Remote sensing for environmental assessment in the context of humanitarian emergencies: a case study of Ethiopia, Gambella region, in Africa

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Abstract. The improvement in remote sensing techniques to obtain environmental information, coupled with a significant expansion in the number of refugee camps, in their size and longevity, and in their impacts on natural resources, has increased the need for better information about the nature of those resources and their resilience to human demands. Large and fast-growing refugee camps place heavy demands on areas to locate new arrivals and may have long-lasting impacts on land cover and land use, forest degradation, environmental services and social dynamics. In this context, the role of remote sensing is becoming increasingly popular in the field of humanitarian action, as it is an independent and reliable source of information and allows both a quick response to emergencies and the monitoring of gradual changes, especially when field observations in the area are not possible. This study was chosen to adhere to the "traditional" meaning of refugee and managed settlements in Africa, under the UNHCR mandate. As a result, certain groups, such as returnees or internally displaced people, as well as city slums and locations of dispersed or informal settlements, were left out of the selection process. The main goal of this study is to use remote sensing to analyse significant land cover changes relatable to refugee camp settlements. The Gambela region of Ethiopia was selected as a region of interest. Already in 2016, several sources reported Ethiopia to be within the top 6th refugee-hosting country worldwide, with the Gambela region having rich natural resources but hosting the country's largest refugee population. Most refugees are from South Sudan and live in seven refugee camps. The four biggest camps, Nguenyyiel, Tierkidi, Jewi, and Kule, were selected to conduct the study. A comprehensive and multidisciplinary literary review investigated existing RS application studies, historical developments, and social and state patterns. C-band synthetic aperture radar (SAR) from Copernicus Sentinel-1 and USGS Landsat-8, Level 2, Collection 2 imagery are used to compare and analyse vegetation cover and land use and land cover changes (LULCC) over a ten-year time series analysis period. Despite several limitations found in assessing optical imagery, SAR data was revealed to be a good alternative. These last have been pre-processed, including radiometric calibration, geocoding, and excluding speckle filtering. A composite time series raster image with a 10-meter resolution was created to display an RGB layer representing buildings and shelters' presence over the years. As a result, this study found a correlation between the trend of SAR backscatter values and refugee population growth, paving the way for future investigations.

1. Introduction

In recent years, both newspapers and the scientific community have discussed migrations and climate change more often, and diverse linkages are still being explored as the world is facing the most severe refugee crisis in history. Natural hazards, climatic and environmental changes, violent regional conflicts and population growth force people to migrate to all parts of the world. Already in 2012, it was estimated that over 15 million people were officially considered international refugees and another 28 million as Internally Displaced People (IDPs) (Braun & Hochschild, 2015), which number is still growing every day (Braun & Hochschild, 2015; Hassan et al., 2018). Hassan et al. (2018) reported that an average of 28,300 people per day were forced to flee their homes due to a variety of causes, such as natural disasters, war, violence, and persecution for their race, religion, ethnicity or political opinion. International Agencies such as the United Nations High Commissioner for Refugees (UNHCR) are still nowadays trying to monitor the trends characterising the millions of refugees migrating throughout the world to escape threats caused by those circumstances (Jaafar et al., 2020; UNHCR, 2020b). However, the wide variations in estimates of the global numbers of people who may be displaced highlight the urgent need for well-formulated policies. These estimates offer an inadequate basis for designing policies and obscure the enormous regional and site-specific variations and responses that might occur and be needed to address the global refugee crisis (Zetter et al., 2008).

The speed and violence of these transformations loosened the earth. They disrupted ecological and geopolitical relations (Bremner, 2020), making it an urgent challenge for social and environmental sustainable development. This trend will likely continue and rise soon as political instabilities increase and land degradation progresses (Braun & Hochschild, 2015). Land degradation, due to the rapid conversion of entire territories into long-lasting refugee camps and makeshift settlements, is one of the most significant catalysts of environmental destruction occurring at a large scale in recent times (Hassan et al., 2018). Empirical studies suggest that deforestation, followed by radical land-use changes driven by anthropogenic activities and informal urbanisation, can have multiple negative impacts on the environment, hitting a series of ecological problems such as the greenhouse effect and environmental services' decrease (Fan et al., 2018; Hassan et al., 2018). Ecological issues include the loss of wildlife habitat, soil erosion and desertification, water cycle disruption, loss of traditional livelihoods, increase in extreme events occurrence, and ecological risks from forest fragmentation. At the same time, challenges related to migration and settlement areas include rapid unplanned urbanisation and sprawl, deforestation, agrochemical pollution, water shortages, abandonment of rural areas, declining health and physical resilience, unsustainable agricultural and production systems, and difficulties in building effective governance systems (UNHCR, 2020b; Zetter et al., 2008). These risks also include the enhancement of conflicts among hosting and hosted communities and ethnic groups that may occur in both developed and developing countries. As Bremner et al. (2020) outlined, deforestation of the hillsides due to informal settlements may also cause adjunctive social tension between authorities, refugees and villagers.

Overall, managed and informal settlements are overgrowing, placing slum upgrading on the political agenda worldwide (Hachmann et al., 2018). The effects of migrants on source and destination communities and ecosystems must be addressed (Zetter et al., 2008). Establishing a framework of typologies of displacement, mapping and monitoring potential environmental ‘hotspots’, changing regional conditions, and tracking migration trends could offer a more fruitful route for policy and governance strategies, which process requires detailed and up-to-date information on the state of slums and settlements, which are usually not available to authorities and should be allied within a clear vision of urban change in both metropolitan and rural regions (Hachmann et al., 2018; Zetter et al., 2008). In this context, coordinated development between urban expansion and ecological protection is crucial to regional sustainable development (Fan et al., 2018). Hence, periodical land use and forest cover change and drivers of such change must be monitored and documented to support policies and management practices to protect, conserve, and sustainably use resources while maintaining ecosystem functions and forest biodiversity (Hassan et al., 2018). The usage of Earth Observation (EO) data acquired from space, aerial and ground platforms for emergency and crisis mapping has greatly increased during recent years (Lang et al., 2017). Through remote sensing techniques and image interpretation, EO can assist information provision and support the decisions of planners, politicians, or humanitarian forces in areas where no field campaigns are possible, or situations that require fast action. (Braun et al., 2015). Recent studies among peer-reviewed scientific publications demonstrate how satellite images might uniquely contribute to assessing such issues. However, the absence of geospatial data for most rural areas worldwide is becoming an increasing concern, with an intense backlash against the sustainable growth of developing countries (Hachmann et al., 2018). Substantially, more research is needed on the environmental change–conflict–migration nexus and the ways it may undermine human security. The main goal of this study is to use remote sensing techniques to analyse significant environmental changes relatable to refugee camp settlements over a specific time period within a selected area of study.

Different methodologies with variable degrees of resources, outlays, accuracy, proficiency, and technology have been explored to assess environmental change detection through EO. The scientific community is still exploring diverse approaches in these contexts, as there is no universal change detection method yet, and only a very few people have experience in successfully managing resources for refugee camps. Thus, such a study should have a large audience, including the UN High Commission for Refugees and the Red Cross.

Several sources reported Ethiopia as among the top refugee-hosting countries worldwide already in 2016, with more than 750,000 refugees estimated. Ethiopia, located in the Horn of Africa, is one of the largest refugee-hosting countries on the African continent, providing asylum to refugees from neighbouring countries such as Sudan, South Sudan, Eritrea, and Somalia (UNHCR, 2020a). The Gambela region, nestled in the western corner of Ethiopia, borders South Sudan and the vast expanse of the Ethiopian highlands. It has emerged as a significant hub for refugee settlement, hosting several refugee camps. Most refugees are from South Sudan and live in seven refugee camps, resulting nowadays in the largest refugee population in the country (Gidron et al., 2021; UNHCR, 2020a). Due to its rich natural resources make it a poignant emblem of the complex interplay between environmental challenges and humanitarian crises (Gidron et al., 2021). Therefore, the four biggest camps in the

Gambela region, Nguenyyiel, Tierkidi, Jewi, and Kule, were selected to conduct the study.

This study aims to delve into the multifaceted dimensions of the above-mentioned refugee-planned camps, examining the challenges faced by refugees living in the camps and the opportunities for improvement and sustainable growth to overcome the main goal stated above. Through a combination of empirical research and theoretical frameworks, this research seeks to contribute to a broader understanding of refugee crises and humanitarian responses. The paper endeavours to shed light on the complexities of refugee life and provide actionable insights for policymakers, humanitarian organisations, and local communities.

2. Background

2.1 Humanitarian displacements general frame

A better understanding of humanitarian emergencies, the categories and concepts surrounding People of Concern (PoC), the global trends about them, and the major issues affecting these contexts, together with the application of remote sensing techniques already in use, is particularly important as it reveals the broad scope of the topic and the need for an interdisciplinary approach.

As reported by Black, R. (2009), from a legal point of view, the most significant starting point for any discussion of refugees is the 1951 Geneva Convention Relating to the Status of Refugees, successively extended by the 1967 New York Protocol.

In 1992, the United Nations adopted the 1951 Convention and the 1967 Protocol relating to the Status of Refugees within its framework to deliver the "*Handbook on Procedures and Criteria for Determining Refugee Status under the 1951 Convention and the 1967 Protocol relating to the Status of Refugees*" (UNHCR, 1992), counting 110 states that have become parties to the Convention, to the Protocol or to both instruments. Indeed, calls for legal recognition and assistance to Internally Displaced Persons (IDPs) who have not crossed an international frontier led the United Nations to publish a set of "*Guiding Principles on Internal Displacement"* in 1998, which have been widely disseminated and implemented. Critical to all legal definitions of refugees are the notions that individuals must cross, or have crossed, an international boundary, that the causes of their displacement should be fundamentally political rather than economic, sociocultural, or environmental, and that they must have had access to an official refugee-determination procedure. Indeed, according to the Geneva Convention's definition of refugees and the United Nations High Commissioner for Refugees (UNHCR), at the end of 2005, the largest refugee numbers worldwide were counted in Africa and Asia (Black, 2009). Legally, refugees are not simply people who have been displaced or in need of assistance; rather, they are people who fall outside the nation-state system – or better, people for whom the relationship between the individual and the state has broken down – and who are entitled by law to protection from another state (Black, 2009; UNHCR, 1992, 2019). By this line of reasoning, the nation-state system is a universal one, in which states have a duty to protect all those considered to be citizens by virtue of birth or naturalisation and where all human beings can call on the protection of at least one state. In circumstances where a state is unwilling or unable to protect some of its citizens – indeed, where an individual has a reasonable fear they may be persecuted rather than protected – the category of refugee is designed to provide appropriate protection by another state until such time as the fear of persecution is removed (Black, 2009; UNHCR, 1992, 2019). However, it must be taken into account that the real number of refugees, even using a legal definition, is not the same as the official number of refugees listed by UNHCR. This is because (1) circumstances change in the home country, so that individuals may no longer fit the legal definition, even though they retain refugee status; but also (2) some people lose refugee status when they obtain full citizenship of their new host nation, but continue to fit the legal definition of a refugee, since the circumstances in their home country which led them to flee remain unchanged. From the perspective of international law, refugees are commonly treated as figures of victimhood – individuals who have crossed an international border and are at risk or have been victims of persecution in their country of origin (Janmyr, 2013). Since 2008, there has been a staggering growth of displaced people due to rapid-onset natural disasters, conflicts, and violence. By the end of 2016, the global number of persons of concern (PoCs) had increased by 58 per cent to reach 67.7 million (UNHCR, 2016) globally. This rapid increase of PoCs, including both refugees and internally displaced people, has required significant expansions of existing camps and the development of new camps. In parallel, many camps have become long-term accommodations following the persistence of armed conflicts, persecution, food insecurity, environmental degradation, poor governance, and countless other factors (Jahre et al., 2018; UNHCR, 2016).

