Exploring the environmental impacts of informal settlements in the Global South: An Application of Remote Sensing Tools in Kampala and Puerto Varas

A thesis submitted by

Magdalena Gomez-Kind

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Advisor: Justin Hollander

Reader: Aggeliki Barberopoulou

Abstract: Informal settlements, ranging from slums to homes built by real estate companies, challenge rapidly expanding cities in the Global South. These unplanned areas face issues like environmental degradation, climate change hazards, pollution, and agricultural land depletion. This thesis studies two informal settlements—Kampala, Uganda, and Puerto Varas, Chile—using satellite imagery and remote sensing tools to analyze land changes. The NDVI index effectively showed vegetation changes in both locations, while the NDBI index struggled to differentiate urban and barren areas, performing better in the more urbanized Kampala than in the rural Puerto Varas. This research offers insights for policymakers planning and monitoring the growth of informal settlements.

Resumen: Los asentamientos informales, que pueden ir desde campamentos hasta casas hechas profesionalmente con todos los servicios básicos, desafían la rápida expansión de las ciudades en el sur global. Estas áreas al margen de la planificación urbana enfrentan problemas como la degradación ambiental, amenazas del cambio climático, contaminación y pérdida de suelo agrícola. Esta tesis estudia dos asentamientos informales —en Kampala, Uganda, y Puerto Varas, Chile— usando imágenes satelitales y herramientas de teledetección para analizar los cambios en la tierra. El índice NDVI logró mostrar efectivamente el cambio en ambas ubicaciones, mientras que el índice NDBI presentó problemas para diferenciar terrenos baldíos de áreas urbanas, funcionando mejor en áreas más urbanizadas como Kampala, y con un desempeño más pobre en la ruralidad de Puerto Varas. Esta investigación ofrece un punto de vista para quienes trabajan en el área de políticas públicas monitoreando el crecimiento de los asentamientos informales.

Keywords: Kampala; Katoogo; Puerto Varas; Club de Campo Residencial; Parcela de agrado; Urban Growth; Informal Settlements; Healthy vegetation; Urban áreas; Barren areas.

Acknowledgments

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Chapter 1: Introduction

In recent years, there has been a noticeable increase in efforts to raise awareness about the consequences of climate change. Reports from the Intergovernmental Panel on Climate Change (Calvin et al. 2023) consistently emphasize the significant responsibility of decision-makers in addressing this global issue, as failure to do so could result in a world that is exponentially heating up, rendering cities unlivable.

These efforts to combat climate change have led many nations to prioritize strategies for adapting to changing climate conditions and reducing carbon emissions. However, despite these global advancements, a critical gap remains, particularly between developed countries and those in the global south (UN Environment Programme 2022). In these regions, cities are experiencing rapid growth, posing challenges for urban planning to accommodate unprecedented population rates.

As cities expand, so does the population residing within them. This trend is driven by factors such as proximity to employment opportunities and access to healthcare facilities (Adamo 2010). However, rising housing costs often force people to seek alternative housing options that fit their budgets. Informal settlements, also known as slums or shanty towns, emerge as housing solutions outside the realm of legal regulations, often in contravention of a city or region's planning or zoning laws. These settlements are particularly prevalent in the Global South (UN Habitat 2018; Agyabeng et al. 2022).

This thesis emphasizes that the term "informal" should not be equated solely with poverty. Evidence indicates that informality can exist in contexts where certain groups hold power (Roy 2005), challenging conventional definitions of informal settlements. Despite varying reasons for migration between these groups, both are associated with similar environmental impacts and are vulnerable to climate change due to inadequate infrastructure planning to support them, like water pollution and waste disposal (Zeilhofer and Topanotti 2008).

In this thesis, I adopt Ananya Roy's understanding of urban informality as a space that encompasses not only slums but also the interface where slums and suburbs intersect (Roy 2011). This perspective broadens the study of informality and raises awareness that the informal expansion of cities is not only attributable to low-income residents but also reflects the housing aspirations of wealthier households and the profit-driven strategies of real estate agencies.

Technological advances have played a pivotal role in studying the rapid expansion of urbanity and climate change's impact worldwide. These advancements enable us to precisely monitor environmental changes, collecting data from anywhere in the world, at any time. Remote sensing technology has emerged as a powerful tool for tracking environmental changes and providing images that facilitate the observation of the aftermath of natural disasters, flood patterns, and heat islands. Early detection of regions most susceptible to the effects of climate change empowers governments to direct their efforts to areas in dire need of assistance.

Informal settlements are particularly vulnerable to the adverse effects of climate change due to their unplanned nature. Unsupervised expansion can result in irreversible environmental consequences such as deforestation, erosion, and pollution (Mudau and Mhangara 2023).There is an urgent need to develop tools to mitigate potential disasters within these communities and ensure the sustainable growth of cities. This thesis aims to explore changes in vegetation and urbanization in two types of informal settlements from the global south using satellite imagery: Katoogo, Kampala (Uganda), and Puerto Varas (Chile). Through the analysis of images from 2016 to 2023, this study will provide evidence of how both areas have experienced changes in vegetation and urban boundaries. This analysis will reveal the significance of their impacts and compare how these areas have responded similarly or differently.

Chapter 2: Background

People migrate to cities for various reasons, including better job opportunities, escaping political crises, pursuing education, and more. In this thesis, I will focus on two types of migration: *forced migration* and *migration for amenity*.

Forced migration refers to situations where individuals are compelled to leave their homes due to factors such as conflict, persecution, natural disasters, or economic hardship. These migrants often are from low-income backgrounds, having limited choices that forces them to relocate to urban areas as a last resort (White 2022). Forced migration encompasses massive human movements compelled by various crises, as described by Castles (Castles 2003). One significant form of forced migration is climate migration, where individuals are forced to relocate due to the climatic unsuitability of their original location. This phenomenon is becoming increasingly prevalent due to the impacts of climate change that we have started to see more frequently.

Climate migrants/refugees often flee regions experiencing extreme weather events, rising sea levels, desertification, or other environmental challenges that render their homes uninhabitable. Upon arriving at their destination cities, they face unique challenges and trajectories as they seek refuge and attempt to integrate into new urban environments (Carper 2019).

On the other hand, *migration for amenity* (Gosnell and Abrams 2011) involves individuals from wealthier backgrounds moving to cities seeking improved quality of life, access to amenities, and desirable living environments. These migrants are often motivated by factors such as recreational opportunities, cultural attractions, and overall lifestyle preferences (Moss 2006). This trend has become more pronounced following the COVID-19 pandemic, as remote work opportunities have allowed individuals to maintain employment while living in quieter, less crowded areas (Eimermann and Carson 2023).

The reasons for migrating to a new city can vary widely. The case of Katoogo in Kampala illustrates the housing situation of people who faced, and still faces, forced migration. While the large flows of population arriving in Puerto Varas reflect the case of migration for amenity. In the following paragraphs, I will provide background information on these two locations.

Kampala, Uganda, has experienced rapid population growth, positioning it among the fastest-growing cities in Africa (UN Environment Programme 2022). Despite efforts to improve living conditions, a significant portion of Kampala's population resides in slums, accounting for 54% in 2020, according to the UN Human Settlements Programme. While this figure represents a decrease compared to previous years, it remains a substantial proportion.

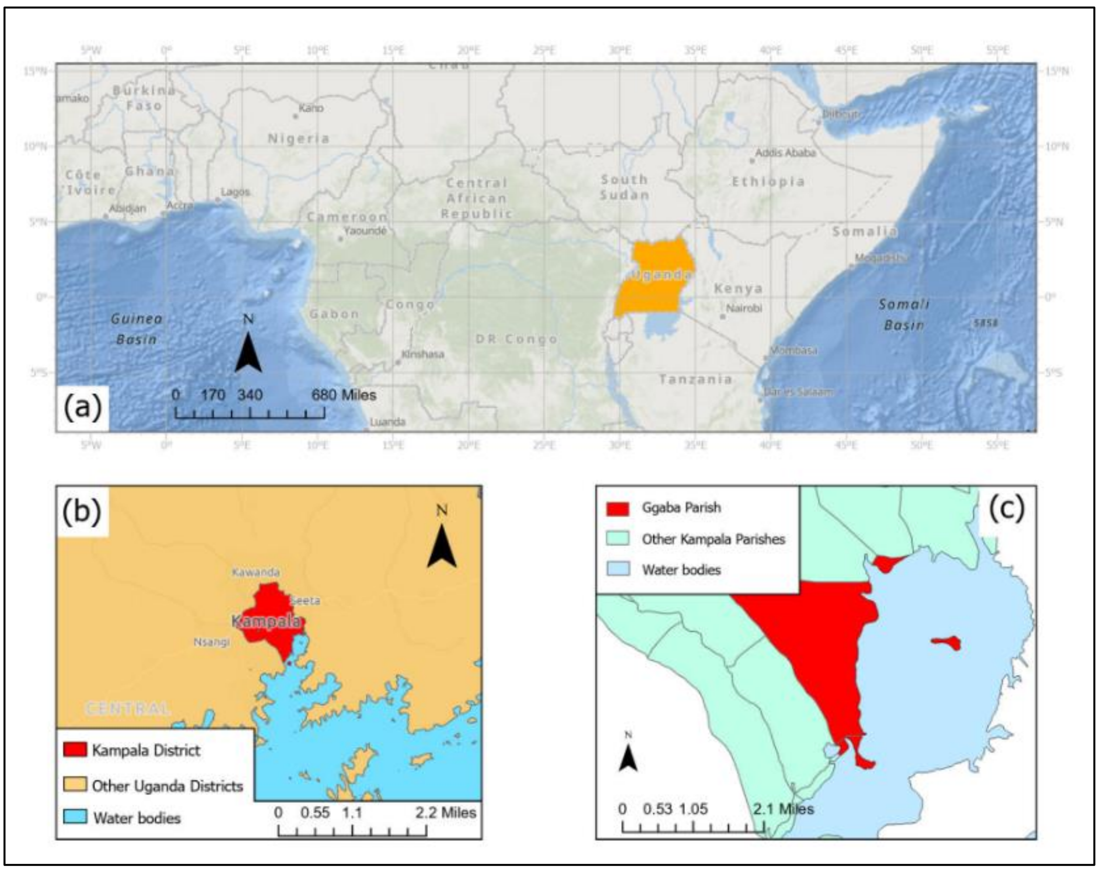


***Figure 1**:* Study area number 1: the informal settlement of Katoogo, Ggaba Parish, Kampala, Uganda.

Figure 2*:* Kampala city. Photo from Travel Tomtom.

Informal settlements in Kampala share common characteristics such as inadequate infrastructure, lack of land ownership titles, and pervasive poverty (Richmond, Myers, and Namuli 2018). Most of the population residing in these settlements are low-income earners and part of the informal job market (Dickson-Gomez et al. 2023). As the capital and main economic center of Uganda, Kampala attracts a steady influx of migrants each year (Migrants Refugees 2021). Migration to Kampala is primarily driven by economic opportunities, climate-induced displacement, and individuals fleeing political instability in neighboring countries (Monitor 2023a).

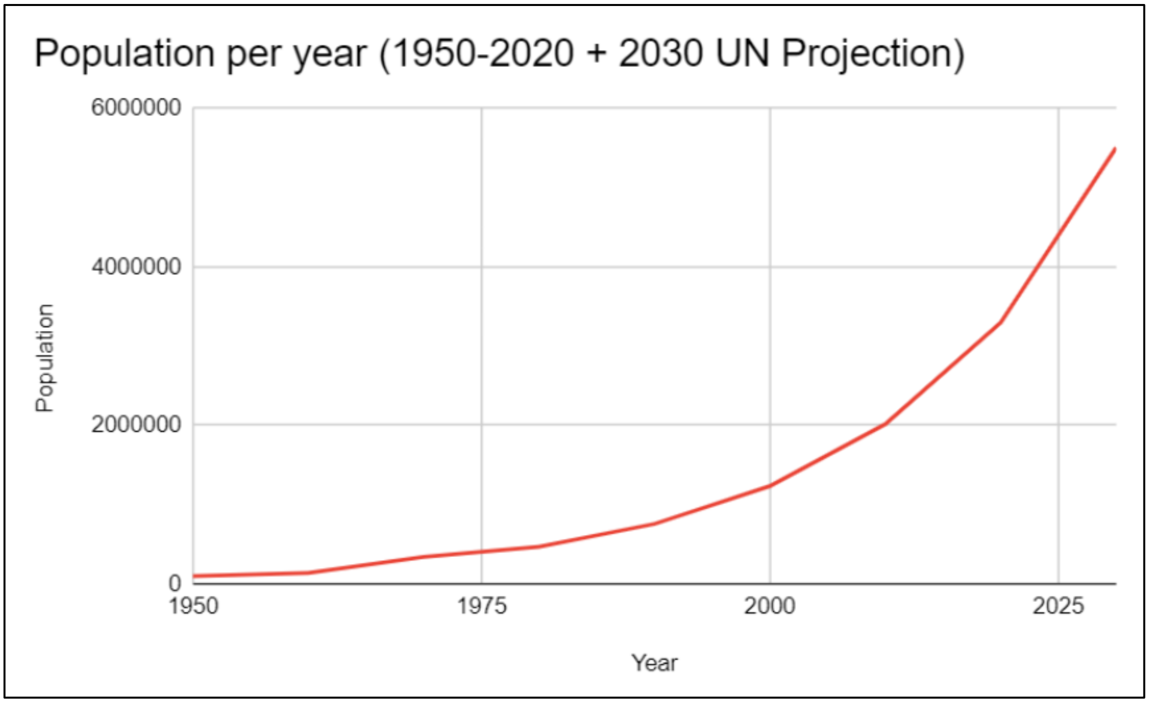


Figure 3*:* Kampala's population growth between 1950 and 2030.

With an increasing population accompanied by rising housing demand, an important percentage of people living in low-income informal settlements, and more frequent climate change-related events, Kampala is a city that is currently in a vulnerable situation (UN Environment Programme 2022). As residents start populating the wetlands, they become increasingly more exposed to house destruction and human displacement (Isunju, Orach, and Kemp 2016). Lake Victoria's water level rise has authorities worried since the rivers that irrigate the lake have doubled their water flow (East African 2024).

The signature housing structure in Kampala's informal settlements is tenements, also called "Muzigos". They are characterized by their basic construction materials and small size. People living in Muzigos are most of the time low-income residents who can't access a safer and affordable housing option. Space within a Muzigo is so small that households alternate the use of spaces depending on the time of the day: what is used as a living room during the day, is used as a bedroom during the night. For more references, see **Figure 4** (Shelter and Settlements Alternatives 2018).

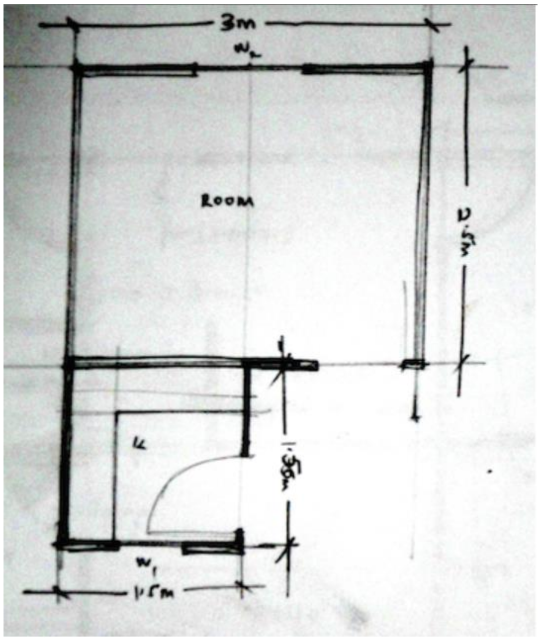


***Figure 4**:* Muzigo layout. Source: Eli Thumu, 2014.

***Figure 5**:* Photo taken in Katoogo Village-Ggaba in 2022. Photo by New Vision.

Muzigos are the housing of people living in Katoogo Village, one of Kampala's biggest informal settlements (Shelter and Settlements Alternatives 2018). It is located at the south of the city, and it's known to be lying in a significant wetland which are sometimes used as dumpsters, affecting their ability to absorb the water from rainfall, leading to flooding to a greater extent (Monitor 2023b). Pollution around this wetland also affects the water quality that is being delivered to households in Kampala, since the Murchison Bay is where most water of the capital comes from (Akurut, Niwagaba, and Willems 2017).

***Figure 6**:* Katoogo Village shown in red. To the south, Katoogo wetland. Image from Google Earth, 2022.

The poor sanitary living conditions of Katoogo have already been documented, highlighting issues such as the lack of pit latrines, frequent flooding, and water pollution (New Vision 2022).

Katoogo is in the open Murchison Bay, where the water from Kampala comes from. The lack of sanitary conditions in Katoogo could eventually make many in Kampala sick with water-borne diseases. The same report by New Vision documented that people have been fleeing the area in the last three years due to Lake Victoria rising water levels because of intense rainfall.

Puerto Varas, located in central-south Chile, Latin America, is renowned for its picturesque landscapes adorned with lakes and volcanoes. The region experiences abundant rainfall year-round, nurturing its fertile lands that sustain agriculture and provide employment opportunities for residents. Additionally, Puerto Varas boasts rich biodiversity, contributing to its allure as a tourist destination (Ilustre Municipalidad de Puerto Varas and Ilustre Municipalidad de Valdivia 2022).

