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Measurement of rapid agricultural land loss in the Pearl River Delta with the integration of remote sensing and GIS

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Abstract. Rapid land-use change has taken place in China since economic reform. A significant amount of agricultural land has been encroached on by urban development in many coastal cities, especially in the Pearl River Delta. This has caused severe land-use problems because China is among the nations with the lowest per capita land resources in the world. In this paper, measurement of agricultural land loss with the integration of remote sensing and GIS is presented. Such measurement consists of land-development monitoring, land evaluation, and GIS overlay analysis. The concept of suitability loss is addressed to measure the degree of encroachment on the agricultural land of good quality as well as the amount of land loss. The approach demonstrates that the simple indicator AREA (total amount of land loss) is inadequate to identify completely the influences of agricultural land loss. It is illustrated that the proposed indicator I_{loss}, which integrates quantity of land loss, spatial integrity of land development, and quality of land, is more useful than AREA in highlighting land-use problems. The indicator AREA may lead to a false perception of agricultural land loss owing to the negligence of land quality.

1 Introduction

Western literature has indicated that most of the land conversion occurs in areas of the best agriculture productivity (Bryant et al, 1982; Gierman, 1977; Howard, 1972). Patterson (1968) reported that a loss of 1.85 million ha of farmland (a reduction of 20.4%) occurred in Ontario, Canada, between 1942 and 1966. Ziemetz (1976) used aerial photographs to analyze the relation between urbanization and cropland removal in the United States. Gierman (1977) reported that, for Canadian cities with a population over 25 000, some 70 ha of rural land were converted to urban use for each increase of 1000 in the urban population between 1966 and 1971. There were a number of debates on how to control urban sprawl in the 1960s when Western countries were facing the same problems that China is experiencing today. Western countries seem to have passed the period of large-scale land encroachment without the accompanying critical instability in their urbanization process.

China is undergoing a similar process of rapid urbanization with the loss of a large amount of agricultural land. According to government statistics, arable land in the Pearl River Delta has decreased from 1.04 million ha in 1980 to 0.89 million ha in 1991, a decrease of 14% in 10 years. This is the figure reported to the government, which may be an underestimate. It is worse to find that agricultural land loss seems to be much faster today in the Pearl River Delta than it was in Western countries in the 1950s and 1960s. Furthermore China has a smaller amount of available arable land per capita and the increase in crop yield resulting from the improvement in technologies cannot make up for the increasing population and decreasing arable land. This is quite different from the case in Western countries which had a phenomenon of overproduction in the 1950s and 1960s (Bryant et al, 1982).

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Available information and the corrective measures provided are far behind the requirements under the fast change of the land-use pattern. Only very limited information on the change of land resources under the rapid economic growth is available in China. Official data are unsatisfactory in the provision of updated information because the land-use pattern is changing very rapidly in the region. There is a need to evaluate the impacts of land loss and to provide some guidelines for land development in the region as well as to monitor land-use change. There are serious concerns over the impacts of land loss because the Pearl River Delta used to produce a large proportion of agricultural products in the Guangdong Province.

2 Land-development monitoring

Monitoring of the state of and changes in the environment is now universally recognized as being of great importance to humankind (Tickell, 1986). Many people are now aware of the severity of global change caused by unwise development patterns (Rhind, 1991). Rapid urban development is phenomenal in many developing countries, resulting in dramatic change of the landscape. The monitoring of land-use change is crucial to planners who usually lack updated information in land-use planning.

The Pearl River Delta has experienced unprecedented expansion of urban areas in recent years. Multitemporal satellite imaging is a promising way to monitor the urbanization process. Two basic methods are employed frequently in the detection of land-use change by remote sensing: pixel-to-pixel comparison, and postclassification comparison (Martin, 1989). The first method is a pixel-to-pixel combination of multidate images without classification of the data. This pixel-to-pixel method has the following variations: (a) image differencing (Toll, 1980); (b) image ratios (Nelson, 1983); and (c) principal components analysis (Byrne et al, 1980). Prior classification is not necessary for the comparisons, and the errors from classification can therefore be avoided. Unfortunately, the results of these above methods are unclear as to the details of the change. Although these methods are sensitive in detecting a pixel that has changed, the conversion matrix of land-use change cannot be generated from the results. The second method compares two or more separately classified images of different dates. Prior classification is carried out before making the comparison. The advantage of this technique is that the land-use types for each pixel of both dates are identified. This postclassification comparison can be used to identify not only the amount and location of change, but also the nature of change (Howarth and Wickware, 1981). Fung and Zhang (1989) indicate, however, that the comparison is subject to the error originating from the misclassification of the two or more independent classified images. Although the use of the unsupervised classification for each data set is an ideal independent analysis, this technique cannot produce the highest classification accuracy and thus lead to the most detailed classification (Johnson and Howarth, 1989).

Overestimation of change has been found to occur in these two methods. Some impossible land-use change may be deduced from classification errors, including the change from built-up areas to cropland. A way to avoid the overestimation of change is to stack multitemporal images so that consistent signatures can be created for change detection (Yeh and Li, 1996).

