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Identifying the trade-offs between climate change mitigation and adaptation in urban land use planning: An empirical study in a coastal city

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ABSTRACT

Cities play a significant role in climate change mitigation and adaptation. Urban land planning shapes the urban form and is considered to be an effective approach for climate change mitigation and adaptation. Yet, there is little knowledge about what urban forms can reduce both greenhouse gas (GHG) emissions and climate stresses while considering trade-offs between them. Here, we investigate the role of urban land use in both climate change mitigation and adaptation. In particular, we assess quantitatively the competition between strategies for mitigation and adaptation and identify potential win-win solutions in land use responses. Using a coastal city as a case study, we find that the land use strategies for unilateral mitigation or adaptation can cause contradicting consequences with respect to the reductions in GHG emissions and climate stresses, i.e. reductions in GHGs could increase climate stresses or vice versa. Poorly integrated strategies potentially may compromise international efforts to meet the Climate Action in the Sustainable Development Goals. Properly integrated mitigation and adaptation strategies, or climate-sensitive land use planning, however, can lead to win-win outcomes and eventually achieve co-benefits. Yet, any co-benefits will gradually diminish if there is a delay in climate-sensitive land use planning, implying growing GHGs and intensified climate stresses. Our analysis indicates that integrating climate change mitigation and adaptation in urban land use needs to be enacted as soon as possible: any delays in implementation reduce the window to act to maximize the co-benefits.

1. Introduction

Cities globally are facing dual challenges of climate change and urbanization. To address these challenges, and reduce the overall adverse effects, climate change mitigation and adaptation deserve an equal priority for planning and action (IPCC, 2014; Pancost, 2016; Rosenzweig et al., 2010). Urbanization is one of the important drivers of greenhouse gas (GHG) emissions, with cities consuming 67–76% of global energy and generating 71–76% of CO_2 emissions (UN-Habitat, 2016; Seto et al., 2014). Additional concerns for cities are caused by rapid urbanization, with population migrating from rural to urban societies, thus requiring more population to be accommodated. This pattern is likely to be maintained in cities over the next few decades (Forman and Wu, 2016; UN, 2015) and an overall increasing trend of energy consumption and GHG emissions is likely in the future. Growing urbanization also increases the difficulties for countries to be able to meet their target set by the 2015 Paris Climate Agreement (McPhearson, 2016). At the same time, cities are at growing risks of extreme climate events due to the compounded impacts of climate change and urban development (Aerts et al., 2014; Birkmann et al., 2016; IPCC, 2012; Mechler and Schinko, 2016). For instance, rising extreme sea levels—due to the simultaneous occurrence of sea-level rise and storm tides, and continued socio-economic development—lead to increasing flood risk in coastal cities, causing potentially severe consequences for urban socio-economic, ecological and infrastructure systems (Hallegatte et al., 2013; Little et al., 2015; Vousdoukas et al., 2018). Another impact of global warming for cities is that heat waves will be exacerbated in urban areas when combined with the urban heat

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island (UHI) effect, which is expected to negatively impact public health (Founda and Santamouris, 2017; Mora et al., 2017; Shen et al., 2016; Ward et al., 2016).Therefore, a key challenge for global urbanization is to develop strategies that enable cities to take an integrated approach to minimize GHGs for mitigation, while building adaptation to climate stresses (Hallegatte et al., 2016; Jones, 2017).

To achieve the climate goals set in 2015 Paris Climate Agreement, and the United Nation's New Urban Agenda and Sustainable Development Goals, cities must identify solutions and take actions. Land use planning has considerable potential to combat climate change as long as the balance between mitigation and adaptation is fully maintained (Bulkeley, 2013), since urban land use affects not only GHG emissions but also climate stresses. There is increasing understanding of the close relationships between the urban form, GHGs and climate stresses, yet in previous studies mitigation and adaptation have rarely been considered simultaneously. Rather, mitigation and adaptation have been considered separately in most of the existing local climate measures related to urban land use planning and implementation. As a result, the trade-offs between mitigation and adaptation in the urban land use sector are not well studied quantitatively. Moreover, there is little understanding, and few empirical studies, of how to plan an urban form to better respond to the needs of both adaptation and mitigation. Here, we provide a holistic approach, together with an empirical study, in a step towards addressing this scientific problem. In this study, we integrate a wide range of multidisciplinary methods, including a household survey for GHGs calculation, a remote sensing interpretation technology for UHI quantification, a high resolution digital elevation model (DEM) for coastal flood modeling and a cellular automata (CA)-Markov model for future land use simulation. In using this holistic approach, our empirical study combines GHG emissions, climate stresses and the urban form to: (1) evaluate the effects of urban form on GHG emissions and climate stresses in order to identify the key urban form drivers; (2) quantitatively examine the competing nature and potential win-win solution between mitigation and adaptation strategies when applying land use planning to respond to climate change; and (3) explore the consequences that arise due to delayed implementation of integrating mitigation and adaptation in urban land use.

Land use shapes the urban form, which is the physical patterns, layouts, and structures that make up the urban environment (Muscato, 2017). The urban form is normally, but not exclusively, measured by density, land use mix, connectivity, accessibility, green space, and geometric shapes, depending on the research field and purpose (Song and Knaap, 2004; Zhao et al., 2011). Previous studies have demonstrated that urban form plays an important role in GHGs, primarily in the transportation sector (Hankey and Marshall, 2010; Ishii et al., 2010; Liu and Sweeney, 2012; Xu et al., 2018). Density, land use mix, accessibility and connectivity are the major urban form drivers of transportation energy use and GHG emissions (Banister, 2011; Seto et al., 2014a). There is consistent evidence that urban forms that are characterized by high density, mixed land uses, and adequate transit connectivity and accessibility can encourage non-vehicle travel and reduce vehicle kilometers traveled, leading to greater savings of GHG emissions by the transportation sector (Creutzig et al., 2016; Lee and Lee, 2014). As a result, land use planning has focused on compact city design that aims to limit sprawl and reduce automobile dependence and thus also reduce vehicle kilometers traveled, energy consumption, and GHG emissions (Zhao et al., 2011). However, as demonstrated by Leibowicz (2017), cities should be cautious about cost-effectiveness when adopting land use controls to reduce GHG emissions: for example, land use controls may decrease the welfare of residents through fostering higher housing prices and can increase the total emissions when deployed in cities with low emission intensities.

There has been extensive study of the effects of urban form on climate stress to determine urban land use planning strategies for adaptation. Most previous studies have explored the role of urban form including land composition, configuration (e.g., size, shape, patterns, and connectivity) and cadastral-demographic-economic factors (e.g., population) on the urban thermal environment, primarily on the UHI. The results have demonstrated that the urban form significantly influences the UHI through many aspects such as urban density, green space, impervious surface area and their shapes and configurations (Estoque et al., 2017; Li et al., 2016; Schwarz and Manceur, 2015; Yang et al., 2017). Recently, an increasing body of literature has emphasized adaptation of the urban form to coastal flood via land use optimization. On one hand, the flood area, rate and duration are sensitive to changes in the landscape, while on the other hand, socio-economic 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 can provide significant coastal protection benefits to people and property (Narayan et al., 2017). Arkema et al. (2013) revealed that the number of people and total value of property exposed to storm tide and sea-level rise can be reduced by half if the existing coastal wetland remains fully intact along United States coastline. An empirical study by Beck et al. (2018) shows that, without coral reefs, the global annual expected damages from coastal flood would double, and costs from frequent storms would triple.

