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Article

Dynamics of Land Cover/Land Use Changes in the Mekong Delta, 1973–2011: A Remote Sensing Analysis of the Tran Van Thoi District, Ca Mau Province, Vietnam

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Abstract: The main objective of this study is to assess the spatio-temporal dynamics of land cover/land use changes in the lower Mekong Delta over the last 40 years with the coastal Tran Van Thoi District of Ca Mau Province, Vietnam as a case study. Land cover/land use change dynamics are derived from moderate to high spatial resolution (Landsat and SPOT) satellite imagery in six time intervals ranging from 1973 to 2011. Multi-temporal satellite images were collected, georeferenced, classified using per-pixel method, validated, and compared in post classification for the land use/land cover change detection in decades. Seven major land cover/land use classes were obtained, including cultivated lands, aquaculture ponds, mangrove forest, melaleuca forest, built up areas, bare lands, and natural water bodies. The accuracies of the land cover/land use maps for 1973, 1979, 1989, 1995, 2004, and 2011 were 81%, 82%, 86%, 87%, 89%, and 89%, respectively. The results show that the area of cultivated lands reduced over the period 1973–2011, however, it still represents the dominant land use in the case study. Aquaculture ponds were almost absent in 1973 but greatly increased from 1995 to 2004, to represent 20% of the land surface in 2011. Overall, from 1973 to 2011, bare lands, cultivated lands, mangrove forest, and melaleuca forest decreased by 104 km^2, 77 km^2, 61 km^2, and 5 km^2, respectively. In contrast, aquaculture lands and built up areas increased by 123 km^2 and 120 km^2, respectively. Temporal analysis highlights that these changes took place mostly between 1995 and 2004. This study is a first step to identify the main drivers of land use changes in this delta region, which include economical policies as well as demographic, socio-economic, and environmental changes.

Keywords: remote sensing; land cover/land use change; SPOT; Landsat; cultivated lands; aquaculture; mangrove; melaleuca; Tran Van Thoi; Ca Mau

1. Introduction

Land cover/land use conversions are due to human activities, socio-economic, biophysical and environmental factors [1]. They may have considerable impacts on worldwide biotic diversity, global and local climate, biogeochemical cycles, soil degradation, hydrology, food security, soil quality and human well-being [2–10] as well as affect the capacity of biological systems to support human demands [11]. However, land cover/land use changes do not have solely negative effects, as some changes are related to the positive increase of food and fiber yields for peoples' health and wealth [12]. Therefore, it is necessary to document land cover and land use changes, and to understand their drivers and consequences, especially in the context of global environmental changes, rapid population growth and rising demands for environmental sustainability.

Land cover/land use in the Mekong Delta changed drastically in the last 40 years due to a variety of biophysical and societal factors. A number of studies have attempted to detect and describe the land cover/land use changes in several different districts of Ca Mau Province—the southern-most part of the delta in Vietnam (Figure 1) [13–15] or in the Mekong Delta [16–20]. These studies, however, analyzed changes over a short time periods or at low spatial or temporal resolution. These studies concluded that mangrove forest decreased significantly since the 1970s due to the war period and human impacts, and changed to aquaculture and agricultural land. No study addressed these issues in details in the Tran Van Thoi District, the western coastal region of Ca Mau, nor the spatio-temporal dynamics of these changes using a multi-temporal time series at high spatial resolution.

Tran Van Thoi District is an important case study because it is characterized by a mixture of diverse land cover/land use types, including mangrove forest referred to as "the physical barrier against tides and ocean" [21], melaleuca forest [22], rice fields, aquaculture ponds, and a high density of settlements along the river and canal network. The area has been the subject of rapid and large-scale changes in land cover/land use types since the end of the second Vietnam War.

A significant body of research regarding land cover/land use change in coastal zones, estuarine areas and river deltas using remote sensing data already exists [17–20,23–41]. In many studies of coastal regions and river deltas, the area of forest sharply decreased over time because of urban development and human activities [18,19,25,29] while urban surfaces, shrublands, shrimp farms and water bodies (natural and man-made) increased at high rate [18,20,23,24,26,30–41]. In some regions, agricultural lands significantly decreased [27,28,38,41], however, in some others, it expanded [17,23]. The study of Sakamoto *et al.* [17] (12 provinces of the Vietnamese Mekong Delta) focused only on agriculture land with single, double and triple crops: they concluded that the available area for triple-cropped rice expanded during two years (from 2002 to 2003).

The main aim of this study is to document the spatio-temporal dynamics of land cover/land use change in Tran Van Thoi District of Ca Mau, Vietnam over the last 40 years. More specifically, the study was designed to address the following objectives (i) identify and map the major land cover/land use categories in Tran Van Thoi District in six time intervals, including 1973, 1979, 1989, 1995, 2004, and 2011; (ii) compile the spatial and temporal distribution of the land cover/land use changes, and detect the magnitude and nature of these changes that occurred over these five time intervals. These outputs will create the basis for understanding the land cover/land use evolution of the region. This documentation will contribute to the long-term understanding of the causes and effects of land cover/land use change, and it will furthermore provide a more solid background for the design of economic, social and environmental policies to ensure the sustainable development of this rural district both at province and district scale.

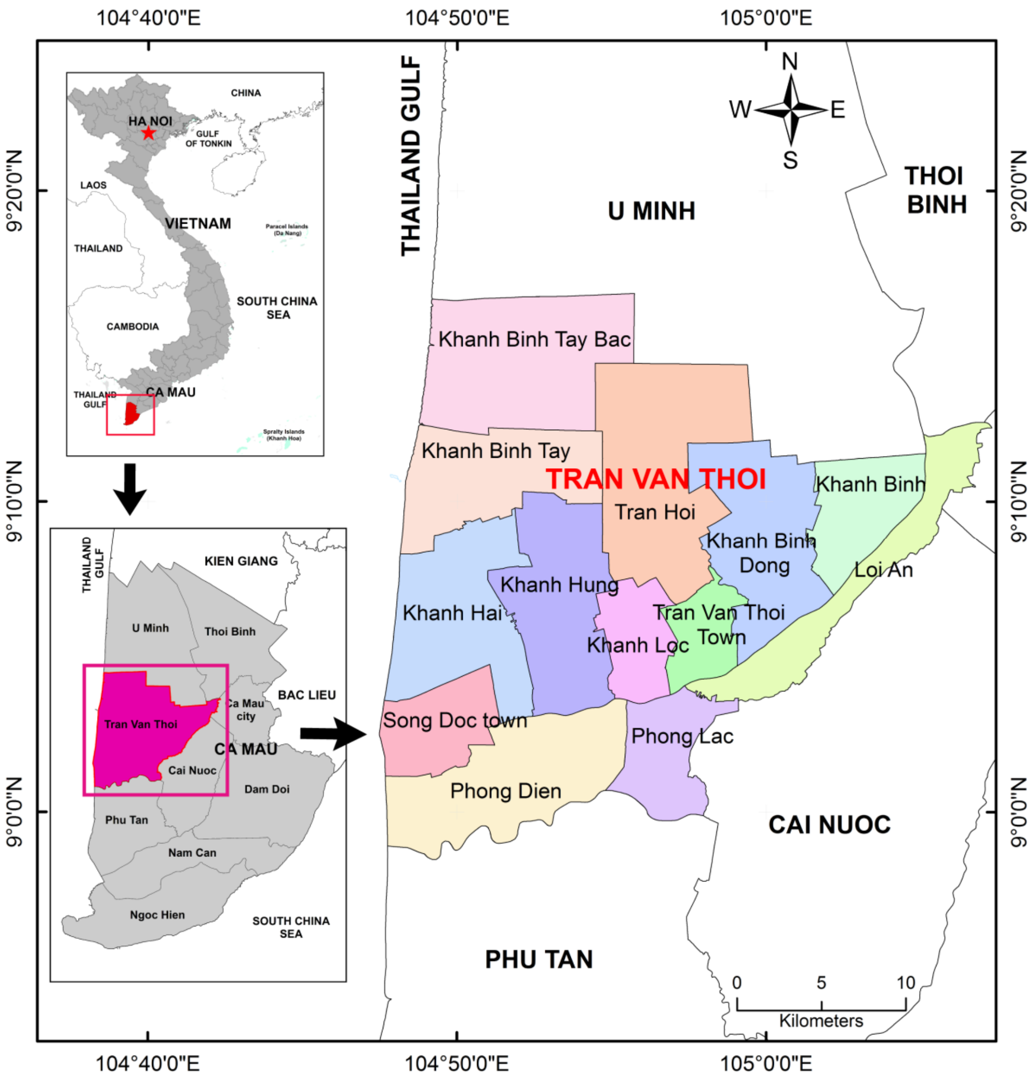

Figure 1. Location of the Tran Van Thoi District, in the Ca Mau Province, the southernmost one of Vietnam. The district is administratively subdivided in 13 municipalities.

