



Assessment of Changes in Agroecosystem Health in Guangzhou, China



ABSTRACT

Agroecosystem health refers to the extent to which a healthy agroecosystem can meet socioeconomic and biophysical needs of all residents over time. According to the attempts at assessing agroecosystem health, agroecosystem health depends on both functional and structural characteristics at regional level. However, both functional and structural characteristics have been altered from their natural state by industrialization and urbanization. Thus, this study reports a system-based assessment index to evaluate the health status of agroecosystem in Guangzhou, South China. Agroecosystem health index (AHI) of Guangzhou decreased from 0.78 in 2000 to 0.71 in 2010. It indicated that this agroecosystem was at relatively healthy state. However, functions of both cultural service and economic sustainable development were not successful as they represented 'worst' and 'sub-healthy', respectively. With the decreased values between 0.7 and 0.9, the other indices also revealed the need for caution. Particularly, both habitat structure index and provisioning service index exhibited well defined declines during this study period. This study suggests that AHI can be potentially employed to monitor the temporal change in agroecosystem health status, although AHI has some certain limitations and needs further improvement for the complexity of agroecosystems..

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Key words: *agroecosystem; agroecosystem health; agroecosystem structure and functions; Guangzhou; South China*

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INTRODUCTION

As complex human-centered ecosystems, agroecosystems can be defined as typically nature-economy-society multi-function ecosystems, which include an array of agriculture-related elements and interactions among these elements (Xu and Mage 2001; Zhu et al. 2012). Agroecosystems play an increasingly crucial role in the sustainability of human beings. Unfortunately, they have become highly dysfunctional and degraded in many regions worldwide, as being affected by rapid urbanization and industrialization (Paoletti et al. 2011). Under such circumstances, it is urgent to develop some concepts and methods to provide an integrated framework for analyzing agroecosystems (Bockstaller et al. 2009). One of the models is 'health' of agroecosystems, which has been proposed to make

an analogy between the physiology of organisms and the functioning of ecosystems (Su et al. 2012). Attempts in ecosystem health assessment have provided useful criteria and properties to describe and evaluate the state of agroecosystem conditions (Rapport et al. 1998; Chen et al. 2010), since this concept model was introduced by Schaeffer et al. (1988) and Rapport (1989). Agroecosystem health assessment is a decision-making process to systematically improve management strategies that maintain or enhance the quality of the environment (Gitau et al. 2008). While there is still lack of a uniform definition and assessment standards of agroecosystem health (Zhu et al. 2012), the model of agroecosystem health may provide a new insight into how agroecosystem conditions can be perceived (Xu and Mage 2001).

Since International Ecosystem Health Association established in 1994, a number of conceptual health models have been used to guide indicator selection in agroecosystem assessment, including the Driving Forces-Pressures-States-Impacts-Responses framework, and Vigor-Structure-Resilience framework (Zhang and Luo 2004; Peterson *et al.* 2017). However, most of conceptual health models are heavily biased towards either the biophysical, economic or social disciplines, and imbalanced in their degree of quantification (Ittersum *et al.* 2008). For example, in China, soil quality and food security have not been given enough consideration in the development of a health model for agroecosystems (Xie *et al.* 2005; Roth and Doluschitz 2008). Researchers usually chose different indicators depending on his/her application scale, dimension, potential utility, specific expertise and interest (Suo *et al.* 2008). Thus, there is an urgent need to simultaneously investigate different aspects of agroecosystem health, including their biotic aspects along with provisioning and other services, so that the nature of agroecosystem health can be better understood (Vadrevu *et al.* 2008). According to the definition of Xu and Mage (2001), a healthy agroecosystem can keep its stability of organizational structure to realize various functions, and also can maintain its structure affected by its functions over a long-term period. As mentioned above, agroecosystem health can be referred to both functional and structural characteristics.

Since China launched the reform and opening-up drive, the rapid industrialization and urbanization have brought various negative effects on agroecosystems around China (Lai and Chen 2008). Agroecosystem health has encountered many problems such as soil pollution, land use/cover change, inappropriate usage of fertilizers and pesticides, and food security, etc. Agroecosystem structure and functions have been obviously changed in China. These problems have resulted in a potential public health threat to consumers, and they also induced some serious ecological impacts and environmental degradation (Lai and Chen 2008; Qin *et al.* 2008; Zhao *et al.* 2008). Therefore, the objectives of this paper are to establish a health conceptual model based on structural and functional characteristics of agroecosystems and to examine temporal change in agroecosystem health using Guangzhou as a case study.

MATERIALS AND METHODS

Study area

Guangzhou (112°57'~114°3'E, 22°26'~23°56'N) is located in the north of the Pearl River Delta of Guangdong

Province, South China (**Figure 1**). Guangzhou enjoys a subtropical monsoon climate with average annual precipitation ranging from 1,689 to 1,876 mm and a mean annual temperature range of 20~22°C. Tiantang Peak at 1,210 m forms the highest point in Guangzhou and the elevation generally rise from the southwest to northeast. Guangzhou includes eleven urban administrative districts. Guangzhou is pressing ahead with the construction of the five National Central Cities in China. Guangzhou's agricultural resources are of varied types and present a wide adaptability. It used to be a major base of agricultural products in South China before economic reform. However, it has experienced rapid urban expansion and unprecedented landscape alteration in the last three decades. Massive agricultural land has been used to satisfy the growing land demand from a rapid industrialization and urbanization processes (**Figure 1**). Agroecosystem health of Guangzhou has been deeply affected by the rapid industrialization and urbanization processes. Despite being a metropolitan area, there is still a large number of forest and agricultural land in the north and south Guangzhou (**Figure 1**). It is reported that vegetable and rice growing are two of the main agricultural activities.

Defining agroecosystem health

Healthy ecosystems can be kept away from 'distress syndrome' if they can actively maintain their organization and autonomy over time and then they are resilient to both the internal and external interference (Costanza 1992; Smit *et al.* 1998). Those ecological health concepts have been increasingly employed to define the meaning of agroecosystem health. These types of definition about health are of little utility to agroecosystem research because agroecosystems are directly managed by humans, and also a 'negatively' defined concept of agroecosystem health provides few directives for maintaining the health of the system (Xu and Mage 2001). According to the World Health Organization, health is described as "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" (WHO 1992). This description clarifies that human's needs and natural resources protection should be under consideration in the definition of health.