Yet, mitigation and adaptation strategies related to land use do not always complement each other and can even be counterproductive (Biesbroek et al., 2009; Di Gregorio et al., 2017; Viguie and Hallegatte, 2012). For instance, a desirable urban form for mitigation is a relatively high-density and compact built environment, while an urban form that addresses adaptation stresses, such as UHI, requires more land left as open space and a less dense built environment (Hamin and Gurran, 2009). Furthermore, low-elevation coastal cities are experiencing a continual increase in population and, by 2050, population density is expected to grow by 25% (Aerts et al., 2014), exposing an overall increase of population to sea-level rise and coastal flooding (Neumann et al., 2015). Ineffective land use planning that fails to consider these trade-offs can potentially compromise the on-going international efforts to meet Climate Action in Sustainable Development Goals, which requires the need to address both mitigation and adaptation. Some recent studies have combined mitigation and adaptation, seeking to find out the optimal urban forms to combat climate change. For example, Pierer and Creutzig (2019) develop a geometrical optimization framework for urban design and report that star-shaped cities can alleviate the trade-offs between the transport GHGs and UHI. Cremades and Sommer (2019) propose the Integrated Urban Complexity model to compute ‘climate-smart urban forms’, where there are reduced emissions related to energy consumption from urban mobility in a situation that also considers urban flood. However, the extent to which mitigation and adaptation may conflict in urban forms is not well studied quantitatively, and when optimizing urban land use to mitigation and adaptation the win-win outcomes need to be quantified through more empirical studies.

2. Material and methods

2.1. Framework

The framework shown in Fig. 1 describes the procedure to assess the trade-offs between climate change mitigation and adaptation in land use planning. Here we conduct an empirical study using Xiamen City as an example. Xiamen is a large, rapidly urbanizing coastal city in China that is prone to climate stresses. A description of Xiamen City is detailed in the Supplementary Information. Although our analysis is conducted in Xiamen, this study presents a set of general conclusions that can be considered by other coastal cities in their development of climate change policy.

As shown in Fig. 1, this study is organized as follows:

(1) The key urban form indicators that influence GHGs and climate stresses are identified, respectively. Here, GHGs are represented by

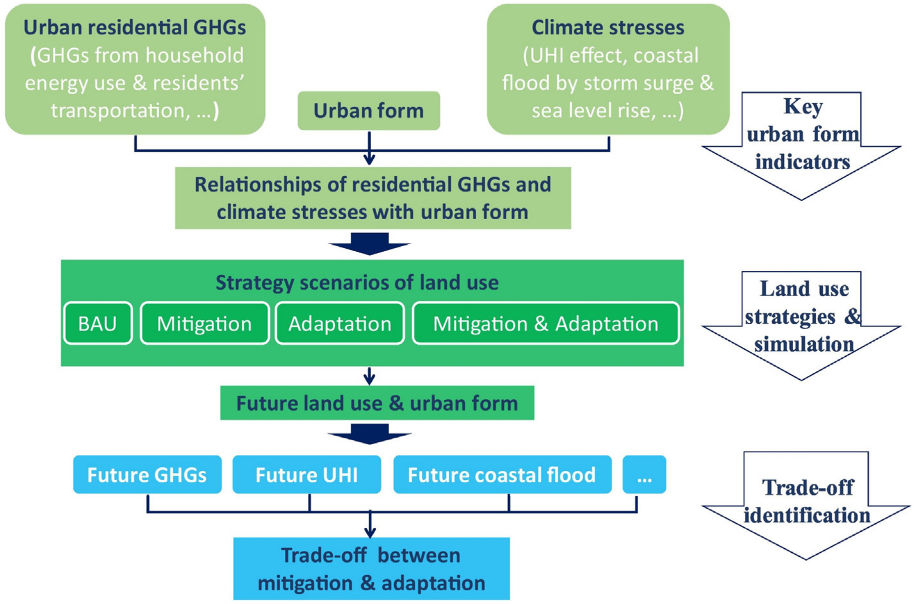

Fig. 1. Framework for investigating the trade-offs between climate change mitigation and adaptation in urban land use planning.

indictors including those generated by household energy consumption and residents' transportation. Climate stresses are represented by indicators associated with the UHI that would change the urban microclimate, plus population exposed to inundation as the result of storm tide and sea-level rise. Forty-five urban communities in Xiamen City, selected by a spatial stratification sampling method, are used to analyze urban form, GHGs and UHI (Table S1, Fig. S1).

(2) Key urban form indicators that influence GHGs and climate stresses, are used to develop several scenarios for land use strategies that address climate action. Future land use under each scenario is projected by the CA-Markov model, and then used to calculate the consequent urban form.

(3) Future GHGs and climate stresses under each scenario are projected by their relationship models with the corresponding urban form indicators. Then mitigation and adaptation effects of urban land use strategies are evaluated, which enables quantification of the trade-offs between mitigation and adaptation in urban land use planning. Also assessed are the consequences that result from the delay in climate-sensitive land use planning.

This study aims to use key indicators to provide insights on the competing nature and trade-offs in implementing coastal urban land use for climate change mitigation and adaptation. The key indicators are related to urban form, GHGs and climate stresses, however if necessary, these potentially could be extended to include additional indicators.

2.2. Methods

2.2.1. Urban form characterization

For each sampling community, the urban form is represented by employing a range of indicators including population density, proportion of green open space, floor area ratio, land use mix, road connectivity, bus accessibility, shape compactness and shape complexity. These indicators depict many aspects of urban form: population density is the measurement of urban density; proportion of green open space is a metric of the green land; floor area ratio measures development intensity of urban land; land use mix refers to the diversity and integration of land uses (e.g., residential, park, commercial land, etc.) in a given area.; road connectivity refers to street density; accessibility is a combination of proximity and travel time but here, due to data limitations, is measured by bus accessibility—distance from a community to the nearest bus stop; shape compactness and shape complexity are the measurements of geometric shapes of built-up areas. Their definitions and calculation methods are described in the Supplementary Information.

We generate the 10 × 10 m high-resolution land use data of Xiamen City for 2009 and 2014 by the inversion of IKONOS satellite data and digitization of land use maps provided by the Xiamen Urban Planning & Design Institute, and then reclassify the land use into thirteen types (Table S2). This is then used to characterize the urban form for each of the sampling communities.