2. Study Area

Tran Van Thoi is a coastal and rural district of the Ca Mau Province, which is the southernmost portion of the Mekong Delta in Vietnam. Tran Van Thoi District borders the Gulf of Thailand and is neighboring Ca Mau City, the capital of the province (Figure 1). This district is traversed by a dense network of rivers and canals and hosts a mixture of diverse land covers/land uses. Tran Van Thoi District is considered as “a small Ca Mau Province” with all the province’s land cover and land use types. Statistical yearbook in 2011 of Ca Mau Statistic Office [42] showed that Tran Van Thoi District has a total area of 700.23 km^2 and a population of 187,916 people; the calculated population density is 268 persons/km^2. There are two seasons: a rainy season and a dry season with an average annual temperature of 27.5 °C and an average annual rainfall of 2442 mm. Tran Van Thoi’s economic activities are mainly based on agriculture (production of 259,000 tons/year of rice and 11.000 tons of livestock); forestry (10.100 m^3 of exploited wood) and fishing (72,000 tons of catching and 21,000 tons of aquaculture). In Tran Van Thoi District, there are two main rice crop seasons per year in areas where the irrigation facilities are available, namely winter–spring (from November to March) and summer–autumn (from May to October) crops [43–45].

The Mekong Delta region of Vietnam is known as the “rice bowl”, as it produces more than 90% of Vietnam’s export rice yields, and is also responsible for the largest share of agricultural production in general [45–47]. It provides rich natural resources for thousands of local households, including rice, aquaculture and forest wood. Ca Mau Province is a flat, low-lying region that is easily flooded due to both its low altitude from −1 to 3 m above sea level, and the high tidal fluctuations of the East Sea and the Gulf of Thailand [48]. A study performed during a period of 20 years, from 1989 to 2010, shows that it is one of the regions of Vietnam that have the highest number of houses damaged due to natural disasters [49].

3. Materials and Methods

3.1. Datasets

Remote sensing and Geographic Information Systems (GIS) are useful and cost-effective technologies for investigating environmental changes caused by human activities or natural phenomena in general, and for land use/land cover change analysis in particular [2,50,51]. The advantages of remote sensing include the ability to cover large areas with high spatial detail and high temporal frequency, the robustness of satellite image classification, improvements on the spatial and spectral characteristics, and the acquisition of valuable multi-temporal datasets comprising different kinds of optical data, while GIS is powerful in mapping and analyzing the emerging patterns [12,52–58]. The ENVI 5.0 and ARCGIS 10.0 (ESRI) software packages were used for image processing and for spatial analysis in this study.

The data used for this study include satellite images, ancillary data such as topographic maps, land use maps, Google Earth© images and data collected from fieldwork (Table 1). The Landsat images were selected from the existing archives based on their limited cloud coverage, spatial and temporal extent. Landsat data are particularly effective for tracking historic changes before the 1990s [59]. The SPOT images provided a higher spatial resolution for 1995 (20 m), 2004 (20 m) and 2011 (10 m). Digital GIS layers derived from topographic maps provided information on administrative boundaries, road, topography, water bodies, vegetation, and residential infrastructure. The Vietnamese Ministry of Natural

Resources and Environment (MONRE) compiled land use maps for 2005 and 2010. For 2005, the map is based on the combination of administrative boundary maps and cadastral maps to verify the community, district and provincial boundaries. The data from the cadastral maps were compared to fieldwork results to determine the correct land type for each parcel of land in order to compile the land use map. The 2010 land use map was created by integrating information from nine land use maps (corresponding to 9 districts of Ca Mau Province) at district scale (data referring to 2010), from the land inventory of the year 2010 and from digital administrative boundary maps, to the base map of Vietnamese Ministry of Natural Resources and Environment. Various thematic maps, such as administrative boundary map, and the distribution maps of paddy rice, forest, and aquaculture, were collected from Vietnam Ministry of Natural Resources and Environment, and Ca Mau Department of Agriculture and Rural Development.

Table 1. Data characteristics.

Type	Data (Scale)	Date of Acquisition	Spatial Scale; Numbers of Bands; Spectral Bands	Source
Remote sensing satellite images	Landsat 1 MSS (District)	3 January 1973	60 × 60 m; 4; Green-Red-NIR-MIR	United States Geological Survey (USGS) (http://earthexplorer.usgs.gov)
	Landsat 1 MSS (Province)	14 March 1975	60 × 60 m; 4; Green-Red-NIR-MIR	
	Landsat 3 MSS (District)	6 February 1979	60 × 60 m; 4; Green-Red-NIR-MIR	
	Landsat 4 TM (District)	31 January 1989	30 × 30 m; 6; Blue-Green-Red-NIR-SWIR-SWIR	
	SPOT3 XS (District)	8 January 1995	20 × 20 m; 3; Green-Red-NIR	National Remote Sensing Department (http://rsc.gov.vn)
	SPOT5 HI (District)	19 March 2004	10 × 10 m; 4; Green-Red-NIR-SWIR	
	SPOT5 HI (Province, District)	3 January 2011	10 × 10 m; 4; Green-Red-NIR-SWIR	
Ancillary data	Topographic maps	1965, 1969 (3rd edition)	1:50,000	Department of Defense (published by the US) (http://monre.gov.vn)
		1988, 2006	1:50,000	Department of Defense (http:// monre.gov.vn)
		2010	1:5,000	
		2002	1:50,000	Ministry of Natural Resources and Environment (http://monre.gov.vn)
	Land use maps	2005 2010	1:25,000 1:25,000	Ministry of Natural Resources and Environment (http://monre.gov.vn)
	Google Earth Imagery	-	-	Google Inc.
	Statistic data	-	-	Ca Mau Statistic Office (http://cucthongke.camau.gov.vn/)
	Field data	December 2012	Sampling unit: 10 × 10 m	Field trip (93 field observations)

3.2. Pre-Processing

All Landsat images used in this study came from the freely available USGS archive. Their L1T correction level included a radiometric correction, a systematic geometric correction and a precision correction [55,60]. Topographic radiometric correction was omitted due to the low relief variation in Ca Mau Province [61]. The atmospheric correction was conducted for all images using calibration tool and FLAASH [62]. The satellite images (Landsat, SPOT) in this case study were geometrically corrected to the Universal Transverse Mercator grid (UTM), zone 48, WGS84 ellipsoid and datum, using nearest neighbor resampling method. Image to map (a topographic map) registration technique was used. Forty-eight and sixty-nine GCPs were used for geometric correction of the image mosaic at province scale in 1975 (3 Landsat scenes) and 2011 (6 SPOT scenes), respectively. A single scene was used for each period at the district scale and each was georeferenced using 11 to 13 GCPs. All the images were geo-registered to the map with a root mean square (RMS) error of less than 0.5 pixels. Figure 2 summarizes the different steps of the methods in a flowchart.

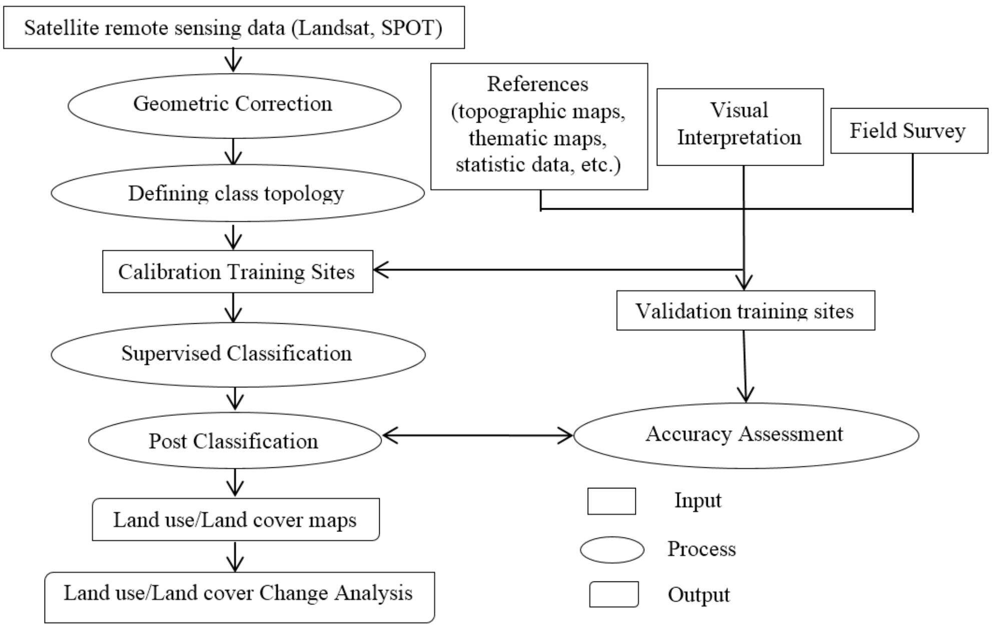

Figure 2. Flowchart of the processing of satellite data in this study.

