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RESEARCH ARTICLE

A method of characterizing land-cover swap changes in the arid zone of China

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Abstract Net area change analysis can dramatically underestimate total change of land cover, even sometimes seriously misinterpret ecological processes of the ecosystem, especially in arid or semiarid zones. In this paper, a suite of indices are presented to characterize land-cover swaps that may seriously damage the ecosystem in arid or semiarid zones, based on swap-change areas extracted from remotely sensed images. First, swap percentage of total area and swap intensity of total changes were used to determine the status of land-cover swap change in an area. Then, dominated swap category and individual swap-change intensity for a land-cover category were used to determine flagged land-cover swap-change categories. Finally, swap-change mode and Pielou's index were used to determine the land-cover swap-change processes of dominant categories. A case study is conducted using this approach, based on two land-cover maps in the 1980s and 2000 in Naiman Qi, Tongliao City, Inner Mongolia, China. This study shows that the approach can clearly quantify the severity and flagged classes of land-cover swap-change and reveal their relationship with ecological processes of the ecosystem. These results indicate that the approach can give deep insights into swap change, which can be very valuable to land-cover policy making and management.

Keywords land cover swap, swap-change status, flagged swap-change categories, swap-change process, arid/semi-arid zone

1 Introduction

Timely and accurate information on land-cover change is vital for better understanding of the relationships and interactions between humans and the natural environment (Li et al., 2003; Lu et al., 2004; Li and Zhou, 2009). In arid environment where fragile ecosystems are dominant, land-cover change from excessive human activities often has the most significant impact on the environment (Zhou et al., 2008). Thus, better understanding of the causes of such change is essential so that effective countermeasures can be taken (Zhou et al., 2011).

Land-cover change detection focuses on four aspects: 1) detecting if change has occurred; 2) identifying the nature of the change; 3) measuring areal extent of the change; and 4) assessing the spatial pattern of the change (Macleod and Congalton, 1998). Among these four, measuring the areal extent of change is the most fundamental in land-cover change analysis (Nagendra et al., 2004; Narumalani et al., 2004).

A commonly used index for measuring this areal extent over a study period is Area Net Change (ANC)(Robbins and Birkenholtz, 2003; Huang et al., 2012; Poulter et al., 2013; Teferi et al., 2013; Wang et al., 2013), which indicates the areal difference for a land-cover type or entire study area between two points in time. These data can be used to analyze annual net or change rate so that we can understand land-cover trends more directly. However, such analyses are limited because net change may fail to reveal total change of the land cover, since zero net change does not necessarily imply lack of change (Braimoh, 2006). Thus, net change can dramatically underestimate total change of the land cover (Pontius et al., 2004) and can sometimes seriously misinterpret ecological processes of the ecosystem, especially in arid or semiarid zones.

As an example, because there is commonly strong variation of annual precipitation in such zones (Kassas, 1995), grassland has been reclaimed as cropland in wet years to produce more grain and profit, together with a rapid increase of population and land development in recent decades. However, in subsequent dry years, some

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cropland reclaimed from grassland or bushland was abandoned owing to water shortage. To combat desertification of the abandoned cropland, trees or bushes were planted. Thus, over a given period, net change of cropland was slight, but land cover related to cropland greatly increased. Thus, results based on the commonly used ANC method underestimate the serious damage to native ecosystems caused by the reclamation and abandonment of grassland or bush ecosystems. It is very important to quantify this type of land-cover swap with regard to ecological processes in arid zones.

Pontius et al. (2004) presented a Swap Change (SC) method to quantify this type of swap. A swap refers to a loss amount of a land-cover type at a location that is accompanied by the same amount of gain of this type at another location. The swap change for this land-cover type is total change minus net change for that category (Pontius et al., 2004; Manandhar et al., 2010). Thus, swap-change areas can be used to determine the amount swapped for a land-cover type.

Analysis of the amount swapped with other land cover for a land-cover type based on the SC method is instructive (Braimoh, 2006; Manandhar et al., 2010; Pérez-Hugalde et al., 2011; Teferi et al., 2013), but it fails to accurately reflect the severity of land-cover swaps as a whole in an area or in a land-cover category. The method also fails to specify whether land-cover swaps occur in all land-cover categories or only for limited land covers, and which are the major categories affected by the land-cover interchanges. Analysis can be linked with ecological processes, especially the ecological damage in arid or semiarid zones, and it is thus very important to quantify the land-cover swaps based on swap-change areas.

In this paper, we present a suite of indices to characterize land-cover swaps that can indicate serious damage to the ecosystem in arid or semiarid zones, based on swap-change areas extracted from remotely sensed images. The rest of the paper is organized as follows. Section 2 introduces the study area and gives the methodology for characterizing land-cover swaps. Case study results are given in Section 3. In Section 4, we discuss our methodology. A brief conclusion is presented in Section 5.

2 Method

2.1 Study area

The study area is Naiman Qi (an administrative unit similar to a county or city in a region with a minority population) in Tongliao City, Inner Mongolia, China (Fig. 1). The area is in a semiarid zone of northeast China, and covers approximately 8,137.6 km^2. Geographic coordinates are 42°37′21″N–43°32′20″N and 120°19′40″E–121°35′40″E. The elevation ranges between 220 m and 270 m a.s.l.

The landscape in Naiman Qi is characterized by sand

Fig. 1 Location of study area.

dunes alternating with gently undulating meadows. Soil on the dunes is sandy in texture, light in color, loose in structure, and susceptible to wind erosion (Zhang et al., 2004). Undisturbed vegetation on the sand dunes is composed of *Stipa grandis*, *Leymus chinensis*, and *Agropyron cristatum* communities with sparsely scattered woods (mainly *Ulmus pumila*), and is currently dominated by *Artemisia halodendron* communities (Li et al., 2003). Extensive areas of meadow between the dunes have been cultivated as cropland.

Naiman Qi is at the eastern fringe of a semiarid zone. The temperate, semiarid, and continental climate is mainly governed by the southeast monsoon, with windy and dry winters and springs. There are warm and comparatively wet summers, followed by short, cool autumns (Li et al., 2002). Annual precipitation ranges from 350 to 450 mm. Annual average temperature varies from 5.8°C to 6.4°C. Annual average wind velocity is from 3.5 to 4.5 m/s.

