The Impact of Various land-use zoning and government restrictions on Environmental Sustainability in San Marcos, Texas.

by

Timmy Szpakowski, BS

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Committee Members:

Edwin Chow, Chair

Rosalie Ray, Co-Chair

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LIST OF ABBREVIATIONS

Abbreviation	Description
AIIA	Agent-Integrated Irregular Automate
ABM	Agent-Based Model
CA	Cellular Automata
CAFUGM	CA and Fuzzy Urban Growth Hybrid model
ED	Euclidean Distance
FEMA	Federal Emergency Management Agency
GOS	Green Open Spaces
HC	High Income with Kids
HNC	High Income without Kids
LC	Low Income with Kids
LNC	Low Income without Kids
MF	Multi-Family
MRV	Multi Resolution Validation
NMHC	National Multifamily Housing Council
SF	Single-Family
SPA	Special Protection Areas
UN	United Nations

ABSTRACT

The purpose of this thesis is to investigate the impact of various land-use zoning and restrictions through government regulations preserving green space to promote environmental sustainability in San Marcos, TX. Located in the I-35 corridor between Austin and San Antonio in Central Texas, this area has experienced tremendous population growth from 2010-2020 and is continuing to have exceptional growth. An Agent-Integrated Irregular Automate (AIIA) model is used combining the spatial benefits of irregular Cellular Automata (CA) while representing urban dynamics with Agent-Based Model (ABM) agents. This project modeled urban growth via AIIA to examine the impacts of government regulations of growth restrictions and multifamily housing on green space preservation and environmental sustainability. The reliability of the urban growth simulation is demonstrated by modelling historical data over 20 years (2000-2020) and comparing the results with the actual 2020 land-use map. In addition to an unrestricted scenario, three scenarios are simulated testing the impact of an urban growth boundary and various housing land-use zoning and regulations. Comparison analysis revealed that government regulations on residential housing preserved more green space than without them. However, the most regulated scenario with restrictions on both single-family and multifamily housing did not result in the largest amount of green space being preserved. A scenario with an urban growth boundary and no regulations on housing produced the best results when comparing the retention of green space. Potential explanations for these results include population demographics and model parameters affecting developer agents' goal to maximize profits.

1. CHAPTER ONE

Introduction and General Information

Exponential population growth has altered how governments are managing land-use in cities to strengthen environmental sustainability in their communities (UN 2022, Imagine Austin 2018, Sustainable Cities 2022). The concept of sustainability was first introduced by the United Nations (UN) in 1987 in the Brundtland Report, a.k.a. "Our Common Future", which has inspired an international effort on sustainability (Rachelson 2018). Among the many ways that environmental sustainability has been defined, it essentially strikes the balance between the human need for resources and the health of the ecosystems that provide these resources for future generations (UN 2022). With that noble goal in mind, the sustainable use of land resources is a practice that originated from the phrase "limits to growth" suggested by Forrester (1969) in his groundbreaking book on Urban Dynamics (Shen 2008). Since then, the implementation of land-use planning has been modeled and applied around the world (Li and Lui 2008, Burhan et al 2020, Aslam et al 2021, Imagine Austin 2018, Environment Texas 2020).

Sustainable land-use is crucial since natural habitats are limited and are difficult to restore if they are degraded or contaminated. The tremendous increase of urban development from population growth has caused environmental dilemmas, such as the destruction of ecosystems (Li and Liu 1999, Jantze al 2005, Heinrich 2013). Within the city or urban landscapes, this occurs when greenspaces are replaced with developed land such as industrial and residential areas. These lost spaces could provide adequate aquifer recharge, mitigate flooding, improve air and water quality, regulate temperature, and help carbon sequestration (Cartier 2021). Additionally, the type of housing development within urban areas is an intrinsic part of how land-use can affect environmental sustainability. According to the National Multifamily Housing Council (NMHC 2019), "increased urban density benefits the environment by preserving green spaces and natural amenities". Multifamily housing increases urban density and allows more population to be living in the central city, and hence decreases urban sprawl. Reducing urban sprawl helps keep the ecosystems around cities intact and allowing these areas to provide the ecological services needed for a sustainable environment (National Wildlife Federation 2022).

Efficient use of land is especially important in areas where rapid population growth and urban development are occurring, such as the I-35 corridor between Austin, and San Antonio in Central Texas (Figure 1). Hays County is part of this area, with several cities bordering the I-35 corridor. According to the US Census Bureau, Hays County was the fastest-growing county in the United States with populations over 100,000 during the decade from 2010-2020 (Weilbacher 2021). Additionally, the City of San Marcos, located in the southeastern portion of Hays County, was the fastest-growing city in the country from 2013 to 2015 (Osborn, 2016). New Braunfels, a neighboring city south of San Marcos, was the 3rd fastest growing city between 2010-2019 (US Census Bureau 2022). From 2020-2021, New Braunfels was the fifth fastest growing city in America (US Census Bureau 2020), but during 2021-2022 it moved to thirteenth place behind Georgetown, TX in first place and Kyle, TX in third place (US Census Bureau 2023).

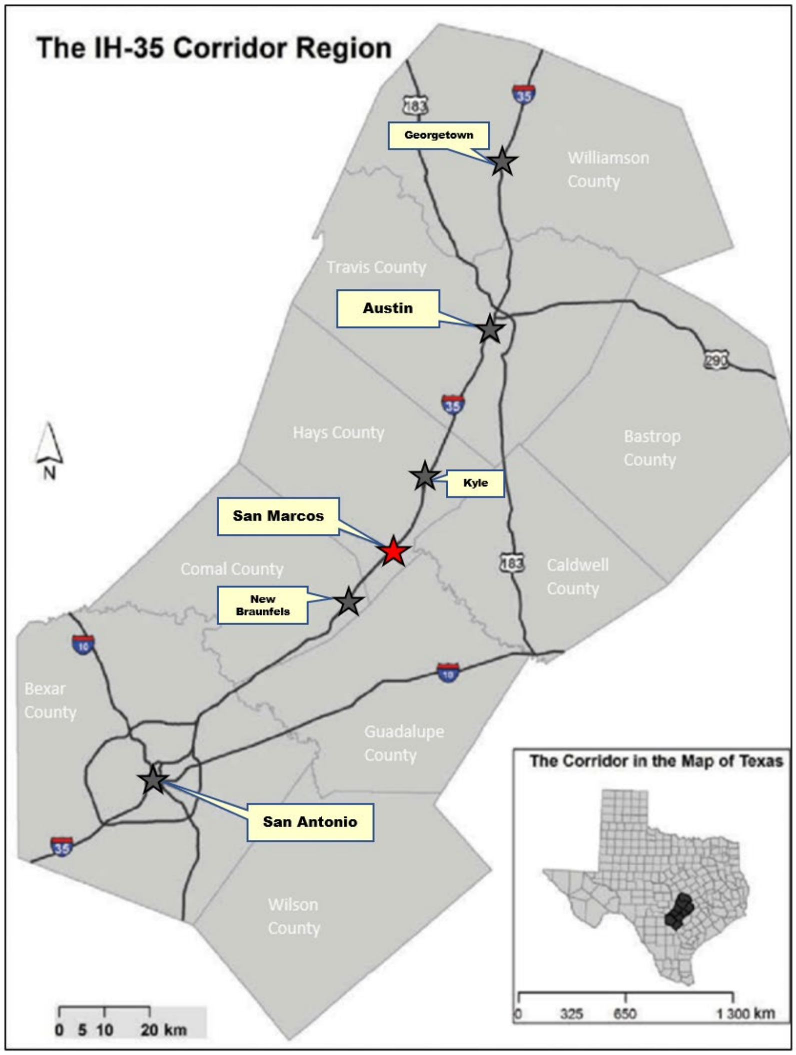


Figure 1. I-35 Corridor area from Austin to San Antonio (Adapted from Dahal and Chow 2014a)

This rapid population growth has caused several dilemmas from development projects impacting the environmental sustainability in the City of San Marcos. In 2013, it was reported that two new apartment complex developments in the city not only threatened an endangered species habitat but were also responsible for filling in karst topography essential for recharging the Edwards Aquifer, a crucial supply of water for the city (Heinrich 2013). More recently, there has been discourse between city officials and environmentalists on a film studio being built within the city limits (Gasti 2022). The environmentalists argue that the expansive studio, and the impervious surfaces around it, threaten the Edwards Aquifer Recharge Zone which is the primary water source for over two million people. Additionally, a report by an engineering consulting firm confirmed that the record breaking 2015 Memorial Day flood was worsened by the building of an apartment complex on the banks of the San Marcos River which directed waters into an older nearby residential area (DeLeon 2016). Due to safety concerns, the impact of the Memorial Day flood has rekindled the debate whether the San Marcos River floodplain should be developed (Walsh 2016).

With the population growing at such a fast rate in this region, it is essential to monitor the urban growth and maintain land development while supporting environmental sustainability. Urban growth modelling, such as Cellular Automata (CA) or Agent-Based Modelling (ABM), benefits both the community and the business sector by helping the local government make informed decisions for land development and stop overdevelopment in sensitive areas (Dahal and Chow 2014a). Several models have been presented focusing on land-use and sustainable urban growth (Li and Lui 2008, Burhan et al 2020, Lagarius 2012), but have not addressed using multifamily housing as a mechanism to enhance environmental sustainability. In this paper, multifamily housing will be used in scenarios as a land-use type to retain green space in San Marcos. Four scenarios will be evaluated using restrictions on different land-use types including industrial, commercial, single-family residential (SF), and multifamily residential (MF).

The purpose of this thesis is to investigate the impacts of various land-use zoning and restrictions through government regulations on environmental sustainability in San Marcos, TX. The Agent-Integrated Irregular Automata (AIIA) model used in Dahal and Chow (2014a) combines the spatial benefits of representing the urban landscape using irregular CA while representing urban dynamics with ABM agents. This project implements government agents with the social convention that conscience government land-use restrictions or zoning will enhance environmental sustainability by preserving green space. Specifically, AIIA will be used to model the impact of government regulations to examine the research question – how do growth restrictions and multifamily housing affect green space? In this context, green space is all of the undeveloped land including parks and recreational areas. The reliability of the urban growth simulation model is demonstrated by modelling historical data over twenty years (2000-2020) and calibrating the results to the actual 2020 map.

2. CHAPTER TWO

Literature Review

This study explored the impact of government restrictions in land-use zoning on environmental sustainability by conducting urban growth simulations in the city of San Marcos, TX. Previous computational growth models applied to other cities around the world have demonstrated that land-use restrictions could mitigate the destruction of ecologically sensitive areas that support environmental sustainability (Li and Liu, 2008, Burhan et al 2020, Al-Darwish et al 2018). These studies use various computational models and their methods and results are discussed herein.

However, these studies have not fully explored the impact of residential zoning in the light of environment sustainability (Li and Liu, 2008, Burhan et al 2020, Al-Darwish et al 2018). Multifamily housing provides a means to reduce the footprint of urban sprawl by contributing to a more compact growth scenario for developing cities. The literature presents some case studies of multifamily housing in Europe, and this review compares their findings against the multifamily housing in the US. In particular, a specific example of Austin, TX will be provided on how the footprint of multifamily housing creates a smaller land-use impact than single-family housing. These examples suggest that promoting multifamily housing could be an approach to improve urban growth models by decreasing the impact of residential land-use. This will improve environmental sustainability by reducing the footprint of urban growth to maintain green space in an urban growth model.

2.1 The Impact of Government Restrictions on Land-use on Environmental Sustainability

Li and Liu (2008) theorize that sustainable land-use should alleviate land-use problems such as the destruction of sensitive ecosystems which negatively impacts environmental sustainability. Li and Liu (2008) use ABM and CA computational modeling as a planning tool to optimize sustainable land-use strategies in Guangzhou, China, and its surroundings. In their work, sustainable land-use strategies are implemented through government agents with rules that prohibit land development in ecological sensitive areas. Human behaviors imposed on the model include developer agents who maximize profits and resident agents that are controlled by location and status (income and family size) factors. Four growth scenarios are completed including a scenario that has no restrictions on development to regulate existing development trends (Li and Liu 2008). The first scenario uses government intervention to control land consumption which produces more compact development. Scenarios two and three use government rules and restrictions to protect the development of farmland and green space. Scenario four eliminates government control on how much residential housing can be constructed satisfying all housing demands from resident agents (Li and Liu 2008).

The outcomes of the scenarios are reviewed with a statistical comparison that indicates the gain and loss of land development. These metrics include "compactness, development suitability gain, agricultural suitability loss, green-land loss, and farmland loss" (Li and Lui 2008). These metrics are combined into a normalized index shown in Figure 2. This analysis demonstrates that compact development and green space protection perform better for sustainable land development as compared to those without government intervention. The scenarios without government intervention, the baseline and scenario five, have the worst performance based on the combined index. These results indicate that there is a need for the government intervention of some land-use types for sustainable land-use. Future work could entail testing more agents, or restriction rules, for the region that include population density, transportation, and industrial restrictions.

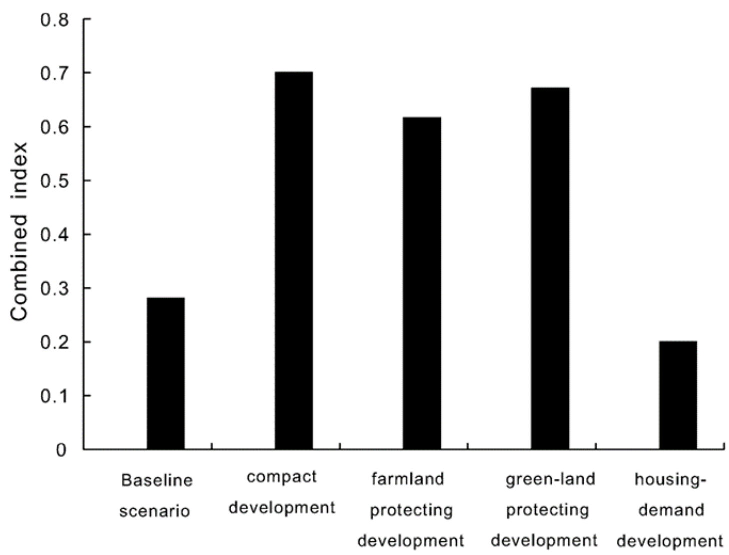


Figure 2. Final assessment of the simulated scenarios using a linear combination of five metrics. (Source: Li and Lui 2008)

Burhan et al. (2020), determined that if land-use is not restricted, urban growth will contribute to environmental problems and diminish environmental sustainability. This was done by generating urban growth models for the coastal city of Banda Aceh, Indonesia. The authors examine the effect on environmental sustainability by modeling urban growth on six different land-uses "water bodies, wetland, reserved area, bare land, settlement and road, and activity centers" (2020). CA is used to model the interactions of these land-use classifications in 2020, 2025, and then 2030. Growth factors incorporated into the model include defining an activity center as an employment rich area, transportation infrastructure, and proximity to current settlement. Two scenarios are simulated with the first scenario predicting the change in land-use based on current trends or no change in regulations. The second scenario incorporates zoning regulations on planned reserved areas which are based on the Spatial Planning scheme of Banda Aceh 2009-2029 and include Special Protection Areas (SPA) and Green Open Spaces (GOS) (2020). No statistical analysis was completed for land loss or gain as was done in Li and Liu (2008). Land changes are described with maps illustrating land-use with a color legend as shown in Figure 3 for scenario 1.