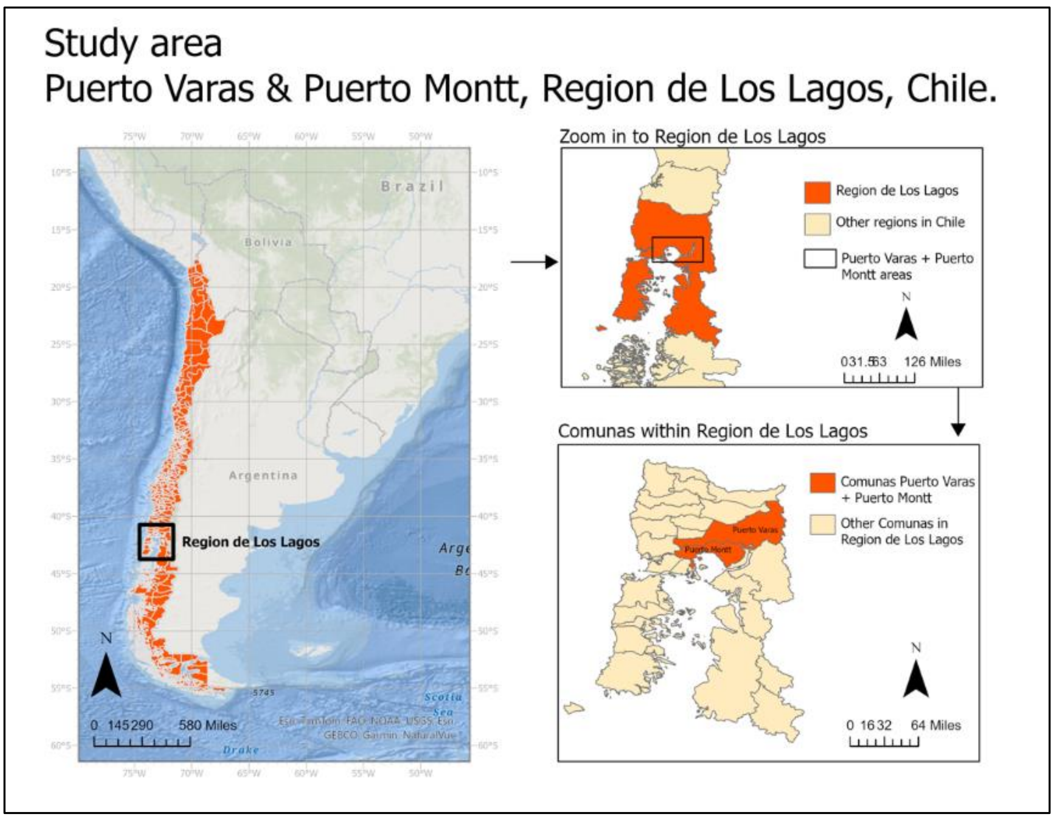


Figure 7*:* Study area number 2: Puerto Varas and Puerto Montt Comunas (districts), Región de Los Lagos, Chile.

Figure 8: Puerto Varas in 2013. Photo from Tripadvisor.

Traditionally known for its tourism industry, Puerto Varas has witnessed a shift in recent years as more people choose to make it their permanent residence. Factors such as the social unrest in the country in 2019 and the COVID-19 pandemic in 2020 have prompted individuals to depart from major cities like Santiago, Valparaiso, and Concepcion (BBC 2022). The expansion of remote work opportunities has further facilitated this migration trend, transforming Puerto Varas into an attractive destination for urban dwellers seeking a lifestyle change.

Chile's cities are tied to Regional Master Plans, and some municipalities have a Master Plan for their jurisdiction. These plans have shaped the existing zoning, which is limited to the urban areas. The areas outside of urban areas are qualified as "rural lands", which are used for agriculture and livestock, and different regulations apply for constructions within the urban limit and those happening outside that boundary. According to Chilean law, these lands can be built only for agricultural purposes linked to the economic activity developing on that land (MINISTERIO DE AGRICULTURA - Biblioteca del Congreso Nacional 1980). Likewise, there are legal requirements for landowners who want to subdivide their parcels: the resulting subdivided lands, and the new constructions, must be used for activities complementing the agricultural use of the original land. Additionally, county-level and central government-level institutions approve and certify the land division and development lawfulness. The law over rural land states these lands can be divided if the resulting lands have an area no smaller than 0,5 hectares (about 1.24 acres) (Ilustre Municipalidad de Puerto Varas 2021). However, the increasing demand for residing in these landscapes has made landowners lean into parceling their lands and sell it to the best bidder under the "arcela de Agrado" figure: a piece of land not meant for agricultural or land stock use, but that is neither meant for residence (CIPER 2022).

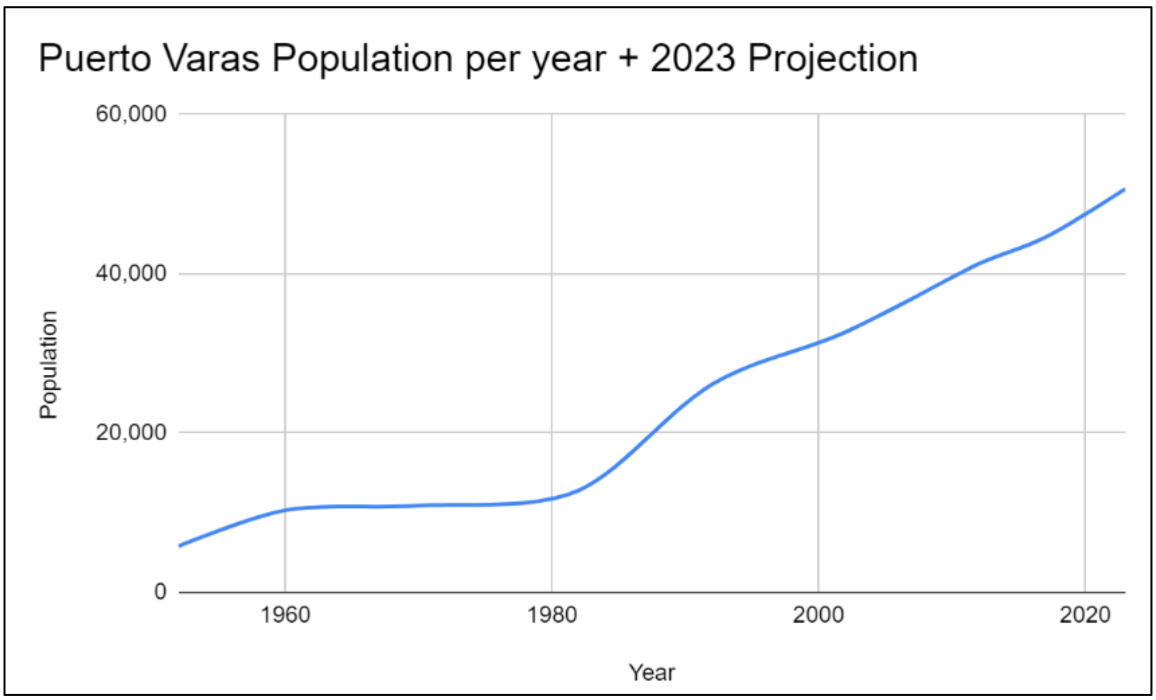


***Figure 9**:* Trend in population growth in Puerto Varas, from 1950. This graph considers population projections from the UN for 2025.

After the Covid-19 pandemic, Puerto Varas' population grew by 27% approximately (La Tercera 2022). Official numbers are to come when the Census process is done around August of 2024. As **Figure 9** shows, the population has been growing in Puerto Varas, especially in the last 35 years. With a population of 44,578 inhabitants according to the 2017 Census, Puerto Varas' population (urban + rural area) will reach 50,000 by 2050 (Biblioteca del Congreso Nacional de Chile 2023). The problem with parcelas de agrado is that, even though they're not intended for residential use, there is weak enforcement of the law, and landowners often sell them for families to build homes, despite the land not being designated for that purpose. Puerto Varas City Hall believes that incentives are missing to convince landowners to retain these lands for district development (Ilustre Municipalidad de Puerto Varas 2021) and identifies this as a reason for the developing boom. Club de Campo Residencial[1] is one of the many developments occurring in the area, and, along with the condominium Parque Las Bandurrias[2], it represents one of the most extensive developing projects already built in the zone (Ilustre Municipalidad de Puerto Varas 2021).

***Figure 10**:* Example of a group of "parcelas de agrado" with built houses. Photo by El Mercurio Journal, 2023.

[1] https://www.virapropiedades.cl/propiedad/loteo-club-de-campo-residencial-parcela-121/
[2] https://www.facebook.com/Parquelasbandurrias/?locale=es_LA

***Figure 11**:* Club de Campo Residencial condominium shown in red. Image from Google Earth, 2023.

Whether driven by economic opportunities or the desire for a scenic environment facilitated by remote work, the migration of individuals to new cities can strain local infrastructure and services. In many cases, receiving cities are ill-prepared to accommodate the influx of newcomers, leading to shortages in housing, waste disposal, water, and other essential amenities (The World Bank 2015).

When cities fail to provide suitable housing options for incoming residents, individuals often seek alternative accommodations that may not comply with urban regulations. This situation presents a challenge for municipalities, as the expansion of urban limits occurs without proper oversight or control over the direction of growth. Consequently, unplanned urban expansion can have detrimental effects, including rapid growth and adverse environmental impacts.

Chapter 3: Literature Review

In this chapter, I will delve deeper into the key topics driving this thesis and how research has contributed to answering my research question.

Changes in land cover have been particularly studied within the field of geology. While maps have existed for a long time, technological advances during the 20th century have enabled the study of larger areas of land with better resolution, in shorter periods of time, and at a more affordable cost. Satellite imagery has made it easier to track changes and expansion to a greater extent. However, free satellite imagery has only become widely available in recent years, which is why a larger volume of studies on land cover has emerged more frequently since 2010. Free access to satellite imagery has provided a new tool to analyze when informal settlements were formed, how long they have been there, and how much the land has changed since the settlements' establishment. Advances in machine learning have made it possible to use classification to understand the spread of informal settlements (Alrasheedi, Dewan, and El-Mowafy 2023). Researchers have even designed models to detect built-up areas (Durieux, Lagabrielle, and Nelson 2008) and slums specifically (Fallatah et al. 2022) through satellite imagery.

Research dating back to 2012 has highlighted Kampala's position as a conurbation within a larger urban area, along with satellite localities, and a concentration of informal settlements near wetlands. The analysis of Landsat imagery over the past three decades reveals a striking trend of explosive growth, underscoring the urgency for reevaluating urban planning strategies (Vermeiren et al. 2012).

Indexes such as NDVI and NDBI are widely used indicators for tracking vegetation changes, predominantly in earth science disciplines. However, there is a limited availability of urban studies on informal settlements using these indicators. Despite this, my literature review reveals that NDVI is considered a reliable index by the academic community. It accurately reflects vegetation health in specific locations, regardless of soil conditions, seasonal variations, or climate phenomena. A study applying NDVI to detect informal settlements highlighted the challenge of identifying these areas due to their variability across different locations. NDVI was used in addition to other indexes to detect informal settlements in various locations, and although it was successful, NDVI alone was not sufficient (Prakash et al. 2011).

Unlike NDVI, there is no clear consensus in the academic community regarding the most reliable index for detecting urban areas. Valdiviezo et al. have summarized various existing indices and their performance with Sentinel-2 images. While NDBI is widely accepted, their study highlights its challenges in distinguishing urban areas from barren ones. In contrast, NBAI (New Built Area Index) demonstrates superior performance in distinguishing between these areas, particularly in non-arid regions when utilizing Sentinel-2 imagery (Waqar, Mumtaz, and Hussain 2012;Valdiviezo-N et al. 2018). However, there is no evidence of the use of this index in Kampala or Puerto Varas, nor any experiences of using this index with Sentinel images.

Academic literature on informal settlements typically focuses on slums. Major technological advances in satellite imagery have facilitated the development of machine learning models capable of detecting the location of these settlements without requiring researcher supervision. This capability enables real-time tracking of the generation and expansion of informal settlements. A study by Fallatah et al. compared the performance of a model using medium-resolution imagery (Landsat) against high-resolution imagery (only available for purchase). They found that Landsat imagery provided sufficient resolution for the model to successfully detect informal settlements (Fallatah et al. 2022), which is particularly important for local governments in budget-constrained areas such as Kampala and Puerto Varas.

In Argentina, the growth of tourist cities has been driven by the practice of "loteos" (a synonym for "parcelas de agrado"), leading to deforestation and the loss of agricultural land and associated economic activities. Migration for amenity has long existed but has significantly intensified in recent years. Conlara Valley has experienced profound changes due to these amenity migrants. One notable impact is the increased demand for water (both for drinking and recreational purposes, such as pools), which has resulted in drought conditions. These newcomers, accustomed to more humid environments and higher water usage, strained the Valley's limited water resources, leading to a drought from which the region is still recovering (Trivi 2018).

In Chile, a study was carried out in Malalcahuello, located 500 km from Puerto Varas, a popular destination for amenity migrants. This development was supported by the local government, which aimed to boost the local industry through tourism centered around its landscape features. The experience of amenity migration brought both positive and negative changes to Malalcahuello. On the positive side, tourism fostered local economic development. On the negative side, rapid real estate development is devastating the very natural resources that attract people to the area, accelerated by the special administrative features of Chilean lands (Marchant and Rojas 2015).

Despite all these advances, these studies fall short of answering my research question. Studies in the Global South have focused on larger cities, but little has been said about growing cities that are becoming urban hubs. At the same time, no studies were found that used remote sensing to track changes in Katoogo, and this is what this study intends to do. Kampala has been largely studied compared to Puerto Varas; however, there are no comparative studies tracking the differences between two different kinds of informal settlements. In this sense, this study represents a contribution to that knowledge gap, and I expect to open a new venue for future studies on new urban hubs and how informal settlements in bigger cities are being affected by climate change, all of this through a remote sensing lens.

Research question

How has vegetation and built-up areas changed in these two settlements?

Chapter 4: Methods

Satellite Imagery

A general description of the images I used is provided in **Table 1**, while **Figure 12** illustrates the workflow I followed. I decided to use Sentinel images (rather than Landsat) because of the high resolution they have available. I acquired images from the Sentinel-2 satellite, accessible via the Copernicus Dataspace website. These images underwent preprocessing and enhancement using ENVI and ArcGIS Pro software to aid their interpretation. For the comparative analysis, images from different years were utilized for both cities: 2017 and 2022 for Kampala, and 2016 and 2023 for Puerto Varas. The images selected were taken during summertime, the driest season for both locations, to know the conditions under water-stress. Each band was downloaded separately and compiled into a single file using ENVI when needed.

	Imagery	Dates	Spatial Resolution	Number of Bands
Puerto Varas	Sentinel-2	01/05/2016 02/17/2023	10m (B2,B3,B4,B8) 20m (B5,B6,B7,B8A,B11,B12) 60m (B1,B9)	12
Kampala	Sentinel-2	01/25/2017 01/29/2022	10m (B2,B3,B4,B8) 20m (B5,B6,B7,B8A,B11,B12) 60m (B1,B9)	12

***Table 1**: Satellite imagery data sources.*

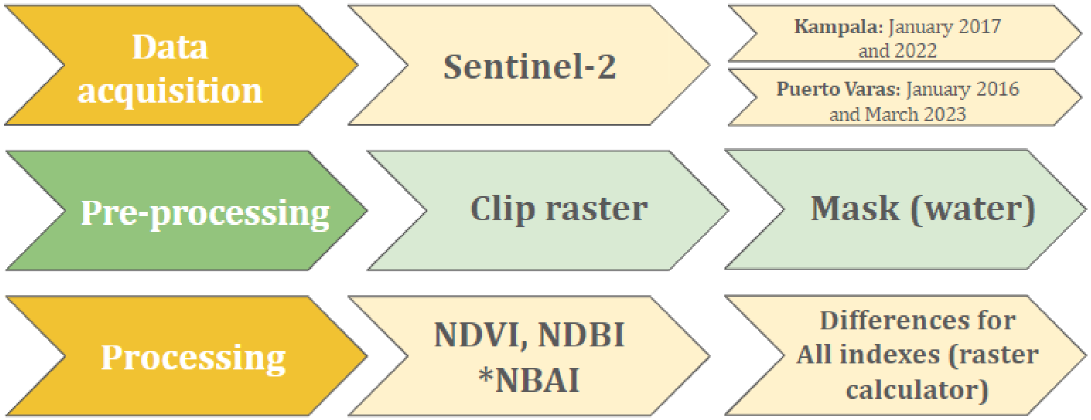


Figure 12*:* Workflow for satellite imagery.

Image pre-processing

The Copernicus platform offers pre-processed images, featuring atmospheric correction and minimal cloud cover (20% or less). As both locations' images originate from the same satellite, they maintain consistent pixel size and spatial resolution.

The images were clipped to a smaller extent to delineate the areas of interest. This helped focus the analysis and reduce noise from surrounding environments. Subsequently, a mask was applied to isolate specific features like large water bodies, ensuring cell values to remain within a relevant range for the study. The final outputs comprised four rasters: two for each city, corresponding to different years. These rasters are included in the appendix.

Indexes

The indices I will use to evaluate the images are as follows:

- **NDVI (Normalized Difference Vegetation Index)**: This index is designed to highlight areas with healthy vegetation in contrast to built-up areas or water bodies. It captures near-infrared (NIR) and red reflectance of vegetation. For Sentinel-2 images, the formula is:

$$\text{NDVI} = \frac{Band\ 8\ (NIR)\ -\ \text{Band 4 (red)}}{Band\ 8\ (NIR)\ +\ \text{Band 4 (red)}}$$

After this operation, the resulting raster will have pixel values ranging from -1 to 1, where values closer to 1 indicate "Healthy Vegetation," positive values closer to zero indicate unhealthy vegetation, and negative values represent "Inanimate objects, water, clouds and/or snow".

