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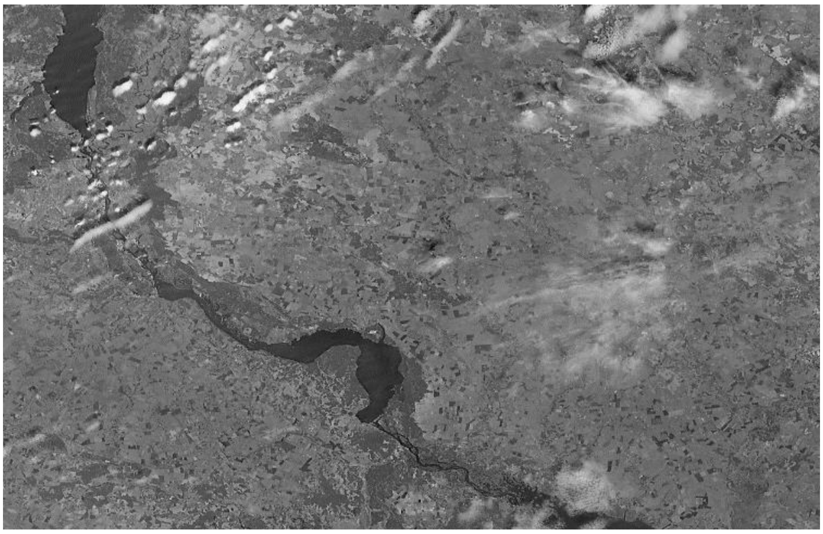
Evaluation of the effect of conflict on fire and GPP in Ukraine



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Disclaimer

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Lilith Kastens

Bachelor thesis, 15 credits, in Physical Geography and Ecosystem Analysis

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Abstract

The war in Ukraine in 2022 has caused environmental damages on different scales which come with their own challenges. One of the factors that can cause environmental damage is vegetation fire. As earlier studies have concluded, in conflict regions the amount of vegetation fires can increase due to (forced) migration, change in agriculture and warfare tactics. Not only conflict can change fire occurrence but also the climate. Climate is predicted to change more dramatically in most regions of the world due to climate change. Ukraine has been already experiencing climate change in terms of for instance temperature increase by 1.5°C (average air temperature 9.3°C) over the last 30 years and the change in precipitation patterns. Moreover, Ukraine was invaded by Russia in February 2022.

In this report the evaluation of fire (VIIRS Active Fire) and the change in GPP (MODIS Gross Primary Productivity) caused by armed conflict (UCDP) was done. It has been concluded even though fire and conflict are not correlated according to the spearman rank correlation analysis ($\rho = 0.30$, $p > 0.05$), the Bivariate Local Moran's I Analysis shows a temporal and spatial correlation in the year 2020, 2021 and 2022. Furthermore, the fires during 2022 and 2020 are in comparison to 2021 not primarily on agricultural land but more spread out into forests. The analysis of the change in GPP during the years 2020, 2021 and 2022 show no specific pattern that can be linked to conflict, but the GPP has decreased from 2021 to 2022. The analysis is complemented with a discussion of the results.

Keywords: Climate Change, Armed Conflict, Fire, GPP, Remote Sensing, Russia-Ukraine War

Figure 1. [Cover page]. Sentinel-2 image from 2022-05-12 showing a part of Ukraine from above. On the left side of the image is Ukraine's capital Kyiv (Copernicus Sentinel data, 2023).

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I. Introduction

Armed conflicts are known to accelerate the number of wildfires in a region (Dinc et al., 2021; Eklund et al., 2021; Jaafar et al., 2022). In regions of armed conflict there is primarily an increase of fires detected which can be due to the abandonment of the land due to (forced) migration, the change in agriculture or as a warfare tactic (Baumann et al., 2015; Butsic et al., 2015). The warfare tactics include the wanted destruction of the other parties' resources like crop fields or indirect ignition of fire through bombs, missiles, and other weaponry (Jaafar et al., 2022). The effects of the increase of fire occurrence are lack of food security, economical losses and decrease of security (Viegas et al., 2009). Through satellite imagery, conflict data, the media, and local correspondents it is possible to circumscribe the events in the regions and evaluate which factors influenced the occurrence of fire (Dinc et al., 2021). This is, nevertheless, difficult to relate completely to each other since media coverage and people's view on events can be subjective, and quantitative data from satellites show the result (the fire) but not the cause (Dinc et al., 2021).

Fires are a common occurrence and can have beneficial effects for the environment, however if fires are beneficial or detrimental is dependent on the frequency, timing, and extent of the fire (Hirschberger, 2016). Some regions in the world have adapted to fire disturbances and the environment's wellbeing and health is dependent on fire. Other regions are sensitive to fire as it harms the environment. Today over 90% of fires have anthropogenic origin and only around 4% are originating naturally through the means of lightning for instance. An explanation to these percentages is that humans have used fire over time in many ways, e.g., to clear areas for agriculture, and they also started preventing and controlling fires to protect their housing and resources. According to Andela et al. (2017) the burned area in the world has been declining by 24.3% ± 8.8%. Nevertheless, it is predicted that the fire regimes will change in seasonality, intensity, and frequency in the upcoming years due to climate change (Carnicer et al., 2022; Ward et al., 2012).

The increasing frequency of fire, as mentioned before, is an issue because combustion is one of the factors bearing the consequence of an increase of carbon dioxide (CO_2) in the atmosphere (Ward et al., 2012). Hence, creating a cycle that leads to an enhancement of climate change. The release of CO_2 into the Earth's atmosphere is an ongoing threat for our environment and ecosystems (IPCC, 2022). Industries, cars, food production and many more factors decide the amount of carbon released into the atmosphere causing an increase in the temperature by several degrees. The current observed increase (2011-2020) in temperature globally is at 1.1°C which is mostly due to industrialization starting in the end of the 19th century. The CO_2 in the atmosphere has been increasing from the 1850s to today by over 100 ppb CO_2 which means the CO_2 in the atmosphere is at 420 ppm CO_2 and the trend is ascending. The consequence is that currently the concentration of CO_2 is the highest it has ever been. As a consequence, it is predicted to lead to an enhancement of extreme weather events, e.g., flooding or drought, caused by a change in temperature and precipitation.

The impact on the environment is severe and can cause a shift in species range, changes in ecosystem structures and in timing regarding phenology (IPCC, 2022). The change in climate, extreme weather events and the environmental impact furthermore threaten the livelihoods of millions of people in terms of food security, water scarcity, health, and infrastructure. In Europe the effects of climate change are already visible; the temperature has been increasing, floods are more frequent, and droughts have devastating effects on agriculture and forests. Due to this change in temperature and increase in droughts it is predicted that there will be a shift in fire regimes especially in already risk prone areas and more fires will feed into the cycle of the release of CO_2 in the atmosphere and the following climate change (Carnicer et al., 2022).

Ukraine is facing the impacts of climate change in terms of increase in temperature and change in precipitation patterns as well as other climate factors, e.g., wind regimes and soil moisture (Balabukh & Malytska, 2017). However, climate change is not the only environmental challenge Ukraine is currently dealing with; since the Russia-Ukraine war escalated in February 2022 when Russia invaded Ukraine further, environmental damage has been observed on different scales (United Nations Environment Programme 2023). This includes for example loss of biodiversity, air pollution, contamination of water, and the possible increase of fire occurrence due to conflict (Klerk et al., 2022; United Nations Environment Programme 2023). The assessment of the environmental damage is important for further mitigation purposes as well as to plan recovery and restoration strategies during and after the Russia-Ukraine war has ended (United Nations Environment Programme 2023).

The purpose of this study is to contribute to this assessment in terms of estimating the impact of gross primary productivity (GPP) due to conflict in the primary combat zones that has also been affected by high fire occurrence using remote sensing.

II. Aim and Objectives

The aim of this study is to evaluate the spatial-temporal relationship between the armed conflict in Ukraine 2022, vegetation fires and GPP. The following objectives are formulated to successfully evaluate this aim:

1) Mapping of the conflict and fire events in Ukraine during the years 2014-2022,
2) Analysing the spatial and temporal relationship between conflict and fire in the years 2020, 2021 and 2022 and on which land cover these fires occur. The special focus will be on the months April to October in 2022,
3) Assessing the impact of conflict on the GPP in the primary combat zones.

The hypothesis is that the occurrence of vegetation fires in the conflict zone increased in 2022, which in turn decreased the GPP in said zones.

III. Background

This section explains the background of the study: the study area of Ukraine, the climate, the Russia-Ukraine war, and land use. In addition, the concept of GPP will be explained.

i. Study Area - Ukraine

Ukraine, the second largest country in Europe with an area of 603 700 km², is located 48.37° North and 31.16° East in eastern Europe bordering seven countries (Fig. 2). The country is divided into 27 administrative regions, where on the eastern side, bordering Russia, are the administrative regions Donetsk, Luhansk, Kharkiv, Sumy and Zaporizhzhia. The country's capital, Kyiv, is located in the northern part of the country by the river Dnipro (Domanitsky & Micklin, 2023).

The river Dnipro has its source in Russia and is flowing through Belarus and Ukraine from the north to the south where the river has its outlet into the Black Sea (Domanitsky & Micklin, 2023). The Black Sea is located by Ukraine's southern border by the regions Sevastopol, Kherson, Odessa and Mykolaiv and the Autonomous Republic Crimea (Fig. 2). Next to the Black Sea in the south is the Sea of Azov. In the southern and eastern regions, the elevation is the lowest of the country (USGS, 2018). On the western side of the country are the highest elevations in the Carpathian Mountains (1941 meters). The average elevation in the Ukraine is 175 meters.