In these simulations, the urban classification (activity centers) developed into the wetlands and vegetation areas, impacting the environmental sustainability in Figure 3. The authors conclude that unrestricted growth will result in "environmental, economic, and social problems" (2020) with the greatest impact on non-urban areas such as wetlands. This will greatly affect the ecosystem services that are needed for a sustainable environment. The biggest contributor to land-use pattern change was the distance to activity centers. It is noted that the coast was considered a tsunami-prone area in the model and was very restricted from residential housing which would, according to the authors, decrease the land value making it less attractive for growth. However, the relationship between land price and residential location was not incorporated into the model, warranting future work to investigate its role to restrict urban growth into sensitive areas.

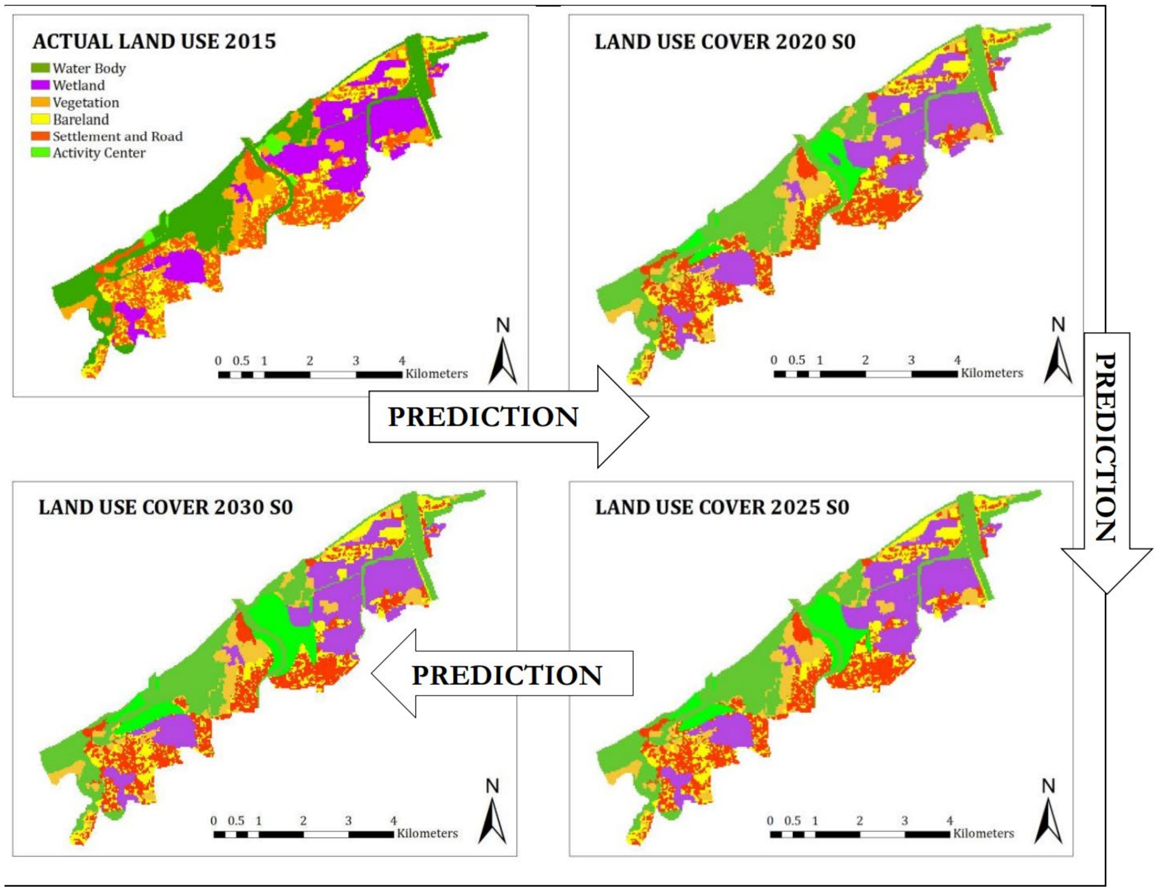


Figure 3. Example of CA simulations in Banda Aceh, Indonesia to measure land-use change from 2015 to 2030. (Source: Burhan et al. 2020)

Al-Darwish et al (2018) concluded that the rapid and uncontrolled urbanization effects on land-use will cause environmental and economic problems for the historic city of Ibb in Yemen. The authors use a CA and Fuzzy Urban Growth Hybrid model (CAFUGM) in the LanduseSim software to weigh the growth factors in the simulation. Four types of land-uses are defined in the model; urban areas, non-urban areas (agriculture and landscape), slopes, and reserved areas. The social-economic factors affecting urban growth, including roads, existing settlements, population density, city center, commercial centers and urban areas, are quantified as Euclidean Distance maps (ED) for input into the model. The model is validated by running a simulation for 2013 based on 2003 data and comparing the results using the Multi Resolution Validation (MRV) method which compares the modelled and actual data. The land changes are illustrated with land-use maps with predicted growth from 2023 to 2033 as seen in Figure 4 below.

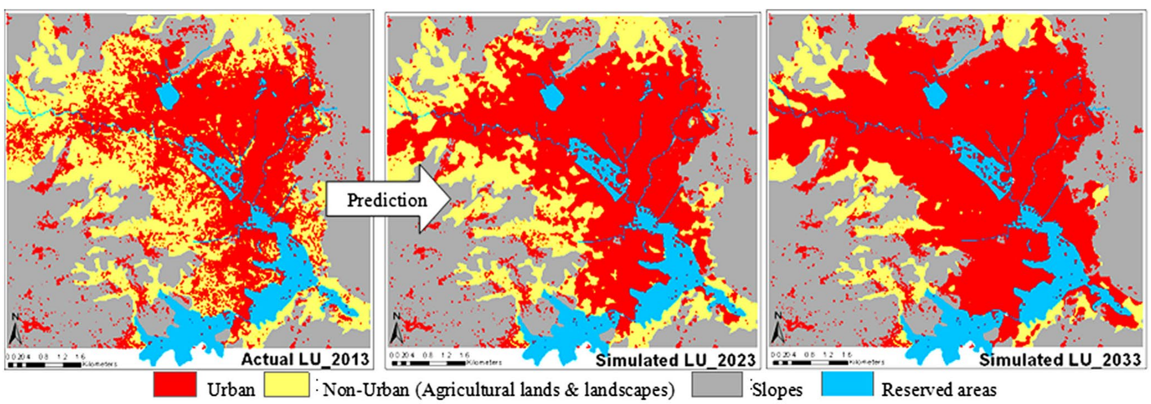


Figure 4. Example of CA simulations in Ibb city, Yemen to measure land-use change from 2023-2033. (Source: Al-Darwish et al. 2018)

The simulation results demonstrate that non-urban land declines dramatically from 24.53% in 2013 to 18.21% in 2023 and to 9.54% in 2033. The greatest impact on the growth model is the location of settlements and secondary roads providing access to far-reaching sprawl. The authors conclude that Ibb city will see rapid random urbanization consume mainly non-urban lands including agriculture lands, landscapes, and tourist sites that are important to the city. They recommend that decision-makers consider strategies for future expansion to include more vertical growth in place of horizontal growth to ensure an ecological balance.

All of the urban growth models predicted that scenarios without restricted land-use always impede on the ecological areas that support environmental sustainability (Li and Liu, 2008, Burhan et al 2020, Al-Darwish et al 2018). By using scenario-based simulation to compare unrestricted land-use against restricted land-use, the former scenarios always have the worst performance based on their impacts to open space and/or environmentally sensitive areas.

However, the mitigation or elimination of the negative impact to environmentally sensitive areas using different types of residential land-use, such as multifamily housing vs single-family housing, has not been fully modeled. The Li and Liu (2008) model includes developer agents who maximize profits and resident agents that are controlled by location and status (income and family size) factors without any preference of multifamily housing or single-family housing. The scenarios restrict urban growth into selected areas but do not control multifamily or single-family residences separately. Burnham et al. (2020) do not use residential housing as a model input, and the relationship of different types of residential land-use was not incorporated into the model. Similarly, Al-Darwish et al. (2018) do not use different types of housing as factors in their urban growth model but focus on roads, existing settlements, population density, city center, commercial centers, and urban areas.

2.2 The Role of Multifamily Housing on Environmental Sustainability

Since urban growth is driven by population, residential housing is a key contributor to the growth of a city. The planning of residential housing within urban areas is an inherent part of land development that can affect environmental sustainability. Exceptional population growth and the demand for multifamily housing has changed the type of housing land-use in cities around the world (Torkington 2021, Charles 2019). As seen in Figure 5, Europe has been increasing its multifamily housing with significant investments since 2009. Additionally, investments into multifamily housing made

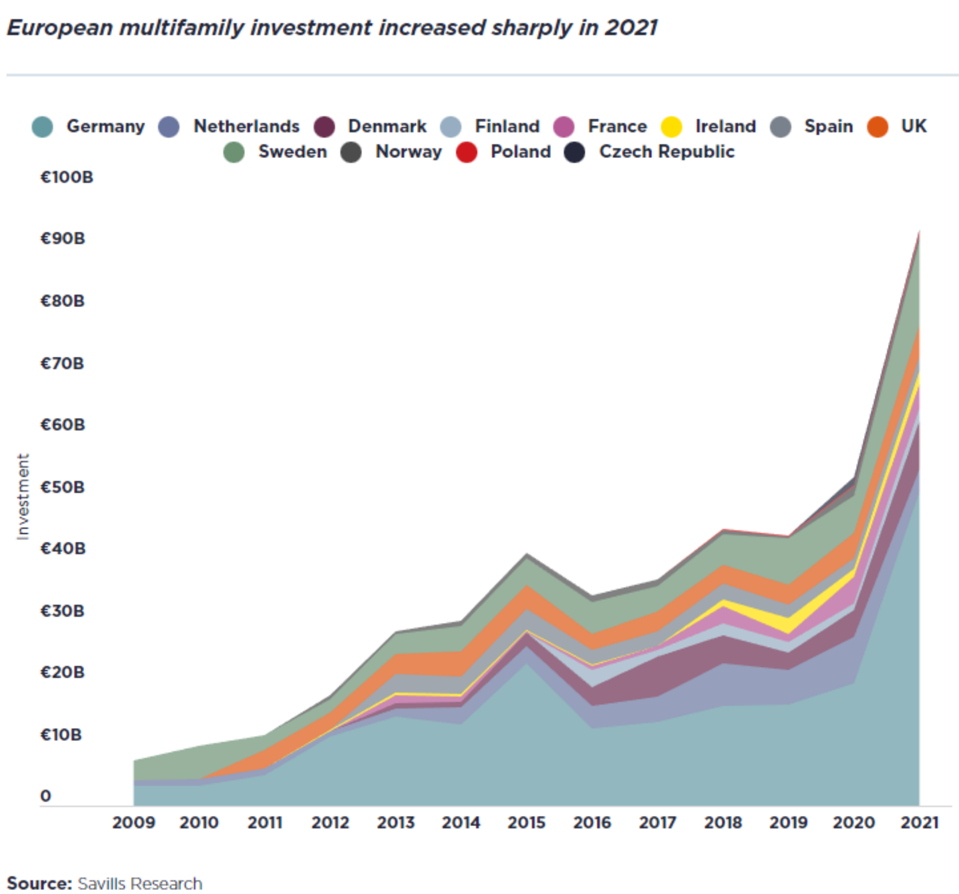


Figure 5. Increasing MF housing investments (Source: Mitsostergiou 2022)

up 28% of total assets in Europe and is expected to continue to rise (Mitsostergiou 2022). This increase has been influenced by the mass migration of people into cities all over Europe and the demand for multifamily housing. In 2019, Europe had 46.1% of its population living in flats, and another 18.5% lived in semi-detached or terrace housing (Torkington 2021). This means that 64.4% of the European population was living in some kind of multifamily housing in 2019. Compared to single-family homes, multifamily housing uses less land leading to a more 'compact' urban landscape. The smaller footprint from multifamily housing benefits the environment because it "helps to preserve open space and undeveloped land, natural amenities that can be difficult to preserve in sprawling areas" (NMHC 2019).

In contrast, the NMHC reported that only 15% of housing in the US was classified as multifamily housing even though there are multiple benefits to this type of housing including increased environmental sustainability (2019). Enhancement to environmental sustainability includes reduced carbon emissions in all phases of multifamily development, less resources used for infrastructure, and the preservation of open spaces by employing compact growth with a smaller footprint (2019). According to the NMHC, the amount of open space and undeveloped land that compact growth can save is 20-45% less than "unplanned, sprawling, 'overspill' development" (2019). The contrast in land consumption from single-family housing over multifamily housing can be demonstrated with an example from Austin TX.

The City of Austin, located in the fast growing I-35 corridor of Texas, has taken a proactive stance towards environmental sustainability within a master plan developed in

2012 referred to as Imagine Austin (2018). Imagine Austin attempts to promote a "compact and connected city" with development directed away from the sensitive environmental areas, protecting existing open spaces and natural resources. This plan is partially the result of tremendous increase in the developed land in the Austin area that went from 53% to 64% from 2003 to 2010. Most of this increase can be attributed to single-family zoning resulting in the loss of natural and open space to urban sprawl (2018).

In 2010, single-family housing comprised 46% (Imagine Austin 2018) of total housing and it occupied 17% of the total land area in Austin (Table 1). On the other hand, 54% of housing in 2010 was comprised of multifamily housing and mobile homes but they only covered 5% of the total land. Even though the percent change in acres used for multifamily housing was greater than single-family housing, the total amount of land was smaller. Multifamily housing creates a smaller footprint on the environment because the land-use is much smaller than the equivalent amount of population in single-family housing. With a smaller footprint, multifamily housing provides a method for a more 'compact' and "sustainable environment' for the city of Austin.

Use	Acres in 2003	Acres in 2010	Percent Change	Percentage of Total Land Area in 2003	Percentage of Total Land Area in 2010
Single-Family	61,703	69,011	12 %	15 %	17 %
Multi-Family	9,013	10,777	20 %	2 %	3 %
Mobile Homes	6,478	7,000	8 %	2 %	2 %
Residential Subtotal	**77,194**	**86,788**	**12 %**	**19 %**	**22 %**

Table 1. Housing Land-Use in Austin from 2003-2010. (Source: Imagine Austin 2018)

One of the reasons-why multifamily housing is not as prevalent in the US as in Europe is because of the misconception that multifamily housing negatively impacts several community interests including schools and real estate values. This has resulted in reduced economic growth because of housing constraints and regulations (NHMC 2019). The NHMC report points out that these misconceptions have been proven wrong and are in fact the complete opposite of these assumptions. Pollakowski et al (2005), found that "large scale, high density mixed income rental developments" in suburban Boston communities do not decrease the surrounding real estate value. Cecchini (2016) reviews several case studies that demonstrate negligible or positive effects on real estate from "dense development". Additionally, the NMHC maintains that multifamily housing does not put undue strain on local public schools because the residents typically have fewer children than single-family homes. This is based on the National Association of Home Builders report (Ford 2017) comparing the number of children in single-family homes to those in apartment units. Based on these facts, multifamily housing can mitigate the impact of urban growth on the environment without negative impacts on economic growth.