Camps have, for several decades, been recognised as "*temporary spaces in which refugees may receive humanitarian relief and protection until a durable solution can be found to their situation*". Locations have often been selected to isolate refugees from the local community, and decisions regarding camp design have generally been made top-down. This can be referred to as the "traditional" approach to camp design. In contrast, a proposed new approach based on longer-term, participatory solutions, meaning that refugees and the local community actively participate in camp development and operation, is gaining increased attention among governments and humanitarian organisations (Table 1). However, multiple challenges hinder its expansion. As camps mature, there is a shift toward the new approach, but most are established using the traditional top-down, temporary, and isolated approach. Implementation depends on several factors, making the universal design approach quite challenging.

Tab. 1: The three key dimensions that have been operationalised to be used for the camps management approach and analysis (Jahre et al., 2018).

Dimension	Traditional	New approach
Time	Temporality Static	Permanence Dynamic
Space	Isolation One-dimensional	Integration Multi-dimensional
Resources	One-way Physical	Two-way Physical, cultural, political, social, economical

The Programme of Action (PoA) of the International Conference on Population and Development (ICPD) acknowledges the critical role population variables play in development planning and, therefore, advocates the effective integration of population variables into the development planning processes of countries. This recommendation is based on international migration's possible impact on population growth and the overall socio-economic development of both sending and receiving countries. This is important for African countries because international migration within the continent has been relatively high, in addition to international migration flows between the continent and other regions of the world. Indeed, in the migration literature, Africa is primarily seen as a source region for international migration. However, the evidence so far suggests that there are more migration flows within African countries than migration from Africa to the rest of the world's developed countries (Kwankye & Anarfi, 2018).Currently, worldwide, increasing demand for space for settlement, agricultural investment and industrial activities is being observed, leading to unprecedented Land Use and Land Cover Change (LULCC), causing both socioeconomic and environmental problems (Degife et al., 2018). Complex emergencies arising from armed conflicts, protracted crises and natural disasters have caused unprecedented population displacements, unfolding the need for efficient humanitarian assistance strategies delivered to refugees or IDPs (internally displaced persons, as the significantly larger share of displaced people) and requiring liable up-to-date information about the situation on the ground and the local/regional context (Lang et al., 2017; UNDRR, 2015).

Thus, the UN Vision calls for designing a compelling intervention plan parallel to the Sustainable Development Goals (SDG), equity ideals, and sustainability, and highlights the importance of distinguishing refugees, asylum-seekers, internally displaced people, stateless persons, and returnees to design specific, practical and strategic managerial frameworks.

2.2 Environmental matters within the humanitarian displacement emergency

The environment and natural resources of the host country have become an emerging issue for the unwanted influx of refugees and its crisis in the present world as temporary shelters are often built up near critically environmentally sensitive areas, including reserve forests, national parks, sanctuary, or agriculturally marginal areas resulting in broadly environmental changes like deforestation and firewood depletion, land degradation, water pollution, or unstable groundwater extraction (Hossain & Moniruzzaman, 2021). Besides, refugees often stay in the host countries for long periods, having a long-term impact on the environment since an unprecedented scale of human migration has led humanitarians to view camps as long-term settlements rather than temporary holding facilities (Jahre et al., 2018).

As refugee settlements are meant to provide shelter and security and support the distribution of aid to refugees, documenting the establishment and growth of refugee settlements over the months and years following refugee arrival is critical for responding to local needs, opportunities, and challenges for displaced populations. Specifically, documenting the types and rates of land cover changes that accompany the habitation of a new settlement, such as the conversion of natural vegetation to roads or dwellings or the clearing of land for agricultural cultivation, is essential for monitoring food security and identifying localised environmental degradation. Understanding the diversity of landscape changes that may result from settlement establishment and growth also informs how settlements can be effectively planned and organised to support current and future displaced populations. (Friedrich & Van Den Hoek, 2020). The first theories on migration, elaborated at the end of the nineteenth century, took account of environmental conditions, but this factor was rapidly forgotten, a state of affairs that continued up to the beginning of the 1990s, so that current migration policies carry the scars of this oversight (Ionesco et al., 2016).

As global refugee populations and the impacts of climate change continue to rise, with large and fast-growing refugee camps making heavy demands on water supplies and stocks of firewood and house poles, and having long-lasting negative impacts through sewage pollution and garbage disposal, there is a critical need to make better use of available environmental and climate data to mitigate future risks for encamped refugee populations and to preserve environmental services and ecosystems' biodiversity, given that these circumstances might enhance camps' exposure to extreme events, worsening both refugee security and environmental health (Owen et al., 2023).

While the need to minimise and mitigate climate and environmental risks is recognised, climate risks are only briefly mentioned in UNHCR's Camp Site Planning Minimum Standards documentation, and minimum standards for climatic and environmental exposure assessments have yet to be adopted by UNHCR.

Owen et al., (2023) report how UNHCR and refugee-hosting countries make limited use of environmental assessments in planning refugee camps, not gauging potential impacts of climate change or the frequency of natural hazards in the interested camps' areas. The sharp increase in refugee numbers has recently caused significant and manifold challenges for the nation-states and their security forces and administrative services, requiring the long-term collaboration of different member states, not only at the administrative levels but also at territorial units.(Komp & Müterthies, 2016).

Among those challenges, refugee camp managers rarely incorporate structured approaches to climate-informed decision-making at the camp level due to the absence of a framework that integrates relevant environmental and climatic datasets to inform spatially explicit and timely decisions. (Hossain & Moniruzzaman, 2021; Komp & Müterthies, 2016; Owen et al., 2023; UNHCR, 2020b). The first level of support might be the supply of information on the geographical distribution of migrating people or refugee-hosting areas, which needs near real-time data to deal with exceptional circumstances (Komp & Müterthies, 2016). Yet, collecting in-situ data to achieve an accurate picture is usually limited in terms of both time and access (Lang et al., 2017). The effectiveness of the decisions is clearly dependent on the quality of the data used to produce the considered criteria maps, as well as on the method used for decision-making analysis. Herein, Geographic Information System-based Multi-Criteria Decision Analysis (GIS-based MCDA) provides powerful techniques and procedures that convert spatial and non-spatial data into information within the decision maker's judgement. Spatial decision problems typically involve a large set of feasible alternatives and multiple, conflicting and incommensurate evaluation criteria. As part of those issues, also finding suitable sites for a refugee camp requires a multi-criteria approach and high levels of accuracy and reliability in the resulting maps in order to be relevant for decision-making and the design of disaster management or humanitarian plans (Çetinkaya et al., 2016).

Remote sensing has become increasingly popular in the field of humanitarian action because it is an independent and reliable source of information and allows both a quick response to emergencies and the monitoring of gradual changes. This is of particular importance when observations in the field area are not possible because of limited budget, legal restrictions, or security reasons (Braun et al., 2019). Although remote sensing studies based on land cover changes other than built-up areas at refugee settlements have considered the establishment of rangelands, agricultural deforestation, decreased woody vegetation and grassland, tree felling for shelters, fuelwood, and fodder, as well as the exposure of bare areas, none of these studies has pursued a continuous monitoring of land cover change at or surrounding refugee settlements nor the sub-annual patterns of change (Friedrich & Van Den Hoek, 2020). Incidentally, localisation, mapping and monitoring have emerged as a concern in various fields of international governance, development programming, and humanitarian aid, as the World Humanitarian Summit committed to "*making humanitarian action as local as possible and as international as necessary*" and to enhancing "*engagement with local and national partners*" (Gidron & Carver, 2022).

3 Material and methods

3.1 Criteria to select the study area

Because spatial decision support systems have become essential tools for planning and understanding specific dynamics at all scales, consistently with the contextual depicted framework, the primary goal of this study was to deepen the criteria behind the distinction of various definitions of People of Concern (PoC) and to select a specific target and settlement typology to sharpen and focus the research (UNHCR, 2023).

The vegetational cover zone was taken into account to facilitate the evaluation of time series land changes. Thus, regions falling within tropical climatic regions were endorsed.

To find a suitable study area, the updated worldwide locations of PoC from the UNHCR webGIS repository, as of February 2024, were overlayed with the global tropical forest watch web database and crossed with data concerning global migration trends, looking at the countries with exponential refugee influx during the last years (Figure 1).

As the concept of refugees was essential to address African migrations and PoC issues in the past, and trends show an increasing concentration of PoC in Africa (UNHCR, 2016, 2020b, 2023), it was chosen to adhere to the traditional meaning of refugees, defined by the international law under the 1951 Convention and the 1967 Protocol (see paragraph 2.1) relating to the Status of Refugees and the UNHCR Handbooks on Procedures and Criteria for Determining Refugee Status (Das et al., 2020; GCIM, 2003; UNHCR, 1992, 2019). Accordingly, due to proven difficulties in data gathering among existing studies held in developing countries, managed settlements under the UNHCR mandate encompass within the chosen target. As a result, certain PoC groups, such as asylum seekers, returnees, environmental refugees, and internally displaced people, as well as city slums and locations of dispersed or informal settlements, were left out of the selection process. NGOs and international agencies' annual global trends reports and peer-reviewed articles were essential for learning more about ongoing complex conflict situations and the major hosting countries, particularly within the African continent and the Sub-Saharan African countries of the IGAD Region (About IGAD | IGAD Structure | IGAD Regional Strategy; (UNHCR & UNCS, 2024)).

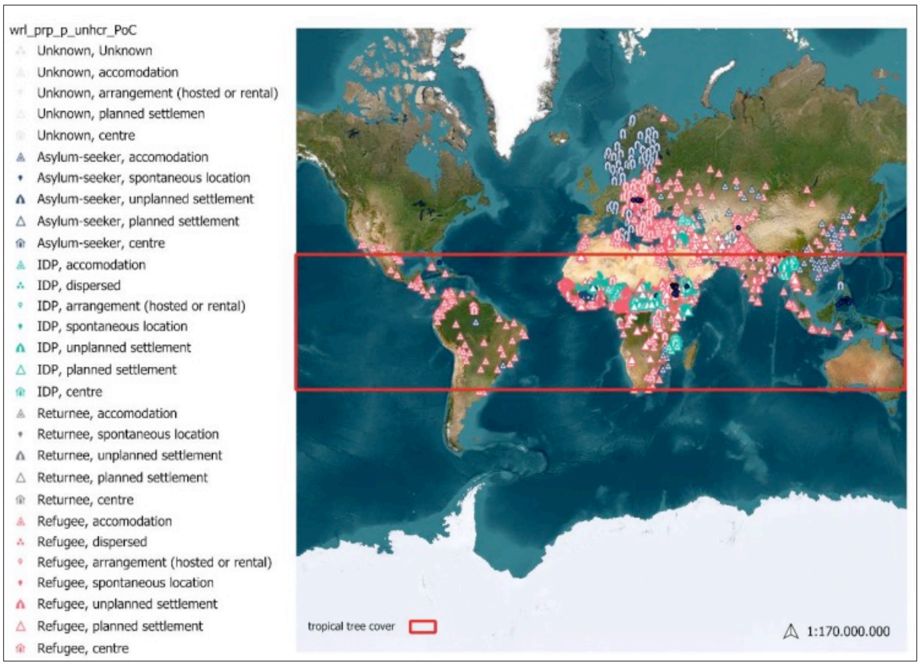


Fig. 1. Worldwide distribution of PoC reported by UNHCR as of February 2024 and tropical vegetation area from the Global Forest Watch. Image generated using QGIS 3.34.

