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To cite this article: Lilai Xu et al 2019 Environ. Res. Lett. 14 044013

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Environmental Research Letters

LETTER

OPEN ACCESS

CrossMark

RECEIVED 31 August 2018

REVISED 24 December 2018

ACCEPTED FOR PUBLICATION 14 January 2019

PUBLISHED 2 April 2019

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Assessing the adaptive capacity of urban form to climate stress: a case study on an urban heat island

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Keywords: climate stress, urban form, adaptive capacity, land use, assessment approach Supplementary material for this article is available online

Abstract

Urban land planning shapes the urban form and is considered to be one of the many tools important for climate adaptation. Yet there is little knowledge about the adaptive capacity of urban forms to climate stress, or of an appropriate assessment method. Through a case study on the urban heat island (UHI) in Xiamen City, China, we propose a novel approach that integrates several aspects to assess the adaptive capacity of urban form to climate stress. These aspects include the calculation of urban form, the determination of climate stress and land use modeling. Our results demonstrate that this approach is applicable for assessing the adaptive capacity of urban form in the historical, current and future multitime scales. Both urban planning aspects (e.g. population density, land use mix, road density and percentage of green open space) and landscape features (e.g. shape complexity, contiguity and compactness) are found to be key urban form drivers affecting UHI. The adaptive capacity of the urban form to UHI in Xiamen City has been declining dramatically, and is expected to continue to decline in the future as long as adaptation continues to not be integrated in urban land use planning. Our analysis suggests that urban managers need to review the past development model of land use and rethink the current approach to urban planning: most urgent is the need to take full account of adaptation in future land use planning and implementation, so as to enhance climate resilience.

1. Introduction

Climate stress refers to the stressors resulting from natural factors (e.g. excessive temperatures, moisture, solar radiation, extreme precipitation, storm tide or sea level rise) and human activities, plus their disruptions to environmental quality and ecosystem integrity (Arup Foresight 2017). The compound stress that stems from climate change and rapid urbanization requires adaptation to become a priority in urban policies (Rosenzweig *et al* 2010, IPCC 2012, Bulkeley 2013, Pancost 2016). Cities are particularly subject to growing risks from climate change and its consequent extreme events, due to the increasing exposure of population and assets, but limited capacity to combat the impacts of extreme events (Aerts *et al* 2014, Birkmann *et al* 2016, Mechler and Schinko 2016). For instance, the intensified heat wave due to global warming will be exacerbated in urban area when combined with urban heat island (UHI) effects, causing dramatic negative effects on public health (Shen *et al* 2016, Ward *et al* 2016, Founda and Santamouris 2017, Mora *et al* 2017). Further concern over this issue has arisen because of ongoing rapid urbanization, with large populations migrating from rural to urban societies, as well as undeveloped land being converted to impervious surface area (ISA), suggesting an overall increasing trend of climate risks in the future (UN 2015, Forman and Wu 2016, Seto *et al* 2017). It is known that land use shapes the urban form, which is considered to be an effective approach for adaptation to climate impacts (Stone *et al* 2010, Adachi *et al* 2014, Seto *et al* 2014). Therefore, investigating how urban form affects climate stress and developing methods to assess the capacity of urban form to adapt climate impacts are vital for climate resilient urban planning, implementation, as well as optimization.

Previous studies have extensively investigated the relationship between urban form and climate stress, seeking to determine urban land use planning solutions to adaptation. The majority of research has focused on exploring the role of urban form on the urban thermal environment, primarily UHI. Among these studies, urban form indicators have been expanded from single dimension to multidimension. There have been many studies of the combined effects of the urban form including land composition, configuration (e.g., size, shape, patterns, and connectivity) and cadastral-demographic-economic factors (e.g., population) on UHI effects at the neighborhood, city, megacity and county levels. The results of these studies demonstrated that urban form significantly influences UHI in many aspects, such as urban density, green space, ISA and their shapes and configurations (Qiao et al 2014, Schwarz and Manceur 2015, Li et al 2016, Estoque et al 2017, Yang et al 2017). In addition, an increasing body of literature emphasizes the role of land use optimization to extreme flood adaptation. On the one hand, the flood area, rate and duration are sensitive to changes in the landscape, and on the other hand socioeconomic and infrastructure exposure is different among different land use types (Bilskie et al 2014, Lentz et al 2016). In particular, green infrastructure such as wetlands and green space play a strongly positive role in flood adaptation (Renaud et al 2013).