Gabbe (2108) confirms that the misconceptions associated with upzoning, or land use changes that allow higher density development such as multifamily housing, which has led to only 1.1 percent of the Las Angelos's land being upzoned from 2002-2014. The author concludes that upzoning is most likely to occur where development opportunity is combined with little political resistance - specifically homeowner resistance to upzoning in desirable neighborhoods. This is due to misconceptions that MF housing negatively impacts neighborhoods and community interests.

2.3 Urban Growth Boundaries

Urban growth boundaries (UGB) have been used by state and local governments to direct the location and intensity of development. This type of restriction on urban growth has been examined in China (Kun et al, 2019), Bangladesh (Bajracharya 2022), and Portland, Oregon (Kim 2014). In Dahal and Chow (2014a), a UGB was used to encourage compact development allowing growth to only occur within the UGB. In this paper, a similar UGB was used to restrict growth to be contained inside the UGB restricting urban development. However, in reality, UGB's do not always have the intended effect of containing development inside the UGB planned locations. In fact, it may cause development to increase outside of the UGB because the immediate response to growth management policies can sometimes be the increased demand for this land before the policy becomes effective.

In Hepinstall-Cymerman et al. (2013), the effects of using UGB's are examined in the Central Puget Sound, Washington, USA. A Growth Management Plan for the Central Puget Sound area was implemented by the Central Puget Sound Regional Council using UGB's to preserve ecologically sensitive areas. In this paper, the authors document land cover and change across six dates (1986, 1991, 1995, 1999, 2002, and 2007) for six counties. Urban growth boundaries designated as a part of a Growth Management Act (GMA) were examined using annualized area and percentage changes. The authors were specifically interested in how land cover patterns changed over time and space and if there were any patterns that were caused by the implementation of the UGB's. The authors used 14-class land cover data for 1986, 1991, 1995, 1999, 2002, and 2007 developed from the Landsat Thematic Mapper™ and Enhanced TM (ETM+) imagery.

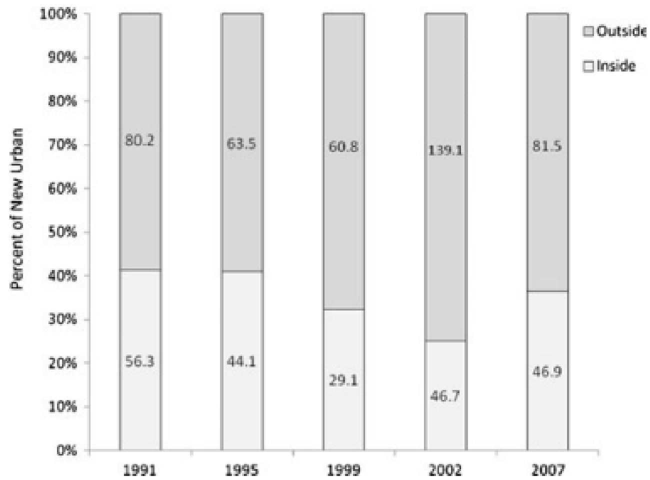


Figure 6. New urban land cover inside or outside of the 2002 UGB by year. Numbers in the bars indicate the annualized area (km^2) (Source: Hepinstall-Cymerman et al. 2011

If the UGB worked, greater urban development by area and percentage within any time period should occur inside the boundaries. However, across all dates, the amount of new urban land that fell outside of the UGB was larger than land that fell inside the UGB (Figure 6). Thus, the GMA was not effective and the intended effect of using UGB's to direct development was not accomplished. A plausible explanation is that the immediate response to the growth management policy may have been to increase the demand for land before the plan to eliminate these areas was enforced. Land consumption was highest outside of the UGB during the time period after the GMA was passed but before it was implemented (1999-2002). Then, after the GMA was implemented, there was a decrease of land consumption outside the UGB (2002-2007) (Hepinstall-Cymerman et al 2013).

2.4 Summary Statement

This review shows that land-use can impact the environmental sustainability of a region and regulated land-use is necessary to mitigate environmental problems. Urban growth models demonstrate that unrestricted urban growth will impact ecological areas that are necessary for the ecosystem services that provide a sustainable environment (NMHC). However, the utilization of separating residential housing into single-family and multifamily land-use has not been fully examined in urban growth models. The premise is that regulating multifamily housing to manage residential growth will provide a smaller urban footprint favoring the survival of green/open spaces. The European market has already embraced multifamily housing reducing the urban footprint on the environment with 2/3 of the population already living in multifamily units. In the US, the NMHC recognizes the benefits of multifamily housing, but must overcome the misconceptions that are associated with it. The impact of single-family housing creating a much larger footprint on developed land is demonstrated in Austin, and is being addressed in the city's Imagine Austin Comprehensive Plan. These examples point to multifamily housing being a method to regulate urban growth and improve environmental sustainability by reducing the impact of urban sprawl on land-use.

In this thesis, the role of restricted residential housing land-use will be investigated in light of environmental sustainability. The research question that this research proposes to answer is if multifamily housing and growth restrictions through government regulation can provide enhanced environmental sustainability for the City of San Marcos. Different land-use categories will be defined such as multifamily (MF) and single-family (SF) housing, as well as green spaces, industrial, and commercial areas. In this investigation, green space is all of the undeveloped land including parks and recreational areas. Specifically, the impact of emphasizing multifamily housing over single-family housing in the residential portion of the urban growth model will be examined. This is based on the social theory that multifamily housing delivers a more sustainable environment by preserving green spaces (NMHC 2019, National Wildlife Federation 2022, Li and Liu 2008).

As seen in the literature review, the NMHC reported that multifamily housing provides multiple benefits to the enhancement of environmental sustainability including the preservation of green spaces by designing compact growth with a smaller footprint (NMHC 2019). The smaller footprint of urban sprawl keeps the ecosystems around cities intact providing a more sustainable environment (National Wildlife Federation 2022). Previous growth models have demonstrated that land-use restriction could mitigate the destruction of areas that support environmental sustainability (Li and Liu, 2008, Burhan et al 2020, Al-Darwish et al 2018). Li and Liu (2008) demonstrated that unrestricted residential housing will produce undesirable effects on green space, but do not specifically examine scenarios regulating single-family and multifamily housing land-use. This thesis will test if highlighting multifamily housing in the growth model provides better results for maintaining or increasing environmental sustainability by preserving green spaces.

3. CHAPTER THREE

Methodology

3.1 Study Area, Data, and Software

The study area for this thesis is the city of San Marcos, TX situated in the middle of the I-35 corridor between Austin and San Antonio in Central Texas (Figure 6). This corridor has experienced tremendous population growth over the 2010-2020 decade and the prediction is that growth will continue at the rate of 18-30% over the next decade. San Marcos has been transformed from this growth with the population increasing by over

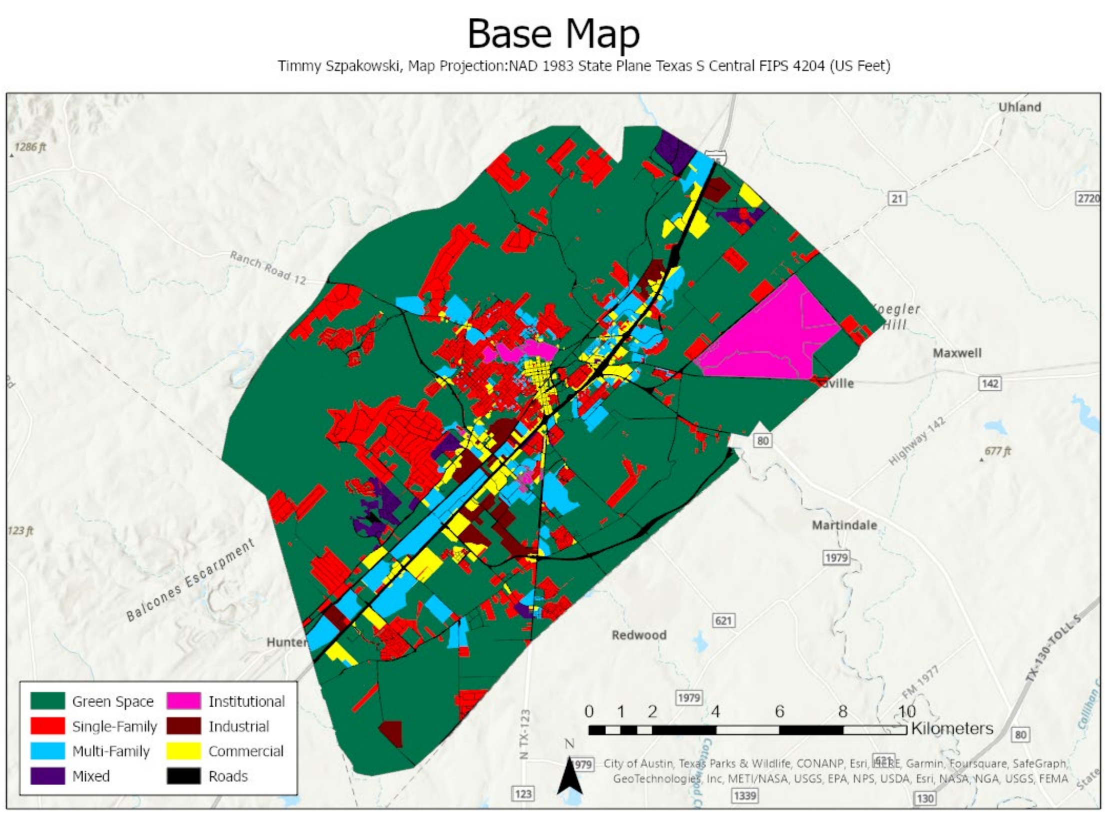


Figure 7. Zoning for the City of San Marcos and the study area.

50% and current growth at 1.9% annually (US Census 2022). This exceptional growth is partially due to the city's location mid-way between San Antonio and Austin, the seventh and eleventh largest cities in the US respectively. As a mid-size city in a rapidly developing economic corridor, San Marco is ideal to simulate micro-level geographic objects using land-use parcels to investigate the proposed relationship of urban growth dynamics. As can be seen in Figure 6, the zoning map for the city of San Marcos includes green space, single-family, multifamily, mixed, institutional, industrial, commercial and roads. Almost all commercial zoning is adjacent to I-35 as is most of the industrial zoning allowing for easy access to and from theses business entities. Institutional, single-family, and multifamily have sections near I-35 but also spread away from this corridor offering sought-after quieter havens for residential areas.

Demographic and geographic data are the two major data sets that are necessary to complete this project. Population and growth rate data was collected from the US Census Bureau for the years 2000, 2010, and 2020. Historical land development data came from K.R. Dahal (personal communication, 2022) for the year 2000. The current geographic data for the study area was obtained from the City of San Marcos which was updated in 2020. This includes city boundaries, zoning codes, parks, Federal Emergency Management Agency (FEMA) floodplain maps, roads, and elevation maps. ArcGIS Pro will be utilized to prepare, analyze and visualize the data. The AIIA program from Dahal and Chow (2014a) will be used and modified to introduce the government agent rules and regulations necessary to test the theory of maintaining environmental sustainability with various land-use scenarios.

3.2 Conceptual Framework

Cellular Automata (CA) is a computational modelling technique frequently used to simulate urban growth processes and expansion. CA models are spatially-explicit so that they can utilize spatial datasets and represent spatial processes directly to simulate a dynamic process and manifest some spatial form of urban growth (Lagarius 2011). In general, CA models consist of 2D cells that can be of any size. In the context of simulating urban growth in a city, each cell represents some type of land-use or urban development. Each cell has a “neighborhood” which includes a focal cell and its surrounding neighbor cells. An initial state is assigned to each cell at the beginning of the simulation, and with each iteration of the simulation, a new “generation” is calculated from a fixed rule and/or mathematical function. Cells are usually updated with the same fixed rule or function, and the resulting next “generation” is a result of the individual cell and its surrounding neighbor cells (Lagarius 2011).

On the other hand, Agent-Based Modelling (ABM) is a method that uses the actions and interactions of “actors,” such as developers, builders, contractors, and real estate agents, to impact and modify the system that is being modelled (Dahal and Chow 2014a). These actors are implemented as “agents” in ABM that can interact with each other and are influenced by the geographic elements of the model, including government, commercial, industrial, environmental, and institutional elements. The agents behave according to a set of rules and are influenced by other agents that are included in the model, and the model results are updated in each iteration. These actions and interactions provide a mechanism that effectively models land-use dynamics by allowing the agents to freely interact with the modelled space as governed by the established rules (Dahal and Chow 2014a).

In a combined model, Agent-Integrated Irregular Automata (AIIA), CA represents the spatial neighborhood and allows diffusion of changes across the 2D grid of cells, while ABM allows socioeconomic factors to be applied across the model with land-use agents (Dahal and Chow 2014a). Specifically, CA will be used to represent the real-world land-use and regulate the spatial influences across the model. ABM will be used to set up the structure of the model using agents to model the socioeconomic factors that impact land-use dynamics such as zoning policies.