3 Analysis of agricultural land loss

The encroachment on agricultural land exerts at least two types of influences on environment: the geometric change of land-use pattern, and the amount of suitability loss. Conventionally, land loss is evaluated simply to measure the total area of land conversion. The total area may be considered as a simple indicator for the environmental impacts induced by land loss. A town will normally bear a large amount of environmental cost if there is a large area of land loss. However, this simple indicator of area is insufficient to address two major popular problems of land loss : (1) urban sprawl, or 'fragmentation' of land use; and (2) encroachment on the best agricultural land. The integration of remote sensing and GIS can address the problems of agricultural land loss more appropriately than conventional methods.

3.1 Analysis of agricultural land loss and suitability loss by GIS

Land resources refer to at least two aspects: the amount (area) of land, and the quality of land. The inventory of land resources, which is a prerequisite for further evaluation of land development, should be carried out to obtain the information about agricultural suitability. The information also implies the availability of land provision for urban development. Planners usually decide on a proportion of existing agricultural land as a stock for future urban land use. This is because urban land supply comes mainly from the conversion of agricultural land. However, as land quality is a an important constraint in agricultural production, the conservation of land of good quality for agricultural production should be considered seriously in the planning of future land development. The integration of remote sensing and GIS can provide updated land information to planners and let them have a better understanding of the potential effects of agricultural land loss before a land-use plan is prepared.

Frequently, a site which is most suitable for industrial development is also very productive for agricultural land use. Land-use conflicts should be resolved on the basis of information from land evaluation. Planners must balance the need of the conservation of important agricultural land with the demand of land for urban development. Remote sensing and GIS can be used to monitor urban development and determine the extent of the trade-offs for preserving agriculture land. A similar study was conducted to protect farmland near cities in Hawaii where there is a need for housing development (Ferguson and Khan, 1992). In the study, GIS was employed to tackle the competition of different land uses according to suitability ratings.

The main products of land evaluation are suitability maps which give scores to indicate the potential of land for a specific purpose. An additive system can be used to combine various variables to obtain the suitability score (S) (McRae and Burnham, 1981):

$$S = \frac{\sum_i W_i X_i}{\sum_i W_i},$$

where W_i and X_i are the weight and score of variable i, respectively.

As GIS can provide a very efficient means of data operation and data analysis, many assessment applications are now carried out within a GIS environment (Wang, 1994). The analysis discussed above can be implemented in a GIS. After the land-use changes are detected from remote sensing, the results can be transferred into the GIS for further analysis. The GIS contains the classification results of satellite images, road maps, administrative maps, river maps, settlement maps, soil maps, and topographic maps. These maps are the basis of the provision of suitability maps for the evaluation analysis.

Besides the amount of land loss, another concern is the loss of good-quality agricultural land. A piece of agricultural land has a certain degree of suitability for a specific agricultural land use. The conversion of agricultural use into urban use, which is an irreversible process, thus results in the loss of suitability for agricultural use forever. Therefore loss of agricultural suitability is an important indicator that should be considered in the evaluation of land conversion. The measurement of the loss of agricultural suitability can be carried out based on the overlay of the land-loss maps from remote sensing and the suitability maps from land evaluation. In the calculation the scores of agricultural suitability are summed in all the places with land loss.

The loss of suitability can be calculated by using the overlay function of ARC/INFO GRID (ESRI Inc., Redlands, CA). The total loss of suitability for agricultural activities during land development is calculated by the following formula:

$$S_{\text{loss}} = \sum_{i,j} S(i,j),$$

where S_{loss} is the total loss of suitability, and $S(i,j)$ is the suitability for agricultural type j in location i where land loss occurs.

Obviously it can be seen that only when $S(i,j) = 1$, and there is one type of agricultural land use, will S_{loss} be equal to the total area of land loss. This means that land quality should be uniform if the area index, instead of S_{loss}, could be used properly.

As land quality is not homogeneous, the equation reflects the fact that the same amount of land loss does not represent the same number of impacts on agricultural production. The cost to agricultural production will definitely be greater for a larger proportion of land loss in the most fertile areas. It is more appropriate to use suitability loss instead of area loss in the evaluation of land loss. Unfortunately, suitability loss is usually ignored in actual land-use planning, partly because the information on land suitability and land loss is sometimes unavailable. The integration of remote sensing and GIS can facilitate the implementation of this concept.

3.2 Geometric change of land-use patterns

The change of land-use patterns relating to land loss has a profound influence on the environment. In the Pearl River Delta, land development usually takes place in a 'leapfrog' pattern owing to lack of proper planning (Xu, 1990). The fragmented conversion of agricultural land into urban use discords with optimal land-development patterns because small patches of land use may increase environmental cost as well as pure economic cost. Many advantages have been associated with a larger unit of land use for human society (Buiton, 1994).