3.3. Field Survey

Field survey was conducted in December 2012 using a Trimble Juno ST handheld GPS receiver and mobile GIS. Random sampling was used to select the sampling units, which were generated at a scale of 10 m, to coincide with the SPOT5 imagery. A total of 93 field sites covering all the land cover categories in the Tran Van Thoi District (Figure 3) were checked in order to determine the land cover/land use types at the exact coordinates. Interviews with local managers and local people of different ages were carried out in order to obtain key information about the temporal evolution and the socio-economic background at each location. Pictures of the specific land cover classes documented in the field, including cultivated lands (paddy rice), mangrove forest, melaleuca forest, aquaculture ponds (shrimp ponds) and built up areas (local houses), are shown in Figure 4. These field observations (93 field sites) were used as training sites for the classification of the 2011 image and were complemented in place with training sites collected from visual interpretation of very high spatial resolution images on Google Earth combined with reference data and ancillary information (128 training sites). Each training site was delineated on the images using polygons covering multiple pixels. For 2011, the 221 (93 + 128) training sites resulted in the identification of about 12,000 pixels. A random selection of 50% of these pixels for each class was used to calibrate the classification, the other half being used for independent accuracy assessment.

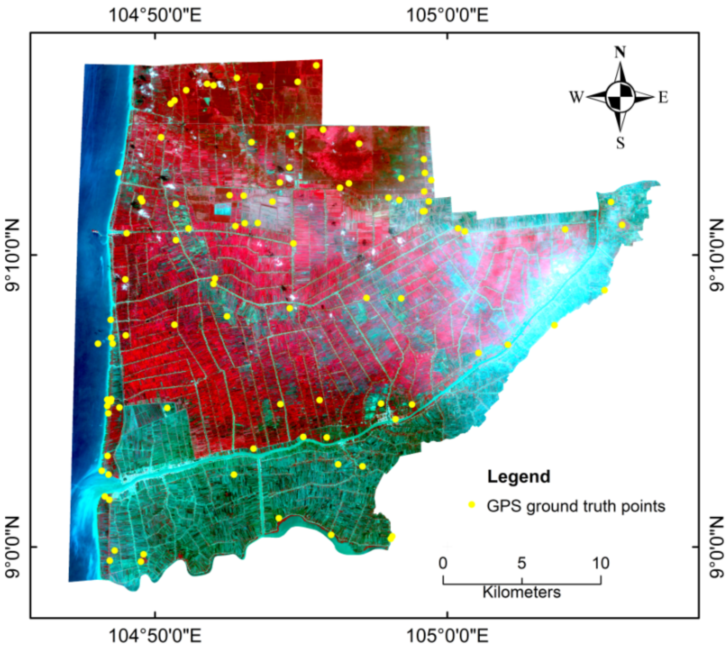

Figure 3. Location of ground control points visited in the field. Background image is the SPOT5 image acquired 3 January 2011.

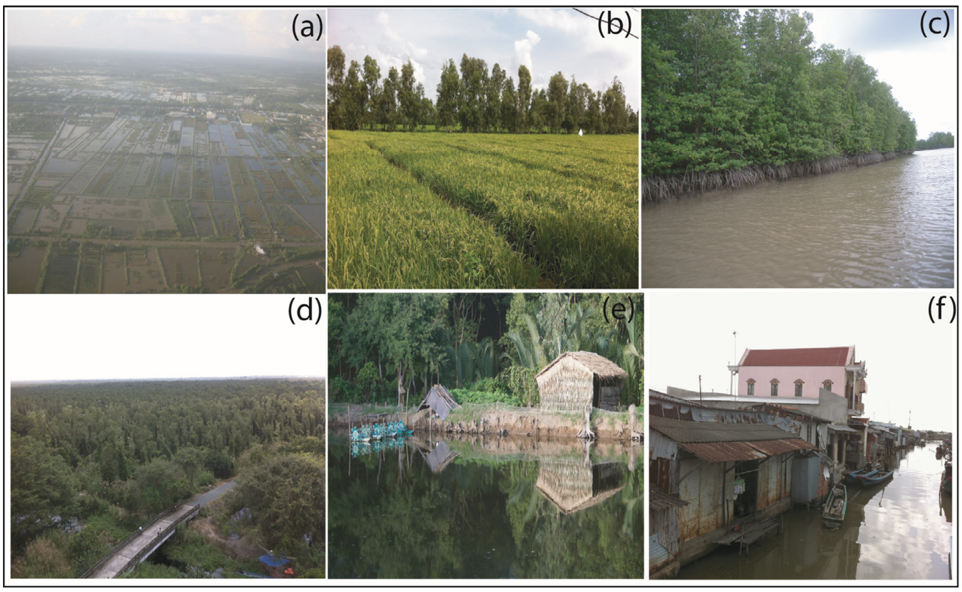

Figure 4. Pictures from the field in the Tran Van Thoi District (**a**) Lowland Ca Mau from airplane; (**b**) Paddy rice; (**c**) Mangrove forest; (**d**) Melaleuca forest; (**e**) Aquaculture pond; and (**f**) Specific houses in the study area.

3.4. Classification

All the satellite images (Landsat, SPOT) were used for land cover/land use classification. Topographic maps, land use maps, Google Earth imagery, and field data were used for training sites. For older time periods, existing land use and topographic maps were used to select unambiguous training sites. Experience gained through visual interpretation of recent images helped to select the most representative training sites for these older dates. In particular, for each satellite dataset (for the years 1973; 1979; 1989; 1995; 2004; 2011) different documents were used as references for calibrating the classification: topographic maps from 1965 (or 1969) for the years 1973, 1979; a topographic map from 1988 for the years 1989, 1995; topographic maps from 2002 and 2006 and a land use map from 2005 for the year 2004; a topographic map from 2010, a land use map from 2010, Google Earth © and field data from 2012 for the year 2011. Due to the lack of ancillary data for some of the periods in the past, we relied on the quality of the original dataset and also on the authors' experience in spectral analysis to identify unambiguous and spectrally homogenous training sites per class.

The number and typology of land cover/land use classes were defined based on field work and available land use statistics for the Ca Mau Province and Tran Van Thoi District, and exploratory analysis of satellite data with unsupervised classification (generating 30 spectral clusters, later merged into 8 land cover/land use classes). The used typology was updated from Anderson *et al.* [52], FAO [63], and USGS [64] to match with the characteristics of the case study. Eight separate main land cover/land use categories of Tran Van Thoi District were identified: cultivated lands (irrigated rice crops); aquaculture ponds (shallow, artificial water bodies used for shrimp and fish production); mangrove forest (natural and semi natural trees in salty water); melaleuca forest (natural and semi natural trees in fresh water); built up areas (settlement, roads and other artificial surfaces); bare lands (fallow, not for agriculture, aquaculture or forest); natural water bodies (seas, lakes, reservoirs, rivers, streams; discriminated from aquaculture ponds by spectral/color information, by their pattern/shapes and the ancillary information); cloud and shadow.

A detailed explanation of the algorithm used for image processing (for instance, geometric correction, unsupervised classification, supervised classification, field data, accuracy assessment, change detection) can be found in Campbell *et al.* [53], Lillesand *et al.* [56], and Bolstad *et al.* [65]. A land cover/land use classification map was created using the maximum likelihood classification method, one of the most well-known parametric classifiers used for supervised classification. According to Bolstad *et al.* [65], the supervised maximum likelihood classification algorithm was demonstrated to provide the best results from remotely sensed data, if each class has a Gaussian distribution. The standard implementation of supervised maximum likelihood classification requires training samples representing the feature types [56]. Training samples for the supervised classification in this case study were selected based on ancillary maps, field data and information from the interviews with the local population. The number of pixels for training each class ranged from 132 (for cloud and cloud shadow class) to 5018 pixels, and the sample separability ranged from 1.9 to 2.0 measured using the Jeffrey-Matusita distance [66]. Finally, a 3×3 majority filter was applied to reduce noise in the land cover/land use maps.

