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Assessment of Land Cover Changes in the Hinterland of Barranquilla (Colombia) Using Landsat Imagery and Logistic Regression

Henry Schubert [1,*], Andrés Caballero Calvo [2], Markus Rauchecker [3], Oscar Rojas-Zamora [4], Grischa Brokamp [5] and Brigitta Schütt [1]

[1] Department of Earth Sciences, Physical Geography, Freie Universität Berlin, Malteserstr. 74-100, Haus H, 12249 Berlin, Germany; brigitta.schuett@fu-berlin.de
[2] Departamento de Arquitectura y Urbanismo, Universidad del Norte, Km.5 Vía Puerto Colombia, Área Metropolitana de Barranquilla 081007, Colombia; andrescaballero@uninorte.edu.co
[3] Institute for Latin American Studies, Freie Universität Berlin, Rüdesheimer Str. 54-56, 14197 Berlin, Germany; markus.rauchecker@fu-berlin.de
[4] Departamento de Química y Biología, Universidad del Norte, Km.5 Vía Puerto Colombia, Área Metropolitana de Barranquilla 081007, Colombia; ozamora@uninorte.edu.co
[5] Botanischer Garten und Botanisches Museum Berlin-Dahlem, Freie Universität Berlin, Königin-Luise-Straße 6-8, 14195 Berlin, Germany; g.brokamp@bgbm.org
* Correspondence: h.schubert@fu-berlin.de; Tel.: +49-30-838-70519

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Abstract: Barranquilla is known as a dynamically growing city in the Colombian Caribbean. Urbanisation induces land use and land cover (LULC) changes in the city and its hinterland affecting the region's climate and biodiversity. This paper aims to identify the trends of land use and land cover changes in the hinterland of Barranquilla corresponding to 13 municipalities in the north of the Department Atlántico. Landsat TM/ETM/OLI imagery from 1985 to 2017 was used to map and analyse the spatio-temporal development of land use and land cover changes. During the investigation period, the settlement areas grew by approximately 50% (from 103.3 to 153.6 km^2), while areas with woody vegetation cover experienced dynamic changes and increased in size since 2001. Peri-urban and rural areas were characterized by highly dynamic changes, particularly regarding clearing and recovery of vegetated areas. Regression analyses were performed to identify the impact factors of detected vegetation cover changes. Computed logistic regression models included 20 independent variables, such as relief, climate, soil, proximity characteristics and socio-economic data. The results of this study may act as a basis to enable researchers and decision-makers to focus on the most important signals of systematic landscape transformations and on the conservation of ecosystems and the services they provide.

Keywords: Colombian Caribbean; urbanisation; tropical dry forest; random forest classifier; woody vegetation changes

1. Introduction

Land cover changes are directly linked to loss of natural habitats and fragmentation of ecosystems and thus are a major threat for biodiversity and a continuous provision of ecosystem services [1–3]. Ecosystems and their services are threatened by both internal and external drivers, as well as by global trends, including increases in human population, agricultural activities, infrastructure projects, and per capita consumption [4–6]. Latin America has been characterized by large-scale losses of forest areas in recent decades [7,8]. Traditional practices of smallholders, such as shifting cultivation and charcoal production [9,10], as well as intensive and expanding cattle breeding, are key drivers of deforestation [8,11]. However, current trends of rural-urban migration [12], decreasing rural population density, and extensification could promote natural recovery [13,14].

Tropical dry forest represents the natural vegetation of large parts of the Colombian Caribbean [15,16], and its protection is a priority for national environmental protection agencies [17]. Tropical dry forests are defined as tree dominant ecosystems characterized by a mean annual temperature of $\geq$25 °C, a total annual precipitation ranging between 700 and 2000 mm, and three or more arid months per year [18]. Since the tropical dry forests in the region of the Colombian Caribbean experienced severe human perturbation in the past they are regarded as secondary forests. However, they still harbour a high biodiversity and provide many important ecosystem services, such as carbon storage, water purification, and erosion control [19]. In the Colombian Caribbean, only 22.5% of the original extent of tropical dry forest is still covered by vegetation, which was diminished to strongly fragmented forest remnants smaller than 25 ha in size, and only 5.1% of the dry forest areas are declared as protected areas [15,20].

Already in pre-Columbian times, the Colombian Caribbean and Magdalena River deltas were favoured and constantly used as settlement areas [21]. Although the colonisation of the Colombian Caribbean was accompanied by a huge population decrease and replacement (from 500,000 inhabitants in 1500 to 60,000 in 1600), tropical dry forest represents the only forest type in Colombia, whose countrywide extent was decreasing between the 16th and 17th century, mainly due to the advent of cattle breeding in the Caribbean region in the 16th century [22]. It is assumed that in the 16th century, the tropical dry forests still covered approximately 58% of its natural extent, which had already decreased to 48% only 100 years later [22]. Continuous deforestation lead to a further decrease down to 10% of the natural tropical dry forest extent in 2000, mainly due to a steadily growing human population and the expansion of livestock production in the region. In the last decades, annual deforestation rates have slowed down significantly [13,22,23].

Currently, Barranquilla is the fourth biggest city of Colombia, and with its harbour and various local industries, it represents the most important economic centre of the Colombian Caribbean. The metropolitan area of Barranquilla was officially formed in 1981 to improve the coordination in spatial planning and comprises the five municipalities Barranquilla, Puerto Colombia, Galapa, Soledad, and Malambo [21]. The metropolitan area's population nearly doubled between 1985 (1.20 million inhabitants) and 2017 (2.07 million inhabitants). In this period, Barranquilla's (municipality) population grew by roughly 33%, while the population growth of the municipalities Soledad (265.3%) and Galapa (212.3%) was much higher (see Section 5.2) [24]. Rapid urban growth generally affects the hinterland of cities and typically goes hand in hand with an increased pressure on (semi-)natural ecosystems [1,3,25]. Random forest classification of multi-temporal Landsat imagery combined with logistic regression is an adequate and approved methodology for studying urbanisation processes and identifying drivers of land use and land cover change (e.g., [26–31]). Since studies on land cover changes and associated driver analyses are unavailable for the region, we want to use our case study as a basis for further research in the Colombian Caribbean. In this article, we present the spatio-temporal patterns of land cover changes from 1985 to 2017 in the hinterland of Barranquilla with a focus on urbanisation and vegetation cover changes to shed light on effects of urbanisation processes on peri-urban environments.

2. Study Area

The study area covers 13 municipalities in the Department Atlántico with a total area of 1500.7 km^2, which we defined as the hinterland of Barranquilla (Figure 1). Natural borders in the north and in the east limited the area: the Caribbean Sea (north) and the Magdalena River (east). There is only one bridge crossing the Magdalena River: the road to Santa Marta. Accordingly, city growth is almost completely restricted to the west and to the south of Barranquilla and follows main axes corresponding to the major roads to Puerto Colombia, Tubará, Galapa-Baranoa and Malambo. Along these roads, construction activities are intensive and newly constructed residential areas alternate with commercial and industrial areas as well as with barren land and sand and gravel open-pit mines [21,32].

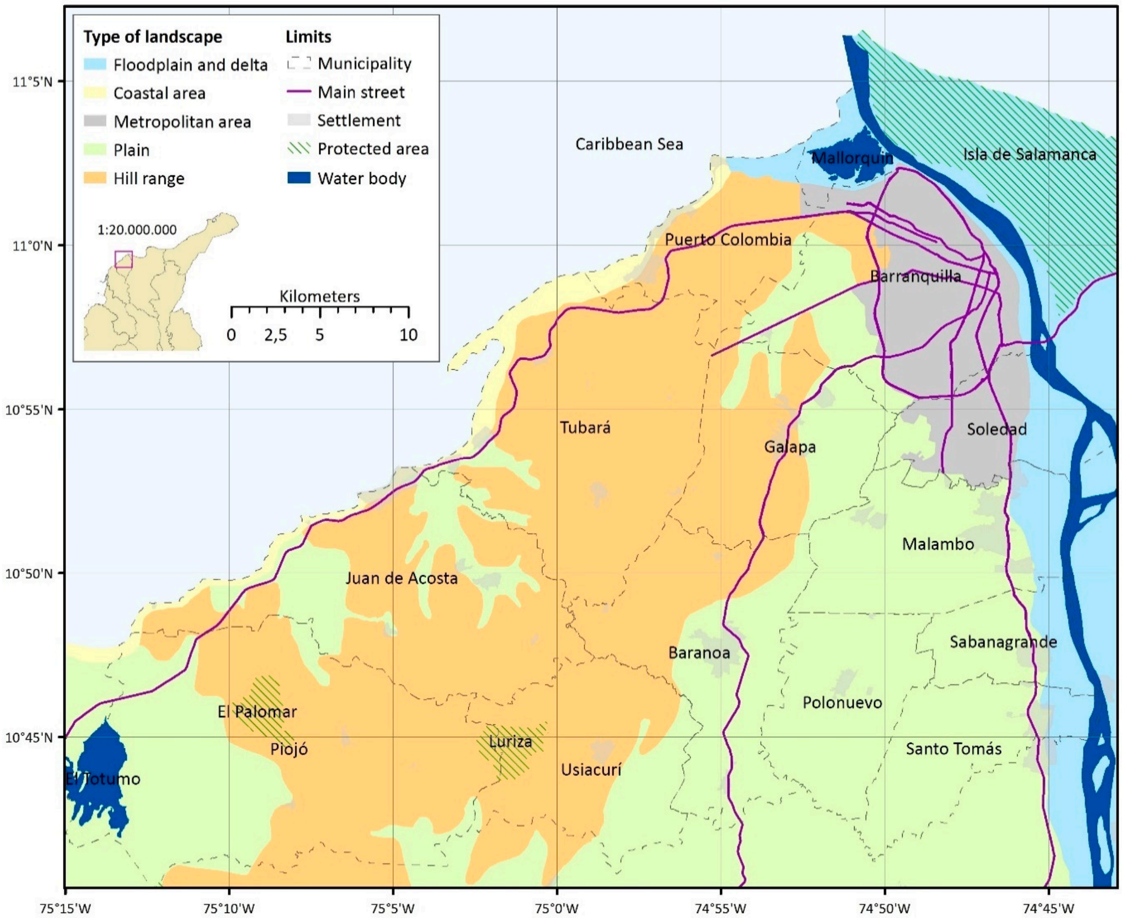

Figure 1. Study area: the hinterland of Barranquilla with settlement structures, administrative and landscape division.