2.2.2. GHGs accounting

We calculate GHG emissions from household energy consumption and residents' transportation by multiplying the activity level by their corresponding emission factors (see Supplementary Information). To obtain the information of activity levels, we carried out a face-to-face questionnaire survey of 1125 urban families in the 45 sampling communities. The samples are chosen by the stratified random sampling method that takes a full account of the diversity of the samples in terms of spatial distribution and socio-economic status. We acquired three aspects of information on the basis of the questionnaire: (1) family socio-economic status; (2) household electricity, natural gas, liquefied petroleum gas and coal consumptions; and (3) each family member's transportation details including destinations, modes (including walking, cycling, private car, taxi, bus, and motorcycle), frequency and distance. We refer to the IPCC (2006) methods to estimate the GHGs (including CO_2, CH_4 and N_2O) from household energy consumption and residents' transportation, respectively (details in Supplementary Information). The data on emission factors are cited from multiple sources. For instance, the emission factors for household energy consumption (including coal, liquefied petroleum gas and natural gas), and the fuel consumption per 100 km vehicle kilometers traveled are from the *Provincial Greenhouse Gas Emission Inventory Guidelines of China*; the emission factors for electricity are from the *13th Five-Year Plan for Energy of Xiamen City*; and the emission factors for energy consumption of transportation are cited from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. These emissions factors and related parameters are shown in Tables S3–S5.

2.2.3. Climate stresses calculation

We analyze the UHI effect of the 45 sampling communities and population exposed to coastal inundation induced by storm tide and sea-level rise, to represent the local climate stresses. We selected two Landsat 8 OLI_TRIS images of July and August—the hottest two months in any year—to derive the land surface temperature (more about methods in Supplementary Information). The UHI is the phenomenon that air and surface temperature is higher in the urban land than the surrounding rural land, which is commonly attributed to changes in biophysical properties of the land surface associated with urbanization (Buyantuyev and Wu, 2010). The UHI represents one of the most pronounced surface climate changes caused by human activities (Grimmond, 2007). Therefore, the magnitude of UHI for each sample community is defined here as the land surface temperature difference between an urban area and its surrounding suburbs (Oke, 2011). Although the overall change in temperatures due to climatic trends may heat local temperatures, both in urban built-up areas and the surrounding areas, the influence mechanism is complex and not well studied. Hence, it is not considered in our analysis.

We identify the intensity and frequency of storm tide and project local sea-level rise, in order to model extreme storm tide scenarios in the future. Then, we model and map the coastal inundation zone using a high-resolution topographic dataset and an ArcGIS based approach. To simplify the calculation, we employ the population as a metric to quantify the exposure to the impacts of coastal flooding. Population is an important indicator that has been widely used in previous studies (Hallegatte et al., 2013; Hinkel and Klein, 2009; Hinkel et al., 2014), because it is highly correlated with other indicators, and is easily quantified. Finally, the population exposed to inundation is quantified by overlaying the population density map with the inundation area (more about methods in Supplementary Information).

2.2.4. Identification of key urban form indicators influencing GHGs and climate stresses

We employ the Pearson correlation analysis to investigate the correlation relationships of urban form with GHGs from household energy consumption, GHGs from residents' transportation, and UHI intensity. It helps to select the key factors that will be involved in the regression model. In this study, we use ridge regression method to build the regression models of GHGs and UHI with their urban form drivers, respectively, owing to the multi-collinearity existing in variables (more about methods in Supplementary Information). Previous empirical studies have shown that urban density calculated at different spatial scales may pose different effects on GHG emissions. For example, in the study by Newman and Kenworthy (1989), they compared the transportation gasoline use in three spatial levels including the whole urban area, inner area and central city. Kim and Brownstone (2013) found that the joint effect of the residential density and the density in the context of its surrounding area on vehicle usage is quantitatively larger than the sole effect of residential density. This indicates that the effects of other urban form indicators on GHGs and climate stresses may also be spatially sensitive. However, in our regression model, the urban form variables only focus on the community scale, because the data relating to the residents' GHG emissions and UHI are also obtained at the same spatial scale. Since population density is involved in the calculation of population exposed to inundation, and it is highly correlated with the other urban form indicators, we identify the key urban form indictors influencing population exposed to inundation via a qualitative approach rather than the statistical methods. We review existing literature and select the widely accepted indicators in this area.

2.2.5. Future land use projection

To investigate the trade-offs between mitigation and adaptation in urban land use sector, we formulate four scenarios of land use strategies: (1) **business as usual** (**BAU**) where future land use planning does not take into account mitigation and adaptation; (2) **mitigation scenario** (**MS**) where future land use planning only considers the reduction of GHGs from residents' transportation; (3) **adaptation scenario** (**AS**) where future land use planning only considers the reduction of UHI and population exposed to inundation; (4) **combined scenarios** (**CS**) where future land use considers both mitigation and adaptation. The rule of land use for each scenario is determined by the key urban form indicators identified above. We build a CA-Markov model to simulate the land use for 2019, 2024 and 2029 under four land use planning scenarios, respectively. The CA-Markov model is a combination of the CA model and the Markov model, which is commonly used to predict future land use change both quantitatively and spatially. In the CA-Markov model, the Markov model functions as a tool to predict the quantitative characteristics of future land use, and then the CA model is responsible for the spatial distribution simulations for each land use type. Here, land use data for 2004, 2009 and 2014 are employed to build and validate the CA-Markov model. To develop the model, a Markov chain is applied to generate the land use transition probability and transition area matrix. Meanwhile, we use a logistic regression to generate the suitability maps, which reflects the effect of physical, socio-economic and policy drivers on land use changes. Cell neighborhood and transition rules are also developed for the model. Finally, we validate the model and evaluate its performance by kappa parameter—a measure of agreement between the simulated land use map and the actual one. In the analysis, the historical transition probability and transition area matrix are directly used to project the land use in the BAU scenario, and they are revised according to the urban land use planning strategies to project the land use under AS, MS and CS, respectively. More details of land use projection including the explanations, steps and validations are provided in the Supplementary Information.

2.2.6. Error analysis

The present study involves a broad range of models to project future GHG emissions and climate stresses. Their utilization and combinations will accumulate the compounding errors. Table 1 shows the main error sources for respective projections of GHG emissions, UHI and population exposed to inundation. Here we calculate the mean absolute percentage error (MAPE) for each model, and then quantify the compounding errors for future GHG emissions, UHI and population exposed to inundation according to the following equation.

$$E = \pm\sqrt{e_1{}^2 + e_2{}^2 + \cdots + e_i{}^2}$$

where E is the compounding error for the modeling of future GHG emissions, UHI or population exposed to inundation, and e_i is the MAPE of model i which is involved in the projection process.

Table 1
Main error sources for respective projections of GHG emissions, UHI and population exposed to inundation.

Item	Error sources
Future GHG emissions	Regression model of GHG emissions with urban form CA-Markov model Grey model (GM (1, 1)) for population forecast GM (1, 1) for urbanization rate forecast
Future UHI	Regression model of UHI with urban form CA-Markov model GM (1, 1) for population forecast Grey model for urbanization rate forecast
Future population exposed to inundation	CA-Markov model GM (1, 1) for population forecast GM (1, 1) for urbanization rate forecast

Table 2
Statistical descriptions for sample communities with respect to current urban residential GHG emissions, UHI intensity and population exposed to coastal flood.