There is also a long history in the estimation of landscape change and its impacts on wildlife (McArthur and Wilson, 1967). It is found that fragmentation of land use is harmful to biological conservation as well as to urban growth. A larger area usually contains a greater diversity of habitats because it provides greater spatial and temporal variation in resources (McArthur and Wilson, 1967; O'Connor et al, 1990). It also permits a favourable undisturbed environment for the production of fauna. Studies indicate that extinction rates of species are inversely related to area (O'Connor et al, 1990). Edge effects also have a significant influence on ecosystems. As the ratio of perimeter to area increases, the interior becomes more exposed to the exterior. This may be unsuitable for the survival of some species. For example, the dark, cool, and moist tropical rainforest is a highly insulated ecosystem. When exposed, dramatic change will penetrate nearly to the core of a 100 ha reserve (O'Connor et al, 1990).

Recent research indicates that the establishment of corridors is another way to maximize connectivity (Andreassen et.al, 1996; Fedorowick, 1993; McCoy and Mushinsky, 1994). This can benefit both agriculture and wildlife. However, the considerations of the connectivity concept are rather complicated in GIS modelling. We will set it aside as beyond the scope of this paper for the sake of simplicity.

The above reasoning indicates that some indices to describe the dispersion or concentration of land use are needed for land-use evaluation and land-use planning. Unfortunately, the issue of the fragmentation of land use seems to be less addressed in conventional GIS land-use approaches. Many studies of land-use planning and modelling basically rely on suitability analysis without proper consideration of the spatial pattern of land use (Carver, 1991; Hallett et al, 1996). However, the measurement of the contiguity or fragmentation of a given land use is important for the formulation of sustainable land-use planning (Yeh and Li, 1998).

Therefore the measurement of spatial integrity of the loss of agricultural land is important for the evaluation of land loss. An amount of land can be assigned to a specific land use in either scattered or aggregated chunks. The degree of dispersion can be calculated by using the relative entropy. The well-known Shannon's entropy is a measure of the discrete probability distribution. The relative entropy which is scaled down to within 0 and 1 is devised as (Thomas, 1981):

$$H_n = \frac{1}{\log n}\sum_i p_i \log\left(\frac{1}{p_i}\right).$$

Before calculation of the relative entropy, observation (x_i) must be transformed as proportion (p_i), divided by the sum of all x_i:

$$p_i = \frac{x_i}{\sum_i x_i}.$$

In theory, if a phenomenon is concentrated maximally at a location, the lowest value (zero) will be obtained. A uniform distribution of the phenomenon across space will lead to the maximum value of 1 for the relative entropy.

The degree of concentration is therefore:

$$C_n = 1 - H_n.$$

The degree of concentration (C_n) is a measure of the spatial distribution of land development. It is convenient to calculate this index by using a GIS buffer function after land loss has been obtained from satellite images. The first step is to calculate the density of land loss ($\mathrm{DENLOSS}_i$) in each buffer zone by means of GIS buffer functions. The relative entropy can thus be obtained by the following formula:

$$H_n = \frac{1}{\log n}\sum_i p\,\mathrm{DENLOSS}_i \log\left(\frac{1}{p\,\mathrm{DENLOSS}_i}\right).$$

where

$$p\,\mathrm{DENLOSS}_i = \mathrm{DENLOSS}_i \Big/ \sum_i^n \mathrm{DENLOSS}_i$$

3.3 An indicator integrating the suitability loss and geometry of the land-use pattern

There is a need to formulate an indicator to evaluate the impacts of land loss. As has been noted, the area index is not a good indicator for addressing all the influences of land loss. This index does not cover the spatial and site information of land loss. A better indicator should be sensitive to the spatial integrity and site attributes as well as the amount of land loss. The combination of the concentration of land loss and suitability loss is better for addressing the two aspects of land loss. This is because dispersed patterns of land loss are associated with great environmental cost. Compact land use is preferred for better utilization of energy and land resources. A larger number of impacts exist if more land of the best quality is encroached on by urban uses. Therefore a simple way is to use the ratio of suitability loss to the concentration of land loss, rather than the area loss, in order to address the impacts of land loss. The proposed indicator is I_{loss},

$$I_{\mathrm{loss}} = \frac{S_{\mathrm{loss}}}{1 - H_n} = \frac{1}{1 - H_n}\sum_{i,j} S(i,j).$$

4 Application in the Pearl River Delta

4.1 Study area

Dongguan, a fast growing city in the Pearl River Delta, is selected for the case study. The city has an area of 2465 km^2, and is situated in the eastern part of the Pearl River Delta between two metropolises, Hong Kong and Guangzhou. It is a conurbation enclosing a city proper and 29 towns. The growth of the economy of Dongguan has been very good since economic reform. The annual growth rate of GDP was as high

Table 1. Conversion matrix of land use in Dongguan in the period 1988–93 (in hectares).