Generally, previous studies have demonstrated the vital effect of the urban form on climate adaptation and have identified the key indicators of the urban form. What remains missing is the use of these indicators to assess the dynamic adaptive capacity of urban form to climate stress. As one of the key factors within the vulnerability framework, adaptive capacity is defined as the ability of a system to prepare for stresses and changes in advance or adjust and respond to the effects caused by the stresses (McCarthy 2001, Smit and Pilifosova 2001). Currently, a variety of frameworks have been proposed, trying to gain a better understanding of the adaptive capacity. For instance, Cinner et al (2018) proposed a framework to depict adaptive capacity of coastal communities across five domains: the assets that people can draw upon in times of need; the flexibility to change strategies; the ability to organize and act collectively; the ability to learn to recognize and respond to change; and the agency to determine whether to change or not.



Hinkel et al (2018) explored societies' abilities to adapt to sea level rise by integrating perspectives from coastal engineering, economics, finance and social sciences. In addition, many case studies have been conducted to quantify to what extent human society is able to adapt to climate stresses, and adaptation capacity was generally defined and described from different perspectives and dimensions. For instance, Chen et al (2015) integrated indicators from natural, engineering, financial, human and social capital to assess the national adaptive capacity to climate-related disasters in China in the 2000s. Juhola and Kruse (2015) proposed a framework for regional adaptive capacity assessment, in which indicators include knowledge and awareness, technology, infrastructure, institutions, and economic resources, and this framework was applied to assess the current adaptive capacity in European. Hogarth and Wojcik (2016) proposed a local adaptive capacity framework to assess the capacity of Soufriere, Saint Lucia to adapt to climate change, which characterizes adaptive capacity based on five elements: asset base; institutions and entitlements; knowledge and information; innovation; and flexible forward-looking decision-making and governance. Although previous literature has reported the frameworks that portray the adaptive capacity and demonstrated their applications via case studies, deficiencies are that (1) urban land use and urban form were not included in these frameworks, and there is a lack of approaches, as well as empirical studies, to assess the adaptive capacity from the urban form perspective; (2) previous quantitative studies tend to assess the historical or current adaptive capacity, and there is a lack of dynamic assessment from history to the future.

Hence, this study proposes a novel approach to address this deficiency. It integrates the urban form calculation, climate stress determination, and land use modeling, trying to quantify the adaptive capacity of urban form in historical, current and future multitime scales. The applicability of this approach is demonstrated through a case study on UHI in Xiamen City, China. The methods and general conclusions drawn from the case study can be considered for application by other cities attempting to assess their adaptive capacity to climate stress.

2. Material and methods

2.1. Framework

The framework shown in figure 1 describes the procedure to assess the adaptive capacity of urban form by taking the UHI in Xiamen City as an example. Xiamen is a large rapidly urbanizing coastal city in China that is prone to climate stress. The more detailed introduction to Xiamen City is included in the supplementary information. The assessment framework consists of four major parts. (1) Current urban area (in 2014) is delimited according to the land use





data, and urban communities are recognized by overlaying community administrative boundaries with the urban area. (2) Indicators from urban planning metrics and landscape indices are employed to quantify the current urban form for each urban community; and climate stress is determined by indicators such as UHI that would alter the urban microclimate. This study uses these indicators to provide insights into the adaptive capacity assessment procedure. The indicators that relate to urban form and climate stress could be extended to additional indicators if required. (3) Statistical analysis is applied to identify the key urban form indicators and their weights that influence the intensity of UHI. (4) These key urban form indicators for each urban community in the past (in 2004 and 2009) and the future (in 2019, 2024 and 2029) are calculated based on their respective land use data. Land use for 2019, 2024 and 2029 are simulated by a CA-Markov model. And finally, the adaptive capacity of the urban form in the past, current and future is assessed by the combination of key urban form indicators and their weights.

