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Comparison of Intensity Analysis and the land use dynamic degrees to measure land changes outside versus inside the coastal zone of Longhai, China

Boqiang Huang[a], Jinliang Huang[a,*], Robert Gilmore Pontius Jr.[b], Zhenshun Tu[c,d]

[a] Coastal and Ocean Management Institute, Xiamen University, 361005, China
[b] Graduate School of Geography, Clark University, Worcester, MA, USA
[c] Fujian Institute of Oceanography, Xiamen 361013, China
[d] Fujian Provincial Key Laboratory of Coast and Island Management Technology Study, Xiamen 361013, China

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ABSTRACT

We compare two popular methods to quantify temporal change among categories: 1) Intensity Analysis and 2) the land use dynamic degrees. We apply the methods to measure land change both outside and inside the coastal zone of Longhai, which is a typical county-level coastal city in Southeast China. The maps show eight categories at four time points: 1986, 1996, 2002, and 2010. Intensity Analysis shows graphically the size and the intensity of changes at three increasingly detailed hierarchical levels in a manner that facilitates interpretation. In contrast, the comprehensive land use dynamic degree (CLUDD) has no practical interpretation because the CLUDD is the sum of loss intensities of categories that have different sizes. The single land use dynamic degree is the annual net change as a percentage of the initial size of the category, which offers limited information because the single degree: 1) fails to reveal the sizes of the category's loss and gain, 2) does not indicate how each category contributes to total change, 3) is sensitive to the category's initial size, and 4) reveals neither the size of the category's annual net change nor the size of the category's initial size.

1. Introduction

1.1. Measurements of land change

Land change in China has drawn much attention because Chinese cities are undergoing rapid intensive anthropogenic development. The remarkable land changes, especially urbanization, that have occurred in coastal China during recent decades have been extensively documented (Liu et al., 2014a; Schneider and Mertes, 2014; Tian, 2015). Several scholars have used various methods to measure land changes. For example, Liu et al. (2013) developed an index system to evaluate the current state of rural area development at the county level in eastern coastal China. Chen et al. (2014) used an urban expansion rate and an intensity index to measure urban expansion patterns in Shenzhen and Dongguan. Quan et al. (2015) used the single and comprehensive land use dynamic degrees to evaluate urban expansion in a small city, Quanzhou, China. Deng et al. (2015) developed an econometric model to estimate the impacts of urbanization on cultivated land in eastern coastal China. He et al. (2017) developed a coupling coordination degree model to examine the relationship between urbanization and the eco-environment in Shanghai. Wan et al. (2015) used land-change amplitudes, a landscape pattern index, and a transition matrix to compare the Honghe National Nature Reserve versus the surrounding region. Several of these methods examine detailed patterns that are so complex or subtle that they can be difficult to interpret, without knowing first some basic metrics of land change. Two particular methods have become popular as a starting point to quantify land change. These two methods are: Intensity Analysis (Aldwaik and Pontius, 2012) and the land use dynamic degrees (Liu et al., 2014a). Our paper compares Intensity Analysis to the land use dynamic degrees in both theory and practice, to gain insight into each framework's abilities and limitations to describe change. We illustrate the concepts with an application to a case study that compares land change during three time intervals in two zones of Longhai, China.

Intensity Analysis is a framework that organizes measurements of changes according to three hierarchical levels, each with its own interpretation (Aldwaik and Pontius, 2012). Authors have applied Intensity Analysis to gain insight into processes of land changes in many countries including Ghana, Australia, Colombia, Japan, and China (Braimoh, 2006; Versace et al., 2008; Romero-Ruiz et al., 2012;

* Corresponding author.
E-mail address: jlhuang@xmu.edu.cn (J. Huang).

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Shoyama and Braimoh, 2011; Huang et al., 2012; Zhou et al., 2014). Intensity Analysis reveals patterns, which can then be linked to the underlying processes. Intensity Analysis can assess the evidence for a particular hypothesized process of change and can help to develop new hypotheses concerning processes of change (Pontius et al., 2013). For example, Alo and Pontius (2008) used Intensity Analysis to quantify land transitions both inside and outside a protected area in Ghana, thereby giving evidence to the hypothesis that logging is the main cause of the loss of closed forest inside the protected areas whereas farming is the main cause of the loss of closed forest outside the protected areas.

The comprehensive land use dynamic degree (CLUDD) and the single land use dynamic degree constitute another popular framework to analyse temporal change among land categories. Liu et al. (2002, 2003) introduced the degrees in Chinese and English, which have been cited more than 1180 times according to Google Scholar as of 2017. However, readers have construed various possible ways to compute the degrees due to confusing mathematical notation. Despite the confusion, the degrees have become extremely popular as authors frequently misinterpret the degrees to compare cases that have various spatial and temporal extents (Pontius et al., 2017). The CLUDD combines measurements across all categories, while the single land use dynamic degree assesses annual net change for each single category. The Materials and Methods section defines the metrics of Intensity Analysis and the land use dynamic degrees, and illustrates the calculations with an application to Longhai, China.

1.2. Case study

Longhai is a county-level coastal city in Fujian province in Southeast China, near the Taiwan Strait. Longhai is rich in natural and cultural resources due to its unique geography and history. Natural conditions, such as shelter from wind, low siltation and appropriate water depth, make the coast an excellent choice for ports. Longhai is also famous for its rich and various kinds of living marine resources. There are more than 200 fish species. The area of mangrove reserve in Longhai is five square kilometres, distributed mostly on the coast of the South River estuary and on Zini & Haimen Islands, making an indispensable contribution to protection of the coastal ecosystem. Woodland and farmland protection areas are of great environmental and economic concern. Longhai has traditional agriculture & aquaculture activities and modern economic development zones. However, it has not been clear how to manage the trade-off between environmental protection and economic development during the most recent three decades, especially concerning land changes inside the coastal zone.

Fig. 1 shows Longhai city situated as a county-level coastal city in Fujian province in Southeast China, covering an area of 8057 square kilometres. The “inside coastal zone” is the 1346 square kilometre area between the provincial road and the sea administrative boundary. The “outside coastal zone” is the 6711 square kilometre area that is not inside the coastal zone. There is an obvious distinction between the two zones in terms of physical factors. Outside the coastal zone is mountainous where more than 80% of the area has a topographic slope in excess of 25°, but slope in excess of 25° occupies only 6% of the area inside the coastal zone. Both of the zones face degradation of Woodland areas. Both of the zones have been undergoing rapid land change and also have been stressed by human activities as a result of economic development.

2. Materials and methods

2.1. Data

Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper plus (ETM+) images at 1986, 1996, 2002 and 2010 serve as the data. Table 1 describes the satellite images. These Landsat images are from the Center for Earth Observation and Digital Earth (CEODE), Chinese Academy of Sciences (http://cs.rsgs.ac.cn/cs_cn/) and the United States Geological Survey (USGS) (http://eros.usgs.gov/).

We performed several steps to create a consistent time series of maps. First, we registered the images geometrically. The 2010 image was registered to topographic maps using features such as road intersections and stream confluences that were clearly visible. The 2010 image was georeferenced to the UTM-WGS 1984 map projection, Beijing 1954 coordinate system, Central Meridian 117 N. Then, this 2010 image was used as the reference to rectify the images for 1986, 1996, and 2002. A first-order polynomial nearest neighbor algorithm with 32 ground control points re-sampled the images so that the root mean square errors were less than half a pixel. All the images were resampled to a 30 m resolution.

We then applied hierarchical classification to derive the land category map for 2010. ENVI software was used to generate the classification thresholds. We used linear stretching based on spectral characteristics to separate the categories. Afterwards, we performed unsupervised classification for each layer by using the Iterative Self Organizing Data Analysis Technique Algorithm (ISODATA). This generated 150 clusters for each layer. We assigned every cluster to one of eight land categories based on visual interpretation of Google Earth images, GIS data and information we collected during field trips. Manual on-screen digitizing was used to edit the classified maps (Yang and Liu, 2005). We created a single map for 2010 by mosaicking using ERDAS Imagine 9.3 software.