In order for the results to be suitable for change detection analysis, it is necessary to perform an accuracy assessment [67]. Classification accuracy refers to the degree of correspondence between the classification from remote sensing data and the reference information [68]. Independent training sites were used to assess the accuracy of each classification. Error matrices, as cross-tabulations of the mapped class and the reference class were implemented to assess the accuracy, and statistical results such as overall accuracy, user and producer accuracies and Kappa statistic measures were computed [2,53,68].

3.5. Change Detection Analysis

The cloud and cloud shadow classes of all dates were grouped into a general cloud class: this area was masked out for subsequent analyses. The classification results for each time period had seven main classes and the same cloud mask. After that, the area of each land cover class was calculated and the land cover/land use changes were analyzed. The land cover/land use change map at province scale, covering a period of nearly 40 years (1975–2011), was first derived in order to see the overall change in the region. The district scale (Tran Van Thoi) was then chosen to characterize the land cover/land use changes in 5 short-term periods (1973–1979, 1979–1989, 1989–1995, 1995–2004, 2004–2011) and 1 long-term period (1973–2011). The exact duration of each time interval was constrained by the availability of cloud-free scene over the study area. Detection of land cover changes was achieved by overlay and post-classification comparison of the land cover/land use maps of the different time periods at province and district scales. The original resolution of the satellite images was preserved, in order to attain the maximum quality of spectral data during the classification process. In order to compare classifications derived at different spatial resolutions, each classification was resampled, using a majority rule, to the spatial resolution of the lower spatial resolution (*i.e.*, oldest date: the resolution in periods 1973–1989, 1989–1995, 1995–2004, 2004–2011, and 1973–2011 is 60 m, 60 m, 30 m, 20 m, 10 m, and 60 m, respectively). The resulting change maps were accompanied by the respective cross tabulation matrices showing the change pathways, in order to determine the quantity of the conversions. Change dynamics are presented in maps using grouping of changes for more clarity in our results.

4. Results

4.1. Land Cover/Land Use in Ca Mau Province

The classification of the land cover/land use in Ca Mau Province in 1975 and 2011 were conducted with seven classes, including cultivated lands, aquaculture ponds, mangrove and melaleuca forest, built up areas, bare lands, natural water bodies, and cloud and shadow. The overall accuracies for the years 1975 and 2011 were 81 and 88%, respectively, and the overall Kappa indices were 0.75 and 0.86, respectively (Table 2). The overall change of the land cover/land use in Ca Mau Province from 1975 to 2011 is presented in Figure 5. The mangrove and melaleuca forest changed a lot to aquacuture and cultivated lands, especially in the north, the west and the south of province. In addition, a wide area of cultivated lands with the main of paddy rice converted to aquacuture in the middle and in the eastern part of the region. Bare lands changed almost entirely to cultivated lands in the west, to forest and aquaculture in the south.

As can be seen from this figure, Tran Van Thoi District is one of the districts in Ca Mau that experienced large scale and variable types of land cover/land use changes. Throughout the study period, Tran Van Thoi District exhibits diverse land cover/land use types, predominantly three types that are specific to the region: forest, paddy rice, and aquaculture.

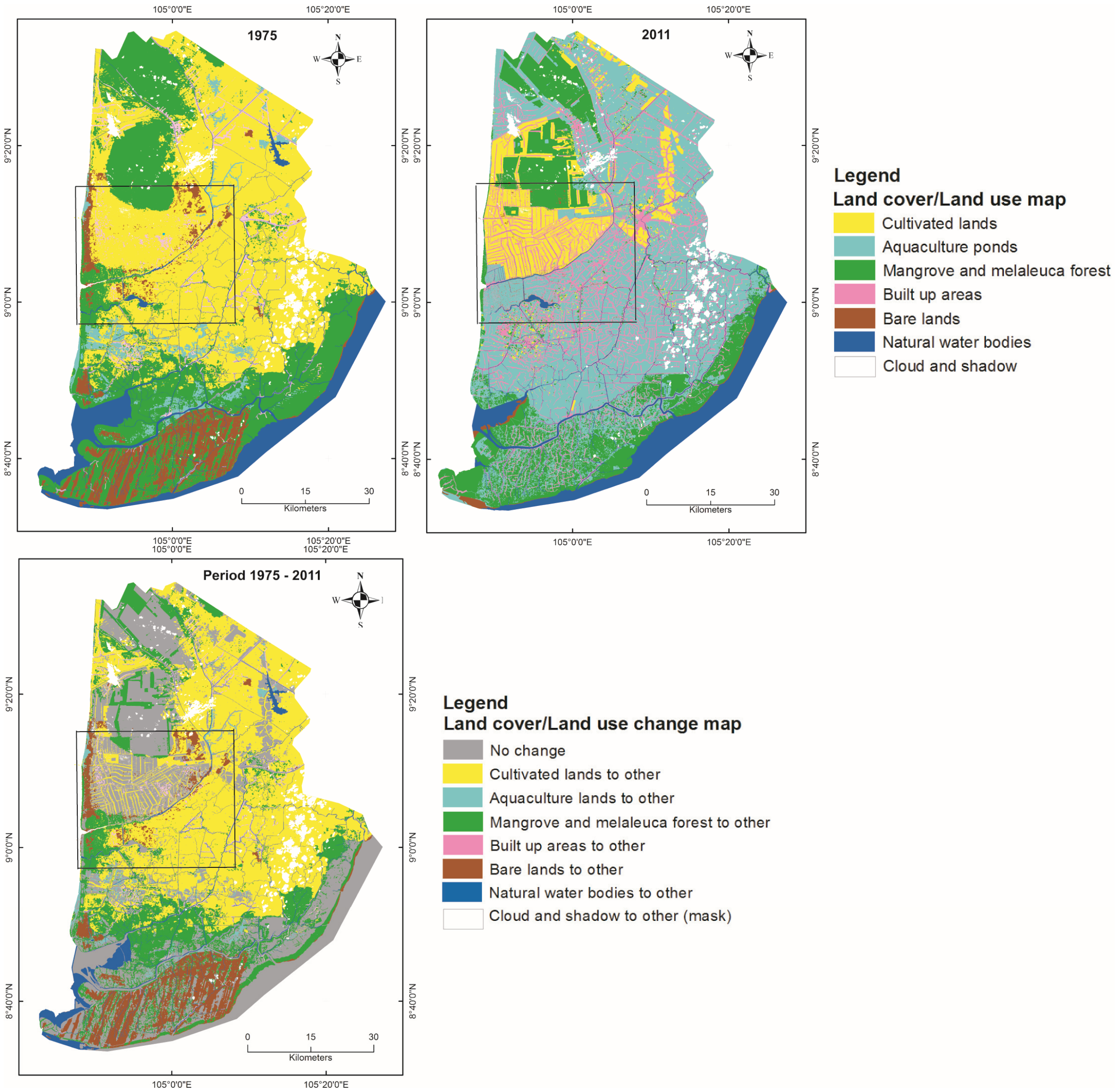

Figure 5. Land use/land cover and change detection of Ca Mau Province in period 1975 and 2011. Black square indicate the localization of the Tran Van Thoi District analyzed in more details in the study.

Table 2. Accuracy assessment statistics of land cover/land use classification in percent (Abbreviation Cultivated lands: Cu; Aquaculture ponds: Aq; Mangrove forest: Ma; Melaleuca forest: Me; Built up areas: Bu; Bare lands: Ba; Natural water bodies: Na).

Land Cover/Land Use Categories		Cu	Aq	Ma	Me	Bu	Ba	Na	Overall Accuracy	Overall Kappa
1973	Producer	72	90	92	67	74	82	89	**81**	**0.77**
	User	91	76	67	84	68	73	100		
1979	Producer	75	90	92	86	94	82	94	**82**	**0.79**
	User	63	82	70	84	86	67	98		

Table 2. *Cont.*

Land Cover/Land Use Categories		Cu	Aq	Ma	Me	Bu	Ba	Na	Overall Accuracy	Overall Kappa
1989	Producer	97	85	76	77	100	74	90	**86**	**0.83**
	User	100	83	82	74	100	100	100		
1995	Producer	100	84	79	98	84	62	93	**87**	**0.85**
	User	100	86	97	75	100	80	73		
2004	Producer	100	92	100	77	65	93	100	**89**	**0.87**
	User	92	89	98	92	66	86	100		
2011	Producer	77	77	100	100	88	85	92	**89**	**0.86**
	User	95	69	100	78	97	78	99		
1975	Producer	85	88	81		71	73	82	**81**	**0.75**
	User	67	86	84		89	93	98		
2011	Producer	84	94	95		83	76	88	**88**	**0.86**
	User	93	85	81		90	100	96		

Notes: In this table: District scale (7 major classes); Province scale (6 major classes).