Several sources reported Ethiopia to be within the top sixth refugee-hosting country worldwide already in 2016, with more than 750.000 refugees estimated, distributed as follows: 67% in the arid area, 16% in the semiarid area, and 17% in the regions covered with rainforest. This number grew remarkably in a relatively short period, with the estimated hosted refugee number exceeding 1.750.900 in 2018 (IDMC, 2020; Jahre et al., 2018; Tafere, 2018; UNHCR, 2020b).

A situational report delivered by UNHCR identifies Ethiopia as the third largest refugee-hosting country in Africa, home to over 972K refugees and asylum seekers, mainly incoming from South Sudan, Somalia and Eritrea (UNHCR & CO Ethiopia, 2024). Following the outbreak of armed conflict in Sudan in April 2023, Ethiopia is receiving thousands of forcibly displaced people at several points of entry. UNHCR and the Government of Ethiopia, through the Refugees and Returnees Service (RRS), in partnership with regional authorities, other UN agencies and NGOs, are working to provide safe asylum access, documentation, protection and solutions to those who need humanitarian support (UNHCR, 2020c; UNHCR & CO Ethiopia, 2024).

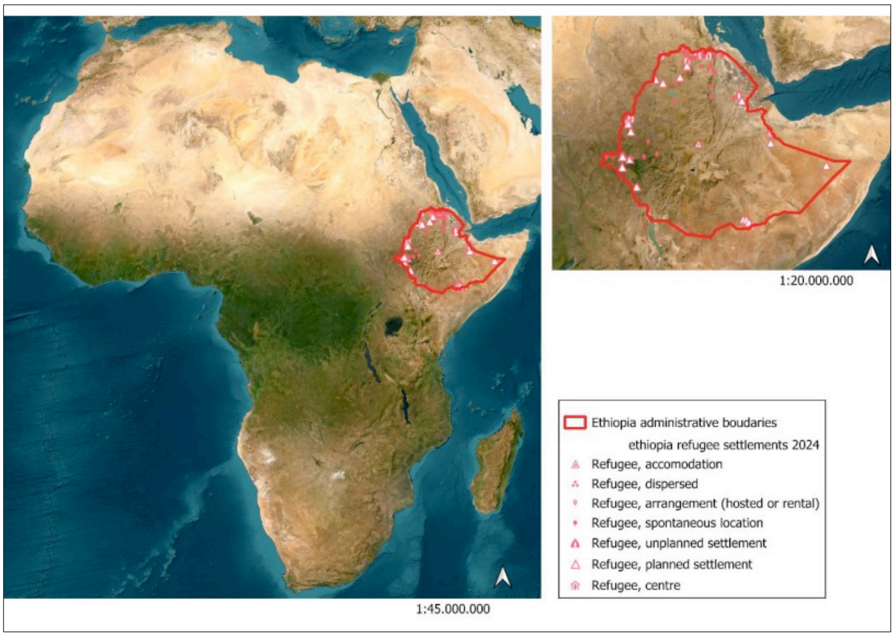


Fig. 2. Ethiopia administrative boundaries and refugee camps distribution reported by UNHCR as of February 2024. Image generated using QGIS 3.34

Among the overall PoC hosted in Ethiopia (Figure 2) as of February 2024, the Gambela region is the direct cross-boarding point from South Sudan (Figure 3a), the primary country for Sudanese refugees suffering from a strong civil war. Indeed, nowadays, Gambela hosts most camps compared to the rest of the country, which is seven in total (Figure 3b). Being one of the wealthiest Ethiopian regions in vegetation, covered by rainforests and strongly impacted by the mentioned circumstances, it has been selected as a region of interest.

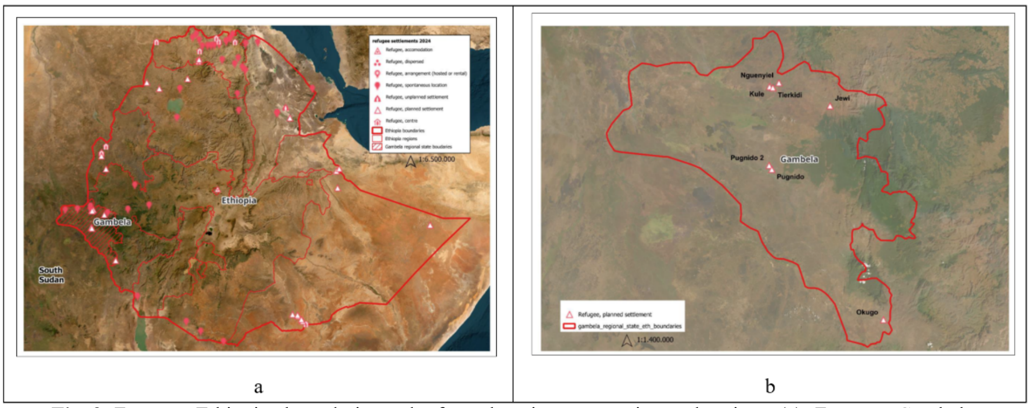


Fig. 3. Zoom on Ethiopian boundaries and refugee locations among internal regions. (a); Zoom on Gambela regional state boundaries and refugee-planned settlement locations under the UNHCR mandate: Kule, Tierkidi, Nguenyyiel, Jewi, Pugnido 1, Pugnido 2, Okugo (b). Image generated using QGIS 3.34. Source: UNHCR (Feb. 2024).

3.2 The study area

The Gambela Peoples National Regional State (GPNRS) is one of Ethiopia's nine federal regions. It has a total land area of 29,783 km^2, is located between 6°28'38'' North Latitude and 33°11'11'' East Longitude, and has a population of about 409,000 (2015 population projection). Gambela town is 777 km from Addis Ababa, the capital city. The region borders South Sudan on its western side and has five official border crossings. (Degife et al., 2018; Hagos, 2021; UNHCR Ethiopia, 2019).

The region comprises three administrative zones (Anyuak, Nuer, and Majang), thirteen districts (woredas), one special district, and one city administration. Gambela is one of the emerging regions in Ethiopia despite a lack of infrastructure and a poor transportation network among the districts. Due to its favourable soil, topography, and climate conditions, the Gambela region is one of the most fertile regions in Ethiopia and is suitable for growing various types of crops (Degife et al., 2018). The Gambela region has both a unique ecology and an extraordinarily rich biodiversity. Due to its climate, vegetation, and terrain diversity, Ethiopia's very heterogeneous flora and rich endemic elements have the fifth-largest flora in Africa. It is estimated to host between 6,500 and 7000 species of higher plants, of which about 12% are endemic. Ethiopia's forest resources are grouped into five major categories: natural closed forests, woodlands, bushlands, plantations, and on-farm trees. However, the current coverage of each category is not available. The Gambela region is partially interested in the moist montane forest ecosystem, which comprises the country's high forests and is mainly found on the southwestern plateau, having an altitudinal range between 800 and 2,500 m. asl. It is the most diverse ecosystem in composition, structure, and habitat types. Its location in the mountainous area allows for broad ecological gradients along the altitudes. As a result, large complexes of mountain forests exist, forming several distinct vegetation units. The southwestern area of the country, delimited within the Gambela regional state and the adjacent areas in Sudan, is mainly covered by lowland tropical forests, a lowland semi-evergreen forest ecosystem restricted to this region. This forest occurs on well-drained sandy soils with an altitudinal range of 450 to 800 m. asl, having more than 106 woody plant species, including lianas.

It is often reported that in the early 20th century, about 42 million hectares, equivalent to 35% of Ethiopia's land area (110 million hectares), were covered with high forest. Including savannah woodlands, about 66% of the country was covered with forest or woodland. However, by the early 1950s, the high forest was reduced to 19 million hectares or 16% of the total land area, 3.6% by the early 1980s, and about 2.7% by 1989. The relatively early and extensive deforestation, coupled with the cultivation of steep marginal lands, overgrazing, and socio-political instability, has resulted in severe land degradation over large areas of the country. Firewood is considered the most essential forest product and the primary energy source for most African households, accounting for 91 % of all wood consumption. FAO reported Ethiopia as one of the countries in this region with an annual deforestation rate of 0.8 %, meaning an annual loss of Ethiopia's high forests estimated to be between 150,000 and 200,000 ha per year, a rate at which, in 15 years, the remnants of these high forests would be scattered patches in inaccessible areas.

The rapidly growing population aggravates the cause, further triggered by poverty. Despite protected areas being established, these are at the expense of local people, often deprived of their traditional economic livelihoods.

As a result, local people consider protected or reserved areas as constraints to their livelihoods. Since it was challenging to create rigid separation between land used by local people to obtain natural resource products and those designated by governments as protected areas, encroachment, poaching, and degradation were inevitable (Awas et al., 2001; Degife et al., 2018; Tegene, 2018; UNHCR Ethiopia, 2019).

Around 5,700 km^2 of the Gambela region was covered by Gambela National Park (GNP). Its boundary has been shifted towards the southwestern parts of the region and now covers around 4,350 km^2 (Figure 4). This means the GNP would lose about 1,500 km^2, corresponding to 25% of its tropical grassland cover. Changes in LU/LC categories within the old GNP showed that approximately 672 km^2, 761 km^2 and 725 km^2 were covered by farm fields in 1987, 2000 and 2017, respectively. In addition, tropical grasslands, which covered an area of 3,385 km^2 in 1987, decreased to 2,584 km^2 in 2000 and 1,887 km^2 in 2017 (Figure 5). Man-made structures and settlements expanded from about 7 km^2 in 1987 to 101 km^2 in 2000. However, the expansion of wetland vegetated areas in the new proposed boundary has positively impacted wildlife conservation and the ecological management of the park because, within the new proposed GNP boundary, agricultural activities and artificial areas have been restricted, and abandoned farming activities and artificial areas will have the greatest chance of being incorporated into the GNP ecosystem. (Degife et al., 2018).