In this thesis, land-use scenarios will be evaluated using ABM to regulate land-use zoning with a government agent and model the actions and interactions of land developer agents and consumer agents. Figure 7 illustrates the flow diagram of the AIIA program conceptual framework and the interactions between the agents in this analysis. First, the model must determine the demand for each type of land-use. This is done using a demand estimation based on existing population change from census data. Next, the government agent will be the force to control the demand and implement the development scenarios. The government agent will also manage and specify which areas will be available for future development. Completing the instructions given by the government agent will lead to a utility function which will calculate a suitability score for land parcels in each iteration. The other agents will be processed after the utility function has administered the demand from the government agent, and the utility function will portion out each agent's number of available suitable parcels. Once the land has been

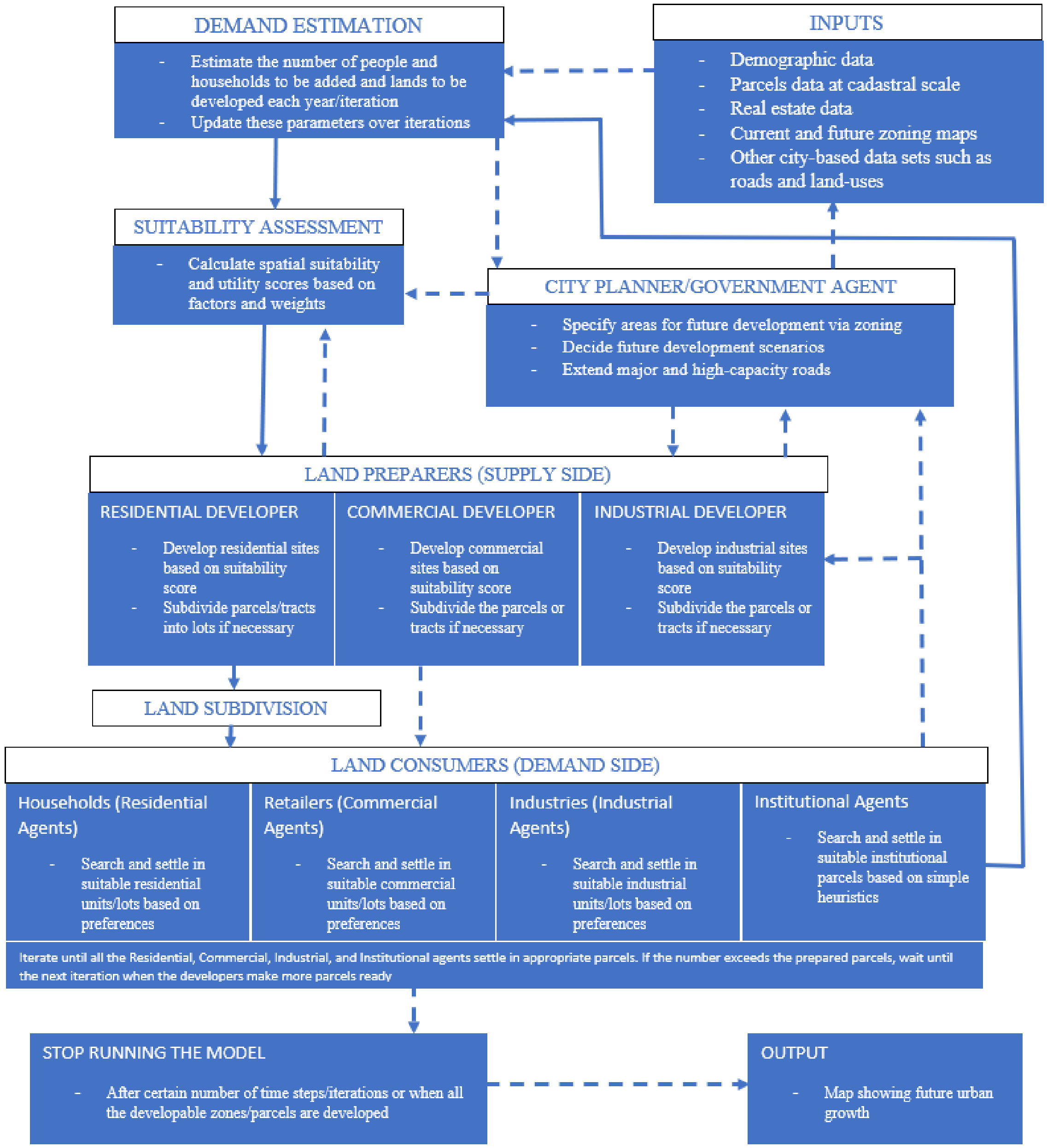


Figure 8. Sequential components of the conceptual framework of AIIA and interactions among agents.

portioned out to each agent, the agents will check the preference of the parcels and confirm the suitability of the land. Then the actual development stage will proceed, meaning that the suitable parcels for each agent will be able to be developed within the time allotted, and this will repeat after each iteration.

3.3 Agents

3.3.1 Government Agent

The government agent will be the entity that provides the rules and restrictions necessary to test the various land-use scenarios impact on environmental sustainability. The government agent will control the scenarios for future development by having rules in place to restrict the amount and type of land that can be developed. This will be done with the government agent introducing a base map land-use map that indicates where residential, commercial, industrial, and institutional development can expand. This base land-use map, which is based on the City of San Marcos current zoning districts, will be the same for all scenarios and provide the initial parcels of land that the land preparer and consumer agents can use for future growth. Seven zoning classes or land-uses will be used: green space, single-family, multifamily, mixed, institutional, industrial, commercial. Roads will be built by the government agent to access new additions to the land-use categories.

Additional rules will be supplied by the government agent to restrict how some land-use may be developed to determine if these restrictions encourage environmental sustainability. The government agent will decide a stratified random sampling of the land parcels for the land developers to portion out and build up the lands. The government agent will also decide whether or not an urban growth boundary (UGB) will be in place for each scenario. This UGB will determine where development can take place and will be a fixed boundary. One of the social theories applied will be the emphasis of multi-family housing to decrease the residential footprint of single-family development in order to improve environmental sustainability. This will be done through the government agent by using rules to make MF housing a higher priority when formulating zoning plans and allocating available parcels into land-uses.

3.3.2 The Land Developers and Consumer Agents

In this model, there will be residential, commercial, industrial, and institutional agents that reflect the criteria that is important in locating these land-uses. The methodology for this project will be to use the current land-use map to derive the weights of these agents. This will be done using a logistic regression that examines the relationship with existing land-use and census household characteristics to derive the preference for how the parcels will be developed (Dahal and Chow, 2014a). In this study, the preferences for urban development are determined from factors based on environment, market, transportation accessibility, centrality influence, and development influence (Appendix). These factors are weighted based on their significance in the logistic regression assessment from the Census 2020 data. The results from the logistic regression are shown in Table 2.

The utility function that was used in Dahal and Chow (2014a), which was referenced in Brown et. al (2008), will be used to apply these weights to the different agents being used in the simulations. The agents will engage in an iterative process to identify suitable land parcels for urban development following different scenarios of land-use planning and how they affect environmental sustainability within San Marcos, TX with the following rules.

Factors or Independent Variables		SF	MF	Comm	Industrial	Low w/ Children	High w/Children	Low w/o Children	High w/o Children
Environmental	Elevation	1.8	0	-3	0	0	1.3	-0.9	1.1
	Slope	-1.2	0	-7.8	-7.7	0	-1.1	1	-1.1
	Distance to River	-8.12	-0.01	-0.01	-0.01	6.1	7.95	0.01	0.01
Market	Population Density	-6688.69	-3584.11	7535.48	7686.96	10108.33	10225.91	9894.95	10209.8
	Land Value	0.09	-0.06	-0.41	-0.11	-0.05	-0.06	-0.06	-0.05
Transportation accessibility	Distance to IH-35	-7.56	0	0.01	-0.01	0.01	0.01	0.01	0.01
	Distance to Railroads	0.01	0	-0.01	0.01	-0.01	-0.01	-0.01	-0.01
	Distance to Major Roads	0	0.01	0.01	0.01	0	-0.01	0	0
	Distance to Airport	-6.59	6.01	9.86	0.01	5.18	0.01	5.97	2.05
Centrality Influence	Distance to TSU	0.01	0.01	-0.01	0	-0.01	-0.01	-0.01	-0.01
	Distance to Hospital	0.01	0.01	-0.01	0	-0.01	-8.74	-9.37	-9.75
	Distance to San Marcos Mall	-4.69	-0.01	0.01	-0.01	3.13	3.83	4.23	0.01
	Distance to CBD	-0.01	0	0.01	0.01	0.01	0.01	0.01	0.01
Development Influence	Residential Neighborhood	8.89	-4	-10.7	-15.6	2.2	3	1.3	2
	Commercial Neighborhood	-5.5	-5.6	17.3	-14.1	-6.7	-10.8	-5.5	-7.8
	Industrial Neighborhood	-6	0	-4.4	13.1	0	0	0	0

Table 2. Results of Logistic Regression. These are weights used to determine the suitability of a land parcel.

The first phase in the model is to regulate the demand for different land-uses to be developed at time $t + 1$. This is done by first establishing the net population growth by determining the annual growth rate, average household size, and the total population at time t. Established by Dahal and Chow (2014a), using these user-specified values, the number of new households coming into the city for each time step is calculated as shown in equation 1.

$$HH_{t+1} = (P_t * G/100)/AH \quad (1)$$

In equation 1, HH_{t+1} is the number of new households at time $t + 1$, P_t is the population at time t, G is the annual growth rate in %, and AH is the average household size. For this thesis, the base year (i.e. 2020) values of G, AH, and Pt for the study area were 1.9%, 2.44 and 68,580, respectively (US Census 2020). Next, for each time step, the total area required for development in residential, commercial, and industrial land-use zones is calculated from the ratios of developed lands in each category for time *t*.

The utility function, or suitability assessment, that was applied in Dahal and Chow (2014a) was introduced in Wu (1998) and Barredo et al. (2003) and will be used to evaluate the suitability of a land parcel for development based on a list of environmental criteria. In this utility function (2), S_i is the suitability score of parcel *i*, F_i is the value of an environmental factor *F* for parcel $_i$, W_i is the weight of factor *F*, *n* is the number of factors included from the linear regression, and finally $\mathcal{E}$ which is a stochastic term. In Dahal and Chow (2014a), *n* was 16 representing the number factors from Tables 2 & 3. The utility function, or composite suitability score is computed with different preferences (weights) from the logistic regression.

$$S_i = \Sigma^n{}_i \, (w_i * F_i) + \mathcal{E} \qquad (2)$$

The model used in this thesis has four types of land developer agents: single-family (SF) residential, multifamily (MF) residential, commercial and industrial. The purpose of the land developer is to subdivide undeveloped land parcels before turning the parcel to the ‘prepared’ state. Land Parcels are undeveloped land areas, and Land Lots are prepared land areas. Lots are therefore undividable and have either ‘prepared’ or ‘developed’ states. The land developer has the goal to maximize profit, so the most profitable parcels will have a higher suitability score. The previous 16 factors used in the logistic regression (Dahal and Chow 2014a) are the independent variables and the development status is the dependent variable. Based on Dahal and Chow (2014a), the amount of land required to accommodate the incoming households for each iteration in the SF and MF residential developers is computed. SF residential area is calculated as shown below in equation 3:

$$SFRA_{t+1} = SFHH_{t+1}{}^{*}ALS \qquad (3)$$

where $SFRA_{t+1}$ is the total SF residential area to be developed at time $t + 1$, $SFHH_{t+1}$ is the number of incoming SF households at time $t + 1$, and *ALS* (average lot size) is a user-defined value. $SFHH_{t+1}$ is derived by multiplying HH_{t+1} (Equation (1)) by SFr_t, which is a ratio (percentage) of SF residential units to the total household units at time *t*. Similarly, MF residential area is calculated as (4):

$$MFRA_{t+1} = MFHH_{t+1}{}^{*}AMFUS \qquad (4)$$

where MFRA_{t+1} is the total MF residential area to be developed at time t + 1, MFHH_{t+1} is the number of incoming MF households at time $t + 1$. AMFUS (average MF unit size) is defined by the user. $MFHH_{t+1}$ is the product of HH_{t+1} and MFr_t, where MFr_t is the ratio (percentage) of MF residential units to the total household units at time t. MFr_t is computed by subtracting SFr_t from 1 (or 100%). If the incoming households exceed the number of prepared lots, then undeveloped parcels in the residential zones, with the highest suitability score, will be used in a descending order. This iterates until there are enough selected parcels to exceed the required land area.

The commercial and industrial developer equations are similar to the MF residential equation. The commercial land equation demonstrates the amount of land to be developed at time *t*+1 is shown below in equation 5:

$$CA_{t+1} = TRA_{t+1}{}^{*}CR_t \qquad (5)$$

where CA_{t+1} is the commercial area to be developed at time $t + 1$. TRA_{t+1} is the residential area that will be developed at time $t + 1$ (i.e. computed by adding $MFRA_{t+1}$ and $SFRA_{t+1}$ from the equations 3 and 4). CR_t is the ratio of developed commercial area to the developed residential area at time t. Undeveloped parcels within the commercial zone with top suitability scores will be selected for development until the total area reaches the amount determine in the model. Commercial land development only occurs in areas zoned as commercial.

The industrial developer equation is the same as the commercial developer equation, but within the program, the term "commercial" will be replaced with "industrial" and given a lower priority. Industrial land development is only selected from land parcels zoned as industrial.

Households are the basic residential unit where SF housing is occupied only by a single household and MF housing has more than one household. With each time iteration, the number of new households is given by Equation (1) and are put into the model based on preferences. Once a lot has been selected for a household, the lot changes from 'prepared' to 'developed'. Comparable to Li and Liu (2008) and Dahal and Chow (2014a), the only attributes assigned to a household is income and household size. The annual median income of $35,000 will be used based on the 2020 US Census. Income above the median is considered High Income and below the median is considered Low Income. When combined with the number of children under the age of 18 in the household, four categories for households are assembled: low income with children

(LC), high income with children (HC), low income no children (LNC), and high income no children (HNC).

The number of incoming households for each iteration is based on the population proportions of the 2020 US Census data. In 2020, the proportions of these categories were, 9%, 8.69%, 41.31%, and 41% for LC, HC, LNC, and HNC respectively (Point2Homes 2020, BestPlaces 2020). With each iteration, household agents for each category move into the model and searches through the 'prepared' lots. Once the utility function is maximized for the agent, the lot changes from 'prepared' to 'developed' and taken out of the available inventory. Once a lot is 'developed', it will remain developed till the simulation ends. If there are more household agents than 'prepared' lots, then the agents wait for the next iteration. The results of the iteration are sent to the housing developer so that there will be additional lots in the next repetition. There are never any changes to the attributes of household income and number of children throughout the simulation. This is a limitation of the program, but would be impossible to calculate because it would be difficult to predict and probably not random.

Household agents assign different weights to different factors because the agents do not have the same preferences. The housing agents will maximize the utility function that is from Brown et al (2008) as shown in equation 6.

$$u_{(i,k)} = \Pi(\gamma_{(i,f)})^{\alpha(k,f)} + \partial_i, \qquad (6)$$

where $u_{(i,k)}$ is the utility of polygon i for resident type k, $\gamma_{(i,f)}$ is the value of factor f for polygon i, $\alpha_{(k,f)}$ is the weight resident k places on factor f, n is the number of factors evaluated, and ∂_i is created by a random number generator to provide for uncertainty in the decision-making made by the individual agents. As explained earlier, logistic regression was used to derive the weights.

Commercial agents are limited in that there can only be one commercial entity on each lot. This is a limitation of the model because in reality there can be more than one commercial entity on a lot. The number of incoming commercial agents for each iteration is calculated with equation 7 shown below:

$$CUT_{t+1} = HHT_{t+1} * RCUT_t + WCUT_t, \qquad (7)$$

where CUT_{t+1} is the number of new commercial units entering the landscape at $t + 1$, HHT_{t+1} is the total number of incoming households, $RCUT_t$ is the ratio of commercial units to residential units at time t. $RCUT_t$ is computed by dividing the number of commercial units by total number of residential units at time t. $WCUT_t$ are the waiting commercial units at time t.

The commercial agents enter the model to searching for 'prepared' lots that match their preferences anywhere within the commercial zone. In the AIIA model, the preference of commercial agents is the same as the suitability score assigned by commercial developer. Similar to the household agents, lots with the highest suitability score are chosen by the agents in descending order. Once the agent has selected a 'prepared' lot, the lot changes from 'prepared' to developed'. Also similar to the household agents, if there are more household agents than 'prepared' lots, then the agents wait for the next iteration. This information is sent to the commercial developer so that there will be additional lots in the next repetition. The model computes the number of incoming industrial and institutional agents the same way as the commercial and household agents. This is done by replacing commercial with industrial or institutional in Equation 7. If the number of agents is larger than the number of available lots, the model handles the process in the same as the commercial agent.