Major landscapes are: (I) the floodplains and delta of the Magdalena River, (II) a small coastal strip, (III) four plains and (IV) the central hill range, which reaches 528 m a.s.l. [32,33]. The plains (III) correspond to a western alluvial and lagoonal plain around the lagoon El Totumo, a larger eastern alluvial and eolian plain around the cities Malambo and Baranoa, and two smaller fluvial plains draining directly to the Caribbean [32,33]. Here, the metropolitan area shows the present-day limits of compacted development and not the territorial planning unit (Figure 1) [34].

In the study area, the annual average precipitation varies from 708 mm (meteorological station of Puerto Colombia, 1981–2000) to 1184 mm (meteorological station of Piojó, 1981–2000) [35]. Precipitation occurs predominantly from September until November, and a second smaller peak occurs in May and June. A dry period is common from December until March with January and February as the driest months. The mean annual temperature varies slightly from 26.3 to 28.2 °C [36,37].

The floodplains and delta of the Magdalena River consist of swamps, marsh areas, abandoned channels, lagoons, and mangroves with high seasonal and interannual dynamics [38]. Recently, construction activities along the coastline and the main road to Cartagena increased including the construction of housing complexes for recreational and touristic purposes [21,32]. Cattle breeding is the most common land use in the plains, with its grasslands interspersed by single trees and small ponds. In the south of Barranquilla, some larger agricultural areas are located. Main agricultural products include maize, yucca, lemon, mango, and legumes [39]. The hill range is covered by a mosaic of forest remnants in widely differing conditions, which are interspersed by pastures and small agricultural fields. Forest patches commonly are situated along periodically draining channels and on steeper slopes. The protected areas Luriza and El Palomar were established to conserve remnant patches of tropical dry forest in 2011 and 2013, respectively [40,41]. Smaller villages and single farms, known as *fincas*, characterize the settlement structure in the hill range. The most common soil types are Inceptisols and Regosols [33].

3. Methods and Data

3.1. Data Acquisition and Processing

Landsat TM/ETM/OLI imagery of the study area was obtained for the time span 1985 until 2017 (Table 1). Temporal range, multispectral characteristics, free availability, spatial resolution and frequency of the Landsat sensors make the imagery highly suitable for mapping land use and land cover changes at a regional scale [25,42,43].

Table 1. Data used for land use and land mapping.

Sensor	Path/Row	Date	Spatial Resolution	Number of Bands
Landsat-5 TM	9/52; 9/53	8 January 1985	30 m	7
Landsat-5 TM*	9/52; 9/53	24 January 1985	30 m	7
Landsat-5 TM	9/52; 9/53	6 January 1990	30 m	7
Landsat-7 ETM	9/52; 9/53	12 January 2001	30 m	9
Landsat-7 ETM*	9/52; 9/53	25 November 2000	30 m	9
Landsat-5 TM	9/52; 9/53	29 January 2010	30 m	7
Landsat-8 OLI	9/52; 9/53	1 February 2017	30 m	11
Landsat-8 OLI*	9/52; 9/53	5 March 2017	30 m	11

* Additional scene.

The EarthExplorer website (https://earthexplorer.usgs.gov/) of the United States Geological Survey (USGS) was used to preview Landsat imagery and to select the best cloud-free scenes. We selected five time steps corresponding to the years 1985, 1990, 2001, 2010, 2017, covering a period with good quality and equal spatial resolution. We used images of the dry period only—favouring the driest months January and February—in order to avoid seasonal variation in vegetation conditions and inundated areas [43]. While the images of 1990 and 2010 are completely free of clouds, parts of the study area are covered by clouds and cloud shadows in the images from 1985, 2001 and 2017. For the latter, cloud masks were calculated by using the QGIS plugin CloudMasking [44]. We selected additional Landsat images from January 1985, November 2000, and March 2017, whose classifications fill the cloud and cloud shadow areas excluded by applied cloud masks in order to obtain the complete land use and land cover information for the whole study area (Table 1).

The utilized Landsat images are standard level-one terrain-corrected (L1T) scenes and have a projection of WGS 1984 UTM Zone 18N. For every band, we calculated the Top of Atmosphere Reflection (TOAR) and an atmospheric correction (DOS1) and created for every scene a raster stack using QGIS Semi-Automatic Classification Plugin [45]. Small parts in the northeast of the study area are covered by a second Landsat image (row: 52). When merging two raster stacks of the same date, the southern images (row: 53) were favoured.

The class division is based on various articles about land use and land cover changes and deforestation in Colombia [27,46–48]. We collected ground truth data of land cover and land use in the study area in October and November 2017. In the scientific literature, typically four vegetation classes are differentiated in the region: mangroves, tropical dry forest, low and high shrubland as succession stages of tropical dry forest [40]. Here, the vegetation class Tropical dry forest was defined by the presence of typical tree species (e.g., *Ceiba pentandra*, *Hura crepitans* or *Bursera simaruba*) with an age of ≥20 years, an average canopy height of 15–20 m and overall a high plant diversity. High shrubland is characterized by the presence of trees with an age of 10–12 years, an average canopy height of 10 m and canopy coverage of up to 50%. Low shrubland is defined here by the presence of small trees only (if present at all) forming an open canopy (<50% coverage) with an average height of 5 m [40]. The transition between vegetation classes is reported to be smooth [49]. Other authors defined three successional stages of tropical dry forests: late, intermediate, and early [50,51]. Here, the late stage—that is, rather intact tropical dry forest—has two layers and a dominant canopy layer with an average height of 30 m. The intermediate stage has two layers, an average height of 10 m with presence of both deciduous and evergreen species. The early stage is characterized by the presence of only one layer with an average height of 6 m harbouring only small deciduous trees and many shrubs [51].

In the present study, low and high shrubland are recapped in one class due to their very similar appearance and reflection properties. Landsat data did not allow differentiation between impervious and permeable areas within the *Settlement* area. For each time step, we created a training data set with 760 points based on ground truth data and adjustments according to Google Earth data. As a result, the training data sets led to 120 randomized points per class; however, the classes *Forest* and *Wetland* were represented by 80 randomized points only because of their smaller spatial extent and due to the low number of corresponding ground truth patches (Table 2).

Table 2. Land use and land cover classes and their definition.

ID	LULC Class	Definition
1	Settlement	Residential, industrial, commercial sites, artificial structures and streets
2	Cleared	Areas with no or only few individual trees, used as pastures or agricultural land, and barren land
3	Forest	Forest patches with closed canopy, riparian forest
4	Shrubland	High and low woody shrubland
5	Bare Soil	Sand dunes, beaches, construction areas, sand and gravel open-pit mines and absence of top soil
6	Wetland	Wet and muddy areas, swamp, frequently inundated grass- and shrubland, mangroves
7	Water	Fresh, brackish and saline water bodies

3.2. LULC Classification, Accuracy Assessment and Change Detection

Seven spectral indices, which relate to different characteristics of secondary tropical dry forests [52,53], were calculated for all utilized satellite images to derive land use and land cover maps: Enhanced Vegetation Index (EVI), Normalized Burn Ratio (NBR), Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), Normalized Shortwave Infrared Index (NSII), Modified Soil Adjusted Vegetation Index (MSAVI) and Modified Single Ratio (MSR). Additionally, the three bands brightness, greenness and wetness of the Tasseled Cap Transformation were added using the R package RStoolbox [54–56].

Land use and land cover maps were created for the years 1985, 1990, 2001, 2010 and 2017 using a random forest classifier for a band stack with the image scenes and the 10 additional bands (EVI, NBR, NDVI, NDWI, NSII, MSAVI, MSR, brightness, greenness, wetness). The study area was split into three landscape units based on the major geomorphological character of the region: *hill range* (HR), *alluvial plains* (AP), and *floodplain, delta, and coastal area* (FC) [32,33]. The current compacted development of the city of Barranquilla, including Soledad and new urban areas in the other municipalities, covers parts of all three landscape units. However, the land use and land cover changes of the urban area are not significant for the changes of the other landscape units. Therefore, we decided to add the *metropolitan area* (ME) as a fourth unit to show the increase of settlement structures and the densification in the city (Figure 1). The statistical analyses were performed for each unit separately.

We created 700 random points stratified for each class in the land use and land cover map 2017 for the accuracy assessment. Verification of ground truth classes of all time steps was done by visual interpretation of the respective satellite images complemented by Google Earth and Bing high-resolution imagery (acquired via Web Map Service, WMS) [27,57,58].