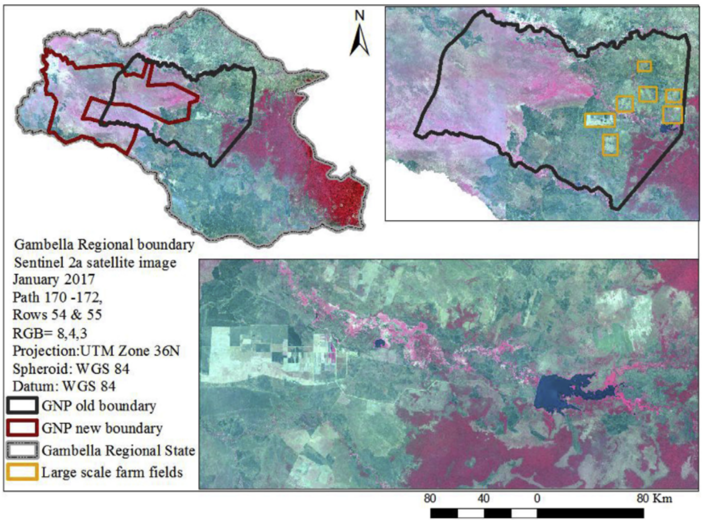


Fig. 4. The old and new proposed Gambela National Park boundary (top left) and rectangles enclosing large-scale commercial farm fields within the old GNP boundary from Sentinel 2a satellite image 2017 (top right) and zoomed-out large-scale commercial farm fields within the old GNP boundary from Sentinel 2a satellite image 2017 (below), (Degife et al., 2018).

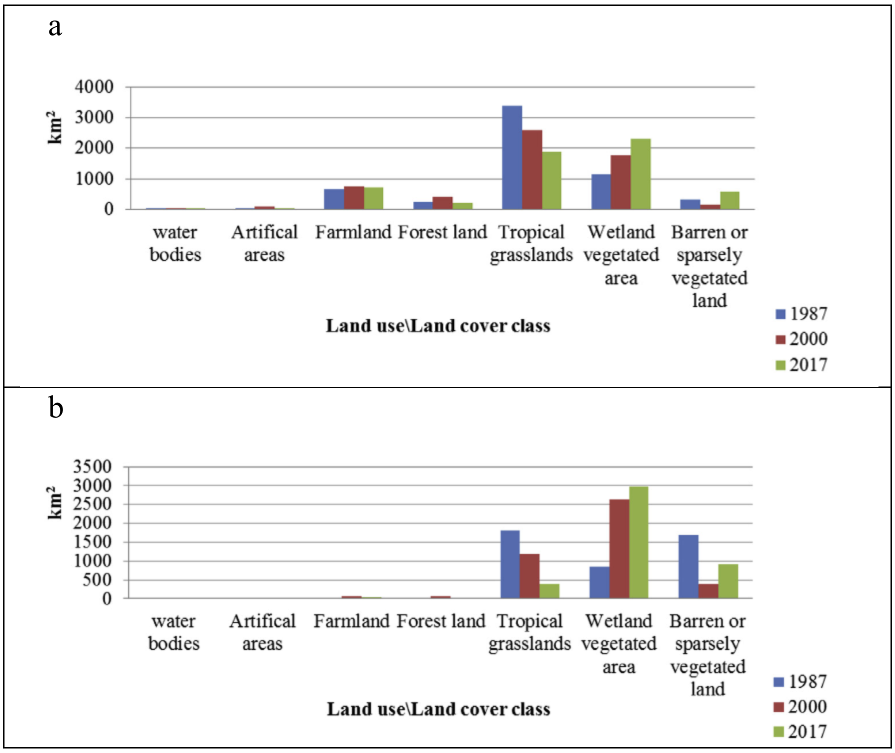


Fig. 5. Changes in the composition of Gambela National Park LU/LC categories in the old (a) and new (b) GNP boundary in 1987, 2000 and 2017 (Degife et al., 2018).

Studying vegetational distribution in response to environmental variables helps to generate information for a better understanding of ecological processes and managing ecosystems (Tegene, 2018). The overall pace of change in land use and cover in Ethiopia depends on three main factors that cause pressure on agricultural land: resettlement programmes, population growth and increasing agricultural commercial investments. Gambela, due to its rich natural resources, is one of the regions that attract large-scale agricultural investments that extensively drive land use and cover changes in the region, besides hosting the largest refugee population in Ethiopia, which seeks protection and causes growing conflicts with the hosting communities (Table 2). Indeed, among those variables, campsites must be taken into account as South Sudanese refugees are generally granted refugee status on a prima facie basis by the Government of Ethiopia, the Administration for Refugee and Returnee Affairs (ARRA), and UNHCR's main Government counterpart in Ethiopia, to protect refugees and other persons of concern (UNHCR Public Information Unit, 2014).

Tab. 2. Summary of Refugee Camp Populations, Host Community and Woreda Populations. Overview of host communities directly and indirectly impacted. In many locations, the population of refugees in camps vastly outnumbers local populations. (UNHCR Ethiopia, 2019)

#	Refugee camp		Host Community adjacent camp		Woreda	
			Direct Impact		Indirect impact	
	Name	Pop.	Village	Population	Name	Pop
1	Jewi	56,188	Gambella	4,417	Gambella	39,605
2	Kule	44,021	Itang	6,958	Itang special Woreda	39,686
3	Nguenyyiel camp (new)	82,614				
4	Teirkidi	62,715				
5	Okugo	11,135	Dimma	11,001	Dimma	3,103
6	Pugnido	41,581	Pugnido	12,836	Gog Woreda	7,617
7	Pugnido II	8,994				
Total		**307,248**[2]		**35,212**		**90,011**

In this framework, the four biggest camps, Nguenyyiel, Tierkidi, Jewi, and Kule, were selected to conduct the study, three of which are not far from the Gambela National Park (Figure 6).

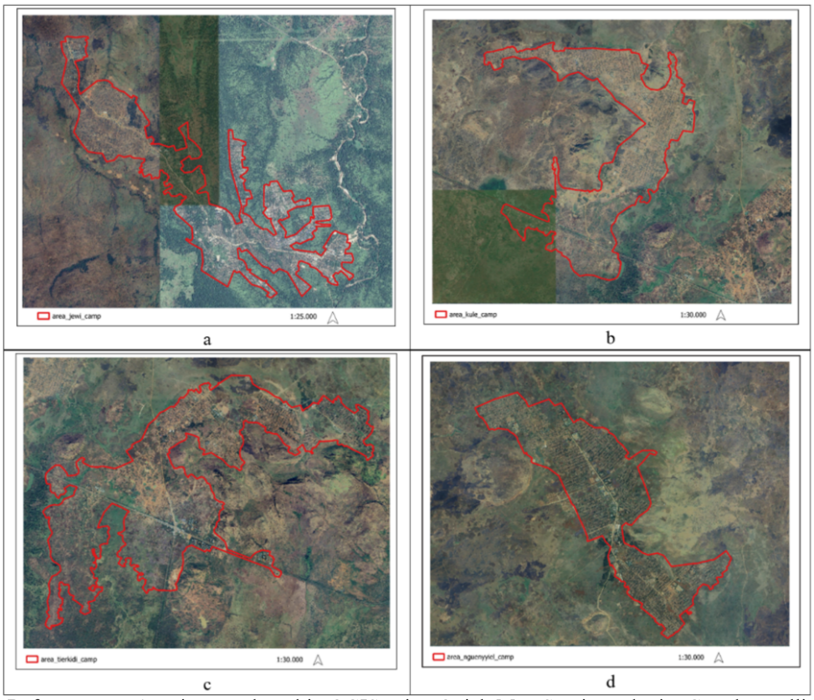


Fig. 6. Refugee camps' perimeter plotted in QGIS using Quick Map Services plugin, Google satellite base map. **Jewi (a)** location at 17°15"22' longitude, 3°17"17' latitude, Area: 441 ha; **Kule (b)** location at 6°01"26' longitude, 6°47"31' latitude, Area: 632 ha; **Tierkidi (c)** location at 6°37"26' longitude, 6°36"00' latitude, Area: 1044 ha; and **Nguenyyiel (d)** location at 7°45"07' longitude, 7°30"43' latitude, Area: 639 ha.

Only a few scientific studies in Ethiopia were found in the literature with a specific focus on the environment, remote sensing techniques, refugee settlements, or linkages among these topics (Degife et al., 2018; Kassa et al., 2022; Leiterer et al., 2018; Moisa et al., 2022; Owen et al., 2023; Rolkier & Yeshitela, 2020; Tadesse et al., 2024). None of them provide suitable information concerning the camps.

3.3 Data Collection

First, a comprehensive literary review was conducted to better understand humanitarian emergencies, the categories and concepts surrounding people of concern, the global trends, the major issues affecting these contexts, and the application of remote sensing techniques already in use. The keywords guiding the search for the peer-reviewed article were: deforestation, land cover change, refugee camps, settlement monitoring, remote sensing, and UNHCR.

The UNHCR web ArcGIS portal was used to investigate the updated worldwide locations of PoC as of February 2024. The data were imported into the QGIS environment and crossed with data downloaded from the global tropical forest watch to find a suitable study area (see paragraph 3.1). Potential regions of interest were briefly overlooked using Google Earth Pro© historical images.

Once a suitable study area was delineated, following the above-described criteria, available open-access platforms and satellite images were explored; as for this study, all data collection and analysis are meant to be based on open-access software and databases. The UNHCR operational data portal was mainly helpful in obtaining camp profiles, population trends, and essential information concerning the characteristics of the camps.

The USGS Landsat-8 mission, Level 2, Collection 2 optical image footprints, and C-band Synthetic Aperture Radar (SAR) from the Copernicus Sentinel-1 mission were used to conduct the research over a ten-year period (Table 3). Due to seasonality influence, optical data have been acquired for January month only, the dry season, while SAR data for entire years. This aspect is better explained within the data processing paragraphs.

Tab. 3 Satellite images acquired to conduct the analysis.

Imagery type	Mission	characteristics	years
Synthetic Aperture Radar (SAR)	Copernicus Sentinel-1	VV/VH polarisation; ascending orbit	2014 to 2024
Optical	Landsat 8 Collection 2 level-2	Optical bands B01 - B07 (surface reflectance)	2014 2024

3.4 Data analysis

PoC location and population trend data were framed and analysed in Excel. Camps' boundaries have been plotted using QGIS tools to determine their extension, perimeter, and area based on the most recent Google satellite images available (Figure 6).

The Google Earth Engine (GEE) environment has been used to facilitate big data acquisition, thanks to its cloud-based platform for planetary-scale environmental data analysis. The GEE cloud code editor has been used to acquire and process data.

The QGIS environment was essential for further processing and interpreting optical and radar images, while the R analysis environment played a key role in running accurate and reliable statistical surveys.

As a first trial, USGS Landsat-8, Level 2, Collection 2 optical image footprints of April 2013, 2016, 2021, and 2023 were acquired for the Jewi camp, and Vegetation Index Differentiation (NDVI) was performed based on optical remote sensing images as the difference between the near-infrared (NIR) and red (R) bands normalised by the sum of those bands. Initially, a time-series NDVI analysis was conducted on the Jewi camp only, producing images displayed in bands of false colours, with a resolution of 30m and values ranging between 0 and 0,3 chosen as minimum and maximum pixel values to enhance vegetational overview. Despite the absence of intense vegetation within the area, there was a significant reflectance decrease between 2013 and 2016, when the camp was opened. However, the increasing and decreasing values reported in 2021 and 2023 clearly show the high sensitivity of the index to rainfall and potential grassland and the delicacy of the optical images to cloud cover, which might represent a meaningful limit and make the representation unreliable.