4.2. Tran Van Thoi District

4.2.1. Land Cover/Land Use Classification and Accuracy Assessment

The overall accuracies for the different time periods varied from 81% to 89% and the overall Kappa indices from 0.77 to 0.87 (Table 2). In Table 2, the producer and the user accuracies were derived for all land cover/land use categories. The accuracy increased for most recent time periods due to higher spatial resolution of satellite images and availability of more detailed and accurate reference datasets.

Land cover/land use classification maps of the Tran Van Thoi District from the six time periods were analyzed and are shown in Figure 6. Mangrove forest was located mainly in the southwestern part of the district around the estuary of Ong Doc River in the 1970s. Since 1995–2004, mangrove is restricted to a 3.5 km wide, discontinuous band along the coastline. On the other hand, melaleuca forest is observed in the northern part of the district over the entire study period. A change in the spatial extent is noticed until 1995 and this forest is now clearly constrained by geometric boundaries. Cultivated lands, consisting almost entirely of paddy rice, are dominant in the central and eastern part of the district. In 1973 and 1979, the western and eastern parts of the district were characterized by high proportion of bare lands. In the Tran Van Thoi District, built up lands are widespread and situated along the rivers, canals and roads. The pattern of settlements is less clear on the 60 m spatial resolution data from the 1970s, but the built up area network increased in density over time. Aquaculture ponds were almost totally absent from the district until the late 1980s. It started to develop in the early 1990s in the southwest. It then increased significantly and rapidly in the period 1995–2004 in the southern and eastern regions which was almost entirely converted from cultivated lands (paddy rice) to mangrove forest.

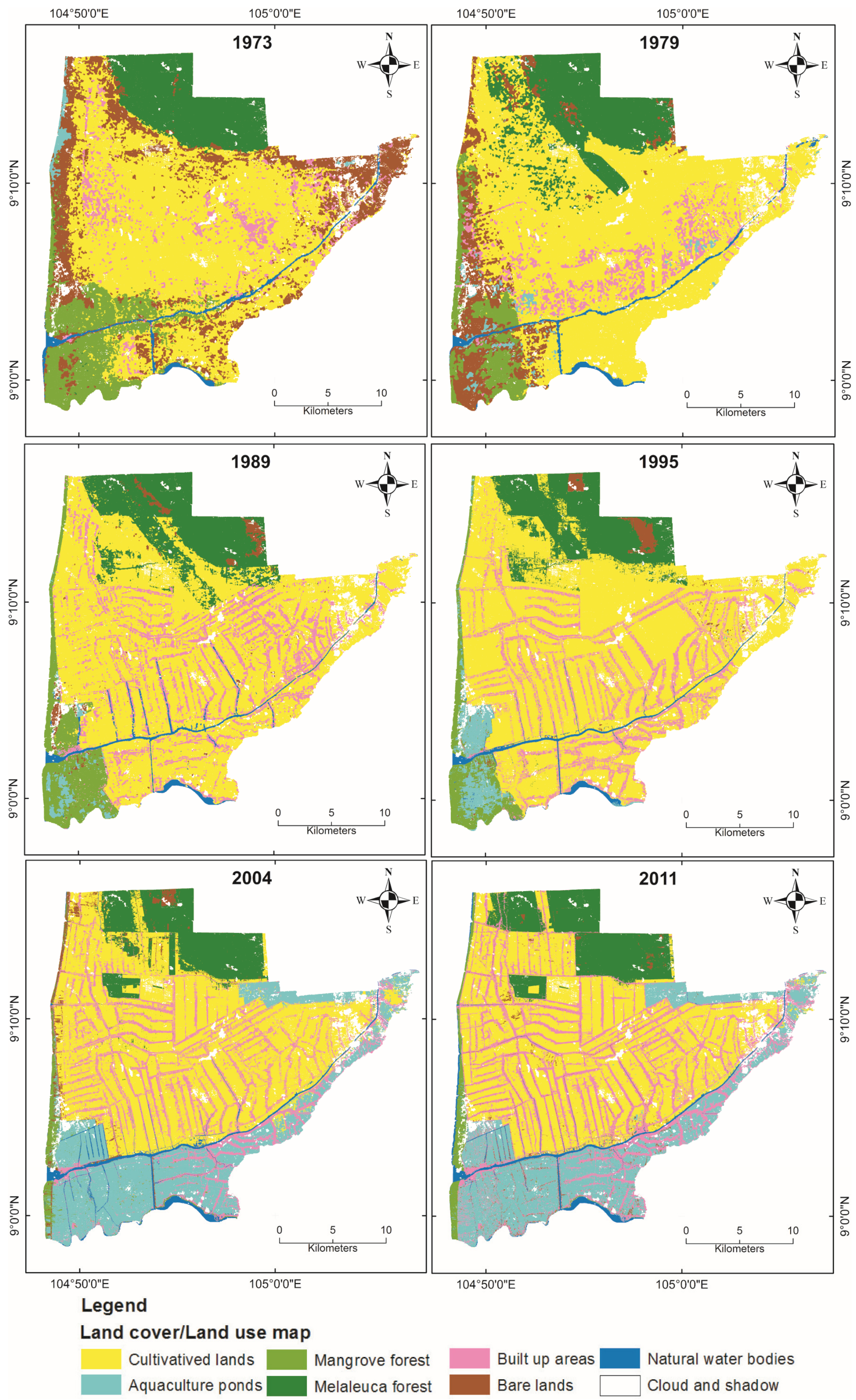

Figure 6. Land cover/land use classification maps of the Tran Van Thoi District in year 1973, 1979, 1989, 1995, 2004 and 2011 based on supervised spectral classification of Landsat MSS (1973, 1979), Landsat TM (1989), SPOT3 (1995), and SPOT5 (2004, 2011) images.

4.2.2. Land Cover/Land Use Change Detection

Figure 7a, shows the surface distribution (in km^2) and the evolution of the proportion of each land cover/land use class in the different time periods. Cultivated lands remain the largest land cover type in the region throughout the 40 years. Aquaculture ponds occupied the least area in the 1970s and 1980s but by the end of the study period, mangrove forest and bare lands have become the smallest land cover types in the district. Trends can be observed in the land cover classes undergoing the largest change namely cultivated lands, aquaculture, mangrove forest, built up areas, and bare lands from 1973 to 2011 (Figure 7b). Bare lands decreased greatly in the first two time intervals, whereas mangrove forest decreased gradually until 2004. Built up areas and aquaculture ponds increased significantly, gradually over the study period for the former and sharply from 1995 to 2004 for the latter. Melaleuca forest and natural water bodies represent a stable percentage of the study area in the last 40 years. Cultivated lands showed a slow increase until 1995, before a rapid decrease until 2011.

Figure 7c illustrates the magnitudes of change in km^2 per year, standardizing the absolute change by the duration of each analyzed interval for the seven main land cover/land use categories. Only the built up areas class shows a continuous increasing trend. The other land cover/land use types fluctuated over the different time periods. Cultivated lands, aquaculture ponds, built up areas, mangrove forest and bare lands had higher magnitudes of change than the limited changes for melaleuca forest and the negligible variation of natural water bodies. Figure 8 illustrates the spatial distribution of the different change types over the different time intervals. The conversion of bare lands spreads from the eastern part of the district in the 1973–1979 period to the west and southwest along the coastal line in the 1979–1989 period. Mangrove forest conversion occurred mainly in the southwest in the periods 1973–1979, 1989–1995 and to a lesser extent, 1995–2004. Mangroves were initially mainly converted to paddy rice and then to aquaculture in more recent periods. Decrease of the melaleuca forest took place regularly during the period from 1979 to 2004. These cut took place at the margin of the main zone of forest in the North of the district but these were partially compensated by the growth of a new zone of melaleuca forest south west of the main forest since 1989. Cultivated lands changed during all the examined periods throughout the district, mostly due to expansion of built up areas. However, a drastic conversion of cultivated lands is observed during the period 1995–2004, especially in the southern and eastern parts of the region, to the benefit of aquaculture land.