1988	1993							Total
	CR	BA	CO	OR	BU	FO	WA	
CR	62 602.4 (64.9)		1 737.8 (1.8)	31 945.8 (33.1)	103.2 (0.1)			96 389.2 (100)
BA				0.2 (100)				0.2 (100)
CO			0.3 (0.0)		2 115.3 (100)			2 115.6 (100)
OR			19 432.0 (29.7)	45 987.9 (70.3)	9.3 (0.0)			65 429.2 (100)
BU					16 235.8 (100)			16 235.8 (100)
FO		136.7 (0.3)				41 462.1 (99.7)		41 598.8 (100)
WA			1 442.9 (8.0)		3.4 (0.0)		16 590.4 (92.0)	18 036.7 (100)
Total	62 602.4	136.7	22 613.0	77 933.9	18 467.0	41 462.1	16 590.4	239 805.5

Notes: CR, cropland; BA, barren soil; CO, construction sites; OR, orchard; BU, built-up areas; FO, forest; WA, water; numbers in parentheses are percentages.

Table 2. Confusion matrix of change detection.

Classified data	Reference data								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1) CR	128			12	4			4	
(2) BA to OR		64							
(3) WA to CO			50		1				
(4) CR to OR	4	4		64				20	
(5) CR to CO			3		90		1		
(6) CO to BU						30			
(7) CO					2		36		
(8) OR	10			14	4			76	2
(9) OR to CO					10				64
(10) FO to BA									
(11) FO								8	
(12) BU					2				
(13) WA									
(14) OR to BU									
(15) CR to BU						2			
(16) WA to BU									
Total	142	68	53	90	113	32	37	108	66

Notes: see table 1.

as 29% in the period 1980–93. The rapid growth of the economy has resulted in increasing demand for land, which is responsible for the loss of a large amount of agricultural land.

4.2 Amount of land loss

The TM satellite images dated 10 December 1988 and 22 November 1993 provide information about the land-use changes in Dongguan. The stacked change-detection method was applied to reduce the overestimation of change (Yeh and Li, 1996). The results from land-development monitoring indicate that a large amount of agricultural land in the study region has been lost in the period. Table 1 shows the land-use conversion matrix of Dongguan in the period 1988–93. There are two main types of land-use changes—from cropland to orchards and from agricultural land (cropland and orchards) to construction sites. The change from cropland to orchards was part of the restructuring of agriculture in Dongguan, whereas the change from agricultural land to construction sites was because of urban development. In the period 1988–93 13.2% (or 21 285 ha) of the total agricultural land has been lost. The annual rate of increase of the expanding urban areas was 30.6%. The land consumption per capita increased rapidly from 128.4 m^2 to 295.8 m^2—both figures are substantially higher than the national standard (about 100 m^2). The loss of primary land in the course of urbanization has had profound impacts on the sustainable development in the region.

Stratified random sampling was conducted for the accuracy assessment of change detection. Aerial photographs taken in 1988 and 1993 were used to determine the ground information. Table 2 is the error matrix constructed from the sampling data. The κ coefficient is 0.85, and the overall accuracy is 0.86. There was less error in the detection of construction sites. The accuracy of detection of construction sites is as high as 0.95.

(10)	(11)	(12)	(13)	(14)	(15)	(16)	Total
		10	6				164
							64
		2					53
	2						94
2							96
					2		32
							38
	6		2				114
							74
52							52
	86						94
		42	4			2	50
			56				56
				62	4		66
				2	54		58
	3					24	27
54	97	54	68	64	60	26	1132

4.3 Analysis of land loss

Before the analysis of land loss, the grid of agricultural suitability was produced in ARC/INFO on the basis of soil maps and contour maps. Soil maps were digitized into ARC/INFO and then ratings were given to each soil type according to its suitability for agriculture. The criterion for the ratings is to grade the land according to its likely yield or investigated yield. Contour maps were also digitized into ARC/INFO. After a slope grid was obtained by using ARC/INFO TIN, ratings were also given according to the slope. The grids from ARC/INFO can be conveniently integrated with the satellites images in the ERDAS imagine format.

The final scores of agricultural suitability were then obtained by adding the rating grids from the following linear formula:

$$\mathrm{SU\_AG} = 0.5\,S_{\mathrm{soil}} + 0.5\,S_{\mathrm{slope}}\,,$$

where S_{soil} and S_{slope} are the score grids of soil type and slope; SU_AG is the final score grid of agricultural suitability. The calculation was implemented in the ARC/INFO GRID module. It created a final grid in which a cell with a high score is considered to be a good location for agricultural production. The grid was simplified into 7 classes. The land rated as classes 1 and 2 cannot be used for agricultural activities. The land rated above class 3 is suitable, but only the land rated above class 5 is very productive for agriculture.

Table 3 indicates the proportions of land classes 3–7 and 6–7 in the total of the land classes, respectively. The proportion of land classes 3–7 represents the percentage generally suitable for agricultural activities whereas the proportion of land classes 6–7 represents the percentage with the best quality for agricultural activities. A town with a large proportion of land classes 6–7 is considered to be most suitable to grow rice and the land should be largely reserved for agricultural purposes. The top six towns with the highest proportion of land classes 6–7 are Gaobu, Shijie, Wangniudun, Daojiao, Zhongtang, and Hongmei. All these towns fall in the Dongjian Alluvial Plain in the northwest part of the city. This reveals the fact that the land resources are unevenly distributed in the city. Therefore land-use planning and land-use policies should consider the spatial distribution of land resources such that urban development will not induce unacceptable impacts on other types of land use. Unfortunately the amount of agricultural land allowed for the conversion into urban use is usually equal to a fixed proportion of the total agricultural land in each town, according to existing planning policies. Therefore the towns with a larger proportion of fertile land will suffer more as a consequence of the 'fixed' development.