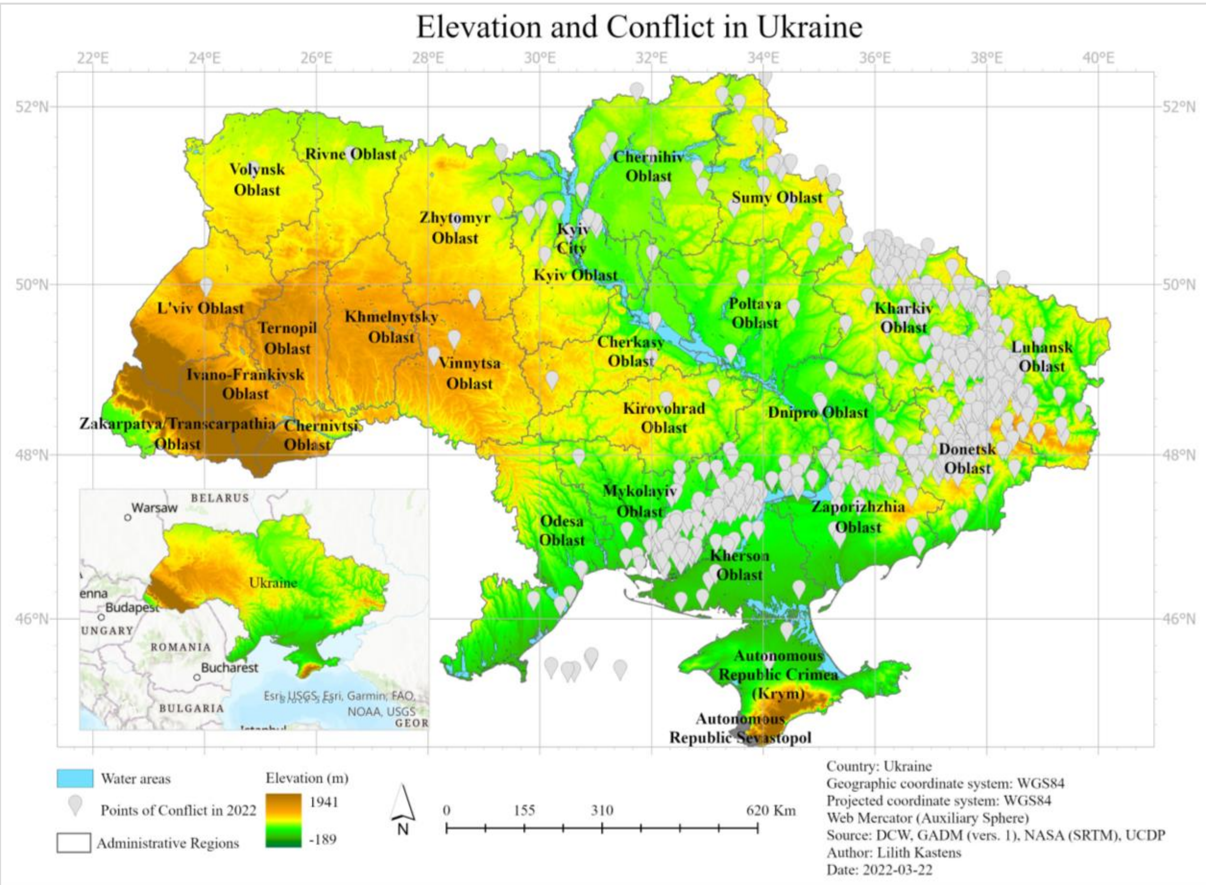

Figure 2. The elevation (m), administrative regions, and water areas in the study area Ukraine. Conflict locations during April to October 2022 are marked with grey points. The map on the lower left corner shows Ukraine and its neighbouring countries. The word "Oblast" is Ukrainian and can be translated to region.

ii. Russia-Ukraine War

After the dissolution of the Soviet Union in 1991 Ukraine and the Russian Federation (Russia) declared its independence in the same year (Bebier, 2015). Over the years, the two countries have been in conflict regarding territory. This reached a peak in 2014 when Russia annexed the autonomous region of Crimea illegally. This was followed by several attacks on Ukrainian cities in the east from Pro-Russian separatists and caused several deaths. The armed conflict between Ukrainian military and Pro-Russian separatists was resolved in 2015 with a peace-treaty. Nevertheless, this treaty was allegedly violated several times afterwards.

On the 24th of February 2022, the conflict escalated once again when the Russian military crossed the border to Ukraine and attacked several cities including Ukraine's capital Kyiv (Belkin et al., 2023; Kottasova, 2023). The attempt to occupy Kyiv city in the beginning of the war failed. Since then, Ukraine has been under constant attack from Russia (Kottasova, 2023). The combat zone has been concentrated mostly to the region in the east and the south of Ukraine.

During the war, Ukrainian citizens have fled over the country's border and sought asylum in countries close by, e.g., Poland, Germany, and the Czech Republic (Kottasova, 2023). An estimated of 5 352 000 people needed to relocate due to the conflict (IOM UN Migration, 2023). Therefore, the most affected area was the east of Ukraine, closely followed by the west. The United States of America and European Union are responding to the illegal invasion, the war and its crimes with sanctions, weaponry, and funding (Archick, 2023; Belkin et al., 2023).

iii. Climate and Extreme Weather

The climate in Ukraine is temperate continental (The World Bank Group, 2021; Wilson et al., 2021). The average air temperature during the last 30 years (1991-2020) in Ukraine has been 9.3°C (The World Bank Group, 2021). More specifically, in the summer months the average air temperature in Ukraine is between 18°C to 22°C and during the winter months between -5°C to 2°C. The mean maximum temperature is 28°C and the mean minimum temperature of -6°C. Important to note is, in the last years, climate change has influenced the temperature meaning that the temperature has increased on average by 1.5°C (Wilson et al., 2021).

Over the last 30 years the average rainfall was at 555 mm/year (The World Bank Group, 2021). The precipitation in Ukraine follows a similar pattern as the temperature, low precipitation during winter and high precipitation during spring and summer. The highest precipitation experiences the months May, June and July and the lowest precipitation is detected during February, March, and April. The precipitation is driven by topography and seasonality; the wettest regions are the mountainous areas of Ukraine in the north and west; the driest regions are in the eastern and southern region (The World Bank Group, 2021; Wilson et al., 2021).

Several climate factors, e.g., temperature, precipitation, wind regimes and relative humidity, control the hazard of natural wildfires (Balabukh & Malytska, 2017). An example being in the southern region of Ukraine, the temperature rules the number of days that can be expected to have fire risks. Hence, the temperature changes (increase by +1.5°C over the last 30 years) the risk for wildfires, especially forest fires, in the southern and western regions has been increasing by a few days a year (Balabukh & Malytska, 2017; Wilson et al., 2021). Kherson, located by the Black Sea, has the highest natural fire hazard in Ukraine. Autumn in Ukraine and other countries in east Europe is identified to have an elevated risk of fire according to Balabukh and Malytska (2017). Nevertheless, the months of April, June and August have the highest increase of maximum days of fire hazard in Ukraine (Balabukh &

Malytska, 2017). In addition, the wind regimes in Ukraine as well as the precipitation have changed – overall decrease in summer and the periods without rain will extend – and relative humidity has decreased in the eastern and northern steppe (Balabukh & Malytska, 2017).

iv. Land Use and Land Cover

Approximately 70% of Ukraine is covered with cultivated and managed vegetation/agriculture (Fig. 3). This land cover is predominantly in the east, south and centre of Ukraine, but spreads out to the north and west as well. The land is used for growing crops all year around; Some examples of the crops grown in Ukraine are winter rape seat, peas, maize, soybeans, spring crops, sunflowers, winter barley, and sugar beet (Hall et al., 2021).

Forests can mostly be found in mountainous areas in the west, in the north-west and north (Fig. 3). The forest types range from deciduous broad leaf, deciduous needle leaf, evergreen needle leaf, and evergreen broad leaf (closed and open). In the south and east are grasslands located and around riverbeds and forests (Hall et al., 2021). Furthermore, Ukraine is covered with herbaceous vegetation in the south and east and herbaceous wetland in the north-west.