2.2 Data and data preprocessing

Land-cover data in the 1980s and 2000 for the study area were obtained from the China National Land Use Database, established by the Chinese Academy of Sciences (http://www.resdc.cn/rescode/data-list.asp). The data were produced by visual interpretation using Landsat TM/ETM+ imagery. A two-level hierarchical classification system was applied to these data (Table 1). Six classes and 25 classes were categorized into a first and second level classification system, respectively. We used a land-cover map with 6 classes based on the first level system. Because overall accuracy of the land-cover classification for this database was high, with 92.9% for the 25 land-cover classes (Liu et al., 2005), we believed this data set to be accurate enough for exploring swap change.

2.3 Methodology

Figure 2 shows the framework of swap-change analysis for indicating serious damage to the ecosystem in arid or semiarid zones. First, a transitional matrix was established based on land-cover change maps over a study period and computed gain, loss, and swap for every land-cover category. Thus, the amount of swap change was obtained for each category.

Second, it was determined whether the land-cover swap change should focus on consideration of the entire study area. Swap percentage of total area (SPTA) and swap intensity of total changes (SITC) were determined (all indices are discussed in detail below). If SPTA or SITC is high in an area, we should pay more attention to land-cover swap change in that area and study related features.

Third, the flagged land-cover swap-change categories were established. Dominated swap category (DSC) and individual swap-change intensity (ISCI) for a land-cover category were used to this end. If DSC or ISCI is high for a land-cover category in an area, this category should be investigated in that area.

Finally, the process of land-cover swap changes of the dominant land-cover categories was evaluated. The swap-change mode (SCM) and Pielou's Index (PI) for a land-cover category were determined. The SCM was used to indicate whether gain and loss of land-cover swap changes for a land-cover category were mainly from the same land cover or from different categories (details are given in Section 2.3.4). PI was used to indicate whether land-cover swaps whose gain and loss were from the same land cover were from most land cover swap types or only limited classes.

2.3.1 Gain, loss, swap, and total change

Table 2 shows the transition matrix for n-land-cover class change from time 1 to 2. Taking row i and column j as an example, P_{ij} represents the area of land cover transformed from category i to j over this period. The first subscript refers to land-cover category i at time 1 and the second to category j at time 2. When i equals j, P_{kk} represents the area of land-cover category k remaining unchanged.

The column "Total," i.e., the sum of all entries P_{ij} in row i, indicates the area of land cover of category i at time 1. The row "Total," i.e., the sum of all entries P_{ij} in column j, indicates the area of land cover of category j at time 2. The column "Loss" on the right indicates the total amount of land cover of category i that changes to other categories between time 1 and 2. The row "Gain" on the bottom indicates the total amount of land cover of category j obtained from other categories between time 1 and 2. For each category j, "Swap" is defined as twice the minimum of the gain and loss, as in Pontius et al. (2004).

Basic notations, indices of gain, loss, and swap are listed in the table and are used in the rest of the paper:

n is the number of total land-cover categories;

i is the i^{th} category at the initial time;

j is the j^{th} category at the final time;

P_{ij} is the area changed from i to j over the period;

Gain_j is the total area changed from other types to j over the study period:

$$\text{Gain}_j = \sum_{i=1}^{n} P_{ij} - P_{jj}, \quad (1)$$

Loss_j is the total area changed from j to other types over the study period:

$$\text{Loss}_j = \sum_{i=1}^{n} P_{ji} - P_{jj}, \quad (2)$$

Nchange_j is the net change area of land-cover type j over the study period:

$$\text{Nchange}_j = \left|\text{Gain}_j - \text{Loss}_j\right|, \quad (3)$$

Table 1 The land-cover classification system (Liu et al., 2005)

1st level classes	2nd level classes	Descriptions
Cropland		Cultivated lands for crops. Including: mature cultivated land, newly cultivated land, and fallow, shifting cultivated land; intercropping land such as crop-fruiter, crop-mulberry, and crop-forest land in which a crop is a dominant species; bottomland and beach that cultivated for at least 3 years.
	Paddy land	Cropland that has enough water supply and irrigation facilities for planting paddy rice, lotus etc., including rotation land for paddy rice and dry farming crops.
	Dry land	Cropland for cultivation without water supply and irrigating facilities; cropland that has water supply and irrigation facilities and planting dry farming crops; cropland planting vegetables; fallow land.
Woodland		Lands growing trees including arbor, shrub, bamboo and for forestry use.
	Forest	Natural or planted forests with canopy cover greater than 30%.
	Shrub	Lands covered by trees less than 2 m high, the canopy cover > 40%.
	Woods	Lands covered by trees with canopy cover between 10%–30%.
	Others	Lands such as tea-garden, orchards, groves and nurseries.
Grassland		Lands covered by herbaceous plants with coverage greater than 5%, including shrub rangeland and mixed rangeland with the coverage of shrub canopies less than 10%.
	Dense grass	Grassland with canopy coverage greater than 50%.
	Moderate grass	Grassland with canopy coverage between 20% and 50%.
	Sparse grass	Grassland with canopy cover between 5% and 20%.
Water body		Lands covered by natural water bodies or lands with facilities for irrigation and water reservation.
	Stream and rivers	Lands covered by rivers including canals.
	Lakes	Lands covered by lakes.
	Reservoir and ponds	Man-made facilities for water reservation.
	Permanent ice and snow	Lands covered by perennial snowfields and glaciers.
	Beach and shore	Lands between high tide level and low tide level.
	Bottomland	Lands between normal water level and flood level.
Built-up land		Lands used for urban and rural settlements, factories and transportation facilities.
	Urban built-up	Lands used for urban.
	Rural settlements	Lands used for settlements in villages.
	Others	Lands used for factories, quarries, mining, oil-field slattern outside cities and lands for special uses such as transportation and airport.
Unused land		Lands that are not put into practical use or difficult to use.
	Sandy land	Sandy land covered with less than 5% vegetation cover.
	Gobi	Gravel covered land with less than 5% vegetation cover.
	Salina	Lands with saline accumulation and sparse vegetation.
	Swampland	Lands with a permanent mixture of water and herbaceous or woody vegetation that cover extensive areas.
	Bare soil	Bare exposed soil with less than 5% vegetation cover.
	Bare rock	Bare exposed rock with less than 5% vegetation cover.
	Others	Other lands such as alpine desert and tundra.