- **NDBI (Normalized Difference Built-up Index)**: This index is designed to highlight urban areas by using the Short-Wave Infrared (SWIR) band (Band 11 for Sentinel-2). The values closer to 1 indicate urban areas, while negative values indicate non-urban areas.

$$\text{NDBI} = \frac{Band\ 11\ (SWIR) - \text{Band 8 (NIR)}}{Band\ 11\ (SWIR) + \text{Band 8 (NIR)}}$$

This index helps estimate urban expansion patterns. Overlaying this layer with a land use map can indicate whether the expansion has been planned by the city. One of the challenges with this index is its potential to confuse bare soil with impervious surfaces (Valdiviezo et al., 2017). To address this issue, it is recommended to use other built-up indices and compare the results. This is the reason why I will use a second built-up index that I will detail below.

***NBAI (Normalized Difference Bareness Index)**: The NBAI serves as a complementary index to NDBI, especially useful in distinguishing between built up and bare soil areas. The formula for NBAI is:

$$\text{NBAI} = \frac{Band\ 12\ (SWIR) - \frac{\text{Band 11}}{\text{Band 3 (NIR)}}}{Band\ 12\ (SWIR) + \frac{\text{Band 11}}{\text{Band 3 (NIR)}}}$$

Since the NBAI was designed for use with Landsat images instead of Sentinel, its results will be included in Appendix 2 and will not be considered in the main results of this study.

Chapter 5: Results

Kampala

NDVI

Figure 13 shows the distribution of NDVI values for Kampala in 2017, where the range goes from -0.16 to 0.75, with an important peak around -0.12 and -0.14, which suggests that a large portion of the area has low/negative NDVI values that indicate non-vegetated areas. The mean value is 0.18 which, again, indicates that on average, the area has low vegetation cover. By looking at the map in Figure 15, we can see these vegetated areas are mostly located within the wetland. The values are well spread out, with smaller peaks in the positive range. This falls within the expected results for a highly urbanized area like the south of Kampala. On the other hand, **Figure 14** shows the distribution of NDVI values for 2022, with a clear decrease in the range if compared to 2017. This indicates there was a reduction in non-vegetated areas, or an increase in vegetation cover in previously barren areas. Regarding peaks, there is a significant one close to 0.02, suggesting similarly to 2017 that there is low vegetation in the area, or water stressed vegetation (existing but not healthy) compared to 2017. The maximum value is still high, but it is less frequent. This means that land with healthy vegetation decreased from one year to the other.

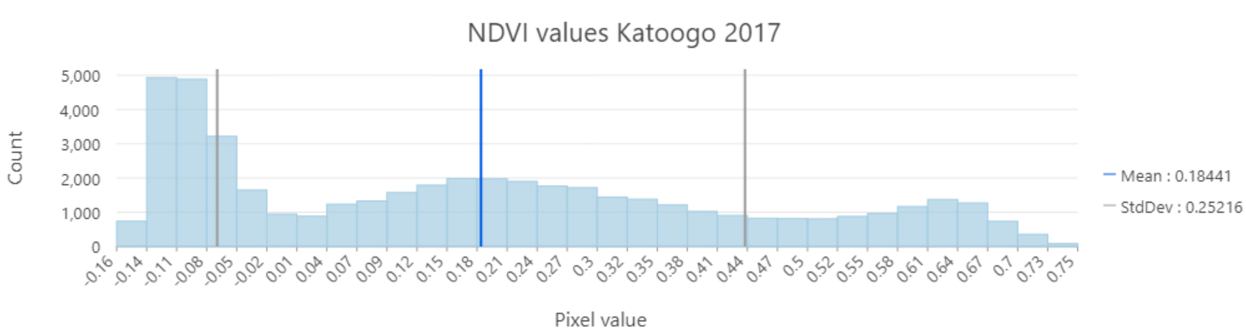


Figure 13*:* Distribution of NDVI values for Kampala in 2017.

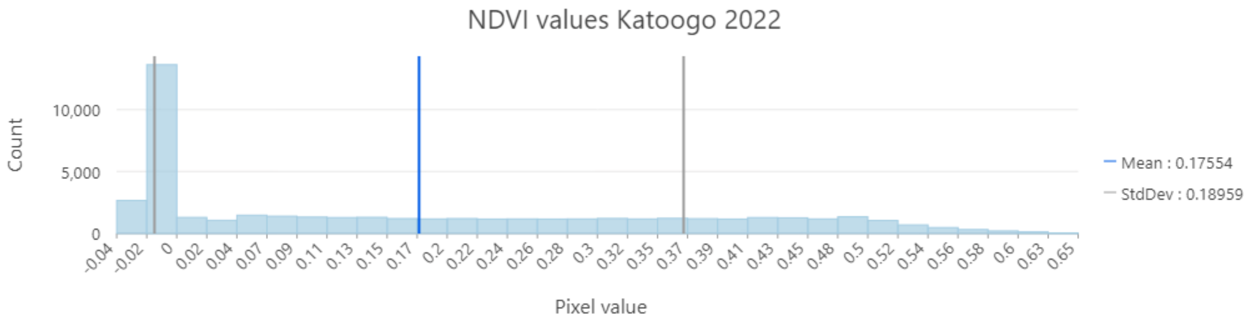


***Figure 14**:* Distribution of NDVI values for Kampala in 2022.

	Minimum	Maximum	Mean	Standard deviation
2017	-0.177	0.798	0.184	0.252
2022	-0.07	0.670	0.175	0.189

***Table 2**:* Summary of statistics for Kampala's NDVI.

The geographic visualization of this data is presented in **Figure 15**. The image shows Katoogo, and the legend indicates areas of healthier vegetation in green, while orange shows barren areas and/or water bodies. Darker green represents healthier vegetation, and the lighter the green gets, the unhealthier the vegetation is. This first map illustrates a notable decline in greener areas/healthy vegetation areas over the five years period. Between 2017 and 2022, there is a clear expansion of barren areas, particularly towards the coast. Although Katoogo had barren areas in 2017, they were less extensive than those to the north. The increase in orange pixels suggests that these areas are predominantly non-vegetated surfaces. It is important to note that both images were taken in January, the driest month for the area[3], reducing the likelihood of flooding events. When comparing the two images, there appears to be little change in the areas of healthy vegetation. However, by 2022, there is a significantly larger expanse of barren areas devoid of vegetation, likely due to urban development.

[3] Source: https://destinationuganda.com/.well-known/sgcaptcha/?r=%2Ftravel%2Fbest-time-to-visit-uganda%2F&y=ipr:185.54.231.50:1722869200.498

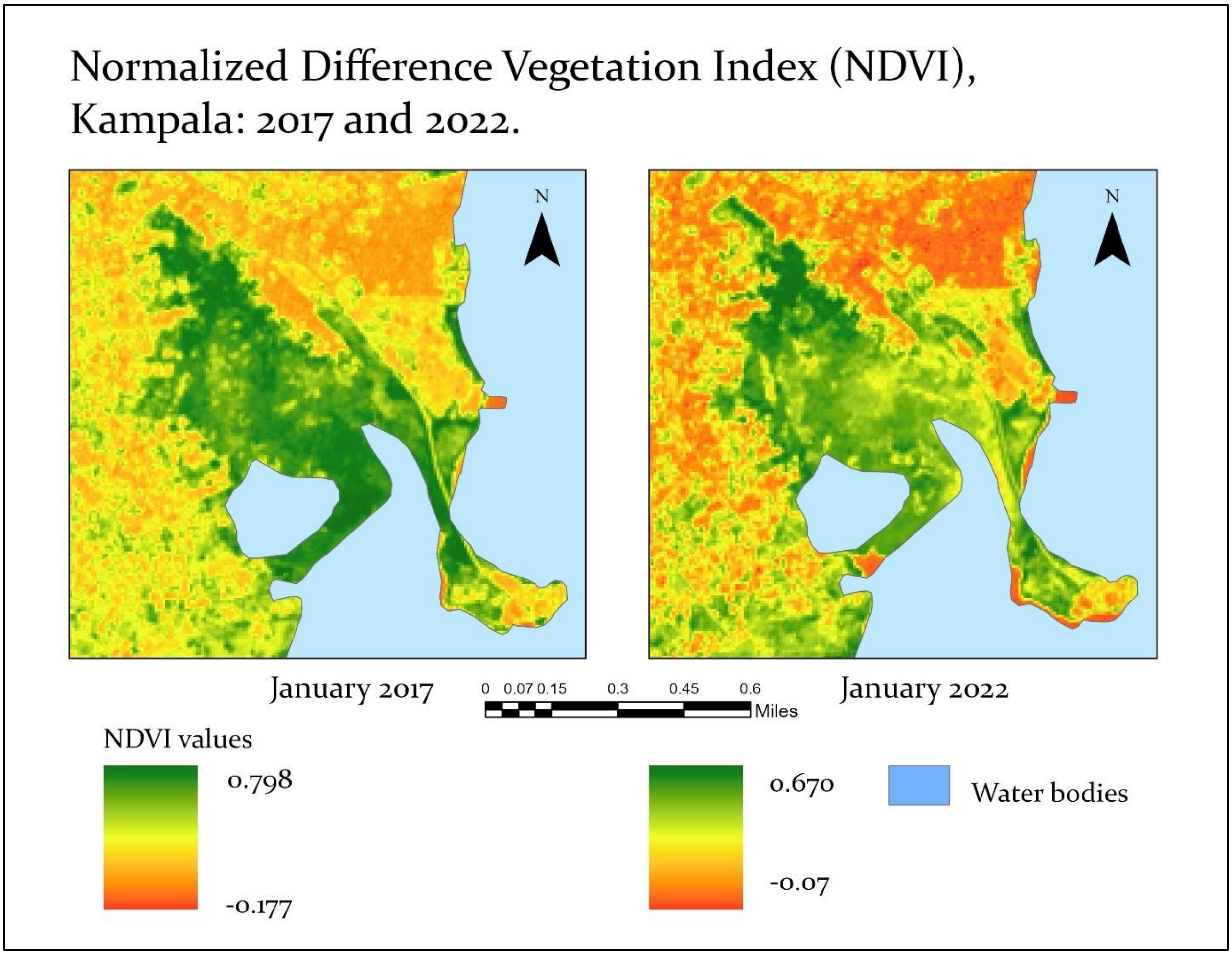


Figure 15*:* NDVI in Katoogo and surroundings, 2017 and 2022.

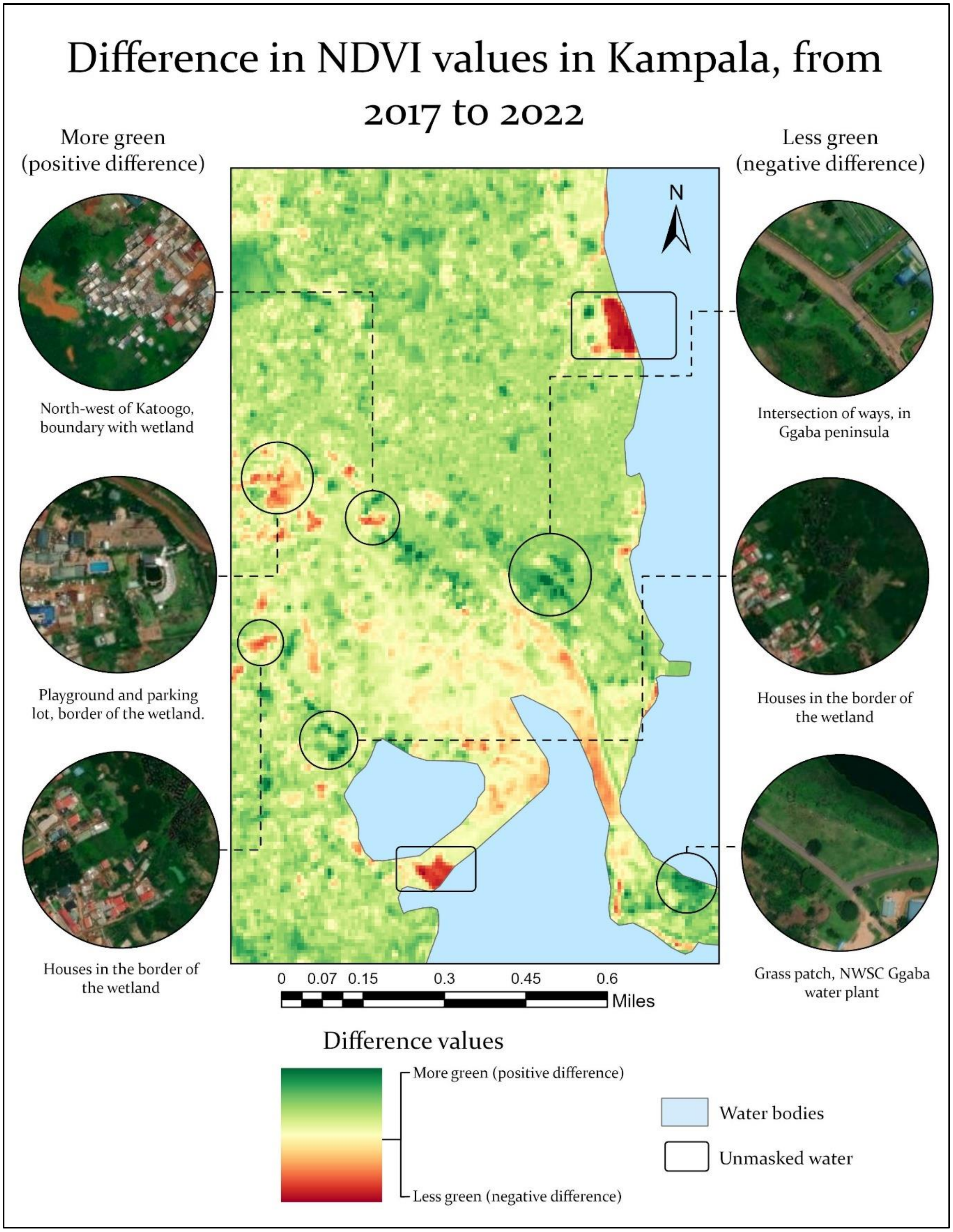


***Figure 16**:* Raster reflecting the difference between the NDVI rasters of 2017 and 2022.

Figure 16 illustrates the difference between the 2022 and 2017 NDVI values, highlighting the extent of vegetation changes over this period. The raster map displays areas where vegetation health improved (positive change, shown in green), areas where it declined (negative change, in red), and areas with minimal change (in yellow). When comparing this raster with Google Earth images, it becomes evident where significant changes occurred, primarily around the wetland.

For example, Katoogo Village experienced an increase in vegetation—a noteworthy result, as vegetation growth occurred in areas previously occupied by houses. This observation is confirmed by comparing Google Earth images, as shown in **Figure 17**, where some parts of Katoogo Village that once housed buildings now exhibit vegetation. This change is likely due to the rising water levels of Lake Victoria, which has encroached into residential areas, leading to the displacement of homes and subsequent vegetation growth. Conversely, vegetation loss is concentrated around the wetlands, particularly near Katoogo, likely due to human activities such as construction. **Figure 17** also reveals that Katoogo Village has experienced both expansion and contraction. While vegetation growth occurred at the expense of former housing areas, the village also expanded into other areas, leading to a loss of vegetation. Therefore, while Katoogo shows signs of expansion through vegetation loss, especially in the northwest, this growth is counterbalanced by a general gain in vegetation at the expense of homes.

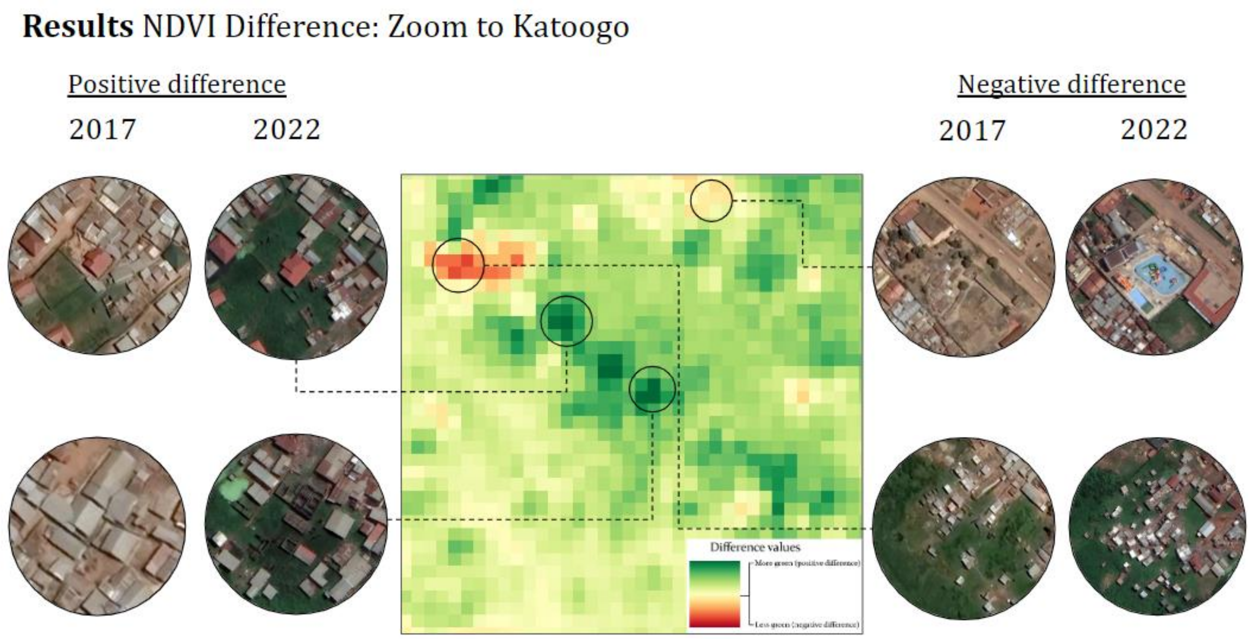


Figure 17*:* NDVI Difference: zoom to Katoogo*.*

NDBI

Figure 18 shows the distribution of NDBI values for 2017. The mean is -0.178, depicting a land that is not predominantly built-up, and that could either be vegetated or non-urban. There are two different peaks in the distribution: one on the negative side, and one on the positive side. The negative peak represents a less developed/built up area, while the positive indicates more developed areas. The range of the distribution of NDBI values is broad, ranging from -0.67 to 0.35, indicating the presence of both built-up areas and vegetated areas.