2.2. Methods

2.2.1. Urban form calculation

Urban form is an integrated concept, which can be depicted from different disciplines. In this study, urban form refers to the physical patterns, layouts, and structures that make up the urban environment (Muscato 2017). We quantified urban form for each urban community from the perspective of urban planning and landscape ecology, because we expect the results to be of explicit implication to urban planning and design. The urban planning indicators emphasize the socioeconomic aspect, thus the most classic indicators including population density, land use mix, road density, and percentage of green open space (GOS) were employed here. Landscape indices emphasize composition, shape and spatial configuration of urban land use, thus patch density, shape index, compactness and contiguity were involved here. Moreover, these indicators have been widely used in previous empirical analysis, such as Connors et al (2013), Li et al (2016), Gage and Cooper (2017). The indicators and their descriptions are shown in table 1, and their definitions and calculation methods are described in the supplementary information. Note that urban form is not limited to being measured by the indicators listed, but can be extended to additional indicators if required, depending on research purpose and data availability. Previous studies have revealed that ISA and GOS play vital, but different, roles in UHI (Peng et al 2016). Thus, we calculated the landscape indices for ISA and GOS separately, in order to investigate their effects on UHI.

We generated the 10×10 m high-resolution land use data of Xiamen City for 2004, 2009 and 2014 by integrating the inversion of IKONOS satellite data and the digitization of traditional land use maps, and then we reclassified the land use into thirteen types. Here, the IKONOS satellite data in 2009 was obtained from Satellite Imaging Corporation (SIC); the traditional land use maps in 2004 and 2014 were from 'Xiamen Master Plan 2004–2020' and 'Xiamen Master Plan 2011–2020' (Xiamen Urban Planning & Design Institute 2004, 2015). With respect to the land use



Urban form	Indicators	Explanation			
Urban planning metrics	Population density	Population density is the measurement of urban density that represents the intensity of human activity.			
	Land use mix	Land use mix is the diversity and integration of different land uses in a given area.			
	Road density	Road density refers to street density and is a measurement of vehicle activity.			
	Percent green open space	Percent GOS is a metric of the occupation of the green land in an urban community.			
Landscape indices	Patch density	Patch density is the number of patches per unit square and is used to depict the fragmentation degree of ISA or GOS.			
	AWMSI	Shape index depicts the complexity of patch shape in comparison to a square pos- sessing the same size, and we calculate shape index via area-weighted mean shape index (AWMSI).			
	Contiguity	Contiguity index (value range: 0 to 1), calculated as the ratio of the largest con- tiguous polygon of ISA or GOS pixels to the total ISA or GOS in an urban com- munity, is a measure of patches' spatial connectedness (LaGro 1991).			
	Compactness	Compactness index is a measure of circularity of ISA or GOS (value range: 0 to 1; 1 is perfect circle) and here we quantify compactness via the proximity index—the value of the average distance from all points in the equal-area circle to its center divided by the average distance to the proximate centre from all points in the shape (Angel <i>et al</i> 2010a, 2010b).			

Table 1. Urban form indicators and explanations.

of 2009, after the preprocessing via the ENVI 4.7 software platform, the satellite image was interpreted to obtain land use information by manual visual judgement instead of digital extraction, because spatial information in urban areas is too complicated to use the digital method. Then, we classified the land use into thirteen types according to the 'China National Standard

for Land Use Classification (GB/T 21010-2017)', and the explanation of each land use type is provided in table S1 (available online at stacks.iop.org/ERL/14/ 044013/mmedia). With respect to land use data for 2004 and 2014, we acquired them by the digitization of traditional land use maps, due to the shortage of satellite images. Since the traditional land use maps consist of 26 land use types, here we reclassified them into thirteen types to retain consistency with those of 2009 (figure 2). Land use in 2019, 2024 and 2029 under the 'business as usual' scenario—without climate adaptation—are predicted according to the CA-Markov model (for methods, see supplementary information). Based on these land use data, we calculate the urban form for each urban community.