The detailed dynamics of the land cover/land use changes in the Tran Van Thoi District from 1973 to 2011 is shown in Table 3. The table presents all the results of the cross tabulation matrices of the land cover/land use change, showing the conversion from each class to another class. For example, considering the entire study period, 1973–2011, at once, 196 km^2 cultivated lands remained stable, 79 km^2 of new cultivated land were created at the expense of bare land and forest, but 155 km^2 of cultivated land were lost to built up areas (93 km^2), aquaculture ponds (46 km^2), and melaleuca forest (10 km^2). Aquaculture ponds and built up areas were the land cover/land use categories that expanded the most over other land types, with 128 and 131 km^2, respectively, mostly from cultivated lands, mangrove forest and bare lands. During this period of 38 years, the areas of cultivated lands, bare lands and mangrove forest experienced the greatest absolute reduction in area, with 155, 111 and 67 km^2, respectively. In relative term, the reduction of bare land (99%) and of mangrove forest (90%) is of larger magnitude than the 50% decrease in cultivated land relative to the 1973 surface area of the respective land cover.

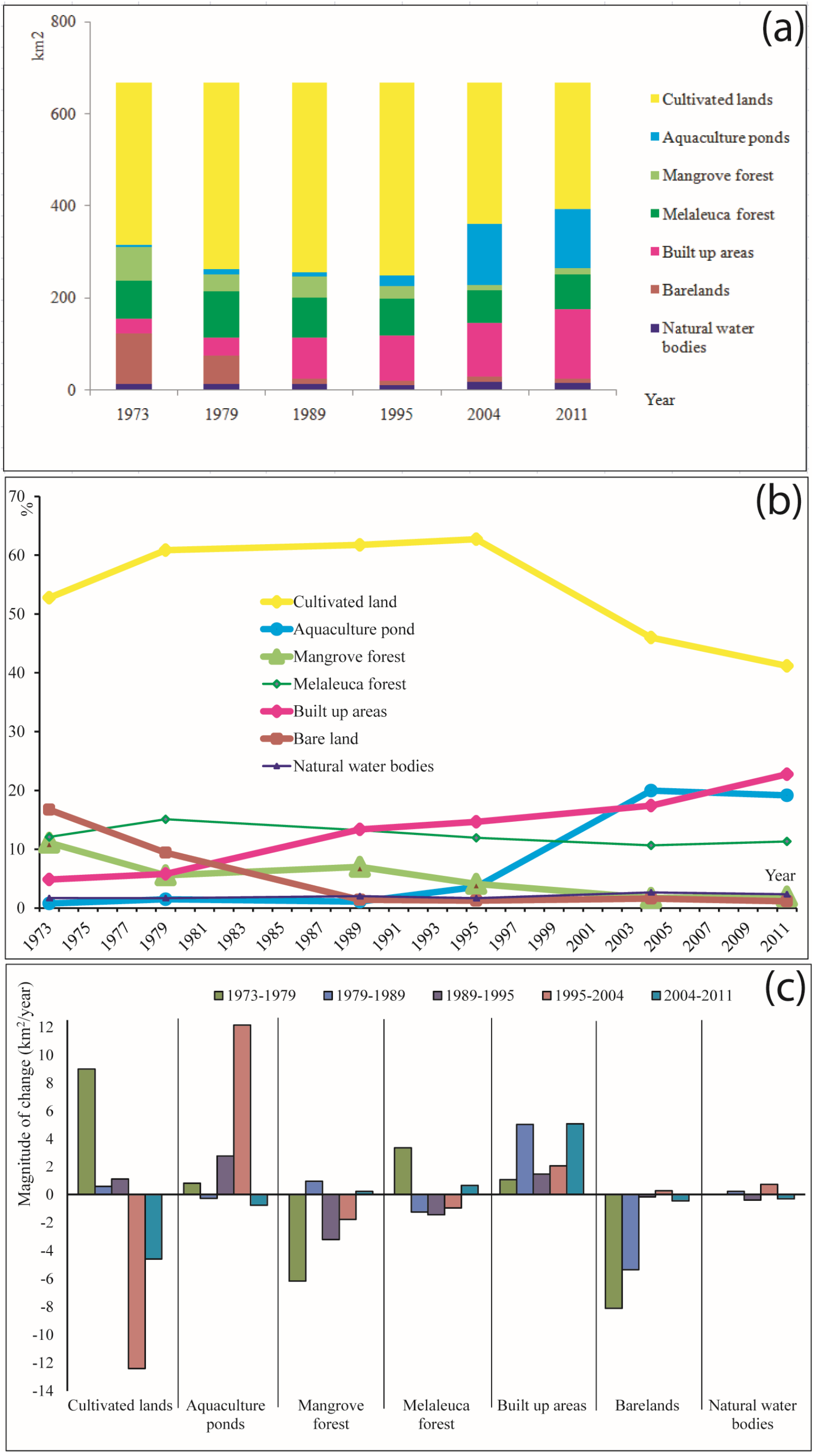

Figure 7. Land cover/land use in the Tran Van Thoi District from 1973 to 2011. (**a**) The distribution of land cover/land use types in km^2 in different years. (**b**) The evolution of the properties of the major land cover/land use types in percent. (**c**) The magnitude of the land cover/land use changes in km^2/year for each time interval.

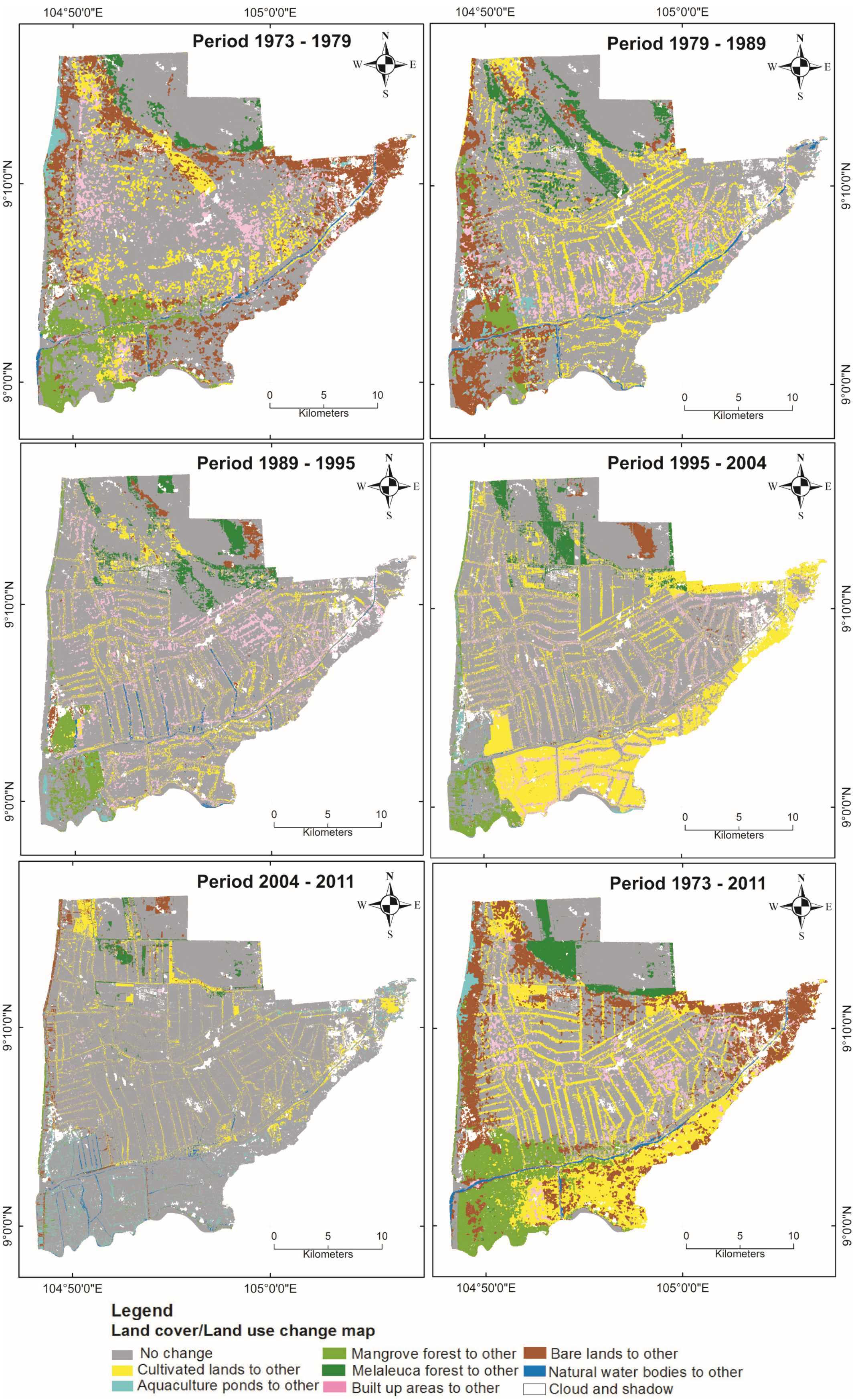

Figure 8. Spatial distribution of land cover/land use changes in the Tran Van Thoi District from 1973 to 2011.

