The most prominent protected area in the study area is Mount Kenya National Park and National Forest, which has experienced only minor changes along its boundaries. These changes are either from one natural landscape category to another or from landscapes dominated by forest or bush- and shrubland to landscapes dominated by rainfed and irrigated agroforestry. In contrast, the small Lusoi Forest Reserve in the south of the study area experienced substantial change. In 1987, it was surrounded by a vast area of natural bush- and shrubland. By 2016, most of this landscape disappeared, and about half of the reserve was converted into a landscape dominated by rainfed farming, albeit still surrounded by a large area of bush- and shrubland. In the west, partially outside the study area, lies the Ol Pejeta Conservancy, which today encompasses about 360 km^2. A cattle ranch in colonial times, it became a wildlife reserve in the 1980s and gradually increased in size to its current extent. Although its natural landscape has largely remained stable, a notable change occurred in the southern part of the reserve, which was converted to large-scale monoculture wheat fields after 1987. This change is clearly visible in the landscape mosaic maps for 2002 and 2016. The 2016 map further shows that land use intensified along the rivers forming the borders of the Ol Pejeta Conservancy. Besides these protected areas, the study area also contains two private ranches: Solio Ranch in the south, dedicated to conserving rhinoceros, and Borana Ranch and Conservancy in the north. On Borana Ranch, the natural landscape still covers a large area, whereas in the southeastern part of Solio Ranch it was recently converted to rainfed smallholder farmland, which is clearly visible on the landscape mosaic map for 2016.

4. Discussion

Important prerequisites for this study were the successful and accurate mapping of the most important natural vegetation covers, the differentiation between rainfed and irrigated cropland, and the identification of greenhouses and irrigation water reservoirs. All three could only be achieved by using multi-seasonal satellite data composites, making subsets of predominantly natural habitats and predominantly cropland areas, and verifying the mapping results through careful visual comparison with Google Earth imagery. We would like to note that settlement areas might be under-represented in our land cover and land use maps, as most individual buildings and small settlements in the study area are too small to be captured clearly in the Landsat data. Furthermore, variations in the shares of natural vegetation covers and bare soil, as well as of rainfed cropland and irrigation cropland, between the three points in time investigated might partially be due to interannual variations in seasonal rainfall. Thus, the observed increase in irrigated cropland might be slightly overestimated. The same applies to the increase in rainfed cropland at the cost of savannah grassland, a small portion of which may have been caused by misclassifications between the two classes due to the very heterogeneous and small-scale pattern of cropland and grazing plots. We estimate these errors to be within one percent of net change.

We would further like to note that the accuracies of the three pixel-based land cover and land use change analyses are only as good as the multiplied accuracies of each individual land cover and land use classification [71]. However, single pixel classification errors in these classification maps have little influence on the landscape-level mosaic maps.

Depending on how agricultural intensification manifests itself, a pixel-level assessment may make sense. This is the case, for example, when natural vegetation cover changes to cropland [72], when plot size increases [73], when irrigated cropland increases [35], or when the number of cropping cycles increases [34]. However, this study shows that when agricultural intensification manifests itself in land use system changes, an assessment at the landscape level may be better suited to capture these processes. Based on the idea that certain landscape types can only be captured by analyzing the combination of land covers and land uses in a certain context area, we defined landscape type categories and developed a decision rule set for each category that enabled us to differentiate landscape types by land use intensity and the amount of woody biomass present. We defined the categories based on the landscape compositions observed in the field. The category definitions might need to be adjusted if the approach is transferred to a different agroecological zone composed of different landscapes and land use systems.