We used the 2010 map to help classify each of preceding years in sequence. The process consisted of overlaying the map of 2010 on the 2002 image so we could use visual interpretation to group pixels with the same characteristics. We repeated this procedure for 1996 and 1986 to produce a sequence of land cover maps at 1986, 1996, 2002 and 2010. We then used post-classification comparison to detect categorical transitions by overlaying pairs of land cover maps from sequential time points using ERDAS. Each pair of time points generates a square contingency table.

Intensity Analysis and the land use dynamic degrees use square contingency tables as inputs for the mathematical computations. Table 2 gives the mathematical notation for Intensity Analysis and the land use dynamic degrees.

2.2. Intensity Analysis

Intensity Analysis is a hierarchical framework that has three levels of analysis, where each increasing level explores increasingly detailed patterns, given the preceding level (Aldwaik and Pontius, 2012, 2013; Pontius et al., 2013). The first level is the time interval level, which examines how the annual change percentage S_t during each time interval $[Y_t,Y_{t+1}]$ compares to a uniform annual change percentage U during the temporal extent $[Y_1,Y_T]$. If $S_t < U$, then S_t is slow, meaning the time interval $[Y_t,Y_{t+1}]$ experiences change slower than if the changes during all time intervals were distributed uniformly during the temporal extent $[Y_1,Y_T]$. If $S_t > U$, then S_t is fast, meaning the time interval $[Y_t,Y_{t+1}]$ experiences change faster than if the changes during all time intervals were distributed uniformly during the temporal extent $[Y_1,Y_T]$. Eq. (1) gives S_t and Eq. (2) gives U, both of which assume the spatial extent is identical at each time point, as is the case in our application; therefore it does not matter which time t the summations in the denominators use.

$$S_t = \frac{(\text{size of change during } [Y_t,Y_{t+1}])100\%}{(\text{size of spatial extent})(\text{duration of } [Y_t,Y_{t+1}])} = \frac{\left\{\sum_{i=1}^{J}\left[\left(\sum_{j=1}^{J} C_{tij}\right) - C_{tii}\right]\right\}100\%}{\left[\sum_{i=1}^{J}\left(\sum_{j=1}^{J} C_{tij}\right)\right](Y_{t+1} - Y_t)} \quad (1)$$

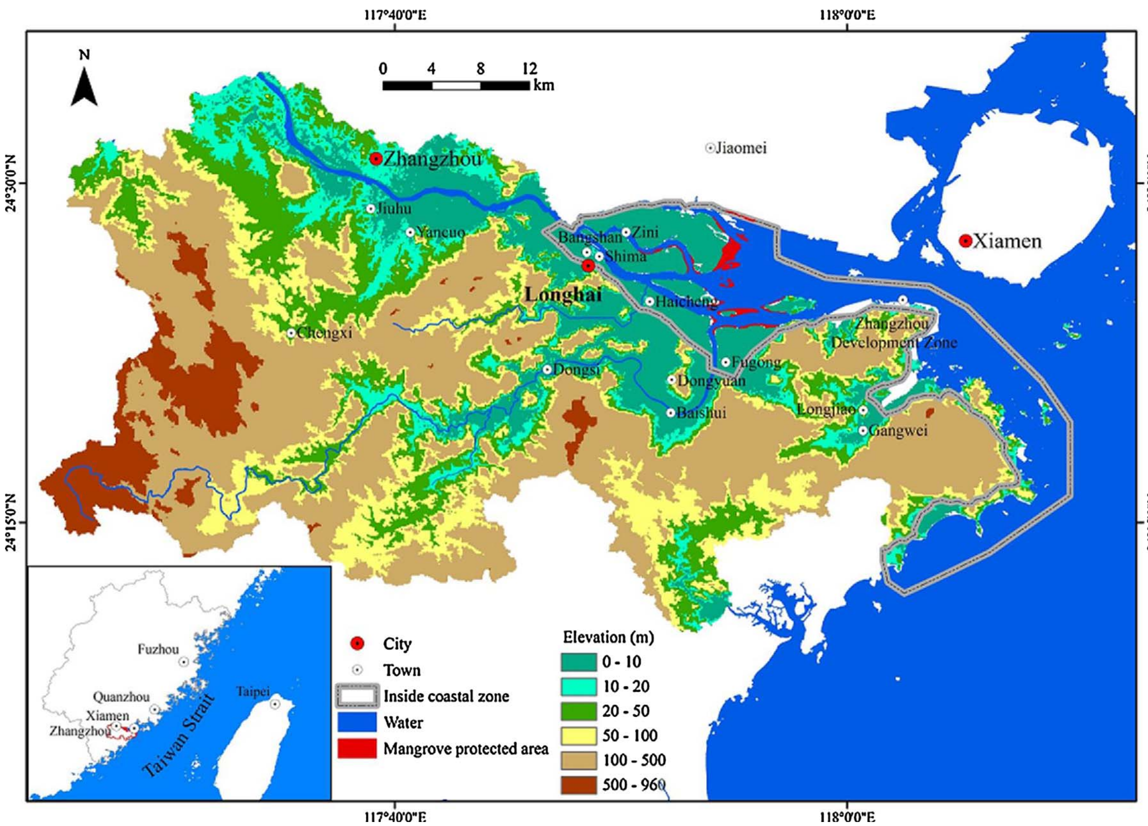

Fig. 1. Location of study area.

Table 1
Landsat satellite imagery.

Date	Path, Row	Landsat Source	Spatial resolution (m)
1986/07/25	119, 43	5 TM	30
1986/11/05	120, 43	5 TM	30
1996/07/20	119, 43	5 TM	30
1996/10/31	120, 43	5 TM	30
2002/02/02	119, 43	7 ETM+	15
2002/09/13	120, 43	7 ETM+	15
2010/11/08	119, 43	5 TM+	30
2010/10/30	120, 43	5 TM+	30

$$U = \frac{(\text{size of change during all intervals})100\%}{(\text{size of spatial extent})(\text{duration of all intervals})} = \frac{\sum_{t=1}^{T-1}\left\{\sum_{i=1}^{J}\left[\left(\sum_{j=1}^{J} C_{tij}\right) - C_{tii}\right]\right\}100\%}{\left[\sum_{i=1}^{J}\left(\sum_{j=1}^{J} C_{tij}\right)\right](Y_T - Y_1)} \tag{2}$$

The second level is the category level, which examines how the loss intensity L_{ti} from category i and the gain intensity G_{tj} to category j compares to a uniform intensity S_t during each time interval $[Y_t, Y_{t+1}]$. If $L_{ti} < S_t$, then L_{ti} is dormant, meaning category i experiences loss less intensively than if the change during time interval $[Y_t, Y_{t+1}]$ were distributed uniformly across the spatial extent. If $L_{ti} > S_t$, then L_{ti} is active, meaning category i experiences loss more intensively than if the change during time interval $[Y_t, Y_{t+1}]$ were distributed uniformly across the spatial extent. Similarly, if $G_{tj} < S_t$, then G_{tj} is dormant; and if $G_{tj} > S_t$, then G_{tj} is active. Eq. (3) gives L_{ti} and Eq. (4) gives G_{tj}.

Table 2
Mathematical Notation.