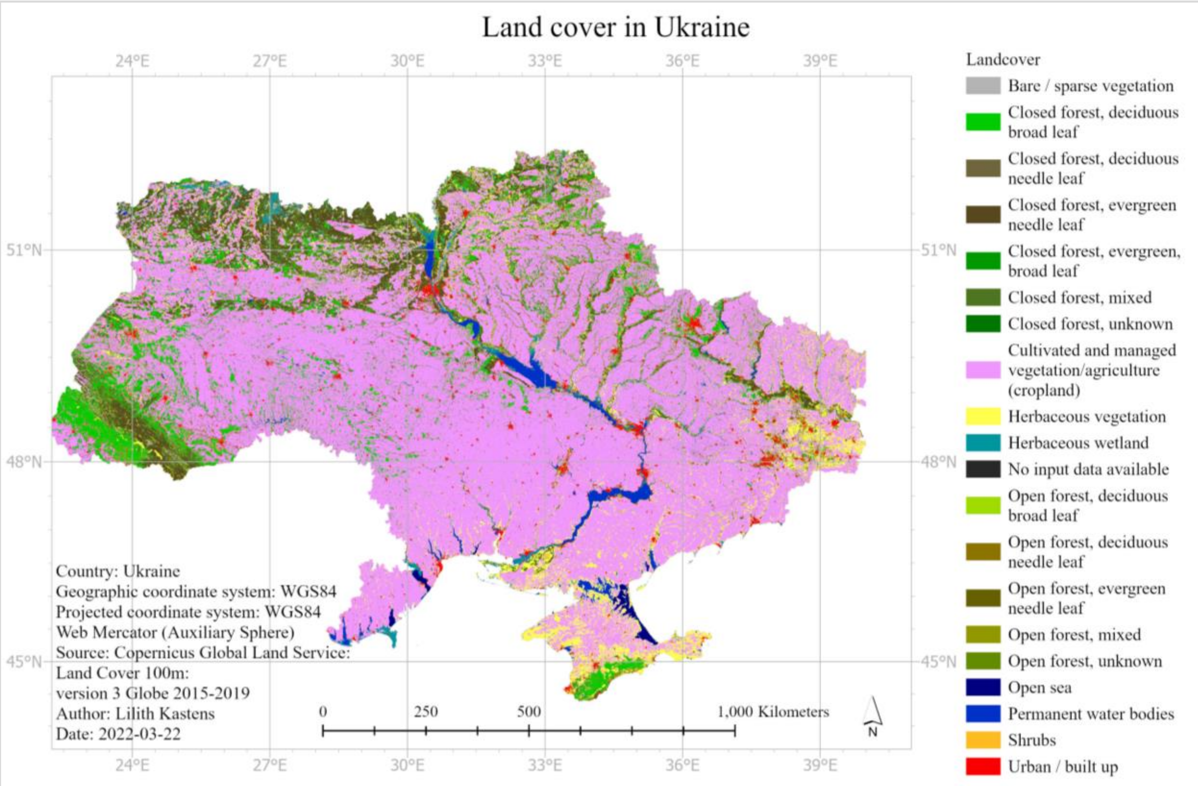

Figure 3. The land cover in Ukraine from Copernicus Global Land Service: Landcover 100m: version 3 Globe 2015-2019 (Buchhorn et al., 2020).

v. Gross Primary Productivity

The gross primary productivity (GPP) describes the amount of CO_2 fixed by vegetation through photosynthesis on an ecosystem level (Chapin et al., 2002). Hence, GPP is controlled by the amount of photosynthetic tissue available within the ecosystem.

Photosynthesis is the chemical process of turning CO_2 into energy and oxygen (O_2) using light (radiation) (Chapin et al., 2002). As a consequence, light availability is one of the driving forces that determines the photosynthetic rate of a plant. The temperature is moreover another driving force since it can determine the rate of photosynthesis in terms of the rate of chemical reactions. Other factors which affect the photosynthetic ability of plants is the availability of water (precipitation and soil moisture), biotic factors (e.g., leaf area), and the nitrogen availability.

According to Chapin et al. (2002) seasonal and diurnal changes in GPP are common because of the influence of temperature, light, and nitrogen availability that governs photosynthesis. During the day, light availability and temperature changes; therefore, the rate of photosynthesis changes as well. Similar behaviour can be observed during the seasons of the year. In the winter months the photosynthetic rate decreases in comparison with summer months.

Correspondingly the climatic conditions where the ecosystem is located influence the amount of GPP in an ecosystem (Chapin et al., 2002; Chen, 2018). Chen (2018) suggests that the climatic conditions like temperature, precipitation, radiation, and biotic factors are influencing GPP. Climate is part of the long-term controls of GPP. According to Chapin et al. (2002) GPP is governed by short-term controls and long-term controls which are interconnected with each other. Long-term controls include time (since disturbance), parent material, and climate while short-term controls are the leaf area, nitrogen, season length, temperature, light, and CO_2 (Chapin et al., 2002).

The CO_2 fixed by vegetation is either released by respiration or combustion (Chapin et al., 2002). Anthropogenic influences can also influence GPP, e.g., harvesting trees and agriculture. Vegetation fire (anthropogonic influenced or natural) will change the amount of CO_2 fixed in vegetation (Lasslop et al., 2019). The response of the environment to fire is a vital factor when it comes to the ability of storing carbon. Depending on the response rate the recovery of an environment can either be fast or slow. Various types of land cover have a different response to combustion and differ in fuel availability for fire. Agricultural land and grassland both have a fast recovery, while deforested areas and peatlands have the slowest recovery. In between these land cover types are forested areas that have a moderate response of recovery.

IV. Data and Methodology

A detailed explanation on the conflict data as well as the fire data and gross primary productivity is provided here (Table 1). The method behind obtaining the results presented is in the section after.

Table 1. Data source, description, time period, format, coordinate system, and spatial resolution of the data used in the analysis.

Data source	Description	Time period	Format	Coordinate System	Spatial Resolution
Uppsala Conflict Data Program (2023)	Conflict in Ukraine	2014-2021	Vector (point data)	WGS84	-
Hegre et al. (2020)	Conflict in Ukraine	2022	Vector (point data)	WGS84	-
NASA FIRMS (n.d.)	VIIRS Active Fire	2014-2022	Vector (point data)	WGS84	-
Buchhorn et al. (2020)	Copernicus Global Land Service: Landcover 100m: version 3 Globe 2015-2019	2019	Raster	WGS84	100 *100m
Running and Zhao (2021)	Gross Primary Production Yearly L4 Global (MOD17A3HGF Version 6.1 product)	2020-2022	Raster	Sinusoidal	500 * 500m

i. Data Collection

i. Uppsala Conflict Data Program

For the analysis five different data sets for fire, conflict and carbon fluxes were used. The first data set is the conflict data from the Uppsala Conflict Data Program (Uppsala Conflict Data Program, 2023). The program which supplies conflict data for each country where at least one person has died in a specific conflict location or during a specific time (Uppsala Conflict Data Program, 2023). Furthermore, the data is categorized in state-based violence, one-sided violence, and non-state violence one location (x-coordinate and y-coordinate) is supplied for the location of where the conflict was present (Uppsala Conflict Data Program, 2023). The coordinate system the location is presented in is WGS84, which was converted for the following analysis into the projected coordinate system WGS84 auxiliary sphere.

Different conflict data sets were used for the analysis; for the years 2014 to 2021 official published data from the "UCDP Conflict Encyclopaedia" was used while for the year 2022 the UCDP Candidate Events Dataset (UCDP Candidate) version 23.0.X was used (Hegre et al., 2020). The reason for that is that the data sets are updated during June every year and the official version was not published by the time this analysis was made (Hegre et al., 2020). Therefore, to make sure the candidate data for Ukraine in 2022 is reliable, only the conflict events marked "clear" were selected which means the source and correctness of the event has been researched and verified.

ii. VIIRS Active Fire

The Fire Information for Resource Management System (FIRMS) is a system from NASA that shares data from different operating satellite systems (NASA FIRMS, n.d.). The Visible Infrared Imaging Radiometer Suite (VIIRS) instrument - aboard S-NPP and NOAA 20 satellites – collects, via infrared radiation, data on a global scale. This includes data on active fire and thermal anomalies. VIIRS has a resolution of 375m and detects fires on land and oceans during the day and night. VIIRS active fire data is furthermore divided into different types: 0 = presumed vegetation fire, 1 = active volcano, 2 = other static land source, and 3 = offshore detection (includes all detections over water).

For the analysis, active fire data from VIIRS during the years 2014-2022 was requested and then extracted in vector format (point) from FIRMS. It was then converted from the coordinate system WGS84 to the projected coordinate system WGS84 auxiliary sphere. The data set was used for the analysis for the count of fire and conflict and the spearman rank correlation.

iii. MODIS Gross Primary Productivity

The NASA product "MOD17A3HGF Version 6.1" provides the yearly GPP (Kg C/m²/year) and Net Primary Productivity (NPP) (Kg C/m²/year) on a global scale from the sum of all 8-day GPP Net Photosynthesis (PSN) products (Running & Zhao, 2021). 8-day GPP Net Photosynthesis (PSN) products refer to the "MOD17A2H Version 6.1 Gross Primary Productivity (GPP)" product that uses the radiation use efficiency concept (Running et al., 2021). This is calculated as follows:

$$GPP = \varepsilon * APAR \quad (1)$$

where ε is the radiation use efficiency coefficient and APAR is the absorbed photosynthetically active radiation (Sulla-Menashe & Friedl, 2018). These variables are obtained via remote sensing and computed from different parameters (Sulla-Menashe & Friedl, 2018).

Furthermore, the data sets are available as a grid with a spatial resolution of 500 meter in a sinusoidal coordinate system (Running et al., 2021; Running & Zhao, 2021). To analyse the change over time the yearly GPP from the MOD17A3HGF Version 6.1 product of the years 2020, 2021, and 2022 were extracted. After that, the data was converted from the sinusoidal coordinate system to the projected coordinate system WGS84 auxiliary sphere.

ii. Data Analysis

The data analysis was made in six steps:

1. **Count** of conflict and fire over the years 2014-2022
2. **Spearman rank correlation** of conflict and fire during 2014-2022
3. **Fire occurrence on land cover** during the years 2020, 2021, and 2022
4. **Bivariate Local Moran's Analysis** on conflict and fire for April to October 2022
5. **Identification** of conflict and fire zones during April to October 2022
6. **Change** of gross primary productivity in 2020 to 2022
7. **Bivariate Local Moran's Analysis** on conflict and fire for 2020 and 2021

The data sets for fire – Active Fire VIIRS (NASA FIRMS n.d.) and UCDP conflict data during the years 2014 to 2022 were selected and counted with the software MATLAB (The MathWorks Inc., 2023). The start year 2014 was selected since the first invasion from Russia into the Autonomous Region of Crimea and Sevastopol took place during that year according to Bebier (2015). This sparked conflicts in Ukraine over the following years and therefore the relationship between conflict and fire as well as the trend of fire could be investigated.