The incidence of agricultural land loss on suitability classes was obtained to reveal the land-use problems in Dongguan. The land suitability grid was converted into the ERDAS IMAGINE format. In the next step the land suitability image (with 7 classes) was treated as a zonal image and the land loss image as a value image by use of the GIS summary function of ERDAS IMAGINE. The overlay of the two images generated a matrix table comparing land loss and land quality. In addition, a town mask was used to separate the comparison into town levels.

It is found that some towns have converted a large amount of the most fertile land into urban use. In Dongguan 41.7% of land loss in 1988–93 consumed the most fertile land (class 6–7). Figure 1 (see over) further illustrates the variation of land conversion in some selected towns. The selected towns include those with a large amount of land development (Tangsha, Zhangmutou, and the city proper) and those with a large proportion of the best agricultural land (Zhongtang and Wangniudun). The city proper, Zhangmutou, and Tangsha suffer the peaks of land loss in classes 4–5. Although the amount of land loss is relatively low in Zhongtang and Wangniudun, the peaks of land

Table 3. Proportions of land classes 3–7 and 6–7 in the total of all land classes.

Town	Classes 3–7		Classes 6–7	
	percentage	rank	percentage	rank
City proper	0.84	14	0.39	15
Zhongtang	0.83	16	0.81	5
Wangniudun	0.88	6	0.88	3
Daojiao	0.87	9	0.86	4
Hongmei	0.80	17	0.79	6
Machong	0.72	24	0.58	11
Humen	0.72	23	0.29	22
Changan	0.61	28	0.12	27
Houjie	0.79	18	0.38	16
Shatian	0.70	25	0.69	9
Liaobu	0.92	4	0.35	19
Dalingshan	0.77	20	0.13	26
Dalang	0.84	15	0.19	23
Huangjian	0.62	27	0.08	29
Zhangmutou	0.44	30	0.06	30
Qingxi	0.78	19	0.30	20
Tangsha	0.87	8	0.19	24
Fenggang	0.74	22	0.14	25
Xiegang	0.70	26	0.30	21
Changping	0.86	12	0.36	18
Qiaotou	0.87	10	0.37	17
Hengli	0.87	7	0.51	12
Dongkeng	0.97	1	0.48	13
Qishi	0.85	13	0.40	14
Shipai	0.87	11	0.75	7
Chashan	0.94	3	0.65	10
Shijie	0.90	5	0.90	2
Gaobu	0.95	2	0.93	1
Shilong	0.75	21	0.72	8
Xinwan	0.53	29	0.09	28

loss occur in class 7. Therefore special care should be taken to preserve the best agricultural land to prevent the peaks from further moving into class 7. This means that land development in the towns with the best agricultural land should be restricted.

The indicator I_{loss} was used to evaluate the impacts of land loss in Dongguan. Indicators S_{loss} and H_n were obtained for each town by using ERDAS IMAGINE and ARC/INFO GRID. The calculation of S_{loss} was needed first to mask out the portion of land loss in the suitability grid. The following command in ARC/INFO GRID was used:

```
P_SU = CON(LOSS_B EQ 1, SU),
```

where P_SU is the agricultural suitability grid of land loss, LOSS_B is the binary grid of land loss, and SU is the suitability grid.

A statistical table containing the total loss of suitability for each town was created by means of the ZONALSTATS command in ARC/INFO GRID:

```
S_LOSS_T = ZONALSTATS(TOWNB, P_SU, SUM), ,
```

where S_LOSS_T is the dBase table containing the total suitability loss for each town, and TOWNB is a town boundary grid.

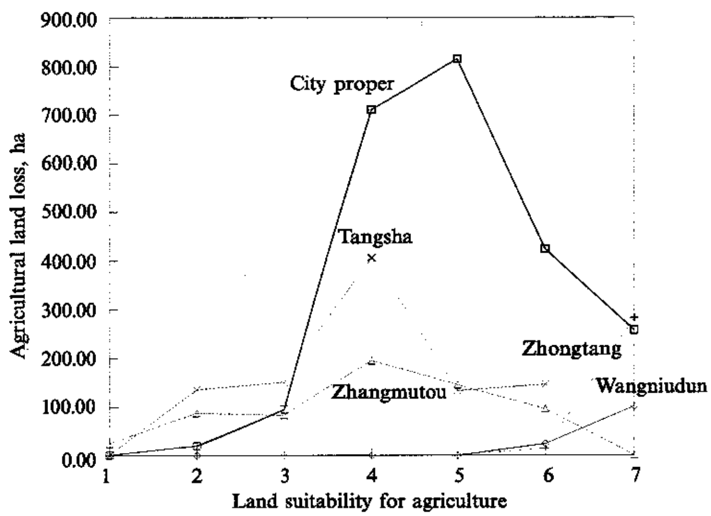

Figure 1. Variation of incidence of agricultural land loss on land suitability for selected towns in Dongguan in the period 1988 – 93.