$Swap_j$ is the total area of swap change of category j:

$$\mathrm{Swap}_j = 2 \times \mathrm{Min}(\mathrm{Gain}_j, \mathrm{Loss}_j), \tag{4}$$

$Tchange_j$ is the total area of land-cover change related to category j; it includes both land-cover net change and swap of category j:

$$\mathrm{Tchange}_j = \mathrm{Nchange}_j + \mathrm{Swap}_j. \tag{5}$$

2.3.2 Determining the status of land-cover swap change in an area

Two indices were used to determine flagged areas of land-cover swap changes. The first was SPTA, which indicates the percentage of total swap-change area to the entire study area. The higher the SPTA, the more important are the land-cover swap changes. SPTA is expressed as

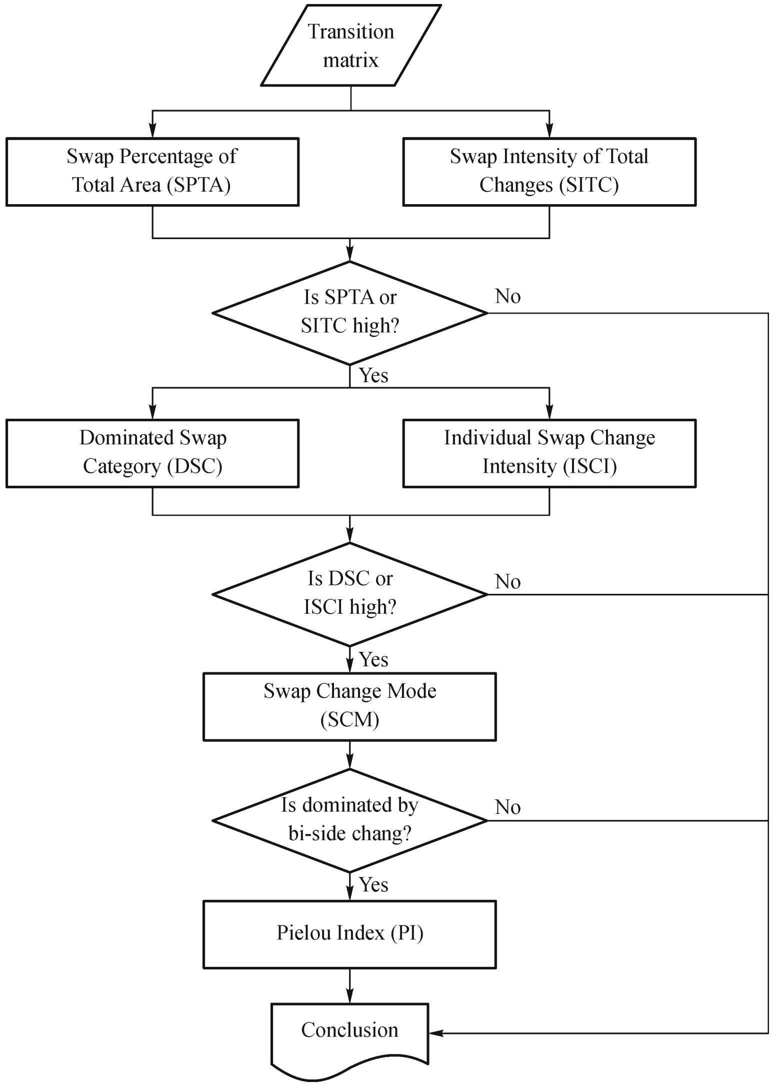

Fig. 2 Framework of swap-change analysis.

$$\mathrm{SPTA} = \frac{\sum_{j=1}^{n} \mathrm{Swap}_j}{2 \times S_w} \times 100\%, \tag{6}$$

where S_w is the entire study area; other notations are explained in Section 2.3.1. The swap area of each land-cover pair is calculated two times in the numerator of Eq. (6). For example, the swap area of cropland and woodland is calculated in the total swap area of cropland, and then it is calculated in the total swap area of woodland, too. Therefore, the total swap change area is computed by $\sum_1^j \mathrm{Swap}_j/2$.

Sometimes total swap change over the study area is not substantial, giving a small SPTA, but land-cover swap represents most land-cover changes. This means that most such changes were swap changes and should be considered. This is quantified by SITC, which is

$$\mathrm{SITC} = \frac{\sum_{j=1}^{n} \mathrm{Swap}_j}{\sum_{j=1}^{n} (\mathrm{Swap}_j + \mathrm{Net}_j)} \times 100\% = \frac{\sum_{j=1}^{n} \mathrm{Swap}_j}{\sum_{j=1}^{n} (\mathrm{Gain}_j + \mathrm{Loss}_j)} \times 100\%. \tag{7}$$

When SPTA or SITC is high, the swap-change phenomenon in an area should be addressed, and it should confirm which land-cover categories contribute most to the entire swap change. The thresholds of SPTA and SITC can be determined based on the impact of swap change on land degradation, and may vary in different ecoregions. In the