Table 3. Nature of the land cover/land use changes in the Tran Van Thoi District from 1973 to 2011 in km^2 (figures are rounded up to entire numbers). (Cloud and shadow class is constant in all tables, 32 km^2). *(*The values on the diagonal represent the amount of each land cover/land use class that did not change, while the remaining values refer to the expansion or reduction of the classes*)*.

Period 1973–1979		**Cu**	**Aq**	**Ma**	**Me**	**Bu**	**Ba**	**Na**	**Total**	**Expansion**
1979	Cultivated lands (Cu)	**303**	2	14	5	7	74	3	406	103
	Aquaculture ponds (Aq)	3	**0**	4	0	0	2	0	10	10
	Mangrove forest (Ma)	2	1	**29**	0	0	4	1	37	8
	Melaleuca forest (Me)	22	0	0	**70**	1	7	0	101	31
	Built up areas (Bu)	9	0	3	0	**22**	5	0	39	17
	Bare lands (Ba)	11	3	23	6	1	**18**	1	63	45
	Natural water bodies (Na)	2	0	0	0	0	1	**7**	11	4
	Total	352	5	74	81	32	112	11	**667**	
	Reduction	49	5	45	11	10	93	4		
Period 1979–1989		Cu	Aq	Ma	Me	Bu	Ba	Na	Total	Expansion
1989	Cultivated lands (Cu)	**334**	5	9	28	6	26	3	412	78
	Aquaculture ponds (Aq)	0	**1**	2	0	0	4	0	7	7
	Mangrove forest (Ma)	1	2	**23**	0	1	19	1	47	24
	Melaleuca forest (Me)	16	0	0	**65**	0	6	0	88	23
	Built up areas (Bu)	49	1	2	2	**31**	4	1	89	58
	Bare lands (Ba)	1	0	1	6	0	**2**	0	9	7
	Natural water bodies (Na)	5	0	0	0	1	1	**6**	13	7
	Total	406	10	37	101	39	63	11	**667**	
	Reduction	72	9	14	35	8	61	5		
Period 1989–1995		Cu	Aq	Ma	Me	Bu	Ba	Na	Total	Expansion
1995	Cultivated lands (Cu)	**387**	0	6	17	4	2	3	419	32
	Aquaculture ponds (Aq)	1	**4**	15	0	1	2	1	24	20
	Mangrove forest (Ma)	0	2	**24**	0	1	0	0	27	4
	Melaleuca forest (Me)	10	0	0	**64**	0	5	0	79	15
	Built up areas (Bu)	12	0	1	0	**83**	0	1	98	15
	Bare lands (Ba)	1	0	0	7	0	**0**	0	8	8
	Natural water bodies (Na)	2	0	0	0	1	0	**8**	11	3
	Total	412	7	47	88	89	9	14	**667**	
	Reduction	26	3	23	24	6	9	5		
Period 1995–2004		Cu	Aq	Ma	Me	Bu	Ba	Na	Total	Expansion
2004	Cultivated lands (Cu)	**284**	0	0	17	4	1	1	307	23
	Aquaculture ponds (Aq)	86	**19**	13	1	12	1	0	133	114
	Mangrove forest (Ma)	1	2	**8**	0	1	0	0	11	3
	Melaleuca forest (Me)	7	0	0	**58**	0	6	0	71	13
	Built up areas (Bu)	33	1	2	1	**79**	0	1	116	37
	Bare lands (Ba)	3	1	3	2	0	**1**	0	11	9
	Natural water bodies (Na)	5	1	1	0	1	0	**9**	18	8
	Total	419	24	27	80	98	8	11	**667**	
	Reduction	135	5	20	21	19	7	2		

Table 3. *Cont.*

Period 2004–2011		Cu	Aq	Ma	Me	Bu	Ba	Na	Total	Expansion
2011	Cultivated lands (Cu)	**261**	1	0	5	3	3	1	275	14
	Aquaculture ponds (Aq)	6	**116**	1	0	2	0	3	128	12
	Mangrove forest (Ma)	0	2	**8**	0	0	3	0	13	5
	Melaleuca forest (Me)	9	0	0	**63**	0	3	0	76	12
	Built up areas (Bu)	26	10	1	1	**111**	1	2	152	41
	Bare lands (Ba)	3	3	0	1	0	**0**	1	8	7
	Natural water bodies (Na)	1	1	2	0	0	0	**12**	16	4
	Total	307	133	11	71	116	11	18	**667**	
	Reduction	45	17	4	8	5	11	6		
Period 1973–2011		Cu	Aq	Ma	Me	Bu	Ba	Na	Total	Expansion
2011	Cultivated lands (Cu)	**196**	2	9	15	6	46	0	275	79
	Aquaculture ponds (Aq)	46	**0**	42	1	4	33	1	128	128
	Mangrove forest (Ma)	0	1	**7**	0	0	3	1	13	6
	Melaleuca forest (Me)	10	0	0	**59**	0	6	0	76	16
	Built up areas (Bu)	93	1	10	4	**21**	20	3	152	131
	Bare lands (Ba)	3	0	2	1	0	**1**	0	8	7
	Natural water bodies (Na)	3	0	4	0	0	2	**6**	16	9
	Total	352	5	74	81	32	112	11	**667**	
	Reduction	155	5	67	21	11	111	5		

5. Discussion

5.1. Accuracy and Limitations of the Method

The SPOT5 images were acquired in January 2011, while the field trip for ground data was conducted in December 2012. All the satellite images of this research were acquired in January or March. Even though the datasets were not collected simultaneously, those dates represent the same rice crop season (winter–spring crop). Additionally, the crop calendar, official ancillary data, the authors' knowledge and interview data from local people were applied for references.

The overall accuracies of the land cover/land use maps ranged from 81% to 89%, which is quite good, although no standard exists for image classification accuracy [69]. Although the producer and user accuracies of some classes were below 70%, the majority ranged from 70% to 100%, which is satisfactory considering the diverse and complex land cover/land use categories in this case study. Patterns are also consistent across the region and between the different images. The classification errors were sometimes due to the spectral mixture between cultivated lands and melaleuca forest, between melaleuca forest and mangrove forest, between cultivated lands and mangrove forest, between aquaculture ponds and natural water bodies, or between built up areas and cultivated lands after harvest. Therefore, careful selection of training sites and majority filters after supervised classification were applied in order to reduce these issues.

5.2. Comparison with Previous Studies in Ca Mau Province

The major land cover/land use transitions in this case study concerning over the study period were the conversions of cultivated lands, bare lands and mangrove forest into aquaculture ponds and built up areas. The research result trends are similar with the results of past conversion analysis by Binh *et al.* [13], Lam-Dao *et al.* [14] and Thu [15] who analyzed a different district within the same province. In the Cai Nuoc District of the Ca Mau Province, Binh *et al.* [13] showed that forest area coverage reduced by 75% between 1963 and 2003, having changed almost exclusively to aquaculture and agricultural land. They also showed that shrimp farms increased tenfold between 1999 and 2000. Saline water covered nearly 200 km^2 in 1968, but it reached 835 km^2 in 2003. Salinization, which is directly related to the expansion of aquaculture, suggests that the development of the shrimp industry affects the environment.

According to Thu [15], mangrove, the dominant land cover of the Ngoc Hien District in the South of Ca Mau, decreased both in quality and quantity due to the war, human activities and its use as firewood. It covered more than 72% of the total area in 1965 but only nearly a half in 2001. Lam-Dao *et al.* [14] conducted research in both the Ngoc Hien and Nam Can Districts in Ca Mau from 1973 to 2008. The typical land use type in those areas is mangrove, which acts as a natural protective barrier for the coastal zone. Mangrove covered over 150,000 hectares before 1961, but due to the war period and human impacts, it has crucially declined, with 40% being lost during the period between 1983 and 2007. Conversion of mangrove into shrimp farms concerned 54% of the area, while forest covered only 42% in 2000, and continued to decrease until 2008.