Agroecosystem health can be determined through a holistic appraisal of both functional and structural attributes at a regional level (Xu and Mage 2001). The concept "ecosystem structure and function" has been taken as implying biological interaction and regulation, and it is useful in understanding the ecological integrity and restorative capabilities trends of different ecosystems (Noy-Meir 1979; Cortina *et al.* 2006;

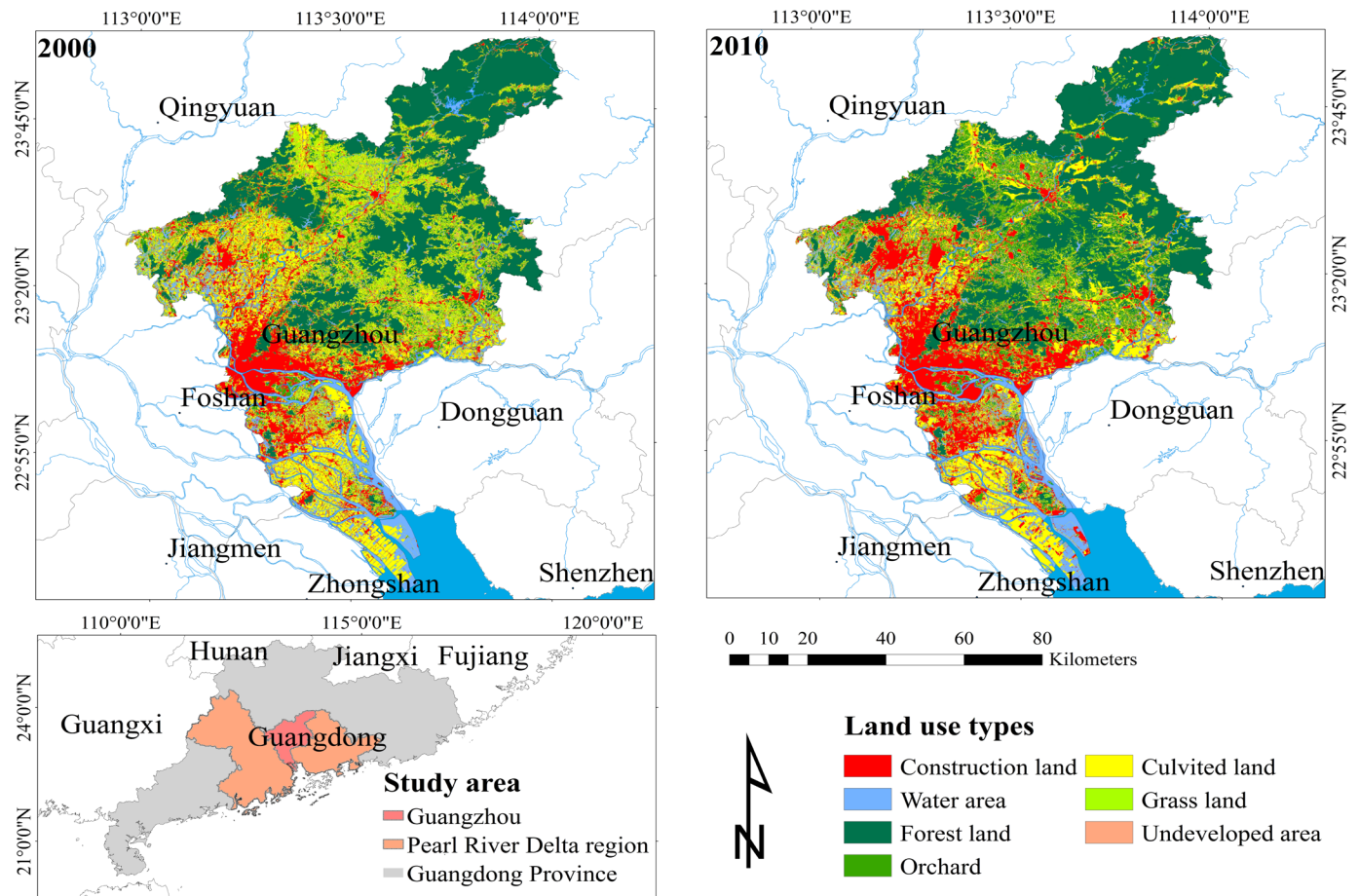


Figure 1. Location and land use change during 2000~2010 of Guangzhou, situated in Pearl River Delta of South China.

Vadrevu et al. 2008; Wu et al. 2015). Structural and functional attributes have been suggested to be sensitive indicators in response to ecological stress (*Schindler 1990; Simmons et al. 2008*). Some conceptual health models have been developed to describe how agroecosystem structure and functioning are correlated (*Xu and Mage 2001; Chen et al. 2010*), given the complexity of ecosystem management and restoration. However, structural and functional attributes do not necessarily respond to ecological stress in a similar manner (*Friberg et al. 2009*). As mentioned above, agroecosystem health can be defined as the system's ability to realize its functions desired by societal needs and expectations, and maintain its structure needed by its functions over a long time (*Xu and Mage 2001*). Given the complexity of agroecosystems, this study constructed an agroecosystem health assessment model, similar to the ecological conceptual models (ECM) developed for Daya Bay, Guangdong Province, China (*Chen et al. 2010*).

Framework of agroecosystem health assessment

Agroecosystem structure and selection of evaluation index. Structural dimensions usually focus on community

composition and biological diversity, which signify the species and complexity in the original formulation (*Cortina et al. 2006*). When subjected to an unpredictable disturbing force, ecosystem structure and function can jointly influence such properties as stability, sustainability, and resilience. Ecosystem structure and function are always interacted with each other, but structure plays a key role in how various functions can be realized. Human-managed agroecosystems typically include many farms and neighboring ecosystems. Agroecosystems interact actively with their external environments and changes over time (*Conway 1987; Okey 1996*). Agroecosystem structure should be defined as both the internal and external structural characteristics. Implicit in agroecosystem health is the idea that structure determines functions, and functions then influence structures in a cyclical pattern. Diversified agroecosystem structures are suitable for providing enough and diverse products and services to human being's needs (*Xu and Mage 2001*). A good habitat structure in a region is an important guarantee to keep and assist the health and sustainability of agroecosystems (*Haas et al. 2000; Broome and Warner 2008*). In this study, structural metrics of ECM reflects both the biotic structure index (BI) and the habitat structure index (HI). BI can be quantified using two indicators while HI

can be derived from seven indicators (**Table 1**).

Agroecosystem functions and selection of evaluation index.

Healthy ecosystems state where their functions can be maintained in the face of external disturbances and stresses. A healthy agroecosystem functions around a 'steady state in biomass dynamic or nutrient influx',

and it also generates agricultural products and services at a high level of 'integrity and sustainability' (Soule 1992). Davis et al. (2012) argued that the greater healthy agroecosystems would be categorized as the more diverse cropping systems and they achieve higher productivity with less input of energy and nutrients. As a nature-economy-society system, agroecosystems perform various

Table 1: Summary of Indices and indicators and their priorities to assess agroecosystem health assessment in Guangzhou.