Figure 19 shows the distribution of NDBI values in 2022, with a mean of 0.176 which is not only higher than 2017 but is also positive. This indicates that in 2022 there was more urban development, but not to a great extent. Otherwise, the value would be closer to 1. The range of the distribution is wider in the positive axe, and shorter in the negative axe, with a high maximum of 0.65 that reflects a higher level of developed areas if we compare it to 2017. The minimum value, -0.04, also moved closer to zero, reflecting a reduction in the lands that are not developed. Overall, the histograms indicate that the area that surrounds Katoogo has undergone noticeable urban development between 2017 and 2022, likely due to urban expansion, or the filling of the wetlands that has already been documented[4].

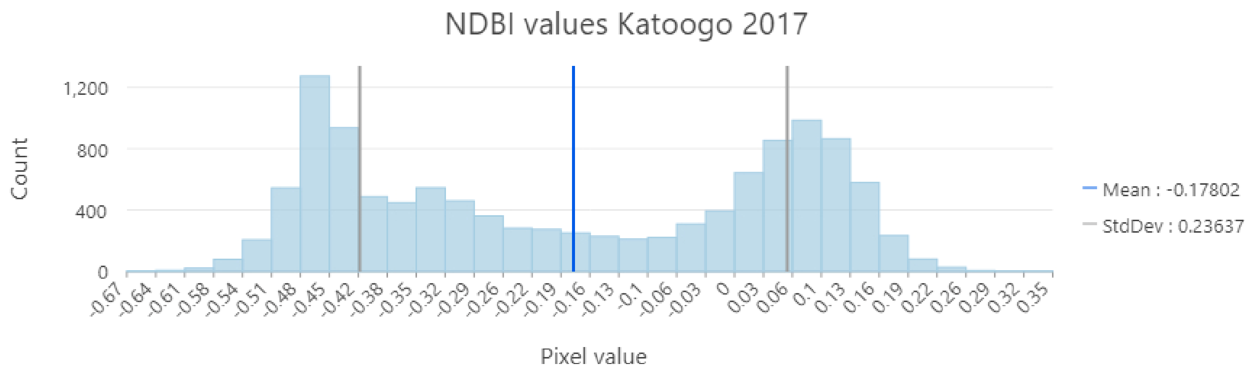


Figure 18: Distribution of NDBI values in the Katoogo area, 2017.

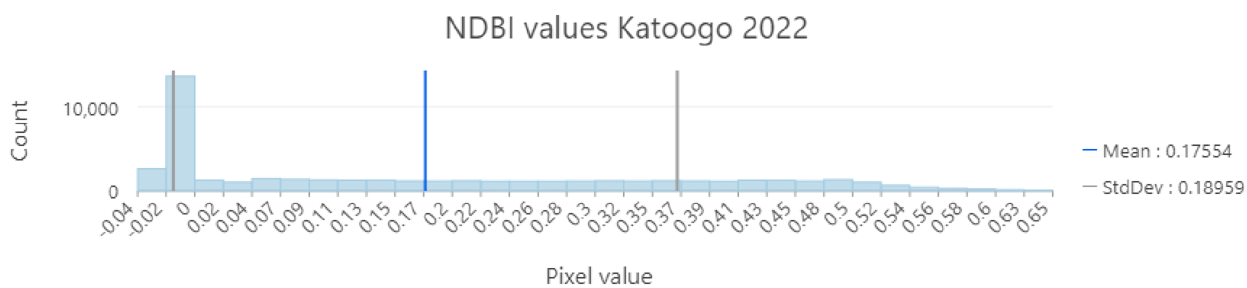


Figure 19: Distribution of NDBI values in Katoogo area, 2022.

	Minimum	Maximum	Mean	Standard deviation
2017	-0.67	0.35	-0.18	0.24
2022	-0.04	0.66	0.16	0.19

[4] https://africanarguments.org/2022/09/the-rich-are-untouchable-uganda-struggles-to-protect-its-wetlands/

Table 3: Summary of statistics for Kampala's NDBI.

Figure 20 visualizes how NDBI values are spatially distributed. Built up areas in 2017 look more concentrated, while in 2022 the distribution of those areas looks more homogeneous. Inversely, areas that didn't look that green in 2017 look greener in 2022. However, this only indicates there is concentration of non-built-up areas. There is more variability among different land uses in 2022 than there are in 2017, and we can conclude there has been more urban development in the surroundings of Katoogo from 2017 to 2022.

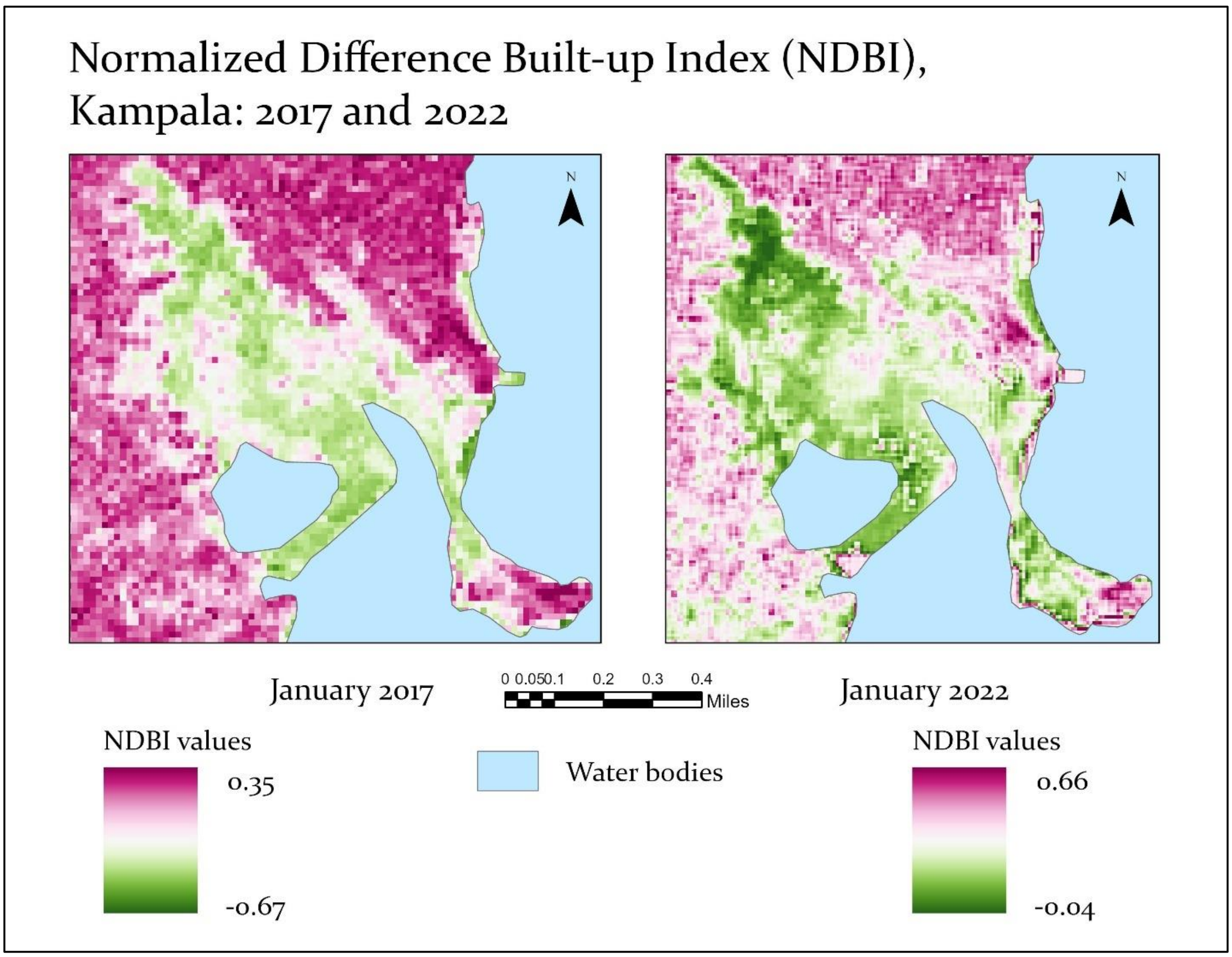


Figure 20: NDBI in Katoogo and surroundings, 2017 and 2022.

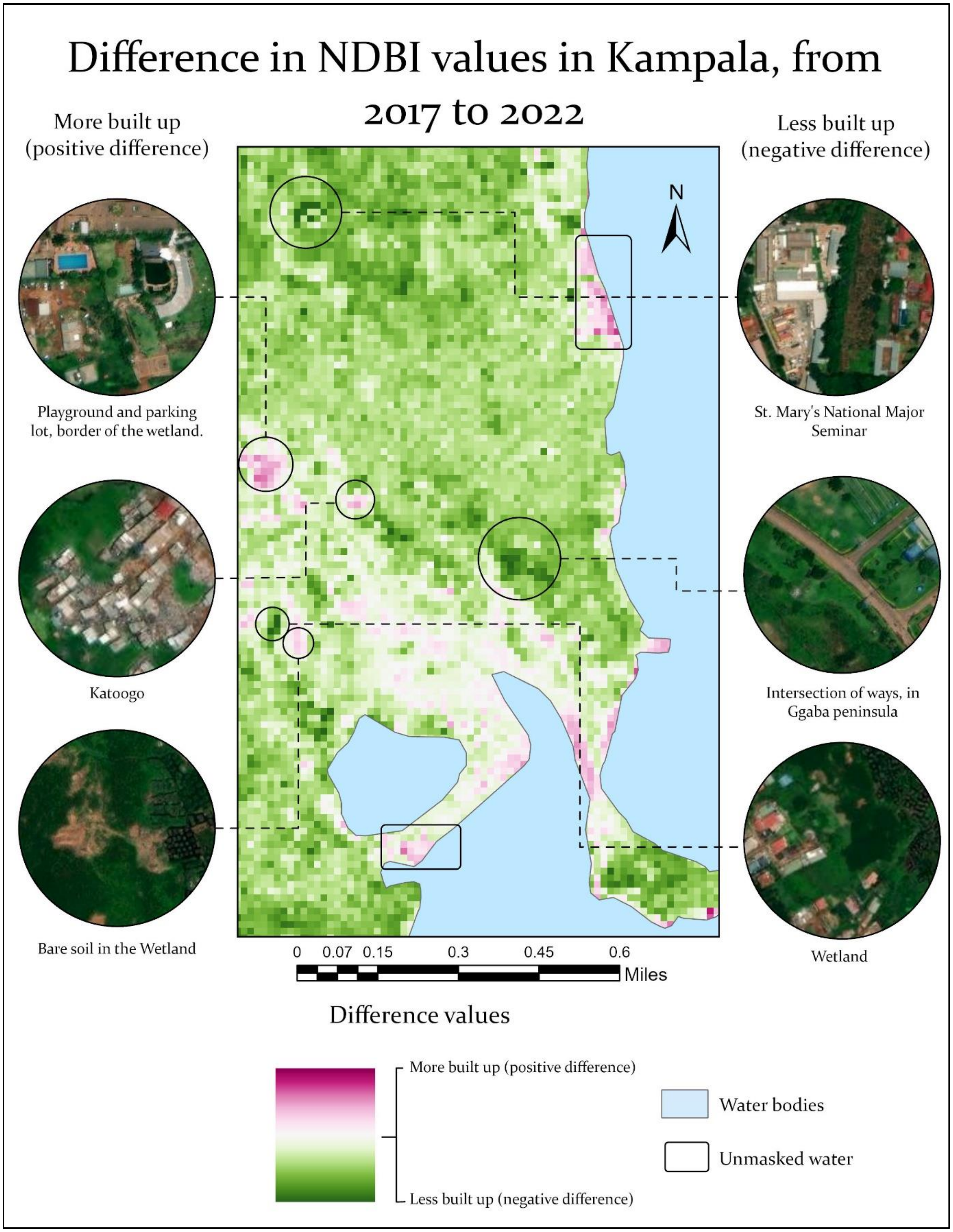


Figure 21*:* Raster reflecting the difference between the NDBI rasters of 2016 and 2022, with zoom to extreme values.

Figure 21 above provides a visual depiction of the difference in NDBI values for both years. In pink are the areas with an increase in built up areas (positive differences), while green means decrease in built up areas (negative difference). The map does not only highlight the differences, but also zooms in to areas with significant differences. In the areas that increased their built-up areas importantly, it's possible to see a greater development of residential areas. The first photo shown belongs to a neighborhood with safer house if compared to our second example of Katoogo village, which also evidences growth. Lastly, I highlighted a soil-filled area of the wetland that the NDBI raster was able to catch. It is likely that this area will be developed for housing. The areas showing a decrease in built up index are a building with a lawn that was potentially developed from one year to the other, a road intersection near Ggaba peninsula and a neighborhood close to the northwest border of the wetland. The highlighting of the road intersection is the first sign that this index is not able to make a difference between barren areas and urban areas.

Figure 22 zooms in on Katoogo Village and highlights areas of significant change. The area appears predominantly green, indicating a decrease in built-up areas. According to this index, Katoogo Village has predominantly experimented recess, and this can be observed because of most of the area being covered by green. There are very few areas that have expanded. In the middle, an example of the reduction in built-up areas is provided, showing that areas where houses existed in 2017 appear to be vegetated in 2022. One possible explanation for this decrease could be the encroachment of water into settlements near Lake Victoria's shore, as discussed in the background section. The destruction of homes and the progression of water into areas previously occupied by built-up structures may contribute to the observed decline in the index over time.

This index proved to be accurate, since it showed urban areas in higher values. However, and just like evidence suggested, this index considered bare soil as built-up, which makes the interpretation a little inaccurate. This confusion was much more noticeable when looking at the greater picture. When zooming into Katoogo village, and by comparing with Google Earth images, the index had a better performance.

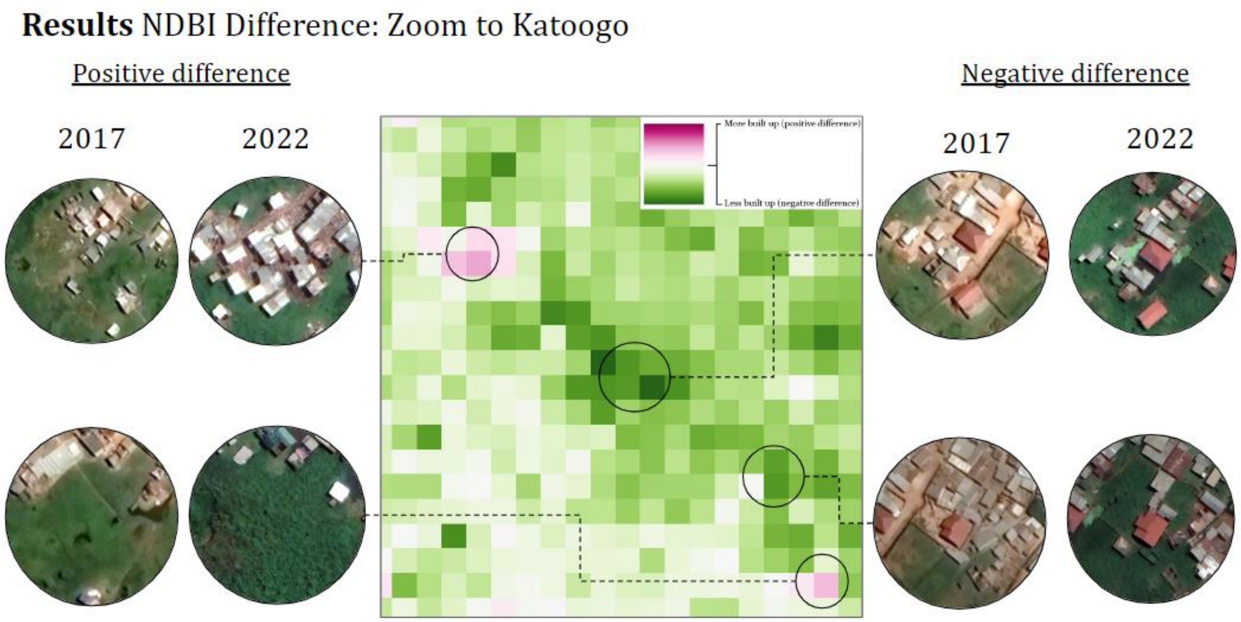


***Figure 22**:* NDBI difference zoom to Katoogo and Google Earth images comparison from one year to the other.

Puerto Varas

NDVI

The graphs below in **Figures 23** and **24** show the distribution of NDVI values for Puerto Varas. 2016 has very high NDVI values, with the distribution skewed to the right, with values very close to 1. Vegetation is predominantly healthy in this area, which is also reflected by the high mean value of 0.7. The small amount of pixel values below zero indicates the small quantity of land surface that is built up. On the other hand, **Figure 24** with the values for 2023 show a decrease in the range of the distribution, as well as in the mean value that goes down to 0.3. The distribution show peaks to the right of the mean, with most of the distribution showing a vegetation not as healthy as in 2023, but still moderately healthy. Non-vegetated areas are more abundant in 2023, reflected by the larger amounts of pixel values below zero. This means that the land is still predominantly non developed, however the vegetation healthiness decreased from 2016 to 2023, and non-vegetated areas increased.