Variables	N	Min	Max	Mean	SD
GHGs from residents' transportation (kg CO_2e capita^{-1}·day^{-1})	45	0.190	1.620	0.594	0.284
GHGs from household energy consumption (kg CO_2e capita^{-1}·day^{-1})	45	1.68	4.79	2.773	0.709
UHI intensity (°C)	45	0.98	8.68	4.76	1.99
Population exposed to inundation (thousand people)	240	0.11	20.25	3.01	3.51

3. Results

3.1. Statistical descriptions

Statistical descriptions of urban residential GHG emissions, UHI intensity and population exposed to coastal flood, for sample communities are detailed in Table 2. The average GHG emissions from residents' transportation of 45 sample communities is 0.594 kg CO_2e capita^{-1}·day^{-1}. Most GHG emissions are produced by the private car (77.47%), followed by bus (13.14%), taxi (6.38%) and motorcycle (3.02%). The average GHG emissions from household energy consumption is 2.773 kg CO_2e capita^{-1}·day^{-1}, in which the electricity, liquefied petroleum gas, natural gas and coal occupy 65.15%, 17.76%, 15.57% and 1.52%. respectively. The intensity of the UHI shows a strong spatial heterogeneity in different urban communities, with a standard error (SD) of 1.99 °C. The average intensity of UHI in the urban area is 4.76 °C, which is generally greater because (1) we only used pure urban and rural pixels to calculate the land surface temperature difference, and (2) land surface temperature is from the hottest month in summer, which is much higher than other months. The spatial distributions of UHI for July and August in 2014 are shown in Fig. S2. The coastal inundation area reaches 16,374.44 ha under an extreme sea level event when considering a 200-year storm tide and 1.2 m sea-level rise (Fig. S3). In that case, 240 urban communities and > 700,000 population will be exposed to coastal flood.

Statistical descriptions of urban form indicators in 2014 are detailed in Table 3. Urban form indicators clearly vary in different urban communities as demonstrated by their standard errors. Generally, the built environment of urban communities in Xiamen City is highly urbanized with a high population density (Mean = 22,472.69 residents per km^2), and a high floor area ratio (Mean = 3.18). However, land use mix is relatively low with the average value of 0.49, indicating that land use in the majority of urban communities is not sufficiently diverse or integrated. Moreover, the proportion of green open space in urban area is relatively low (30%). The average values of road connectivity and bus accessibility imply that roads are generally well connected and residents in most urban communities can access bus stations by walking, however their standard errors also show that traffic conditions of different communities vary greatly. The geometric shapes of urban settlement patches are generally irregular, and their perimeter is of high roughness.

Table 3
Statistical descriptions of urban form for 45 sample communities in 2014.

Indicators	N	Min	Max	Mean	SD
Population density (residents per km^2)	45	1167.96	60,529.01	22,472.69	17,736.84
Floor area ratio (≥0)	45	0.95	5.57	3.18	1.29
Land-use mix [0, 1]	45	0.11	0.72	0.49	0.15
Proportion of green open space (%)	45	0.00	78.98	19.00	19.14
Road connectivity (road nodes per km^2)	45	0.44	53.61	13.70	12.04
Bus accessibility (≥0)	45	0.10	6.68	1.87	1.36
Shape compactness [0, 1]	45	0.03	0.50	0.22	0.14
Shape complexity (≥0)	45	1.20	3.51	1.82	0.47

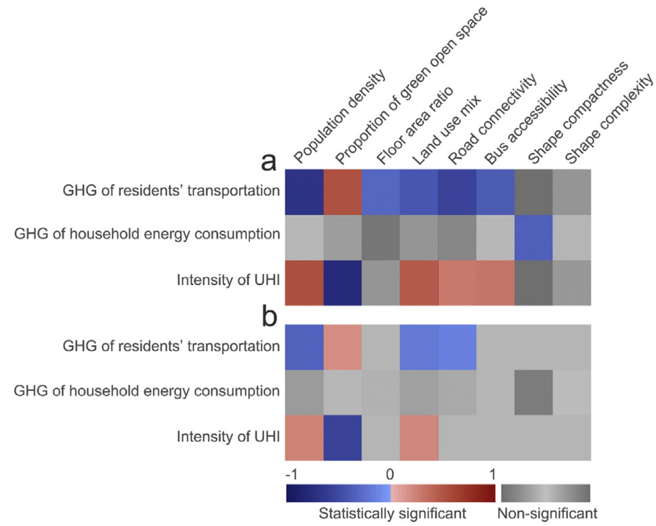

Fig. 2. Relationships of residential GHGs and UHI intensity with urban form, respectively. **a**, Pearson correlation coefficients of residential GHGs and UHI intensity with urban form. **b**, Standardized beta coefficients of ridge regression, which represent relative strength of the effect of each individual spatial form indicator on the residential GHGs and UHI. Statistically significant means that correlation coefficients in **a** and regression coefficients in **b** are statistically significant at $p < 0.05$, while non-significant means no statistically significant at $p < 0.05$ level.

3.2. Urban form drivers of GHGs and climate stresses

Fig. 2-a shows the statistical correlations of residential GHGs and UHI intensity with urban form. GHGs from residents' transportation displays a strong correlation with the urban form, while GHGs from household energy consumption have little correlation with the urban form except those forms that have a compact shape. The intensity of UHI is significantly correlated with population density, proportion of green open space, land use mix, road density and bus accessibility.

Our further regression analysis identifies the key urban form indicators and their strengths that affect the residents' GHG emissions and UHI. As shown in Fig. 2-b, the population density, land use mix and road connectivity exhibit significant negative effects on GHGs per capita from residents' transportation, while the green open space exhibits a significant positive effect. This implies that an urban form that is characterized by high population density, mixed land use and high road connectivity with adequate road intersections is beneficial to GHG mitigation. Although the shape compactness is statistically significant in the correlation analysis, all the urban form indicators show no significant effect on GHGs from household energy consumption in our regression model. We argue that urban form may pose much more impact on the behaviors of resident's transportation than household energy consumption. This is consistent with IPCC AR5, in which the linkages between urban form and the GHG emissions of human settlements were systematically reviewed. This review found most of the literatures focus on urban density, land use mix, connectivity and accessibility and how these factors affect residents' traffic behaviors and the consequent GHG emissions (Seto et al., 2014). With respect to the climate stress, the green open space displays a significant negative effect on the UHI intensity, while the population density and land use mix show a significant positive effect. This implies that urban form with a high proportion of green open spaces, a low density of population, as well as lower land use mix, may have a positive impact on the adaptation of cities to UHI. With the key urban form indicators identified above, the final regression models for GHGs from residents' transportation and intensity of UHI are built, respectively (Tables S6, S7).