Theme (priority)	Subtheme (priority)	Indicator (priority)	Overall priority	Reference value
1. BI (0.1567)	1. diversity in planting structure (1)	1. crop diversity (0.8333)	0.1306	0.48
2. HI (0.1567)	2. natural habitat diversity (0.5)	2. multiple cropping index (0.1667)	0.0261	2.42
		3. water area (0.5579)	0.043	9.57%
		4. forest area (0.2634)	0.0206	35.65%
		5. orchard area (0.0569)	0.0045	15.21%
		6. grass and shrub land area (0.1219)	0.0095	11.05%
	3. landscape pattern of the cultivated land (0.5)	7. area of the largest cultivated land patch (0.1667)	0.0131	0.89%
		8. average area of cultivated land patches (0.8333)	0.0653	33.18 ha
3. SI (0.2602)	4. productivity (0.5390)	9. primary productivity (1)	0.1402	5.55 t ha ⁻¹ yr ⁻¹
	5. soil quality (0.2973)	10. organic material content in soil (0.4331)	0.0335	40 g kg ⁻¹
		11. Cu content in soil (0.0483)	0.0037	50 mg kg ⁻¹
		12. Cd content in soil (0.2110)	0.0163	0.3 mg kg ⁻¹
		13. Pb content in soil (0.2110)	0.0163	250 mg kg ⁻¹
		14. Zn content in soil (0.0483)	0.0037	200 mg kg ⁻¹
		15. Cr content in soil (0.0483)	0.0037	250 mg kg ⁻¹
	6. regional environmental quality (0.1638)	16. frequency of acid rain (0.3333)	0.0142	0
		17. pH of rainfall (0.3333)	0.0142	5.6
		18. water quality index (0.3333)	0.0142	5
4. PI (0.2602)	7. crop yield (0.5)	19. grain yield per capita (0.3333)	0.0434	154.09 kg capita ⁻¹
		20. vegetable yield per capita (0.6667)	0.0867	485.50 kg capita ⁻¹
	8. heavy metals and pesticide residues in major vegetables (0.5)	21. Pb content in vegetable (0.2222)	0.0289	0.2 mg kg ⁻¹
		22. Hg content in vegetable (0.2222)	0.0289	0.01 mg kg ⁻¹
		23. Cd content in vegetable (0.2222)	0.0289	0.05 mg kg ⁻¹
		24. Cr content in vegetable (0.0556)	0.0072	0.5 mg kg ⁻¹
		25. As content in vegetable (0.0556)	0.0072	0.5 mg kg ⁻¹
		26. qualification rate of pesticide residues in vegetable (0.2222)	0.0289	100%
5. RI (0.04064)	9. climate and air regulation (0.0738)	27. emissions of CH ₄ and N ₂ O (0.5)	0.0015	89286.16 t
		28. emissions of O ₂ (0.5)	0.0015	2687704 t
	10. disaster regulation (0.6434)	29. irrigation rate (0.5)	0.0131	100%
		30. yield maintenance under drought and flood disaster conditions (0.5)	0.0131	100%
	11. farmland regulation (0.2828)	31. utilization ratio of fertilizer (1)	0.0115	100%
6. CI (0.0628)	12. culture heritage (1)	32. basic farmland conservation area (0.25)	0.0157	221,138 ha
		33. arable land area per capita (0.25)	0.0157	0.24 ha capita ⁻¹
7. ESI (0.0628)	13. coordination function of rural economic (1)	34. engel's coefficient (0.25)	0.0157	35%
		35. rural- urban income ratio (0.25)	0.0157	1
		36. ratio of people educated above junior high school (0.25)	0.0157	100%
		37. average net income per capita (0.25)	0.0157	US\$1,937

functions related to their own special characteristics of energy flows and nutrient cycles (Li *et al.* 2007). When an agroecosystem is under stress for a trend of continuous growth, socio-economic development and environmental improvement (Zhao *et al.* 2008), its ability to function is disrupted, hence deliver services fluctuates (Rao and Rogers 2006). Thus, an agroecosystem is healthy with respect to the health of its socioeconomic and environmental dimensions in a sense (Yiridoe and Weersink 1997). According to Mooney *et al.* (2004) and Chen *et al.* (2010), functional performance of agroecosystems can be categorized as supporting, provisioning, regulating, and cultural services and also sustainable economic development. Function indices, such as supporting services index (SI), regulating services index (RI), provisioning services index (PI), cultural services index (CI) and sustainable economic development index (ESI) are used to assess ecosystem functions and their related indicators (**Table 1**). These indices for ecosystem services are based upon those adopted for the Millennium Ecosystem Assessment (MEA) (Chen *et al.* 2010).

Indicators and methods for data collection

Agroecosystem structure

Biotic structure: It describes the way organisms interact within an agroecosystem. Diversity in planting structure is important to long-term agroecosystem structure and processes (Chapin III *et al.* 1997; Xu and Mage 2001). Agroecosystems that incorporate a diversity of crops and surrounding biota are generally considered more stable, resilient, and ultimately, sustainable (Okey 1996). Agricultural farming diversification may increase the ability of the system to avoid the economic loss and minimize the uncertainty induced by price fluctuation in the market, and it may also improve the utilization efficiency of natural resources through increased nutrient cycling (Ilbery 1991; Xu and Mage 2001). Furthermore, multiple cropping index refers to the times of sequential crop planting in the same arable land in one year. A rise in the multiple cropping index may be beneficial as it signifies an increase of crop diversity and improved sustainability of a cropping, or farming, system (Peng *et al.* 2004; Zhao *et al.* 2008). Therefore, both cropping diversity and multiple cropping indices were applied to indicate the structure of agroecosystem. According to the ratio of planting area of each agricultural species, cropping diversity is calculated using the method of Shannon's Diversity Index. The higher cropping diversity means the higher agricultural species. Multiple cropping index was measured as follows: The total annual sown

area of crops/the total cultivated land area $\times 100\%$ (Xie and Liu 2015). The high multiple cropping index indicated that different agricultural species was sown in different seasons.

Habitat structure: Agroecosystems are controlled by biological processes located within (and influenced by) an environmental content (Conway 1987; Okey 1996). A good habitat structure is an important guarantee to keep and assist the health and sustainability of agroecosystems (Haas *et al.* 2000; Broome and Warner 2008). It is also a benefit for improving the quality and quantity of agriculture products due to decrease in the frequencies of diseases and pests, and other natural disasters (Harnly 2004; Zhao *et al.* 2008). At the same time, a good structure (landscape pattern) of cultivated land reflects the success of human management to a certain extent (Peng *et al.* 2004). In a word, a good external and internal habitat structure (diversification in nature habitat) indicates a favorable ecological condition. Nagendra and Gadgil (1999) reported that habitat structure is correlated well with land use/cover types. In order to understand these internal and external characteristics of structure, land use data has been derived from Landsat TM images for three different time periods (early 1990s, 2000 and 2010). Landsat images were put through both geometric and atmospheric corrections. Land use data was retrieved from the images by supervised classification using the maximum likelihood method available with ENVI 4.8 software. Moreover, land use change encompasses some of the most important human alterations affecting habitat structures. Cultivated land is more or less modified by human management. In addition, cultivated land is mostly affected by urbanization and industrialization in China. Cultivated land area is the most importantly ecological landscape pattern. Thus, both the largest area and average area of cultivated land patches were all derived using Fragstats 3.3.