As a second attempt, in order to avoid seasonality, regional climate and weather were investigated. The index was rerun for ten years of time series coverage in January, the dry season, for all camps: Jewi, Nguenyyiel, Tierkidi, and Kule.

Subsequently, land surface temperatures were investigated, where the higher the temperature, the lower the vegetation. USGS Landsat-8, Level 2, Collection 2 Band 10 optical image footprints of January 2014, 2016, and 2018 for all camps were processed, and Celsius degrees values were plotted using the designated scaling factor (0.00341802 + 149.0). Subsequently, maps at 30m resolution were produced, displaying surface temperatures within a values range of -6°C minimum and +61°C maximum.

In order to estimate pixel values and quantify and assess the vegetation trend over the years, 400 sample points were allocated over the four camps.

A multiple-year composite raster image was produced to estimate the overall amount of variation or dispersion among values over time so the pixels with the lowest values could be used as a reference to weight and additionally normalise all the other pixels' values to obtain a more reliable result and enhance the NDVI. Several attempts were made to find a procedure whose outcomes could be consistent. However, the obtained results made it difficult to select specific training areas to reassess the NDVI on the entire study site, as the threshold chosen among low standard deviation values within the area of study might reveal a high level of uncertainty and compromise the outcomes.

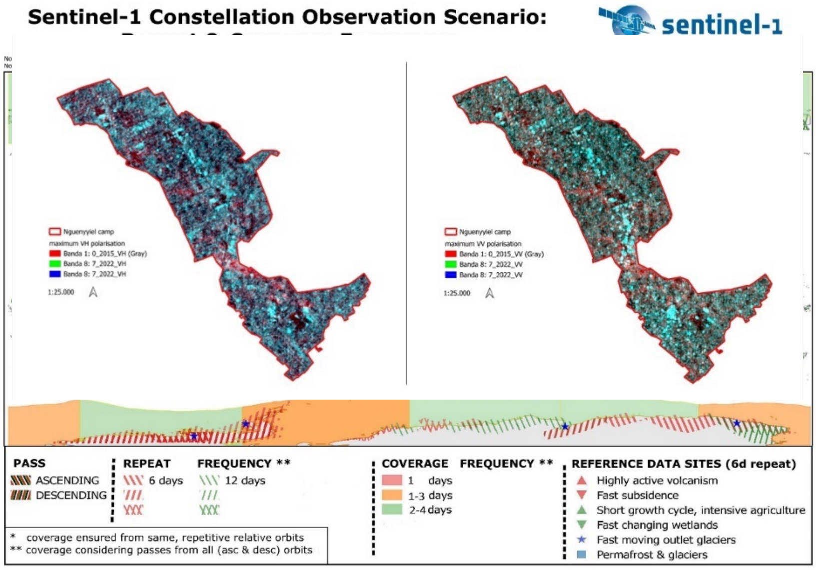
Literature and current applications describe optical data spatial resolution to be often too coarse to provide a high level of detail on the ground or to distinguish between different vegetation types because satellites do not penetrate clouds and smoke or cannot penetrate forest canopy. After considering the limits and the inconsistencies found with previously observed optical data, Synthetic Aperture Radar (SAR) has been taken into account, as its potentiality and advantages with respect to the optical data. SAR backscatter values were considered a good alternative to provide information concerning ground coverage.

Among the SAR satellites available nowadays, Sentinel-1 is part of the European Space Agency's (ESA) Copernicus program. It provides open-access continuous C-band SAR data for a wide range of applications. The mission was launched in the first half of 2014, and image acquisition happens around every 12 days through ascending and descending orbits (Figure 8). The GEE environment has been used to facilitate data acquisition and process SAR images.

The Sentinel-1 mission provides data from a dual-polarization C-band Synthetic Aperture Radar (SAR) instrument at 5.405GHz (C band). This collection includes the S1 Ground Range Detected (GRD) scenes, processed using the Sentinel-1 toolbox to generate a calibrated, ortho-corrected product. This collection contains all of the GRD scenes. Each scene has one of 3 resolutions (10, 25 or 40 meters), four band combinations (corresponding to scene polarisation, where the possible combinations are single-band VV or HH and dual-band VV+VH and HH+HV, depending on the instrument's polarisation settings), and three instrument modes. Each scene also includes an additional 'angle' band that contains the approximate incidence angle from the ellipsoid in degrees at every point. This band is generated by interpolating the 'incidence angle' property of the 'geolocation grid-point' gridded field provided with each asset. Thus, although backscatter is derived by two non-crossed polarisation bands providing different information about the surface, it still allows for detailed analysis: VV (Vertical-Vertical), where both the transmitted and received signals are vertically polarised, and VH (Vertical-Horizontal), where the transmitted signal is vertically polarised, and the received signal is horizontally polarised. Overall, backscatter in SAR provides valuable information about the earth's surface and is a fundamental parameter for interpreting SAR images and conducting various geospatial analyses, including land cover classification, vegetation analysis, water bodies mapping and environmental disaster management. Since SAR technology does not suffer from weather or cloud limitations, it was judged more suitable to analyse entire years of acquisition to further reduce seasonal dispersion and variability. Data from January 1st to December 31st have been acquired and processed for each year from 2015 to 2023, depending on data availability due to the beginning of the mission. Although both cross-polarised orbits, as mentioned above, would produce a better result, only the descending orbit has been considered for the present application since the ascending orbit does not cover the study area (Figure 7).

GEE pre-processed scenes were displayed through the Sentinel-1 toolbox using thermal noise removal, radiometric calibration, and terrain correction. Speckle filtering was avoided to maintain a high level of detail. Afterwards, a script was created and run through the GEE cloud code editor to analyse SAR Sentinel-1 data and obtain 10-year raster composite images with 10-meter resolution representing the study area's VV and VH backscatter values. The same code has been repeated for the following statistic variables: maximum VH, maximum VV, mean VH, mean VV, minimum VH, and minimum VV.

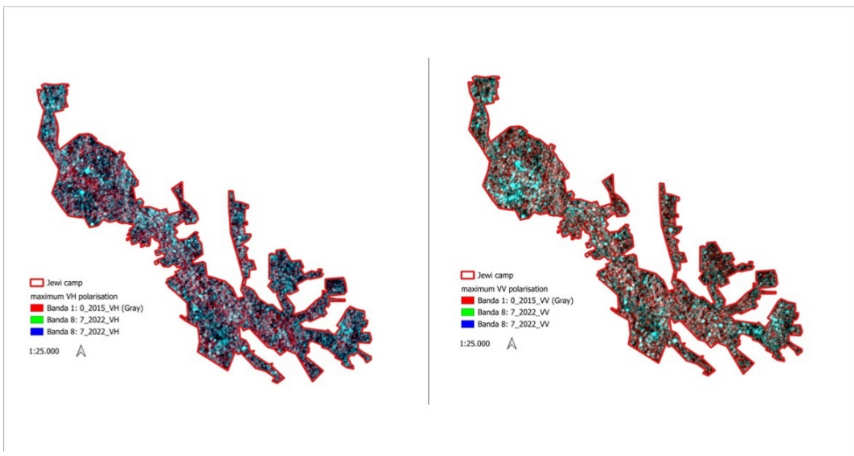
Fig. 7. ESA Copernicus program Sentinel-1 worldwide orbit coverage.



Source: www.sentinels.copernicus.eu.

Lastly, Landsat optical data were integrated to enhance the result, creating RGB false colour images that could facilitate the interpretation of radar images and the reassessment of NDVI trends. Backscatter 10-year composite RGB raster images were exported on QGIS, and representative thematic maps were created for each camp (Figure 8). The thematic maps displayed in Figure 9 show the maximum backscatter values for both VV and VH polarisations. Every image comprises several layers where diverse bands of different years can be selected and crossed to obtain representative false colour images displaying shelters' presence at a specific time and the differences incurring with other years, depending on how the Red, Green or Blue bands are selected and filtered. In the above maps, 2015 was assigned to the Red band, while both the Green and the Blue bands were assigned to 2022 to better enhance the overall differences between the pre and post-camps' development. The bigger the backscatter showed in light blue, the greater the presence of facilities' buildings or shelters. However, mud-made shelters are partially visible because they are easily conformable to land surfaces. Moreover, it must be considered that VV and VH results rely on the signal incidence angles and camp-specific positioning. Indeed, for instance, on the Kule camp, maximum VV backscatter values (Figure 8H) better enhance the presence of buildings with respect to maximum VH values (Figure 8I).

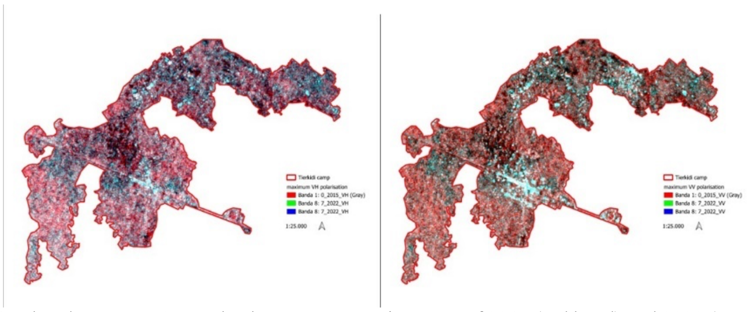
A | B
C | D



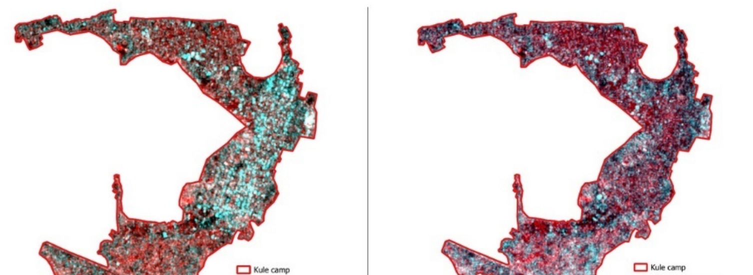
E | F

H | I

Fig. 8.