3.4 Calibration, Scenarios, and Evaluation Methods

3.4.1 Calibration

How successful the scenarios were at enhancing environmental sustainability was measured by how much green space was maintained in the final urban growth maps. The first step in this process was to analyze if the simulation was producing an accurate growth model by calibrating the resulting map from a twenty-year simulation, 2000-2020, with an actual 2020 map of San Marcos, TX. Initially, it was thought that gathering historical imagery data for multiple dates could be checked for calibration in ERDAS. However, available imagery for San Marcos, TX did not define the area into land-use categories. In developed areas, only a designation of developed was given, no separation into SF, MF, etc. This negated the calibration in ERDAS as originally proposed.

Instead, using the 2000 data for the study area provided by Dahal (email correspondence, June 2022), a simulation was run over 20 years and compared to the actual 2020 land-use map. A thorough comparison of the results was completed and the simulation appeared to be reasonably accurate when comparing the amount of developed and undeveloped parcels (Figure 8). Developed parcels were not always in the same location as the actual 2020 map, but the amount of developed area was approximately the same.

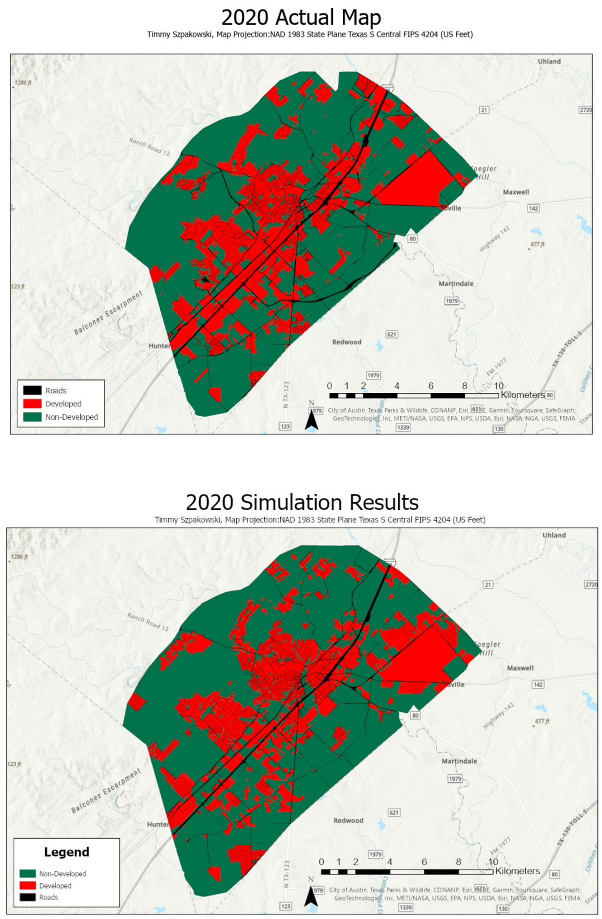


Figure 9. City of San Marcos 2020 from actual data compared to City of San Marcos 2020 from simulation

A numeric comparison of the actual 2020 map to the resulting simulation is given in Table 3 shown below. As can be seen, the percentage difference in developed acreage between the actual data and the simulation is close to zero when rounded to a whole number. This means that the total developed acreage is being accurately predicted in the AIIA model. The percentage difference in undeveloped acreage, or green space, is minimal at 2% which is significantly smaller than the predicted changes in undeveloped acreage in the modelled scenarios. However, it could mean that there might be a minor increase in green space predicted in the scenarios than might actually occur in reality. Since the purpose of this paper is to compare the scenario results to each other, and a minor increase might occur in all of the scenarios, these comparisons should still provide realistic informative results.

Table 3. Numeric comparison of the City of San Marcos 2020 actual data to City of San Marcos 2020 data from simulation

3.4.2 Scenarios

As previously stated in the discussion of the government agent, the base land-use map was the same for all scenarios. Since one of the purposes of this project was to evaluate if promoting MF housing can provide a method to maintain green spaces, MF housing parcels were increased. The base land-use map has 15% more MF housing than the 2020 San Marcos actual map to reflect current status (Ray, 2023). The new housing was located along I-35 and Hwy 80 (Figure 9).

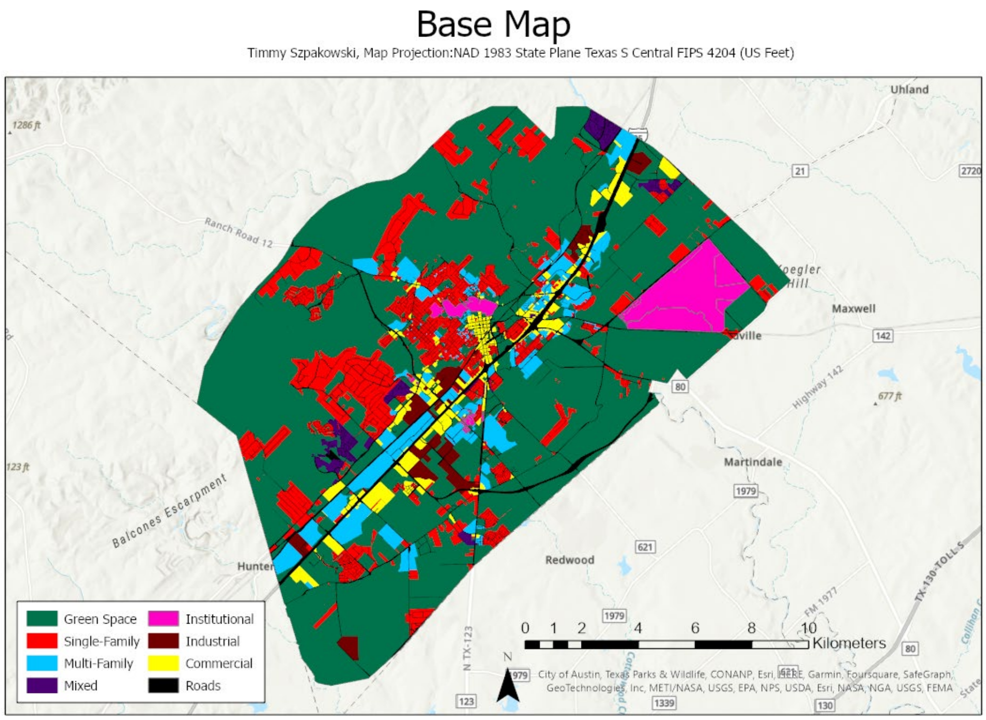


Figure 10. Base Map with 15% increase in MF housing.

In this study, the scenarios tested do not have government restrictions on developing green space or ecologically sensitive areas. It was shown in the literature review that restrictions on developing green space was indeed a method that worked on retaining these land-use areas. In this study, government regulations addressing MF and SF land-uses are tested to determine if changes to residential housing regulations could effectively reduce the impact on developing green spaces.

The first scenario, Unrestricted Growth (no UGB), was completed by continuing the growth pattern that was used in the simulation of the 2000-2020 historical data. No UGB was used to restrict the urban sprawl within the urban growth model. This scenario was completed to demonstrate urban growth if the pattern of development continued without restrictions.

The second scenario, Compact Growth (with UGB), was completed with the same growth pattern as the first scenario, but was restricted with a UGB. Urban growth boundaries have been used to encourage compact development, and this type of restriction on urban growth has been examined in China (Kun et al, 2019), Bangladesh (Bajracharya 2022), and Portland, Oregon (Kim 2014). In Dahal and Chow (2014a), a UGB was used to encourage compact development allowing growth to only occur "within a distance of 1 mile from IH 35 on both sides and a radius of 2 miles centering on the Texas State University main campus".

In this study, the UGB was set for the first 10-years of growth at 1.5 miles from IH 35 on both sides and a radius of 3 miles centering on the Texas State University main campus. For the next 10 years, to reach 20 years of growth, the UGB was set at 2.0 miles from IH 35 on both sides with a radius of 4 miles centering on the Texas State University main campus Figure 10. This is based on the results from Dahal and Chow (2014a) where more than 90% of the newly developed area in the simulations fell within the distance of 300 meters. It was anticipated that expanding the boundary to the stated parameters would allow for 100% of the development to complete. This UGB was not used to specifically keep urban growth from spilling into green spaces or environmentally sensitive areas. It was used to control the urban sprawl within the urban growth model. It is expected that some green space will be lost inside the UGB because there are no specific restrictions on developing these spaces.

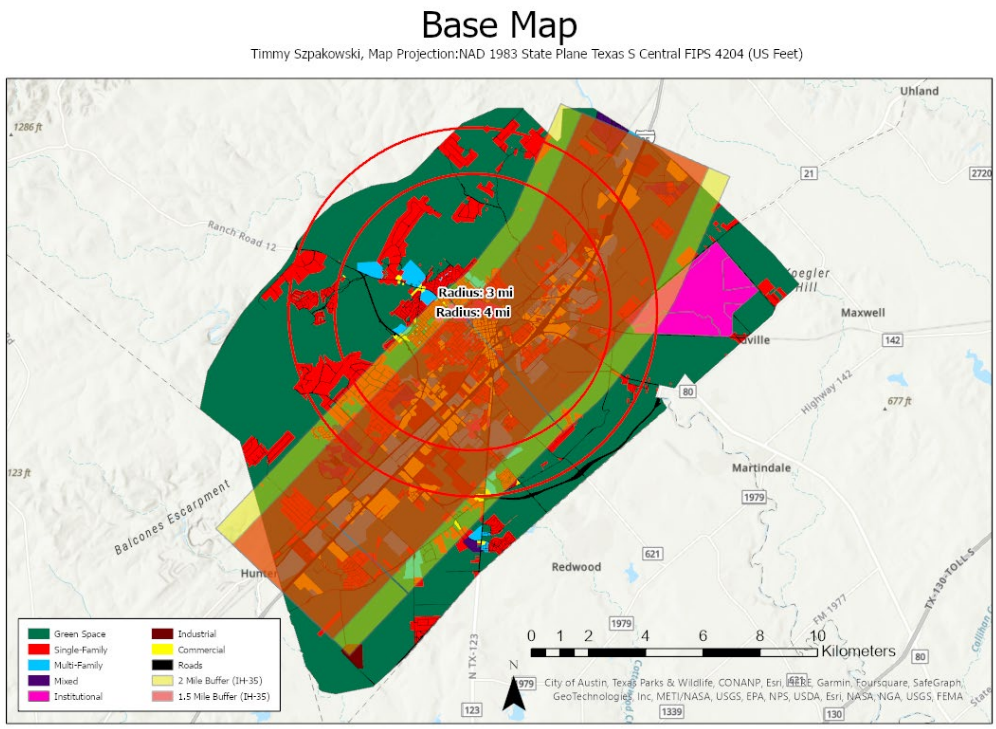


Figure 11. UGB for 10-year and 20-year simulations.

The third scenario, SF Simulation (with UGB), also used the growth pattern from the calibration and the UGB applied in scenario 2. It was simulated by having the government agent decrease the SF Average Lot Size (ALS) by 25% so more SF lots fit into each area zoned as SF. The hypothesis was that fitting more SF housing into these SF zoned areas would reduce the impact of SF housing spreading into green space. Presumably, this would put more residential housing on less land mitigating the loss of green space. This scenario evaluated if reducing the footprint of SF housing provided environmental sustainability by maintaining green space.

The fourth scenario, MF Simulation with (UGB), was simulated by instructing the government agent to decrease the SF Average Lot Size (ALS) by 25% as was done in scenario 3. Additionally, the MF AMFUS was increased by 25% from the base map to have more room for MF housing to be developed and occupied. The UGB used in scenarios 2 and 3 was applied restricting urban sprawl. Accordingly, this scenario evaluated the social theory that an increase of MF housing encouraged environmental sustainability by maintaining green space.

3.4.2 Evaluation

An evaluation and ranking of the scenarios will be done by comparing the change in green space land loss or land gain for each scenario. Other land-uses will be examined especially the SF and MF housing results since scenarios 3 and 4 have used regulations specifically targeting residential housing. This will be done comparing scenario maps and extracted numeric results in tables and graphs.

4. CHAPTER FOUR
Results

4.1 Scenario Results

As previously stated, the SF and MF housing regulations put into place by the government agent do not specifically restrict development into green spaces. However, it was shown in the literature review that urban growth would expand into the green spaces without specific government regulations making these areas unavailable (Li and Liu, 2008, Burhan et al 2020). The scenarios tested herein allow growth into the green spaces, with the objective of government regulations reducing the impact from residential growth. Therefore, it is expected that there will be growth into the green space because these parcels are not specifically restricted. Scenarios 3 and 4 specifically target SF and MF housing regulations.

Each scenario will have figures illustrating the base map, 10-year growth map, and 20-year growth map. These provide a geographic perspective as to where land-use changed around the City of San Marcos. A more analytical analysis is provided using the numeric results (e.g. acres for each land-use, percentage change) in each scenario. Finally, a comparison analysis across the four scenarios will be presented.

Scenario 1 **–** Unrestricted Growth (No UGB)

The first scenario was completed by continuing the growth pattern that was confirmed from the historical data without any restriction (Figure 11). Map results are shown in Figure 11.