In order to investigate the relationship between conflict and fire in the past years in Ukraine the spearman rank correlation was selected:

$$r_s = 1 - \frac{6 \sum d_i^2}{n\,(n^2-1)} \qquad (2)$$

Where r_s is the spearman rank correlation coefficient. Spearman rank tests the monotonic relationship between ranked variables. The range of r_s is $-1 \geq r_s \geq 1$, and the closer coefficient is to ± 1 the stronger the monotonic relationship is between the variables. The null hypothesis for the spearman rank correlation stated that if ρ equals 0 (H_0: ρ = 0) there is no significant relationship between conflict and fire in Ukraine whereas the alternative hypothesis (H_a: ρ ≠ 0) stated that ρ is not equal to 0 there is a relationship. Moreover, the critical probability was set to α = 0.05.

Since, the Spearman rank correlation may only imply a correlation between variables, and not causality, it was determined to investigate this relationship further. Therefore, the spatial and temporal relationship of fire and conflict in Ukraine during 2022 was investigated. The conflict and fire data set were divided into monthly periods from April to October 2022. These seven months are the growing season in Ukraine and therefore fuel for fires is likely to be in higher abundance in comparison to the months November to March. In addition, for this analysis only fire data marked with the type "0 = presumed vegetation fire" was selected to rule out other sources that are marked as thermal anomalies but are not fires. For the months of September and October 2022 the type "0" could not be selected since the categorization was not available in the data set from FIRMS.

A graph of the occurrence of fire on different land cover for the years 2020, 2021 and 2022 was made. For the land cover the Copernicus Global Land Service was used. The fire data from VIIRS was reclassified into 1 = fire occurrence and 0 = no fire occurrence and then multiplied with the land cover data. The data was summed up and the percentage of each fire occurrence on land cover was calculated with ArcGIS Pro (Esri, 2020).

The spatial analysis was made with the Bivariate Local Moran's I analysis (BiLISA) that describes the relationship between two different variables by using the location and value of one variable and the value of another neighbouring variable. The first step of this analysis was the division of the country into equal grid cells with an extent of 10x10km in ArcGIS Pro (ESRI, 2020). Then the variables fire and conflict for each month were spatially joined to the grid cells to count the number of fires or conflicts located within each grid cells. The layer was then converted into a shapefile and uploaded into the open-source software GeoDa (Anselin et al., 2006). GeoDa is a software specialized in spatial analysis. The grid cells were spatially weighted with the queen contiguity which includes neighbouring polygons that either share an edge or a vertex and creates a spatial weight matrix. In this case a maximum of 8 neighbouring cells were possible. After that, the analysis of conflict (independent variable) and fire (dependent variable) was made. In addition, the regions with high fire and high conflict clusters were identified to further analyse the change in GPP.

After the administrative regions were selected with high fire and high conflict clusters, the GPP was extracted for the years 2020, 2021 and 2022; to compare the yearly GPP of those three years, the average of every administrative region that had high conflict and high fire events was calculated. These years are selected to compare the change in GPP due to conflict. Since the years 2020 and 2021 have a similar count of conflict but different number of fires whereas in 2022 was a high count of fires, a comparison could be made between the years since they have several factors that might influence the GPP. In addition, using years that are close to each the likelihood of change in GPP due for example extensive land use change could be decreased. Furthermore, the years 2020 and 2021 were also tested if there is a spatial relationship between conflict and fire with the BiLISA analysis.

V. Results

In this section the results are presented starting with the count of fire and conflict in all of Ukraine, the corresponding spearman rank correlation and fire occurrence on different land use classes followed by the BiLISA analysis and the change in GPP over time.

i. Fire and Conflict in Ukraine (2014-2022)

Over the past 8 years the number of fires in Ukraine have decreased overall (Fig. 4). In the beginning of the conflict period in 2014 the fire count is at its highest and in 2021 at its lowest. In 2022 the amount of fire is increasing slightly again. For conflict on the other hand, 2022 is, with a total count of 4520 conflicts, the highest year, whereas 2016 is, with a count of 127, the lowest year. The two second highest are the years 2014 (1294 conflicts) and 2017 (722 conflicts) and the remaining years range between 145 and 199 conflicts per year.

During the years 2014 to 2020 fire shows a similar pattern as conflict; an increase of conflict equals an increase in fire and vice versa. This pattern however cannot be observed for the year 2021 where the count of conflict again increases but fire decreases to its lowest count during all the years. The year 2022 shows a fourfold of conflict but only a minor increase in fire. Furthermore, the relationship between conflict and fire in Ukraine tested with the Spearman rank correlation shows no significant correlation in the years 2014 to 2022 ($\rho = 0.30$, $p > 0.05$).

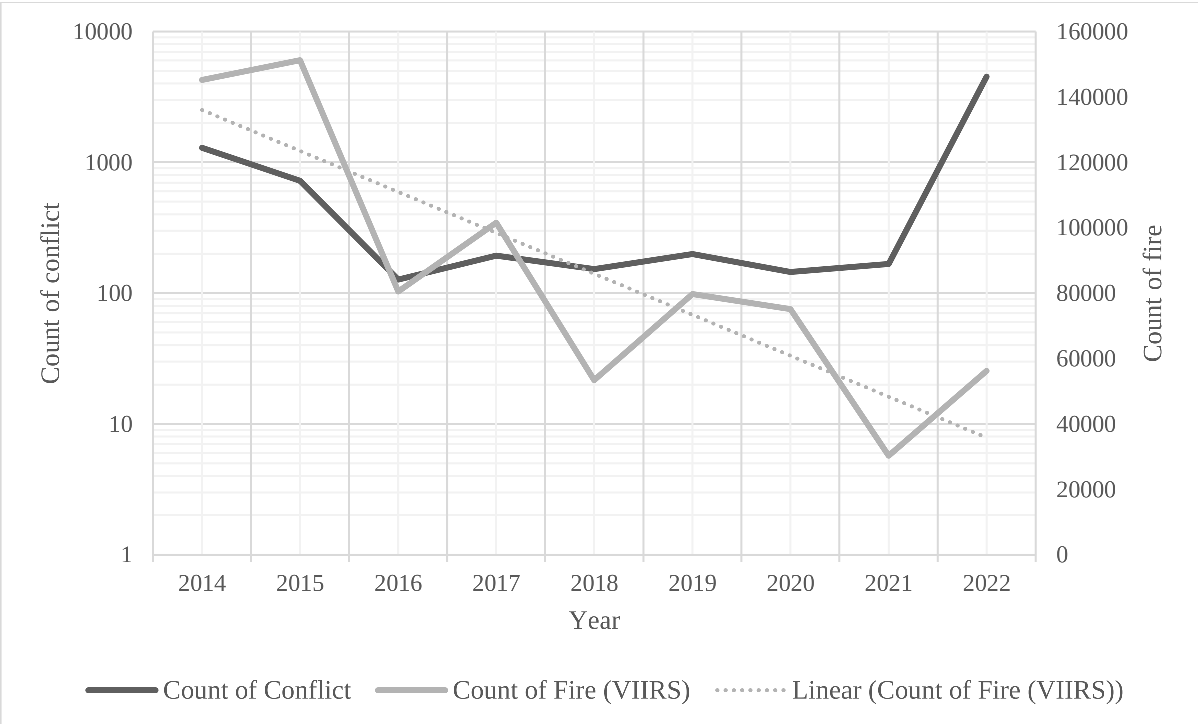

Figure 4. The count of conflict (y axis (left) in a logarithmic scale from UCDP and the count of fire (y axis (right)) from the satellite instrument VIIRS during the years 2014-2022 (x axis) for the country Ukraine (Hegre et al., 2020; NASA FIRMS n.d.; Uppsala Conflict Data Program n.d.).

Looking at the last three years (2020, 2021, and 2022) most of the fires in Ukraine occur on cultivated and managed vegetation/agriculture (Fig. 5). The leading year is 2021 where about 75% of fires are detected on agricultural land. In comparison to the year before and after, only approximately 53% of fires are on agricultural land. Noticeable is also, in the year 2020 and 2022 fire is in evergreen needle leaf forest which is not the case for 2021.

Furthermore, in 2020 about 4% more fires are detected in urban and build up areas. Otherwise, the pattern of the fire on land cover classes is similar in the three years. Most fires that are not on agricultural land are in forest areas, e.g., unknown open forest, mixed open and closed forest, deciduous broadleaf forest, and in herbaceous wetland.