Here we determine the population density and proportion of green open space as the key urban form indicators that influence the population exposed to inundation. Population density is employed because it is a vital component in the calculation of flood impacts. In the studies by Wang et al. (2014) and Xu et al. (2016), population density functioned as a key indicator when assessing the coastal flood exposure in South East Queensland and Xiamen, respectively. In addition, an empirical study by Viguie and Hallegatte (2012) in Paris revealed that controlling population density via prohibition of new buildings in flood-prone areas will decrease six million households exposed to flood, compared to the do-nothing scenario. Green open space serves as a critical green infrastructure to adapt flood risk in urban areas. On one hand, green open space such as wetlands, parks and fields within the floodplain enables critical ecosystem services, contributing to reduce surface water run-off, store storm water and aid with infiltration (Brody et al., 2008; Zimmermann et al., 2016). On the other hand, as demonstrated by Brody and Highfield (2013), green open space removes people and structures from the most flood-prone areas, eliminating the opportunity for property loss and economic disruption.

3.3. Future urban form under different land use strategies

In light of the key urban form indicators identified above, we can determine the respective rule of land use for four scenarios of land use strategies. In the BAU, we assume that Xiamen's future land use will follow its historical trend without interference from climate change mitigation or adaptation actions. In the MS, the aim of future land use is to reduce the residents' transportation GHG emissions. Hence urban sprawl is strictly controlled, and any new built-up areas grow mainly in the current urban centers and integrate more types of urban land, in order to establish a more centralized, compact and mixed urban land use pattern. In the AS, low urban density and high percentage of green open space is necessary to reduce the UHI and coastal flood risk. Therefore, part of the urban land in the current built-up areas is encouraged to move outward, and new built-up areas are only allowed to be allocated far from the urban center, in order to establish a decentralized and dispersed land use pattern. In addition, green open space will expand to a large extent. In the coastal flood zone, urban area is forbidden to grow and even will be gradually replaced by green open space. In the CS, land use seeks to balance climate change mitigation and adaptation. Several urban sub-centers are about to be developed to accommodate the moderate growth of built-up areas as well as green open space. In the coastal flood zone, urban growth is still not allowed.

In this study, the scenario analysis seeks to explore the possible future GHGs and climate stresses by considering alternative possible land use strategies, not to forecast their exact values. Thus, the four scenarios presented here are generalized and simplified. Table S8 gives the specific information of each scenario. Table S10 and Fig. S6 demonstrate a robust performance of the built Ca-Markov model, and therefore it is applicable to forecast future land use under BAU, MS, AS and CS, respectively. As shown in Fig. 3, future land use under four scenarios show great differences and embody their respective rules set in the scenarios. Land use pattern is irregular in the BAU, concentrated in the MS, decentralized in the AS, and polycentric in the CS.

Based on the forecasted land use data, the key urban form indicators including population density, proportion of green open space, land use mix and road connectivity are calculated, and the results are shown in Fig. 4. Generally, the urban form under different scenarios of land use planning strategies varies considerably. The urban area under BAU maintains the current trend of an uncontrolled land use sprawl. Meanwhile, the built-up areas in the expanded city under MS cluster around the current city center, making the city more centralized while absorbing a growing population. It leads to a significant increase in the urban density and obvious enhancement in land use mix as well as road connectivity, but much lowered proportion of green open spaces. In contrast, the decentralized urban form under AS leads the population to migrate outside the current city center, and thus reduces the overall urban density to a very low level. In association, the green open space under AS expands significantly, but the land use mix and road connectivity decline due to the scattered distributions of built-up areas. On the other hand, the urban form under CS shows a compromised outcome between MS and AS. In this case, the new built-up areas distribute around the current city center as well as new established sub-centers. The modest growth not only ensures the current central area is not overcrowded, but also keeps the urban sprawl under check. As a result, the population density, land use mix and road connectivity are maintained at a moderate level, while the green open space is also well protected.

3.4. Mitigation and adaptation effects of urban land use strategies

The future GHGs per capita from residents' transportation and magnitude of UHI under each scenario are projected according to their regression models in association with the corresponding urban form indicators. Although these may be affected by varying factors, here we focus only on the influence of urban land use on GHGs and climate stresses. As demonstrated by the R^2 and MAPE (Tables S6, S7, Fig. S10), the built regression models are sufficient to forecast future GHGs and UHI. Although global warming will lead to a temperature increase in urban heat island areas, their interaction is complicated (Krayenhoff et al., 2018), so in this study we do not consider climate change effects on future UHI. Future population exposed to inundation is estimated according to spatial overlay analysis of the population density distribution with inundation areas. According to the error analysis, the compounding errors for the projections of future GHG emissions, UHI and population exposed to inundation are 20.56%, 17.90% and 10.96%, respectively (Fig. S10), implying that the accuracy is acceptable. Considering all scenarios, the results suggest that the urban form, in relation to the land use planning strategies, could generate a considerable influence on both GHGs and climate stresses, but in an opposite way. This will affect the overall effectiveness in utilizing land use planning for climate change mitigation and adaptation.

As shown in Fig. 5-a, the daily GHGs per capita from residents' transportation under BAU decrease slightly as a result of an increase in population density in urban areas. However, the UHI intensity under BAU would experience a growing trend, when adaptation would not be implemented. Similarly, population exposed to inundation under BAU scenario also shows a trend of rapid increase in comparison to the current exposure, after an uninterrupted growth of built-up areas in the coastal zone.

The degree of GHGs and climate stresses varies significantly when considering different land use planning strategies. We compare the GHGs per capita from residents' transportation, UHI intensity and population exposed to inundation under all scenarios, and identify the consequences as the result of implementing those strategies in the future. As shown in Fig. 5-b, the land use under MS, when compared to the BAU, could improve climate change mitigation in terms of an accelerated reduction in the GHGs per capita from residents' transportation, up to19.19%, 20.21% and 23.73% by 2019, 2024 and 2029, respectively. Nevertheless, in comparison to the BAU, it would also result in an intensification of UHI, up to 13.08%, 15.34% and 17.96%, and increase in population exposed to inundation up to 27.57%, 28.45% and 33.46%, by 2019, 2024 and 2029, respectively. In contrast, the land use planning strategy under AS, compared to the BAU, could dramatically alleviate the future climate stresses, with 15.36%, 21.52% and 24.11% reduction, respectively, in the UHI intensity. Meanwhile, population exposed to inundation is also remarkably reduced up to 60.80%, 60.80% and 67.36% by 2019, 2024 and 2029, respectively.