We calculated five cross-tabulated change detection matrices for the time intervals 1985–1990, 1990–2001, 2001–2010, 2010–2017, and for the entire study period 1985–2017. Percentages of the three types of spatial changes quantity, exchange and shift were calculated by using R package diffeR for error assessment and in order to shed light on the land use and land cover changes [59].

3.3. Vegetation Cover Changes

The classes *Forest* and *Shrubland* were fused before estimating the spatio-temporal changes of vegetation-covered areas, and the changes between these two classes were ignored. We defined four transition classes: *stable vegetated, woody vegetation loss*, *stable unvegetated,* and *woody vegetation gain* (Table 3). Areas classified as *Water* in both classifications and the class *Other* with all areas not covered by the transition classes were recapped for the cartographic illustration. The changes from vegetation-covered areas to *Wetland* and *Water* as well as the changes in the opposite direction were ignored, because of interannual differences and partially differing recording times. We created five maps of vegetation cover change for each time interval of the land use and land cover maps (1985–1990, 1990–2001, 2001–2010, 2010–2017 and 1985–2017) to identify local hotspots and spatial patterns of changes (see Section 4.3; Supplementary Materials, Figures S1–S4). Net loss or net gain is the difference between the classes *woody vegetation loss* and *woody vegetation gain*.

Table 3. Established transition classes used for the description of areas that experienced changes of vegetation cover and as a basis for the binomial logistic regression analysis.

Transition Class	From LULC Class	To LULC Classes
Stable vegetated	Forest Shrubland	Forest, Shrubland Forest, Shrubland
Woody vegetation loss	Forest Shrubland	Settlement, Cleared, Bare Soil Settlement, Cleared, Bare Soil
Stable unvegetated	Cleared Bare Soil	Cleared, Bare Soil Cleared, Bare Soil
Woody vegetation gain	Settlement Cleared Bare Soil	Forest, Shrubland Forest, Shrubland Forest, Shrubland

3.4. Binomial Logistic Regression

When connected with GIS, binomial logistic regression is an appropriate tool for explanatory analysis of the factors of land cover changes [31,57,60]. Accordingly, we used logistic regression models to identify drivers and determining factors leading to vegetation cover changes. Applied models estimate the relationship between dichotomous dependent variables (*stable vegetated/woody vegetation loss* and *stable unvegetated/woody vegetation gain*) and a set of independent variables. The AUC value, which refers to the area under the Receiver-Operating-Characteristic (ROC) curve, was determined. Calculation of this value helps to reveal the statistic fit between dependent and independent variables. The AUC value is defined as an interval from 0 to 1, where 0 and 1 indicate a perfect fit and 0.5 indicates no predictive power of the model [61].

The influencing variables considered include characteristics of relief, climate and soil, proximity characters and socio-economic data (Table 4). Selection of these variables was based on information obtained from scientific literature [10,42]. All input data used are freely available online: relief data are based on SRTM 1 Arc-Second Global data [62]; climate data were retrieved from the open-access database WorldClim version 2, which provides average data for the years 1970–2000 with a spatial resolution of 30 seconds [37]; soil characteristics are provided by the open access database SoilGrid with a spatial resolution of 250 m [63]; the main streets and roads are derived from OpenStreetMap data [64]. We calculated the inverse distance rasters for the proximity characters with a spatial resolution of 10 m. The socio-economic data used (x_{19}–x_{20}) are on a municipality level; the nature of the other factors is continuous (Table 4).

Table 4. Independent variables included in the binomial logistic regression analysis.

ID	Description	Unit	Source
y	Transition class (0 = stable, 1 = change)		
x_1	Altitude about sea level	m	[62]
x_2	Slope	°	[62]
x_3	Annual mean temperature	°C	[37]
x_4	Temperature seasonality (SD x *100)		[37]
x_5	Annual precipitation	mm	[37]
x_6	Precipitation seasonality (coefficient of variation)		[37]
x_7	Precipitation in the driest quarter	mm	[37]
x_8	Precipitation in the wettest quarter	mm	[21]
x_9	Depth to bedrock	cm	[63]
x_{10}	Cation exchange capacity in 0.15 cm depth	cmolc/kg	[63]
x_{11}	Soil organic carbon content in 0.15 cm depth	g/kg	[63]
x_{12}	Soil pH value x 10 in H_2O in 0.15 cm depth		[63]
x_{13}	Distance to settlements	m	[35]
x_{14}	Distance to metropolitan area	m	[35]
x_{15}	Distance to main streets	m	[64]
x_{16}	Distance to roads	m	[64]
x_{17}	Distance to drainage channel	m	[65]
x_{18}	Distance to protected area	m	[41]
x_{19}	Variation of population density		[24]
x_{20}	Density of cattle	n/km^2	[66]

We created random points in the landscape units *hill range* and *alluvial plains* equally stratified for the four transition classes *stable vegetated*, *woody vegetation loss*, *stable unvegetated* and *woody vegetation gain* based on the vegetation cover map of the entire period 1985–2017. After deletion of outliers, a set of 22,875 randomized points was assembled. For every period, we selected all points, which are classified as *stable vegetated* (y = 0) and *woody vegetation loss* (y = 1). Firstly, the areas under the ROC curves (AUC values) were calculated for each of the independent variables separately and their behaviour (direct/positive or indirect/negative) and significance level were identified. An independent variable has a high impact if it is continuously significant, its behaviour remains the same in all periods, and the AUC value is closer to the values 0 or 1 than to 0.5 [61]. As a second step, we calculated the probability of *woody vegetation loss* for each period with a logistic regression model (Equation (1)):

$$P(y) = \frac{1}{1 + \exp(-(\beta_0 + \sum_{i=1}^{n} \beta_i x_i))} \tag{1}$$

Several logistic regression models that included all 20 independent variables were tested, two of which are presented here. One of them did not take the relations between independent variables into account and the second model included the relations between the variables of the same group, which are: relief (x_1–x_2), climate (x_3–x_8), soil (x_9–x_{12}), proximity characters (x_{13}–x_{18}), and socio-economic data (x_{19}–x_{20}) (Table 4).

For each period, we then selected all points, which were classified as *stable unvegetated* (y = 0) and *woody vegetation gain* (y = 1) and repeated the steps already described above: Calculation of AUC values for each independent variable and calculation of the probability of *woody vegetation gain* based on two logistic regression models. We calculated the statistical measures AUC, Percentage of Correct Predictions (PCP), True Positive Rate (TPR), and True Negative Rate (TNR) in order to evaluate the model performance [61]. The Percentage of Correct Predictions is defined as the percentage of correctly predicted points to the total number of points [60]. The True Positive Rate gives the proportion of correctly classified positive sampling points. The True Negative Rate is the proportion of the correctly classified negative sampling points [31,61].

4. Results

4.1. Settlement Dynamics and Urbanisation

The land use and land cover classes *Cleared* and *Shrubland* cover a major portion of the study area (Figure 2). During the observed period (1985–2017), artificial structures and impervious surfaces continuously increased in the whole study area. *Settlement* areas grew by 48.7% from an extension of 103.3 km^2 in 1985 to 153.6 km^2 in 2017 (Table 5), especially in the municipalities Soledad (+15.5 km^2, increase of 158.2%), Barranquilla (+13.4 km^2, 21.4%), Malambo (+6.4 km^2, 164.2%), Galapa (+4.9 km^2, 330.9%) and Baranoa (+3.2 km^2, 136.2%).

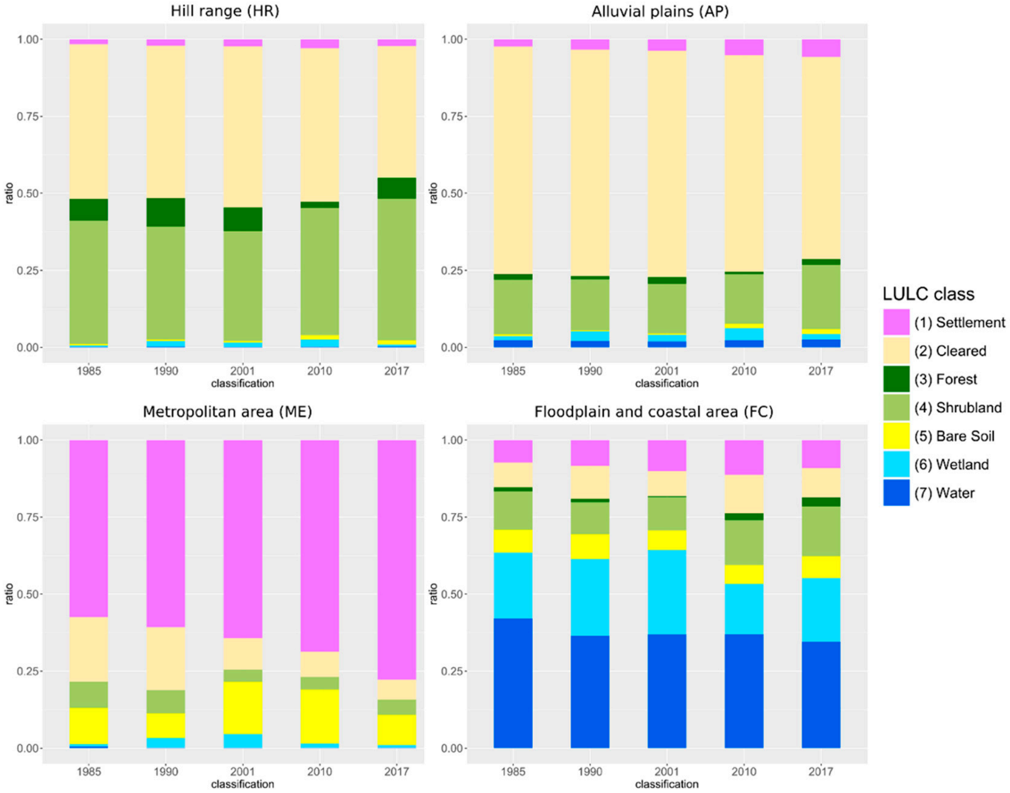

Figure 2. Ratio of land use and land cover classes in the hinterland of Barranquilla differentiated per landscape unit for the years 1985, 1990, 2001, 2010, and 2017.