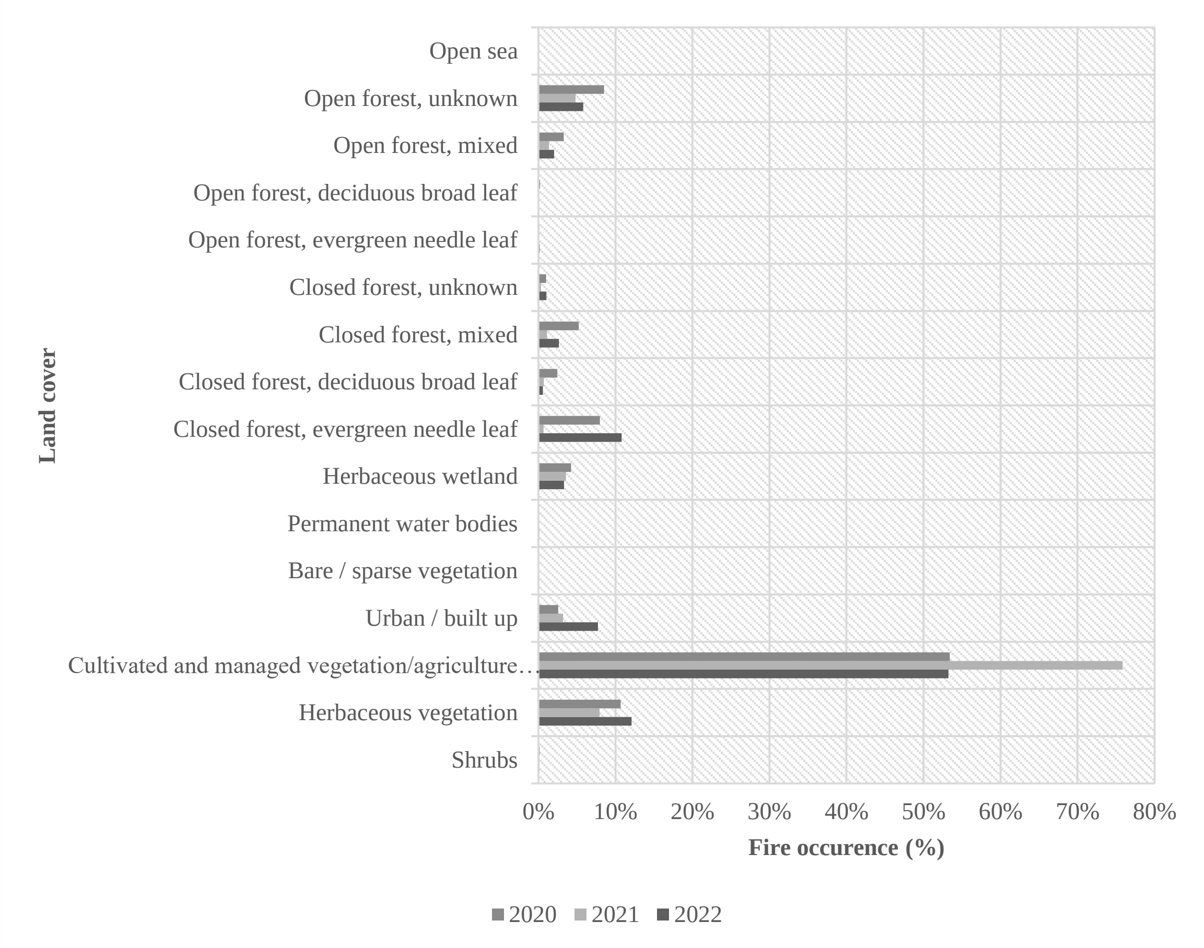

Figure 5. The occurrence of fire (in %) on different land cover classes from the Copernicus Global Land Service in the years 2020, 2021, and 2022 (Buchhorn et al., 2020).

ii. Bivariate Local Moran's I Analysis

The high-high (high conflict - high fire) conflict and fire areas with a significance of $p \leq 0.001$, $p \leq 0.01$, or $p \leq 0.05$, derived from the BiLISA analysis, are dominant in south-east Ukraine (Fig. 6). The regions include Kharkiv, Luhansk, Donetsk, Zaporizhzhia, Mykolayiv and Kherson in the month April to October of 2022.

Figure 6. The regions Kharkiv, Luhansk, Donetsk, Zaporizhzhia, Mykolayiv and Kherson with highest count of conflict and fire (BiLISA analysis) (April to October 2022).

In the regions presented above, the number of high-high areas (high conflict - high fire) fluctuates during April and October (see Appendix A). June is the month with the highest number of high-high events (71) and the high-high conflict-fire zones are mostly concentrated in Luhansk, Donetsk and Kharkiv (Fig. 7). On the border between Zaporizhzhia and Mykolayiv a few high-high areas are also located. Surrounding the high-high grid cells are mostly low-high (low conflict - high fire) zones and a small amount of high-low (high conflict – low fire) zones.

During October the lowest number of high-high zones (46) are detected and show a difference to June (Fig. 8). Even though most high conflict and high fire zones are in Luhansk, Donetsk, and Kharkiv the previous month there is only one high-high area detected in Kharkiv. Zaporizhzhia, on the other hand, has a higher number of high-high areas than in July. The low-high zones are also more spread out than in June. In fact, the amount increases and can be detected in higher abundance in other regions. Moreover, it is important to mention the two high-high areas in Dnipro, a region excluded from the six regions that show the highest conflict-fire zones in Ukraine.

While the month September shows a similar pattern as October, the other months, April – August, are following the same pattern as June (see Appendix A). The second highest month in 2022 is August with 70 high-high counts and 1011 low-high counts that are concentrated in the six administrative regions mentioned above. August is followed by July with 65 high-high counts and 896 low-high counts. Low-low counts range in all months from 0 to 56 where April, May, July, and August have 0 and October

56, September 45, and June 25 counts. Most of the country has nevertheless been determined to be not significant.

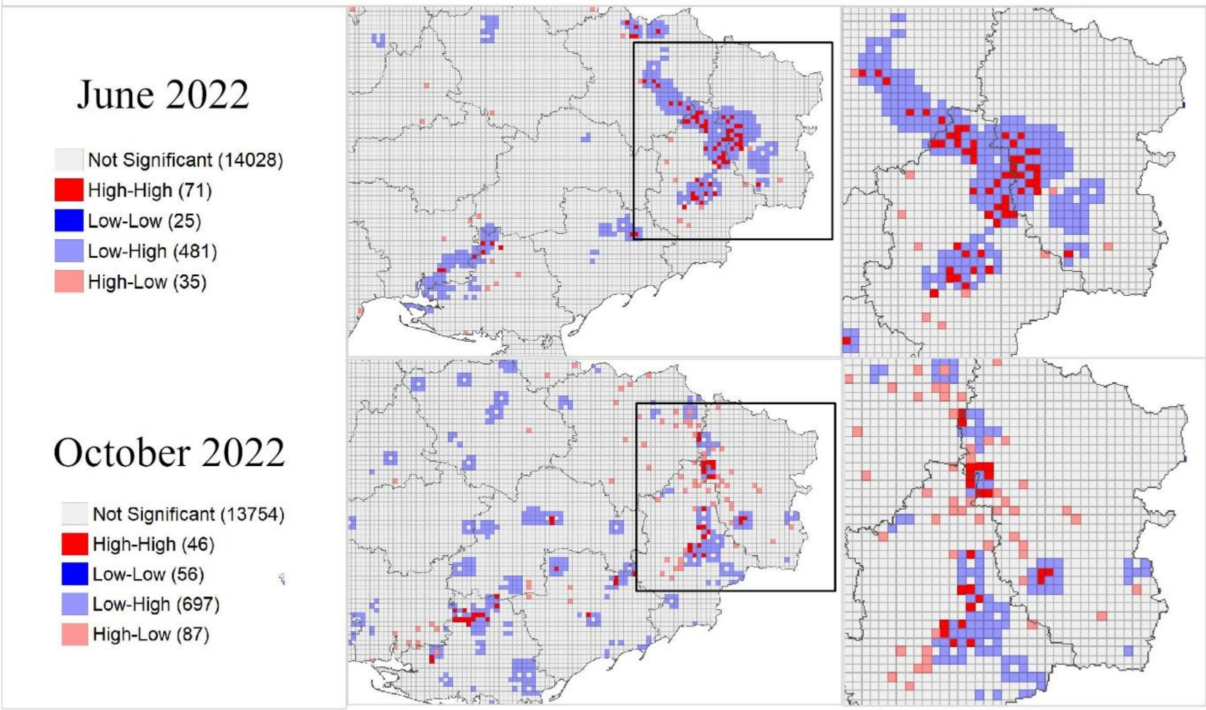

Figure 7. The Bivariate Local Moran's I Analysis for 2022 showing the south-east of Ukraine (middle) and a zoom in of the regions Luhansk and Donetsk (right). The red squares (10x10km extent) show high conflict and high fire areas, light red shows high conflict and low fire, blue squares correspond to low conflict and low fire, light blue to low conflict and high fire, and grey squares are not significant areas.

The year 2020 has 36 high-high (high conflict - high fire) areas (Fig. 8). Those high-high areas are in the regions Luhansk and Donetsk and around the areas are low-high areas similar to the pattern in April to August in 2022 (Fig. 6 & Fig.5). Low-high areas can also be found in the north of Ukraine; however, no conflict areas are observed. In fact, no high-low (high conflict-low fires) is present in 2020. Otherwise, the country during the year 2020 has the highest amount of low-low (low conflict - low fire) clusters which are spread over the entire country. In the south and south-west are the highest amounts of low-low clusters.

During the year 2021 a similar pattern can be observed as in the year 2020 (Fig. 8). High-high clusters (15) are located in the same regions - Luhansk and Donetsk – nevertheless they are only half of the number of clusters then in 2021. Around the high-high clusters are low-high clusters as well. These low-high clusters spread out from the high-high clusters to the south of the country. Low-low clusters are less in the year 2021 in comparison to the year 2020; however, they are but also spread out over the country.