Table 2 General transition matrix for detecting land-cover change

From (time 1)	To (time 2)							Total	Loss
	Class 1	Class 2	…	Class k	Class j	…	Class n		
Class 1	P_{11}	P_{12}	…	P_{1k}	P_{1j}	…	P_{1n}	$\sum_{j=1}^{n} P_{1j}$	$\sum_{j=1}^{n} P_{1j} - P_{11}$
Class 2	P_{21}	P_{22}	…	P_{2k}	P_{2j}	…	P_{2n}	$\sum_{j=1}^{n} P_{2j}$	$\sum_{j=1}^{n} P_{2j} - P_{22}$
…	…	…	…	…	…	…	…	…	…
Class k	P_{k1}	P_{k2}	…	P_{kk}	P_{kj}	…	P_{kn}	$\sum_{j=1}^{n} P_{kj}$	$\sum_{j=1}^{n} P_{kj} - P_{kk}$
Class i	P_{i1}	P_{i2}	…	P_{ik}	P_{ij}	…	P_{in}	$\sum_{j=1}^{n} P_{ij}$	$\sum_{j=1}^{n} P_{ij} - P_{ii}$
…	…	…	…	…	…	…	…	…	…
Class n	P_{n1}	P_{n2}	…	P_{nk}	P_{nj}	…	P_{nn}	$\sum_{j=1}^{n} P_{nj}$	$\sum_{j=1}^{n} P_{nj} - P_{nn}$
Total	$\sum_{i=1}^{n} P_{i1}$	$\sum_{i=1}^{n} P_{i2}$	…	$\sum_{i=1}^{n} P_{ik}$	$\sum_{i=1}^{n} P_{ij}$	…	$\sum_{i=1}^{n} P_{in}$		
Gain	$\sum_{i=1}^{n} P_{i1} - P_{11}$	$\sum_{i=1}^{n} P_{i2} - P_{22}$	…	$\sum_{i=1}^{n} P_{ik} - P_{kk}$	$\sum_{i=1}^{n} P_{ij} - P_{jj}$	…	$\sum_{i=1}^{n} P_{jn} - P_{nn}$		

semi-arid zone of China we suggest that the thresholds of SPTA and SITC are 5% and 25%, respectively, over the study period.

2.3.3 Determining flagged land-cover swap-change categories

Two indices for a land-cover category were used to ascertain the flagged land-cover swap-change categories. One was DSC, which indicates the percentage of each land-cover category swap change to total swap change. Land-cover categories with a higher DSC will be dominant. DSC can be defined as

$$\mathrm{DSC} = \frac{\mathrm{Swap}_j}{\sum_{j=1}^{n} \mathrm{Swap}_j} \times 100\%. \tag{8}$$

Sometimes, the swap change of a land-cover category is not great, and therefore DSC is smaller. However, the land-cover swap change represents most land-cover change related to a particular type of land cover. This means that most land-cover changes of this type were swap changes and should be considered. Thus, ISCI was introduced to quantify this process:

$$\mathrm{ISCI} = \frac{\mathrm{Swap}_j}{\mathrm{Swap}_j + \mathrm{Net}_j} \times 100\% = \frac{\mathrm{Swap}_j}{\mathrm{Gain}_j + \mathrm{Loss}_j} \times 100\%, \tag{9}$$

where $0 \leqslant \mathrm{ISCI} \leqslant 100\%$. A zero ISCI indicates no swap change for category j, i.e., category j persistently changed to or gained from other categories over the study period. An ISCI of 100 indicates that changes are all swap change for category j, i.e., the amount of category j changed to and gained from other categories is equal, or there is no change (no gain and no loss).

High values of DSC or ISCI indicates that the swap-change phenomenon is very serious for a land-cover category, and we can analyze the land-cover swap-change process for such categories.

2.3.4 Determining land-cover swap-change process of dominant categories

Land-cover swap change was grouped into two categories: namely, swap from the same land cover (SSLC), and swap from different land cover (SSDC). SSLC means that gains and losses determining the swap area are from the same land-cover type, and SSDC indicates that such gains and losses are from different land-cover types. SSLC_j is the total swap area of swap from the same land cover in category j:

$$\mathrm{SSLC}_j = \sum_{i=1, i \neq j}^{n} \mathrm{Swap}_{ij}, \tag{10}$$

where Swap_{ij} is the swap area of a land-cover (i, j) pair in category j, $Swap_{ij} = 2 \times \mathrm{Min}(P_{ij}, P_{ji})$, n is the number of total land-cover categories as in Table 2.

SSDC_j is the total swap area of swap from the different land cover in category j:

$$\mathrm{SSDC}_j = \mathrm{Swap}_j - \mathrm{SSLC}_j. \tag{11}$$

SSLC and SSDC indicate different ecological processes in arid or semiarid zones. For an example of SSLC, grassland was reclaimed as cropland, and at the same time cropland returned to grassland. For an example of SSDC, grassland was reclaimed as cropland, and at the same time cropland was converted to woodland. In arid or semiarid zones, frequent interchanges between two land covers can destroy the native vegetation species, thereby causing serious ecological damage. Therefore, SSLC generally translates to more serious ecological damage to ecosystems, and should be given more attention.

We used two indices for a land-cover category to determine the dominant land-cover swap-change process among all land cover categories. The first was SCM, which was used to indicate whether SSLC is more important in land-cover swaps. If so, the land-cover swap will occur only between two specific land-cover pairs, and we term this type of swap change a bi-side change. If SSDC is more important, the land-cover swap occurs among different land-cover types, and we call this swap change a multiple-side change. SCM can be measured as

$$\mathrm{SCM} = \frac{\mathrm{SSLC}_j}{\mathrm{Swap}_j} \times 100\%. \tag{12}$$

If SCM is high, the swap of category j mainly indicates a bi-side change; otherwise a multiple-side change.

Given that bi-side land-cover swap change is a sign of more serious ecological damage, it is valuable to establish an index to determine whether swap change is from limited pairs or all pairs with other land-cover types for a land-cover category. For example, in an arid or semiarid zone, the swap change of grassland is bi-side, but the swap may only be caused by that between cropland and grassland, or between grassland and all the other land types, respectively. We used PI to describe the distribution evenness of components in swap changes of land-cover types. Through this index, we can determine whether we must focus on all other land-cover categories or only limited categories when analyzing land-cover swap change for a land-cover category.