Symbol	Meaning
C_{tij}	number of pixels that are category i at time point t and category j at time point $t+1$
G_{tj}	intensity of annual gain of category j during time interval $[Y_t, Y_{t+1}]$ relative to size of category j at time point $t+1$
i	index for a category
j	index for a category
J	number of categories
L_{ti}	intensity of annual loss of category i during time interval $[Y_t, Y_{t+1}]$ relative to size of category i at time point t
L_{t+}	comprehensive land use dynamic degree, which is sum of L_{ti} over i
N_{ti}	single land use dynamic degree for category i during time interval $[Y_t, Y_{t+1}]$, which is intensity of annual net change of category i during time interval $[Y_t, Y_{t+1}]$ relative to size of category i at time point t
R_{tij}	intensity of annual transition from category i to category j during time interval $[Y_t, Y_{t+1}]$ relative to size of category i at time point t
S_t	annual change percentage during time interval $[Y_t, Y_{t+1}]$
t	index for a time point
T	number of time points
U	uniform intensity of annual change percentage during the temporal extent $[Y_1, Y_T]$
W_{tj}	uniform intensity of annual transition from all non-j categories to category j during time interval $[Y_t, Y_{t+1}]$ relative to size of all non-j categories at time point t
Y_t	year at time point t

$$L_{ti} = \frac{(\text{size of loss of } i \text{ during } [Y_t,\ Y_{t+1}])100\%}{(\text{size of } i \text{ at time } Y_t)(\text{duration of } [Y_t, Y_{t+1}])} = \frac{\left[\left(\sum_{j=1}^{J} C_{tij}\right) - C_{tii}\right]100\%}{\left(\sum_{j=1}^{J} C_{tij}\right)(Y_{t+1} - Y_t)} \tag{3}$$

		Categories at year Y_{t+1}					
		j=1	j=2	…	j=J	Loss Intensities	Land Use Dynamic Degrees
Categories at year Y_t	i=1	R_{t11}	R_{t12}	…	R_{t1J}	L_{t1}	N_{t1}
	i=2	R_{t21}	R_{t22}	…	R_{t2J}	L_{t2}	N_{t2}
	…	…	…	…	…	…	…
	i=J	R_{tJ1}	R_{tJ2}	…	R_{tJJ}	L_{tJ}	N_{tJ}
	Uniform Transition Intensities	W_{t1}	W_{t2}	…	W_{tJ}		
	Gain Intensities	G_{t1}	G_{t2}	…	G_{tJ}		
	All categories during $[Y_t, Y_{t+1}]$					S_t	L_{t+}

Fig. 2. Relationship among intensities and land use dynamic degrees during time interval $[Y_t, Y_{t+1}]$.

$$G_{tj} = \frac{(\text{size of gain of } j \text{ during } [Y_t,\ Y_{t+1}])100\%}{(\text{size of } j \text{ at time } Y_{t+1})(\text{duration of interval } [Y_t, Y_{t+1}])} = \frac{\left[\left(\sum_{i=1}^{J} C_{tij}\right) - C_{tjj}\right]100\%}{\left(\sum_{i=1}^{J} C_{tij}\right)(Y_{t+1} - Y_t)} \tag{4}$$

The third level is the transition level, which examines how the transition intensity R_{tij} from category i to category j compares to a uniform transition intensity W_{tj} given the gain of category j during time interval $[Y_t, Y_{t+1}]$. If $R_{tij} < W_{tj}$, then the gain of j avoids i, meaning the gain of j transitions from i less intensively during time interval $[Y_t, Y_{t+1}]$ than if the gain of j were to have transitioned uniformly from the space that is not j at time Y_t. If $R_{tij} > W_{tj}$, then the gain of j targets i, meaning the gain of j transitions from i more intensively during time interval $[Y_t, Y_{t+1}]$ than if the gain of j were to have transitioned uniformly from the space that is not j at time Y_t. Eq. (5) gives R_{tij} and Eq. (6) gives W_{tj}. The order of subscripts j and i in C_{tji} in the denominator of Eq. (6) is intentional, so that the summation over i subtracts category j at the initial time Y_t.

$$R_{tij} = \frac{(\text{size of transtion from } i \text{ to } j \text{ during } [Y_t,\ Y_{t+1}])100\%}{(\text{size of } i \text{ at time } Y_t)(\text{duration of } [Y_t,\ Y_{t+1}])} = \frac{(C_{tij})100\%}{\left(\sum_{j=1}^{J} C_{tij}\right)(Y_{t+1} - Y_t)} \tag{5}$$

$$W_{tj} = \frac{(\text{size of gain of } j \text{ during } [Y_t,\ Y_{t+1}])100\%}{(\text{size of not } j \text{ at time } Y_t)(\text{duration of } [Y_t,\ Y_{t+1}])} = \frac{\left[\left(\sum_{i=1}^{J} C_{tij}\right) - C_{tjj}\right]100\%}{\left\{\sum_{i=1}^{J}\left[\left(\sum_{j=1}^{J} C_{tij}\right) - C_{tji}\right]\right\}(Y_{t+1} - Y_t)} \tag{6}$$

2.3. Land use dynamic degrees

The CLUDD and the single land use dynamic degree are popular (Liu et al., 2014a; Quan et al., 2015). However, the literature has various versions of the equations. Our paper uses the versions that Eqs. (7) and (8) express. Eq. (7) gives the CLUDD, denoted L_{t+} during time interval $[Y_t, Y_{t+1}]$. L_{t+} is the sum of fractions that have different denominators when the sizes of the categories at time Y_t are different. L_{t+} does not account for the various sizes of the categories, thus the CLUDD lacks clear interpretation (Pontius et al., 2017). Quan et al. (2013) give a popular misinterpretation of L_{t+} that "The land use dynamic degree is thus defined as the rate of change of the total land area that was converted into other types of land use. The dynamic expresses in a comprehensive manner the dynamic change in land use for a given region." That interpretation is an appropriate description of the annual change percentage S_t, but S_t is different than L_{t+}.

$$L_{t+} = \sum_{i=1}^{J}\left\{\frac{(\text{size of loss of } i \text{ during } [Y_t,\ Y_{t+1}])100\%}{(\text{size of } i \text{ at time } Y_t)(\text{duration of } [Y_t, Y_{t+1}])}\right\} = \sum_{i=1}^{J}\left\{\frac{\left[\left(\sum_{j=1}^{J} C_{tij}\right) - C_{tii}\right]100\%}{\left(\sum_{j=1}^{J} C_{tij}\right)(Y_{t+1} - Y_t)}\right\} = \sum_{i=1}^{J} L_{ti} \tag{7}$$

Eq. (8) gives a popular version of the single land use dynamic degree N_{ti} during time interval $[Y_t, Y_{t+1}]$ for category i. N_{ti} is the annual net change expressed as a percentage of the size of category i at Y_t. N_{ti} reveals neither the loss nor the gain of category i. For example, N_{ti} is zero when the loss of category i equals gain of category i. The order of subscripts j and i in C_{tji} in the numerator of Eq. (8) is intentional, so that the first summation computes the size of category i at the final time Y_{t+1}.

$$N_{ti} = \frac{(\text{size of net change of } i \text{ during } [Y_t,\ Y_{t+1}])100\%}{(\text{size of } i \text{ at time } Y_t)(\text{duration of } [Y_t, Y_{t+1}])} = \frac{\left[\left(\sum_{j=1}^{J} C_{tji}\right) - \left(\sum_{j=1}^{J} C_{tij}\right)\right]100\%}{\left(\sum_{j=1}^{J} C_{tij}\right)(Y_{t+1} - Y_t)} \tag{8}$$

2.4. Organization of measurements

Fig. 2 shows the conceptual organization of the various intensities and land use dynamic degrees during time interval $[Y_t, Y_{t+1}]$. Intensity