2.2.2. Urban heat island quantification

The UHI is the phenomenon that the air and surface temperature is higher in urban land than in the surrounding rural land, which is commonly attributed to changes in biophysical properties of the land surface associated with urbanization (Rizwan *et al* 2008, Buyantuyev and Wu 2010). The UHI represents one of the most pronounced surface climate changes caused by human activities (Grimmond 2007). The UHI increases the intensity of heat waves in cities, thus aggravating heat stress on urban residents (Li and Bou-Zeid 2013). In terms of the quantification of UHI, air temperature data was widely used in traditional studies, however it is constrained by the location and limited number of meteorological stations. In recent empirical analysis, utilizing remote sensing technology to obtain land surface temperature is becoming a sophisticated approach to quantify the surface UHI (Schwarz and Manceur 2015, Alobaydi et al 2016, Cao et al 2016, Zhou et al 2017). Here, we selected two Landsat 8 OLI_TRIS images of July and August in 2014-the hottest two months in a year-to derive the land surface temperature (for methods, see supplementary information). The average value of July and August is used to represent the average daytime land surface temperature in summer for 2014. The magnitude of UHI is defined as the land surface temperature difference between an urban area and its surrounding suburbs (Oke 2011), and therefore the UHI for each urban community is calculated by subtracting the average land surface temperature of the nonurban area from the average land surface temperature of the urban community. Here, the nonurban area includes forest, farmland, rural residential areas and water outside the urban area.

2.2.3. Adaptive capacity assessment

Pearson correlation analysis is employed to investigate the correlation relationships of urban form with UHI intensity. Urban form indicators that hold significant correlation are used in the regression model, which helped us to select the key urban form indicators and to estimate their weights on UHI intensity. In the study, we used the ridge regression method to build the regression model of UHI with their urban form drivers, owing to the multicollinearity that existed in the variables (more about methods in supplementary information). The estimation of weights for urban form indicators is outlined in the following equation:

$$w_i = |r_i| / \sum_{i=1}^n |r_i|$$



	Original land use types	Reclassified land use types		
1	Forest	Forest	1	
2	Farmland	Farmland	2	
3	Commercial land	Commercial land		
4	Land for business affair			
5	Entertainment supporting land			
6	Other service facilities land			
7	Industrial land	Industrial land		
8	Warehouse land	Warehouse land	5	
9	Urban residential land	Urban residential land	6	
10	Rural residential land	Rural residential land	7	
11	Administrative land			
12	Cultural facilities land			
13	Education & research land			
14	Sport land	Public services and administration	8	
15	Medical and health land			
16	Municipal utilities			
17	Other public supporting facilities land			
18	Green & square land	Green space	9	
19	Road			
20	Railway	Road	10	
21	High way			
22	Intercity transportation land	Intercity transportation land	11	
23	Water			
24	Ocean			
25	Specially-designated land	Other		
26	Unused land			

Figure 2. Land use reclassification.

where w_i is the weight of indicator *i*; r_i is the standard regression coefficient of indicator *i*.

In order to ensure uniformity and comparability among the indicators, a standardization procedure is conducted as follows:

$$x_{ij} = \frac{y_{ij} - y_{i\min}}{y_{i\max} - y_{i\min}}$$

where x_{ij} is the standard value of indicator *i* for urban community *j*; $y_{i \text{ max}}$ is the maximum value of indicator *i*; $y_{i \min}$ is the minimum value of indicator *i*; and y_{ij} is the original value of indicator *i* for urban community *j*.

It is assumed that some of the indicators might have positive effects on minimizing UHI (positive indicators), whereas other indicators may have negative effects (negative indicators). Hence, we employed the following approach to calculate the adaptive capacity of urban form to UHI for each urban community:

$$A_{UHI_j} = rac{\sum x_{ij_p} imes w_{i_p}}{\sum x_{ij_n} imes w_{i_n}} \; .$$

where A_{UHI_j} is the adaptive capacity of urban form to UHI for urban community j; x_{ij_p} is the standard value of positive indicator i for urban community jand w_{i_p} is its weight; x_{ij_n} is the standard value of

Table 2. Statistical descriptions of urban form for urbancommunities in 2014.