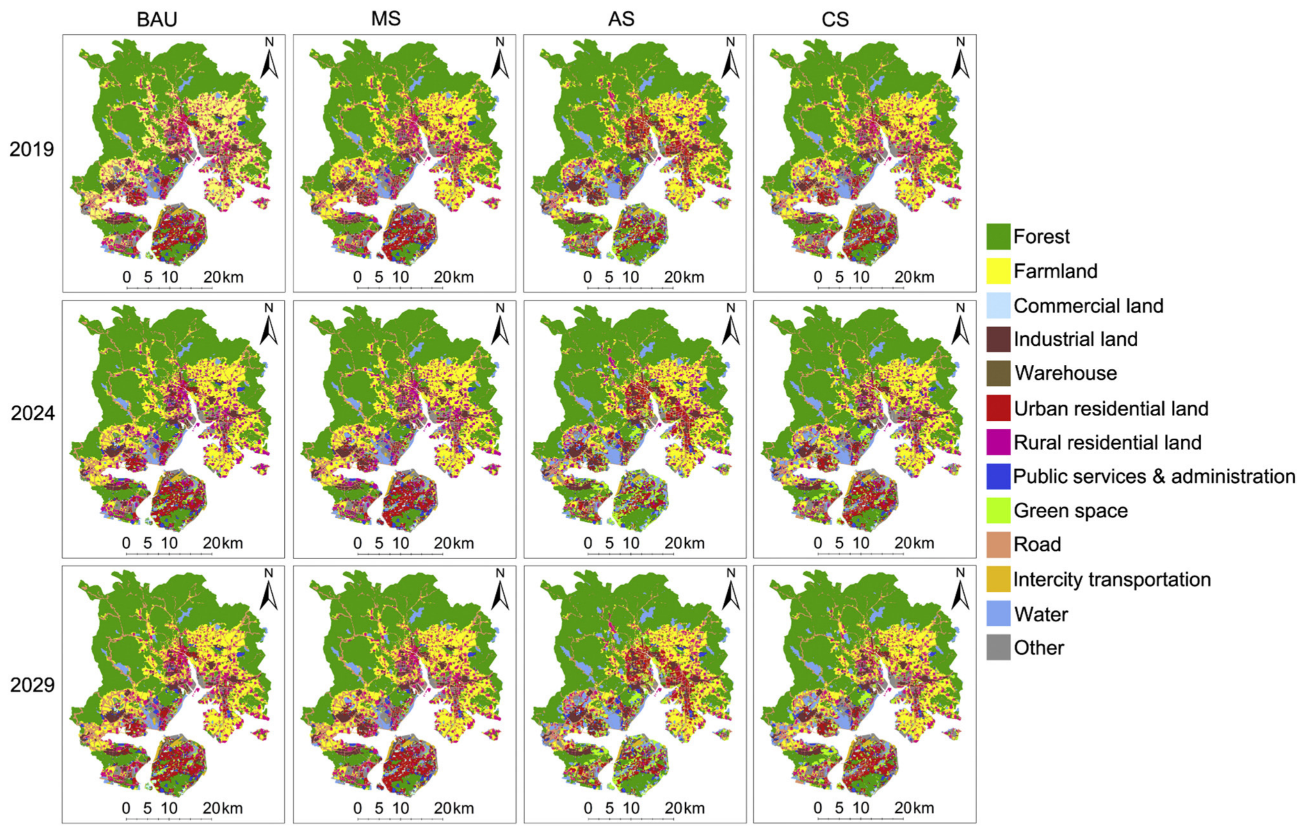

Fig. 3. Future land use maps under BAU, MS, AS and CS by 2019, 2024 and 2029, respectively.

However, there is a marked increase in the GHGs per capita from residents' transportation, which leads to a counter effect on climate change mitigation. It is noted that, under the CS, the land use could otherwise improve both mitigation and adaptation. For instance, development with moderate population density and green open space protection could simultaneously reduce the GHGs per capita from residents' transportation and UHI intensity in comparison to the BAU scenario, and no new built-up area in inundation zones can effectively

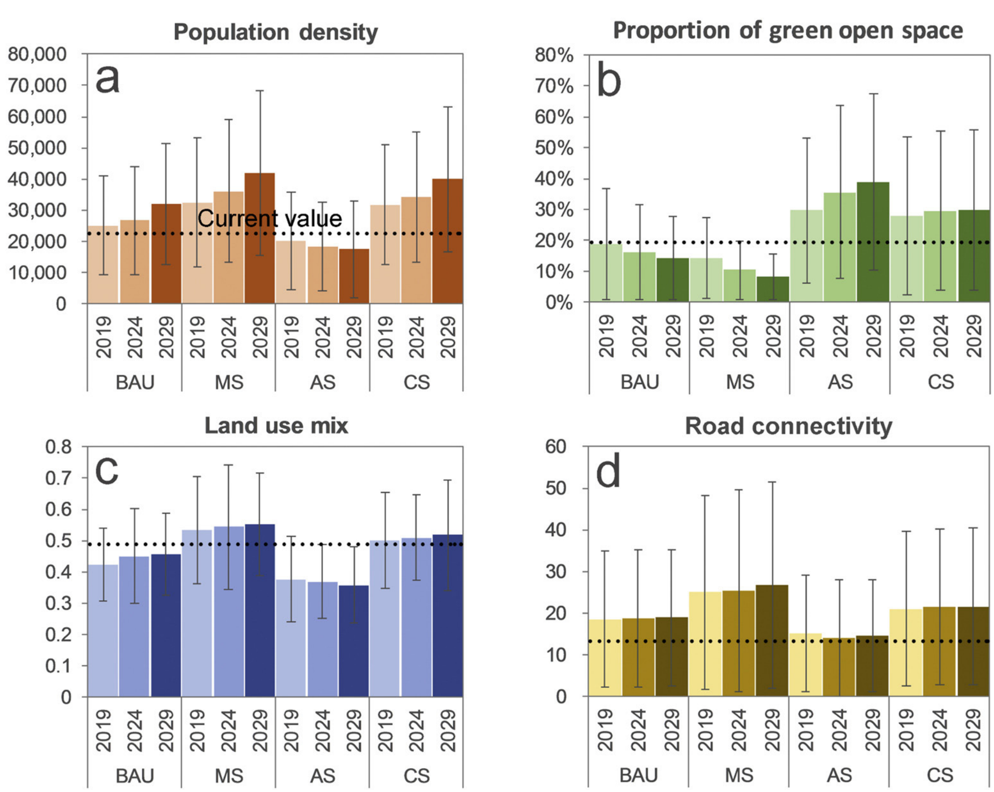

Fig. 4. Future urban form under BAU, MS, AS and CS by 2019, 2024 and 2029, respectively. **a**, Population density (residents per km^2). **b**, Proportion of green open space (%). **c**, Land use mix [0, 1]. **d**, Road connectivity (road nodes per km^2). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

