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## Article

# Illuminating fuzziness about Istanbul's urban growth dynamics through the lens of climate change impact with fuzzy modelling

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### ABSTRACT

The fact that taking an action about controlling urban growth to minimize risks and adopt climate change is considerably significant in this century. This study explores the influence of urban growth dynamics on climate change indicators in İstanbul, Türkiye's largest metropolitan area. Unlike many other studies that primarily focus on individual indicators, this research comprehensively examines the association between urban growth indicators (UGIs) and climate change impacts (CCIs) by defining direct and indirect relations, contributing valuable insights to the literature by considering the main components of urban growth in the context of urban areas. Primarily, the literature was reviewed to release CCIs originated from urban growth and to highlight UGIs. After the study area was chosen as an İstanbul, population rate, economic structure and quality of life (QoL) as three main indicators of urban growth one by one were examined and some values/indexes about UGIs was compared with the İstanbul's value. Fuzzy Decision Making Technique (FDMT) in MATLAB programme was chosen as a methodology to be applied through main indicators which affect CCI in İstanbul. What the urban growth dynamics have effects on climate change was concluded by FDMT graphs that had been interpreted through five scenarios (the worst, bad, medium, good, the best). The study's results reveal a significant correlation between population, economy, QoL, and CCIs. Specifically, it is proof that a high population rate, low economic wealth, and low QoL are associated with heightened CCIs in İstanbul.

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## INTRODUCTION

In the early 1990s, 15% of the global population lived in urban areas. By 2010, this figure reached 50.5%, and projections indicate it could reach 68% by 2050 (Ritchie, 2018). Urbanization, driven by anthropogenic factors, significantly impacts natural resources such as land, water, soil, and the atmosphere, triggering climate change and global warming (Neumann et al., 2015). Converting undeveloped land into urban areas disrupts ecosystems and generates climate change. This unrestricted urban growth paradigm leads to adverse environmental effects for both cities and nature (McEvoy and Wilder, 2012; Cooley et al.,

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2006; Johnson, 2001), exacerbating negative CCIs linked to greenhouse gas emissions (GHGs), the urban heat island (UHI) effect, extreme weather events, floods, and social challenges resulting from rapid urbanization.

The main aim of the research is to evaluate how urban growth patterns relate to CCIs through the utilization of the FDMT. This methodology allows for the evaluation of which urban growth indicators (UGIs) influence climate change and to what extent each indicator contributes, achieved through IF-THEN predictions implemented in the MATLAB program. In essence, uncontrolled and rapid urban growth stands as a principal driver of climate change, which is one of today's most critical global challenges (Ren et al., 2020; Zhang et al., 2020; Bektaş and Sakarya, 2023). This research focuses on understanding the extent of climate impact resulting from population growth, changes in economic structure, and alterations in quality of Life (QoL), all considered key components of urban growth. These selected UGIs offer the advantage of easier data access compared to other indicators, making them more representative and suitable for analysis.

This study distinguishes itself by considering selected UGIs collectively and making comprehensive inferences through an assessment of these indicators in urban areas in Türkiye. Initially, a literature review on urban growth and climate change was conducted. Subsequently, İstanbul was chosen as the case study area based on justifications. The inputs (UGIs) and output (CCIs) in İstanbul were evaluated using the FDMT. The methodology, conducted literature review, and the study's outcomes can provide guidance for future studies and policymakers.

## LITERATURE REVIEW

The literature review encompasses two primary components, namely, the ramifications of urban growth on climate change and the assessment of UGIs on the climate change effects. First, this review delves into the consideration of GHGs, which are both a significant contributor and a consequence of climate change, attributed to urban growth. Subsequently, it evaluates various CCIs stemming from urban growth in leading countries engaged in climate change research. In the second section, a review of the relevant literature elucidates UGIs within the framework of all these climate change effects. Some of these indicators are more readily quantifiable due to their accessibility to data, whereas others necessitate local situational assessments and analyses, resulting in prolonged data acquisition processes. As part of this research, the forthcoming section will concentrate on relevant UGIs in İstanbul, Türkiye's largest metropolitan city, based on accessible data for evaluation.

GHGs not only constitute the principal driver of climate change but are also a fundamental component within the spectrum of CCIs (Worrell et al., 2001). Although the recent studies especially show that there are many indicators of climate change as annual mean temperature, maximum temperature, maximum precipitation, extreme weather events, UHI, sea level rise, and drought (Seneviratne et al., 2021; EPA, 2023), GHG is taken as the main indicator of climate change (WMO, 2017; EPA, 2023) due to their pivotal role in influencing Earth's temperature and climate system. GHGs, including carbon dioxide ($CO_2$), methane (CH4), and nitrous oxide, are responsible for the GHG effect. These gases trap heat from the Sun, preventing it from escaping back into space. This process, known as radiative forcing, is well-established in climate science. IPCC reports, such as the Fifth Assessment Report, extensively discuss the radiative forcing of GHGs and their impact on global temperatures (IPCC, 2013). Moreover, GHGs are a clear driver of changes in other climate indicators. For instance, rising $CO_2$ levels are closely correlated with rising temperatures (Hansen et al., 2005). By monitoring GHGs, scientists can better understand the primary drivers of various climate changes. Therefore, many international climate agreements, like Kyoto Protocol, are based on controlling GHG emissions. Monitoring GHGs is crucial for tracking progress toward emissions reduction goals and assessing the effectiveness of climate policies (Rosenqvist et al., 2000).

Anthropogenic factors, primarily driven by factors such as increasing population and economic policies, significantly contribute to the escalation of GHG emissions. The emission rates of GHGs vary among nations, leading to the formulation of distinct GHG emission scenarios for each country in compliance with international agreements addressing climate change, such as the Kyoto Protocol and the Paris Agreement (Figure 1).