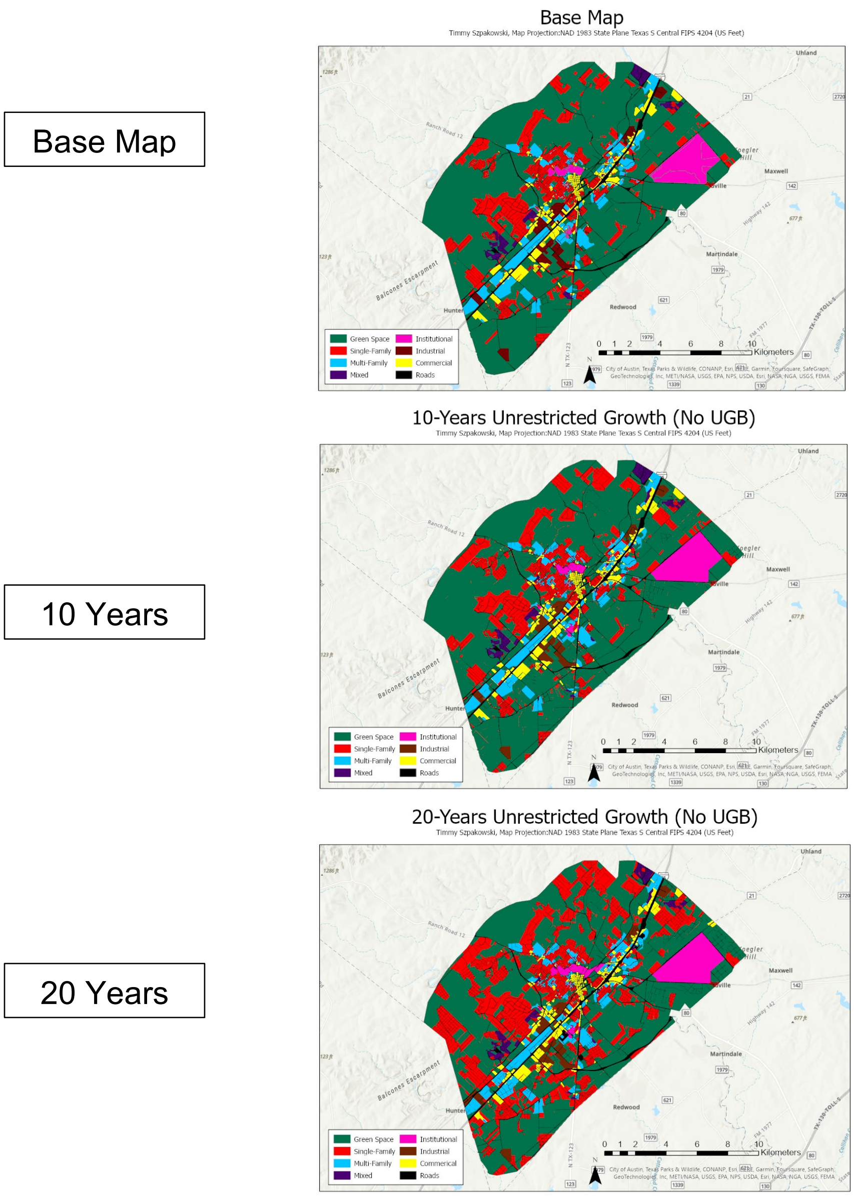


Figure 12. Scenario 1 Results from 10- and 20-year simulations

The numeric changes in the different land-use parcels are described below in Table 3:

	Scenario 1 Land-Use Changes (Acres)			
Land-Use	Base Map	20 year Growth	Numeric Difference	Percentage Change
Green Space	36488	28318	-8170	-22
Single-Family	7287	13631	6344	87
Multi-family	3359	3281	-78	-2
Commercial	1897	1815	-82	-4
Industrial	1148	1192	44	4
Institutional	2418	2512	93	4
Mixed	703	759	56	8

Table 3. Results of Scenario 1 in acres.

Notable changes:

The impact of unrestricted growth allows development over the entire study area as compared to the base map. As can be seen from the results in Table 3, the biggest change is in SF housing with an 87% increase. The maps in Figure 11 also demonstrate that impacts the green space which is reduced by 22%. These are the two most significant changes seen in scenario 1. The green space is impacted the most outside of the city center with SF housing causing the greatest impact. The maps show a sizable decrease in green space southeast, southwest, and northwest of the city. The area to the northeast of the city is dominated by a large swath of institutional land-use which decreases the growth of other land-uses in this area. MF housing decreases by 2% and mixed land-use has an 8% increase. The other land-use changes are small.

Scenario 2 – Compact Growth (With UGB)

The second scenario was conducted with the same growth pattern as the first scenario, but was restricted with the UGB. The results are shown in Figure 12.

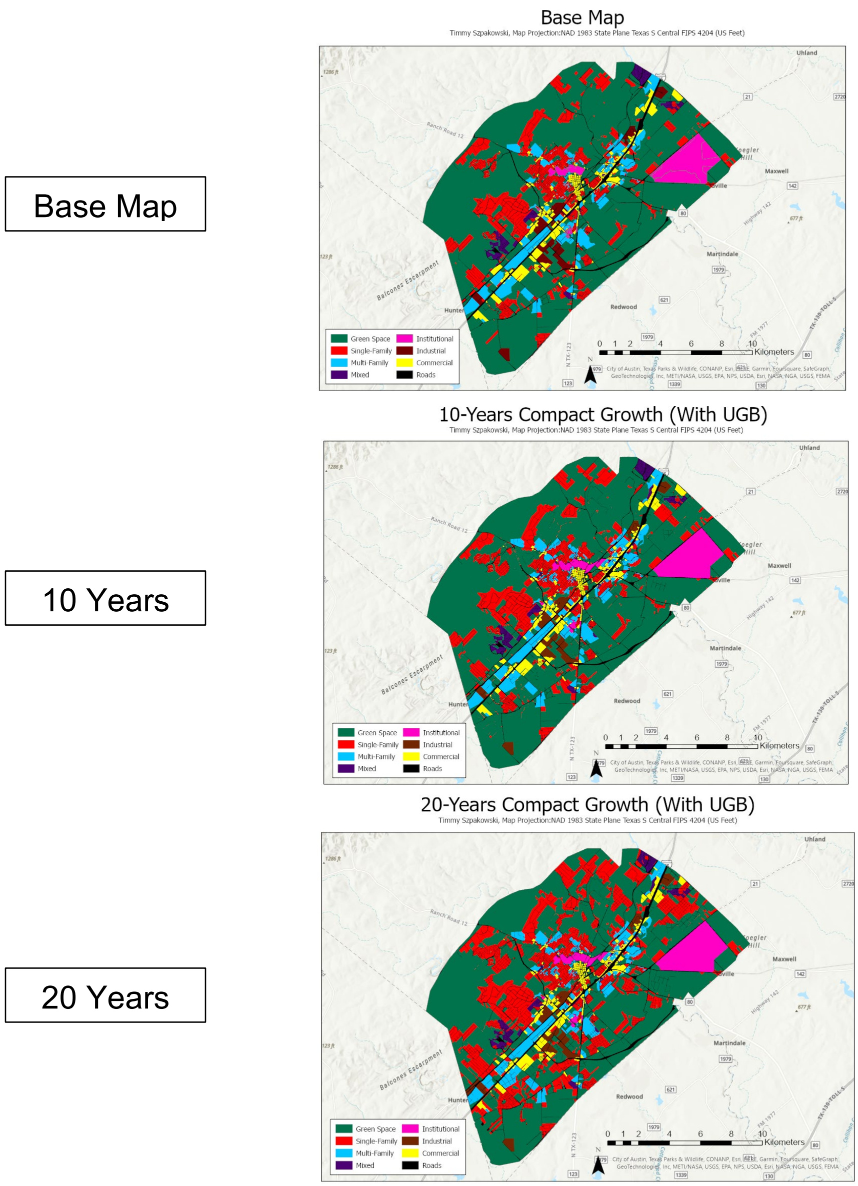


Figure 13. Scenario 2 Results from 10- and 20-year simulations

The numeric changes in the different land-use parcels are described below in Table 4:

	Scenario 2 Land-Use Changes (Acres)			
Land-Use	Base Map	20 year Growth	Numeric Difference	Percentage Change
Green Space	36488	30770	-5718	-16
Single-Family	7287	11927	4640	64
Multi-family	3359	3282	-77	-2
Commercial	1897	1784	-113	-6
Industrial	1148	1184	36	3
Institutional	2418	2512	93	4
Mixed	703	785	82	12

Table 4. Results of Scenario 2.

Notable changes:

The impact of compact growth using a UGB restricts development outside the UGB as compared to scenario 1. The biggest change is in SF housing with a 64% increase (Table 3). Examination of the maps (Figure 12) reveals that this impacts the green space which is reduced by 16%. These are the two most significant changes from Scenario 2. Most of the reduction in green space is once again outside the city center however, the impact of using the UGB can be seen southwest of the city center where there is less development and the green space is retained outside the UGB. This confirms that restricting development with a government regulation can produce compact growth preserving green space outside the UGB**.** The area to the northeast of the city is dominated by a large swath of institutional land-use and is also outside of the UGB. MF housing decreases by 2% same as scenario 1 and mixed land-use has a 12% increase. The other land-use changes are small.

Scenario 3 – SF Simulation (With UGB)

The third scenario was simulated by decreasing the SF ALS by 25% so more SF lots fit into each area zoned as SF. The map results are shown below in figure 13.

Base Map

10 Years

20 Years

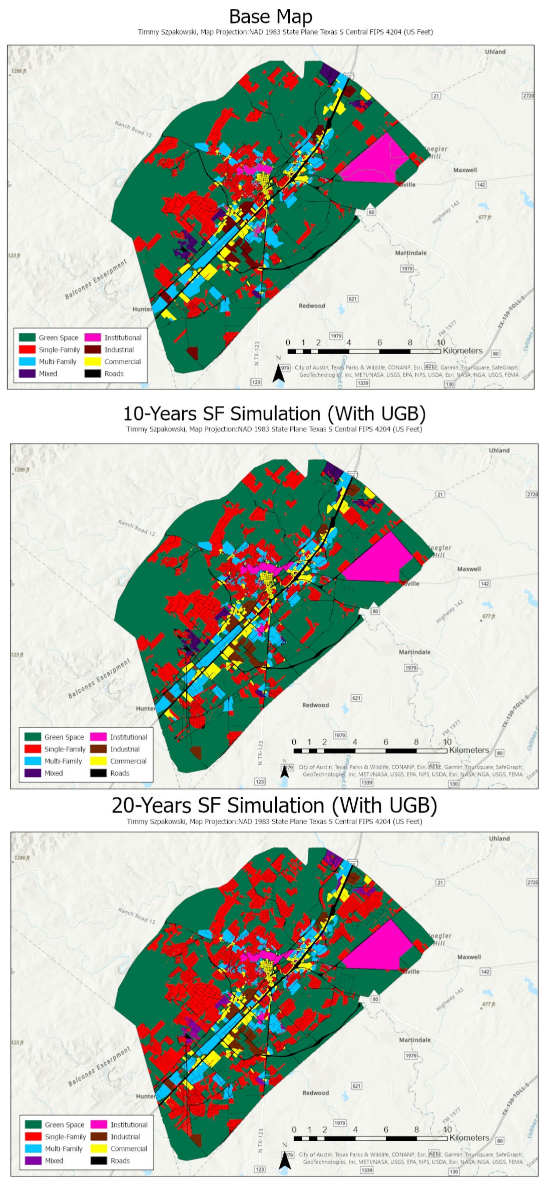


Figure 14. Scenario 3 Results from 10- and 20-year simulations

The numeric changes in the different land-use parcels are described below in Table 5:

	Scenario 3 Land-Use Changes (Acres)			
Land-Use	Baseline	20 year Growth	Numeric Difference	Percentage Change
Green Space	36488	29293	-7195	-20
Single-Family	7287	13142	5855	80
Multi-family	3359	3247	-112	-3
Commercial	1897	1732	-165	-9
Industrial	1148	1139	-9	-1
Institutional	2418	2514	96	4
Mixed	703	686	-17	-2

Table 5. Results of Scenario 3.

Notable changes:

The impact of SF housing regulations with a UGB appears to increase SF land-use and decrease green space and MF land-use as compared to the base map. The results in Table 5 indicate that the biggest change is in SF housing with an 80% increase. A review of the maps indicate that this impacts the green space which is reduced by 20%. These are the two most significant changes from Scenario 3. Most of the new development is outside the city center. The growth is inside the UGB and the green space southwest of the city center and to the northeast, outside of the UGB, remains intact. MF housing decreases by 3% which is the largest decrease out of all the scenarios. More land-uses are decreased with mixed land-use decreasing 2%, which is the first decrease in this land-use. Commercial land-use drops 9% and industrial land-use decreases 1%.

Scenario 4 – MF Simulation (With UGB)

The fourth scenario was simulated by decreasing the SF ALS by 25% as in scenario 3 and increasing the MF AMFUS by 25 %. Results are shown in Figure 14.

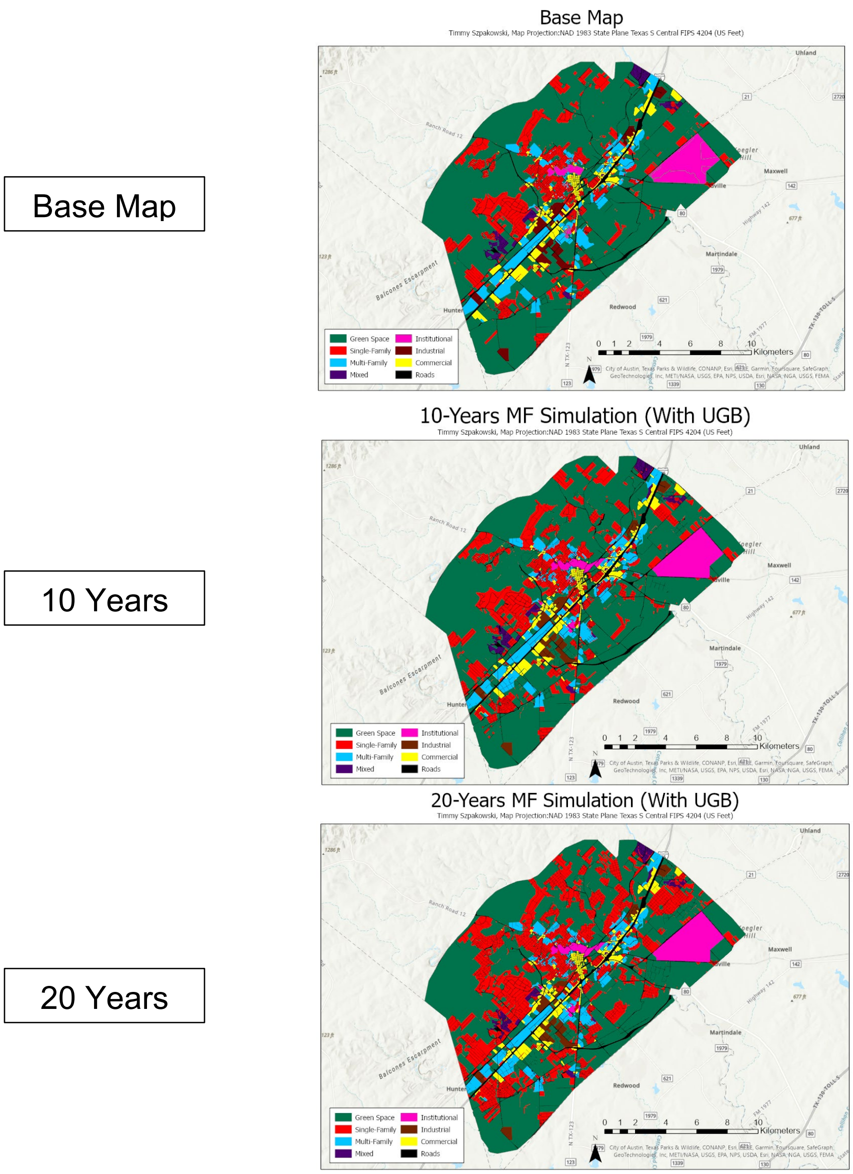


Figure 15. Scenario 4 Results from 10- and 20-year simulations

The numeric changes in the different land-use parcels are described below in Table 6:

	Scenario 4 Land-Use Changes (Acres)			
Land-Use	Baseline	20 year Growth	Numeric Difference	Percentage Change
Green Space	36488	29459	-7029	-19
Single-Family	7287	12982	5695	78
Multi-family	3359	3365	5	0
Commercial	1897	1742	-155	-8
Industrial	1148	1108	-40	-3
Institutional	2418	2516	97	4
Mixed	703	684	-19	-3

Table 6. Results of Scenario.