The results presented in this paper show impressively how much, where, and at the expense of which landscapes cropland has expanded and land use has intensified since 1987. The transformation from extensive agropastoral use to rainfed smallholder farming mainly happened between 1987 and 2002, but it still continues wherever land, and, more importantly, water is available. Between 2002 and 2016, we can observe a shift away from purely rainfed to increasingly irrigated smallholder farming, as well as the development of high-input commercial vegetable and flower farming, which is practiced in open fields and increasingly also in greenhouses. Commercial growers require year-round irrigation to supply export markets regardless of the season. Indeed, commercial water use is highest precisely when the least water is available: one reason being that European demand for vegetables peaks during the study area's driest period. The same is true of flowers, with Valentine's Day falling in February, the driest month in the study area. Increasing commercial use strains water resources during times of scarcity and sets the stage for conflicts among different water users [48,51]. To avoid such conflicts while further increasing production, most horticulture farms in the study area have begun to reduce their dependence on local river water. Over the last decade, they have invested in the construction of irrigation water reservoirs and boreholes. This explains the increase in surface water by 97 ha between 1987 and 2016. Furthermore, most commercial farms harvest rainwater from the greenhouse roofs and apply drip irrigation. Nonetheless, it remains unknown whether the intensification of water use will have long-term impacts on the groundwater table, be it in the highlands or in the Merti aquifer downstream. Furthermore, intensive small- and large-scale farming is impairing the water's quality, as it affects the physico-chemical properties of surface waters [16,74–76]. Muriithi and Yu [16] took water samples in the study area and examined several physico-chemical parameters.

They found high pollutant concentrations in areas with intensive small-scale farming and large-scale commercial horticulture.

Our results regarding land use system changes further show that natural habitats in the study area have decreased in the last 30 years. Some of the protected areas—which are important habitats for Kenya's wildlife—are continuously shrinking. The southern part of the Ol Pejeta Conservancy was converted into large-scale monoculture wheat fields. In the case of Solio Ranch, the Government of Kenya purchased the southeastern part of the rhinoceros reserve in 2007 to resettle landless small-scale farmers, leading to a transformation of the natural habitat into rainfed farmland [77]. The farmers had previously been evicted from their original homes in the Mount Kenya and Aberdare forests due to concerns about adverse environmental impacts of the area's overpopulation, and since then had had to live as squatters in the surrounding towns. Bond [15] found that, besides water, the local population perceives land and pasture as the main natural resources related to conflicts in Laikipia County. The potential for conflict between pastoralists, smallholder farmers, large-scale ranches, and wildlife is particularly prevalent during the dry seasons, when migrating pastoralists move into the area in search of pasture, water, and idle land to feed their livestock [15].

The massive reduction in natural vegetation and the intensification of agricultural land use also have consequences for biodiversity and cause land degradation. The replacement of bush- and shrubland, grassland, and forests with crops reduces plant species diversity, although mixed cropping and agroforestry conserve native plant species better than single-crop farming [10]. In formerly less forested areas, such as the area northeast of Timau that used to consist mainly of large monoculture wheat farms, mixed cropping and agroforestry has led to an increase in trees, which may also have led to an increase in biodiversity by attracting new species of birds [10]. However, wherever farming is intensified and habitat diversity is reduced, biodiversity also declines. Land degradation is affected in a similar way: soil erosion increases with decreasing vegetation cover, and the productivity of agricultural land declines unless manure or other fertilizers are added. The main drivers of land degradation besides soil erosion are the depletion of organic matter (soil organic carbon), degradation of the soil structure, and a decline in the availability of major nutrients (N, P, K) and micro elements in the soil. Furthermore, toxicity may increase due to acidification and salinization, especially in land used for irrigated farming [10].

In sum, agricultural intensification and the expansion of horticulture agribusinesses further increase pressure on the study area's limited natural resources, potentially aggravating the condition of the environment and the situation of disadvantaged land users. These developments certainly offer new economic opportunities, but they also come with constraints for sustainable development [17,78]. Therefore, it is important to ensure that agricultural production in Africa is intensified in a sustainable manner.