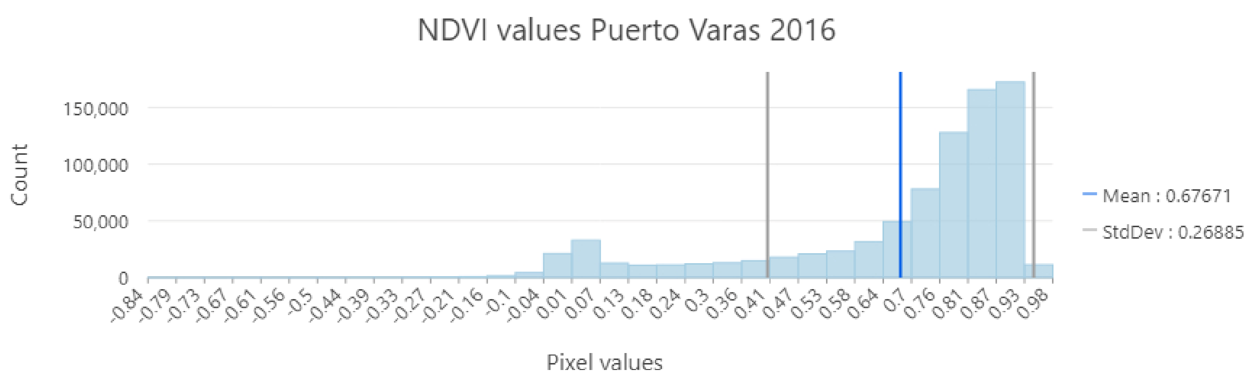


Figure 23: Distribution of NDVI values for Puerto Varas in 2016.

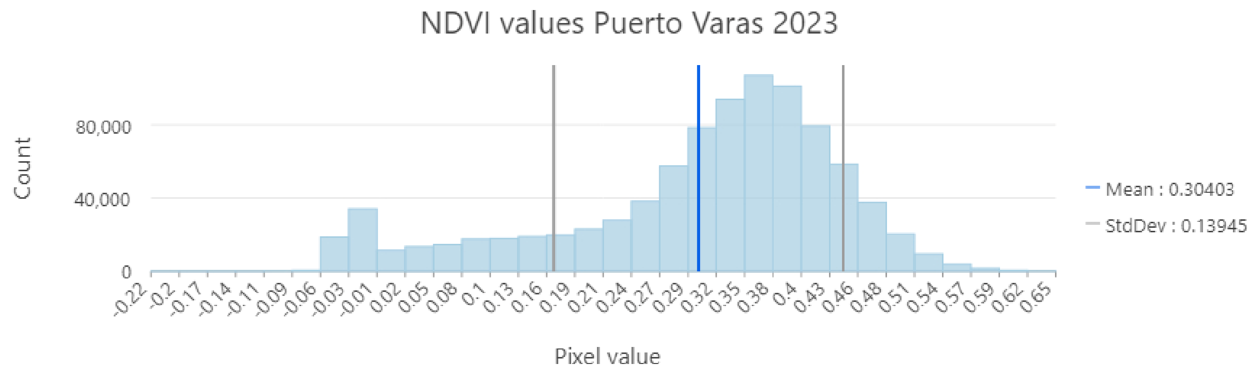


Figure 24: Distribution of NDVI values for Puerto Varas in 2023.

	Minimum	Maximum	Mean	Standard deviation
2016	-0.84	0.98	0.68	0.27
2023	-0.22	0.65	0.30	0.14

Table 4: Summary of statistics for Puerto Varas's NDVI.

Figure 25 shows the spatial distribution of NDVI values for 2016 and 2023. Between the two years, 2016 contains a higher level of healthier greener areas, while 2023 looks much drier. The area closer to the lake corresponds to the City of Puerto Varas, which explains the red. As we get away from the city, forests start to appear. The southwest area of the image is the one showing more recess in vegetation.

Something to note is that negative values (barren/urban/water) went up from one year to the other, which could be a sign of how the area has been seeing urban development in the last years, by getting rid of rainforest that surrounds the area.

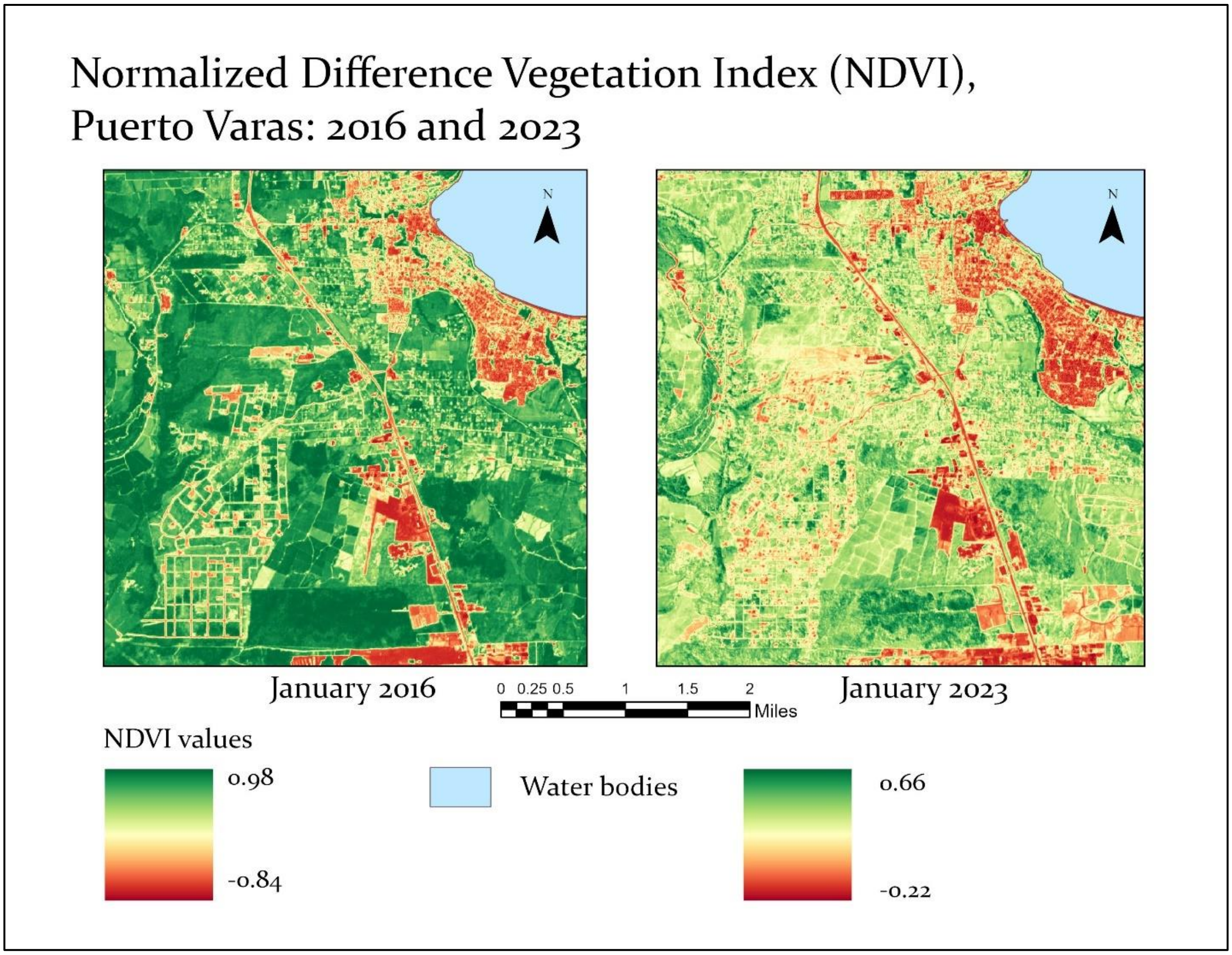


Figure 25: NDVI in Puerto Varas and surroundings, 2016 and 2023.

Figure 26 illustrates the year-to-year differences in vegetation health within a single image. Areas in green indicate significant increases in vegetation health, while areas in red show notable decreases. The figure also includes a zoomed-in view of some of these areas. Locations with "positive differences" (an improvement in vegetation health) include a parcel of land previously occupied by a land parcellation company and a cement factory. On the negative difference side (decrease in health vegetation), the most outstanding examples are two public housing developments happening on the outskirts of the city.

It is notable that a considerable increase in greener vegetation occurred in the residential area corresponding to Club de Campo Residencial. It would be interesting to know if the less healthy area in 2016 was in those conditions due to the preparation of the land to be built upon. Even though the map shows some green areas, the area mostly was hit by a vegetation decrease. We can conclude this by looking at the colors of **Figure 26**, most of them showing colors from yellow to red, a clear sign of loss in vegetation healthiness.

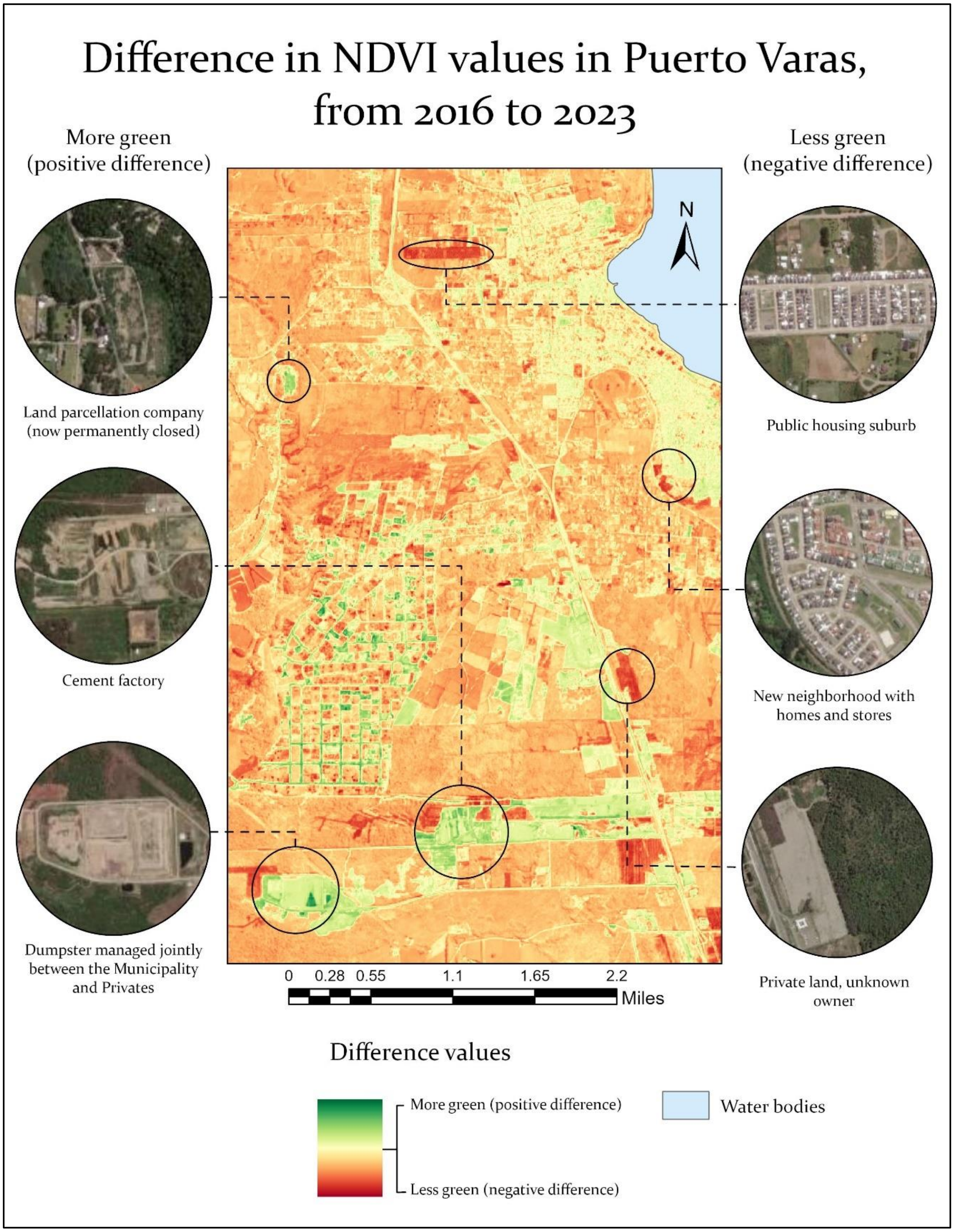


Figure 26: NDVI Difference in Puerto Varas area, from 2016 to 2023.

Figure 27 zooms in to Club de Campo Residencial condominium. It looks generally orange, meaning that vegetation decreased from 2016 to 2023. The green spots represent areas where vegetation health increased, many of which are along the roads where trees were planted. Larger green patches are visible in house patios, categorized under the "positive difference" title. Some areas appeared barren in 2016, likely because the land was being prepared for construction. In subsequent years, the houses appear established, with well-maintained gardens and surrounding forests.

The right side of **Figure 27** shows the negative differences, indicating areas where vegetation health decreased within the condominium. All selected examples are from areas that previously had forest or grass, but by 2023, had more houses, either already built or under construction, and new roads. The parcellations are especially evident in the first two images.

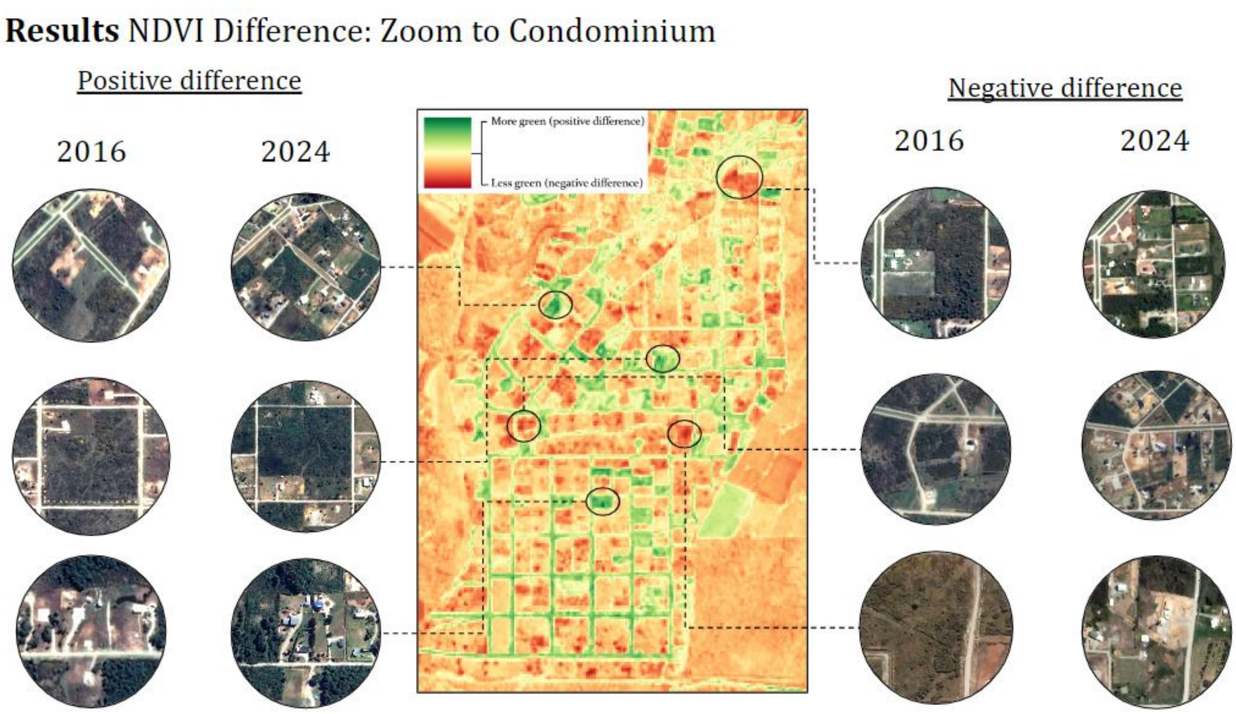


Figure 27: NDVI Difference: Zoom to Condominium.

NDBI

The results for this index show this region had predominantly non-built-up areas in 2016. This can be observed in the distribution of pixels in **Figure 28** and **29**, where most of the pixels are below zero. There was an increase in the built-up areas from 2016 to 2023, which can be observed by looking at the pixel distribution for this last year, with a curve more skewed to the right and more balanced on both sides if we focus on the mean, but still predominantly in the negative axes.

This is the first time a result for the indexes raises questions for me. If we look at the values distribution in **Figure 28**, we will see that the higher value is 1, while for 2023 is 0.23. This makes me think there was an error in the image processing that would require more time to understand. After pixel value 1, there are many other high numbers that vanish once we move to 2023. This story would make sense if we consider that some of the condominium developments were stopped in 2021 after the City Hall found out about their unlawful existence. However, if we zoom in to these high values, we will see they are not urban-barren areas that turned into a forest: they are stagnant water bodies. This is the first time the index doesn't work well and does not show what is supposed to show, confusing stagnant water with developed land.