As shown in Figure 1, MLT means mid-level transition, and the representation of $CO_2$ emissions is based on the classification of countries into Annex I and Non-Annex (Annex II) groups. In the context of the United Nations Framework Convention on Climate Change and the Kyoto

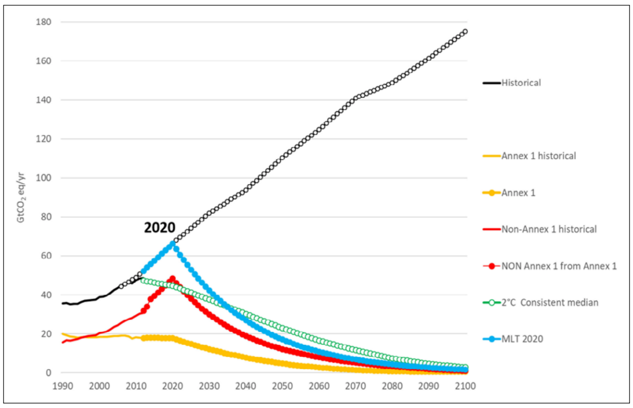



**Figure 1**. Yearly $CO_2$ emissions 1970–2100 and global scenario in the world (Perissi et al., 2018).

Protocol categorize countries based on their responsibilities and commitments regarding GHG emissions as "Annex I" and "Annex II" countries. Annex I countries are industrialized and developed nations that were historically responsible for the majority of GHG emissions. These countries include most of Western Europe, the United States (USA), Canada, Japan, Australia, and the United Kingdom (UK) among others. Since their emissions over the industrialization period have significantly contributed to the agglomeration of GHGs in the atmosphere, Annex I countries are considered to have historical responsibility for climate change. Therefore, Annex I countries committed to providing technological and financial assistance to Annex II for their efforts in addressing and adapting to climate change. Conversely, Annex II countries are a subset of Annex I countries. They include the most developed countries within Annex I. Annex II nations are anticipated to offer increased technological and financial aid to developing countries. Moreover, according to the Kyoto Protocol, Annex II countries are under a specific obligation to enhance financial support to developing nations for their climate change mitigation efforts (Rosenqvist et al., 2000).

However, as illustrated in Figure 1, immediately following the signing of the Kyoto Protocol, it is evident that the emission rates in countries falling within the Annex II category, such as China and India, significantly exceeded those in developed nations (Annex I). Furthermore, empirical studies have indicated that, according to projected trends, emissions from Annex II countries are anticipated to surpass those of other nations well into the 2070s. This phenomenon may be elucidated by the propensity of developed countries to engage in GHG-emitting investments within Annex II nations or by the pursuit of GHG-intensive investments by countries already situated within the Annex II group, as they endeavor to achieve economic development (Perissi et al., 2018).

It is important to note that these categories have evolved in international climate negotiations, and the obligations of countries under newer agreements such as the Paris Agreement are more diverse and flexible. Under the Paris Agreement, all countries, both developed and developing, are expected to contribute to global climate action based on their capabilities and responsibilities. The concept of historical responsibility remains relevant in discussions about climate justice and equity, but it is not the sole basis for determining emissions reduction targets and commitments in modern climate agreements (UN, 2015). Given that climate change manifests varying impacts/indicators across different geographic regions, encompassing a spectrum of factors such as GHGs, meteorological and climatic patterns, marine environments, snow and glacial dynamics, public health and societal dynamics, and ecological systems, it is imperative to comprehend the distinct political responses associated with climate change in diverse nations. Consequently, this study focuses on the Netherlands, the UK, and the USA as exemplars of countries at the forefront of formulating climate change policies in response to CCIs. In addition, China positioned among the primary contributors to GHG, and Türkiye representing a notable case study within the context of this research, are also included. Within this framework, a comparative analysis is conducted to elucidate the climate change effects stemming from urban growth among these selected five nations.

Urban growth associated with climate change is a complex interplay that encompasses various critical indicators. Sea-level rise, while pivotal for countries with coastal areas such as the Netherlands (Amsterdam and Rotterdam) and the UK (London and Cardiff), may not directly correlate with urban growth. To grasp the complete picture, it's essential to connect sea-level rise data with urban development trends (Roggema, 2014). UHI effect, conversely, is a localized temperature rise within cities compared to the outskirts of rural areas affected by human actions and urban infrastructure. While it might not encapsulate the full spectrum of climate impacts, especially in diverse metropolitan areas, it remains a significant indicator, notably in rapidly urbanizing regions such as the Netherlands, the USA, and Türkiye. Rapid urbanization exacerbates the UHI effect, intensifying heat waves in cities and linking it directly to urban growth (Oke, 1982; Stone and Norman, 2006). Furthermore, urbanization can alter drainage systems, increasing vulnerability to flooding, especially in low-lying areas, as seen in the Netherlands and Türkiye. In Turkish cities like İstanbul, rapid urbanization heightens the risk of urban flooding events, demonstrating the adverse impact of urban growth on flood risk (Gedikli and Balaban, 2018).

Urban expansion and land-use changes are significant climate change indicators, closely associated with urban growth. Monitoring land-use transitions, such as converting green spaces to urban infrastructure or agricultural zones into urban areas, helps understand urban sprawl. This is especially relevant in the UK and China, where urban expansion contributes to climate change by increasing energy consumption and GHG emissions, as observed in the USA (Scheraga and Furlow, 2001). Conversely, urbanization can lead to increased air pollution, notably in the UK and China (e.g., Beijing and Shanghai). Monitoring air quality parameters like PM2.5, $NO_2$, and $O_3$ highlights the influence of urban growth on the quality of the air and its impact on public health. It is not only attributed to urban growth but also industrial activities resulting from rapid urbanization (Song et al., 2017), as seen in Türkiye's industrial cities such as İstanbul, Kocaeli, and Bursa. Finally, water stress is a multifaceted issue shaped by the mixed impacts of urban growth and climate change. Chinese municipalities, experiencing escalating urbanization, face increased water stress due to rising demand. Türkiye also witnesses urban water demand contributing to water stress, influenced by factors such as agricultural practices and regional climate patterns. Monitoring variables such as drought frequency and severity aids in understanding climate-related impacts on urban water resources (Gedikli and Balaban, 2018).

In conclusion, while contemporary times witness the presence of virtually every climate indicator in every country, Table 1 presents the predominant CCI specifically within the case countries (Table 1).