The average quality of land that has been converted into urban use was calculated by the ratio of suitability loss (S_{loss}) to the area loss (AREA):

$$\frac{S_{\text{loss}}}{\text{AREA}} = \frac{1}{\text{AREA}} \sum_{i,j} S(i,j) \,,$$

where AREA is the total area of land loss. A town with a higher value of $S_{\text{loss}}/\text{AREA}$ denotes that on average the land conversion occurs in land of better quality.

Table 4 demonstrates clearly the differences between AREA, S_{loss}, and I_{loss}. First, it is found that suitability loss is more appropriate than area loss in addressing land-use problems. Second, I_{loss} is more suitable than AREA and S_{loss} as an indicator for the evaluation, because I_{loss} also reflects the geometric features of land loss.

The two towns, Liaobu and Shatian, provide a good example for the first situation. Liaobu had an area of 774.8 ha of land loss between 1988 and 1993. The area of land loss in Shatian was 709.6 ha, which was slightly less than that of Liaobu. However, the value of S_{loss} indicates that much more suitability loss occurred in Shatian. The reason is quite simple: Shatian is located in the most fertile alluvial plain whereas a large part of Liaobu is located in a hilly area. More valuable land was lost in Shatian than in Liaobu during the period 1988 – 93.

The usefulness of I_{loss} is illustrated by the comparison of land loss patterns in the two towns Tangsha and Fenggang. In the period 1988 – 93, Tangsha suffered 2004.1 ha of area loss and the suitability loss was 964 034, whereas the figures for Fenggang were 1307.0 ha and 503 087, respectively. Tangsha may be considered to be costlier because the values of area loss and suitability loss are higher. However, the values of I_{loss} for Tangsha and Fenggang are 5 385 700 and 5 953 700, respectively. This means that the costs for the two towns were almost the same because the values of I_{loss} are close. It is easy to find that the land loss pattern was more dispersed in Fenggang than in Tangsha and therefore the same amount of agricultural land loss in Fenggang has resulted in a greater environmental cost. Another example is seen in the two towns Dalingshan and Liaobu. In the period 1988 – 93, Dalingshan and Liaobu had 1060.3 ha and 774.8 ha of land loss, respectively. The area loss of Dalingshan was 36.8% higher than that of Liaobu. However, the values of the suitability loss were 432 729 and 272 319 for the two towns, respectively. The suitability loss of Dalingshan was 58.9% higher than that of

Table 4. Indices for the description of impacts of agricultural land loss.

Town	Area loss, ha	Suitability loss	Suitability loss/area loss	I_{loss}	I_{loss}/land area
City proper	2941.9	1 234 884.5	419.8	6 113 300	287.1
Zhongtang	398.5	210 643.4	528.6	659 300	114.9
Wangniudun	192.8	79 335.1	411.5	241 500	78.9
Daojiao	421.5	277 274.1	657.9	1 056 300	201.4
Hongmei	159.8	96 639.8	604.6	378 200	118.5
Machong	410.5	96 127.0	234.2	377 700	43.5
Humen	1 149.5	521 198.6	453.4	2 536 200	196.2
Changan	1018.3	398 758.5	391.6	1 647 800	172.6
Houjie	975.2	348 441.9	357.3	1 968 600	161.9
Shatian	709.6	481 111.0	678.0	2 486 400	238.1
Liaobu	774.8	272 318.7	351.5	1 035 400	123.8
Dalingshan	1 060.3	432 728.6	408.1	2 747 500	260.2
Dalang	603.1	198 676.3	329.4	718 500	58.4
Huangjian	449.6	109 978.4	244.6	420 600	31.8
Zhangmutou	787.8	284 798.3	361.5	929 200	82.5
Qingxi	1 553.7	806 818.6	519.3	3 347 800	322.9
Tangsha	2 004.1	964 034.4	481.0	5 385 700	433.4
Fenggang	1 307.0	503 086.5	384.9	5 953 700	750.5
Xiegang	428.9	347 666.3	810.5	1 329 500	152.0
Changping	795.7	334 875.4	420.9	1 810 100	181.5
Qiaotou	403.2	161 848.1	401.4	739 000	137.8
Hengli	294.2	105 356.0	358.1	310 800	64.9
Dongkeng	189.5	103 957.3	548.5	270 000	105.6
Qishi	500.5	607 954.1	1 214.7	2 908 900	519.0
Shipai	307.2	119 386.2	388.7	420 400	79.4
Chashan	511.6	239 289.3	467.8	719 700	132.3
Shijie	268.4	185 458.2	691.0	694 600	196.5
Gaobu	144.5	134 096.8	928.3	465 600	138.3
Shilong	212.4	602 201.1	2 835.2	2 247 000	1 779.5
Xinwan	311.9	56 073.5	179.8	187 200	36.5

I_{loss} is the ratio of suitability loss to the concentration of land loss.