Notable changes:

The impact of adding MF housing regulations with a UGB appears to decrease SF land-use and slightly decrease the impact in green space as compared to Scenario 3. Table 6 indicates that the biggest change is in SF housing with an 78% increase. Figure 14 demonstrates with the resulting maps that this scenario does impact the green space which is reduced by 19%. These are the two most significant changes from Scenario 3. This impact is most notable outside of the city center with development contained within the UGB and the green spaces outside of the UGB are untouched. Multifamily housing stays approximately even with a minor addition of 5 acres. More land-uses are decreased with mixed land-use decreasing 3%, another decrease in this land-use. Commercial land-use drops 8% and industrial land-use decreases 3%.

4.2 Comparison of Scenario Results

Figure 15 compares the map results for each scenario from the 20-year simulations. The base map is shown to compare the scenario results to the initial state map. Tables 7&8 compare land-use in acres and changes from base in percentage values.

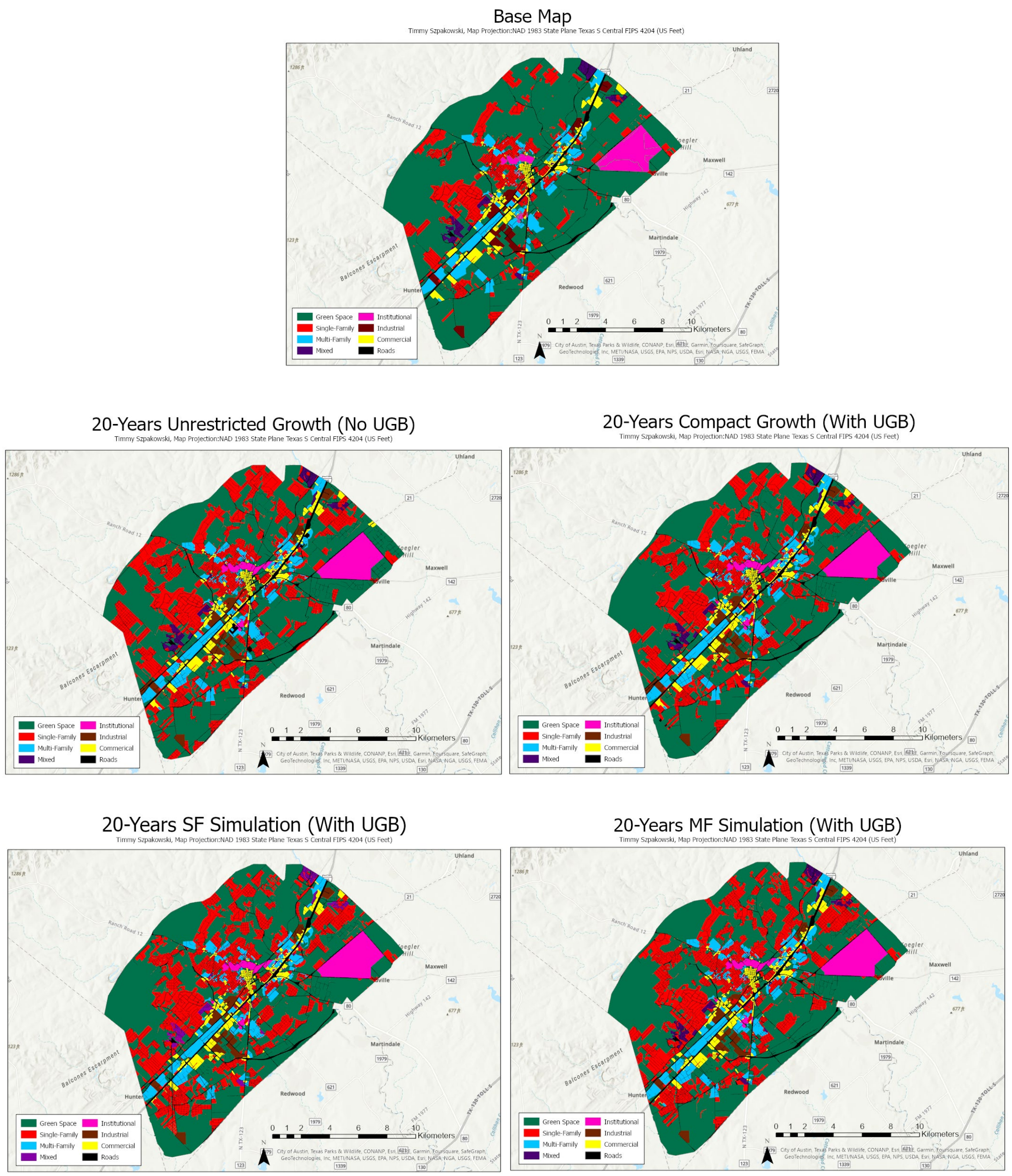
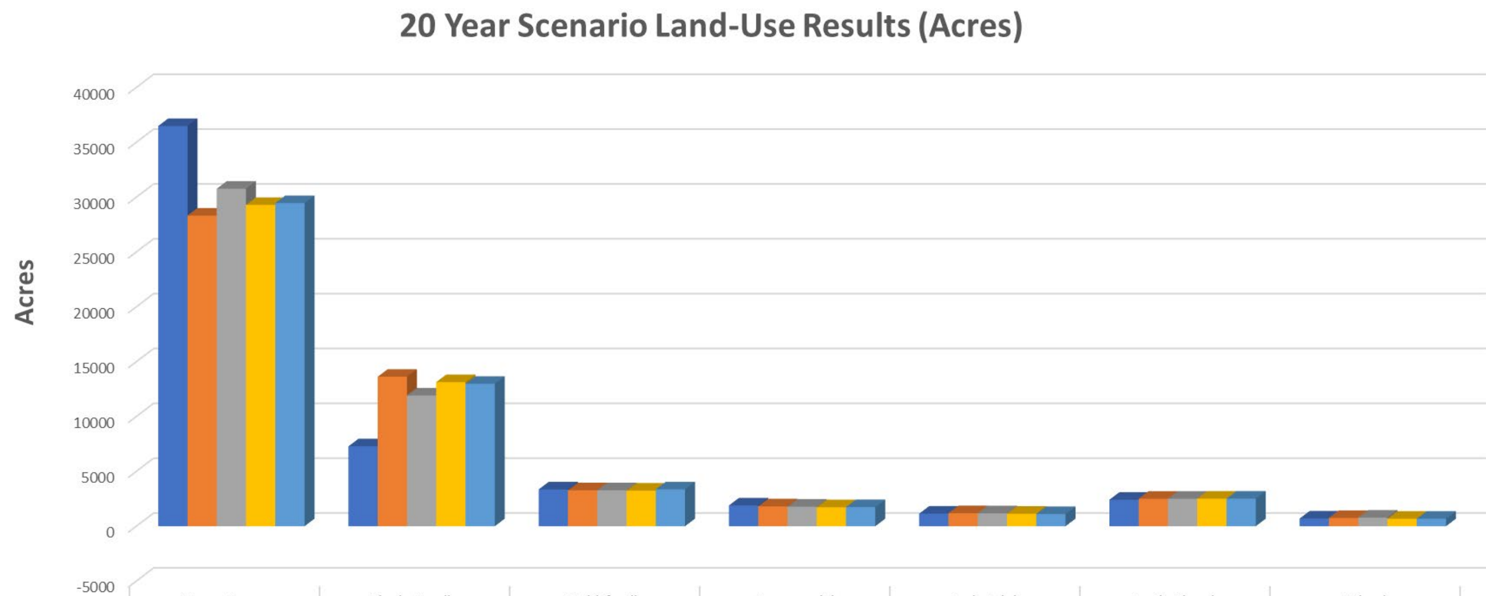
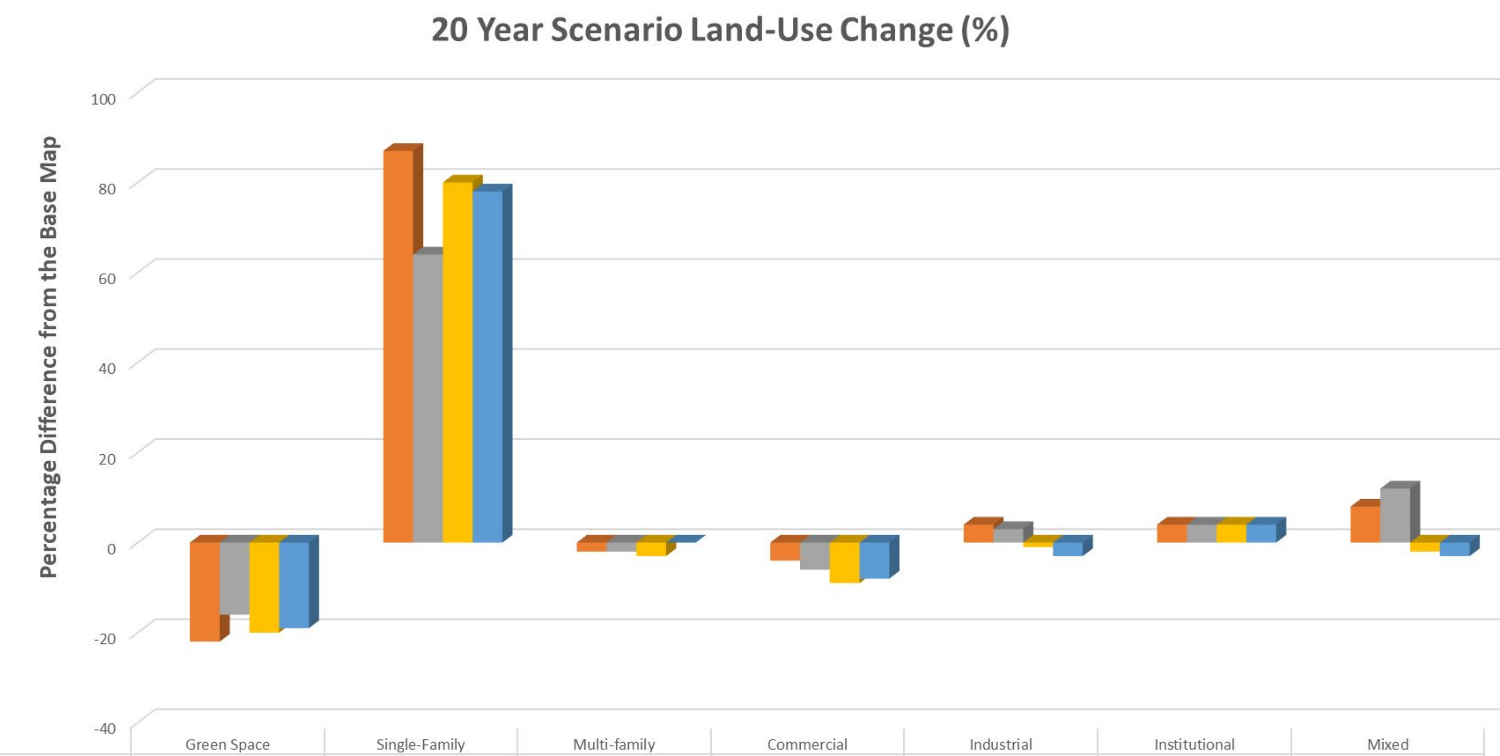


Figure 16. 20-year simulation results of the 4 scenarios.



	Green Space	Single-Family	Multi-family	Commercial	Industrial	Institutional	Mixed
0 Base Map	36488	7287	3359	1897	1148	2418	703
1 Unrestricted (No UGB)	28318	13631	3281	1815	1192	2512	759
2 Compact (UGB)	30770	11927	3282	1784	1184	2512	785
3 SF Housing (UGB)	29293	13142	3247	1732	1139	2514	686
4 MF Housing (UGB)	29459	12982	3365	1742	1108	2516	684

Table 7. Comparison of Scenarios in acres



	Green Space	Single-Family	Multi-family	Commercial	Industrial	Institutional	Mixed
0 Base Map							
1 Unrestricted (No UGB)	-22	87	-2	-4	4	4	8
2 Compact growth (UGB)	-16	64	-2	-6	3	4	12
3 SF Housing (UGB)	-20	80	-3	-9	-1	4	-2
4 MF Housing (UGB)	-19	78	0	-8	-3	4	-3

Table 8. Comparison of Scenario Land-Use in Percentage Change

Green Space observations from comparing the 20 -year scenarios:

In tables 7 & 8, green space decreased in every scenario which can also be seen when comparing the scenario maps to the base map. The greatest reduction to green space occurs in scenario 1, the unrestricted with no UGB, producing a decrease of 22%. Green space has the least reduction in the compact growth with a UGB simulation, scenario 2, with a decrease of 16%. Scenario 4, making changes to ALS and AMFUS, preserves slightly more green space with a reduction of 19% compared to Scenario 3, changing only the SF ALS, with a decrease of 20%. Thus, green space is preserved slightly better in scenario 4 than scenario 3. A comparison of all the scenarios demonstrates that using a government restriction retains more green space than without any restrictions on development, confirming that these types of restrictions provide a method to preserve green space.

Observations about other land-use categories:

Tables 7 & 8 also demonstrate that SF housing increases from the base in every scenario with scenario 1, unrestricted with no UGB, increasing the most at 87%. SF housing increases the least, 64%, in scenario 2, compact growth with a UGB. SF increased by 80% when SF lots were decreased in scenario 3. SF increased by only 78% in the MF simulation which did not reduce the MF parcels. Thus, there appears to be an impact on SF housing by increasing the MF AMFUS. SF is 2% less in scenario 4 than scenario 3.

Tables 7 & 8 also indicate that MF decreases in total area slightly in every scenario except scenario 4 where AMFUS was increased. In this scenario, there was basically no change from the base map. Commercial acreage decreases in every scenario. Industrial is mixed with more acreage in unrestricted Scenario 1 and compact growth in scenario 2. Institutional increases in every scenario and by nearly the same amount. Mixed use increases in scenarios 1 and 2, and decreases in scenarios 3 and 4 the SF and MF simulations.

5. CHAPTER FIVE

Discussion

In this research, the hypothesis that putting government regulations on SF and/or MF housing would preserve more green space, did result in decreasing the impact on green space as compared to no regulation. The urban growth models discussed in the literature review demonstrated that scenarios without restricted land-use always impeded on the green spaces that support environmental sustainability (Li and Liu, 2008, Burhan et al 2020, Al-Darwish et al 2018). These studies used scenario-based simulations to compare unrestricted land-use against restricted land-use, and the unrestricted scenarios consistently had the least favorable results based on the retention of green space and/or environmentally sensitive areas. Thus, green space was expected to decrease in all of the scenarios because there were no specific restrictions curtailing the development of these areas. However, previous studies did not examine the impact of government regulation on SF and MF housing to reduce the impact of urban growth on green spaces. The contribution from this research demonstrates that regulations on SF and MF housing can reduce the impact of urban growth on green space compared to no government regulation, but the use of a UGB to restrict growth provides better results.