Index	Ν	Min	Max	Mean	SD
Population density (people/ha)	220	6.72	148.15	94.46	37.47
Land use mix	220	.18	.63	0.51	0.08
Road density (m/ha)	220	7.21	318.45	82.00	51.92
Percent GOS	220	0%	95%	18%	19%
Patch density_GOS	220	.14	80.12	10.44	6.17
AWMSI_GOS	220	.86	5.32	1.60	0.59
Contiguity_GOS	220	.11	1.00	0.56	0.27
Compactness_GOS	220	.05	0.76	0.36	0.20
Patch density_ISA	220	.20	17.99	5.19	3.88
AWMSI_ISA	220	.91	8.15	2.38	1.07
Contiguity_ISA	220	.22	1.00	0.87	0.12
Compactness_ISA	220	.04	0.88	0.58	0.18

negative indicator *i* for urban community *j* and w_{i_n} is its weight.

3. Results

3.1. Statistical description

Statistical descriptions of urban form indicators in 2014 are detailed in table 2. Urban form indicators clearly vary in different urban communities as





demonstrated by their standard errors (SD). Generally, the built environment in Xiamen City is highly urbanized with high population density, high road density and mixed land use. However, the GOS in the urban area is relatively low with a percentage of less than 20% in 2014, which is far below the national recommended value (30%). When looking at the landscape indices, there is an obvious difference between ISA and GOS. As revealed by the path density and AWMSI, GOS is more fragmented and the shape of GOS patches are more regular. However, ISA is more connected and more compact than GOS, as demonstrated by the value of contiguity and proximity index.

Figure 3 depicts the spatial distribution of daytime UHI for summer in 2014. As shown in figure 3, the intensity of UHI shows a strong spatial heterogeneity in different urban communities, with a standard error of 2.10 °C. The average intensity of UHI in the urban area is 4.25 °C, which is generally greater because (1) we only used pure urban and rural pixels to calculate the land surface temperature difference, and (2) the land surface temperature is from the hottest months in summer, which is much higher than normal months. The spatial distributions of UHI for July and August in 2014 are shown in figure S3.

3.2. Urban form drivers of climate stress

3.2.1. Correlations between variables

Figure 4 represents the correlations between UHI and urban form and correlations among urban form indicators. All of the urban planning indicators including population density, percent GOS, land use mix and road density—display a close correlation with UHI, in which population density, land use mix, and road density exhibit significant positive correlations, yet percentage GOS displays a significant negative correlation. Similarly, the majority of landscape metrics for both ISA and GOS significantly correlate with UHI, but have weaker correlation coefficients compared to urban planning indicators. The AWMSI of GOS, compactness of GOS and the AWMSI of ISA show significant negative correlations with UHI. In contrast, the compactness of ISA and contiguity of ISA display significant positive correlations. However, the path density both for ISA and GOS, and the contiguity of GOS, are not significantly correlated with UHI in our analysis. As shown in figure 4, intercorrelations are detected among the indicators of urban form, suggesting that these indicators are not independent, but mutually influential.

3.2.2. Key urban form drivers and weights

Using the statistically significant urban form indicators that were identified by the correlation analysis, a regression analysis model was built to investigate the effects of urban form on UHI. Considering the interrelationships among urban form indicators, multicollinearity may exist, so we employed ridge regression in this study. The regression model built yields acceptable fit to data, as evidenced by $R^2 = 0.68$, F = 45.57 and p < 0.001 (detail of the regression model is shown in table S2). As shown in table 3, the percent GOS, AWMSI of GOS, compactness of GOS and AWMSI of ISA display a significant negative effect on the UHI intensity, while the population density, land use mix, road density, contiguity of ISA and compactness of ISA show a significant positive effect.





Figure 4. Correlation matrix between variables ('Statistically significant' means that correlation coefficients are statistically significant at p < 0.05, while 'nonsignificant' means not statistically significant at p < 0.05 level.).

Table 3. Ridge regression model of UHI with its influencing factors.