Agroecosystem function

Supporting services. These are basic functions for all other ecosystem services. The primary function of biophysical components is realized through plant photosynthesis and material transfer in food chains and webs (Xu and Mage 2001). Net primary productivity (NPP) generally describes the ability of an ecosystem to produce outputs. With both higher rates of primary productivity and greater capacity to retain soil nutrients, ecosystems can be considered ecologically more efficient (Okey 1996). NPP is very useful for assessing the agricultural food-production efficiency. NPP was estimated using the following formula:

$$NPP = \left(\sum_{i=1}^n C_i \times Q_i \times (1 - F_i) / E_i \right) / T_a \quad (1)$$

Where n denotes the number of crop types involved, C_i is the carbon content in crop type i ; Q_i signifies crop yield in crop type i ; F_i represents the moisture content of the crop type i ; and T_a stands for the total planting, or crop, area. Estimated parameters of NPP for the most common main crops in Guangzhou can be found in the study of *Zhu et al. (2013)*.

Soil quality refers to the soil function of physical, chemical, and biological characteristics, which maintains agricultural productivity (*Su et al. 2012*). Moreover, soil quality affects many key ecosystem functions, such as providing a medium for crops to grow in, the recycling of nutrients and supporting human health and habitation (*Lowdermilk 1953; Nelson et al. 2009*). Especially, soil heavy metals pose a great threat to agroecosystem health, given their toxicity and persistence (*Su et al. 2012*). For example, soil environmental pollution may decrease agricultural product quality. Soil organic matter (SOM) is a key factor of soil fertility. Soil heavy metal pollution, such as Cu, Cd, Pb, Zn and Cr, is relatively serious in the study area (*Chai et al. 2003; Chai et al. 2004*). In order to determine the current situation of soil quality in the surface soil layers, a total of 96 mixed-soil samples were randomly collected around Guangzhou. Forty-two mixed-soil samples were from paddy field and the other soil samples came from vegetable field. The analytical methods for organic matter (SOM) and selected heavy metals (such as Cu, Cd, Pb, Zn and Cr) of soil samples were those used in *Chai et al. (2003)* and *Li et al. (2009)*. The data of SOM and heavy metal contents were derived from the result of previous researches in the year 2000 (*Zhang et al. 1997; Liu et al. 2002; Chai et al. 2003; Chai et al. 2004*). Other than soil quality, regional environmental quality also affects the supporting service. For example, agricultural products may be polluted through material cycle process if agricultural ecosystems were irrigated by the polluted water. These environmental data (including acid rain and water quality) were collected from environmental state bulletins and statistical yearbooks of Guangzhou. Water environmental condition for Guangzhou has been derived from the study of *Ye (2011)*.

Provisioning services: These can be partially described as food security, providing sufficient quantity and quality of agricultural products for everyone at all times (*Fernando et al. 2009; Gomiero et al. 2011*). Accumulation of the toxic elements (such as heavy metals and pesticides) is one of major concerns in agricultural

products (*Li et al. 2009*). Sufficient food is also of interest and concern to ensure food security and support economic development in China (*Zhao et al. 2008*). Thus, much more attention should be given to crop yield as well as heavy metals and pesticide residues in China. Heavy metal contents and pesticide residues in vegetables have been investigated by different researches (*He et al. 2003; Tan et al. 2005; Yu et al. 2010; Wang 2012*) and their results have been applied in this study. Both grain yield and vegetable yield per capita were estimated by statistical yearbooks of Guangzhou.

Regulating services: Millennium Ecosystem Assessment defines regulating services as benefits obtained from the regulation of ecosystem processes (*Bockstaller et al. 2009; Sydorovych et al. 2009*). Regulating services are rarely estimated in the literature even though they have strong effects on the ecosystem (*Carpenter et al. 2006; Chen et al. 2010*). A reasonable regulation strategy often keeps agroecosystem from some natural disasters such as flood and drought, and even decreases the outputs of green-house gases, etc. Climate and air regulation (two indicators), disaster regulation (two indicators) and farmland regulation (one indicator) were used to assess the regulating services. Due to lack of estimation models in South China, fertilizer use efficiency has been estimated by the ratio between the net quantity of applied chemical fertilizers and the net quantity found in crop tissues. Contents of chemical elements in the crop tissues were based on the research of *Bai et al. (1986)* and *Chen et al. (2002)*. Total emission amount of N_2O and CH_4 were estimated using the formula as follows: Emission rates of green-house \times planting area of rice and vegetable according to *Xing and Zhu (1997)* and *Lin et al. (2012)*. Total emission amount of O_2 was estimated according to NPP of agroecosystem of different years (such as 2000 and 2010). Other indicators (such as irrigation rate, maintenance of yield under drought and flood disaster conditions) were collected from statistical yearbooks of Guangzhou. The fundamental formula of irrigation rate is as follows: The total effective irrigation area/the total cultivated land area $\times 100\%$. Effective irrigation area means that how much cultivated land area can be normally irrigated by the neighboring water resources using agricultural irrigation facilities.

Cultural services: These are nonmaterial benefits (e.g., spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences). The quantity of cultivated land is not only related to food security and sustainable agricultural development (*Fernando et al. 2009*), but it is also at the core of its cultural services function because cultivated land is agricultural-culture

carrier. This paper considered that both indicators such as basic farmland conservation area and arable land area per capita, were essences of culture heritage in agroecosystems. This is due to a lack of data related to the aesthetic value of agroecosystems as well as a dearth of information on their education and recreation value. These mentioned data were collected from statistical yearbooks of Guangzhou.

Sustainable economic development. Because of the increasing income disparity between city and country along with urbanization and industrialization process, cultivated land abandonment has become a great concern in China and high proportion of farmers have been away from their own counties. Agricultural economic development is the pivotal problem of which affecting China's economy development. Moreover, agricultural development is prone to increase conflicting tensions between economic development and environmental protection (Li *et al.* 2009). One way to resolve this tension may be afforded by the pursuit of sustainable economic development (Xie *et al.* 2005). As the improvement of both economic development level and living standard of people, consciousness of environmental protection will be strengthened. Thus, rural economic conditions should be considered in assessment of agroecosystem health. The selected economic metrics include Engel's coefficient, the rural-urban income ratio, the ratio of people educated above junior high school and average income per capita. Engel's coefficient is a measure of the proportion of family income that is spent on food. All mentioned data were collected and then calculated from statistical yearbooks of Guangzhou.