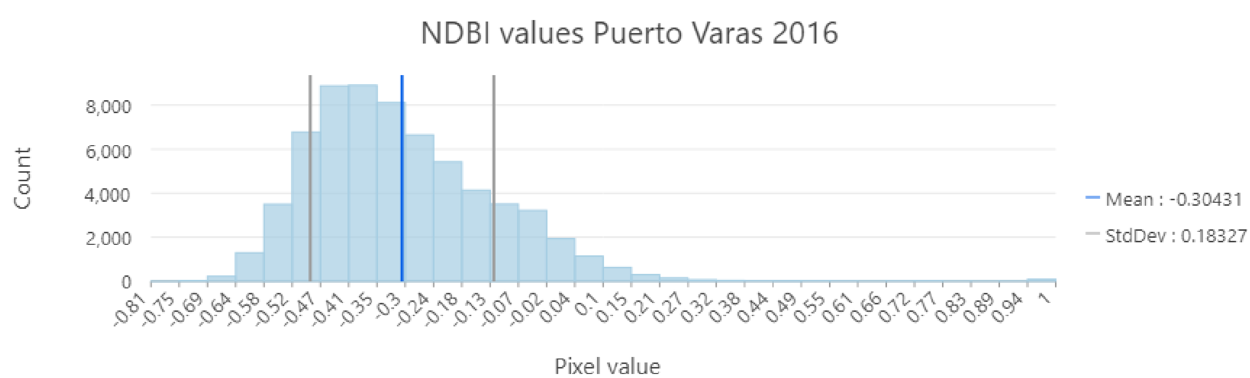


Figure 28: Distribution of NDBI values for Puerto Varas in 2016.

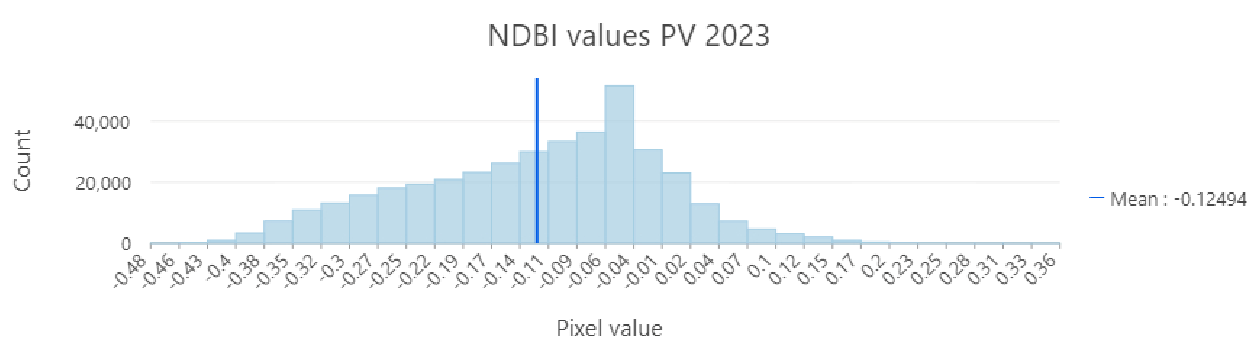


Figure 29: Distribution of NDBI values for Puerto Varas in 2023.

Figure 30 illustrates the two rasters obtained when running NDBI for both years, allowing a visual comparison. At a first glance, it can be observed that 2016 urban areas were scarcer, while in 2023 urban areas are easier to spot, and in fact the image looks much pinker than in 2016, indicating an increase in NDBI values in general. There is an important advance of urban areas within the already existing city, its near surroundings and the roads that get there. Suburban areas are clearly developed in 2023, very different from 2016 where most of the image looks like deep forest surrounding the city of Puerto Varas.

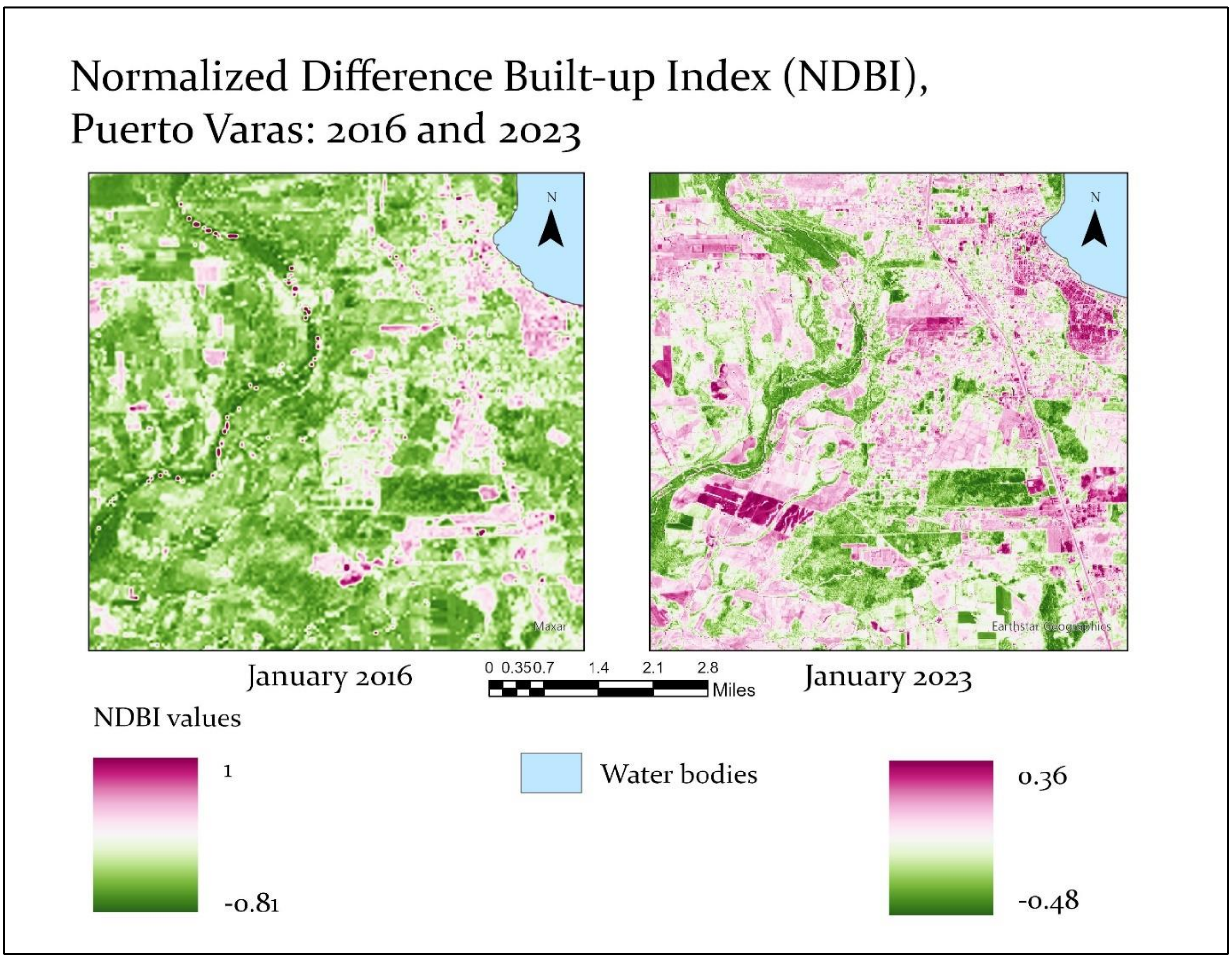


Figure 30: NDBI in Puerto Varas and surroundings, 2016 and 2023.

	Minimum	Maximum	Mean	Standard deviation
2016	-0.81	1	0.3	0.8
2023	-0.48	0.36	0.1	0.1

***Table 5**:* Summary of statistics for Puerto Varas's NDBI.

Figure 31 below shows the differences between the two years, highlighting the areas where significant changes occurred. Zones with a substantial increase in built-up areas from 2016 to 2023 are depicted under "positive differences." The examples provided include the development of a dumpster where residents of Club de Campo Residencial recently started disposing of their trash, as well as a forest, and a new condominium project, also developed under the figure of parcelas de agrado, which began in 2016 and is now fully built.

On the "negative differences" or the places where urban areas have decreased from year to year, the highlighted areas are not actually urban in 2023, nor were they in 2016. This raises questions about whether the NDBI index worked as expected and possibly confirms findings from the literature review: that NDBI may not effectively differentiate between urban and barren areas.

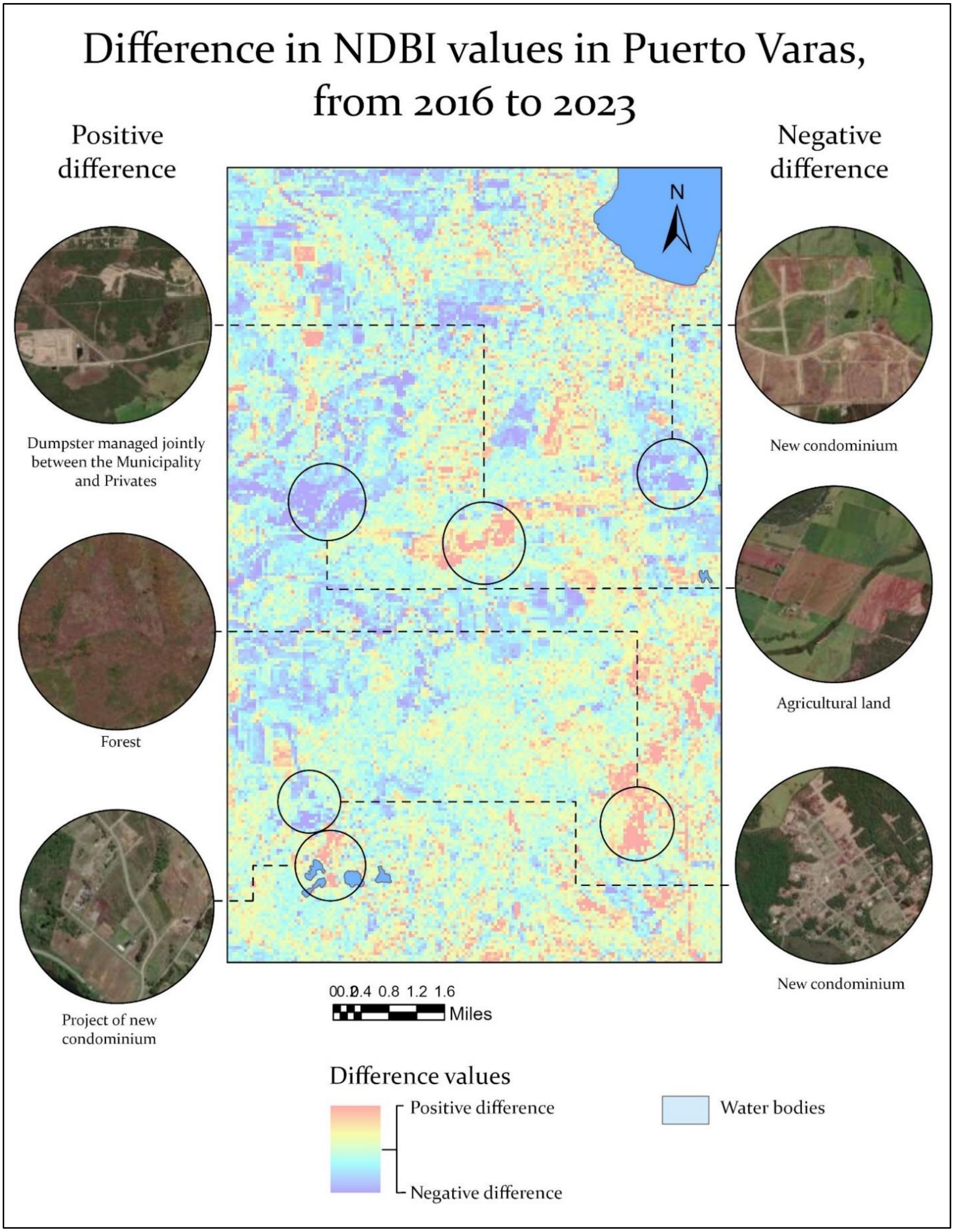


***Figure 31**:* NDBI Difference in Puerto Varas area, from 2016 to 2023.

Now, when zooming into the condominium as depicted in **Figure 32**, it is possible to see that the increase in urban areas (positive difference) is represented by more roads, more homes, clearer land parcellation, and occasional loss of vegetation. On the right, the negative differences, or the decrease in urban areas, are shown. However, these negative differences display a pattern very similar to the positive differences, including parcellated lands, an increase in road and house building, and a regression of forests. This confirms what was stated in the previous paragraph: even though the numbers indicate that urban areas increased in Puerto Varas, specifically in the condominium and its surroundings, and this seems to be true when comparing Google Earth images, the NDBI index does not perform well in this area. It detects barren areas as built-up areas, complicating the effort to determine whether built-up areas have increased in this settlement or not.

This makes me conclude that NDBI didn't have a good performance in this area that is mostly surrounded by vegetation. In the greater picture, it confused urban areas with stagnant water, while when zooming into the area it wouldn't make a clear difference between urban and non-urban. This is a challenge when trying to address the expansion of the settlement, because if this index doesn't work correctly is hard to get an idea of the extent of the urban development in these more remote areas.

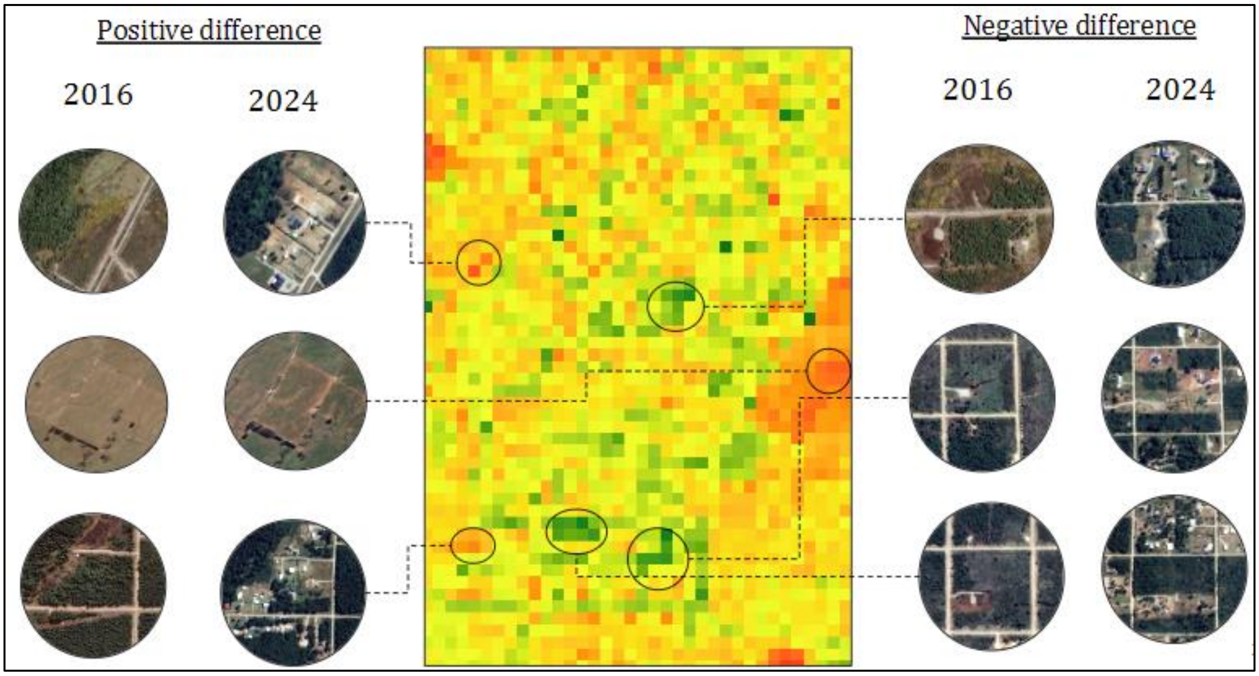


Figure 32: NDBI Difference: Zoom to Condominium.

Comparison between Kampala and Puerto Varas' informal settlements

This section compares the performances of NDVI and NDBI in assessing vegetation health and urban growth in Katoogo, Kampala and Club de Campo Residencial, Puerto Varas.

Normalized Difference Vegetation Index (NDVI)

NDVI effectively captured changes in vegetation health both in Katoogo and Club de Campo Residencial. For the first location, it highlighted the increase in the index in areas where water level raised and entered the settlement, forcing people to move away from their homes and letting vegetation grow due to the abandonment of those specific areas of the settlement, as can be observed in **Figure 17**. Vegetation healthiness doesn't seem to be attributable to policy decisions on improving the neighborhood by adding more green areas, for example. A question that raises is the highlighted areas belong to areas of Katoogo that were evicted in the past, and therefore vegetation started to grow after people left, or if people living there made the decision of leaving when they found out that Lake Victoria water levels were raising and getting into the houses. On the other hand, Club de Campo Residencial NDVI showed a successful performance as well. The index was effective in identifying large-scale agricultural land and parcels. Differently than Katoogo, the increase in vegetation came from private agents (families) working on their home gardens, planting new trees and extending patches of lawn that are irrigated daily, reflecting the green that is captured by the larger NDVI numbers.

NDVI	Katoogo		Club de Campo Residencial	
Year	**2017**	**2022**	**2016**	**2023**
Mean	-0.18	0.175	0.7	0.30
Maximum	0.8	0.67	0.98	0.7
Minimum	-0.18	-0.07	-0.84	-0.22

Table 6: Katoogo & Club de Campo Residencial Statistics comparative table.