Independent variables	Unstandardized coefficients	Standardized coefficients			
independent variables	B	SE(B)	Beta	Т	Sig
Population density	4.6233	0.7203	0.2195	6.4190	0.0000
Land use mix	0.0020	0.0007	0.1136	2.9735	0.0033
Road density	0.0082	0.0018	0.1707	4.5357	0.0000
Percent green open space	-5.9487	0.4994	-0.4496	-11.9108	0.0000
AWMSI_GOS	-0.0445	0.2264	-0.0690	-1.9644	0.0444
Compactness_GOS	-0.0852	0.4632	-0.0666	-1.8398	0.0454
AWMSI_ISA	-0.3028	0.0962	-0.1140	-3.1478	0.0019
Contiguity_ISA	1.3456	0.6229	0.0765	2.1604	0.0320
Compactness_ISA	0.7109	0.3189	0.0784	2.2288	0.0270
Constant	2.6450	0.8701	0.0000	3.0399	0.0027

Note: $R^2 = 0.68, F = 45.57 (p < 0.001).$

This implies that urban form with a high proportion of GOS, highly complex shape both for GOS and ISA, and high compactness of GOS, but a low density of population, less mixed land use, low road density, as well as low contiguity and compactness of ISA, may contribute positively to the adaptation of cities to UHI. In terms of the absolute values of standard regression coefficients, the order of effects is: percent

GOS > population density > road density > AWM-SI_ISA > land use mix > compactness_ISA > contiguity_ISA > AWMSI_GOS > compactness_GOS. Clearly, the percent of green open space and population density are proven to be the dominant factors influencing UHI.

According to the standard regression coefficients, the weight for each urban form indicator was calculated and





shown in figure 5. The order of weights is: percent GOS (0.3311) > population density (0.1616) > road density (0.1257) > AWMSI_ISA (0.0840) > land use mix (0.0837) > compactness_ISA (0.0577) > contiguity_ISA (0.0564) > AWMS_GOS (0.0508) > compactness_GOS (0.0490).

3.3. Urban form dynamics

Future land use under the 'business as usual' scenario in 2019, 2024, 2029 are depicted in figure S6, which shows that the urban area in the future maintains the current trend, featuring an uncontrolled land use sprawl. On the basis of land use of Xiamen City from 2004 to 2029, urban form for each urban community was quantified. Future values of the land use mix, percentage of green open space, AWMSI, compactness and contiguity were directly calculated according to future land use; however, for population density and road density, additional information including future population and lengths of road are required. Population by 2019, 2024 and 2029 were cited from 'Xiamen Master Planning 2017-2035' (Xiamen Urban Planning & Design Institute 2017). As shown in figure S7, we found a close linear relationship between built-up area and road length, thus future road length was forecasted according to the growth rate of builtup area.

The dynamic trends of key urban form indicators influencing UHI are presented in figure 6. With regard to urban planning indicators, population density, land use mix, road density displayed varying degrees of increase from 2004 to 2014, and are assumed to retain this trend in 2019, 2024 and 2029. In particular, population density and road density have grown rapidly, due to continuous migration of residents from rural areas to urban, and increasing road stocks after vast construction, respectively, in the process of rapid urbanization. However, the proportion of GOS does not change too much and is still at a relatively low level (around 20%), indicating that the development—even conservation—of green infrastructure was not ranked as a priority for urban planning in Xiamen. With regard to landscape metrics, AWMSI for both GOS and ISA declined substantially from 2004 to 2014, and will likely decline from 2014 to 2029, notably in ISA, yet their compactness shows considerable increase from 2004 to 2029, also more notable in ISA. This revealed that the patches of GOS and ISA are becoming increasingly irregular in shape, and they are exhibiting increasing circularity as they tend to distribute more closely to the geographic center of the entire GOS or ISA. The contiguity of ISA shows unstable trends over the timescale.