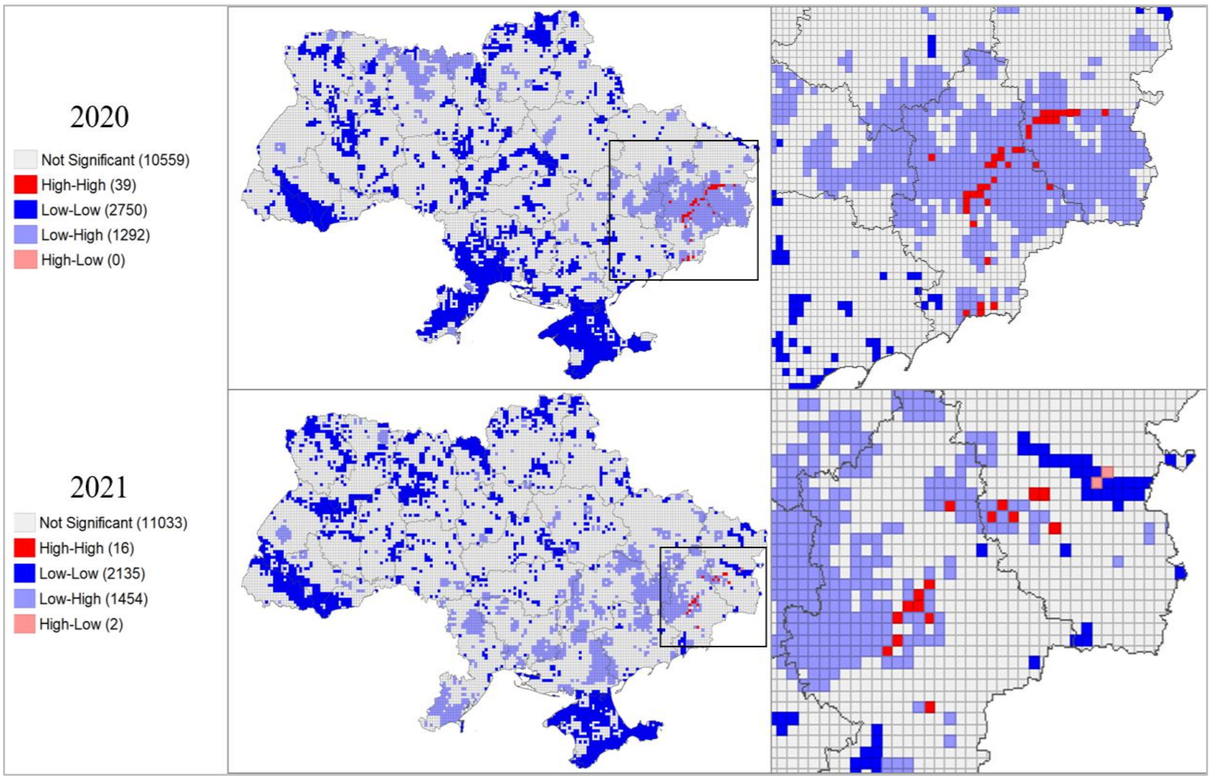

Figure 8. Bivariate Local Moran I Analysis in 10x10km grid cells for conflict and fire in Ukraine during the years 2020 and 2021. High-high corresponds to high conflict and high fire, low-low is low conflict and low fire and low-high to low conflict and high fire and vice versa. The left maps are zoom-ins of their corresponding maps on the left.

iii. Gross Primary Productivity in Conflict Regions (2020-2022)

The yearly GPP fluctuates between the three years 2020, 2021, and 2022 in the regions Kharkiv, Luhansk, Donetsk, Zaporizhzhia, Mykolayiv and Kherson (Fig. 9). The year 2020 is the lowest average GPP (0.657 ± 0.189 Kg C/m²/yr) (see Appendix B). Four regions are following a similar pattern of 2021 being the year with the highest GPP. Only two regions show a different pattern: Kharkiv and Luhansk. In both regions, Kharkiv and Luhansk, is the highest GPP detected in 2022 in comparison to the other two years (Kharkiv - 0.760 ± 0.192 Kg C/m²/yr and Luhansk - 0.698 ± 0.182 Kg C/m²/yr).

Although the GPP is highest in 2022 in those regions, all three years are almost similar in contrast to the other regions. For example, in Zaporizhzhia 2022 and 2020 have an almost similar amount of yearly GPP (2022 - 0.637 ± 0.186 Kg C/m²/yr and 2020 - 0.636 ± 0.190 Kg C/m²/yr).

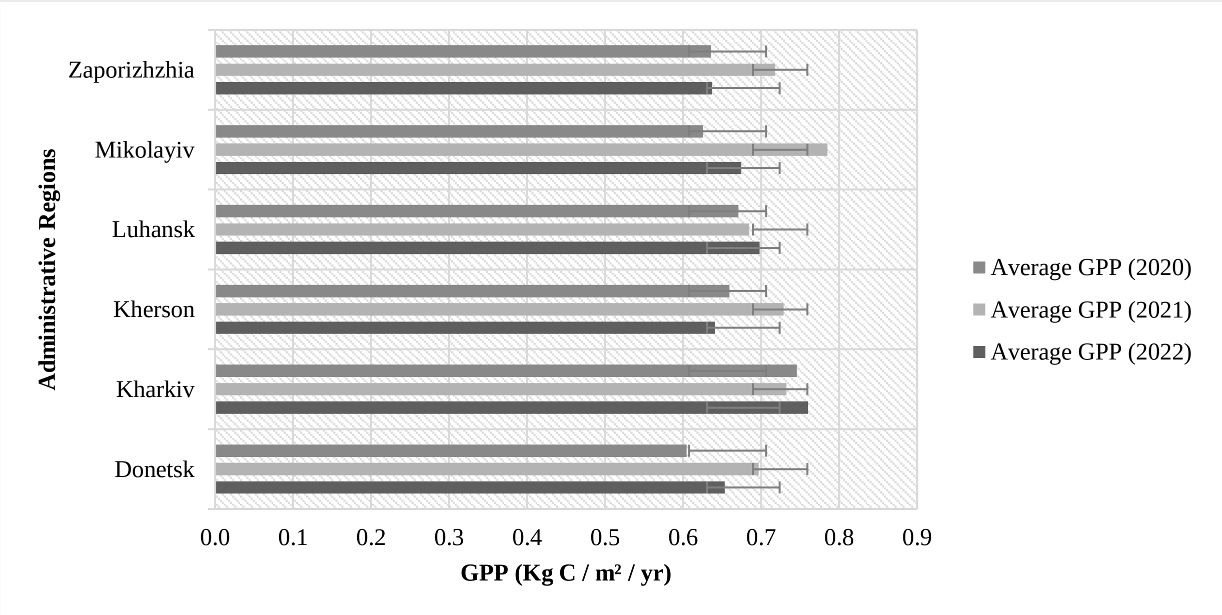

Figure 9. The average GPP in regions Kharkiv, Luhansk, Donetsk, Zaporizhzhia, Mykolayiv and Kherson during the years 2020, 2021 and 2022

The change in GPP from 2020 to 2021 (Fig. 10a), 2021 to 2022 (Fig. 10b), and 2020 to 2022 (Fig. 10c) can be seen in figure 10. As mentioned above, the GPP is higher in 2021 than 2020. Mykolayiv experiences an overall increase of GPP especially in the western part (-0.29 – 0 Kg C/m²/yr). In Kherson, Zaporizhzhia, and Donetsk on the other hand GPP is fluctuating more equally. The decrease in GPP is especially visible in the southern part of Luhansk and Kharkiv. In Luhansk there is on the western part a sharper decrease of GPP in an area (-0.59 - -0.3 Kg C/m²/yr) and some smaller areas show an even higher decrease in GPP (-0.75 - -0.6 Kg C/m²/yr).

The difference between 2021 and 2022 shows a different pattern in terms of decreasing GPP in the west and south. Looking at Kherson and Mykolayiv, there are some areas that have a higher decrease (-0.59 – 0.3 Kg C/m²/yr). An increase in Luhansk and especially Kharkiv can be observed. The northern part of Donetsk is also experiencing an increase in GPP.

In contrast, the change over two years (2020 to 2022) is shifted where the west experiences an increase of GPP and the Kharkiv and Luhansk decrease in GPP. The area that has a decrease of -0.59 - -0.3 Kg C/m²/yr in Luhansk that was mentioned earlier shows a similar pattern. At the border of Kherson and Zaporizhzhia there can be also a decrease of -0.75 - -0.6 Kg C/m²/yr on small areas observed.