PI is commonly used in ecology to measure the distribution evenness of different species living within a particular region (Pielou, 1966; Kempton, 1979; Condit et al., 1996; Gray, 2000). PI is generally used to indicate how close in numbers each species is in an environment. The higher PI, the closer the numbers of species is. In addition, species richness (the number of species) and heterogeneity diversity (proportional abundances of the species) can be simultaneously measured by PI. This index can be measured through

$$\mathrm{PI} = \left(- \sum_{i=1, i \neq j}^{n} \mathrm{SwapComp}'_{ij} \times \ln \left(\mathrm{SwapComp}'_{ij} \right) \right) / \ln(m), m = n - 1, \tag{13}$$

$$\mathrm{SwapComp}'_{ij} = \frac{\mathrm{SwapComp}_{ij}}{\sum_{i=1, i \neq j}^{n} \mathrm{SwapComp}_{ij}}, \tag{14}$$

$$\mathrm{SwapComp}_{ij} = \frac{\mathrm{Swap}_{ij}}{\mathrm{Swap}_j}, i \neq j, \tag{15}$$

where $0 < \mathrm{PI} \leqslant 1$, j is the land cover class to determine its swap change, n is the number of total land-cover categories. Swap_{ij} is the swap-change area between land cover i and j, Swap_j is the total swap-change area of land cover j. m is the number of swap-change pairs for land cover j, and $m = n - 1$ because a land cover can swap with all land covers except for itself. If $\mathrm{Swap}_{ij} = 0$, it means that there is no swap between land-cover category i and j, and this kind of no-swap class will be excluded when computing PI index.

If the index is low, it indicates that the swap distributions are relatively uneven. If land-cover swaps indicate uneven distribution, it means that some categories of swaps will be dominant among all the swap classes. Thus, we can just focus on those dominant swaps when analyzing land-cover swaps. In this study we suggest that the swaps of the land-cover pairs for a land-cover category is uneven if PI is less than 0.5.

3 Results

3.1 Net changes and total land-cover change

Land-cover net changes were slight for all the land-cover change categories. The net changes for all the land-cover categories ranged from 0.2% to 4.4% of the entire study area. However, total land-cover changes, which ranged from 0.3% to 8.1% of the entire study area, were much greater than those of net changes. Especially for cropland and grassland (both occupying over 30% of the total study area), net changes of these two major land-cover types were 0.7% and 4.0%, respectively, but corresponding total land-cover changes were 5.3% and 8.1% (Table 3; Fig. 3). It is clear that net changes dramatically underestimated total change of the land cover, as Pontius et al. (2004) and Braimoh (2006) suggested when dealing with land-cover swap changes.

Underestimation of total land cover was caused by the land-cover swap changes, since the total change equals gain plus loss for a land-cover category. The land-cover swap changes were from 0.1% to 4.6% of the total study area. Except for unused land and built-up area, the changes exceeded those of net changes. In particular, for cropland, swap change was over six times higher than net change.

3.2 Status of total swap change of all land-cover categories

Land cover changed remarkably in the study area over the 1980s–2000. The area across which land-cover types changed was 84,795.4 ha, or 10.4% of the total study area (Table 4). Thus, it is very important to address land-cover change in the study area.

Among all land-cover changes, land-cover swap change was very important in the study area. Total swap-change area was 41,908.7 ha, SPTA was 5.2% of the total study area, and SITC was 49.4% of total land-cover swap area. Thus, nearly half the land-cover change was caused by land-cover swap change.

3.3 Flagged land-cover swap-change categories

DSC was from 0.9% to 44.5% of total land-cover swap changes for all land-cover categories. Swap areas of cropland and grassland were 37,248.0 ha and 32,856.3 ha, respectively, and the ISCI of both exceeded 40% (Table 5). Thus, the land-cover swap of these two land-cover types should be flagged for urgent attention.

Although unused land and water body DSCs were 8.2%

Table 3 Net change and total change for all land-cover categories

Land cover	1980s		2000		Gain		Loss		Net change		Swap		Total change	
	Area/ha	%	Area/ha	%	Area/ha	%	Area/ha	%	Area/ha	%	Area/ha	%	Area/ha	%
Cropland	258,310.9	31.7	263,991.3	32.4	24,331.4	3.0	18,635.1	2.3	5,696.3	0.7	37,270.2	4.6	42,966.5	5.3
Woodland	19,470.5	2.4	55,526.9	6.8	38,002.6	4.6	1,953	0.2	36,049.6	4.4	3,906	0.5	39,955.6	4.9
Grassland	276,598.7	34.0	243,959.2	30.0	16,438	2.0	49,069.7	6.0	32,631.8	4.0	32,876	4.0	65,507.7	8.1
Water body	29,357.2	3.6	28,044.1	3.4	1,057.9	0.1	2,359.9	0.3	1,302	0.2	2,115.8	0.3	3,417.8	0.4
Built-up area	20,988.1	2.6	22,222.1	2.7	1,627.5	0.2	406.9	0.1	1,220.6	0.2	813.8	0.1	2,034.4	0.3
Unused land	209,034.6	25.7	200,016.4	24.6	3,417.8	0.4	12,450.5	1.5	9,032.7	1.1	6,835.6	0.8	15,868.3	2.0