5. Conclusions

This study provides spatially explicit information about the expansion of farming and its more recent intensification in the northwestern foothills of Mount Kenya. We analyzed how these changes affect the landscapes in the study area. We made use of Google Earth Engine to access the USGS Landsat data archive and to generate cloud-free seasonal composites. These seasonal composites then enabled us to differentiate between rainfed and irrigated cropland with considerably high accuracy (F1 class values ranging between 73.5% and 84.7% for the two classes). By applying a landscape mosaic approach to the land cover and land use classifications, we were able to derive landscape types categorized by land use intensity and the amount of woody biomass present. The results and their analysis led us to the following conclusions:

- Rainfed and irrigated cropland expanded by 47,752 ha, mainly at the expense of savannah grassland, bush- and shrubland, and forest, which showed overall losses of 46,105 ha, 11,837 ha, and 605 ha, respectively. This amounts to a 30% decrease in natural habitats in the study area over the last 30 years. The conversion to rainfed cropland mainly happened between 1987 and

2002, although it continued on after that at a much lower level. The intensity of agricultural land use began to increase between 2002 and 2016, as further humid forest, bush- and shrubland, and grassland areas along rivers, as well as rainfed cropland areas were converted into irrigated cropland. Not only large-scale producers, but also many smallholders have begun to practice irrigated farming. In addition, the area has seen a rapid development of high-input commercial greenhouse horticulture farming (since 2002, greenhouses increased by 604 ha and irrigation water reservoirs by 73 ha).

- Natural wildlife habitats continue to shrink. Agricultural expansion and intensification affects not only non-protected areas, but also private ranches and wildlife reserves as well as small forest reserves in the study area. However, Mount Kenya National Park and National Forest remained fairly stable. The overall forested area has decreased only slightly thanks to a number of afforestation projects near the boundary of Mount Kenya National Park and National Forest.
- The massive reduction in natural habitats and the intensification of agriculture have diverse impacts on biodiversity. While the observed reduction in natural habitats has reduced biodiversity at the regional level, the observed increase in agroforestry farming has increased it locally. The changes also affect land degradation. Potential future consequences of agricultural intensification include soil erosion and—unless fertilizer is applied—a decline in the soil's organic matter, degradation of the soil structure, and a reduction in major nutrients.
- Water availability defines the spatial pattern of agricultural expansion and intensification in the study area. Water has always been a scarce resource in the region. Agricultural intensification and the expansion of horticulture agribusinesses further increase pressure on this limited natural resource. Furthermore, the observed changes have also heightened pressure on pasture and idle land due to the decrease in natural and agropastoral landscapes. As a result, conflicts between pastoralists, smallholder farmers, large-scale ranches, and wildlife might further increase, particularly during the dry seasons and in years of extreme drought.

Spatially explicit information on agricultural expansion and intensification is highly relevant to understand patterns of land use change and their impacts on the environment and human well-being. Particularly in developing countries, which often lack such spatial information and where land use is undergoing substantial change, such up-to-date spatial information can support policymakers, land use planners, and land users in achieving sustainable agricultural intensification.

Supplementary Materials: The following are available online at www.mdpi.com/2072-4292/9/8/784/s1, Figure S1: Number of Landsat surface reflectance products sorted by year, month, and season that were available in Google Earth Engine. Collections highlighted in green were chosen for the analysis. Table S1: Overall and class-wise accuracies for 1987 (A), 2002 (B), and 2016 (C). Table S2: Matrix of land cover and land use class changes between 1987 and 2002. Table S3: Matrix of land cover and land use class changes between 2002 and 2016.

Acknowledgments: The research for this publication was conducted as part of the BELMONT Forum and FACCE–JPI project "African Food, Agriculture, Land and Natural Resource Dynamics, in the context of global agro-food-energy system changes (AFGROLAND)" (Grant Number: 40FA40_160405). The project is funded by the Swiss National Science Foundation, the French National Research Agency, and the South African National Research Foundation.

Author Contributions: Sandra Eckert and Julie Gwendolin Zaehringer conceived and designed the experiments; Sandra Eckert processed and analyzed the data and wrote the paper; Boniface Kiteme and Evanson Njuguna contributed to the collection of field reference data and to the writing of the paper; and Julie Gwendolin Zaehringer contributed to the writing of the paper as well.

Conflicts of Interest: The authors declare no conflict of interest.

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