Among the five examined countries, UHI, urban expansion/sprawl, and air quality issues emerge as the most frequently encountered CCIs stemming from urban growth as shown in Table 1. Furthermore, numerous urban growth effects exhibit a direct relationship. It is essential to recognize that each indicator possesses inherent strengths and limitations. Hence, a comprehensive comprehension of the interplay between urban growth and climate change within a specific region necessitates the utilization of a multifaceted indicator approach. Nevertheless, it is noteworthy that Türkiye stands out as the province experiencing the most pronounced CCIs in comparison to its counterparts. Hence, there is an urgent requirement for an expansion in research efforts pertaining to this subject matter within the Turkish case.

UGIs pertaining to the climate change effects are addressed in the second part of the literature review. These indicators encompass quantifiable variables that signify the growth and progression of urban regions and elucidate their ramifications on the local and regional climatic conditions. First, land-use changes, involving the conversion of green spaces or forests into urban areas, are discernible through land cover data and satellite imagery (Lambin et al., 2001; Zhang et al., 2020). These alterations can impact surface properties, affecting temperature, precipitation, and local climate patterns. Human-induced alterations in land use and land cover influence climate through two pathways: the biogeophysical pathway, which involves altering physical land surface characteristics such as albedo, soil moisture, and roughness, and the biogeochemical pathway, which considers changes in GHG concentrations (e.g., $CO_2$, CH4, $N_2O$) resulting from shifts in land-atmosphere fluxes of these gases (Kennedy et al., 2009). Furthermore, the density, design, and layout of urban infrastructure and the built environment affect local climates. Compact urban forms with mixed land uses can reduce energy use and transportation emissions (Newman and Kenworthy, 1999).

As urban populations continue to expand, cities will exert an increasingly pronounced influence on climate change. This heightened urban impact makes urban areas more vulnerable to various climatic events, including floods, rising water levels, heat waves, droughts, and storms. The relationship between expanding urban development and its impact on local climates is especially significant when considered at a provincial scale that encompasses both urban and rural areas (Bektaş and Sakarya, 2023). Land uses paramount influence on climatic conditions becomes particularly evident within urbanized territories. The expansion of urban centers, combined with higher population density, leads to significant shifts in land use patterns, increased energy consumption, and modifications in surface characteristics, resulting in UHI phenomenon, where urban areas experience localized temperature elevations compared to rural surroundings (Stone, 2009). Thirdly, indicators related to transportation patterns, such as the vehicle numbers on the road, mode shares (e.g., walking, cycling, and public transit), and congestion levels, are crucial for understanding emissions and air quality (Sallis et al., 2016).

Conversely, the population is a pivotal UGI linked to CCIs. It signifies urban residents and significantly shapes cities' environmental footprint and vulnerabilities in the climate change context (Chen et al., 2014; Yi et al., 2016; Ren et al., 2020). Growing urban populations demand expanded infrastructure, causing notable changes in land use patterns that impact climate dynamics (Black et al., 2008; Bektaş and Sakarya, 2023). Urban population encompasses size, density, demographics, migration, and social dynamics. High densities increase energy usage for heating, cooling, transport, and infrastructure, affecting GHG emissions (Seto et al., 2016). The number of urban residents influences

**Table 1.** Climate change indicators due to urban growth

| Climate change indicators/impacts | Countries | | | | |
|---|---|---|---|---|---|
| | The Netherlands | United States (USA) | United Kingdom (UK) | Türkiye | China |
| Sea level rise | * | | * | | |
| UHI | * | * | | * | |
| Flooding | * | | | * | |
| Urban expansion and urban sprawl | | * | * | | * |
| Air quality | | | * | * | * |
| Water stress | | | | * | * |

GHG emissions from transportation, heating, industry, and waste (Kennedy et al., 2009). Urban population growth rates and distribution affect land use, transportation, land cover, local climate, air quality, and ecosystems (Wu, 2014).

Figure 2 illustrates the United Nations' country categorizations based primarily on economic factors but also incorporating human development and other criteria. More developed countries, such as the USA and Western European nations, exhibit advanced industrialization, technology, and high per capita income, leading to a high living standard and Human Development Index scores. Less developed countries, including parts of Latin America and Asia, are in transition from low to high income, typically with lower industrialization and technology levels. Least developed countries represent the poorest nations with low income, limited industrialization, and basic infrastructure, categorized using UN criteria such as income, human assets, and economic vulnerability (UN, 2011).

In light of these, it is predicted that less developed regions reached high population rate while the population rate of developed countries is stable. The high population in less developed or developing countries highly concentrates GHG emissions. They classified the population into three groups according to CCIs as 2–4 million has low impact, 10 million has medium impact and approximately 15 million has high impact on climate change (Jiang and Hardee, 2011; UN, 2011).

Urban economy/economic structure can be considered another significant UGI related to CCIs the urban economy encompasses financial activities and their role in climate change (Commission on Growth and Development, 2009; Kahn et al., 2019). Limited research explores how the economy triggers CCIs (Commission on Growth and Development, 2009; Stern, 2008). It involves factors such as GDP, industry composition, employment, income distribution, and economic resilience within urban boundaries (Yi et al., 2016; Ren et al., 2020). Urban economic composition, including sectors such as manufacturing

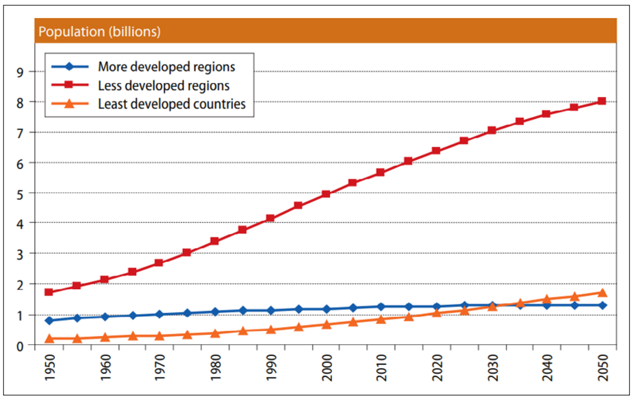



**Figure 2.** Projected population by development regions (1950–2050) (UN, 2011).

and services, affects energy use, resource consumption, and emissions. High-emission industries contribute to climate change, while green sectors mitigate it (Stern, 2008; Lu, 2018). The economy can increase or decrease a city's climate change vulnerability. Energy-intensive industries, transportation, and buildings are key GHG emission sources. Sustainable urban development aims to separate economic expansion from emissions (Bowen et al., 2012). The urban economy also provides jobs and income. Economic disparities affect the vulnerability and adaptive capacity of urban populations to climate change (Zografos et al., 2016).