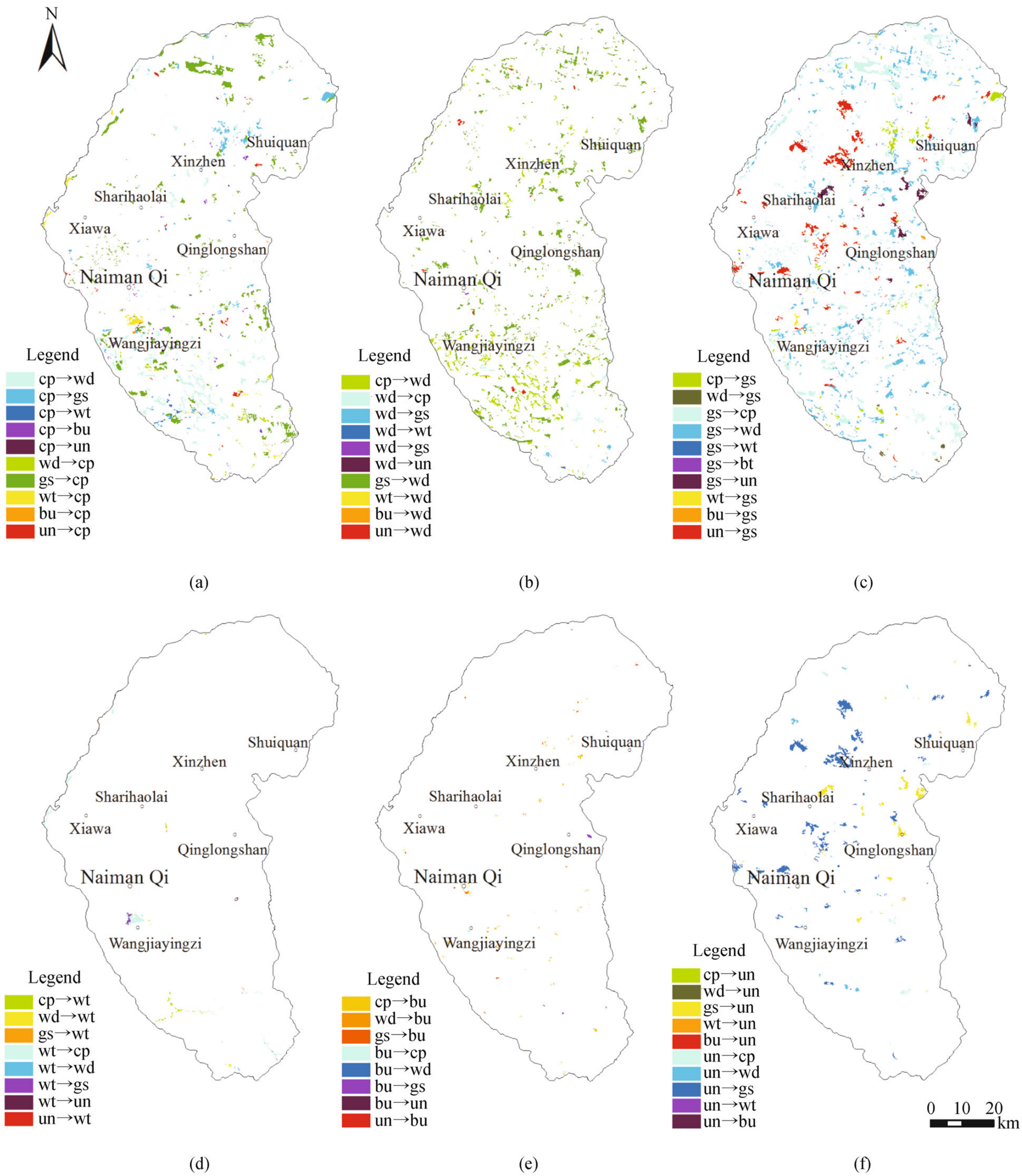

Fig. 3 Land-cover change maps for cropland (a), woodland (b), grassland (c), water body (d), built-up area (e), unused land (f) of Naiman Qi between the 1980s and 2000. cp, wd, gs, wt, bu, and un stand for cropland, woodland, grassland, water body, built-up area, and unused land, respectively.

and 2.5% of the total study area, respectively, their ISCIs were 43.1% and 61.6% of their total land-cover changes (Table 5). Thus, the land-cover swap of these two land-cover types should also be of concern.

The DSCs of woodland and built-up area were only 4.6% and 0.9% of total land-cover swaps, respectively, whereas their ISCIs were 9.6% and 38.1% of their total land-cover changes (Table 5). Thus, land-cover swaps of

Table 4 Land-cover change matrix from the 1980s to 2000 in study area

1980s	2000/ha						
	Cropland	Woodland	Grassland	Water body	Built-up area	Unused land	Total
Cropland	239,517.1	11,523.8	4,967.6	844.4	1,213.4	90.5	258,156.7
Woodland	1,349.8	17,538.3	414.2	67.2	68.4	21.0	19,458.9
Grassland	19,942.4	25,585.3	227,368.3	28.6	298.4	3,210.7	276,433.7
Water body	1,919.3	68.3	295.2	26,976.0	0.0	80.8	29,339.6
Built-up area	194.9	41.9	131.7	0.0	20,596.1	11.0	20,975.6
Unused land	910.2	736.2	10,636.7	111.2	32.5	196,483.1	208,909.8
Total	263,833.7	55,493.7	243,813.6	28,027.4	22,208.9	199,897.1	813,274.3

Table 5 DSC and ISCI for all land-cover categories

Land cover	DSC/%	ISCI/%
Cropland	44.5	86.8
Woodland	4.6	9.6
Grassland	39.3	50.2
Water body	2.5	61.6
Built-up area	0.9	38.1
Unused land	8.2	43.1

Table 6 SCM and PI for all land-cover categories

Land cover	SCM/%	PI
Cropland	40.0	0.61
Woodland	98.6	0.51
Grassland	53.2	0.57
Water body	97.1	0.32
Built-up area	100.0	0.76
Unused land	100.0	0.18

these two types may be ignored when analyzing land-cover swap changes.

3.4 Land-cover swap-change processes of dominant categories

SCM varied greatly, from 40.0% to 100%, for all six land-cover categories. Based on SCM, land cover can be classified into two groups. One group includes cropland and grassland, with SCM of 40.0% and 53.2%, respectively. The other group includes woodland, water body, built-up area, and unused land, with SCM from 97.1% to 100% (Table 6). Since SCM indicates whether the swap-change composition was dominated by bi-side or multiple-side change, it is clear that the swap changes of cropland and grassland were multiple-side and those of woodland, water body, built-up area, and unused land were bi-side.

PI varied greatly, from 0.18 to 0.76, for the six land-cover categories. Land cover can be also separated into two groups, based on this index. One group includes unused land and water body, with PI values 0.18 and 0.32, respectively (Table 6). The other group embraces cropland, woodland, grassland, and built-up area, with values from 0.51 to 0.76. PI indicates whether swap changes are from limited pairs or all pairs of land-cover types. Thus, it is clear that for unused-land and water-body swap changes, we can just focus on limited pairs of land-cover swap changes. For swap changes of cropland, woodland, grassland and built-up area, we should focus on more pairs of those changes.