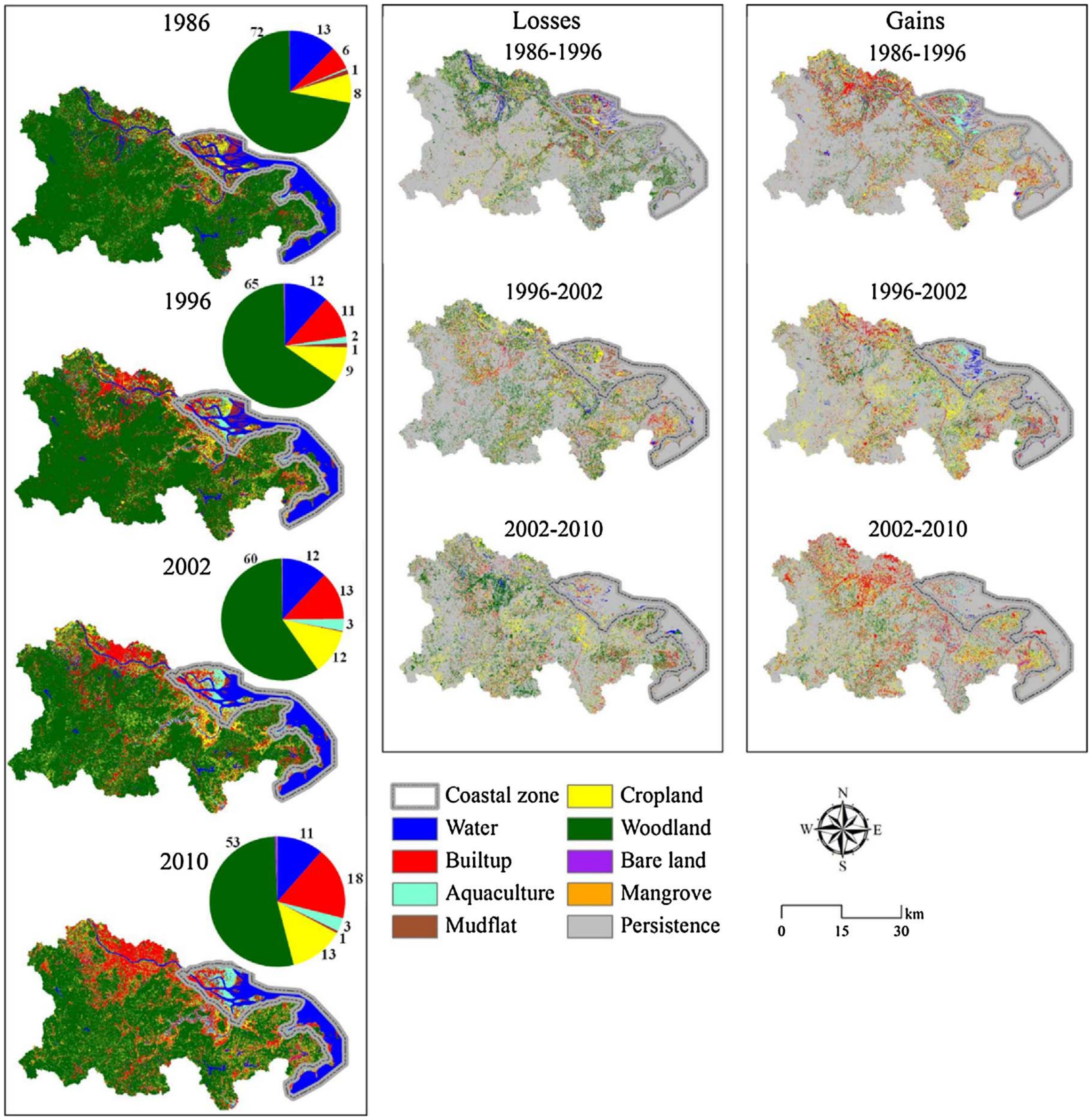

Fig. 3. Maps of land categories at four time points and three time intervals. The legend applies to all the maps. The maps of Loss and Gain include persistence, which means no change during the time interval. Numbers around the pies are percentages that are greater than one half of one percent.

Analysis' transition level compares the uniform transition intensity W_{ti} to its corresponding transition intensities R_{tij} within each column j to determine whether the gain of category j either avoids or targets its transition from category i. Intensity Analysis' category level compares the annual change percentage S_t to the loss intensities L_{ti} and the gain intensities G_{tj} to determine whether each loss and gain is dormant or active. The single land use dynamic degree N_{ti} reflects the annual net change of each category i relative to the size of category i at the interval's initial time. The CLUDD L_{t+} in the lower right corner of Fig. 2 is the sum of the loss intensities.

3. Results

3.1. Maps and contingency tables

Fig. 3 presents maps of the eight land categories at the four time points, along with losses and gains during each time interval. Table 3 shows transitions outside the coastal zone while Table 4 shows transitions inside the coastal zone. Woodland accounts for 70% or more of the area outside the coastal zone at all time points, and Water accounts for 56% or more of the area inside the coastal zone at all time points. Woodland has net decrease while Builtup has net increase in both zones during all time intervals. During 1986–2010, Cropland has net increase from 7% to 13% outside the coastal zone but net decrease from 10% to 7% inside the coastal zone.

3.2. Time interval level

Fig. 4 shows the results from the time interval level Intensity Analysis. The change percentage outside the coastal zone is less than the change percentage inside the coastal zone during the first time interval, while change percentages are equal in both zones during the second time interval. The change percentage outside the coastal zone is greater than the change percentage inside the coastal zone during the third time interval. If the annual changes were constant during the temporal extent, then the three bars that extend to the right from the middle axis would be at the uniform line U within each zone. Annual change is fastest during the second interval in both zones. Land change is faster than uniform during the second and third intervals outside coastal zone, while land change is faster than uniform during only the second interval

Table 3
Percent of area outside coastal zone for transitions from the categories in the rows to the categories in the columns. For each transition, the top number is during 1986–1996, the middle number is during 1996–2002, the bottom number is during 2002–2010. Blanks indicate less than one half of one percent. Bare lands and Mangroves had no transitions that are greater than one half of one percent. The Sum column at the right shows the category sizes at the initial year of each time interval. The Sum row at the bottom shows the category sizes at the final year of each time interval. Numerical rounding causes the illusion that some Sums appear incorrect. Loss is Sum at initial time minus persistence. Gain is sum at final time minus persistence.

From Category	Year	Water	Builtup	Aquaculture	Mudflat	Cropland	Woodland	Sum	Loss
Water	1986	1					1	3	2
	1996	2						3	1
	2002	2	1					3	1
Builtup	1986		3			1	2	6	3
	1996		6			1	4	11	5
	2002		8			2	3	12	5
Aquaculture	1986								
	1996							1	
	2002			1				1	1
Mudflat	1986								
	1996								
	2002								
Cropland	1986		1			2	4	7	5
	1996		3			3	3	9	6
	2002		2			5	5	13	8
Woodland	1986	1	7			6	69	83	14
	1996		3			9	63	76	13
	2002		7			7	55	70	15
Sum	1996	3	11	1		9	76	100	24
	2002	3	12	1		13	70	100	26
	2010	2	18	2		15	63	100	29
Gain		1	8	1		7	7	24	
		1	7	1		10	7	26	
		1	10	1		9	8	29	

inside coastal zone.

Table 5 compares the annual change percentage to the CLUDD for during three time intervals in the two zones. The annual change percentage is S_t of Intensity Analysis. The CLUDD outside the coastal zone is greater than the CLUDD inside the coastal zone during all three intervals, in spite of the fact the annual change percentage outside the coastal zone is not greater than the annual change percentage inside the coastal zone during the first two intervals. This illustrates how the CLUDD is not the annual change percentage S_t.

3.3. Category level

Fig. 5 shows the results from the category level Intensity Analysis, which gives one graph per time interval per zone. If the categorical losses and gains were uniform within each zone during each time interval $[Y_t, Y_{t+1}]$, then the bars that extend to the right from the middle axis would be at the uniform line S_t within each zone.

Some results are consistent during all three time intervals outside the coastal zone. Builtup, Cropland and Woodland have the largest losses and gains. Bare land and Mudflat have some of the highest intensities, but the sizes of their losses and gains are small, which indicates that their small sizes account for their high intensities. The intensities of Woodland's losses and gains are dormant due to Woodland's large size. The intensities of Builtup's and Cropland's losses and gains are active.

The region inside the coastal zone also has some results that are consistent across time intervals. Cropland and Woodland have the largest active losses while Builtup, Aquaculture and Cropland have the largest active gains. Bare land has some of the most intense losses and gains, due mainly to Bare land's small size, which accounts for at most 1% of the region inside the coastal zone at any time point.