On the other hand, the economic situation of the developed countries is more resilient due to transforming their economies from carbon dependent to clean and green economy than less developed and developing countries; therefore, there are no negative impacts of climate change (Raddatz, 2009; Dell et al., 2008). However, for instance, Türkiye is among the developing nations globally can affect the climate change due to its economic growth policies. The growth policies mostly depend on carbon-based sectors (industry and agriculture) (OECD, 2020), which leads to increase sensitivity to climate change. Moreover, economic structure has unique variables for each city in a country. According to the OECD Better Life Index, it is assumed that the average household net disposable income per capita is 30.563 USD (227.331 TL) in a year while it reaches 69.477 USD (516.778 TL) in a year for highly developed countries. In addition to this, household income in undeveloped countries has on an estimated 11.026 USD (82.012 TL) a year (OECD, 2020). It is obviously that there exists a substantial disparity between countries' economic situation originating from development status, which is an important dynamics for taking action against climate change.

QoL is a multifaceted indicator of urban growth (Rahman et al., 2011). Some studies suggest that urban growth negatively affects QoL, attributing this to population growth and environmental issues (El Din et al., 2013). However, others argue that as the economic structure, a key UGIs, improves labor skills, QoL can also improve. High living standards often lead to the expansion of living environments, positively impacting QoL. Urban growth's macroform, encompassing city spatial layout, and structure, significantly influences residents' QoL. Factors such as urban sprawl, density, access to amenities, and green spaces play vital roles in well-being. For instance, higher-density, transit-oriented development can reduce vehicle use, improve air quality, and enhance QoL indicators such as reduced traffic congestion and lower healthcare costs (Ewing and Cervero, 2010). However, the relationship between QoL and urban growth is complex. Effective, sustainable urban planning can enhance QoL by improving access to services, economic opportunities, and cultural amenities, reducing spatial inequalities, and promoting social inclusion (Stratigea et al., 2019).

Conversely, uncontrolled urban growth with issues such as congestion, pollution, inadequate infrastructure, and reduced green spaces can harm QoL, leading to stress and health problems (Gehl, 2013). Mitigating negative impacts and enhancing positive aspects of urban growth on QoL requires effective land use planning, sustainable transportation, green infrastructure, and social services.

In general, in contrast with the population growth, improving QoL has a positive impact to adapt climate change. According to OECD Better Life Quality Index, the environment which consists of air quality and water quality is one of the indicators of QoL and it affects climate change. Environmental index values of developed countries such as Norway, Sweden, Finland, and Australia are very high in there (approximately 10) (the values from 1 to 10). However, the QoL in terms of environmental conditions value equal to 3 in Türkiye as one of the developing countries, which demonstrates that the vulnerability of climate change partially high in contrast to developed countries. Similarly, NUMBEO index which is online data to calculate the QoL in the world cities demonstrates that İstanbul in Türkiye is ranked approximately 112 score (Values from 40 to 200), while developed cities are ranked approximately 200 score. It takes into account various factors that impact one's QoL, including purchasing power, pollution levels, housing affordability, cost of living, safety, healthcare quality, commute times, and climate conditions in NUMBEO. The index is designed to provide a comparative measure, where a higher index value indicates a better QoL.

Finally, the Climate Change Performance Index for the year 2019 was scrutinized. This index incorporates GHG emissions (weighted at 40%), renewable energy (weighted at 20%), energy use (weighted at 40%), and climate policy (weighted at 20%) as its key components. Accordingly, Sweden holds the top position with a score of 76.28, followed by Australia, Norway, and Finland in succession. Türkiye, on the other hand, ranks 50th with a score of 40.22 (Burck et al., 2018). In light of these findings, the assessment of the literature regarding the relationship between UGIs and CCIs is presented in Table 2.

As observed in Table 2, CCIs are associated with UGI in both direct (indicated in red as "D") and indirect (indicated as "I") manners. It is demonstrated that GHG emissions can be directly influenced by all UGI. Furthermore, for instance, when there is any alteration in land use, GHG emissions, UHI effect, flooding, and urban expansion are directly affected, whereas sea-level rise, air quality, and water stress are indirectly impacted. Alternatively, if the economic structure transitions towards greater sustainability and eco-friendliness, there can be a direct interaction since GHG emissions and UHI may decrease while air quality improves. Additionally, increased budget allocations for investments in urban systems can lead to measures being taken to mitigate flooding. QoL is indirectly related to nearly all CCIs among UGI. This suggests that the QoL indicator is contingent upon population and economic structure and falls within their purview. Population exacerbates the effects of climate change, whereas economic structure can either mitigate or exacerbate these effects. However, a high QoL mitigates the impacts of climate change.

Consequently, the indicators highlighted within the delineated area marked by the dashed red line (population, economic structure, and QoL) have been designated as three criteria for evaluation. The choice is made considering the greater ease of data accessibility and measurability in İstanbul in comparison to other UGIs (Figure 3).