Combining multiple data to access agroecosystem health

Non-dimensional assessment of indicators according to reference values. Functional and structural conditions of the 1990s agroecosystem were used as the reference conditions because of their historical and ecological significance: In the initial stage of China's Economic Reform and Opening-up drive, agroecosystem of Guangzhou remained relatively stable with relatively lower level of urbanization and industrialization. Significant change did not occur in land use/cover change and environmental quality until the 1990s; Enough assessment data can be collected from the 1990s in Guangzhou, and these data is comparatively complete and reliable. If there is lack of historical data for some indicators, these data around the 1990s can be used as reference values (Chen *et al.* 2010). Unfortunately, no research has been found for heavy metal contents of both

soil and vegetables in Guangzhou around the 1990s. Thus, limit values of national standard were used as reference values according to National Soil Environmental Quality Standard (GB 15618-2008) and National Food Safety Standard (GB 2762-2005). Because the heavy metal contents of both soil and vegetables are affected by background values (a_0), it is necessary to eliminate these effects when indicator values are non-dimension processed.

In order to eliminate the problem of incomparability amongst the different indicators with different dimensions, continuous scaling method was employed to standardize the data set (except for both soil and vegetable related indicators) using the following formula:

$$V_i = \begin{cases} \frac{a_i}{a_{ir}} & (a_i \leq a_{ir}) \\ 1 & (a_i \geq a_{ir}) \end{cases} \quad (2)$$

$$V_i = \begin{cases} 1 - \frac{a_i}{a_{ir}} & (a_i \leq a_{ir}) \\ 0 & (a_i \geq a_{ir}) \end{cases} \quad (3)$$

Where V_i is the normalized value of indicator i th, and a_{ir} is the reference value of indicator i th, a_i is the observed value of indicator i th. Positive indicator values were non-dimension processed using the formula (2) while negative indicator values were non-dimension processed using the formula (3). However, heavy metal contents in both soils and vegetables were processed using the formula (4) according to National Standard.

$$V_i = \begin{cases} \frac{a_{ir} - a_i}{a_{ir} - a_0} & a_i \geq a_0 \\ 1 & a_i \leq a_0 \end{cases} \quad (4)$$

In general, all non-dimension processed indicator values are bounded between 0 and 1, where 1 means the highest 'healthy' statue. As the value becomes lower than 1, or decreases, agroecosystem health declines. Using the data (Table 1), under reference value, the scores of each indicator were computed.

Application of analytic hierarchy process (AHP) in combining data. AHP has been widely employed to establish a hierarchical framework toward a multi-objective decision-making process. It could be described as a process for combining data before agroecosystem health assessment. The following steps in AHP employed to agroecosystem health are: structuring multiple indicators/index into a hierarchical framework, deriving models to combine these indicators/index according to their relationships with agroecosystem health at each level in the hierarchy,

aggregating the data according to the hierarchical model into a single index, and evaluating the result (Vadrevu *et al.* 2008). Before aggregating the data into a single index, all indicators/indices were assessed and scored by an expert panel including 12 experts. This expert panel was selected from the associated disciplines such as environmental science, soil and fertilizer science and agricultural science. Considering its relevance to agroecosystem health, these experts were asked to assign a score between 1 (very unimportant) and 9 (very important) for each indicator/index. AHP was used to make pair wise comparisons and then create judgment matrices according to the result of expert scoring. Priorities of each indicator/index could be calculated according to constructing the verdict matrix, hierarchy total array and consistency test (Li *et al.* 2007).

Agroecosystem health index (AHI) calculating.

Column A refers to the 7 sub-indices, or themes, that can be used to derive the overall AHI in Guangzhou (Table 1). These 7 sub-indices can be characterized by 12 subthemes which are given in column B. The 12 subthemes can be quantified using different multiple indicators. In this study, there were 37 indicators as shown in column C. AHI can be calculated as follow:

$$AHI = \sum P_{ij} M_{ij} \quad (i, j = 1, 2 \dots n) \quad (5)$$

Where P_{ij} represents priorities in different levels; M_{ij} represents the value of each indicator/index. Index values 0 and 1 are assumed to be the worst and the best situations, respectively. Grading standard of agroecosystem health were assessed according to previous studies (Li *et al.* 2007). The agroecosystem health assessment of Guangzhou was based on a grading standard criterion (Table 2).

Table 2. Grading standard of agroecosystem health assessment in Guangzhou.

Value	< 0.4	0.4~0.55	0.55~0.7	0.7~0.9	>0.9
Criterion	Worst	Not healthy	Sub-healthy	Relative healthy	Very healthy

RESULTS AND DISCUSSIONS

Agroecosystem structure

Biotic structure. Both crop diversity and multiple cropping index were selected to signify the biotic-structure change in the agroecosystem of Guangzhou (Table 1). Crop diversity slightly decreased by 4.35%, while multiple cropping index increased by 22.16% during this decade (Table 3). Due to the different change trends

between crop diversity and multiple cropping index, BI only slightly decreased. The BI weakly decreased from 0.93 to 0.92 during this period from 2000 to 2010 (Figure 2). This value (being above 0.9) signifies a healthy biotic structure in the agroecosystem of Guangzhou. It was obviously noted that BI declined as a result of the crop-diversity decrease. To pursue high economic benefits, farmers prefer to increase the proportion of crop types with higher economic benefits and they also incline to increase the agricultural land use intensity (Zhao *et al.* 2008). Agricultural land use gradually evolve from various functions into a single one. For example, vegetable sown area sharply increased while rice sown area decreased from 2000 to 2010 (Figure 3). This is because of the higher economic return in vegetable planting.

Habitat structure. It has been deeply affected by land use/cover change as a result of urbanization and industrialization in Guangzhou. Habitat structure mainly includes two aspects: natural habitat diversity, and landscape pattern of the cultivated land (Table 1). Natural habitats are typically categorized as forest, orchard, grass and shrub. Forest was one of dominant natural habitats and proportion of forest area increased (Table 3). Important natural habitats included both water and orchard in Guangzhou. Water-area proportion ranging from 10.76% to 11.31%, remained relatively stable. Orchard-area proportion increased from 8.73% to 13.80% during this period. Area proportion of grass and shrub sharply decreased from 6.47% to 1.69%. Due to overall stabilization of dominant/important natural habitats, natural habitat diversity slightly decreased in the study area (Table 3). It was observed that a 24.29% decrease happened in the area of the largest cultivated land patch, and a 31.39% decrease occurred in the average area of cultivated land patches (Table 3). As a result, landscape pattern of the cultivated land changed from the relative healthy state (0.72) to sub-healthy state (0.50). It was indicated that due to human activities like urbanization and industrialization, fragmentation of cultivated land increased with time (Weng 2002; Li and Yeh 2004). As mentioned above, HI change was mainly affected by the landscape pattern change of cultivated land in Guangzhou. It was obvious that HI decreased from 0.81 to 0.70 during last one decade (Figure 2). It was indicated that habitat structure was being compromised to some extent, although HI was at a relatively healthy state.