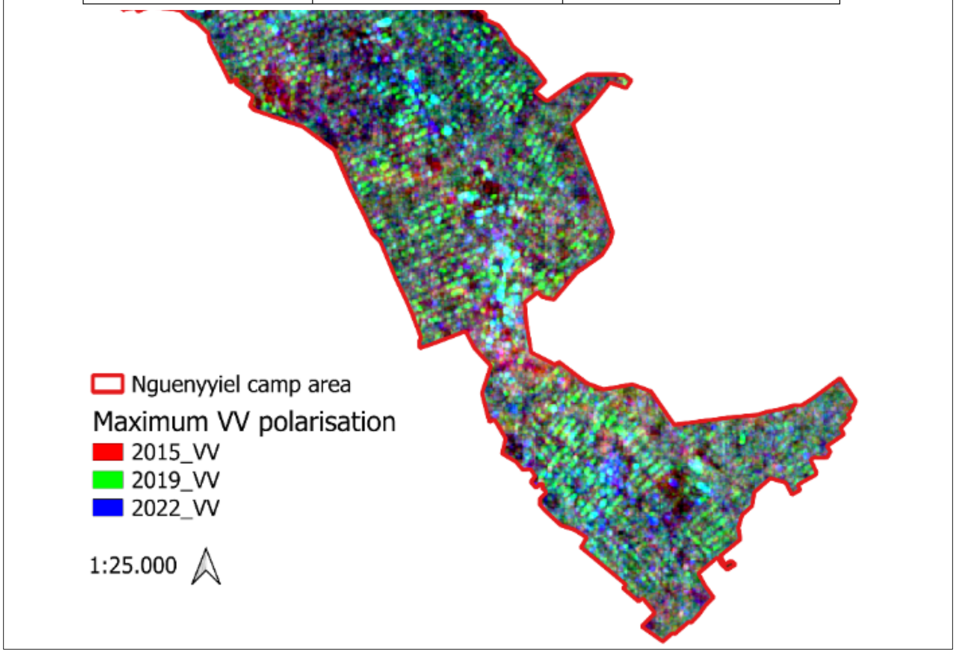
Sentinel-1 C-band SAR **maximum** backscatter composite raster of 2015 (red band) and 2022 (green and blue band) of **VV polarisation on Jewi (a)**, **Nguenyyiel (c), Tierkidi (e)** and **Kule (h)** camp; Sentinel-1 C-band SAR **maximum** backscatter composite raster of 2015 (red band) and 2022 (green and blue band) of **VH**



polarisation on Jewi (b), **Nguenyyiel (d), Tierkidi (f)** and **Kule (i)** camp. QGIS. Scale 1:25000. Resolution 10m.

All years' VV and VH polarisation values can be assigned to all RGB bands to obtain and compare any contrast or difference over the years for which satellite data have been acquired and processed. An example is shown for the Nguenyyiel camp (Figure 9).

Fig. 9. Sentinel-1 C-band SAR **maximum** backscatter composite raster of 2015 (red band), 2019 (green) and 2022 (blue band) of **VV polarisation on Nguenyyiel** camp. QGIS. Scale 1:25000. Resolution 10m.



Once this composite raster was obtained, the R analysis environment was used to explore numerical values and run statistical analysis for both VV and VH polarisation. Within the QGIS environment, integrating the R tool allowed for statistical analysis, plotting backscatter values, and assessing maximum VH, maximum VV, mean VH, mean VV, minimum VH, and minimum VV trends for each camp for each year.

Situational reports called 'camp profiles', occasionally delivered by UNHCR, were used to get an overall idea of camps' expansion regarding the number of refugees hosted, major challenges, and relevant initiatives concerning environmental protection.

Figure 10 shows the increasing number of incoming refugees, mainly arriving from South Sudan seeking protection, accommodation, and food provision, which, coupled with the economic resources gap, make effective managerial strategies challenging and disclose the need for adjunctive shelters and primary services.

Only the most recent reports call attention to environmental protection, registering some reforestation activities (Table 4).

Camp	Report Date	Reforested ha
Jewi	Oct 2020	16,9
Kule	Oct 2020	10
Nguenyyiel	Oct 2020	6
Tierkidi	Oct 2020	17,2

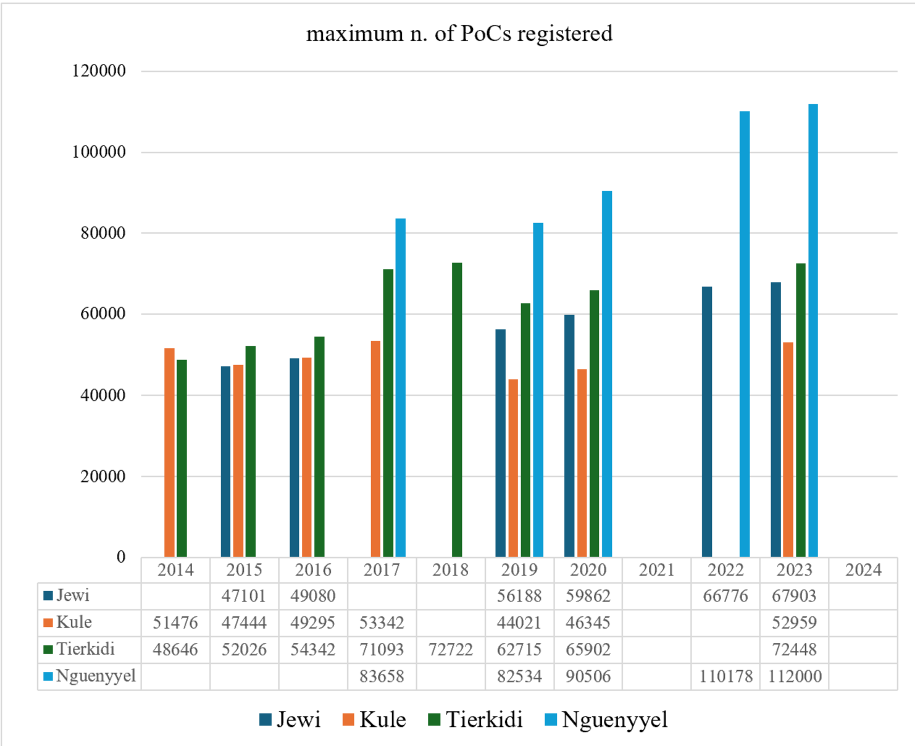
Tab. 4: Reforested land (ha) in every camp as of October 2020 within every camp under study.

However, no additional information was found concerning natural landscape assessment, criteria for selecting reforestation areas, or the species used for environmental restoration.

Fig. 10. Comparison of the maximum number of PoCs hosted annually within camps under study, depending on available reports. Source: UNHCR.

Despite Nguenyyiel's camp opening being strategic to redistribute people from overcrowded camps and welcome new arrivals (Figure 10: note the decreasing trend in Kule and Tierkidi camp concurrent with Nguenyyiel camp opening), monitoring inconsistencies additionally pauperise the already demanding circumstances. Moreover, the need for extra shelters and camps area expansion might cause the little reforestation efforts to be insignificant.

4. Results and discussion



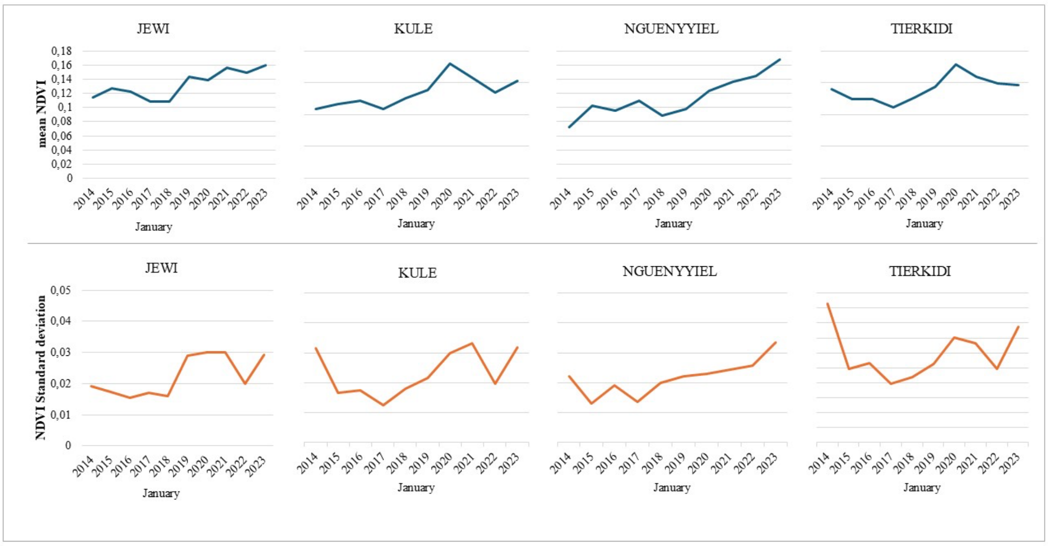
	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Jewi		47101	49080			56188	59862		66776	67903	
Kule	51476	47444	49295	53342		44021	46345			52959	
Tierkidi	48646	52026	54342	71093	72722	62715	65902			72448	
Nguenyyel				83658		82534	90506		110178	112000	

To assess the effectiveness of remote sensing techniques in the four largest refugee camps within the Gambela region and the rate at which these can be applied for enhanced camp management purposes and environmentally sustainable development, satellite optical and raster data over a ten-year time frame, along with influx trends, were explored.

The NDVI optical images quantitative analysis results of the 400 random plots distributed within the campsites confirmed the high sensitivity and variability of the index due to cloud cover, rainfall and subsequent grassland growth within the interested areas (Figure 11).

Fig.11. Charts reporting mean and deviation standard trends for NDVI pixel values of Landsat 8-L2C2 of 400 random points collected within camp areas.

Although there might seem to be an increasing NDVI trend over the years, resulting from mean pixel values, this does not necessarily reflect an actual increase in forest vegetation cover, as the standard deviation trends demonstrate high variability among pixel values. Despite these trends having some significant thresholds with respect to



	NDVI mean - January				Standard deviation NDVI - January			
	JEWI	KULE	NGUENYYIEL	TIERKIDI	JEWI	KULE	NGUENYYIEL	TIERKIDI
2014	0,1138	0,1084	0,0720	0,1393	0,0192	0,0316	0,0221	0,0466
2015	0,1267	0,1166	0,1032	0,1247	0,0172	0,0165	0,0131	0,0246
2016	0,1229	0,1223	0,0953	0,1247	0,0154	0,0176	0,0191	0,0267
2017	0,1087	0,1092	0,1098	0,1112	0,0171	0,0126	0,0136	0,0196
2018	0,1085	0,1260	0,0885	0,1268	0,0159	0,0180	0,0199	0,0218
2019	0,1432	0,1382	0,0983	0,1436	0,0290	0,0216	0,0223	0,0264
2020	0,1391	0,1800	0,1240	0,1786	0,0300	0,0299	0,0231	0,0352
2021	0,1567	0,1584	0,1360	0,1596	0,0300	0,0331	0,0243	0,0331
2022	0,1495	0,1344	0,1445	0,1485	0,0199	0,0196	0,0258	0,0248
2023	0,1596	0,1531	0,1684	0,1465	0,0292	0,0318	0,0335	0,0389

the reforested activities conducted by 2020 (Table 4), data reliance and the impossibility of conducting further ascertainment make the outcome untrustworthy and inaccurate.

Land surface temperature trends estimated, always using the Landsat 8 L2C2 optical images and the 400 plots distributed over the camps sites, fall under the same research analysis thoughts.

Sentinel-1 SAR backscatter values and statistical analysis for both VV and VH polarisation were assessed running maximum VH and VV, mean VH and VV, minimum VH and VV and maximum yearly NDVI trends for each camp for each year**.** Among all the results obtained, the maximum VV and the maximum VH polarisation trends (Figure 12) were the most significant, where higher backscatter values corresponding to nearer-to-zero values, the higher the presence of shelters.