3.4. Adaptive capacity dynamics

The adaptive capacity of urban form to UHI for each urban community was assessed separately by combining the key indicators and their weights. As revealed by the regression analysis, percent GOS, AWMSI of GOS, compactness of GOS and AWMSI of ISA are positive indicators, while population density, land use mix, road density, contiguity of ISA and compactness of ISA are the negative indicators for adaptive capacity of urban form to UHI. As shown in figure 7, the average values of adaptive capacity to UHI from 2004 to 2029 are below 1, suggesting that the urban form of urban communities is generally unable to adapt to UHI. Moreover, the adaptive capacity of urban form to UHI has been dramatically declining from 0.77 in 2004 to 0.49 in 2029, with an annual decline rate of 1.8%. When looking at the dynamics of the urban form indicator, this declining trend is attributable to the increase in population density, road density, land use mix, and the compactness of ISA compounded with the decrease in shape complexity of GOS and ISA. The declining phenomenon of the adaptive capacity of





Figure 6. Urban form dynamics from 2004 to 2029. (a) Population density; (b) land use mix; (c) road density; (d) percentage of green open space; (e) AWMSI of GOS; (f) compactness of GOS; (g) contiguity of ISA; (h) AWMSI of ISA; (i) compactness of ISA. The solid dot represents the average value of all urban communities, and the range represents the standard deviation.



standard deviation.

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urban form demonstrates that (1) the historical and current model of land use development in Xiamen City is not suitable for adaptation to climate stress like UHI; and (2) more notably, the 'business as usual' land use model that fails to adopt proper adaptation strategies can lead to more severe situations regarding climate stress.

4. Discussion

4.1. Applicability of the present approach

Climate change is likely to induce local extreme events and cause risks in many aspects of urban areas, especially for cities in developing countries that are experiencing a rapid urbanizing process alongside overdevelopment in climate impact-prone areas while lacking sufficient technical, financial, and institutional abilities to handle this issue (Hung and Chen 2013). Confronted with this challenge, it is vital for urban managers to understand both the current and future status of their urban form to adapt to climate stress, and accordingly review their urban land use model and planning. In this study, we present an innovative approach to assess the adaptive capacity of urban form to climate stress. The case of Xiamen City has demonstrated the robust applicability of this approach. Unlike previous studies, our research attempts to progress the quantification of the adaptive capacity of urban form and analyze its trends across historical, current and future multitime scales. This novel approach involves a wide range of indicators including: (1) urban form indicators from urban planning metrics and landscape indices; and (2) climate stress indicators like UHI. Moreover, the future adaptive capacity of urban form is also assessed on the basis of land use modeling. The steps, and their respective methods, of this approach are also specified, so they can be easily applied by other cities worldwide. Meanwhile, this approach is not constrained as described here but can be updated according to the individual study and data accessibility. In particular, the indicators that relate to urban form and climate stress could be extended to additional indicators if required. For example, future increases in flood frequency and severity due to changes in extreme precipitation are expected (Prein et al 2017). On the one hand, such increasing trends will cause severe direct and indirect socioeconomic impacts, and on the other hand, socioeconomic change such as land use change and population migration due to urbanization also serve an important drivers of flood risk (Winsemius et al 2016). Therefore, including more climate stress like precipitation-induced flooding in this approach serves as a useful way to update our proposed approach, which will make the adaptive capacity assessment more comprehensive. Furthermore, synergies or trade-offs may exist among multiple climate stresses when adjusting urban form to enhance the adaptive capacity, namely, altering one urban form indicator to adapt one climate stress may simultaneously reduce or increase the others. Hence, considering more climate stresses in the assessment may help to identify such synergy or trade-off effects, which will make this approach more viable in decisionmaking.

4.2. Implications for adaptive urban planning

This study reveals that the urban form is of considerable importance to climate adaptation. As demonstrated by the correlation analysis and regression analysis, the impact of urban planning indicators on UHI intensity is greater than landscape metrics. Population density, land use mix, road density and percentage of GOS exhibit different degrees of impact on UHI, with relatively high coefficients. Although the coefficients are relatively lower, the landscape metrics (such as AWMSI of GOS, compactness of GOS, AWMSI of ISA, compactness of ISA and contiguity of ISA) are also found to have significant effects on UHI, in line with results of previous empirical studies (Bereitschaft and Debbage 2014, Debbage and Shepherd 2015). It indicates that adapting to climate stress in urban areas will be inadequate if it is based on land use planning that only considers traditional urban form indicators. Landscape characteristics of impervious surface and green space (e.g. shape, compactness and contiguity) need to be considered when planning and designing new construction. It is worth paying extra attention to the percentage of GOS and population density because, in support of previous studies, we also find that these are the two dominant urban form indicators that significantly influence UHI. GOS has been demonstrated to significantly lower land surface temperature during daytime and nighttime owing to its strong cooling effect by creating more latent heat flux and less sensible heat flux (Hathway and Sharples 2012, Bokaie et al 2016, Wang et al 2016, Gunawardena et al 2017). Population density is a comprehensive indicator which has been found to be related to high impervious surface, land use mix and road density, however, relatively lower green space. It represents the intensity of human activity in a given area, hence the increase in urban density, producing more anthropogenic heat (Li et al 2011, Du et al 2016).