Table 5. Changes of area size per land use and land cover class in the hinterland of Barranquilla for the years 1985, 1990, 2001, 2010, and 2017 across all landscape units.

LULC Class	1985		1990		2001		2010		2017	
	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%
Settlement	103.3	6.88	117.4	7.82	127.6	8.50	146.9	9.78	153.6	10.23
Cleared	801.8	53.42	797.6	53.14	800.6	53.34	768.6	51.21	688.7	45.88
Forest	59.8	3.98	70.4	4.69	64.5	4.30	22.0	1.47	60.1	4.01
Shrubland	396.7	26.43	362.6	24.16	349.4	23.28	392.3	26.14	454.7	30.29
Bare Soil	29.4	1.96	23.9	1.60	35.3	2.35	46.0	3.06	38.9	2.59
Wetland	39.7	2.65	67.3	4.49	62.5	4.17	62.0	4.13	42.9	2.86
Water	70.3	4.68	61.7	4.11	60.8	4.05	63.1	4.21	62.1	4.14

However, changes of land use and land cover show different trends for the four landscape units: While the *Settlement's* extent expanded by around 35% between 1985 and 2017 in the *hill range* and the *metropolitan area* (*HR*: from 10.7 to 14.4 km^2; *ME:* from 69.2 to 93.7 km^2), the *Settlement* area grew by approximately 142% (from 13.9 to 33.7 km^2) in the *alluvial plains* (Figure 2 and Table A1).

New *Settlement* areas were mainly established on previously *Cleared* areas and to a minor extent on *Shrubland* and *Bare Soil*. Figure 3 depicts the increase of *Settlement* in the urban area and adjacent municipalities. In the city of Barranquilla, a redensification took place in the centre and in the harbour area. In the south of the city, i.e., in Soledad, and in the northern and western fringes new urban districts developed. The main axes of the cities' development correspond to the major streets connecting Barranquilla with Puerto Colombia, Tubará, Galapa and Baranoa and Malambo. Between Barranquilla and Galapa a large soil sealing took place in the course of the establishment of commercial areas. Growth in the fringes of the towns nearby, i.e., Puerto Colombia, Galapa, and Malambo, is also evident. A new bypass connecting Galapa directly with the south of Malambo is currently under construction to relieve the city traffic; it is expected to act as an additional urbanisation axis in the near future (Figure 3).

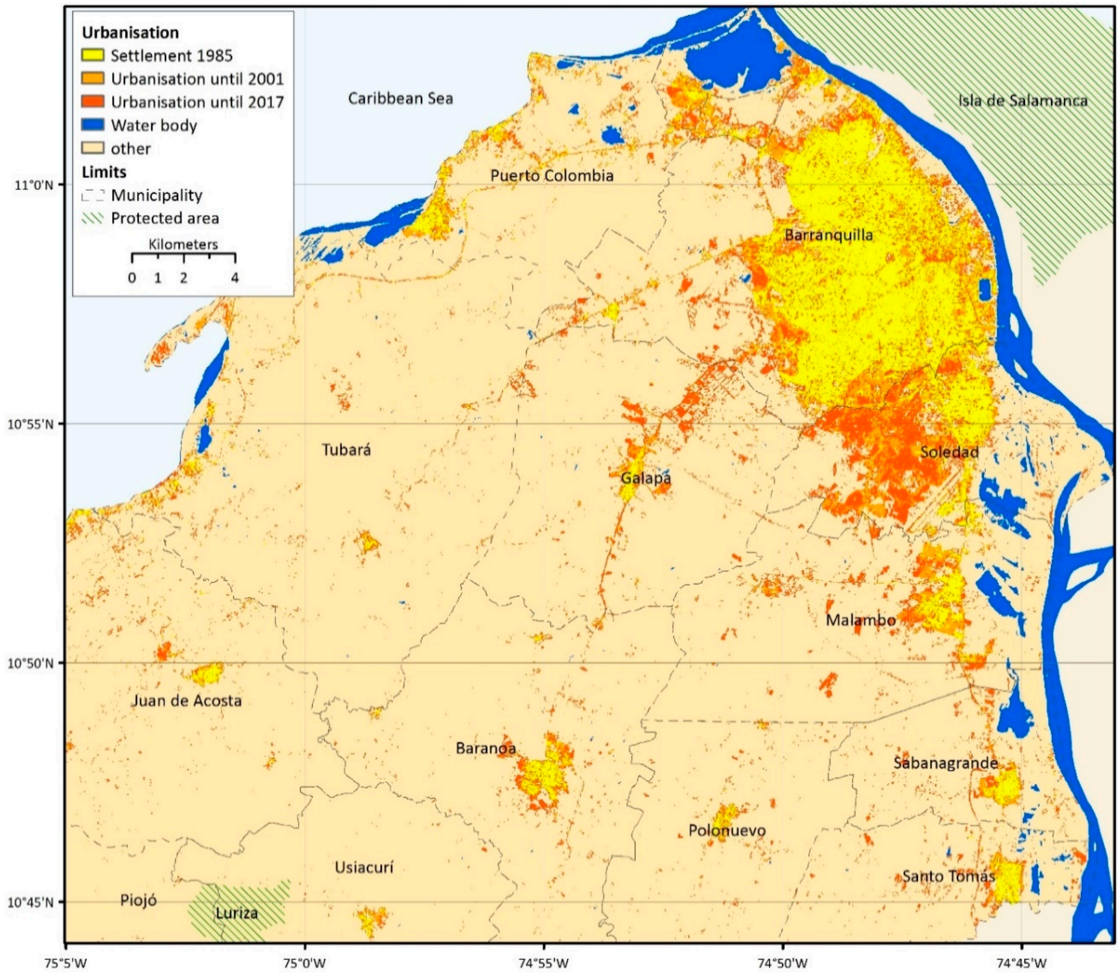

Figure 3. Urbanisation and gain in impervious surfaces in the hinterland of Barranquilla in the years 1985, 2001, and 2017.

Over the entire observation period (1985–2017), the majority of changes were detected among the land use and land cover classes *Cleared* and *Shrubland*. The *Cleared* area decreased continuously during the observation period (Table 5), predominantly in the *hill range* (−49.1 km^2) and in the *alluvial plains* (−48.5 km^2). Changes regarding the classes *Water* and *Wetlands* correspond to inter-annual alterations of the floodplains and the swamps near the lagoons and on a smaller scale of ponds for livestock. We also detected changes of the coastline in the municipality Tubará, where a new headland arose, which now is used for touristic purposes, and the coast shifted in the south of the headland. In the municipality Puerto Colombia and near the lagoon Mallorquin the coastline shifted back. In the landscape unit *floodplain and coastal area* (FC), the *Water* area decreased from 42.1 to 34.6 km^2 due to the shift of the coastline and the Magdalena River, which has shifted to the east, outside of the study area. The unit *Bare Soil*, i.e., essentially sandy beaches and sandbars, remained relatively stable (Figure 2 and Table A1).

4.2. Accuracy Assessment

Overall accuracy of the land use and land cover maps varied between 80.1% (1990) and 84.1% (2017). The highest user's accuracies were determined for the classes *Water* (mean 98.4 ± SD 1.8%), *Wetland* (93.0 ± 3.5%) and *Cleared* (87.6 ± 2.8%). Less well classified are the classes *Forest* (52.6 ± 7.9%), *Shrubland* (77.3 ± 2.5%) and *Bare Soil* (79.3 ± 2.9%) (Table A2).

The differentiation between *Bare Soil* and *Settlement* is partially inaccurate. Especially high-density residential areas with corrugated iron roofs have very similar spectral characteristics to those of beaches and sandbars. Thus, the area sizes of *Bare Soil* in the *metropolitan area* and of the *Settlement* area in the coastal strip are somewhat overestimated (Figure 2 and Table A1). The highest degrees of misclassification were detected between the classes *Forest* and *Shrubland*, which explains the lower values of the user's and producer's accuracies of these two classes (Table A2).

Table 6 sums up the results of analysis of spatial change types. The longest period between 1990 and 2001 has the highest value of overall changes. The values of quantity express the net gain or net loss of one class and include among other the growth of the *Settlement* area and the *vegetation cover gain* after 2001. The high percentage of exchange over all periods indicates that opposite processes of transformation took place at various locations in the study area. In the rural areas, this is attributable to transformations especially between the classes *Cleared*, *Shrubland*, *Forest* and *Bare Soil*. The low percentages retrieved for shift indicate that there are only marginal change pattern of a shift of land cover changes along altitudinal gradient or inverse distance to new roads.

Table 6. Percentages of change types and overall change per time period and the entire study period, respectively.