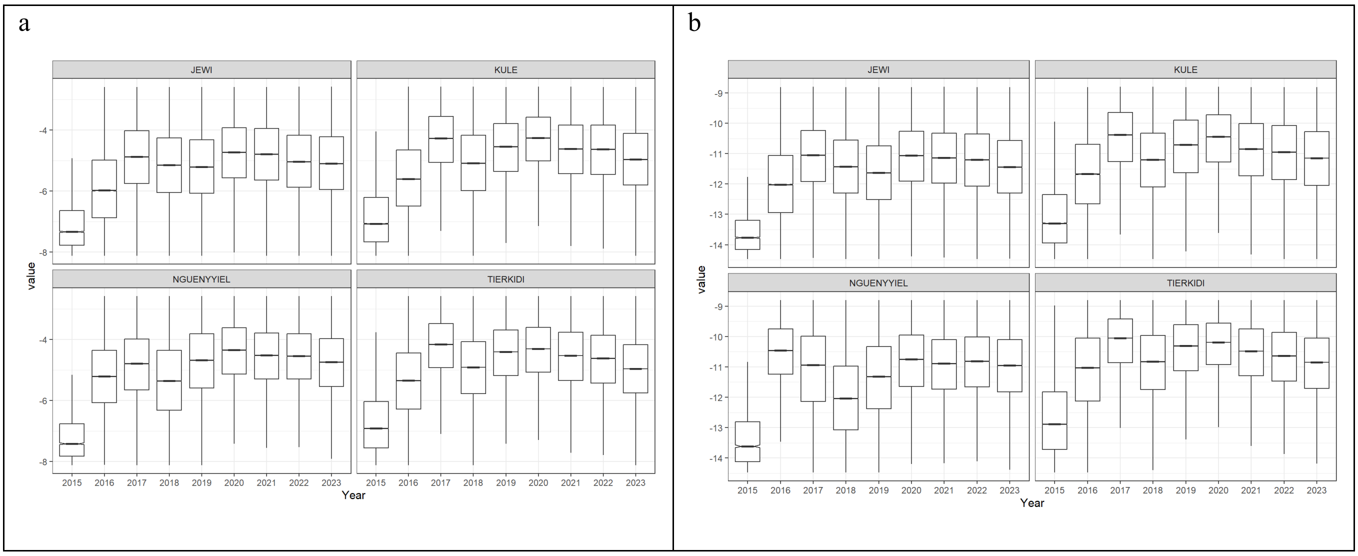


Fig. 12. **Maximum VV** (a) and **Maximum VH** (b) polarisation value from 2015 to 2023 for all study areas.

A correlation was found between the SAR maximum backscatter values trend, representing building presence, camps opening and refugee population growth (Table 5). As all camps opened between 2014, 2015, and 2016, it is possible to observe a significant boost in backscatter values between 2015 and 2016, corresponding with the effective enchantment built up in all the refugee settlements under observation in the present study. The most explicit outcomes are represented by Nguenyyiel camp, for both maximum VV and VH trends, which opened precisely in 2016.

Tab. 5: Selected refugee camps population comparison in Gambela region, for reports delivered in corresponding time frames. Source: UNHCR.

Regional State	Settlement	Population: total refugees hosted		
		April 2014	December 2019	September 2023
Gambela	Nguenyyiel	Not opened	82.614	112.000
	Tierkidi	Not opened	62.715	72.448
	Jewi	Not opened	56.188	67.903
	Kule	36,340	44.021	52.959
Total		36,340	245.538	305.310

Despite the backscatter maximum values trend showing a low increase in the subsequent years after the opening, not matching the sharp ever-growing number of new refugee arrivals registered, the result is still pertinent with the assumption of backscatter values representing the presence of buildings and shelters, as all the situational reports delivered by UNHCR display the incapacity of supplying appropriate accommodation for all PoCs and seek the need for camp expansion and extra shelters.

All things noted, the present study revealed important meanings in the application of remote sensing techniques to assess environmental peculiarities and land surface features concerning areas interested by refugee camps built up in response to humanitarian emergency occurrences, despite the absence of historical images and extra data that does not allow for deeper cross-sectoral considerations.

5. Conclusion

An unprecedented influx of South Sudanese refugees into Southeastern Ethiopia is putting the ecologically fragile region on the edge of both environmental and social challenges, as the total refugee population (383,795) is rapidly going to match the local population (508,004) with a ratio of 1:1 reported by UNHCR 2023 Gambela operational overview.

Indeed, it has become widely accepted that human activity and anthropogenic pressure are at the root of climate change, which represents perhaps the largest threat to future generations (Warren, 2016). Within the advent of one of the most relevant civil wars of present times, the depth of the Sudanese crisis urges the need to use novel tools, such as geo-computational methods, to assess the environmental health and services and the potential for relocation to avoid the backlash of social injustice (Hassan et al., 2018; Vaz et al., 2018).

Under time and data scarcity conditions, remote sensing offers a rapid and efficient approach to creating detailed reconnaissance maps (Wendt et al., 2015).

Satellite-based analysis systems can provide important near-real-time (NRT) information about forest changes to national governments, non-governmental organisations (NGOs), and local communities and play a vital role in reducing deforestation and greenhouse gas emissions, as well as cover issues related to the extent of disasters, on-site crisis, number of people in need, etc.

Based on remote sensing data, this study documented land surface features' changes resulting in the four largest refugee settlements located in the Gambela region over a ten-year time frame.

The land surface backscatter maps produced from this study, the evidence obtained from the quantitative analysis of SAR data, crossed with camps' population trends and UNHCR reports, suggest that growing areas of lowland tropical forest and lowland semi-evergreen forest ecosystem, which characterise the Gambela region, might quickly and extensively be turned into semi-urbanised areas, endangering the natural ecosystems. Such degradation of these critical ecological resources might trigger multiplicative impacts on the environment, biodiversity, wildlife habitat and overall socioeconomic health of the entire region. Lands that were formerly vegetated and forested are converted to refugee camps as populations urgently seek shelter and safety in areas unequipped and unprepared to deal with the crisis.

Since detailed geological maps of the surroundings of refugee and IDP camps are difficult to obtain in most cases because they have never been produced or are not released by the national authorities of the country where the camp is located, this study highlights the use of free and open-access platforms and databases in order for every stakeholder to benefit from the findings eventually.

Many studies use optical remote sensing datasets for land cover and land use classification in different regions. Still, their limitations of weather and night-time imaging and occasional difficulties of land cover features recognition make it hard for land use classes' visual interpretation, owing to its unique imaging mechanism. In geological applications, remote sensing analysis strongly depends on visual interpretation. The Maximum Likelihood (ML) classification used in many other studies has also been discarded for the present research due to the high variation of land cover classes and the subsequent misclassification of some areas. The confusion matrices for both SAR and optical data show that most of the misclassification occurs between settlements and barren land, while some others are between vegetation and barren land. As a matter of fact, while testing and exploring several approaches, yearly vegetation loss and land use cover classification have been abandoned for the present study due to a lack of accuracy and consistency in the results.

On the other side, many scientists point towards the fact that using optical and radar satellite datasets together in a single classification scheme would give higher accuracy as compared to independent classification results, as Synthetic Aperture Radar (SAR) remote sensing imagery can be used in most weather conditions for land cover and use changes.

However, as Franke et al. (2016) reported, these planning and policy development innovations express less about enhancements to the agency's responsiveness to displaced persons and, instead, more about their greater management as subjects and objects of protection and assistance.

In this scenario, GIS tends to communicate and allow knowledge to flow in only one direction, depleting the transition from a traditional up-to-down managerial approach to the recently proposed bottom-up strategies. Quite so, for the purpose of keeping displaced persons' interests at the forefront, the use of GIS in UNHCR begs for a counterweight, recognising the need for balance and participatory GIS (PGIS) methods implementation, wherein displaced persons contribute to how they and their interests become features in the mapping of their displacements. The hope is that GIS instruments may be re-directed away from mere scientific and calculative purposes towards equal and constructive social interaction, learning, and planning between displaced persons and UNHCR, even though the potential success of these aims is questionable, as such empowerment aims are debated with respect to the politics of PGIS projects of all sorts.

In the Gambela region, the refugee response is currently dominated by UN agencies and international NGOs and staffed mainly by Ethiopians from outside of the region, creating a gap between humanitarian actors and the people they seek to assist. However, given the speed, number of migrants, and spontaneous nature of the recent refugee influx, the Ethiopian government has been at the forefront of implementing the 2016 Comprehensive Refugee Response Framework (CRRF) and the 2018 Global Compact on Refugees (GCR), which clearly emphasise the importance of local civil society in refugee programming and envisage a more prominent role for refugees themselves. The UNHCR Tool for Participatory Assessment in Operations (2006) seeks to bring forcibly displaced persons into what UNHCR terms situation analysis as persons who can provide knowledge and be agents of analysis themselves. UNHCR's PGIS approach is meant to allow for the recognition and the address of social power relations amongst the population of displaced persons it serves.

Overall, the resulting geographical information and thematic maps with the methodology produced from this study may provide a valuable tool for policymakers and concerned authorities to assess the spatial features of large-scale refugee movements and concentrations in the context of effective crisis management.

The total absence of previous similar studies conducted over the region of interest explored in the present research, the use of SAR texture features and dual-polarization SAR data, provided a comprehensive understanding of the observed scenes and are recommended to be explored for further research in the direction of sustainable development, as if no measures are taken now or in the near future to protect the vegetation cover, forests, and overall local environment, there will be long-term and irreparable damage that may cause more significant problems for the country and the population as well.