## CASE STUDY: ISTANBUL IN TÜRKİYE

Research endeavors aiming to assess the interplay between UGIs and the ramifications of climate variability reveal that population size, economic structure, and the QoL serve as the primary determinants of urban growth, which subsequently exert considerable influence on climate change dynamics (McDonald et al., 2011; Neumann et al., 2015). Developing countries like Türkiye, driven by

**Table 2.** Literature review about urban growth and climate change impacts

| | Urban growth indicators (UGI) | | | | | |
|---|---|---|---|---|---|---|
| **Climate change indicators/impacts** | **Land-use change** | **Built environment** | **Transportation pattern** | **Population** | **Economic structure** | **Quality of life** |
| GHG | D | D | D | D | D | D |
| Sea level rise | I | D | I | I | I | I |
| UHI | D | D | I | I | D | I |
| Flooding | D | D | D | D | D | I |
| Urban expansion and urban sprawl | D | D | D | D | D | I |
| Air quality | I | I | D | I | D | I |
| Water stress | I | I | I | D | I | I |

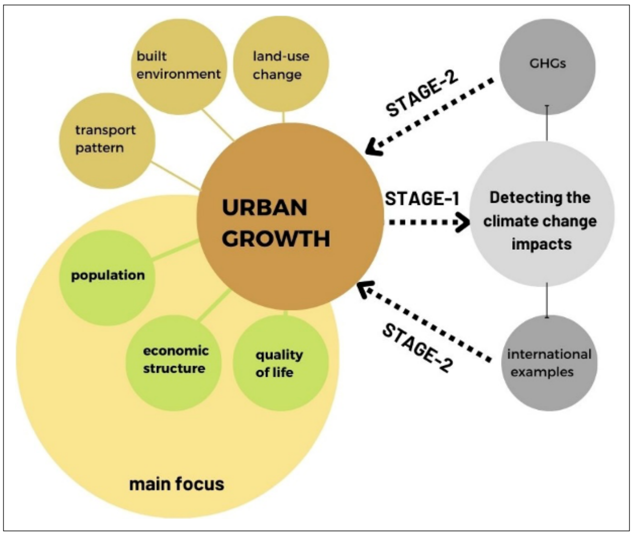



**Figure 3**. The content of literature review.

their urban expansion ambitions, can exhibit to increase susceptibility to the CCI. To explore the outcomes of urban growth in relation to climate change, Istanbul was chosen as a case study within Türkiye. This choice is underpinned by İstanbul's status as Türkiye's most populous city, as high urban population densities, as evidenced in the literature, tend to intensify CCIs due to anthropogenic factors. As Türkiye's top GHG emitter, İstanbul has a vital role in spearheading mitigation and adaptation efforts. In 2015, İstanbul accounted for about 10% of Türkiye's total emissions, equivalent to 47.3 million metric tons of $CO_2$ (İMM, 2018) (Figure 4).

As shown in Figure 4, İstanbul's 2015 GHG inventory totals 47.3 million metric tons of $CO_2$ equivalent. Due to ongoing growth, especially in population, emissions are expected to peak in 2050. Under the Business As Usual scenario, İstanbul's emissions are projected to reach 84.7 million metric tons of $CO_2$ by 2030 and 117.9 million metric tons by 2050, aligning with Türkiye's Intended Nationally Determined Contribution target of a 21% reduction by 2030. This ambitious goal highlights the need for climate adaptation and mitigation measures, which can bring additional benefits such as improved air quality and QoL. Evaluating population, current economic conditions, and QoL is vital for addressing climate change impacts in İstanbul (İMM, 2018).

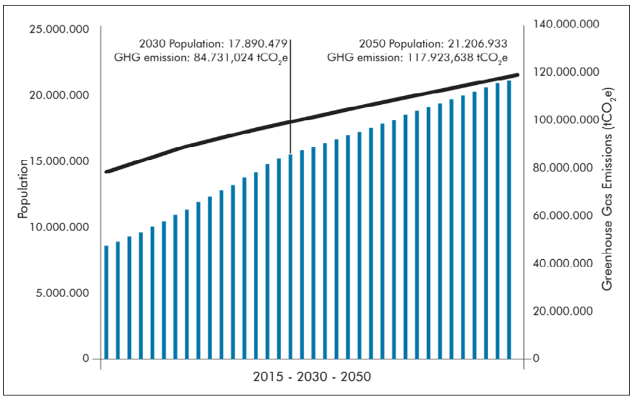



**Figure 4**. Istanbul's greenhouse gas emissions projections for 2015–2050 (İMM, 2018).

First, İstanbul currently hosts an estimated population of around 16 million, the highest in Türkiye, and is projected to reach approximately 18 million by 2025, as reported by TURKSTAT in 2019a (Figure 5).

Figure 3 shows the population rate in past, current, and predicted population in İstanbul. İstanbul with the highest population in Türkiye is totally urbanized city. After 2000s, population increases eventually, which causes dense GHG emissions in the city (İMM, 2018). This can be the main output of economic structure. The economic structure is the second reason why İstanbul was selected as case study. İstanbul accounts for producing some 31% of Türkiye's economy (TURKSTAT, 2019b), so İstanbul is called as the heart of the economy. Likewise, it is explained in İDA report in 2017, İstanbul is defined as economic engine of not only city scale but also country scale growth. This leads to increase urbanized population. Due to the current economic structure and growth energy uses and GHG emissions are concentrated in city (McDonald et al., 2011; İMM, 2018), which triggers CCIs. However, it is approved that economy is more vulnerable and financial collapse can be occurred by the impacts of climate change (Ren et al., 2020; Chen et al., 2014; Yi et al., 2016). Therefore, there are two-side interaction among economic structure and the impacts of climate change.