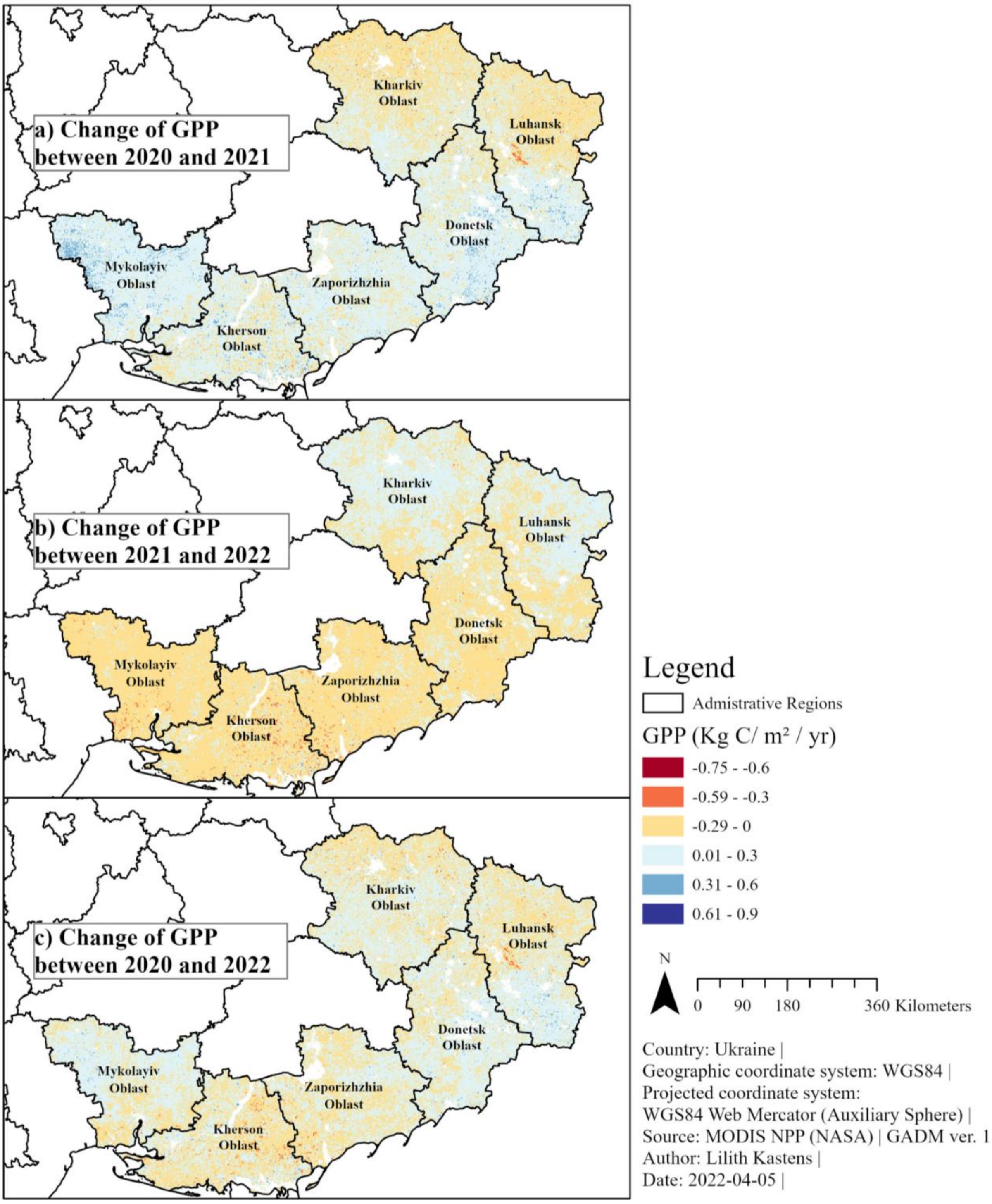

Figure 10. The change of GPP in Kg C / m² / yr in a 500 m spatial resolution from 2020 to 2021 (a), from 2021-2022 (b), and 2020-2022 (c) in the regions Kharkiv, Luhansk, Donetsk, Zaporizhzhia, Mykolayiv, and Kherson. The white areas within those regions are either build up areas, water (ocean or inland), barren, very sparsely vegetated, permanent wetlands, marshes or unclassified according to Running and Zhao (2021).

VI. Discussion

This section is a discussion of the results obtained through the Spearman rank correlation, Bivariate Local Moran's I Analysis, and the change of GPP in the last three years (2020-2022). Another part of the discussion are the sources of error and a perspective on future studies.

i. Relationship of fire and conflict

The Spearman rank correlation analysis revealed that conflict and vegetation fire in Ukraine are not significantly correlated with each other ($\rho = 0.30$, $p > 0.05$). In this correlation analysis the entirety of Ukraine is considered where in large parts no conflict is detected. This is an explanation for the very weak correlation between the two variables. The reason behind this is that when analysing the temporal and spatial relationship between the two variables a pattern of fire occurring close to conflict events can be established. The results from the BiLISA analysis for 2022 show that there is in fact a significant relationship between fire and conflict in certain areas (Fig. 7). The same result can be seen in 2020 and 2021 where in the conflict areas also the number of fires is higher (Fig. 8). Furthermore, previous studies from Dinc et al. (2021); Eklund et al. (2021); Jaafar et al. (2022) concluded that fire and conflict can be related to each other. Nonetheless, the study from Dinc et al. (2021) pointed out that the cause of fire can usually not be explained by only one variable, in this case conflict, however variables such as climate and management also have to be considered.

As Ukraine experienced climate change in terms of temperature increase, change of precipitation, and numerous other variables that influence each other, the fire hazard has been increasing (Balabukh & Malytska, 2017; Wilson et al., 2021). Especially in the southern and eastern parts of the country fire risk has been enhanced (Balabukh & Malytska, 2017). These areas have been affected by conflict as well. Since the east and south are prone to have a higher fire count due to climate change the relationship between climate variables and fire needs to be assessed to eliminate the possibility of climate being the primary factor of fire and not conflict. The fact that the trend of the number of fires in Ukraine has been steadily declining since 2014 contradicts climate (change) being the reason (Fig. 4). Even though climate change has been progressing the trend going down is an indicator for conflict being the primary factor that an increase in the fire count in southern and eastern parts of Ukraine in 2022 (Fig. 4).

Furthermore, fire has been detected less in agricultural land in 2022 in comparison to 2021, which suggests that cultivation practices have been declining (Fig. 5). In Ukraine agricultural practices include the preparation of fields after harvesting and before sowing the seeds to burn the residues (Hall et al., 2021). Despite laws existing to prevent said practice it is still in use and explains why Ukraine accumulates the highest fire count in Europe. In war times the management of agricultural land can change, due to for example migration. After the invasion of Ukraine in February 2022 many people have been migrating to other parts of Ukraine and even to other countries (IOM UN Migration 2023). Therefore, less crop is planted, less crops need to be harvested and burning fields becomes obsolete. This is reflected in figure 5, where the land use classes are listed and the percentage of fire occurrence on it. As mentioned, in comparison to 2021, in 2022 fire has been less visible on agricultural fields despite the total fire count being higher. This leads to the conclusion that fire has not been used as much in cultivation practices.

To draw conclusions on the relationship between fire and conflict it is also important to look at the type of conflict. The conflicts in Ukraine might have a similar origin but different parties are involved in the conflicts. In 2014, the annexation of Crimea sparked conflicts between the Ukrainian military, private parties, and Pro-Russian separatists whereas in 2022 the Russian military invaded Ukraine (Bebier, 2015). The magnitude of these conflicts, as well as strategies, make it difficult to compare them with each other. That implies, the relationship between fire and conflict can be different depending on who is involved in the conflict. Comparing the conflict-fire relationship in countries which experience conflicts of similar magnitude, and which might also use similar tactics might be more sufficient than comparing it to previous years in Ukraine.

ii. Conflict and Gross Primary Productivity

The GPP in 2022 is on average less than in 2021 which suggests that conflict influences the GPP in general (Fig. 9). However, in the regions of Donetsk and Luhansk, where most of the conflicts are located, the GPP increases from 2021 to 2022; consequently, there is another reason for the GPP fluctuations from 2021 to 2022 (Fig. 10). Migration of the people, for instance, can lead a change in land use so there is a possibility of less disturbance of the environment which leads to a more thriving environment (Butsic et al., 2015; Hanson et al., 2009). Further evidence of this can be seen in the change between 2020 to 2021 when conflict slightly increases but also the GPP overall increases (Fig 4 & Fig. 10).

A different view on the fluctuations of GPP is the occurrence of fire. Since conflict seems to have only negligible effect on the decrease of GPP in certain areas, fire can be an explanation. GPP in general is dependent on the photosynthetic tissue available in the ecosystem which is influenced by different factors (Chapin et al., 2002). When fire occurs in an area the photosynthetic tissue is removed by combustion and in turn photosynthesis decreases and that suggests GPP decreases as well (Chapin et al., 2002). The year 2020 was recorded as a dry year with a higher number of wildfires according to Wilson et al. (2021), see also figure 4, which explains the lower GPP. In contrast, 2021 has the lowest recording of fires during 2020-2022 and vice versa a higher GPP. While the fires in 2020 are associated with climate, the fires in 2022 are likely to be caused by conflict. So even if conflict does not have a direct effect on the GPP it is indirectly connected through the fire occurrence that has overall increased in the area.

Another factor that can explain the low fluctuations of GPP is the vegetation type in south and east Ukraine. Agricultural land can be found primarily in those regions which is known to recover faster than, for instance, woodland from disturbances like fire (Lasslop et al., 2019). In the results, it shows that only small areas experienced a higher decrease or increase in GPP (Fig. 10). As discussed, agricultural lands are burned to prepare for the crops that are sown. The decrease and increase in small areas can be attributed to that. So even though fire is occurring in higher numbers in Ukraine, the agricultural fields can recover faster, and the photosynthetic tissue is available again. The analysis of GPP was made yearly and in that area winter crop is usually also grown and fire is more prominent during the other seasons. Hence, the GPP could have been balanced out during the year and extreme fluctuations would only be visible on a smaller time scale.

iii. Sources of Error

The sources of error identified in this study include the fire data set for October and September 2022, the MODIS Gross primary productivity product, and UCDP conflict detection.

In the fire data set from FIRMS for October and September 2022 the “type” classification is not included. Therefore, the thermal anomalies that are not vegetation fires could not be excluded in the analysis. These two months show a different pattern in the BiLISA analysis for conflict and fire. Even though that this pattern can emerge with the classification included, the pattern appears only in September and October which suggests that it is influenced by the missing “type” classification.

MODIS uses daily photosynthesis data to calculate 8-day periods of GPP in an area which is then added together to create yearly GPP (Running et al., 2021; Running & Zhao, 2021). Assessments have been made on the reliability of the MODIS products GPP 8-day period and GPP yearly. The results indicate that the product GPP 8-day period is not as reliable as GPP yearly (Wang et al., 2017). However, the MODIS GPP yearly product is still showing a low reliability in comparison to ground measurements. Consequently, to have significant and definite results on the GPP in Ukraine other GPP products, e.g., Global Land Surface Satellite (GLASS) need to be used in addition. GLASS is a satellite that produces several products including GPP and variables that are used by MODIS as well; one of which being FPAR (Liang et al., 2021). FPAR is part of the variable APAR (Equation 1). The study from Wang et al. (2017) found out that replacing MODIS FPAR with GLASS FPAR can improve the accuracy of GPP. Even though the amount of GPP from MODIS is not dependable, the fluctuations between years can still be used. The possible underestimation or overestimation will be similar in each year and the difference can be used meaning it does not have a marginal influence on this study.