Liaobu. There is a greater disparity between the two towns when index I_{loss} is used for the comparison. The values of I_{loss} were 2 747 500 and 1 035 400 for Dalingshan and Liaobu, respectively. The I_{loss} value of Dalingshan was 165.4% higher than that of Liaobu. It is obvious that Dalingshan suffered much greater environmental cost than Liaobu. The reason is that the land loss pattern in Dalingshan was more dispersed than that in Liaobu. This can easily be confirmed by a study of the satellite images.

The ratio S_{loss}/AREA can reveal the proportion of the best land lost in the total area. For example, the four towns Shilong, Gaobu, Qishi, and Xiegang had higher values of the ratio S_{loss}/AREA—4.99, 1.63, 2.14, and 1.43 respectively times the average. It means that the land loss in these towns is concentrated mainly in the best agricultural land.

As the land area may vary between towns, the value of I_{loss} should be normalized so that the density of I_{loss} (I_{loss}/land area) can be obtained. A higher value of the density of I_{loss} is not favourable for resource conservation. Table 4 shows that the top five towns with the higher values of the density of I_{loss} are Shilong, Fenggang, Qishi, Tangsha, and Qingxi.

Figures 2 and 3 (see over) demonstrate clearly that different patterns may be obtained between the use of the AREA index and the I_{loss} index. For example, Shilong

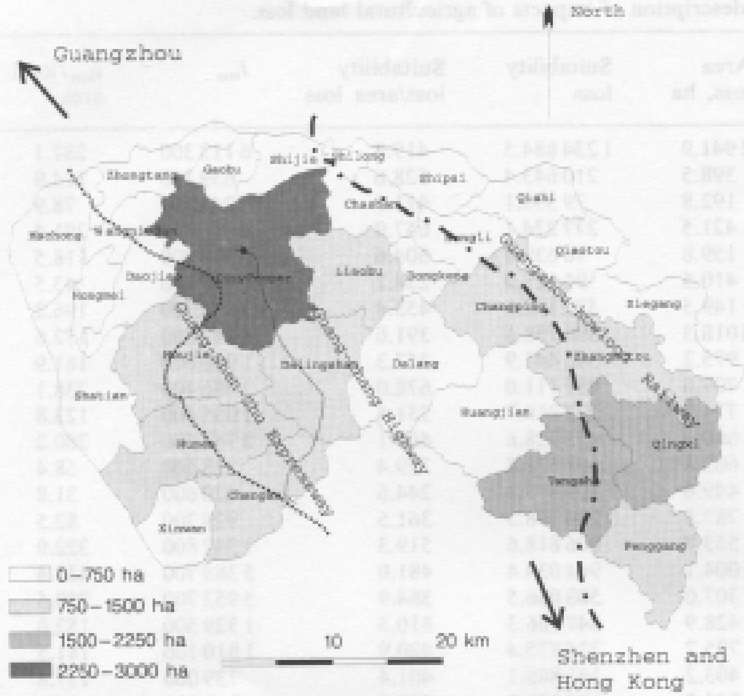

Figure 2. Amount of land loss in the towns of Dongguan.

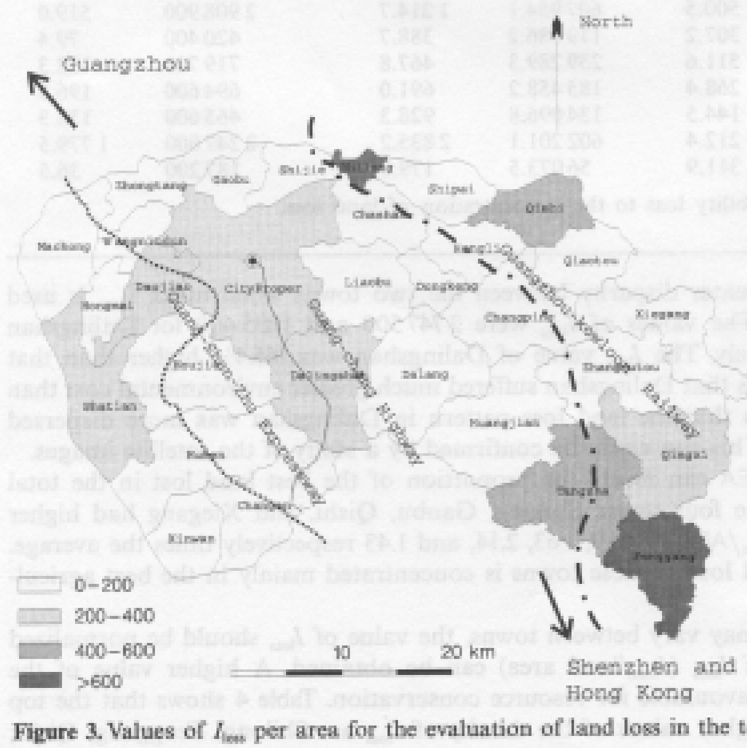

Figure 3. Values of I_{loss} per area for the evaluation of land loss in the towns of Dongguan.