It is well established that urban land planning shapes the urban form and is considered to be an effective approach for climate adaptation (Biesbroek *et al* 2009, Di Gregorio *et al* 2017). However, there is a lack of consideration of adaptation as one of the top priorities in current urban land use planning in most cities (Wamsler *et al* 2013). As shown by our case study, the adaptive capacity of urban form to climate stress is declining remarkably, and this trend will continue in the future if land use continues to develop as usual. It implies that adaptation responses in urban land use planning could make a positive difference in future climate stress. In particular, for cities in developing countries like China, the overarching trend displays a persistent growth in urbanization rate over the past four decades, and is likely to continue to increase and reach a higher status (Bai et al 2014, Fang 2016). The consequence is that the conversion to impervious surfaces from other land use types, and population migration to urban from rural area, which may act as the primary cause of increasing climate stress such as UHI. Fortunately, China has now released its National Climate Change Adaptation Strategy, Urban Climate Change Adaptation Action Plan and Work Plan for Climate-Adaptive-Cities Construction, in an attempt to cope with climate-related risks in urban area. In 2017, the Chinese government launched pilot climateadaptive-city construction programs in 28 cities, which requires full consideration of climate stress in urban planning. Therefore, city managers need to list climate adaptation as one of their urban policy goals, and recognize that pursuing just one of them is insufficient to achieve the sustainable development of cities (Gao and Bryan 2017). Urban planners need to review the past development model of land use and rethink current urban planning. Most urgently, they need to take full account of adaptation in future land use planning and implementation, in order to establish a climate-resilient urban form.

4.3. Limitations

This study has several limitations that need to be addressed through future research. First, more aspects of indicators, both for urban form and climate stress, need to be expanded in order to further understand the driving forces of climate stress in urban areas, and thus assess the adaptive capacity of urban form more comprehensively. Second, in our case study, we did not consider the impact of climate change on UHI owing to the uncertainty of temperature projection at the city level. This could be addressed with the support of more observed local temperature data and an enhanced local climate model. Third, our study analyzes the future adaptive capacity of urban form by only considering the 'business as usual' land use scenario; more land use scenarios need to be developed in order to investigate their respective efficacy to respond to climate risks. Fourth, the adaptive capacity was assessed from the perspective of urban form; a more comprehensive assessment that incorporates urban form, along with social, institutional, environmental and technological dimensions should be conducted.

5. Conclusions

A novel approach to assessing the adaptive capacity of urban form to climate stress was proposed in this study. As demonstrated by a case study of UHI in Xiamen City, major conclusions can be drawn: (1) this approach is applicable for assessing the adaptive capacity of urban form and characterizing its dynamics



over multitime scales in the past, present and future; (2) urban form drivers from both urban planning and landscape metrics play significant roles in UHI, in which the percentage of GOS and population density are the dominant indicators; (3) the adaptive capacity of urban form to UHI has been declining dramatically in Xiamen City, and will decrease in the future if land use develops as usual, where adaptation is not included; (4) adaptation should be prioritized as an urban policy goal and be fully considered in urban land use planning and implementation, so as to enhance the capacity of urban form to minimize climate risks and accordingly improve the climate resilience of cities.

Acknowledgments

This study was supported by the National Key Research and Development Program of China (2017YFC0506603), the National Natural Science Foundation of China (41371205 and 41661144032), and the Bureau of International Co-operation Chinese Academy of Sciences (132C35KYSB20150005).

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