Time Period	Years	Quantity [%]	Exchange [%]	Shift [%]	Overall [%]
1985–1990	5	3.49	26.77	1.21	31.48
1990–2001	11	1.64	30.39	2.17	34.20
2001–2010	9	5.00	25.39	2.08	32.47
2010–2017	7	7.14	21.10	3.56	31.80
1985–2017	32	8.09	31.34	1.71	41.14

4.3. Vegetation Cover Changes

Relevant forest areas, i.e., mostly secondary tropical dry forests, were detected only in the landscape units *hill range* with an estimated spatial extent of 44.7 km^2 in 2017 and *alluvial plains* with 11.5 km^2 (Table A1). In 2017, the municipalities with the highest percentages of *Forest* were Piojó with an estimated spatial extent of 17.5 km^2 and Tubará with 11.7 km^2. Dense mangroves in the delta area and near the lagoons were partially classified as *Forest*. High and low shrubland accounted for the majority of vegetated areas in all landscape types.

Figure 4 shows vegetation cover changes during the four time periods and the total extent of transition classes in the landscape types of *hill range* and *alluvial plains*. A considerable portion of the area corresponds to the transition classes *woody vegetation loss* and *woody vegetation gain*, which underlines a high dynamic through rotating land uses. The majority of the change class *woody vegetation gain* reflects recovery of woody vegetation in abandoned pastures, fields and barren land. In the *hill* *range* the *stable vegetated* area has values between 200.3 (1990–2001) and 238.5 km^2 (2010–2017). In the last period, the area of *woody vegetation loss* decreased to 47.5 km^2 and the *woody vegetation gain* increased to 102.0 km^2. In the *alluvial plains*, the *stable unvegetated* area continuously decreased from 374.0 (1985–1990) to 342.8 km^2 (2010–2017), while the *other* area, which includes urbanisation areas, increased from 45.1 (1985–1990) to 72.2 km^2 (2010–2017).

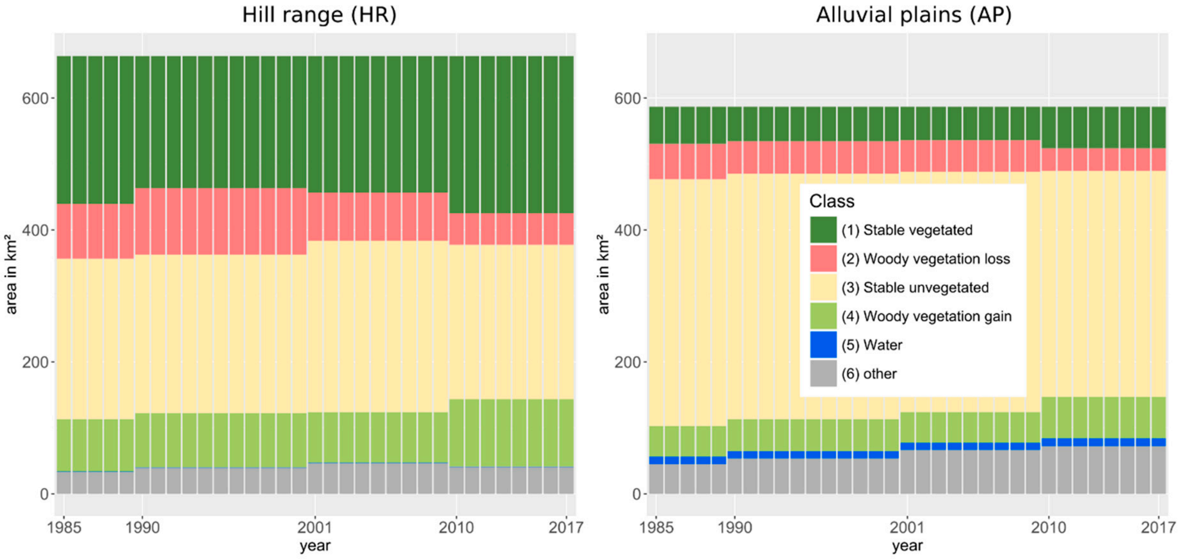

Figure 4. Vegetation cover changes and total extent of the transition classes in the *hill range* (HR) and *alluvial plains* (AP).

In the entire study area, we found a net loss of areas with woody vegetation cover until 2001. From 1985 to 1990, the annual net loss of vegetated areas was detected mainly in the *alluvial plains* and from 1990 to 2001 rather in the *hill range*. However, after 2001 a net gain was observed. Especially after 2010, vegetated areas were increasing rapidly, with an average of 12.48 km^2 per year (Table 7).

Table 7. Annual rate of the net change of woody vegetation cover for the whole study area (Total) and for the four landscape units: *hill range* (HR), *alluvial plains* (AP), *metropolitan area* (ME) and the *floodplain, delta and coastal area* (FC). All values in km^2.

Time Period	Total	HR	AP	ME	FC
1985–1990	−2.74	−0.68	−1.47	0.07	−0.65
1990–2001	−1.98	−1.69	−0.04	−0.33	0.08
2001–2010	0.15	0.47	−0.13	−0.14	−0.06
2010–2017	12.48	7.78	4.08	0.10	0.52
1985–2017	1.70	1.19	0.63	−0.13	0.02

In the first two periods (1985–1990 and 1990–2001), eight municipalities encountered a net loss of areas covered with woody vegetation, while in the other five municipalities, a net gain was detected. Piojó was the municipality with the highest net loss in the first period with 2.15 km^2 and in the second period it was Usiacurí with a net loss of 1.76 km^2. The changes in the municipality Tubará are contrary to the trend. In the first two periods, a net gain of 2.61 and 1.70 km^2 was detected here, while in the third period (2001–2010) we found a net loss of 2.32 km^2. Overall, seven municipalities within the study area encountered a net loss and six experienced a net gain of woody vegetated areas in the third period and in the fourth period (2010–2017) all municipalities saw a net gain of areas covered with woody vegetation.

Generally, the vegetation cover maps indicate a highly dynamic spatio-regional pattern of change (gain and loss) with regard to woody vegetated areas in the region. For 1985–1990, we found hotspots of *woody vegetation loss* in the area between Barranquilla and Puerto Colombia, in between Usiacurí and Baranoa, and in the east of the municipality Piojó. For 1990–2001 hotspots of *woody vegetation loss* were detected in the environs of Galapa, Usiacurí and Puerto Colombia, while for 2001–2010 the hotspots were identified in Tubará, Malambo, and in various areas around Barranquilla (see Supplementary Materials, Figures S1–S4).

Figure 5 depicts vegetation cover changes for the entire study period: Large areas of *woody vegetation loss* were detected for the northwest and west of Barranquilla and in the municipalities Usiacurí and Piojó, where existing remnant tropical dry forest patches and the protected areas Luriza and El Palomar are situated. Large areas of *woody vegetation gain* were identified between Barranquilla and Tubará, in between Galapa and Baranoa, and along the Caribbean coast (Figure 5).

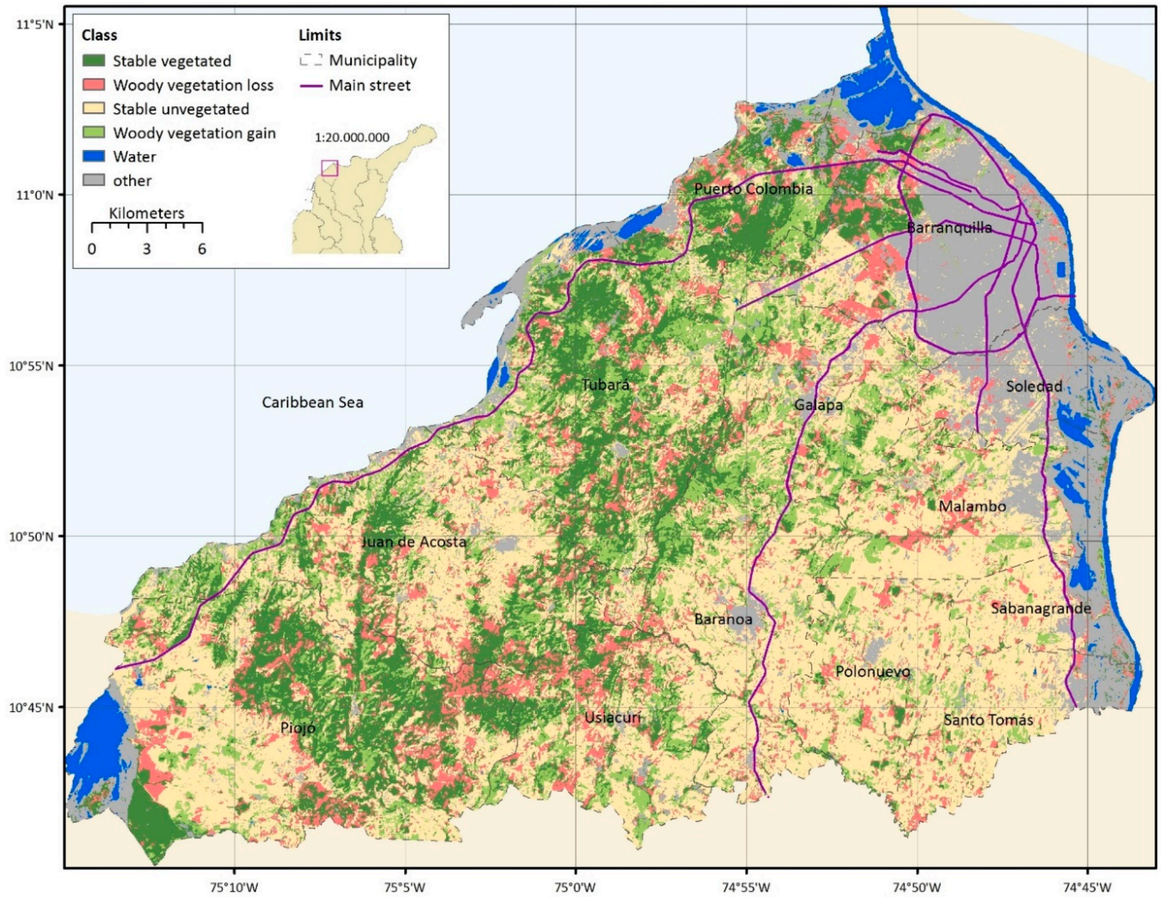

Figure 5. Vegetation cover changes in the hinterland of Barranquilla for the entire study period (1985 to 2017).