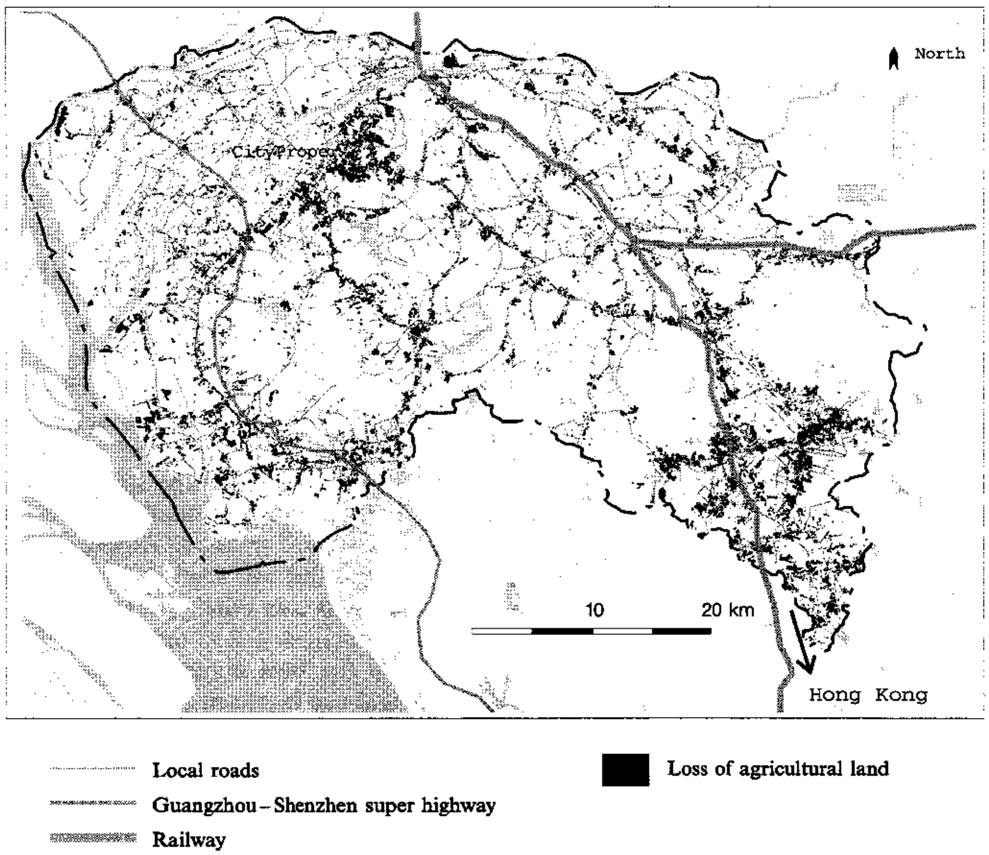

Figure 4. The internal pattern of agricultural land loss.

and Qishi had a small amount of land loss but the values of I_{loss} per area indicate that these two towns should have large 'costs'. The explanation is that the land loss may have occurred either in fertile land or in a dispersed pattern. The aggregation into town units can provide valuable information for local officers and planners to evaluate the impacts of land development in each town. However, it has been found that the modifiable areal unit problem may exert influences on the results of spatial analysis and result in the loss of detailed information (Openshaw, 1991). The loss of detailed information can be prevented without the aggregation. For example, figure 4 can map clearly the internal pattern of agricultural land loss without the aggregation. The land loss is highly concentrated along roads and the fringe of urban centres.

Without question, the strict protection of high-quality agricultural land may result in the leapfrog development patterns. As there is a trade-off between preserving good-quality agricultural land and maintaining compact development, planners should balance the two objectives properly. The proposed index is useful in identifying worse development patterns and seeking better alternatives. Encroachment on good-quality land and the development of dispersed patterns will both produce low values of the index. A partition line in GIS modelling may be used to assist in a fair resolution of the conflicts (Yeh and Li, 1998).

5 Conclusion

Agricultural land loss has been found to occur in the Pearl River Delta. In this study it has been shown that about 13.2% of total agricultural land was lost in the study area in the period 1988 – 93. Complete depletion of the agricultural land would occur if the rate were sustained. Land development in the Pearl River Delta should be examined carefully to avoid the wasteful use of land resources. Being a nation with a high population and limited per capita land resources, it is in China's interest to protect agricultural land. Although China has urged local governments to conserve fertile agricultural land for food supply during urban development, the effort seems to be wasted with careless development patterns.

It is also found that a high proportion of urban development is taking up good-quality agricultural land in the study area. For the evaluation of the impacts of agricultural land loss it is necessary to know not only the total area of land loss, but also the amount of the best land which has been lost. For the sake of agriculture, it would be better if urban development did not encroach on the best land available. Before planning urban development, planners should first determine the spatial variations of land quality. Only a few parts of the city are granted good land for growing rice. Planners should take care to maintain this agricultural treasure. However, it is found that sufficient effort is not being made to protect the best land in the existing development patterns. Satellite images reveal that the land loss usually occurs without a proper pattern favouring the conservation of land resources. It is found that there are intense land-use conflicts in Dongguan because the best agricultural land has frequently been encroached on by nonagricultural land use in recent years.

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