Agroecosystem functions

Supporting service. Primary productivity, soil quality and regional environmental quality have been selected to signify the functional state of supporting service in the

Table 3. Change of structure related indicators during 2000~2010 in Guangzhou.

Subtheme	Indicator	2000	2010	Unit
1. diversity in planting structure	1. crop diversity	0.46	0.44	/
	2. multiple cropping index	1.85	2.26	/
	3. water area	11.31	10.76	%
2. natural habitat diversity	4. forest area	32.36	35.28	%
	5. orchard area	8.73	13.80	%
	6. grass and shrub land area	6.47	1.69	%
3. landscape pattern of the cultivated land	7. area of the largest cultivated land patch	0.70	0.53	%
	8. average area of cultivated land patches	23.61	16.20	ha

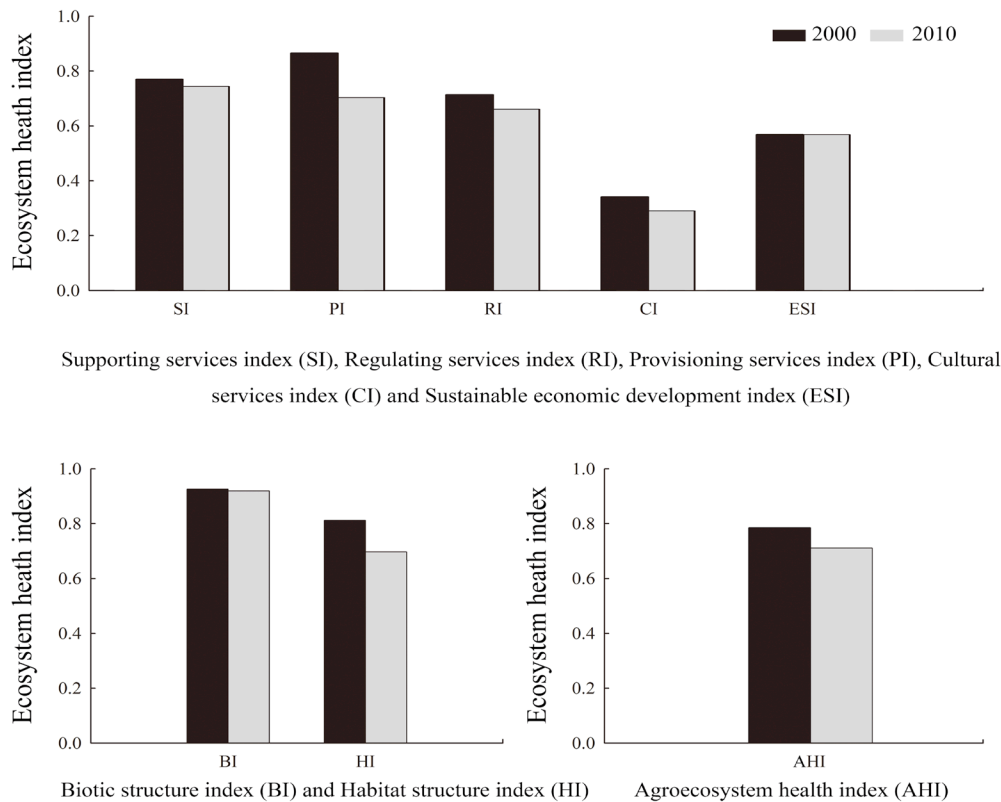


Figure 2. Change of ecosystem health index during 2000~2010 of Guangzhou.

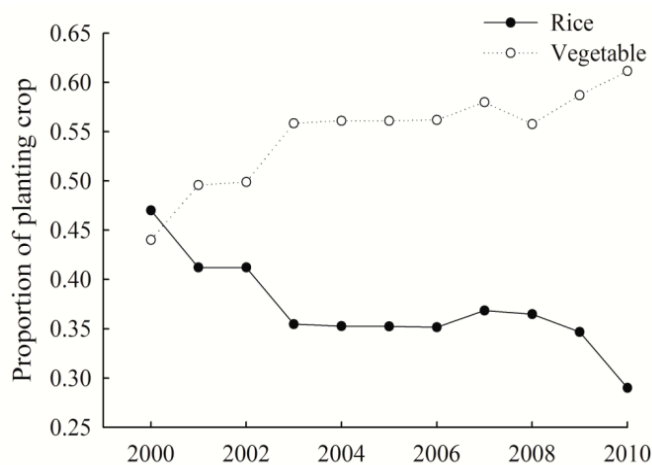


Figure 3. Change of rice and vegetable sown area in Guangzhou, South China.

agroecosystem (Table 1). Firstly, primary productivity decreased by 8.87% from 5.07 to 4.62 t ha⁻¹ yr⁻¹ (Table 4). Increasing demand for vegetables has resulted in more farmers engaging in vegetable farming, since they fetch a good price in the markets (Nonga *et al.* 2011). Due to the relatively lower primary productivity of vegetables, average primary productivity changed from very health (0.91) to relative health (0.83) in Guangzhou (Table 4). Secondly, soil quality has been greatly threatened by polluted-water irrigation, deposited solid waste, polluted atmospheric deposition and the abuse of fertilizer and pesticide (Wong *et al.* 2002; Chai *et al.* 2003; Li *et al.* 2009). Soil quality was at a sub-healthy state during this period (Table 4). SOM content increased from 27.41 to 29.83 g kg⁻¹, indicating that soil fertility increased in the past decade. Moreover, contents of all heavy metals were

Table 4. Change of supporting function related indicators during 2000~2010 in Guangzhou.