In these two very different locations, NDVI performed well. Katoogo got smaller numbers because it's an area that is largely urbanized, while Puerto Varas is surrounded by agricultural land and forest, and is developed to a lower extent. Not only is Puerto Varas not developed, but is surrounded by very healthy vegetation, expressed by its larger means compared to Katoogo. Decrease in NDVI happened in both locations, but Puerto Varas had a large decrease in the index. The main differences come from the reasons why changes happened. A shared result for Katoogo and Club de Campo Residencial is that increases in NDVI indexes didn't come from local government's actions and was not a part of the City's plan.

Normalized Difference Built-up Index (NDBI)

In Katoogo, NDBI had a good but not flawless performance. As the literature review warned, it confused urban and barren areas. This issue occurred more frequently in Club de Campo Residencial, likely due to the larger portions of unoccupied land that could be easily mistaken for urban areas. Google Earth photos of Katoogo and its surroundings show that it is in an already developed area, whereas Club de Campo Residencial is surrounded by agricultural land that has not yet been developed.

NDBI	Katoogo		Club de Campo Residencial	
Year	**2017**	**2022**	**2016**	**2023**
Mean	-0.18	0.16	0.3	0.1
Maximum	0.35	0.66	1	0.36
Minimum	-0.67	-0.04	-0.81	-0.48

Table 7: Katoogo & Club de Campo Residencial NDBI Statistics comparative table.

NDBI could be used to assess urban expansion in Katoogo if supplemented by other indexes that can compensate for its weakness in differentiating urban from barren areas. The poor performance of this index in Club de Campo Residencial suggests the need to try other built-up indexes that are more effective in rural environments.

Chapter 6: Summary

Conclusions

This thesis could partially address the question of how vegetation and built-up areas have changed in these two settlements. The first section of the question was answered through the use of NDVI, showing that vegetation has generally decreased in both locations. NDVI is a reliable indicator, despite the weather differences and distance between the two locations of Kampala and Puerto Varas. The comparison of the resulting NDVI rasters with Google Earth images proved that high values did show healthy vegetation. NDVI values generally decreased in the two locations of interest, indicating a reduction in vegetation cover.

The second part of the research question on how have built up areas changed was addressed using the NDBI. The values for this index increased in both locations, signaling potential urban expansion potentially at the expense of vegetation cover. However, NDBI's reliability is compromised by the index's tendency to confuse urban and barren areas, and even stagnant water, as well as its performance depending on the surrounding areas: it worked better in areas that are already more urbanized like Kampala and was not good at showing urban areas in Puerto Varas where more rural lands surround the city.

NBAI was not enough to answer the question of how have built up areas changed; however, I believe I am close to an answer, and for this I would need to make the proper transformations to be able to use this index with Sentinel-2 images.

The three indexes together can provide a general idea of the expansion of these two kinds of informal settlements, observing that when NDVI goes down, NDBI/NBAI goes up, and vice versa.

The combination of these indexes could help policy and decision-makers to develop more targeted and effective strategies for managing urban growth and preserving green spaces in rapidly developing areas. This integrative approach can guide interventions aimed at balancing urban development with environmental sustainability, ultimately leading to more resilient and sustainable urban environments.

Policy Implications

The findings from this study underscore the importance of integrating environmental studies into city planning processes, particularly using remote sensing and satellite imagery. These tools offer a valuable means to track urban and environmental changes, providing crucial data to inform decision-making.

Municipalities must extend their planning efforts beyond city limits, especially in areas experiencing informal housing growth and significant vegetation loss. Expanding municipal authority to include adjacent areas, which share similar needs as urban regions, is essential for comprehensive and effective planning. This broader jurisdiction will enable municipalities to address the challenges posed by informal settlements and environmental degradation.

Enforcement of land use regulations and control over expansion areas are critical to managing urban growth and protecting natural resources. As urban areas continue to expand, it is imperative that policies are implemented to provide adequate housing solutions for newcomers while simultaneously safeguarding the environment.

The differential expansion observed in various settlements highlights the need for tailored urban planning and resource management strategies. Local governments must develop adaptive approaches to address the unique challenges posed by differing patterns of expansion.

The use of indices offers a cost-effective method for policymakers and stakeholders to monitor urban expansion. By regularly deploying these tools, they can achieve near real-time tracking of changes, which supports more informed and responsive decision-making. Continued use and refinement of these indices will enhance the ability to manage urban growth and environmental impact effectively.

Limitations and challenges

In terms of the study area, it was limiting not to have personal familiarity with Kampala. Satellite imagery provides a valuable resource for studying areas that we may never visit. Despite my efforts to familiarize myself with Kampala's weather, vegetation, and architectural materials, there are nuances that I may not fully grasp without firsthand experience. While one visit alone may not provide a comprehensive understanding, it would at least offer more insight into the local context, cultural dynamics, and on-the-ground realities that are often missed in remote sensing data. This firsthand experience could enhance the interpretation of satellite imagery and lead to more accurate conclusions. Future research should consider integrating field visits with remote sensing analysis to bridge the gap between data and real-world conditions, ensuring a more holistic understanding of the study area.

Continuing with the study area, it was challenging to find sufficient research on wealthier informal settlements. This presents both an opportunity to contribute to knowledge in a field with limited research and a challenge in determining the most relevant questions, methods, and conclusions.

Regarding the quality of available imagery, images were provided in two formats depending on the year. In some cases, bands with higher resolution (10m) were also available in lower resolutions (20m and 60m), allowing for the interchangeable use of bands when constructing indices. However, for other years, images were only available in their original resolution. Therefore, when constructing indices that incorporated bands of different resolutions, raster resizing was necessary.

During this process, the higher-resolution image had to be downsized, resulting in the loss of valuable details and impacting the analysis.

Finally, the insufficient evidence regarding the performance of the NBAI with Sentinel-2 images made it challenging to interpret the results obtained. I even reached out to the creator of the index to understand the discrepancies, and he suggested that the values of my Sentinel rasters differed significantly from those of Landsat. While this presents an opportunity to generate new evidence, it is challenging to proceed without existing references to guide and help interpret the results.

Future work

There is more work to be done regarding indices, especially concerning built-up areas. Additional time would allow us to explore other built-up area indices among the many existing ones. Research indicates that their success depends heavily on the characteristics of the study area. NBAI may not be the most suitable index to use in the Puerto Varas area, suggesting the need for future research to continue exploring other indices that can effectively distinguish between urban areas and bare soil, which is the most challenging aspect of using built-up indices. In this sense, an alternative to relying on indices could be using machine learning to detect urban areas and bare soil. With sufficient training, the model would have the ability to discriminate between the two.

Future research should delve into more detailed analyses of index changes over time. One approach could involve analyzing images from every month of the year, regardless of the season, and calculating an average index (such as NDVI, NDBI, NBAI, and other useful indices) for each season or year. This would capture patterns more effectively and address the issue of how representative an image from a single year can be.

Regarding different techniques that could contribute to this field, it would be interesting to perform supervised classification in both areas and leverage machine learning tools available in

ArcGIS Pro and ENVI to train a model capable of detecting the locations of these two types of settlements. This would expand the methods available for tracking changes and enable real-time detection not only of their expansion but also of the number of parcels present.

An aspect that could be beneficial for future studies in the Puerto Varas area is obtaining the results of the recently conducted 2024 Census throughout the country. The Census results will provide an accurate count of how many new households and houses are in the area, as well as demographic information about the people living in the settlements of interest. Moreover, comparing the real numbers with the projected population growth in this area will give an idea of how accurate the projection was. This is information that I am eager to have available, as is the Puerto Varas City Hall, which believes this new Census will help them gain a clearer picture of the current situation regarding the informal wealthy developments that have occurred in recent years.

Additionally, to enhance the availability of information, more studies can be conducted using higher-quality imagery. While Sentinel-2 is an excellent source of information, it would be valuable to compare its use with Maxar or other high-resolution imagery. However, it's worth noting that these images come at a cost (ranging from $156.25 to $568.75 per square kilometer, according to a conversation I had with a team member of a Maxar reselling company), which is always a scarce resource when conducting research.

Appendix 1

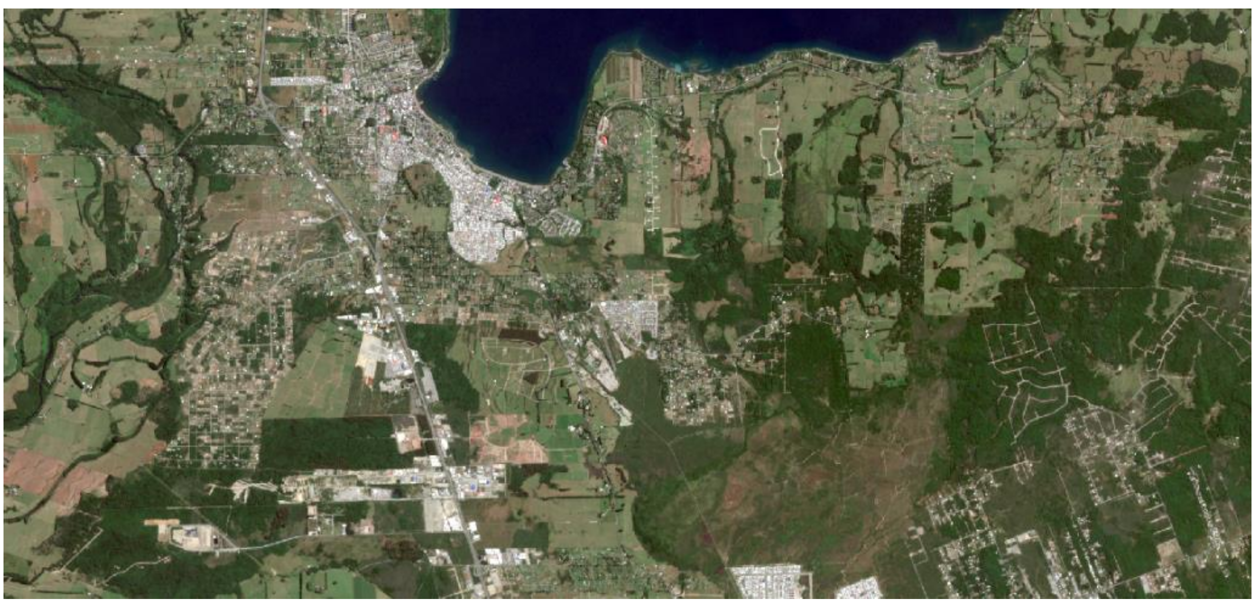
Rasters used

Clipped raster of Kampala area 2017

Clipped raster of Kampala area 2022

Clipped raster of Puerto Varas area 2016

Clipped raster of Puerto Varas area 2023



Appendix 2

NBAI Results

Kampala

The distribution of pixel values for NBAI in this location is narrow, with variation limited to just a few percentage points. As stated in the Methods section, I expected the values to range from -1 to 1. However, in this case, the variation is confined to the right tail of the distribution. This suggests that the entire image corresponds to urban areas, which contradicts our expectations. The values are consistently positive and concentrated on the higher end of the distribution. This result is unexpected because the index is designed to show a broader range of variation and, like other indices, is intended to operate within an interval of -1 to 1. The limited distribution observed may be due to the index's design for use with Landsat images.

Continuing with the analysis, **Tables 33** and **34** show that the mean value of NBAI grew from 2017 to 2022, meaning that urban areas grew from one year to the other. **Table 8** shows the minimum NBAI values grew from 2017 to 2022, but maximum values stayed the same. The mean grew, giving us a sense that urban expansion happened between the two years.

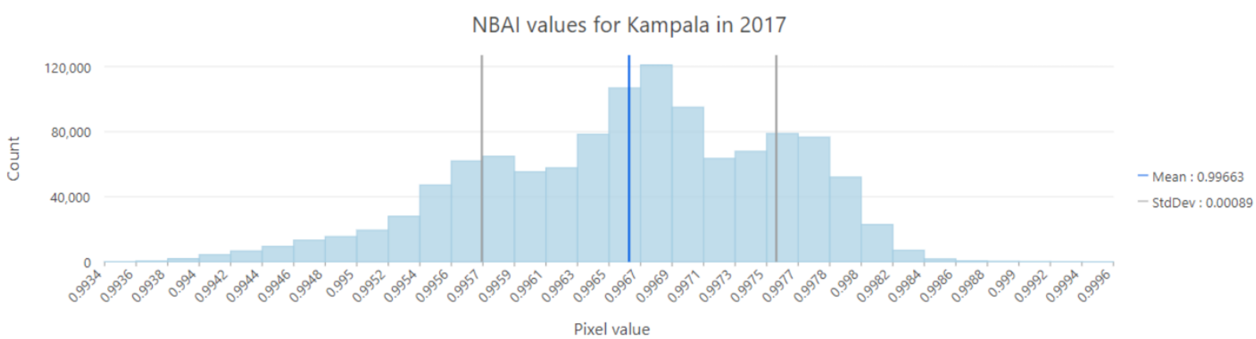


Figure 33: Distribution of NBAI values for Kampala in 2017.

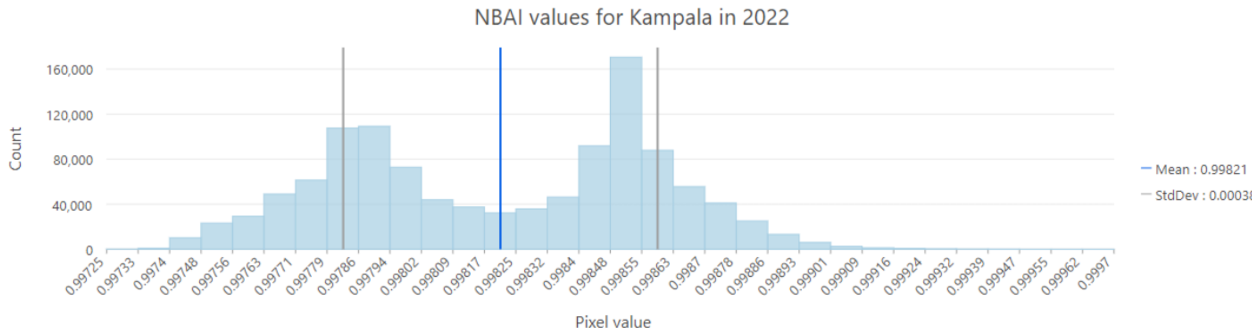


Figure 34*:* Distribution of NBAI values for Kampala in 2022.

	Minimum	Maximum	Mean	Standard deviation
2017	0.993	0.999	0.996	0.00089
2022	0.997	0.999	0.998	0.00038
Difference	0.004	0	0.002	-0.00051

Table 8*:* Summary of statistics for NBAI in Kampala.

Figure 32 visually displays the geographic distribution of NBAI values. Darker purple areas show urban areas, and in orange are the non-urban areas. This somehow matches the reality: the wetlands appear orange. However, when looking into the details of what was detected as "urban" discrepancies arise.