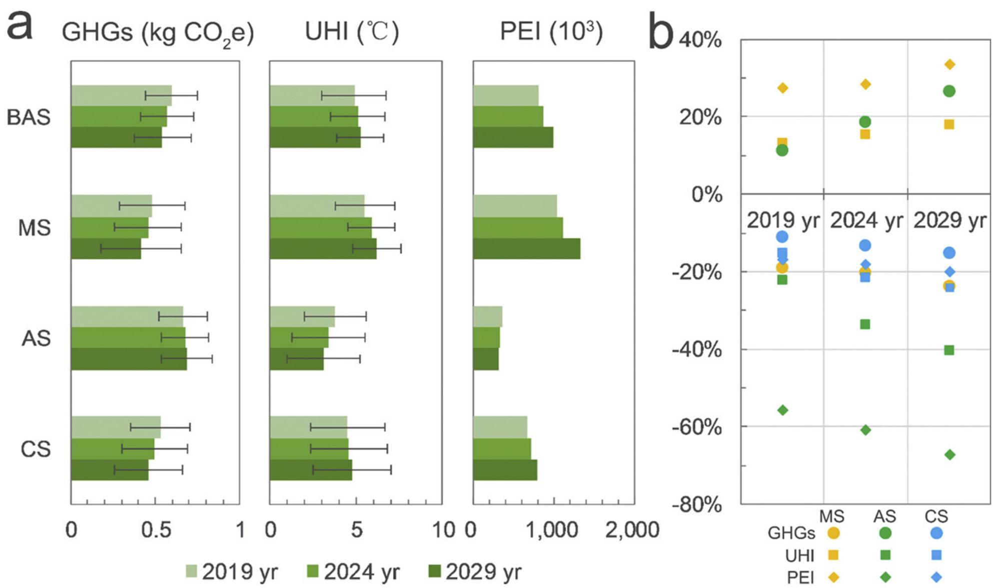

Fig. 5. Effects of different urban land use strategies on climate change mitigation and adaptation.
a, Daily GHGs per capita from residents' transportation, UHI intensity and population exposed to inundation (PEI) under BAS, MS, AS and CS by 2019, 2024 and 2029, respectively. **b**, Effects of implementing the land use strategies under BAS, MS, AS and CS on GHGs, UHI and population exposed to inundation, in comparison to the BAU. A negative value means land use strategy could reduce GHGs, UHI or population exposed to inundation, which is of advantage to climate change mitigation or adaptation; while a positive value means the opposite in that they would inhibit mitigation or adaptation.

protect more population from coastal inundation risk.

3.5. Window for urban land use to integrate mitigation and adaptation

Our analysis reveals that consideration of land use strategies for mitigation or adaptation in isolation can have opposite effects with respect to the reduction in GHG emissions and climate stresses. On the other hand, the land use planning strategy that integrates climate change mitigation and adaptation under the CS suggests that the issue is not irreconcilable. However, there is a window in which it possible to achieve a win-win outcome for both mitigation and adaptation when land uses are properly managed.

Therefore, we investigate the potential to develop win-win solutions and identify the timing to achieve this solution, by looking into the consequence of integrated land use planning strategies in CS when implemented in 2019 and 2024, respectively. Land use maps of 2029, when integrated land use strategies are implemented in 2019 and in 2024, respectively are shown in Fig. S7, and their results of urban form indicators are shown in Fig. S8. As shown in Fig. 6-a, the co-benefits of mitigation and adaptation by 2029 will decline substantially with the delay in implementation of the land use strategy. This suggests that the potential advantages of the strategy will gradually diminish, or even disappear, if it is enacted too late. One explanation is that uncontrolled sprawl of urban areas could reduce land spaces available in the future, thus reducing the potential for other actions to be implemented. Moreover, as shown in Fig. 6-b, the declining co-benefits can be compounded with growing GHGs, together with intensified UHI and increasing population exposed to inundation because of the delay in actions. As a result, by then, it would require much more effort for climate change mitigation and adaptation. For example, by 2029 there would be an additional 33.11 (3.24%) thousand tonnes CO_2e GHGs from residents' transportation for the whole of Xiamen City, an additional 0.43 °C (9.68%) UHI and an additional 70.10 (8.28%) thousand population exposed to inundation if the strategy is implemented in 2024, in

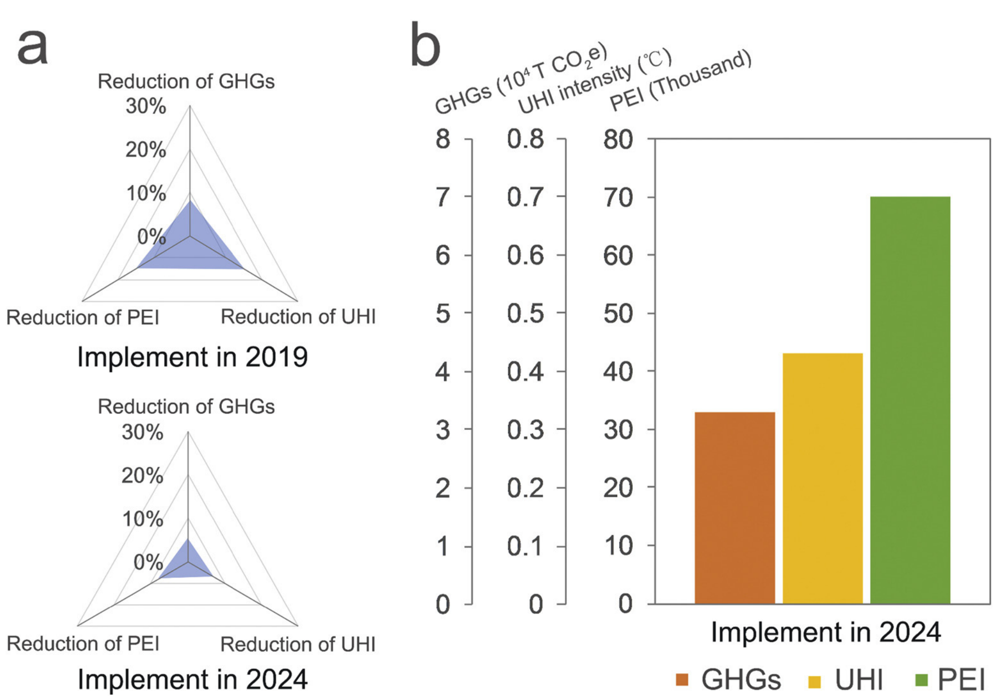

Fig. 6. Window for urban land use to combat climate change. **a**, Potential of a win-win solution to achieve both mitigation and adaptation via integrated land use strategies when implemented in 2019 and 2024, respectively. Values on the axes of the radar chart are the effectiveness of the land use strategy under the CS on the reductions in GHGs from residents' transportation, UHI and population exposed to inundation (PEI) by 2029, in comparison to the BAU. The corresponding area represents the magnitude of potential co-benefits. **b**, Additional stresses by 2029 due to delayed implementation to integrate mitigation and adaptation in land use, in comparison to its implementation in 2019.

comparison to if it is implemented in 2019. It demonstrates that the window to maximize benefits by applying coastal urban land use to effectively combat climate change will gradually close, if the response is delayed.

4. Discussion

Out study confirms quantitatively the findings that have been extensively discussed in previous literatures, that urban planning is of immense importance to combat climate change, not only for climate change mitigation, but also climate adaptation. Enacting or not enacting responses through land use planning could make a great difference in future GHG emissions and climate stresses. Additionally, different strategies in land use planning also result in different effectiveness of mitigation and adaptation. However, at the moment, coping with climate change is often done through approaches such as technological innovation, alternative energy and engineering protection solutions (Adenle et al., 2015; Stewart, 2015). There is a lack of consideration of mitigation and adaptation as one of the top priorities in current urban land use planning (Wamsler et al., 2013). This may be explained by the lack of pragmatic planning advice for urban land use for urban planners and decision-makers to develop strategies for climate change mitigation and adaptation. Researchers are increasingly realizing that balancing mitigation and adaptation in urban land use is complex and requires cross-disciplinary knowledge and methods. Here, we combine the GHG emissions accounting, climate stresses calculation, urban form quantification and urban land use modeling, and integrate a broad range of methods. Despite the uncertainties, such a holistic approach enables our empirical study to shed a light on the effectiveness of land use strategies for climate change mitigation and adaptation, as well as to provide insight on how to effectively implement a strategy to achieve win-win outcomes for both mitigation and adaptation.