6. Acknowledgements

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7. Bibliography

Awas, T., Bekele, T., & Demissew, S. (2001). An ecological study of the vegetation of Gambella region, Southwestern Ethiopia. *SINET: Ethiopian Journal of Science*, *24*(2), 213–228. https://doi.org/10.4314/sinet.v24i2.18187

Black, R. (2009). Refugees and Displacement. In *International Encyclopedia of Human Geography* (pp. 125–129). Elsevier. https://doi.org/10.1016/B978-008044910-4.00824-5

Braun, A., Fakhri, F., & Hochschild, V. (2019). Refugee camp monitoring and environmental change assessment of Kutupalong, Bangladesh, based on radar imagery of Sentinel-1 and ALOS-2. *Remote Sensing*, *11*(17), 2047. https://doi.org/10.3390/rs11172047

Braun, A., & Hochschild, V. (2015). Combined use of SAR and optical data for environmental assessments around refugee camps in semiarid landscapes. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XL-7/W3*, 777–782. https://doi.org/10.5194/isprsarchives-XL-7-W3-777-2015

Bremner, L. (2020). Sedimentary logics and the Rohingya refugee camps in Bangladesh. *Political Geography*, *77*, 102109. https://doi.org/10.1016/j.polgeo.2019.102109

Çetinkaya, C., Özceylan, E., Erbaş, M., & Kabak, M. (2016). GIS-based fuzzy MCDA approach for siting refugee camp: A case study for southeastern Turkey. *International Journal of Disaster Risk Reduction*, *18*, 218–231. https://doi.org/10.1016/j.ijdrr.2016.07.004

Das, S. K., Naskar, K., & Sahu, C. S. (2020). Why does refugee generates? An empirical perspective. In S. K. Das & N. Chowdhary (Eds.), *Refugee Crises and Third-World Economies* (pp. 3–19). Emerald Publishing Limited. https://doi.org/10.1108/978-1-83982-190-520201004

Degife, A. W., Zabel, F., & Mauser, W. (2018). Assessing land use and land cover changes and agricultural farmland expansions in Gambella Region, Ethiopia, using Landsat 5 and Sentinel 2a multispectral data. *Heliyon*, *4*(e00919). https://doi.org/10.1016/j.heliyon.2018.e00919

Fan, H., Xu, J., & Gao, S. (2018). Modelling the dynamics of urban and ecological binary space for regional coordination: A case of Fuzhou coastal areas in Southeast China. *Habitat International*, *72*, 48–56. https://doi.org/10.1016/j.habitatint.2016.12.011

Franke, M. F. N. (2016). UNHCR's territorial depoliticization of forced displacement through the governance mechanisms of Participatory Geographical Information Systems. *Territory, Politics, Governance*, *4*(4), 421–437. https://doi.org/10.1080/21622671.2015.1088465

Friedrich, H. K., & Van Den Hoek, J. (2020). Breaking ground: automated disturbance detection with Landsat time series captures rapid refugee settlement establishment and growth in North Uganda. *Computers, Environment and Urban Systems*, *82*, 101499. https://doi.org/10.1016/j.compenvurbsys.2020.101499

GCIM. (2003). *The Mandate*. Global Commission on International Migration. https://www.iom.int/global-commission-international-migration

Gidron, Y., & Carver, F. (2022). International organisations and "local" networks: localisation and refugee participation in the Ethiopian-South Sudanese borderlands. *Refugee Survey Quarterly*, *41*(1), 1–25. https://doi.org/10.1093/rsq/hdab019

Gidron, Y., Carver, F., & Deng, E. (2021). More local is possible: recommendations for enhancing local humanitarian leadership and refugee participation in the Gambella refugee response. *Oxfam*. https://doi.org/10.21201/2021.8267

Hachmann, S., Jokar Arsanjani, J., & Vaz, E. (2018). Spatial data for slum upgrading: Volunteered Geographic Information and the role of citizen science. *Habitat International*, *72*, 18–26. https://doi.org/10.1016/j.habitatint.2017.04.011

Hagos, S. Z. (2021). Refugees and local power dynamics: The case of Gambella Region of Ethiopia. *Discussion Paper*. https://doi.org/10.23661/DP25.2021

Hassan, M., Smith, A., Walker, K., Rahman, M., & Southworth, J. (2018). Rohingya refugee crisis and forest cover change in Teknaf, Bangladesh. *Remote Sensing*, *10*(5), 689. https://doi.org/10.3390/rs10050689

Hossain, F., & Moniruzzaman, Dr. Md. (2021). Environmental change detection through remote sensing technique: A study of Rohingya refugee camp area (Ukhia and Teknaf sub-district), Cox's Bazar, Bangladesh. *Environmental Challenges*, *2*, 100024. https://doi.org/10.1016/j.envc.2021.100024

IDMC. (2020). Global report on internal displacement 2020. *Internal Displacement Monitoring Centre*. https://www.internal-displacement.org/publications/2020-global-report-on-internal-displacement-grid/

Ionesco, D., Mokhnacheva, D., & Gemenne, F. (2016). The Atlas of Environmental Migration (1st ed.). *Routledge*. https://www.routledge.com/The-Atlas-of-Environmental-Migration/Ionesco-Mokhnacheva-Gemenne/p/book/9781138022065

Jaafar, H., Ahmad, F., Holtmeier, L., & King-Okumu, C. (2020). Refugees, water balance, and water stress: Lessons learned from Lebanon. *Ambio*, *49*(6), 1179–1193. https://doi.org/10.1007/s13280-019-01272-0

Jahre, M., Kembro, J., Adjahossou, A., & Altay, N. (2018). Approaches to the design of refugee camps: An empirical study in Kenya, Ethiopia, Greece, and Turkey. *Journal of Humanitarian Logistics and Supply Chain Management*, *8*(3), 323–345. https://doi.org/10.1108/JHLSCM-07-2017-0034

Janmyr, M. (2013). Protecting civilians in refugee camps: unable and unwilling States, UNHCR and International Responsibility (Vol. 1). *Brill* | Nijhoff. https://doi.org/10.1163/9789004256989

Kassa, H., Abiyu, A., Hagazi, N., Mokria, M., Kassawmar, T., & Gitz, V. (2022). Forest landscape restoration in Ethiopia: Progress and challenges. *Frontiers in Forests and Global Change*, *5*, 796106. https://doi.org/10.3389/ffgc.2022.796106

Komp, K.-U., & Müterthies, A. (2016). Supporting management of European refugee streams by earth observation and geoinformation. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLI-B7*, 967–972. https://doi.org/10.5194/isprsarchives-XLI-B7-967-2016

Kwankye, M., & Anarfi, J. K. (2018). International migration and Africa's development. In J. Teye, M. Awumbila, & D. Badasu (Eds.), Migration in a globalizing world: perspectives from Ghana (pp. 31–50). *Sub-Saharan Publishers.* https://doi.org/10.2307/j.ctvh8r2m4

Lang, S., Schoepfer, E., Zeil, P., & Riedler, B. (2017). Earth Observation for humanitarian assistance. *GI_Forum*, *1*, 157–165. https://doi.org/10.1553/giscience2017_01_s157

Leiterer, R., Bloesch, U., Wulf, H., Eugster, S., & Joerg, P. C. (2018). Vegetation monitoring in refugee-hosting areas in South Sudan. *Applied Geography*, *93*, 1–15. https://doi.org/10.1016/j.apgeog.2018.01.013

Moisa, M. B., Gabissa, B. T., Hinkosa, L. B., Dejene, I. N., & Gemeda, D. O. (2022). Analysis of land surface temperature using Geospatial technologies in Gida Kiremu, Limu, and Amuru District, Western Ethiopia. *Artificial Intelligence in Agriculture*, *6*, 90–99. https://doi.org/10.1016/j.aiia.2022.06.002

Owen, M., Kruczkiewicz, A., & Van Den Hoek, J. (2023). Indexing climatic and environmental exposure of refugee camps with a case study in East Africa. *Scientific Reports*, *13*(1), 7533. https://doi.org/10.1038/s41598-023-31140-7

Rolkier, G., & Yeshitela, K. (2020). Vegetation classification and habitat types of Gambella National Park. *International Journal of Forestry Research*, *2020*, 1–12. https://doi.org/10.1155/2020/8612593

Tadesse, D., Suryabhagavan, K. V., Nedaw, D., & Hailu, B. T. (2024). A model-based flood hazard mapping in Itang District of the Gambella region, Ethiopia. *Geology, Ecology, and Landscapes*, *8*(1), 8–25. https://doi.org/10.1080/24749508.2021.2022833

Tafere, M. (2018). Forced displacements and the environment: Its place in national and international climate agenda. *Journal of Environmental Management*, *224*, 191–201. https://doi.org/10.1016/j.jenvman.2018.07.063

Tegene, A. S. (2018). Vegetation types, composition and conservation status of forest ecosystems in Ethiopia. *Journal of Natural Sciences Research*, *8*(19), 20–30. https://doi.org/10.7176/JNSR

UNDRR. (2015). Sendai Framework for Disaster Risk Reduction 2015—2030 (1st edition). *United Nations Office for Disaster Risk Reduction.* https://www.undrr.org/

UNHCR. (1992). Handbook on Procedures and Criteria for Determining Refugee Status under the 1951 Convention and the 1967 Protocol relating to the Status of Refugees. *UNHCR*. https://www.unhcr.org/media/handbook-procedures-and-criteria-determining-refugee-status-under-1951-convention-and-1967

UNHCR. (2016). Global trends: Forced displacement in 2015. *United Nations High Commissioner for Refugees.* https://www.unhcr.org/statistics/unhcrstats/576408cd7/unhcr-global-trends-2015.html

UNHCR. (2019). Handbook on procedures and criteria for determining refugee status and criteria for determining refugee status and guidelines on international protection under the 1951 convention and the 1967 protocol relating to the status of refugees. *UNHCR*. https://www.unhcr.org/media/handbook-procedures-and-criteria-determining-refugee-status-under-1951-convention-and-1967

UNHCR. (2020a). Gambella regional state: Ethiopia 2019 pledge progress report [Situation report]. *UNHCR* Ethiopia. https://data.unhcr.org/en/documents/details/79020

UNHCR. (2020b). Global trends: Forced displacement in 2019. *United Nations High Commissioner for Refugee*s. https://www.unhcr.org/media/unhcr-global-trends-2019
UNHCR. (2020c). Refugees and asylum seekers from South Sudan in Gambella region: Situational update. *United Nations High Commissioner for Refugees.* www.unhcr.org
UNHCR. (2023). Global trends: Forced displacements in 2022.*United Nations High Commissioner for Refugees.* www.unhcr.org
UNHCR, & CO Ethiopia. (2024). Ethiopia: Refugees and asylum-seekers as of February 2024. *United Nations High Commissioner for Refugees.* www.unhcr.org
UNHCR Ethiopia. (2019). Gambela regional state: Ethiopia 2019 Pledge Progress report. *United Nations High Commissioner for Refugees.* www.unhcr.org
UNHCR Public Information Unit. (2014). UNHCR Gambella 2014 in review (Vol.1, Issue 1). *United Nations High Commissioner for Refugees.* https://data.unhcr.org/
UNHCR, & UNCS. (2024). Regional bureau for East Horn of Africa and great lakes: Refugees, returnees and IDPs in the IGAD Region as of 29 February 2024. *United Nations High Commissioner for Refugees.* https://data.unhcr.org/en/search?text=ethiopia
Vaz, E., Lee, K., Moonilal, V., & Pereira, K. (2018). Potential of Geographic Information Systems for refugee crisis: Syrian refugee relocation in urban habitats. *Habitat International*, *72*, 39–47. https://doi.org/10.1016/j.habitatint.2017.02.001
Warren, P. D. (2016). Forced migration after Paris cop21: Evaluating the 'climate change displacement coordination facility. *Columbia Law Review*, *116*(8), 2103–2144. https://doi.org/10.1163/9789004322714_cclc_2017-0142-008
Wendt, L., Hilberg, S., Robl, J., Braun, A., Rogenhofer, E., Dirnberger, D., Strasser, T., Füreder, P., & Lang, S. (2015). Using remote sensing and GIS to support drinking water supply in refugee/IDP camps. *GI Forum – Journal for Geographic Information Science*, *1*, 449–458. https://doi.org/10.1553/giscience2015s449
Zetter, R., Boano, C., & Morris, T. (2008). Environmentally displaced people: Understanding the linkages between environmental change, livelihoods and forced migration. In *Refugee Studies Centre* (Vol. 1, p. 44). Refugee Studies Centre. https://www.rsc.ox.ac.uk/publications/search?keywords=Environmentally+displaced+people&year=2008