3.5 Modes of land-cover swap change for every land-cover category

Cropland was severely affected by swap change, and was very important in swap change over the study area (ISCI was 86.8% and DSC was 44.5%). Swap change was dominated by multiple-side change (SCM was 40.0%). Multiple-side swaps were mostly from land-cover change ways of both grassland changing into cropland (19,942.4 ha) and cropland changing into woodland or grassland (11,523.8 and 4,967.6 ha, respectively) (Figs. 4 and 5; Table 4).

The cropland swap mode indicated features of ecological damage and simultaneous rehabilitation. First, local residents destroyed the grassland to make cropland for grains. However, the study area is in the Horqin Sandy Land in a semiarid zone. After the grassland was reclaimed, cropland on the sand dunes desertified rapidly under strong winds in spring. Finally, to combat desertification, trees were planted on the desertified cropland. Ultimately, grassland with high productivity was transformed into shelter trees that do not provide very profitable products, and only provides ecological functions.

Grassland was also severely impacted by swap change, and was very important in swap change over the entire study area (ISCI was 50.2% and DSC was 39.3%). The swap change was again dominated by multiple-side change (SCM was 53.2%). Multiple-side swaps were mostly from land-cover change of unused land or transforming cropland

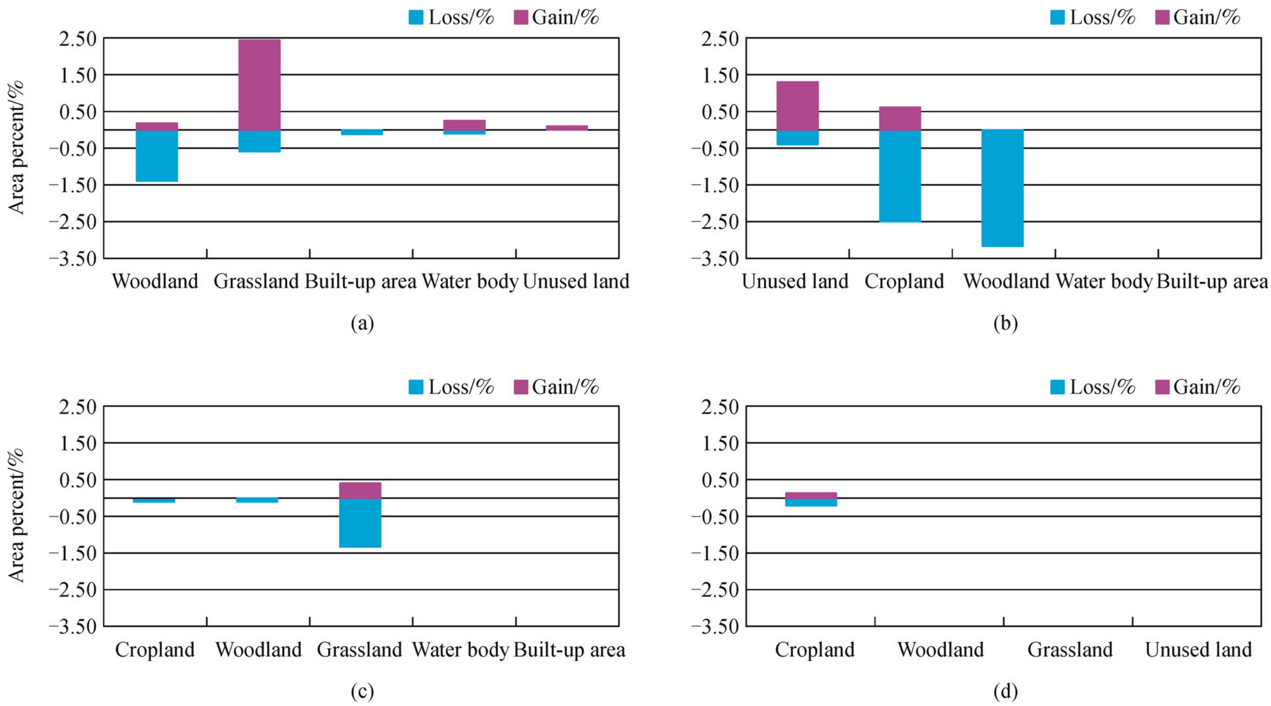

Fig. 4 Land-cover change compositions of cropland (a), grassland (b), unused land (c), and water body (d). Blue bars represent area percent of one land-cover category losses to another one. Red bars represent area percent of one land-cover category gains from another one.

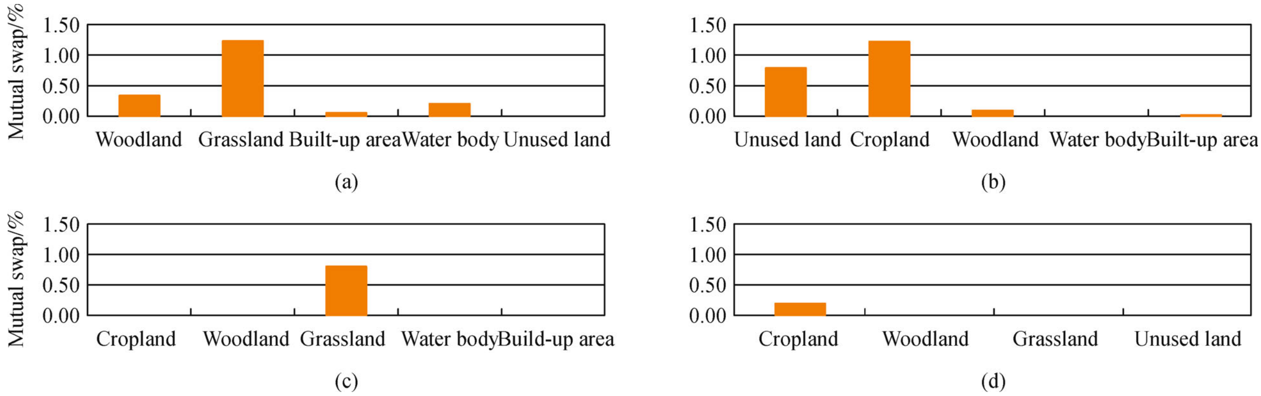

Fig. 5 Land-cover swap compositions of cropland (a), grassland (b), unused land (c), and water body (d) with other land-cover categories. Orange bars represent mutual change area percent between one land-cover category and another.

into grassland (10,636.7 and 4,967.6 ha, respectively) and grassland into cropland or woodland (19,942.4 and 25,585.3 ha, respectively) (Figs. 4 and 5; Table 4).