Figure 6 illustrates the use of average personal disposable income as a metric for measuring urban economic structure at the city scale, based on data from TURKSTAT in 2019a. This choice stems from the initial phase of economy involves augmenting wealth through increased personal income, as suggested by Neumann et al. in 2015. Alongside population and economic structure, QoL emerges as another UGI intertwined with CCIs. Unlike other urban growth metrics, an improvement in QoL corresponds to a reduction in CCIs. To gauge İstanbul's QoL, data from NUMBEO (Url-

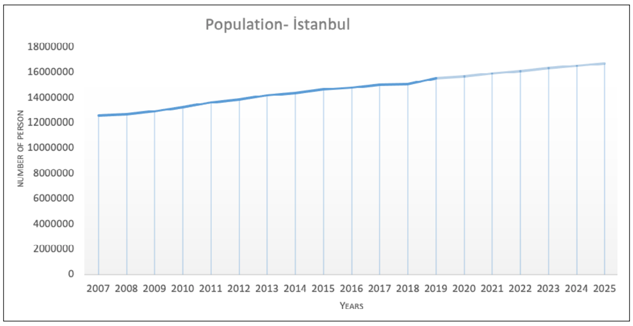



**Figure 5**. Yearly population rate from 2007 to 2025.

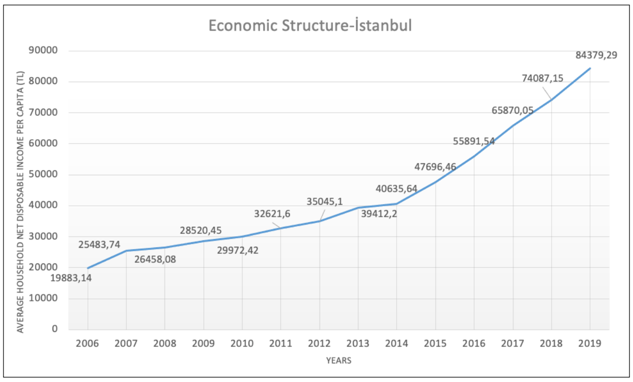



**Figure 6**. Yearly economic situation from 2006 to 2019.

1), a repository with an extensive cost-of-living database, was employed. This assessment considered various indices, encompassing power, pollution, house price-to-income ratios, cost of living, safety, healthcare, traffic commute times, and a climate index. These factors were incorporated with differing weightings to derive an overall QoL estimate, as depicted in Figure 7.

Figure 7 graphically portrays a consistent decline in İstanbul's QoL index from 2016 onwards. This decline is a direct reflection of İstanbul's enduring urban growth, which encompasses economic, social, and spatial dimensions. İstanbul is not the sole Turkish city with a quantifiable QoL index; other cities such as Ankara and Bursa also possess such metrics. However, İstanbul's QoL index is markedly lower than that of these cities, underscoring its vulnerability to CCIs.

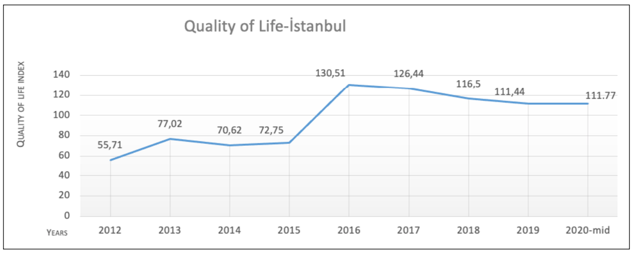



**Figure 7**. Yearly life quality index from 2012 to 2020-mid.

To avert such outcomes, it is crucial to implement preventive actions in İstanbul. This includes addressing urban growth-related issues and defining solutions through structured planning stages. Identifying primary action areas guided by UGIs drawn from the literature is crucial. Techniques like the FDMT can be employed to ascertain which indicators have the most substantial impact on climate change in İstanbul and propose effective strategies for climate change adaptation. Table 3 synthesizes insights from both the literature review and İstanbul's unique context, with the values for general inputs extracted from Section 2 of the literature review.

Table 3 categorizes values into two groups: One derived from the literature review, and the other from specific to İstanbul, all based on UGIs influencing climate change. To facilitate comparison, logarithmic equations were used to normalize these values. These normalized values hold significance in the execution of a fuzzy logic model in MATLAB.

## METHODOLOGY AND APPLICATION

The literature review's second part identified UGIs linked to CCIs, selecting specific indicators for the methodology. Fuzzy logic, defined by Lotfi Zadeh in 1965, offers a variable logic system where truth values range from 0 to 1 (Zadeh, 1973; 2009). Fuzzy models, using IF-THEN rules/predictions and membership functions, allow for visualizing uncertainty and handling imperfect data (García et al., 2014). This approach excels in dealing with uncertain information. To illustrate, in analyzing the UGIs-CCIs relationship in İstanbul, fuzzy logic was employed. Inputs

**Table 3.** Entries/variables for applying fuzzy logic model

| | Literature review | | | İstanbul | |
|---|---|---|---|---|---|
| **Indicators** | **Values in general** | | **Normalized values** | **Values in 2019** | **Normalized values** |
| Population (Jiang and Hardee, 2011; UN, 2011) | 4 million | low | 6.60 | 15.519.267 | 7.19 |
| | 10 million | medium | 7 | | |
| | 15 million | high | 7.20 | | |
| Economic structure (OECD, 2020) | 82.012 TL | low | 4.91 | 84.379 TL | 4.92 |
| | 227.331 TL | medium | 5.35 | | |
| | 516.778 TL | high | 5.71 | | |
| Quality of life (NUMBEO, 2019) | 42 | low | 1.62 | 112 | 2.04 |
| | 130 | medium | 2.11 | | |
| | 203 | high | 2.30 | | |

included population, economic structure, and QoL, and MATLAB's Fuzzy Toolbox Software was used for analysis. The process unfolded in three modules, revealing CCIs drivers. The following steps provide concrete examples of the MATLAB process:

- Initiating the fuzzy inference system (FIS) editor with entry variables (Figure 8)
- Structuring membership function plots (Figure 9)
- Applying fuzzy operators through membership functions and the rule editor (Figure 10)
- Aggregating all outputs using the results viewer (Table 4) in the evaluation phase (evaluation part).

Figure 8 shows FIS editor which is one of the MATLAB interfaces. FIS was developed as three inputs and one output with Mamdani type.

Figure 9 displays membership function plots for three key indicators: population (measured by the number of individuals), economic structure (represented by net disposable income per capita), and QoL. They were selected due to their pertinence and previous examination in the literature review (Section 2). For the İstanbul case, these indicators have been normalized and assigned membership functions. In addition, specific value ranges (low, medium, high) have been defined and gathered from the from the literature review.