5.3. Potential Drivers of Land Cover/Land Use Changes

5.3.1. Reduction in Forest Land Covers

A detailed analysis of the drivers of the observed changes goes beyond the scope of this contribution but some preliminary elements can be mentioned based on existing statistics and previous studies in similar areas in Vietnam, the Mekong Delta or South-East Asia more generally. Results show that mangrove forest area decreased dramatically in Ca Mau Province, especially for the case study—Tran Van Thoi District—where it reduced by nearly 90% between 1973 and 2011. The major factors that might have contributed to the loss of forest cover are the Vietnam War, the expansion of paddy rice cultivation, and shrimp farming [13,14,18–20,70], wood extraction, and coastal industrialization [15]. During the second Vietnam War, the Mekong Delta in general and the Ca Mau Province in particular was sprayed strongly by herbicide defoliants, first in 1962 and later during the years 1966–1970 [71–74]. Hence, many of the trees including both forest and cultivated species died, resulting in an increase in the bare land area. The second war concluded in 1975 but the effect of this treatment can still be traced both in human beings and ecosystems. After the war and until 1989, mangrove areas partly recovered in Ca Mau Province [48,75].

5.3.2. Increase in Aquaculture Ponds

During 1973 and 1979, aquaculture ponds were rare while forest and cultivated lands were the major land cover. In 1986, the “Doi Moi” policy—the economic reforms initiated by the Vietnamese government with the goal of creating a "socialist-oriented market economy"—created more opportunities for farmers [76]. The life of Vietnamese people improved rapidly afterward, especially terms of trading agriculture production [77]. From 1989 to 1995, aquaculture ponds started to appear in larger proportion in the southwest of the district. In addition to the Doi Moi policy, two additional policies/resolutions had a great impact on the land use change in the Ca Mau: in 2000 the National Government passed the resolution 09/NQ-CP [78] allowing farmers to transform coastal saline rice fields into shrimp farms; in 2001, the Ca Mau Province passed the resolution 1116/QĐ-CTUB [79] to encourage the local people to develop shrimp farming due to salt intrusion. This resulted in a rapid development of aquaculture ponds in the case study. Our results show an increase of aquaculture area by 2600% from 1973 to 2011 in Tran Van Thoi District with a specifically rapid development in the period 1995–2004. The conversion of cultivated lands and mangrove forest to aquaculture occurred in this case study and in other locations, such as Cai Nuoc, Ngoc Hien, Nam Can Districts (Ca Mau) [13,14], Soc Trang, Bac Lieu, Long An (Vietnamese Mekong Delta) [20,70], or southern Thailand [80]. The major reasons of this conversion include the policies mentioned above, the salt intrusion issue, and the economic factor (income). The intrusion of salty water is due to flat and low-lying region, dense network of rivers and canals, high tidal fluctuations of the East Sea and the Gulf of Thailand, and sea level rise issue [48,81,82]. Besides, shrimps provide higher profit [13,70] (200,000 VND/kg) than paddy rice (5000 VND/kg).

Statistics at district level [42,83] show that the yields of aquaculture including fed shrimps and fishes in tons in Tran Van Thoi District increased 11 times from 1996 (2400 tons) to 2011 (26,000 tons). These rapid changes have possible positive and negative consequences. The rise of aquaculture might help the economy of the district with high shrimp production and generate labor for aquaculture processing industry. The number of employees in the non-farm individual business enterprises increased about 10 times from 1997 (1500 persons) to 2011 (16,000 persons). The number of non-farm individual business enterprises rose approximately 25 times from 1997 (300 enterprises) to 2011 (7700 enterprises) [42,83]. However, it might also impact the environment and cause pollution [13,84,85].

5.3.3. Increase in Built Up Areas

These policies changes mentioned above, population growth, the development of new road and canal networks, and socio-economic development (especially after "Doi Moi" economic reforms [31–33]) can therefore account for the observed increase in built up areas. According to Ca Mau Statistic Office [42,83,86], the average population in Tran Van Thoi District went up: 184,000, 194,000, and 198,000 persons in 1997, 2004, and 2011, respectively (with correction in 2011 for homogeneous consideration of non-permanent migrants). More specifically, Song Doc and Tran Van Thoi, which are the two towns of the Tran Van Thoi District, have seen the construction of new administrative buildings (in Tran Van Thoi town) and many shrimp processing factories (in Song Doc town). This increase in built up areas also correlates with the 7% increase in population observed over the last 14 years (local people and factory workers).

On the one hand, this observed growth probably reflects an improvement of the economic and social conditions within the study area. However, urban or rural built up growth have also been shown in other parts of the world to lead to destruction of the environment, manifesting as an increased impact of natural hazards, air pollution and dangers for public health, water and noise pollution, increased needs for solid waste management, decrease of biodiversity, loss of natural resources, and food shortages [34–41,87–90].

5.3.4. Decrease in Cultivated Land

Cultivated lands slightly increased until 1995, then it rapidly decreased until 2011. In total, it reduced by about 22% between 1973 and 2011. The rise of aquaculture ponds and the expansion of built up areas were made at the expense of cultivated lands. Cultivated lands changed into built up areas during all the examined periods due to the population growth and the socio-economic development. A similar evolution was witnessed for other case studies in Vietnam, the Mekong Delta, or Asia [13,27,28,36,39]. A significant conversion of cultivated lands into aquaculture ponds for the entire regions on the southwest, south, and southeast of the Song Doc, the Phong Lac, the Phong Dien and the Lac An communes, which are along the Ong Doc River (an estuary connecting directly to sea) in the Tran Van Thoi District. In other regions in the Mekong Delta, aquaculture ponds were replaced by cultivated lands [13,20]. However, cultivated lands still remain the largest land cover type in the case study during 40 years.

In the Tran Van Thoi District, although the area of cultivated lands decreased, the yields in tons of produced crops increased by 200% from 1996 (126,000 tons) to 2011 (260,000 tons) [42,83]. It has been due to the support of Government and provincial policies, the implementation of new technologies, such as newer and higher value rice varieties, higher quality agricultural species, machinery, the transfer of new technology to the local farmers, and the investment in dyke and irrigation systems [91].

5.3.5. Environmental Drivers of Land Cover Changes

The climate and environmental changes, the economic development and the rapid population growth, have led to serious negative impacts for the Mekong Delta in general and for Ca Mau Province in particular. Those are sea level rise, storm surges and typhoons, inundation in the rainy seasons, saline intrusion in the dry seasons, shortage of fresh water for cultivation and domestic uses, acid sulfate soils and acid water, impacts on biodiversity and ecological changes [81,82,92–98]. All the above factors are assumed to have contributed to the observed rapid changes of land cover/land use types, as examined in this case study.

6. Conclusions and Perspectives

In conclusion, the results of our study demonstrate that the Tran Van Thoi District is a coastal and rural district with diverse land cover/land use patterns that exhibits significant changes since the end of the second Vietnam War. This research is the first detailed land cover/land use analysis of Tran Van Thoi District. The main conclusions are that (i) the main land cover/land use categories of the Tran Van Thoi District, for the last 40 years from 1973 to 2011, include cultivated lands, built up areas, aquaculture ponds, mangrove forest, melaleuca forest, natural water bodies, and bare lands; (ii) while aquaculture ponds and built up areas increased significantly, bare lands and mangrove forest decreased greatly in the last 40 years; (iii) almost all land cover/land use types display variations in magnitude over the different time periods, with aquaculture ponds, cultivated lands and built up areas changing more drastically compared to the other types; and (iv) aquaculture ponds and built up areas were converted mainly from cultivated lands, bare lands and mangrove forest. The increase of aquaculture in the period 1995–2004, the decrease of bare lands in the period 1973–1989, and the initial expansion of cultivated lands until the mid-1990s followed by a replacement by aquaculture in the south are the main spatial trends highlighted by our analysis.

These results of land cover/land use maps and change detection may be used to help in understanding the impact of past policies and the role of several factors such as socio-economic trends and environmental changes in controlling the dynamics on land use changes. Understanding the drivers of land use change might in turn contribute to model future evolution of land use patterns and better steer future land use planning policies at the district or province level.

Future research will focus on the identification of the drivers and impacts of land cover/land use change in the case study area. There is a need to further understand the drivers controlling the individuals decision to convert their land use and their spatial patterns. Further, it would be interesting to research the cause of rapid land use dynamics, their impacts on the environment, on the livelihoods and access to natural resources for local people, and on their vulnerability to natural hazards and expected environment changes.

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Author Contributions

Hanh Tran led the research design, data processing and analysis, and drafted the article. Matthieu Kervyn supervised the research, reviewed and edited the manuscript. All authors have read and approved the final version of this manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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