Using a UGB did decrease the impact of urban sprawl on green space without putting specific restrictions on green space. It also reduced the impact of SF housing development when compared to the unrestricted model. This was expected since the UGB would restrict the urban sprawl into a smaller range than the whole study area. In all of the scenarios using the UGB, the areas outside of the boundary maintained the green space, but other land-uses were also not developed. The restrictions, in this case the UGB, were not specific to restricting development on green space, but the outcome was the retention of green space. Therefore, it can be seen that implementing a development restriction on an area can protect that area from urban growth as seen in the literature review.

Unexpectedly, the regulations put on the SF and MF simulations did not do a better job than the compact growth in scenario 2. As expected, the unrestricted model with no UGB, scenario 1, did the most "damage" to green spaces, reducing the green space by 22%. However, scenario 2, the compact model using the UGB, but with no other restrictions, preserved the most amount of green space with a decrease of only 16%. This is consistent with the results from Li and Liu (2008) where compact development outperformed other scenarios including those that protected green spaces and farm land. Compact growth in both models is preserving green space by restricting growth into specific areas.

In this research, the compact growth scenario does not have additional regulations, like those used in scenarios 3 and 4, that may modify developer or consumer agents' actions. As will be discussed, these regulations may be causing decreases in green space due to changes in human behaviors caused by these regulations. The human behaviors may include how developer agents maximize profits when SF ALS or MF AMFUS is changed. The model may actually be maximizing profits for the developer agents based on changes in land value, and consumer preferences may be different because of increased SF affordability. These type of behavior changes may be causing a decrease in green space as compared to the compaction scenario.

Scenario 3, the SF simulation, had a 20% decrease of green space while scenario 4, the MF simulation, had a 19% decrease of green space. This indicates that increasing the AMFUS in scenario 4 was slightly better than scenario 3 in preserving green space. This was an expected result, albeit small, based on the hypothesis that increasing MF housing would encourage the retention of green space over SF housing. Thus, encouraging MF housing with government restrictions is a worthwhile method to protect green spaces, but may be improved with a more aggressive regulation. The results from scenario 4 indicate that a more aggressive AMFUS might be necessary to achieve the desired result of a significant increase in MF housing to reduce the impact of urban development on green space. How much increase to the AMFUS is necessary to reduce this impact will vary based on the population proportions and the agent preferences.

Unexpectedly, SF housing had tremendous growth in all of the scenarios. One of the reasons that SF housing had this growth may be due to the developer agents' preference of maximizing profits. This is a consideration in scenarios 3 and 4, where SF ALS is smaller, allowing for more SF development on available parcels. Additionally, smaller lot size also means more affordable SF homes which may allow residential consumer agents to choose SF housing instead of MF housing. Thus, in scenarios 3 and 4, the combination of these agents' preferences maybe encouraging the exceptional increase in SF housing as compared to the compact scenario.

In this paper, the total population is projected from the net population growth with the same annual growth rate, average household size and initial total population at time *t* (equation 1). Using the same total population for each scenario, the base year (i.e. 2020) values of G, AH, and Pt for the study area were 1.9%, 2.44 and 68,580, respectively (US Census 2020). The implication is that the modeling results show that it is possible to cope with the projected growing population with regulatory tools and policy crafted by urban planning, and this study provides a case study to evaluate their effectiveness. However, other drivers for the growth in SF housing may differ by space and time. The number and type of incoming households was based on the population proportions of the 2020 US Census data for the City of San Marcos. These proportions would be different in other cities, countries, and cultures, possibly providing different results for the impact of SF and MF housing regulations on sustaining green space.

Another unexpected result was the lack of MF housing growth in all of the scenarios. Every scenario had a decrease in MF housing except for scenario 4 where AMFUS was increased. Increasing the AMFUS also decreased the impact on green space as compared to scenario 3 which only included SF parcel size changes. The reason MF decreased in every scenario but scenario 4 could also be a result of the incoming household data based on the 2020 Census, and might have different results with different population proportions and consumer preferences.

The population proportions for this study were, 9%, 8.69%, 41.31%, and 41% for LC, HC, LNC, and HNC respectively (Point2Homes 2020, BestPlaces 2020). Thus, in San Marcos the split between Low Income and High Income was basically fifty-fifty. In cities that have lower income populations, people that cannot afford the purchase and maintenance of SF residences, may be more receptive to MF housing eliminating these costs. Worldwide, mega-cities with large lower income populations may be more interested in centrally located MF housing which provides a more walkable lifestyle reducing transportation costs. Some locations, such as rural areas, where cities might be the only place that provide a livelihood with jobs and education, instead of being sprawled out among a greater urban area, the population might be more accepting of multifamily housing within walking distance of these necessities. Higher proportions of a No-Children population, such as a senior community, might be more amenable to not having a yard for children to play, and seek multifamily housing as a method to reduce the stress and work of owning a home. Therefore, with different population proportions of LC, HC, LNC, and HNC, the results of the AIIA model should be different from those used in the San Marcos study.

In addition to the changes in green space and residential housing, it was found that industrial land-use had increased in the unrestricted scenario 1 and compact growth in scenario 2. This may be due to the lack of regulations to increase residential housing allowing for more industrial growth in the study area. In contrast, scenarios 3 and 4 with government regulations favoring SF and MF housing, the amount of industrial land-use decreases. Another reason the industrial land-use decreases in scenarios 3 and 4 is that the residential housing parcels may be of more value to the developers causing the agents to develop less land for industrial growth. Finally, institutional land-use remains approximately the same in every scenario. This may also be due to the developer agents maximizing profits in other land-uses such as SF housing.

There are several limitations to the assumptions that drive the model. An automated integrated approach combining the AIIA with the logistics regression in a cascaded sequence would be better because iterations could run faster allowing more testing of the weights assigned to the different agents. This would not only provide better input into the model but also provide more confidence in the weights because they could be optimized by investigating more permutations of the logistic regression weight assignments. Another limitation of the model is the assumption of characterizing the commercial and industrial entities as a single category within each lot. If a lot is deemed commercial, only one commercial entity will be placed into the parcel. However, in reality, multiple commercial entities could be in one parcel. On the other hand, a commercial entity may occupy more than one parcel. An additional limitation is that the AIIA model will overwrite any land-use type to create roads. These limitations would require additional data and work to calibrate properly.

The assumption that green space is a single category which is comprised of different types of space could be another limitation. These spaces could be divided further into parks, reserved land, and farm land and may have different purposes and value to the community. An additional limitation to this AIIA model is that it cannot model infill development or the redevelopment of a parcel. Similar in nature, the model cannot convert SF parcels to MF parcels or conversely. The model can only convert undeveloped land to a type of developed land or leave it alone. In reality, infill development is a way to remodel or revamp outdated structures into new businesses or other uses.

Other influencing factors such as cost of different infrastructure types could be incorporated to provide improved performance of the model. These might be independent variables that are added to the weights in the utility function using a logistic regression to define them.

Finally, a limitation to the calibration process was the lack of land-use parcels in the calibration data. A better calibration method might be available in other areas where historical land-use data is available. This would provide a better, more detailed analysis of the calibration.

6. CHAPTER SIX

Conclusion

In this thesis, the role of certain restrictions on land-use was investigated in light of environmental sustainability. The research question proposed was: how do growth restrictions and multifamily housing affect green space? The result of using a UGB was explored comparing an unrestricted simulation with a compact simulation using a UGB. Changes to SF and MF parcel sizes were examined to investigate the impact on green space. This was done to investigate the impact of emphasizing MF housing over SF housing in the residential portion of the urban growth model. This was based on the social theory that multifamily housing delivers a more sustainable environment by preserving green spaces.

Past studies examining the impact of urban growth on green space did not investigate the use of government regulation on SF and MF housing to reduce the impact of urban growth on green spaces. The contribution from this research demonstrates that SF and MF housing regulations reduces the impact of urban growth on green space compared to no government regulation. In these scenarios, changes to the SF and MF parcel sizes resulted in a smaller impact on green space than the unrestricted model. These results suggest that government regulations on residential land-use preserve more green space than without government restrictions. Furthermore, regulations on MF AMFUS had better results than without this type of regulation at preserving green space and retaining MF housing. These results indicate the social theory that multifamily housing can preserve more green space is correct using the population proportions and other parameters implemented for the City of San Marcos.

Closer examination of the results from the scenarios revealed both expected and unexpected results. Using a UGB decreased the impact of urban sprawl on green space, compared to the unrestricted scenario, without putting specific restrictions on green space which was an expected result from the literature review. However, the impact from implementing government housing restrictions on the SF and MF housing parcel sizes did not produce an increase over the UGB alone which was unexpected. It was expected that decreasing the SF ALS by itself (scenario 3), or in combination with increasing the AMFUS (scenario 4), more MF housing would be produced, and green space loss would be less than both the unrestricted and compact scenarios. Unexpectedly, both of these implementations of government restrictions resulted in less green space being preserved than the compact growth with UGB results (scenario 2).

This may be because decreasing SF ALS reduces the cost of a SF lot for the residential consumer agents encouraging more of these agents to purchase SF homes. Dividing SF parcels into smaller lots increases the value of the overall area because there are now more lots. Land value is part of the weights included in the suitability score and utility function. This causes the developer agents to develop more SF housing instead of other types of development because it maximizes profits. Increasing AMFUS may just be adding more housing to the picture but had a different impact on SF housing and green space compared to scenario 3. The addition of AMFUS restrictions in scenario 4 did produce a slightly better result of retaining green space than scenario 3 which did not have the AMFUS restriction.

This may mean that changing the AMFUS could still be a way to reduce housing impact on green space and may have different results in areas with different population proportions. In cities that have lower income populations, or areas where amenities are more localized in the city center, multifamily housing might be more acceptable. However, based on these results, San Marcos city planners would be best served to implement UGB's if the purpose of land-use changes is to solely protect green space and preserve ecologically sensitive areas. Other city planners will need to evaluate their location and population demographics to conclude if the UGB is the best solution to retain green space.

Another unexpected result was that both of the scenarios with these housing restrictions did not produce an increase in MF housing! Even with government restrictions in place to encourage MF housing, MF housing actually decreased in Scenario 3 and remained about the same as the base map in Scenario 4. MF housing decreased in all scenarios except scenario 4, and SF housing grew at a tremendous rate in all scenarios. These results may be a product of the weights and parameters put into the program. More permutations of the SF and MF parameters needs to be done to optimize the most effective proportion and size of SF ALS and MF AMFUS. As taken, these results indicate that if City of San Marcos planners want to encourage multifamily housing by increasing the AMFUS, they may need to be more aggressive than the parameters used in this study.

For this research, investigating the urban growth in the City of San Marcos, the results imply that using the types of government housing restrictions investigated would preserve more green space than an unrestricted scenario, but will not preserve a greater amount of green space than using a UGB without these restrictions. Thus, government housing restrictions could improve the retention of green space and increase MF housing. In addition to the ALS and AMFUS regulations, the results of this research might be a function of other parameters used in the program. Future work is needed to examine variations in LC, LNC, HC, HNC parameters in the program. Alternate population proportions for different types of cities and cultures could impact the results of the urban growth model.

Additional future work might investigate different independent variables in the logistic regression that are used in the suitability scores and utility function. Other independent variables that may contribute to the suitability score and utility function might be public transportation accessibility, neighborhood walkability score, and employment accessibility. It would also be interesting to compare to other cities or countries where MF housing has an initial starting point greater than what was used in this project and other various permutations. Furthermore, the consideration of a study area that could provide initial land-use maps for historical calibration could possibly provide a better starting point for the initial state base map.

This study demonstrated that although the results were not as dramatic as expected, the regulations on SF and MF housing that were done to increase MF and preserve green space were successful at retaining more green space than the unrestricted model. The compact model using the UGB alone had the best performance at retaining green space, but may not always be an acceptable tool to produce the desired outcome because of the size, location, and demographics of a city. City planners may need to use the tools of SF and MF restrictions on land-use to effectively reduce impacts on green space. This research demonstrates that these tools can be successful at producing effective results. However, more permutations of the SF and MF demographic parameters and parcel regulation need to be investigated to optimize the most effective balance to preserve green space.

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APPENDIX

Data Availability

Data	Year	Date last accessed	Source
Elevation	2019	9/22/20222	https://data-cosm.hub.arcgis.com/datasets/CoSM::contour-10ft/explore?location=29.751026%2C-97.939610%2C11.59
Slope			https://data-cosm.hub.arcgis.com/datasets/CoSM::contour-10ft/explore?location=29.751026%2C-97.939610%2C11.59
Rivers	2022	9/22/20222	https://data-cosm.hub.arcgis.com/datasets/CoSM::san-marcos-river-corridor/explore?location=29.876855%2C-97.921904%2C14.88
Population Density	2020	9/22/20222	Dahal, K. R. 2014. Urban Growth Simulation Through Agent-Integrated Irregular automata (AIIA). PhD Diss., Texas State University
Land Value	2020	9/22/20222	Dahal, K. R. 2014. Urban Growth Simulation Through Agent-Integrated Irregular automata (AIIA). PhD Diss., Texas State University
Roads and highways	2021	9/22/20222	https://www.arcgis.com/home/item.html?id=9b3e54473dd44e648a419a1448e5cf29
Railroads	2016	9/22/20222	https://gis-txdot.opendata.arcgis.com/datasets/90f8c6d733274c26b9c8ea25e41fff62_0/explore?location=31.087560%2C-100.115652%2C6.93
Roads and highways	2021	9/22/20222	https://www.arcgis.com/home/item.html?id=9b3e54473dd44e648a419a1448e5cf29
Airport	2020	9/22/20222	https://data-cosm.hub.arcgis.com/datasets/CoSM::zoning-1/explore?location=29.881158%2C-97.930200%2C12.63
TSU	2020	9/22/20222	https://data-cosm.hub.arcgis.com/datasets/CoSM::zoning-1/explore?location=29.881158%2C-97.930200%2C12.63
Hospital	2020	9/22/20222	https://data-cosm.hub.arcgis.com/datasets/CoSM::zoning

			-1/explore?location=29.881158%2C-97.930200%2C12.63
Outlet Mail	2020	9/22/20222	https://data-cosm.hub.arcgis.com/datasets/CoSM::zoning-1/explore?location=29.881158%2C-97.930200%2C12.63
CBD	2020	9/22/20222	https://data-cosm.hub.arcgis.com/datasets/CoSM::zoning-1/explore?location=29.881158%2C-97.930200%2C12.63
Residential Neighborhood	2020	9/22/20222	https://data-cosm.hub.arcgis.com/datasets/CoSM::zoning-1/explore?location=29.881158%2C-97.930200%2C12.63
Commercial Neighborhood	2020	9/22/20222	https://data-cosm.hub.arcgis.com/datasets/CoSM::zoning-1/explore?location=29.881158%2C-97.930200%2C12.63
Industrial Neighborhood	2020	9/22/20222	https://data-cosm.hub.arcgis.com/datasets/CoSM::zoning-1/explore?location=29.881158%2C-97.930200%2C12.63
Historical data	2021	9/22/20222	https://www.mrlc.gov/data/nlcd-land-cover-conus-all-years