Subtheme	Indicator	2000	2010	Unit
4. productivity	9. primary productivity	5.07	4.62	t ha ⁻¹ yr ⁻¹
	5. soil quality			
	10. organic material content in soil	27.41	29.83	g kg ⁻¹
	11. Cu content in soil	24.02	39.77	mg kg ⁻¹
	12. Cd content in soil	0.2808	0.4803	mg kg ⁻¹
	13. Pb content in soil	58.02	38.46	mg kg ⁻¹
	14. Zn content in soil	162.6	92.68	mg kg ⁻¹
	15. Cr content in soil	64.65	69.22	mg kg ⁻¹
6. regional environmental quality	16. frequency of acid rain	62.30	50.70	/
	17. pH of rainfall	4.71	5.06	/
	18. water quality index	1.9	1.9	/

elevated compared to the corresponding threshold values of natural background. An increase in Cu, Cd and Cr may finally pose long-term environmental and health implication on Guangzhou's agroecosystem (**Table 4**). In general, soil heavy metal pollution has become a non-ignored threat to the quality of agricultural products and subsequently the health and welfare of residents (Wong et al. 2002). This result of assessment was in agreement with other regions of China (Huamain et al. 1999). Regional environmental quality of Guangzhou has experienced a process of continuous improvement although water quality index has remained practically unchanged (**Table 4**). However, regional environmental quality was still at a sub-healthy state. These external factors such as rainfall and water quality, provide a broader environment within which an agroecosystem operates its functions and maintains its structure (Smit et al. 1998; Xu and Mage 2001). With respect to water quality, it is noteworthy that this evaluation standard is the fifth class of water quality according to Chinese national standards. This signifies a standard of water quality that the fifth-class water resources can be only used to meet the water needs of agriculture and urban landscape. Water quality is not optimistic in Guangzhou. Fortunately, acid-rain frequency decreased while falling-rain pH increased. This result signifies that regional environmental quality has been improved to some extent. However, falling-rain quality values were lower than their background values. Based upon combining the indices of supporting services, SI slowly decreased from 0.77 to 0.74, suggesting that the supporting service functions were relatively healthy but weakened (**Figure 2**). The healthy state in soil quality and regional environmental quality, were mainly responsible for the decreased SI in Guangzhou. It has been reported that agricultural soil quality has not been given sufficient consideration in the previous health assessments of agroecosystem in China. According to the results from this study, it is supported that future health assessment should concern about soil quality.

Provisioning service. Functional assessment of provisioning services can be determined by two aspects: crop yield, and heavy metals and pesticide residues in major vegetables of Guangzhou (**Table 5**). Crop yield index changed from relatively healthy state (0.88) to sub-healthy state (0.67). Both grain and vegetable yields per capita declined (**Table 5**), due to population growth and cultivated land loss in Guangzhou (Weng 2002; Zhao et al. 2008). Especially, grain yield per capita sharply decreased by 65.06%. Food security of Guangzhou is in a downward trend during this period. It was also found in other regions of the Pearl River Delta (Yuan 2011). Unfortunately, food quality also decreased with many concerns. During the last decade, heavy metal contents in major vegetables generally increased, except for Hg (**Table 5**). However, qualification rate of pesticide residues in vegetables has decreased from 95.96% to 84.37% (Tan et al. 2005; Yu et al. 2010). High-frequency use of chemical fertilizers and pesticides, along with industrial pollution and atmospheric deposition, has been served to increase the accumulation of heavy metals and pesticide residues in the soil. In turn, polluted soils subsequently increase the contents of these toxic elements in vegetables and other crops (Wong et al. 2002). Because of the decrease trend in crop yield and food quality, PI changed from relatively healthy state (0.71) to sub-healthy state (0.66) during the past decade (**Figure 2**). It indicated a growing need for caution regarding the provisioning service function of the agroecosystem in Guangzhou.

Regulating service. In this study, regulating service of Guangzhou's agroecosystem has been assessed by these following indicators: emission of CH₄ and N₂O, emission of O₂, irrigation rate, yield maintenance under drought and flood disaster conditions, and utilization ratio of fertilizer (**Table 6**). First, it was found that the ability of climate and air quality regulation was at not healthy state although slightly increased. This is attributed to the change of cropping structure, cultivated land loss and fertilizer over-consumption. During this studied period,

Table 5. Change of providing function related indicators during 2000~2010 in Guangzhou.

Subtheme	Indicator	2000	2010	Unit
7. crop yield	19. grain yield per capita	127.54	53.84	kg capita ⁻¹
	20. vegetable yield per capita	437.40	404.39	kg capita ⁻¹
8. heavy metals and pesticide residues in major vegetables	21. Pb content in vegetable	0.048	0.050	mg kg ⁻¹
	22. Hg content in vegetable	0.0019	0.0013	mg kg ⁻¹
	23. Cd content in vegetable	0.0071	0.0305	mg kg ⁻¹
	24. Cr content in vegetable	0.0404	0.0647	mg kg ⁻¹
	25. As content in vegetable	0.0133	0.022	mg kg ⁻¹
	26. qualification rate of pesticide residues in vegetable	95.96	84.37	%

Table 6. Change of regulating function related indicators during 2000~2010 in Guangzhou.

Subtheme	Indicator	2000	2010	Unit
9. climate and air regulation	27. emissions of CH ₄ and N ₂ O	64,975.36	31,612.95	t
	28. emissions of O ₂	21,52215	12,40074	t
10. disaster regulation	29. irrigation rate	70.62	80.2	%
	30. yield maintenance under drought and flood disaster conditions	62.92	69.95	%
11. farmland regulation	31. utilization ratio of fertilizer	86.92	48.85	%

cultivated-land area proportion declined from 24.83% to 18.98% in Guangzhou (**Table 3**) while fertilizer consumption increased from 0.18 to 0.48 t ha⁻¹ according to Statistical Year Book of Guangzhou. Land use change from paddy field to vegetable field was benefit to decrease the emission of CH₄ and O₂, but increase the emission of N₂O due to much more fertilizer applied in vegetable field (*Xing and Zhu 1997*). Emissions of greenhouse gases and O₂ all decreased by over 40% during the last decade, but they were all much smaller than the reference values (**Table 1** and **6**). Thus, it was still weak in the regulation of climate and air. Moreover, two indicators (such as irrigation rate, and yield maintenance under drought and flood disaster conditions) were used to assess the ability of disaster regulation. Obviously, the ability of disaster regulation has been improved (**Table 6**). This could be attributed to the improvement of agricultural infrastructure as agricultural science and technology developed. For example, agricultural irrigation rate has been increased by 13.57%. However, the ability of farmland regulation changed from 0.87 (relatively healthy) to 0.49 (not healthy). The reason of weakened farmland regulation is that utilization ratio of fertilizer decreased with an increase in agricultural fertilizer consumption (*Chen et al. 2002*). In Guangzhou, RI decreased from 0.71 to 0.66 (**Figure 2**), suggesting that the regulation services became weakened. Farmland regulation was mainly responsible for the decrease of RI.

Cultural service and economic sustainable development. Cultural service metrics include two indicators such as basic farmland conservation area and arable land per capita (**Table 7**). Two indicators of cultural

service significantly decreased, in comparison with the reference value (**Table 1**). Basic farmland conservation area decreased by 6.28%. Similarly, arable land area decreased from 0.17 to 0.13 ha capita⁻¹. With the rapid urbanization and industrialization as well as pursuing high economic return, agricultural land were usually converted to construction land (*Zhao et al. 2008*). In the health assessment, the CI ranged from 0.29 to 0.34 (**Figure 2**), and this reached the worst level. It was suggested that agricultural heritage protection has been challenged in Guangzhou.