The major similarities between outside and inside the coastal zone are that both zones experience sizeable losses of both Woodland and Cropland and active gains of both Builtup and Cropland. The major differences are that Mangrove does not exist outside the coastal zone and that Aquaculture outside the coastal zone is less than Aquaculture inside the coastal zone.

Table 6 gives the single land use dynamic degrees for the three time intervals and two zones. Table 6 lists 45 single land use dynamic degrees; 11 of the 45 are greater than 13%. Each of those 11 largest degrees derive from a category that accounts for less than 2% of the zone, implying that each large single degree is a combination of a small amount of change divided by small denominator. Moreover, Table 6 shows that degrees between −6% and 6% constitute 28 of the 45 single land use dynamic degrees, but those categories with the smallest absolute degrees account for more than half the change during each time interval in each zone. Furthermore, all the categories experience simultaneous loss and gain, but the single land use dynamic degree reflects net change, which is equal to gain minus loss. The sign of the single land use dynamic degree can be helpful to compare categorical intensities of net change, but the single land use dynamic degree does not show how each category contributes to overall change. In contrast, the left side of each graph in Fig. 5 shows that Intensity Analysis reveals how each category contributes to overall change, because the sum of losses equals the sum of gains, which equals overall change.

3.4. Transition level

This subsection shows Intensity Analysis' results for the transition level, for which the land use dynamic degrees offer no insight. We use the transition level Intensity Analysis to examine the gain of Builtup and the gain of Cropland.

Table 4
Percent of area inside coastal zone for transitions from the categories in the rows to the categories in the columns. For each transition, the top number is during 1986–1996, the middle number is during 1996–2002, the bottom number is during 2002–2010. Blanks indicate less than one half of one percent. Bare lands and Mangroves had no transitions that are greater than one half of one percent. The Sum column at the right shows the category sizes at the initial year of each time interval. The Sum row at the bottom shows the category sizes at the final year of each time interval. Numerical rounding causes the illusion that some Sums appear incorrect. Loss is Sum at initial time minus persistence. Gain is sum at final time minus persistence.

From Category	Year	Water	Builtup	Aquaculture	Mudflat	Cropland	Woodland	Sum	Loss
Water	1986	52	1	2	2		1	58	6
	1996	52	1	1		1		56	3
	2002	54	2	1	1			58	4
Builtup	1986	1	4	1		2	1	8	4
	1996	1	8	1		1	1	11	3
	2002		11	2		1		15	4
Aquaculture	1986			2				2	
	1996			6				7	1
	2002	1	1	9		1		12	3
Mudflat	1986	2		1	4			7	3
	1996	5			1			7	5
	2002				1			1	
Cropland	1986	1	1	1		5	2	10	5
	1996		4	3		3	1	11	8
	2002		2	1		3		7	3
Woodland	1986	1	5			4	6	15	10
	1996		2	1		4		9	5
	2002		2			1	3	7	3
Sum	1996	56	11	7	7	11	9	100	28
	2002	58	15	12	1	7	7	100	26
	2010	55	18	12	2	6	5	100	19
Gain		4	7	5	3	6	3	28	
		6	7	6		4	2	26	
		1	7	4	1	3	1	19	

Fig. 6 shows results from Intensity Analysis' transition level for Builtup's gain. The gain of Builtup derives mainly from Woodland and Cropland in both zones. A substantial portion of Builtup's gain inside the coastal zone derives from Water, which reflects reclamation processes. If Builtup's gain were spread uniformly across the non-Built categories at the initial time, then the intensity bars would end at the uniform line W_{tj}. Builtup's gain targets Cropland in both zones. Outside the coastal zone, Builtup's gain avoids Woodland, which reflects the large size of Woodland. Inside the coastal zone, Builtup's gain targets Woodland, which reflects the large transition from Woodland to Builtup.

Table 5
Results for annual change percentage S_t and the comprehensive land use dynamic degree (CLUDD) L_{t+}.

	1986–1996		1996–2002		2002–2010	
	Outside	Inside	Outside	Inside	Outside	Inside
Annual Change Percentage	2.4	2.8	4.3	4.3	3.7	2.3
CLUDD	41	30	64	60	43	32

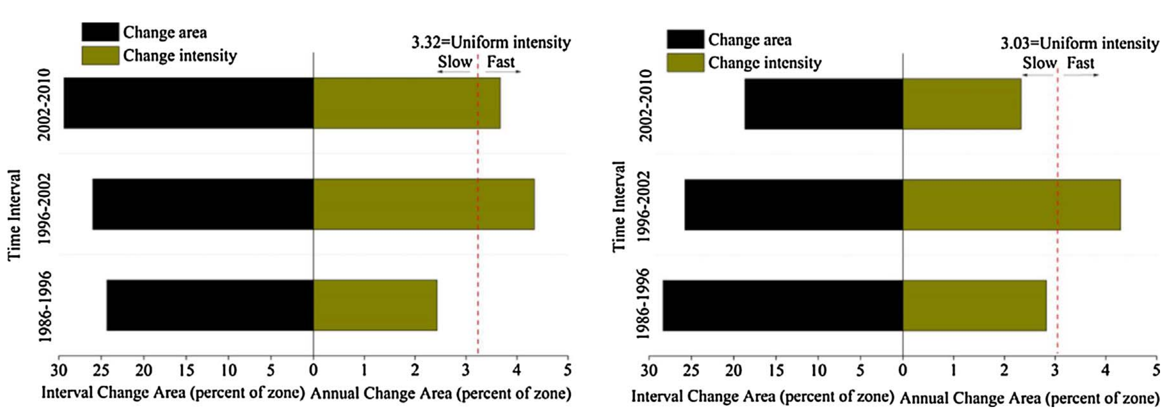

Fig. 4. Time Interval level Intensity Analysis for three time intervals. Graph on left shows outside the coastal zone. Graph on right shows inside the coastal zone. Each bar that extends from the middle axis to the left is the size of the change during the time interval as a percentage of the zone. Each bar that extends from the middle axis to the right is the annual change percentage S_t. Each intensity bar to the right is equivalent to the size of the bar to the left divided by the time interval's duration. Each dashed line is the uniform temporal intensity U within each zone.