Figure 10 displays the membership function editor, allowing customization of titles, ranges, and parameters for input and output variables. It facilitates IF-THEN predictions using selected membership functions. In this context, there are twenty-seven rules per urban growth dimension, coming from the literature review and TURKSTAT data. In addition, three membership function plots (low, medium, high) assess CCIs in İstanbul. The results reveal how indicators interact, their collective impact on climate change, and which indicator has a dominant role in exacerbating climate change effects. After defining these rules in MATLAB, the aggregation of outputs, influenced by input variables, is presented in the results viewer within the Results and Evaluation section (Figure 11).

## FINDINGS

The findings depict the status of UGIs-population, economic structure, and QoL-within the scope of climate change in İstanbul. Drawing from the outcomes acquired from MATLAB Fuzzy Logic, five distinct scenarios are defined, covering outcomes from the least favorable to the most favorable. In these scenarios, initially, all three indicators are considered of equal weight. However, the weights for each indicator change in line with scenario priorities (e.g., low-medium-high). For instance, in one scenario, the

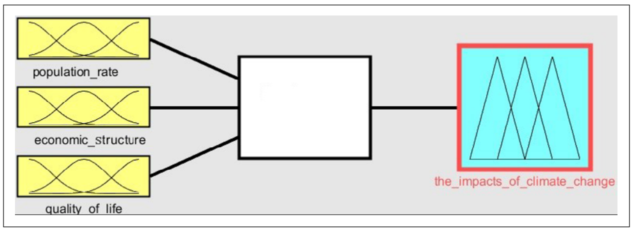



**Figure 8**. FIS editor.

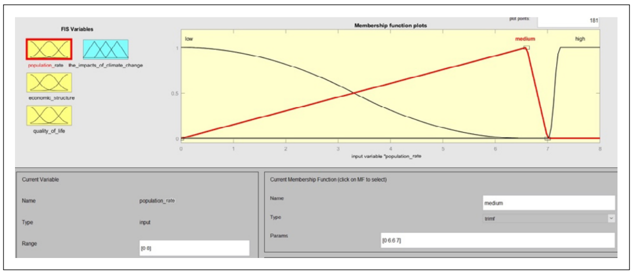


**Figure 9**. Membership function plots.

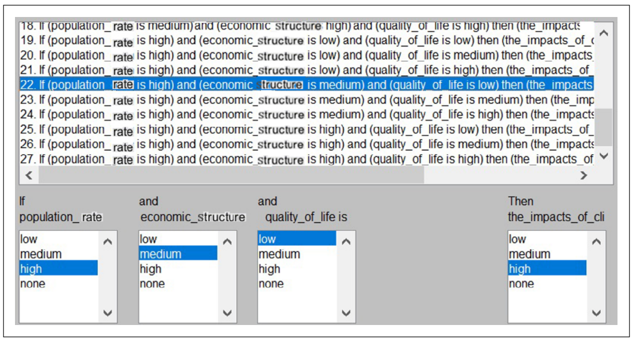



**Figure 10**. Membership function editor.

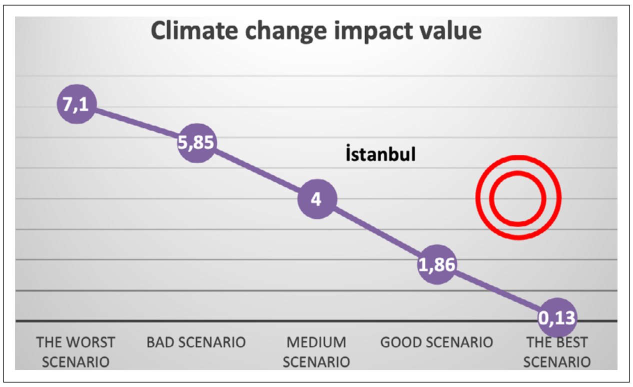
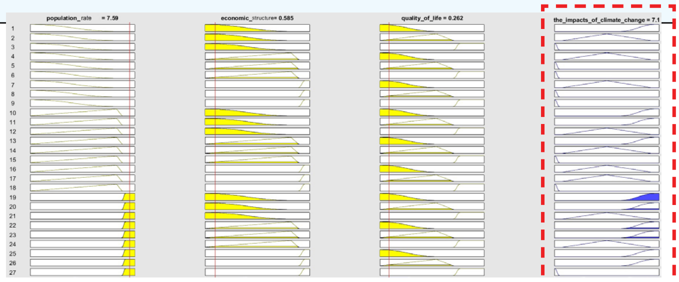
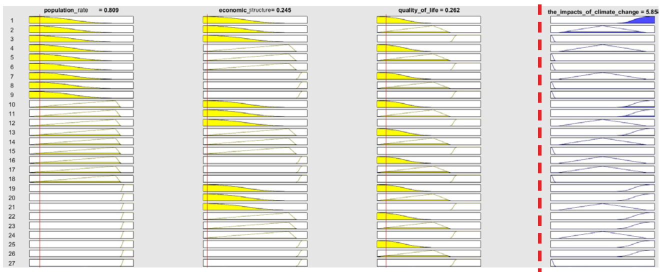
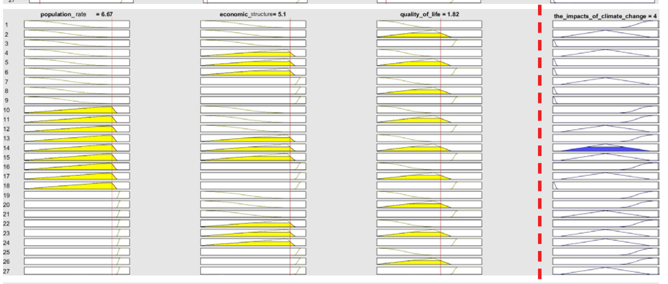
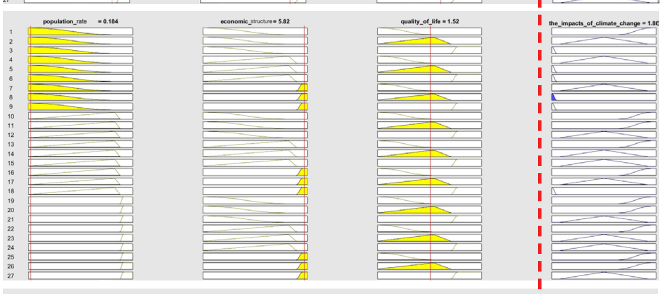
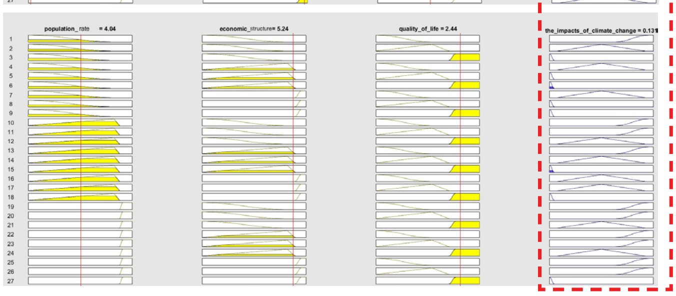