Our case study indicates that urban form with high density, land use mix and transit connectivity, though at the cost of reduced green open spaces, is appropriate for carbon mitigation; however more green open spaces and less dense built-up areas provide more benefits to adaptation. These conflicting requirements for mitigation and adaptation may cause a dilemma in land use planning. Our scenario analysis reveals that, if land use strategies for mitigation or adaptation are considered in isolation they can adversely affect each other, i.e. reductions in GHGs could increase the intensity of UHI and the population exposed to coastal inundation, or reductions in the UHI and flood impact could increase GHG emissions. The solution is to integrate mitigation and adaptation and develop urban form that balances the requirement in mitigation and adaptation, and minimizes their conflicts (Hamin and Gurran, 2009; Laukkonen et al., 2009). Here, we quantitatively confirm that climate-sensitive land use planning that considers both climate change mitigation and adaptation can lead to co-benefits regarding the reductions of GHGs per capita from transportation, UHI and population exposed to coastal inundation. This is consistent with the study by Viguie and Hallegatte (2012), who examined the effects of three urban climate policies: a greenbelt, a flood zoning and a transportation subsidy, to achieve climate change mitigation, climate change adaptation and other three urban policy goals. Their results indicate that separately, each of these policies seems to be unacceptable because each one negatively affects at least one of the different policy goals; however, when all three policies are applied together, the average daily distance driven in car per household and population in flood-prone areas both are expected to decline, together with the improvement in other urban policy goals. Cremades and Sommer (2019) also demonstrate that the ‘climate-smart urban forms’ can reduce GHG emissions from urban mobility by half, while also controlling effectively population density in the flood area. Therefore, combating climate change in urban areas via land use planning goes beyond a matter of choice between mitigation and adaptation, but is a matter of balance between them—and is far more complex.

According to our results, the appropriate urban form, we argue here, typically possesses features including moderate population density that limits urban sprawl and eases overcrowding of urban centers; moderate mixed residential uses, workplaces, retail, and leisure uses; a high road connectivity with adequate intersections; and properly planned and well-protected green open space, while minimizing its negative impact on urban density. This partially overlaps with the idea of the polycentricity, which advocates multiple centers in the same metropolitan area to distribute population as well as most economic activities evenly across centers of comparable size, rather than being concentrated in a main center (Hajrasouliha and Hamidi, 2017; Taubenböck et al., 2017). Using the traditional statistics and emerging geographic big data of 100 cities in China, Li et al. (2018) found that the polycentric urban form can significantly promote commuting efficiency. However, unlike polycentricity, the urban form we propose here, highlights the importance of green open space including its proportion and layout. As demonstrated by Yue et al. (2019), polycentric urban development that fails to include adequate and well-allocated green or blue areas will deteriorate the urban thermal environment. The star-shaped cities proposed by Pierer and Creutzig (2019), in contrast to radially symmetric cities, perform well to reduce the trade-offs between transportation GHGs mitigation and UHI adaptation. However, as an ideal model, the star-shaped model's population density, land use pattern and green area are not discussed and investigated.

Although smart approaches in a land use planning strategy can be designed to minimize trade-offs and to achieve a win-win solution for mitigation and adaptation, its potential co-benefits would diminish when implementing the strategy too late, with growing GHGs and intensified climate stresses. In that case, it would require much more efforts, even going beyond the capacity of urban land use planning for climate change mitigation and adaptation, because finite land resource may constrain alternative in the context of rapid urbanization. Essentially, the window for coastal urban land planning to integrate climate change mitigation and adaptation will rapidly close if implementation is delayed, implying that timely climate action must be taken now. Some literatures also call for the urgent needs of timely climate actions, given the substantial cumulative economic impact due to climate inaction (Ricke et al., 2018) and the early benefits of climate change mitigation in risk reduction of regional climate extremes (Ciavarella et al., 2017). In addition, achieving targets in combating climate change also requires substantial contributions from other sectors, because the competing nature and trade-offs of mitigation and adaptation relevant to land use cannot be completely eliminated (Gao and Bryan, 2017; Seto et al., 2017).

Although our analysis focuses on Xiamen, the holistic approach and main findings from the empirical study are generic and likely to be valid for relevant researches in other cities. The holistic approach provides a clear procedure for how to identify the key urban form indicators influencing GHGs and climate stresses, how to develop land use scenarios and simulate future urban form, and how to identify the trade-offs and win-win solutions between mitigation and adaptation. The steps, and their respective methods, of this approach are also specified, so they can be easily applied in similar research in other locations. Additionally, the indicators related to urban form, GHG emissions and climate stresses are dynamic and flexible to change, depending on each individual study. Despite the differences in geography, climate, initial urban form in other cities, the major findings in our study, to a large extent, are generalizable and transferable. For example, the results related to the relationships of urban form with GHGs, UHI and population exposed to inundation are solid, and are applicable in other cities with the similar problems. Moreover, we demonstrate the competing nature between mitigation and adaptation in urban form, and the possibility to balance them, which may emerge in other cities and with important policy implications. However, our results are not expected to the same for all other cities. The characteristics of GHGs and climate stresses are diverse in cities with different geographic locations, climatic conditions and initial urban form, which may lead to different aspects and extents of trade-offs in urban land use sector. Consequently, there is likely to be different optimal urban form that could alleviate the trade-offs and achieve both mitigation and adaptation. Actually, such findings from various cities are urgently needed, since the puzzle is yet to be solved on how to tightly integrate climate change mitigation and adaption in urban land use to establish climate-smart urban form.

5. Conclusion

An empirical study for investigating the trade-offs between climate change mitigation and adaptation in urban land use planning is conducted. As demonstrated by a case study of the coastal city Xiamen in China, the following major conclusions can be drawn: (1) urban land use planning serves as an important approach to climate change mitigation and adaptation, but its effectiveness of reducing GHGs and climate stresses depend on the goals and priorities of land use strategies; (2) the land use strategies for unilateral mitigation or adaptation can cause contradicting consequences with respect to the reductions in GHGs and climate stresses, while integrating mitigation and adaptation strategies into land use can achieve a win-win outcome for both sides; (3) however, the co-benefits will gradually diminish with any delay in implementation of integrated urban land use planning, which indicates the growing GHGs, together with intensified climate stresses. Our analysis implies that integrating climate change mitigation and adaptation in urban land use needs to happen now before the time window closes.

Declaration of competing interest

The manuscript is original work, not published or under consideration for publication elsewhere. We certify that all authors have agreed to all the contents in the manuscript, and have no conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2019.105162.

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