The grassland swap mode also indicated features of ecological damage and simultaneous rehabilitation. First, local residents destroyed grassland to make cropland for grains. At the same time, to combat desertification, parts of unused land and cropland were changed into grassland, and trees were planted on some grassland. However, grassland was changed into woodland, which actually destroyed the ecosystem because woodland does not grow sustainably and thus did not prevent soil wind erosion owing to water shortage in the semiarid climate.

Unused land was clearly influenced by swap change and was important in swap change over the entire study area (ISCI was 43.1% and DSC was 8.2%). The swap change was dominated by bi-side change (SCM was 100.0%). Swap changes were composed of land-cover change of limited pairs of land-cover types (PI of 0.18). The swap change was almost entirely unused land interchanged with grassland (Figs. 4 and 5; Table 4).

The unused land swap mode also indicated features of damage and simultaneous rehabilitation. The grassland was changed to unused land mostly by overgrazing. At the same time, to combat desertification, unused land was also rehabilitated into artificial grassland.

Water body coverage was also strongly impacted by swap change and played a role to a certain degree in swap change over the entire study area (ISCI was 61.6% and DSC was 2.5%). The swap change was dominated by bi-side change (SCM of 97.1%). Swap changes were composed of limited pairs of land-cover types (PI of 0.32). Swap changes were mostly water body coverage interchanging with cropland (Figs. 4 and 5; Table 4).

The water-body swap mode indicated the impact of natural factors on land-cover change, such as floods. The affected cropland was mostly along rivers. Cropland was flooded on early or later dates over the study period. This kind of swap change can be neglected when analyzing the land-cover changes.

Neither woodland nor built-up area was seriously affected by swap change, and they had minor roles in swap change across the study area. Their respective DSCs were 4.6% and 0.9%, and their ISCIs 9.6% and 38.1%. Thus, swap changes of these two categories can be ignored when analyzing land-cover changes.

4 Discussion

4.1 Improvement of methodology

Land-cover swap is a common phenomenon in land-cover change, and swap amount has been the most frequently used index to describe this phenomenon. However, this amount fails to indicate the severity and flagged classes of land-cover swap change, both as a total within an area and as a land-cover category, and the relationship with ecological processes of the ecosystem. This paper presents a suite of indices to characterize these kinds of land-cover swap changes explicitly and in detail.

4.2 Significance of this method

In land-cover change analysis, more attention has been given to net change than swap change. However, land-cover change trends and ecological processes can sometimes be misunderstood based on net change analysis, especially in arid or semiarid zones. Taking cropland change in the Naiman Qi study area from the 1980s to 2000 as an example, net change of cropland was only 0.7% of the total study area, suggesting that cropland was stable over this period. This conclusion is incorrect, because its swap area was 4.6% of the total study area, six times higher than that of the net change. Therefore, it is very important to understand land-cover change accurately because of land-cover swap changes. Using our method, the severity and the flagged classes of land-cover swap change and their relationships with ecological processes of the ecosystem can be quantified clearly. The results indicate that from the 1980s to 2000 in the study area, land-cover swap change was very important with high SPTA and SITC values. Land-cover swaps of cropland, grassland, unused land, and water bodies should be urgently addressed, based on high DSCs or ISCIs. Swap changes of cropland and grassland were of multiple-side change, and those of woodland, water body, built-up area, and unused land of the bi-side change. The multiple-side swaps of both cropland and grassland indicated features of the ecological processes of damage and simultaneous rehabilitation. Such explicit understandings of ecosystem ecological processes could be very valuable to land-cover policy making and management.

The newly developed indices are also very significant in ecological process characterization. SPTA and SITC indicate the intensity of spontaneous disturbances by local residents. In the arid zone, the land cover changes caused by policies or climate changes generally show a trend and focus on some specific land cover change types. For example, the land-cover changes are mainly from cropland to grassland or woodland under the policies of reversing cropland to grassland or woodland. With the high intensity of spontaneous disturbances by local residents, the landscape will become more fragmented, and rapid loss of native vegetation will also happen. Thus the ecosystems will show degradation and their ecological functions are also damaged clearly.

5 Conclusions

We presented a suite of indices to characterize land-cover swaps that can indicate serious damage to the ecosystem in arid or semiarid zones based on swap-change areas extracted from remotely sensed images. First, SPTA and SITC were used to determine the status of land-cover swap change. Then, DSC and ISCI were used to establish the flagged land-cover swap-change categories. Finally, SCM and PI were used to assess the dominant land-cover swap-change process of all land-cover categories. Following this framework, land-cover swap change in a region can be quantified explicitly and in detail.

A case study was conducted using this method, based on two land-cover maps in the 1980s and 2000 of Naiman Qi in Tongliao City, Inner Mongolia, China. This study showed that our method can clearly quantify the severity and flagged classes of land-cover swap change and their relationships with ecological processes of the ecosystem. The results indicate that from the 1980s to 2000 in the study area, land-cover swap change was very important based on SPTA and SITC. Land-cover swap of cropland, grassland, unused land, and water bodies should be urgently addressed, based on high DSCs or ISCIs. The swap changes of cropland and grassland were of a multiple-side way and those of woodland, water body, built-up area, and unused land were of bi-side change, based on SCM and PI. Multiple-side swaps of both cropland and grassland indicated features of ecological processes of damage and simultaneous rehabilitation. These results demonstrate that our method gives deep insight into swap change, and these clear understandings of land-cover swap changes can be very valuable in land-cover policy making and management.

The land-cover swap-change analysis herein can be used to quantify characteristics of land-cover swaps, and are sufficiently generic for application to areas with swap change, especially in arid or semiarid zones. This new approach is an important supplement for net change in land-cover change analysis, and can help landscape ecologists and geographers understand ecosystem ecological processes and their driving forces.

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