**Figure 11**. Climate change impact value by scenarios.

population rate may be high while the economic wealth rate is low, whereas in another scenario, this combination may differ (Table 4). In the result column, yellow colors are related to UGIs, and the blue color represents the amount of impacts of climate change.

As evident in Table 4, under the most unfavorable scenario, if the population is high but economic conditions and QoL are low, the potential CCIs can be exceptionally severe. It

**Table 4.** Evaluation chart

| | Population rate | Economic wealth | Quality of life rate | Results |
|---|---|---|---|---|
| The worst scenario | high | low | low |  |
| Bad scenario | low | low | low |  |
| Medium scenario | high | high | medium |  |
| Good scenario | low | high | medium |  |
| The best scenario | medium | high | high |  |

is plausible to anticipate that CCI will be strongly felt in İstanbul. In contrast to this worst-case scenario, changes in population rate from high to low alone directly influence the potential climate change scenario in a positive manner. Nevertheless, it can be discussed that CCIs will persist unless improvements are made in QoL and the economy is shifted toward a climate-oriented approach in İstanbul.

When both population and economic conditions are high, and QoL remains at a medium level, the resulting CCIs are moderate, signifying a neutral outcome. These parameters closely align with İstanbul's present situation, reflecting the city's current scenario. However, the study findings offer insights into how this condition can be improved. When population is low, economic conditions are high, and QoL is at a medium level, the CCIs are rarely severe, indicating minimal effects in İstanbul. This scenario can be realized through increased climate awareness among citizens and support from local and national governments. It serves as a guide for İstanbul in addressing climate change and hints at the city's potential for enhanced sustainability. Furthermore, in a scenario where economic prosperity and QoL are high, coupled with a moderate population, the CCIs would be extremely limited. İstanbul could join the ranks of sustainable, climate-adaptive cities like those in Norway and Finland. CCIs in İstanbul would be systematically managed, aligning with practices seen in climate-adaptive cities.

In summary, this study assessed possible CCIs through five scenarios, analyzing the interaction among climate change and UGIs within a specific case (İstanbul) using FDMT.

## CONCLUSION AND EVALUATION

This study used an FDMT based on MATLAB to examine the impacts of UGIs on climate change in an effort to contribute to the literature by conceptualizing a systematic comprehensive approach using the current values at the urban level. The model is exemplified by population, economic situation, and QoL, which could be used by decision-makers to produce climate change adaptation policies with decreasing the area of CCI.

The study evaluated the results in accordance with the research objective. The unique aspect of this study is its comprehensive approach, which brings together UGIs (population, economic structure, and QoL) that are often studied independently in the literature and highlights them in the concept of climate change effects, defining both direct and indirect relationships. This provides a holistic conceptual perspective that does not rely on a single cause for CCIs.

The impact of climate change varies across different scenarios, with the best scenario having the lowest impact and the worst scenario having the highest. İstanbul's current situation aligns with the 3rd scenario (represented by the red circles). If İstanbul's population continues to grow rapidly, it may end up in the worst-case scenario (Scenario 1). However, implementing economic transformations to reduce population density and enhance QoL could lead to the best possible climate scenario. Notably, changes in QoL are closely linked to population rate and economic structure (Figure 11).

In contrast to previous research (Dell et al., 2008; Filion, 2010; Jiang and Hardee, 2011; Mourya et al., 2020) on the topic, this study highlights the need for a thorough and all-encompassing approach to the interplay of factors influencing climate change. Given the model's emphasis on the multifaceted nature of urban growth, policies aimed at mitigating CCIs can be more qualitative and context specific. For instance, İstanbul grappling with dwindling natural resources, a burgeoning population, and a weak economic structure. These considerations must inform measures taken in İstanbul regarding climate change. Controlling population growth through family planning and awareness initiatives is essential to reducing CCIs. Additionally, transforming the current economic growth model by prioritizing green, clean, and sharing economy sectors plays a pivotal role in mitigating CCIs. Once population and the economy, the two primary components of urban growth, are brought under control, the QoL in İstanbul can significantly improve.

It is proofed that while the effects of the selected indicators under the scope of urban growth are initially equally weighted, these weights change in various situations, leading to variations in potential CCIs. Policymakers have the option to formulate comprehensive urban planning strategies that encompass population growth, economic progress, and enhancements in QoL. These strategies should incorporate measures for both mitigating and adapting to climate change. In addition, policymakers can make localized decisions by selecting the most appropriate scenario and prioritizing specific areas. Investing in sustainable and efficient public transportation systems to reduce reliance on individual vehicles, thereby decreasing GHGs and traffic congestion are crucial. They should promote green infrastructure, renewable energy (solar/wind power) to enhance air quality, reduce heat island effects. Incentives for businesses and industries to adopt sustainable and eco-friendly practices, such as tax benefits for green initiatives and energy-efficient technologies should be offered.

This study has some important contributions expected to guide future research in similar areas. The methodological approach (FDMT) used to examine the relationship between UGIs and climate change effects in this study may assist in identifying and analyzing priority problems in different cities in future studies. It also provides insights into how different scenario analyses related to the topic can be created and evaluated. The recommendations developed for policymakers can serve as guidance for improving sustainable growth and climate adaptation in other cities.

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