Engel's coefficient increased from 38.21% to 45.91% while the rural-urban income ratio decreased from 0.51 to 0.46 during this study period (**Table 7**). These indicated that the urban-rural dual structure was strengthened and that the living standards of rural residents decreased. Although two indicators (such as ratio of people educated above junior high school, and average income per capita) have been improved to some extent over this study period, they were still much lower than urban residents. For example, average income per capita was US\$ 461 in 1992 and US\$ 2,207 in 2010. It only accounts for about 50% of urban residents at the same period. The ESI remained unchanged (0.57) at a sub-healthy state during the past decade, perhaps indicating that sustainable economic development of the agroecosystem has not been improved and unsuccessful in Guangzhou (**Figure 2**).

Health assessment of agroecosystem

As a whole, AHI decreased from 0.78 to 0.71 (**Figure 2**), suggesting that Guangzhou's agroecosystem

Table 7. Change of both cultural and sustainable economic development function related indicators during 2000~2010 in Guangzhou.

Subtheme	Indicator	2000	2010	Unit
12. culture heritage	32. basic farmland conservation area	146,900	137,681	ha
	33. arable land area per capita	0.17	0.13	ha capita ⁻¹
13. coordination function of rural economic	34. engel's coefficient	38.21	45.91	/
	35. rural- urban income ratio	50.69	46.47	/
	36. ratio of people educated above junior high school	49.5	59	%
	37. average net income per capita	982	2207	\$

was at a sub-healthy state but weakened. It was indicated that Guangzhou's agroecosystem was under pressure by human disturbances including the urbanization and industrialization (Zhao *et al.* 2008; Walter and Stützel 2009 a, b). AHI was categorized as structure and functions including seven different indices such as BI, HI, SI, PI, RI, CI and ESI. From the year 2000 to 2010, HI and PI clearly declined; SI, RI and CI exhibited a limited decrease whilst BI and ESI showed no obvious change. This result indicated that the decline in AHI was mainly driven by HI and PI with a lesser contribution being made by SI, RI and CI. It was noted that the assessment index ranked from high to low in the year 2010 as follows: BI<SI<PI<HI<RI<ESI<CI, with only BI exceeding 0.9 and CI being below 0.4. This ranking and the values of the indices suggests that the biotic structure Guangzhou's agroecosystem is relatively stable and successful. At the other extreme, CI represents a "worst". Also, ESI (0.57) indicated that economic sustainable development is not successful. With scores in the range of between 0.7 and 0.9, the other indices revealed the need for caution. Especially, HI and PI exhibited well defined declines in the past decade.

It is the first attempt to assess the healthy variation of the Guangzhou's agroecosystem. The conceptual framework AHI appears very useful for assessing the healthy state of an agroecosystem in terms of ecological structure and functions. Structural and functional indicators have been well defined and selected according to the uniqueness of an urban agroecosystem. Given the complexity of agroecosystems, data sources of these indicators were complicated, e.g. land use data and landscape metrics retrieved from remotely sensing images, soil quality and vegetable pesticide/herbicide residues collected from other researchers' publications, and the other data mainly obtained from the government reports/yearbooks. It may be challenging to integrate different-source data. Fortunately, AHI can integrate internal and external indicators at different spatial scales using the AHP method. Moreover, it has been suggested that food security and soil quality have not received

enough consideration in the health assessment (Vadrevu *et al.* 2008) and agroecosystem health assessment of Ohio is a notable exception. In addition, health assessment can support the decision-making service for agricultural sustainable development (Zhu *et al.* 2012).

The AHI conceptual frameworks have been advocated as an appealing guideline for health assessment. However, most of these frameworks are still at the stage of conceptual model construction. Despite huge effort to describe agroecosystem health, the healthy state of agroecosystems still cannot be comprehensively captured (Xu and Mage 2001; Vadrevu *et al.* 2008). Most of AHI frameworks are heavily biased towards either the biophysical, or economic and social aspects, and they are not balanced in the indicators used (Ittersum *et al.* 2008; Nelson *et al.* 2009). Due to lack of uniform definition and norms, it is very difficult to establish a systematic and scientific evaluation system (Haworth *et al.* 1998; Mooney *et al.* 2004). There is an urgent need for a more rigorously definition and a more uniform norm of agroecosystem health, in order to establish a scientific, systematic and comprehensive indicator system or index (Carpenter *et al.* 2006). In the future, agroecosystem health assessment can provide comprehensive and accurate information for agricultural management.

Furthermore, it is still a challenge in identifying a minimum set of indicators and these indicators will be benefit to yield appropriate results (Vadrevu *et al.* 2008; Zhu *et al.* 2012).

CONCLUSIONS AND RECOMMENDATIONS

Many have argued that a healthy ecosystem can maintain its ecological structure and function over time while continue to meet socioeconomic and biophysical needs. Agroecosystems are human-center complicated systems with their typical structure and function, which determine the complex of health assessment. It is not easy to simultaneously investigate different aspects of agroecosystem health. An AHI conceptual model has been

built to quantify the health state of an agroecosystem at a given time, in terms of its structure and function using a case study of Guangzhou. Agroecosystem structure has been defined by biotic structure and habitat structure. Indices that characterize functional performance including the supporting, provisioning, regulating, and cultural service and sustainable economic development. Health assessment indicated that agroecosystem health has been affected by the rapid urbanization and industrialization in Guangzhou. AHI decreased from 0.78 to 0.71 (suggesting “sub-healthy”) during the last decade. Except for ESI, indices of both structural and functional indices decreased. The CI represents “worst” with the lowest value less than 0.4. Moreover, ESI (0.57) signifies that agricultural economic sustainable development is not successful. As noted above, AHI can be an appealing reference to agroecosystem restoration and management in a region of urban agriculture like Guangzhou.

Despite huge effort to define and access agroecosystem health, some remained problems may limit the wider application of AHI model in other regions. Firstly, reference conditions signify the natural conditions with least human disturbance or without disturbance. Identification of these reference conditions has been a major problem in ecological health assessment. In this study, most of reference conditions have been set in 1990s of Guangzhou, China. However, these reference conditions of heavy metal contents in soil and vegetable have been according to national quality standards due to lack of historical data. National quality standards may be partly biased from the natural conditions. Secondly, the priority of each indicator/index was confirmed by AHP. Judgment matrix of AHP was built according to the result of expert scoring. Thus, the result of health assessment may be partially affected by experience and knowledge. Lastly, some data redundancy may be caused by the correlation relationships among these selected indicators. Unfortunately, it is difficult to confirm their correlation relationships due to lack of enough data analysis. Further research is needed to determine a minimum set of indicators and indices to assess agroecosystem health according to the result of correlation analysis.

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ACKNOWLEDGMENT

The authors would like to thank the Science and Technology Program of Guangzhou, China (201707010142), and National Natural Science Foundation of China (No. 51039007 and NO.40901278) for an extensive support of this study.