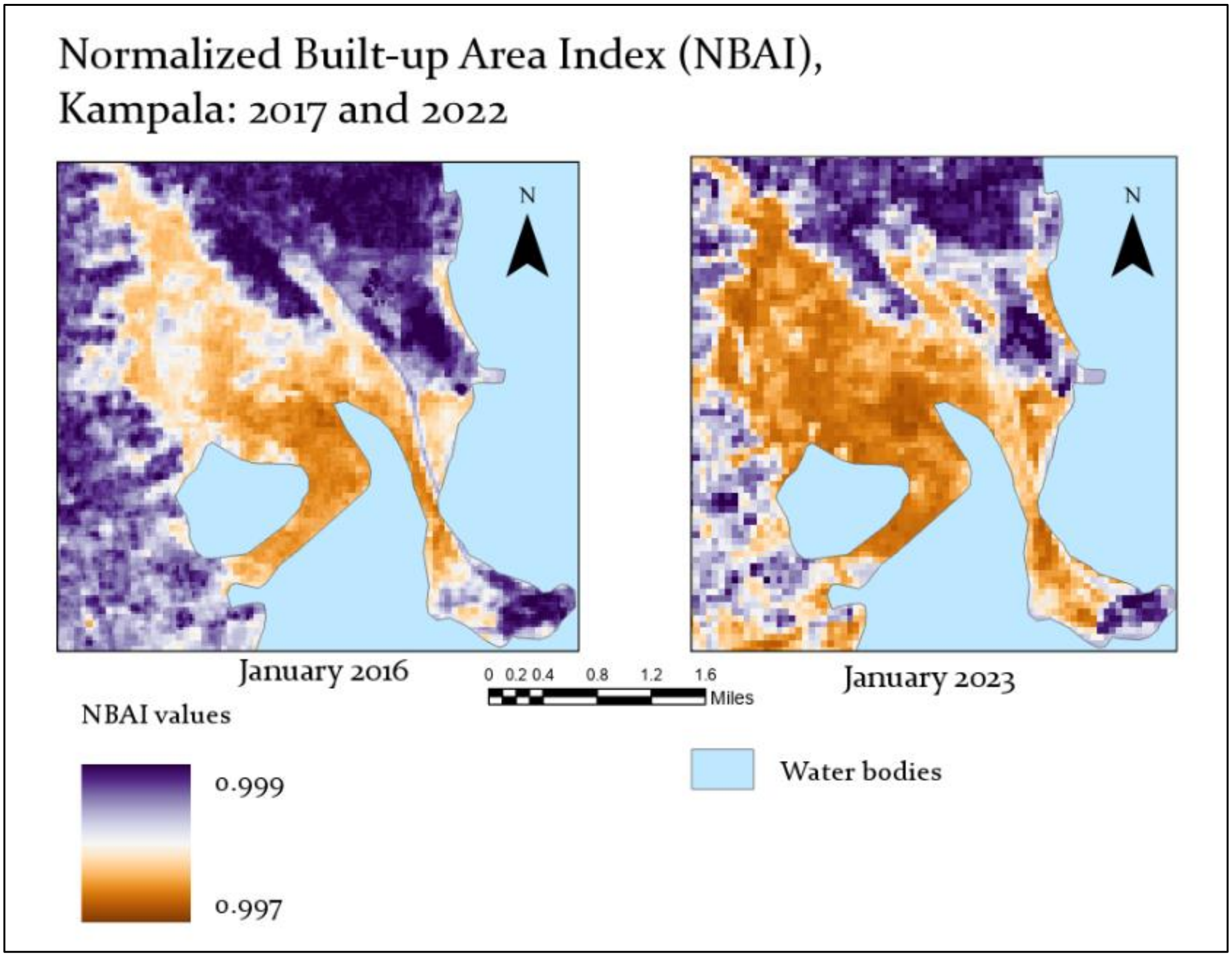


***Figure 35**:* NBAI in Katoogo and surroundings, 2017 and 2022.

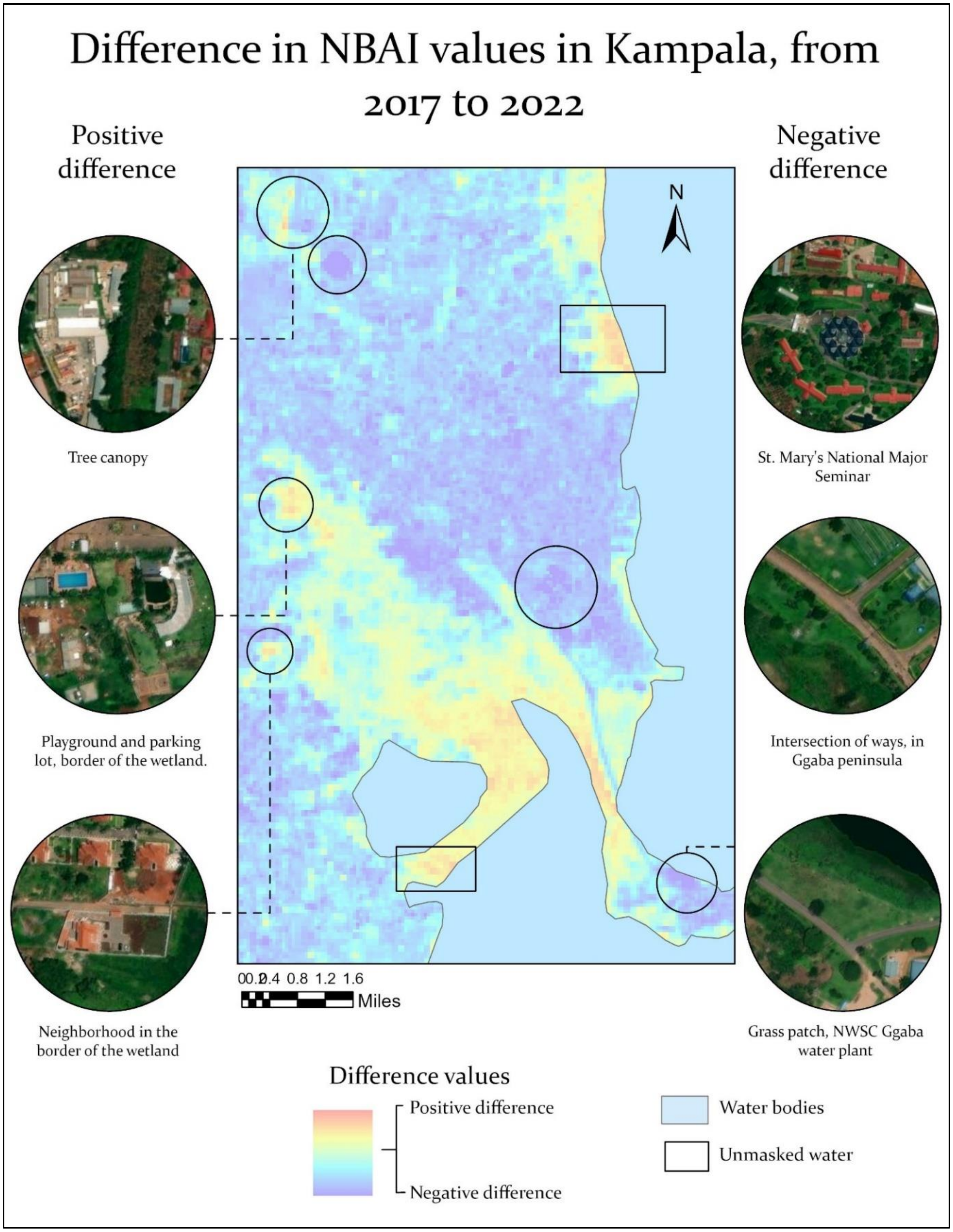


Figure 36*:* Raster reflecting the difference between the NBAI rasters of 2017 and 2022 in Kampala, with zoom to extreme values.

Furthermore, the NBAI results indicate that the Katoogo informal settlement has not significantly expanded during this period. Even though some areas have, the significant changes in NBAI have not happened within Katoogo Village.

Puerto Varas

Figures 37 and **38** show the results for the distribution of NBAI values in 2016 and 2023. The first thing to note, just as it happened in with Kampala's NBAI, the pixel values are only in the positive side, instead of the expected positive and negative results. Regardless of this detail, there is an increase in the NBAI mean value from 2016 to 2023. If we could trust this index, we could say there was an increase in urban areas. This conclusion would make sense because more area was constructed in 2023 if compared to 2023. However, we can't conclude this only by looking at this index. Indeed, by

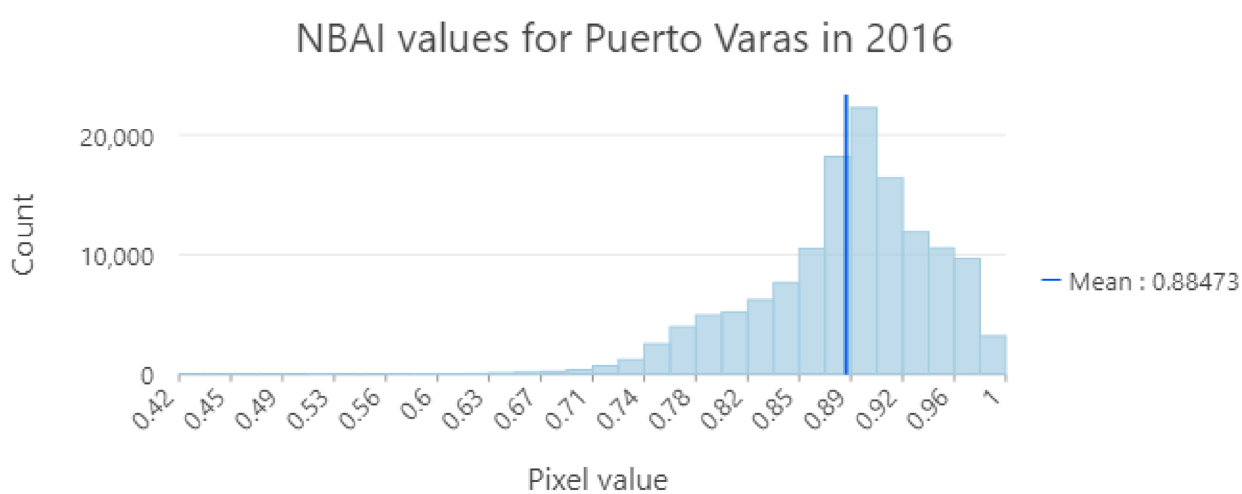


***Figure 37**:* Distribution of NBAI values for Puerto Varas in 2016.

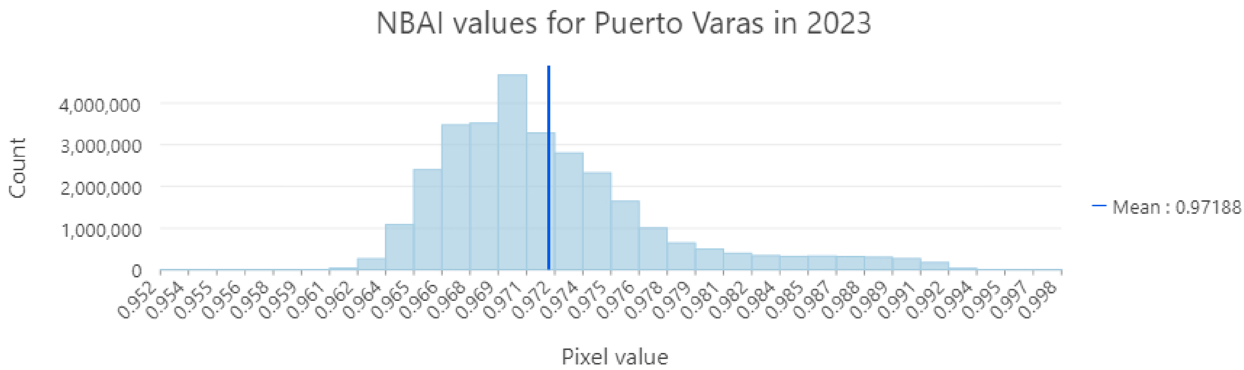


***Figure 38**:* Distribution of NBAI values for Puerto Varas in 2023.

Looking at **Figure 39**, the results appear confusing. In 2016, the range of values is wider, with higher values represented in dark purple, indicating built-up areas. The 2023 results seem reasonable, but the range of values is too narrow. If we assess the results based on value ranges alone, we might conclude that everything in the image is urban, as all values are positive and indicate some level of urbanization. However, analyzing the higher and lower values shows a pattern where higher values represent urban features like asphalt, streets, and houses, while lighter colors represent forest, lawns, or water. There might be an issue with the value range in Sentinel images that needs adjustment for accurate NBAI calculation. The current results only partially make sense, and further exploration is needed to accurately calculate NBAI with Sentinel images and obtain values that align with the expected outcomes for this index.

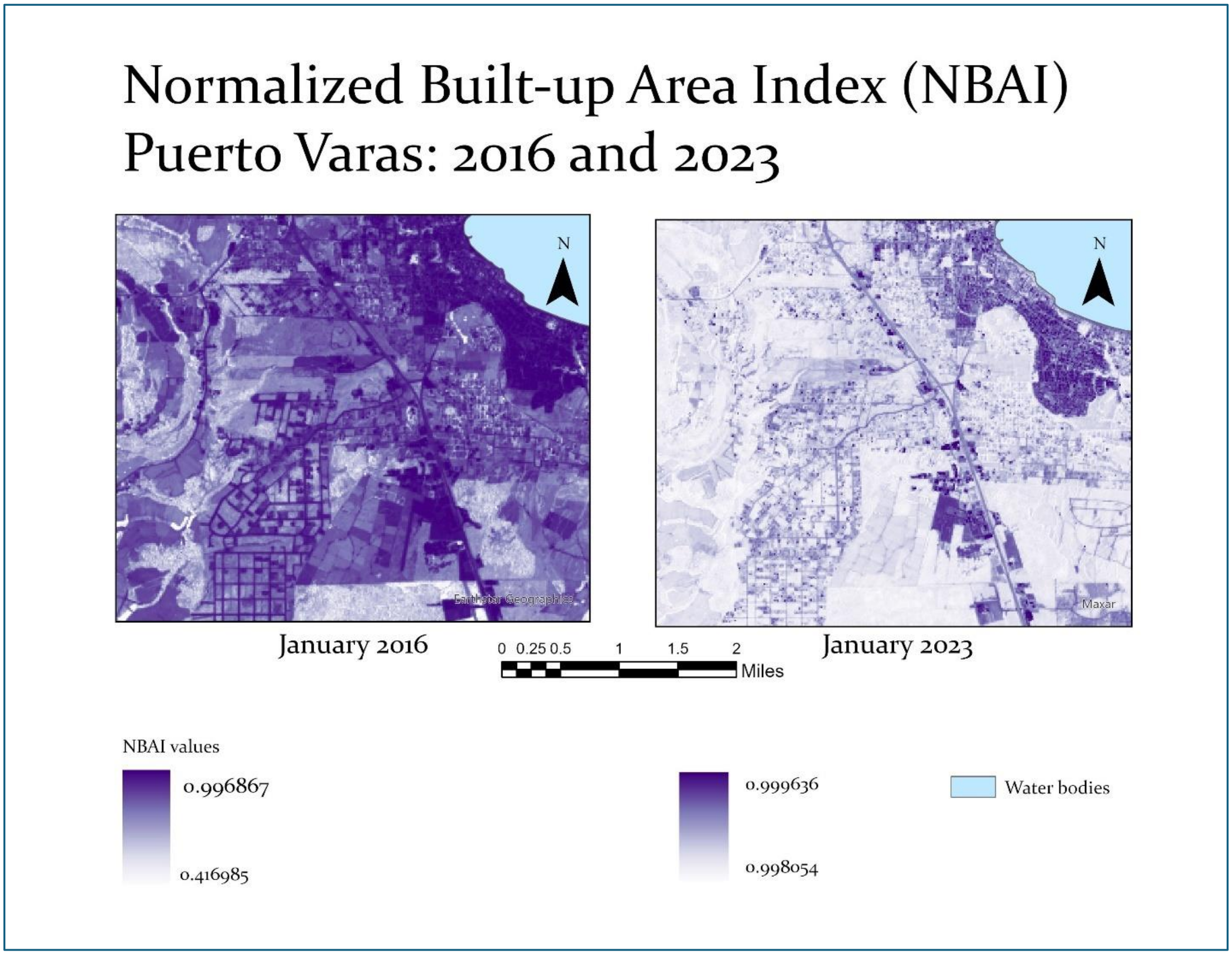


***Figure 39**:* Puerto Varas and surroundings, 2016 and 2023.

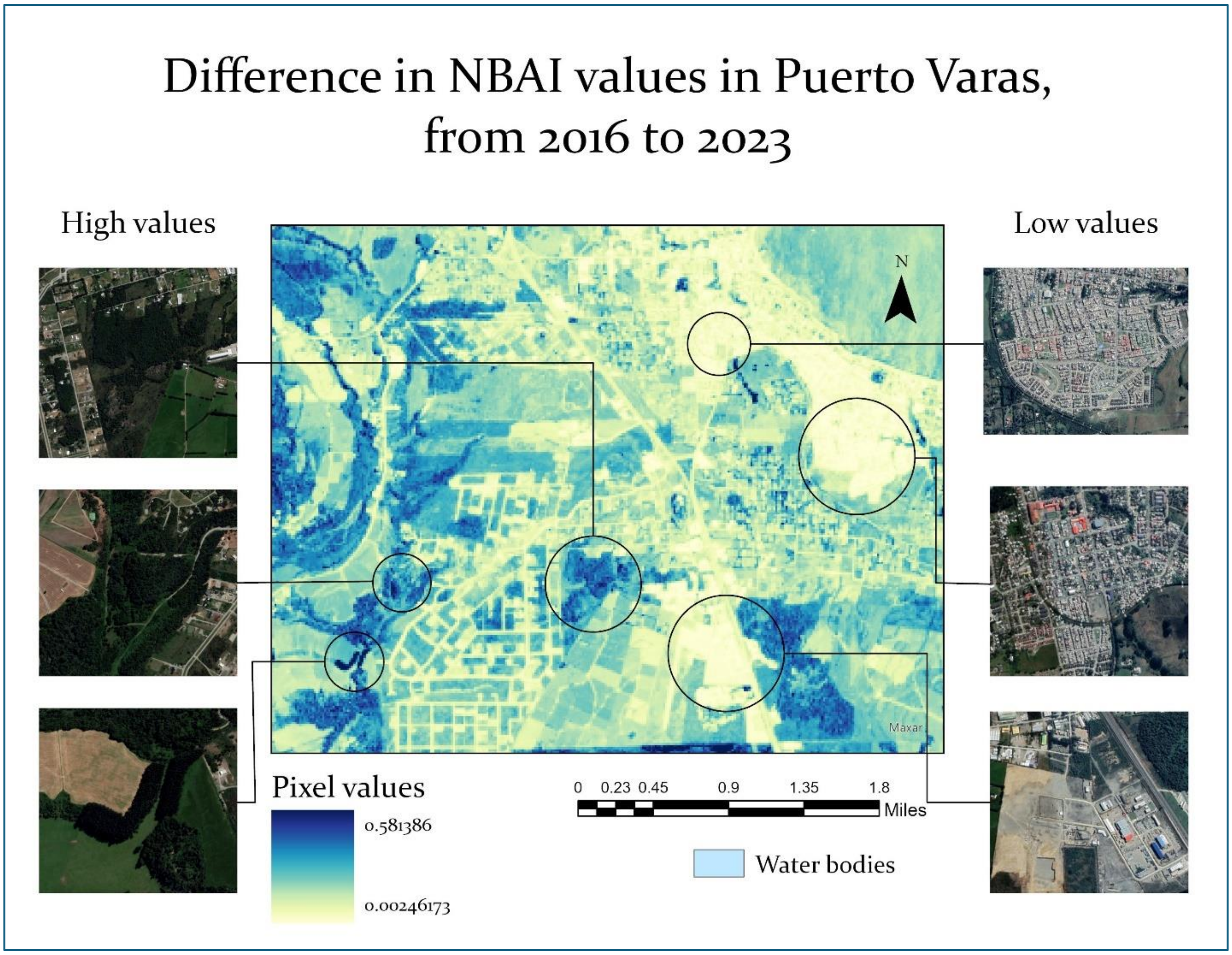


Figure 40*:* Raster reflecting the difference between the NBAI rasters of 2016 and 2023 in Puerto Varas, with zoom to extreme values.

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