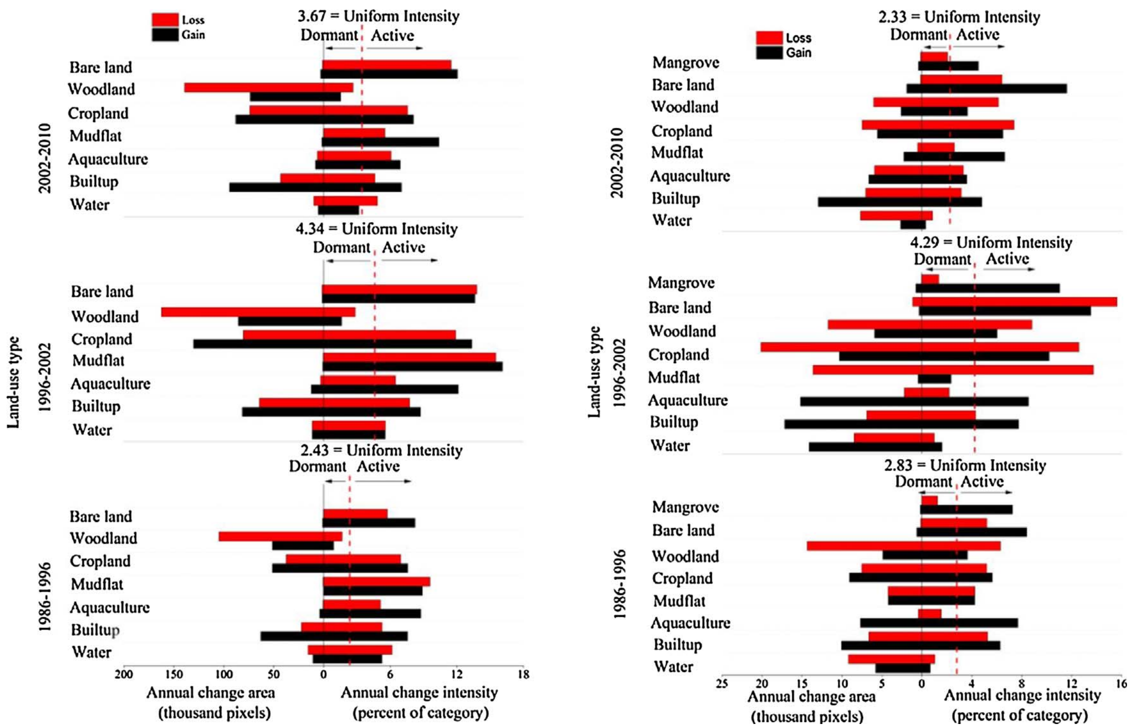

Fig. 5. Category level Intensity Analysis for three time intervals. Graphs on left show outside the coastal zone. Graphs on right show inside the coastal zone. Each category has a pair of bars, where the top bar shows loss and the bottom bar shows gain. Bars that extend from the middle axis to the left are the sizes of annual loss or gain. Bars that extend from the middle axis to the right are the intensities of loss L_{ti} or gain G_{tj}. Each intensity bar to the right is equivalent to the size of the bar to the left divided by the category's size. Each dashed line is the uniform spatial intensity S_t during each time interval within each zone.

Table 6
Results for the single land use dynamic degrees N_{ti}.

Single Category	1986–1996		1996–2002		2002–2010	
	Outside	Inside	Outside	Inside	Outside	Inside
Water	−2	0	0	1	−2	−1
Builtup	10	3	2	6	5	3
Aquaculture	30	26	21	13	2	0
Mudflat	−6	0	19	−13	29	9
Cropland	3	1	7	−6	1	−2
Woodland	−1	−4	−1	−4	−1	−3
Bare land	14	20	−1	−11	16	72
Mangrove		22		29		4

Fig. 7 shows results from Intensity Analysis' transition level for Cropland's gain in a format parallel to how Fig. 6 shows Builtup's gain. The gain of Cropland derives mainly from Woodland in both zones. There are substantial transitions from Builtup to Cropland, which might indicate error in the data. Cropland's gain usually avoids Woodland outside the coastal zone, which is due to Woodland's large size. Cropland's gain targets Woodland inside the coastal zone during all three time intervals.

4. Discussion

4.1. Intensity Analysis versus the land use dynamic degrees

Intensity Analysis gives insight to land change mainly because Intensity Analysis shows graphically the sizes and the intensities of the changes at each of three levels of analysis. The land use dynamic degrees were not particularly helpful to understand the patterns of land change, because the CLUDD lacks clear interpretation while the single degree does not show the size of each category's loss, gain and net change.

The CLUDD outside the coastal zone is greater than the CLUDD inside the coastal zone during all time intervals mainly because the region outside the coastal zone has some small categories that lead to large loss intensities due to small denominators. The CLUDD is the sum of the loss intensities across all categories during a time interval in a zone. Fig. 5 shows that some of the largest loss intensities are associated with some of the smallest losses. For example, Bare land has consistently one of the largest loss intensities, but Bare land accounts for at most 1% of either zone at any time point. This illustrates how small categories can have large influences on the CLUDD, and how the CLUDD does not indicate the annual change percentage. Furthermore, Fig. 5 shows that Woodland has the largest losses but the smallest loss intensities during all three time intervals outside the coastal zone, thus Woodland's large losses do not contribute very much to the CLUDD outside the coastal zone. The CLUDD indicates mainly whether a zone has a few large loss intensities, but large intensities frequently derive from small categories. Furthermore, it is misleading to compare the CLUDD outside the coastal zone versus the CLUDD inside the coastal zone, because outside the coastal zone has seven categories while inside the coastal zone has eight categories, due to the addition of mangroves. Thus the CLUDD outside the coastal zone is the sum of seven loss intensities while the CLUDD inside the coastal zone is the sum of eight loss intensities.

The single land use dynamic degrees are sensitive to the sizes of the categories. Fig. 8 shows that the categories that are largest at the initial time tend to have degrees near zero, while the categories with the largest degrees have small sizes at the initial time. The reason is that the size of the category at the initial time is in the denominator of the single degree.

The inclusion of large dormant categories influences both Intensity Analysis and the land use dynamic degrees. Water is the large dormant category inside the coastal zone, meaning that Water accounts for most of the area and is dormant according to category level Intensity Analysis. Fig. 1 shows how the boundary for inside the coastal zone includes a substantial amount of persistent Water, which is somewhat

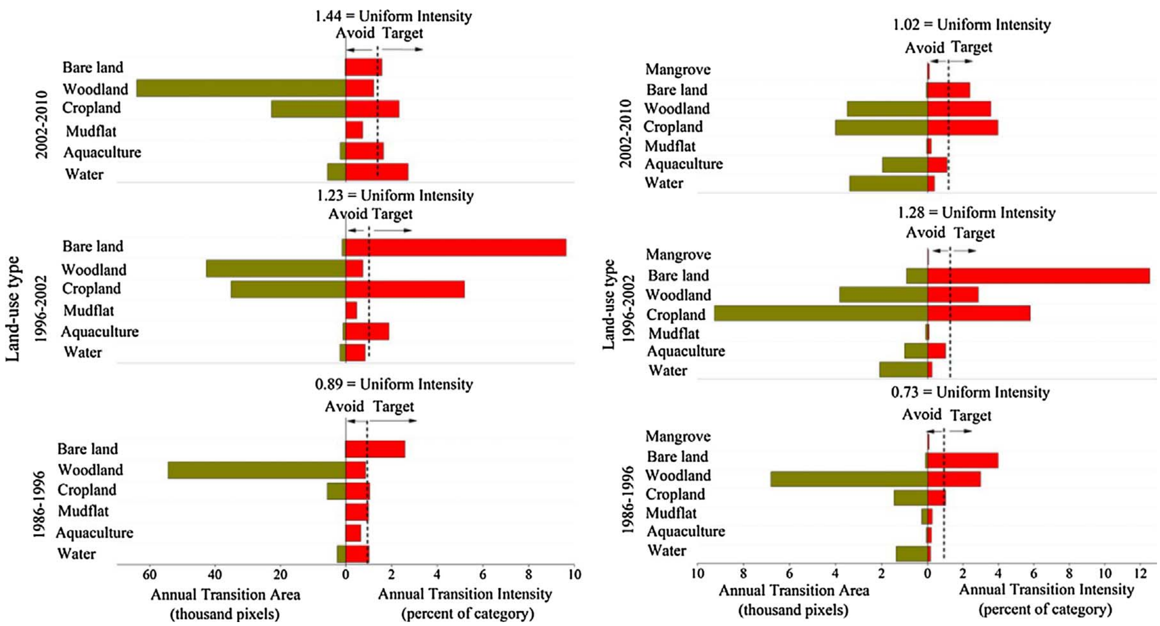

Fig. 6. Transition level Intensity Analysis for Builtup's gain. Graphs on left show outside the coastal zone. Graphs on right side show inside the coastal zone. Bars that extend from the middle axis to the left show the size of each annual transition. Bars that extend from the middle axis to the right show the intensity R_{tij} of each annual transition. Each intensity bar to the right is equal to the size of the bar to the left divided by the size of the losing category at the interval's initial time. Each dashed line is the uniform transition intensity W_{tj} for Builtup's gain during each time interval within each zone.

arbitrary because the boundary is a political boundary. Scientists have no clear rules for how much water should be included in a spatial extent when examining coastal zones. If we were to have included more persistent Water, then the overall annual change percentage and Water's single degree would decrease. If we were to have included less persistent Water, then the overall annual change percentage and Water's single degree would increase. Similarly, Woodland is a large dormant category outside the coastal zone. It is not clear that it makes sense to include regions of Woodland where the Woodland is remote from human activity and is on steep slopes that are undesirable for cultivation or habitation. Scientists have no clear rules for how to draw a boundary for a spatial extent, but the boundary of the spatial extent influences the results. This fact hampers comparison between spatial extents. For example, the uniform lines in Fig. 4 show that annual change percentage outside the coastal zone is greater than inside the coastal zone during the temporal extent, but one reason is that substantial area of persistent Water exists inside the coastal zone. Therefore, it can be challenging to compare the annual change percentage across zones. Consequently, it is more important to interpret the intensities relative to each other, as opposed to relative to only the uniform line within each graph of Intensity Analysis. Inclusion of a large dormant category influences the uniform line, but does not influence the intensities of the other categories.