4.4. Binomial Logistic Regression

Using binomial logistic regression analyses we identified the influence of each of the 20 included independent variables on the class *stable vegetated* or change (i.e., transition class: *woody vegetation loss*). The analyses unveiled a continuous indirect influence of the variables altitude (mean AUC value across all periods 0.569 ± 0.032), slope (0.628 ± 0.020), temperature seasonality (0.609 ± 0.041), precipitation seasonality (0.556 ± 0.027), soil organic content (0.646 ± 0.021), and distance to roads (0.553 ± 0.027). This means that if the value of the variable is increasing, the probability for *woody vegetation loss* will be decreasing in every period. Here, soil organic content, slope, and temperature seasonality had the highest influence. The analyses indicated a continuous direct effect of the variables annual mean temperature (0.600 ± 0.027), precipitation in the driest quarter (0.580 ± 0.029), soil depth (0.617 ± 0.043), increase of population density (0.571 ± 0.019), and cattle density (0.616 ± 0.044) on *woody vegetation loss*. Annual precipitation amounts, precipitation in the wettest quarter, cation exchange capacity, and distance (to villages, to the metropolitan area, to primary roads, to drainage channels, and to protected areas), had no significant or no consistent influence on the classes *stable vegetated* or *woody vegetation loss*, respectively.

The influence of each of the 20 independent variables on the classes *stable unvegetated* or change (transition class: *woody vegetation gain*) were identified in a second step. Here, a continuous direct behaviour resulted for the variables altitude (0.561 ± 0.024), slope (0.593 ± 0.024), temperature seasonality (0.645 ± 0.045), soil organic content (0.634 ± 0.019), and soil pH value (0.582 ± 0.018). Annual mean temperature (0.595 ± 0.029) and cattle density per municipality (0.619 ± 0.027) had a continuous indirect behaviour. The variables annual precipitation amount (0.584 ± 0.042), precipitation in the driest (0.567 ± 0.034) and in the wettest quarter (0.527 ± 0.011), and soil depth (0.598 ± 0.057) had an indirect influence in four of the five study periods; precipitation seasonality (0.534 ± 0.029) had a direct effect in four of the five study periods. The period from 2001 to 2010 is the exception, with no significant influence for any of the five variables observed. The remaining variables, i.e., cation exchange capacity, increase of population density, and the distances (to villages, to the metropolitan area, to primary roads, to all roads, to drainage channels, and to protected areas) had no significant or no consistent influence on the classes *stable unvegetated* or *woody vegetation gain*, respectively.

With the integration of all 20 variables in the logistic regression models, we can explain the bulk of vegetation cover changes and its spatial patterns. Figure 6 depicts the ROC curves of the logistic regression models with all independent variables for every period with and without including relations between the variables, respectively. AUC values between 0.700 and 0.744 were retrieved with respect to the estimation of areas that were *stable vegetated* or that experienced *vegetation cover loss* (first model version), respectively, predicting between 67.4 and 80.4% of the points correctly. However, the prediction in the case of the *stable vegetated* points (0.854 ± 0.105) was much better than for the points of *woody vegetation loss* (0.380 ± 0.211; Figure 6a). When integrating the relations between the independent variables of the same group (second model version), the AUC values of *woody vegetation loss* increased to 0.757 ± 0.015, and the prediction of corresponding points was enhanced (0.432 ± 0.202; Figure 6c).

For the estimation of *stable unvegetated* point or those that experienced vegetation cover gain (first model version), AUC values range between 0.673 and 0.730 and can predict between 67.4 and 80.2% of the points correctly (Figure 6b). The prediction of *stable unvegetated* points (0.910 ± 0.248) is much better than of the *woody vegetation gain* points (0.248 ± 0.214). When integrating the variables' relations (second model version) the AUC values increased to 0.744 ± 0.022 and the prediction of *woody vegetation gain* was improved (0.312 ± 0.194; Figure 6d). In summary, the calculated models have a good predictive power; however, they are more capable in explaining areas that maintained stable than the areas that experienced vegetation cover changes. Integration of the independent variables' relations increased the model quality and the models' capability to predict areas where changes of the vegetation cover occurred.

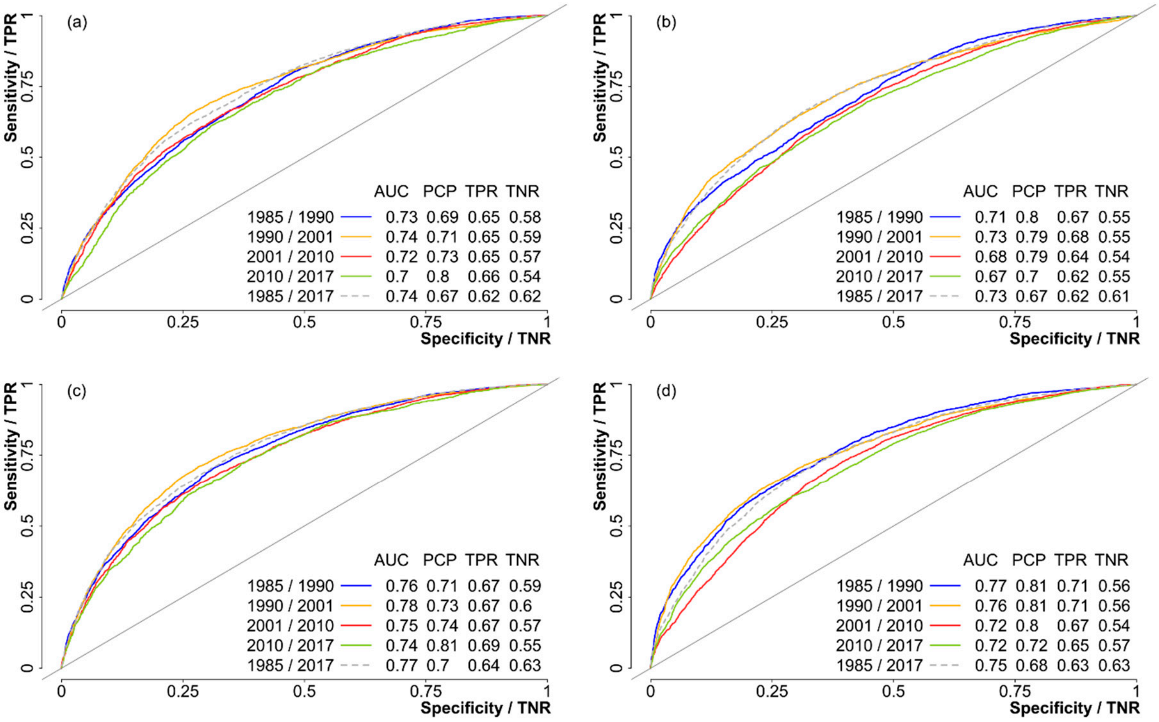

Figure 6. Receiver operating characteristic (ROC) curves corresponding to the binomial logistic regression analyses for (**a**) *stable vegetated* or *woody vegetation loss* and (**b**) *stable unvegetated* or *woody vegetation gain* without incorporation of relations among the independent variables, as well as for (**c**) *stable vegetated* or *woody vegetation loss* and (**d**) *stable unvegetated* or *woody vegetation gain* considering the variables' relations. AUC—area under the curve, PCP—Percentage of Correct Predictions, TPR—True Positive Rates, TNR—True Negative Rates.

5. Discussion

5.1. Land Use and Land Cover Classification

Land use and land cover classification are always a simplification of the reality associated with a strict separation of land use types into classes and the corresponding classification errors [43]. Given that the hinterland of Barranquilla represents a complex mosaic of semi-natural ecosystems (in various conditions), pastures, agricultural fields, and settlement structures, the spatial resolution of Landsat images of 30 m appears to be too coarse with respect to some parts of the study area. A small-scale mosaic of land cover produces mixed pixels, which can increase the classification errors and can affect the detection of pseudo changes [43]. The reduced number of spectral bands of the available satellite imagery makes it difficult to differentiate between ecosystem and vegetation types present in the area [51,67]. Analysis of remote sensing data of urban areas is also very complex due to their heterogeneity and the presence of numerous small-scale structures. These problems may be addressed by using multi-temporal Landsat imagery, aggregation of built-up areas, and heterogeneous training data [68]. Nevertheless, the obtained results are reasonable and mostly agree with the results presented in available scientific publications on national, continental or global level [27,69,70].

The land use and land cover classification results, which represent the basis of all other analyses presented, are characterized by an overall accuracy of 80.1 to 84.1% (see Section 4.2). These misclassifications have to be considered in regard to the results of detected vegetation cover changes and their spatio-temporal patterns. The highest degree of misclassification is found between the classes *Forest* and *Shrubland*, which results in an inaccurate estimation of *Forest* (Table A2). Possible reasons may be the availability of only few training areas of small extent in El Palomar, Luriza and near the villages El Morro and Juaruco (in the municipality Tubará) assuming, due to the age of the trees, that these areas were forested continuously during the past three decades. All forest training areas were situated on steep slopes and along drainage channels. Therefore, terrain characteristics and water availability had a higher impact than desired [51,71]. During the validation we noticed that the classification of 2001 underestimates the extent of *Forests* in the study area, while the other four classifications slightly overestimate it. Due to the inaccurate differentiation of *Forest* and *Shrubland*, we decided to fuse these two classes for the description of vegetation cover changes (see Section 4.3).