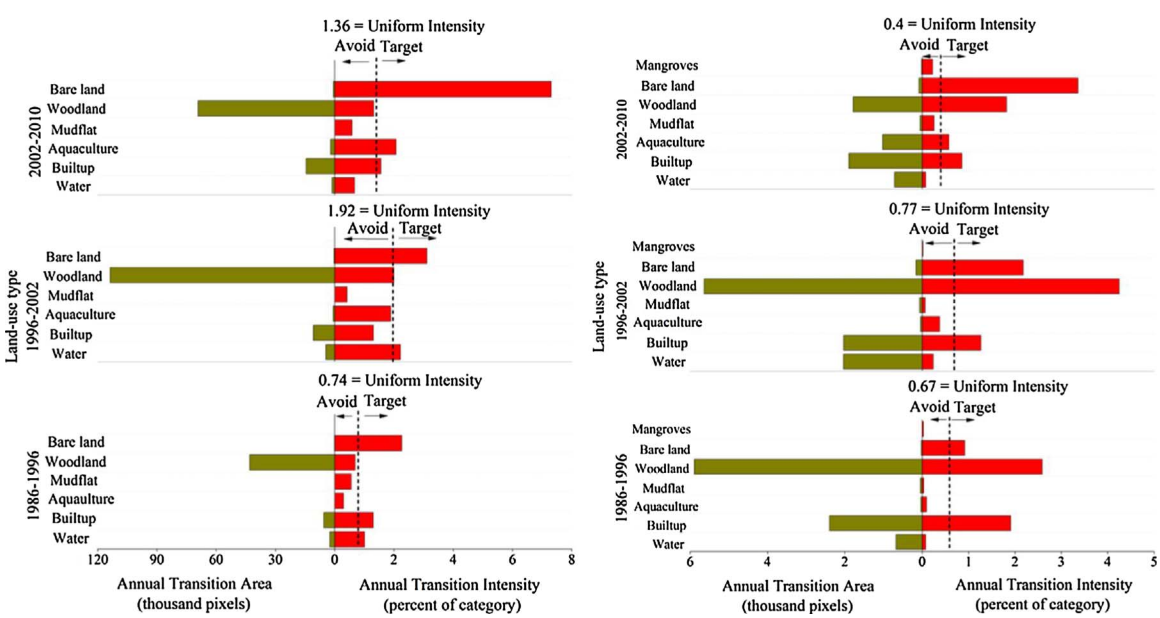

Fig. 7. Transition level Intensity Analysis for Cropland's gain. Graphs on left show outside the coastal zone. Graphs on right side show inside the coastal zone. Bars that extend from the middle axis to the left show the size of each annual transition. Bars that extend from the middle axis to the right show the intensity R_{tij} of each annual transition. Each intensity bar to the right is equal to the size of the bar to the left divided by the size of the losing category at the interval's initial time. Each dashed line is the uniform transition intensity W_{tj} for Cropland's gain during each time interval within each zone.

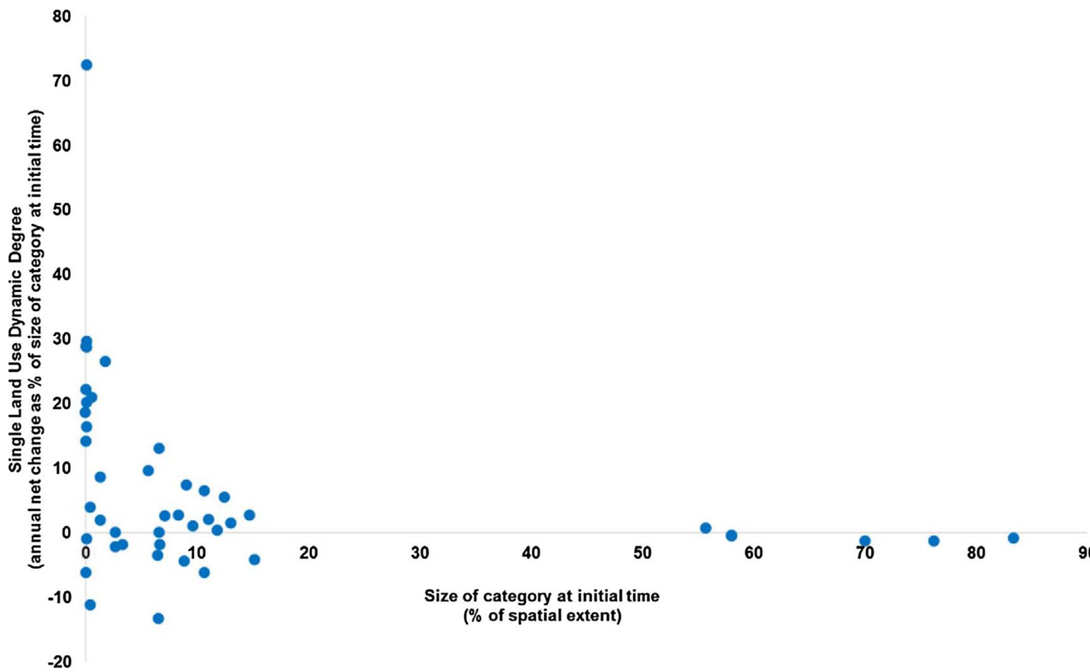

Fig. 8. Single land use dynamic degree from Table 6 versus size of category at initial time, where each point is a category during a particular time interval in a particular zone.

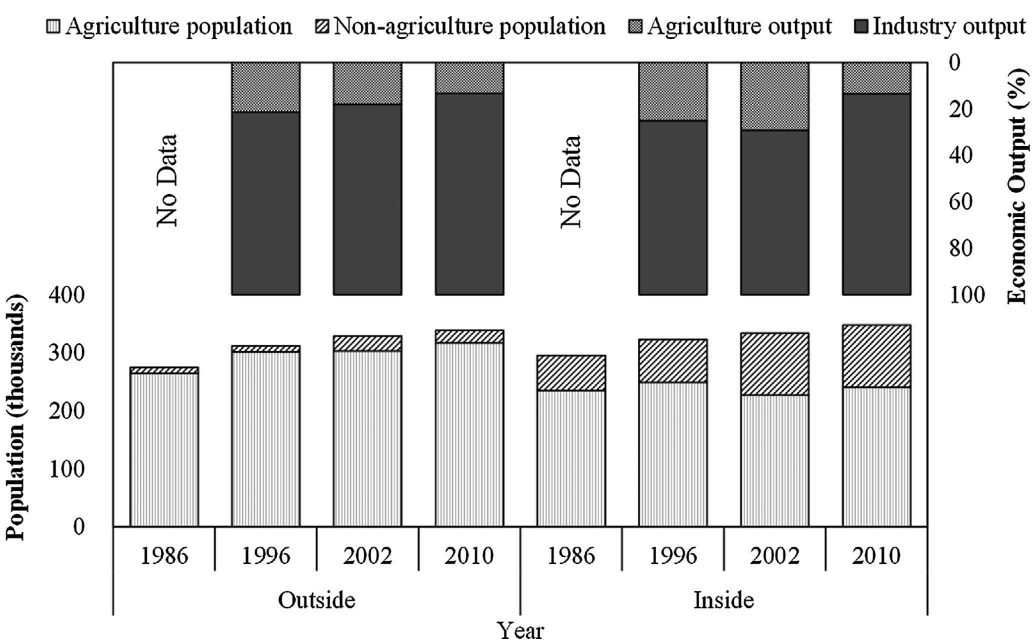

Fig. 9. Population and composition of output of industry and agriculture in Longhai. Data are from Longhai Statistical Yearbooks.