However, the trends regarding vegetation cover changes, i.e., in particular the recovery of woody vegetated areas since 2001, agree with the results presented in available scientific publications for larger study areas in the region [14,23]. Aide et al. [14] identified a small reforestation hotspot in the Department Atlántico between 2001 and 2010. Sánchez-Cuero et al. [23] estimated the net change of woody vegetation in Colombia on the municipality level between 2001 and 2010. A net change of 17.3 km^2 was estimated for the 13 municipalities under study; however, absolute values in 2001 and 2010 of woody vegetation were not represented, which allowed only a comparison of tendencies. A net loss of woody vegetation was detected in the municipality of Santo Tomás, stable woody vegetation for Galapa and Polonuevo, and a net gain of woody vegetation for the remaining 10 municipalities [23].

5.2. Causes of Land Use and Cover Changes

The increase of settlement structures in Barranquilla and its immediate environs is related to various processes, such as population and economic growth, development of infrastructure, and urban sprawl. Aldana-Domínguez et al. [21] defined historical periods in the course of Barranquilla's development. The last two periods are referred to as *urban decay* (1958–1989), characterized by a massive rural-urban migration, and *globalisation* (1989-today), characterized by low rates of population growth, economic recovery, high capital expenditure, and segregation between city quarters. According to this classification almost the entire study period is part of the *globalisation* phase. Spatial segregation into a rather rich north and a rather poor south went hand in hand with the construction activities implemented between Barranquilla and Puerto Colombia and with the associated migration. Over the past years the southern areas of Barranquilla and Soledad received the majority of Colombians displaced by the armed conflict and a considerable influx of migrants from Venezuela [21]. The trends in Barranquilla, such as urban sprawl, segregation, re-densification and urban growth along primary streets, are similar to other cities in the Global South, although each city has its individual characteristics [26,28,31,72,73]. A decisive characteristic of Barranquilla represents its location at the mouth of the Magdalena River, and hence the city development is limited to the north and east. Barranquilla is also vulnerable for sea level rise, as is common for cities situated close to river deltas [74].

The results obtained through the analyses of vegetation cover changes permit an array of conclusions: firstly, we found that (semi-)natural woody ecosystems are exposed to a high risk of complete transformation through the implementation of numerous infrastructure and urbanisation projects. The most severely affected areas are by far the fringe area of Barranquilla with the adjacent municipalities and the coastal strip with a short distance to the next road. These are frequently described patterns for the transformation of forest ecosystems [1,8,10,49]. Artificial structures and impervious surfaces considerably reduce provisioning of ecosystem services and the ecosystems' potential of recovery [2]. We also found numerous temporary sand and gravel open-pit mines, which provide the building material for construction in the whole study area. Here, the vegetation cover is cleared completely, and the soil layer is removed, which favours increased erosion [75]. The logistic regression models show that environmental circumstances, proximity characters, and social factors explain large parts of the spatial patterns of the vegetation cover changes (see Section 4.4). However, the focus is set on natural location characteristics, i.e., not including important socio-economic factors such as land ownership, land size, and income (see Table 4), because these data are not available in the corresponding spatio-temporal resolution. The models explain areas that maintained stable better than the areas that experienced vegetation cover changes. This is due to an inherent problem that the random points are based on the map of vegetation cover changes from 1985 to 2017, and therefore in the other periods, there are more stable points than change points (*woody vegetation gain* and *woody vegetation loss*), which influences the prediction of the change points negatively [61].

On the other hand, we found a net gain of woody vegetation starting in 2001, which became even more distinct from 2010 on. In contrast to other regions of the world where an increase in forest areas has been detected in recent years [5,76], reforestation programs are only implemented to a minor extent in the study area. Most of the detected gain of woody vegetation can be attributed to natural recovery and secondary succession in areas that have been abandoned or that are used less intensively today. Overall, it appears that the pressure on rural and woody vegetated areas decreased considerably in the past decade, which is in line with what other scientists working on Colombia published recently [23,77,78], and with the global and continental trend of rural-urban migration [12–14]. A conclusion about biological diversity, ecosystem conditions and provided ecosystem services in areas where *woody vegetation gain* was detected cannot be made on the basis of the available data. However, field observations indicate that natural recovery of almost or completely cleared tropical dry forest areas most likely requires several decades. Without implementation of certain ecosystem restoration measures, the first stadia of secondary succession appear to be very lengthy and clearly dominated by representatives of the legume family whose species are fast-growing and capable of biological nitrogen fixation (through symbiosis with diazotrophs). In abandoned areas formerly used as pasture land we found *Gliricidia sepium* (Jacq.) Kunth ex Walp. (by the residents referred to as *mata ratón*) to be extraordinary dominant. No wonder, since it is one of the most utilized species in the production of fence posts, most of which develop into trees again since the species is propagated easily [79,80].

The net gain of woody vegetation since 2001 is probably due to the interaction of various factors, such as changes in settlement structures, occupational changes of the rural population, diminution of areas used for crops and cattle breeding, implementing of spatial planning, and reduction of timber extraction for the charcoal production. Other scientists have specified the influence of similar networks of several economic, social and political factors and drivers [14,49,77,78].

Due to the rural-urban migration, the population growth in peripheral municipalities is lower than near Barranquilla. Piojó experienced even a population decrease between 1985 and 2017 (Table 8) [24]. In addition, there is a trend towards a concentration of the rural population in central villages and small towns, which is associated with the abandonment of individual farms (*fincas*). In recent years, the economic activities of the rural population changed considerably from an occupation in the agricultural sector to an employment in the construction and service sector [13,78]. The municipal councils report the total extent of agricultural areas (per crop) to the departmental planning agency. The absolute numbers are to be considered with caution, due to possibly inexact surveys, the inclusion of two growing periods, mixed cultivation and a notable variation between the years. However, apparently there is a trend towards the decrease of agricultural land, i.e., from 133.4 km^2 (mean value of the period 1990–1999) to 107.4 km^2 (2000–2009) and 119.3 km^2 (2010–2017) [39]. In particular, the municipalities Juan de Acosta (−340%) and Piojó (−286%) experienced a strong decrease in the total extent of agricultural land, while in the same period of time the total extent nearly doubled in the municipalities Tubará, Malambo and Santo Tomás [38]. In some parts of the study region cattle breeding is an important source of income and the municipal cattle density clearly favours vegetation cover changes (see Section 4.4). Overall, the number of cattle slightly increased during the past three decades; however, individual trends in the municipalities differ considerably (Table 8) [66].

Looking at the effects of political regulation on the increase of woody vegetation area from 2001 to 2017, we distinguish two types of environmental policy instruments. Firstly, new policy instruments evolved together with new state entities from the "green" Colombian constitution of 1991, which is based on international environmental protection policies: river basin planning and management (*Planes de Ordenamiento y Manejo de Cuenca*, POMCAs) and municipal spatial planning (*Planes de Ordenamiento Territorial*, POTs). Secondly, in the past decades, former policy instruments regarding protected areas and forest use were newly implemented in the Department Atlántico.

Table 8. Population density (PD) and mean cattle density (CD) per km^2 in the study area for 1985 to 2017 and 1990 to 2017, respectively [24,66].

Municipality	Area [km^2]	PD 1985	PD 2017	Change [%]	CD 1990–00	CD 2001–09	CD 2010–17
Baranoa	120.2	301.0	490.8	63.1	74.9	91.7	107.3
Barranquilla	159.7	5804.5	7691.1	32.5	14.3	16.0	9.7
Galapa	97.3	148.4	463.4	212.3	63.1	65.6	51.0
J. de Acosta	171.2	63.3	100.8	59.2	49.5	61.8	52.2
Malambo	98.9	544.9	1266.4	132.4	56.1	67.8	56.5
Piojó	252.1	22.9	20.5	-10.5	30.7	37.3	39.0
Polonuevo	74.6	138.4	208.3	50.5	84.4	93.0	86.8
P. Colombia	73.1	316.8	367.6	16.0	10.1	7.8	2.6
Sabanagrande	42.6	335.9	774.8	130.7	63.4	125.6	110.8
Santo Tomás	65.2	283.0	392.1	38.6	76.6	99.2	89.7
Soledad	61.9	2871.4	10486.4	265.2	20.5	39.0	54.1
Tubará	184.1	46.9	59.9	27.7	25.1	31.4	33.2
Usiacurí	99.8	62.8	95.1	51.4	56.6	56.6	63.0
Study area	**1500.7**	**870.9**	**1499.7**	**72.2**	**43.6**	**53.2**	**51.1**

The river basin planning and management, which is the superior planning instrument, is still in progress in the northern part of the Department Atlántico: the POMCA *Ciénaga de Mallorquín* and the POMCA *Canal del Dique* were approved in 2007 and 2008, respectively [81,82]; the two other POMCAs (*Río Magdalena* and *Mar Caribe*) are in the process of declaration [83]. Based on 15 possible protected areas selected in 2008 [84], three protected areas were declared in 2011 and 2013 (El Palomar, Luriza and Los Rosales, the latter in the south of the study area). Because of the delayed implementation of these policy instruments in the Department Atlántico in comparison to other parts of Colombia, they clearly cannot have had a supporting effect on the overall increase of vegetation cover since 2001.

However, there is a timely coincidence with the approval of the first spatial planning policies in the municipalities of Atlántico in 2000 and with the reform of the forest use regulations in 1996. The municipal spatial planning policies were approved before the river basin planning and the establishment of protected areas and therefore lack the environmental protection determinants, which should be fixed by the river basin planning and the protected areas. This incoherent development of the different levels of the environmental protection system in Atlántico was partly compensated with the obligatory approval of the environmental aspects of the municipal spatial planning by the environmental authority of Atlántico (*Corporación Autónoma Regional del Atlántico*, CRA). The main goal of the municipal spatial planning in the study area is the protection and recovery of water resources. Further goals include the protection against flooding and erosion. The protection and recovery of forests and other vegetated areas was only included in most municipal spatial planning in connection with the before mentioned goals. Several municipalities included forest protection as a separate instrument of spatial planning but with a low priority only [85–95]. Therefore, the impact of the spatial planning on vegetation cover can be only locally. Two aspects shed doubt on the effects of the spatial planning on land use in general: (I) the spatial planning was elaborated by the municipalities to fulfil a requirement of national law, but without the adequate expertise such as the use of georeferenced data; (II) the spatial planning lacks effective control capacities [96]. Lack of (environmental) policing is a common and well-known problem in Colombia and in Latin America in general. Reasons for it include rather economically oriented political agendas, corruption, lack of knowledge of environmental policies by the local population, insufficient human resources and inadequate training, equipment, and mobility of law enforcement agencies [97]. The use of timber for charcoal production was already regulated several decades ago, adopting an obligatory permission for forest use [98]. However, policing was mostly absent, and therefore this regulation was updated and specified in 1996 [99], but maintained the basic idea of the obligatory permission [100]. Documents of sanctions, newspaper articles, and interviews with local leaders indicate that the policing increased in the Department Atlántico since 1996 and only then the charcoal production dropped notably. Some farmers still practice it with commercial purpose, which is evident from the charcoal interceptions by the police [101–105]. The decrease in timber extraction mainly for the production of charcoal not only has political reasons but also social ones: in the past, charcoal was mainly used for cooking in Barranquilla and in the countryside, but today more and more households are using gas for cooking. This change is also evident in other Latin American countries [21,77].

6. Conclusions

Within the past three decades, vegetation cover changes in the hinterland of Barranquilla were highly dynamic as a result of clearing, rotating cultivation, and cattle breeding on the one hand, and from abandoning of formerly used land, extensification, and natural recovery of vegetated areas on the other hand. We found an overall increase in woody vegetation after 2001, which may be explained by less pressure on vegetated areas through a decline of timber extraction, agriculture, cattle breeding, and by changes of the inhabitants' occupations and of the settlement structures in rural areas. However, further research is urgently required in order to assess the condition, composition, and ecological structure of areas with stable woody vegetation and areas that are in the process of natural recovery. The probability that woody vegetation areas are conserved increases with increasing slope steepness, elevation, and distance to the next road, as well as with decreasing municipal cattle density and population growth. The transformation probability of woody vegetation increases with increasing annual mean temperature, precipitation in the driest quarter, soil depth, as well as with decreasing precipitation and temperature seasonality; these areas are suitable for agriculture activities and cattle breeding. We observed an opposite pattern for *stable unvegetated* and *woody vegetation gain*: the probability that cleared areas remain unchanged increases with increasing precipitation (total, in the driest, and in the wettest quarter), annual mean temperature, and soil depth, as well as with decreasing temperature seasonality. The probability of natural recovery is relatively high, if cleared areas are located on steep elevated slopes, in municipalities with relatively low cattle density, and if the soil is relatively alkaline with a high organic content.

Relevant environmental policy instruments to prevent further fragmentation and transformation of (semi-)natural environments are in place already, but require improvement, particularly in regard to a more sustainable use and management of forested areas and corresponding resources. Corruption and lack in policing need to be tackled. Extension of punctual proactive control activities carried out by the environmental authorities and the police is highly recommended. Offering training courses in environmental education and protection to stakeholders (i.e., local population, economic actors, state officials, police officers, attorneys, and judges) may help to increase their esteem towards the natural environment and its protection in comparison to the relevance of economic activities.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-445X/7/4/152/s1, Figures S1–S4: Maps of vegetation cover changes for the periods 1985–1990, 1990–2001, 2001–2010, and 2010–2017.

Author Contributions: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Resources, Data Curation, H.S., Writing—Original Draft Preparation, H.S. & M.R.; Writing—Review & Editing, A.C.C., M.R., O.R.-Z., G.B. & B.S.; Visualization, H.S.; Supervision, A.C.C. & B.S.; Project Administration, G.B. & B.S.; Funding Acquisition, G.B. & B.S.

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Appendix A

Table A1. Area size calculation of the four landscape units separated per LULC class for 1985, 1990, 2001, 2010, and 2017.

LULC Class	1985		1990		2001		2010		2017	
	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%
Hill range			**663.7**							
Settlement	10.7	1.62	13.8	2.08	15.3	2.31	19.0	2.86	14.4	2.17
Cleared	333.1	50.19	327.9	49.41	346.6	52.23	330.6	49.82	284.0	42.79
Forest	47.0	7.09	62.0	9.34	51.4	7.75	13.8	2.07	44.7	6.73
Shrubland	265.7	40.04	243.3	36.66	236.3	35.60	274.2	41.32	305.5	46.03
Bare Soil	2.8	0.42	2.6	0.39	4.0	0.60	9.0	1.36	8.6	1.29
Wetland	2.9	0.44	12.4	1.86	8.9	1.34	15.6	2.35	4.4	0.66
Water	1.4	0.21	1.7	0.25	1.1	0.17	1.4	0.22	2.1	0.32
Alluvial plains			**586.8**							
Settlement	13.9	2.36	19.6	3.35	21.7	3.71	30.5	5.19	33.7	5.74
Cleared	433.0	73.79	431.1	73.47	431.2	73.47	411.9	70.19	384.5	65.53
Forest	11.0	1.88	6.8	1.16	12.7	2.17	5.3	0.90	11.5	1.96
Shrubland	104.4	17.80	96.8	16.49	94.4	16.09	94.3	16.07	122.4	20.86
Bare Soil	2.8	0.49	1.4	0.23	2.6	0.45	7.8	1.32	9.2	1.56
Wetland	8.2	1.39	18.7	3.18	12.6	2.14	23.5	4.01	10.7	1.83
Water	13.5	2.29	12.4	2.12	11.6	1.97	13.5	2.30	14.9	2.53
Metropolitan area			**120.5**							
Settlement	69.2	57.47	73.1	60.72	77.5	64.30	82.8	68.72	93.7	77.78
Cleared	25.2	20.94	24.6	20.45	12.3	10.19	9.8	8.13	7.8	6.50
Forest	0.0	0.02	0.1	0.06	0.0	0.00	0.0	0.03	0.0	0.04
Shrubland	10.3	8.52	9.0	7.49	4.8	3.96	4.9	4.06	5.8	4.81
Bare Soil	14.1	11.75	9.5	7.92	20.4	16.93	21.2	17.57	11.9	9.86
Wetland	0.9	0.74	3.9	3.20	5.4	4.48	1.7	1.39	1.0	0.83
Water	0.7	0.56	0.2	0.16	0.2	0.14	0.1	0.09	0.2	0.18
Floodplain and coastal area			**130.0**							
Settlement	69.2	57.47	73.1	60.72	77.5	64.30	82.8	68.72	93.7	77.78
Cleared	25.2	20.94	24.6	20.45	12.3	10.19	9.8	8.13	7.8	6.50
Forest	0.0	0.02	0.1	0.06	0.0	0.00	0.0	0.03	0.0	0.04
Shrubland	10.3	8.52	9.0	7.49	4.8	3.96	4.9	4.06	5.8	4.81
Bare Soil	14.1	11.75	9.5	7.92	20.4	16.93	21.2	17.57	11.9	9.86
Wetland	0.9	0.74	3.9	3.20	5.4	4.48	1.7	1.39	1.0	0.83
Water	0.7	0.56	0.2	0.16	0.2	0.14	0.1	0.09	0.2	0.18

Table A2. User's accuracy (UA, %), producer's accuracy (PA, %), overall accuracy (%) and Kappa coefficient (%) for LULC classifications.

Class	Settlement		Cleared		Forest		Shrubland		Bare Soil		Wetland		Water		Overall	Kappa
	UA	PA	UA	PA	UA	PA	UA	PA	UA	PA	UA	PA	UA	PA		
1985	80.2	83.3	90.6	91.7	52.5	66.0	76.4	78.5	78.4	80.0	95.5	70.3	80.2	83.3	83.1	79.6
1990	77.8	81.8	86.7	87.3	45.9	56.0	74.1	75.4	78.0	76.2	90.2	70.5	77.8	81.8	80.1	76.0
2001	81.9	81.9	84.1	92.3	55.4	66.0	79.2	74.2	78.3	90.4	97.6	76.2	81.9	81.9	83.7	80.5
2010	78.7	80.4	85.5	95.9	65.9	54.0	75.9	84.0	76.7	85.2	88.0	61.7	78.7	80.4	82.7	79.3
2017	87.9	90.4	91.1	86.2	43.4	81.8	81.0	66.2	85.0	90.7	93.5	81.1	87.9	90.4	84.1	81.4

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