4.2. Linking patterns with processes

Population growth and economic development can help to drive land change in some places but not in others (Lambin et al., 2001; Schneider and Mertes, 2014). Fig. 9 shows population and two components of economic output at the time points of our maps. Total population has been consistently increasing in both zones, while Agricultural population has been fairly constant inside the coastal zone. In both zones, industry accounts for an increasing percentage of the economic output from 1996 to 2010. We see no immediately obvious connections between the socioeconomic information in Fig. 9 and the land change information in Fig. 4. Land change is fastest during the middle of three time intervals in both zones of Longhai. Quan et al. (2015) had a similar observation in Quanzhou during the intervals 1995–2000, 2000–2005, and 2005–2010, when land change was fastest during the middle interval but population growth was not greatest during the middle interval. Quanzhou and Longhai are similar cities that are close to each other on the coast. They are undergoing relative slow population growth, compared with larger cities such as Shenzhen and Dongguang. Table 6 shows the single land use dynamic degree for Builtup ranges from 2% to 10% outside coastal zone and from 3% to 6% inside coastal zone during three time intervals in Longhai, whereas the single land use dynamic degree for urban ranges from 4% to 21% in Shenzhen and Dongguan city (Chen et al., 2014).

From 1986–1996, Cropland increased outside the coastal zone but decreased inside the coastal zone. The national agricultural policy has aimed to influence cropland. The Household Contract Responsibility System was formulated in the late 1970s and spread widely during the early 1980s in Fujian province. This policy greatly stimulated the local farmers to seek the maximum benefit from agricultural production (Ye and Huang, 2009). Since 1994, national and local governments have put forward a series of policies and regulations, including the Regulation for the Protection of Basic Farmland in 1994, which to some degree prohibited the removal of basic farmland from cultivation (Chen et al., 2007; Lin and Ho, 2005; Liu et al., 2014a). The policies also encouraged agricultural industrialization in Longhai (Wu, 2002; Ye et al., 2005). In addition, advantageous climate conditions and proximity to Taiwan might have contributed sustaining agricultural activities in Longhai city during the recent three decades (Huang et al., 2012).

Spatially expanding urban growth is one of the leading causes of arable land loss in eastern coastal China (Seto and Fragkias, 2005; Liu et al., 2013; Deng et al., 2015). The gain of Builtup derives mostly from Woodland and Cropland in Longhai. Agricultural activities have historically been located in flat areas, thus towns have tended to be in flat areas (Aspinall, 2004; Muller et al., 2010; Dubovyk et al., 2011; Li et al., 2013; Ye et al., 2013). Thus, if the Builtup area expands spatially, then the gain of Builtup area is likely to derive from cropland. This might explain why the gain of Builtup targeted Cropland during all three time intervals in both zones of Longhai. The gain of Builtup avoids Woodland outside coastal zone during all time intervals. This is most likely due to the fact that Woodland is far away from expanding cities, and Woodland is a large dormant category outside coastal zone. These results in Longhai are similar to our prior studies in the Jiulong River watershed (Huang et al., 2012; Zhou et al., 2014).

Inside the coastal zone has limited space with higher requirements for development compared to outside the coastal zone of Longhai. Ocean reclamation can provide space for industrialization and urbanization, thus reclamation is a common way for humans to use oceans in coastal zones. Consequently, some of the gain of Builtup derives from Water inside the coastal zone.

Figs. 6 and 7 show that the gains of Builtup and Cropland avoid Mangroves during all three time intervals, offering some evidence of the effectiveness of mangrove protection. Xue (2006) report that the government attempted to protect mangroves through steps such as the establishment of the Longhai provincial mangrove nature reserve area in 1986 within the Jiulong river estuary; nevertheless, wharfs and shrimp ponds were built in coastal areas during the middle 1980s. The expansion of wharf and shrimp ponds might explain why Aquaculture's land use dynamic degree is the highest in both zones during 1986–1996. Since then, local governments have paid more attention to the ecological benefits of mangroves and their economic impact on the surrounding communities. The extent of the mangrove protection area in Longhai was expanded with the support of the Fujian provincial government from 200 ha in 1988 to 420 hectares in 2006.

4.3. Implications for land management

There can be a tension between economic development and environmental protection. Cropland has increased outside the coastal zone while Aquaculture has increased in both zones. Mangrove has increased during all three time intervals, indicating that efforts at mangrove protection might be having the desired effect.

Both zones experienced substantial losses from Cropland. Livelihoods of landless peasants have become a major concern in several rapidly urbanizing coastal areas of China (Long et al., 2010; Liu et al., 2014b). It is not clear whether local governments are protecting farmer's rights sufficiently. Given that Cropland shrunk and Aquaculture grew inside the coastal zone, future plans for reclamation and urbanization should consider the costs and benefits to farmers in Longhai, especially concerning the transition from Cropland to Builtup.

Deforestation should be taken seriously especially inside coastal zone. Longhai's valuable Woodland and Cropland are now in jeopardy of becoming Builtup in the near future as land for urban development is already limited inside the coastal zone. This is analogous to the situation of the Philippines' Metro Manila, which faces losses of green space in an environment that has already been seriously damaged (Estoque and Murayama, 2015). Meanwhile, outside the coastal zone of Longhai still has large tracts of land that can accommodate future urban development, which is similar to Thailand's Bangkok Metropolitan Region (Estoque and Murayama, 2015). We wonder whether urbanization in Longhai will cause its future outside coastal zone to become similar to its current inside coastal zone, which has limited open space.

5. Conclusions

Our paper compares Intensity Analysis to the land use dynamic degrees to reveal each framework's abilities and limitations. Intensity Analysis shows graphically both the sizes and the intensities of changes, arranged in hierarchical levels. Intensity Analysis is helpful when interpretation focuses more on the relative sizes of the intensities, and less on how the intensities relate to the uniform intensity, because arbitrary selection of the spatial extent can create large dormant categories that influence the uniform intensity. In our Longhai example, Woodland and Water influence the uniform intensity at each level of analysis, because Woodland is a large dormant category outside the coastal zone and Water is a large dormant category inside the coastal zone.

We recommend that authors do not use the version of the CLUDD that is the sum of loss intensities, because that version of the CLUDD has no practical interpretation. Many authors misinterpret the CLUDD to be the annual change percentage, which the CLUDD is not. In Longhai, the CLUDD reflects the behaviour of a few small categories, while the CLUDD discounts the categories that are responsible for the majority of change. The single land use dynamic degree requires careful and constrained interpretation. The single degree shows whether a single category has a negative or positive net change. However, the single degree fails to reveal a category's loss, gain and size of net change. The single degrees in Longhai tend to be large for small categories and small for large categories, because the size of the category appears in the denominator of the single degree, as Eq. (8) shows. Meanwhile, small categories typically account for a minority of the overall change while large categories typically account for the majority of overall change.

For the application to Longhai, Intensity Analysis revealed information that gives insight to processes of change. Intensity Analysis at the time interval level showed that overall change was fastest during the middle of the three time intervals in both zones of Longhai, which is something that the CLUDD failed to show. Land change did not follow population, which increased consistently during the temporal extent. Intensity Analysis at the category level showed that Woodland and Cropland accounted for the largest losses while Builtup and Cropland accounted for the largest gains in both zones. The presence of Mangrove and substantial gains in Aquaculture exist inside the coastal zone but not outside the coastal zone. Intensity Analysis' transition level showed that Builtup's gain derived mainly from Woodland and Cropland, while Builtup's gain intensively targeted Bare land in both zones. Cropland's gain derived mainly from Woodland, while Cropland's gain intensively targeted Bare land in both zones. The transition from Cropland to Builtup was substantial in both zones in spite of policies to conserve Cropland, as industry accounted for an increasing percentage of the economy.

Conflicts of interest

None.

Acknowledgements

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