The UCDP conflict detection is only detecting a conflict when at least one person died during a specific time or location (Uppsala Conflict Data Program, 2023). For this reason, the movement and actions during a war cannot be traced if they are not deadly. Burning agricultural fields, for instance to destroy the yield of the farmers and eliminate a food source, is not necessarily deadly. The conflict detection is therefore one-sided and will not take into consideration other types of warfare tactics. To increase the accuracy of relating fire and conflict research of media coverage and people's account of events during the fire occurrences would be necessary; this would be conducted in a similar manner to the study from Dinc et al. (2021).

iv. Future Studies

To gain insight and assess the extent of the damage to the environment during and after the Russia-Ukraine war in Ukraine it is important to formulate reparation and mitigation strategies (United Nations Environment Programme, 2023). Included in that assessment is the monitoring of the long-term effect of war on the ecosystem, which is not yet possible, but should be part of future studies. Long term effects of damage are, for instance, the soil quality in the conflict areas. Soil is vital for plant growth and depending on the location and severity of fire soil characteristics can be altered in a positive or negative way (Santín & Doerr, 2016). In addition, vegetation needs time to regrow after it was burned which can change the GPP (Lasslop et al., 2019).

Regarding the extent of the environmental damage, since the Active Fire VIIRS data was extracted as point data to do the BiLISA analysis, there is no indication of the extent of fires. After analysing the relationship between fire and conflict it also relevant to analyse the extent of fire to assess the damage. The extent and intensity of fire can be an indicator of the fire's origin. Naturally caused wildfires are usually more intense and damaging than anthropogenic caused fires. VIIRS and MODIS both have burned area products which can be used to assess the damage.

Long term effects are not only measured in the environmental damage caused but also in terms of how mitigation and adaptation plans for climate change are implemented in the future. Ukraine has been decreasing the fire occurrence in the past years, however with the necessary reparation and the impact on the economy of the country those plans will have a lower priority. In 2022 the gross domestic product (GDP) GDP of Ukraine has been affected by the war and displacement of the people and was predicted to decline by approximately 45% in 2022 (Guenette et al., 2022). These long-term effects need to be monitored.

Furthermore, it would be interesting to compare the GPP in the conflict regions to other parts of the country that are not as heavily affected by the war. This may lead to further understanding of the fluctuations of GPP in conflict regions and yield more insights on the relationship of GPP and conflict and GPP and fire. In future studies, this may be complemented with research on other countries that are affected by conflict and possible GPP changes.

VII. Conclusion

The Russia-Ukraine conflict escalated in February 2022 by a large-scale invasion of Russia into Ukraine. Since then, the impact on the environment has been detrimental. This study focused on the impact of armed conflict on fire and GPP and the following conclusions have been reached:

1) The conflict and fire events in all of Ukraine during the years 2014 to 2022 show no significant relationship. Furthermore, during the growing season (April to October) in 2022, fire and conflict are concentrated in the same regions.
2) Fire and conflict during the growing season in 2022 show a significant spatial and temporal relationship in the regions Kharkiv, Luhansk, Donetsk, Zaporizhzhia, Mykolayiv and Kherson. In contrast, the years 2020 and 2021 only show a significant relationship in the regions Luhansk and Donetsk. The fires in 2020 are likely to be caused by the drought and in 2022 by conflict.
3) Neither a positive nor a negative impact of conflict on the gross primary productivity in the six regions can be detected. The fire occurrence in the six regions on the other hand, suggests an influence on GPP during 2020, 2021, and 2022.

The hypothesis is partially accepted that the occurrence of vegetation fires in the conflict zones increased in 2022 but the gross primary productivity did not decrease significantly due to conflict.

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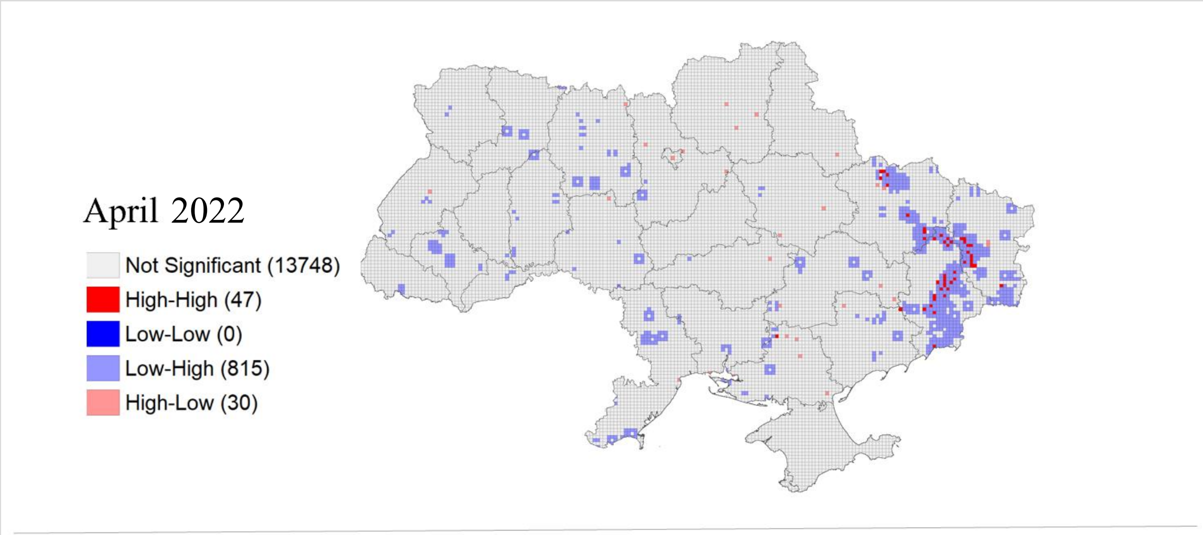
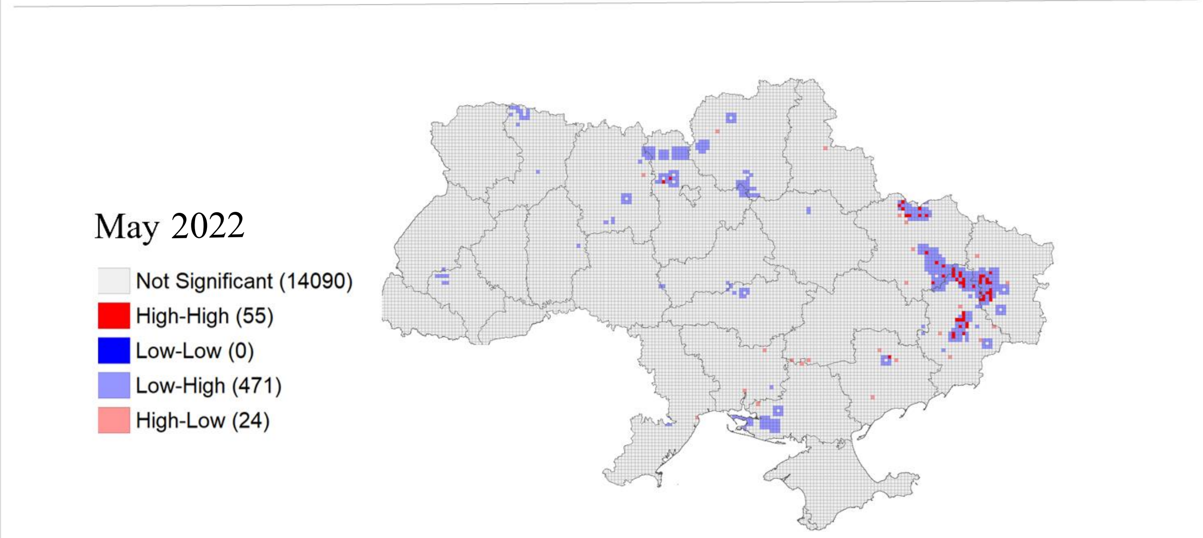
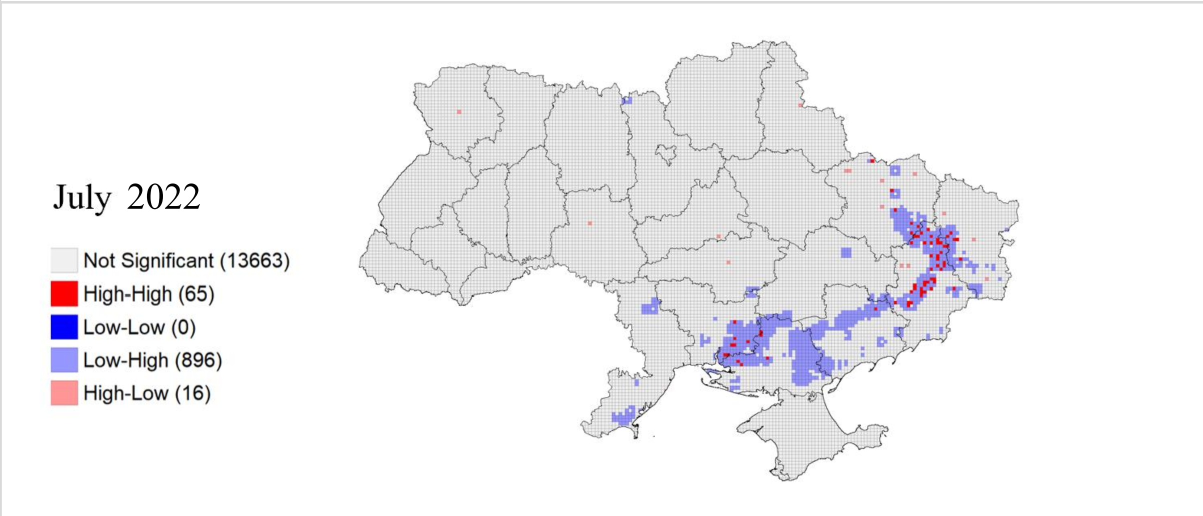
Appendix A - Bivariate Local Moran's I Analysis







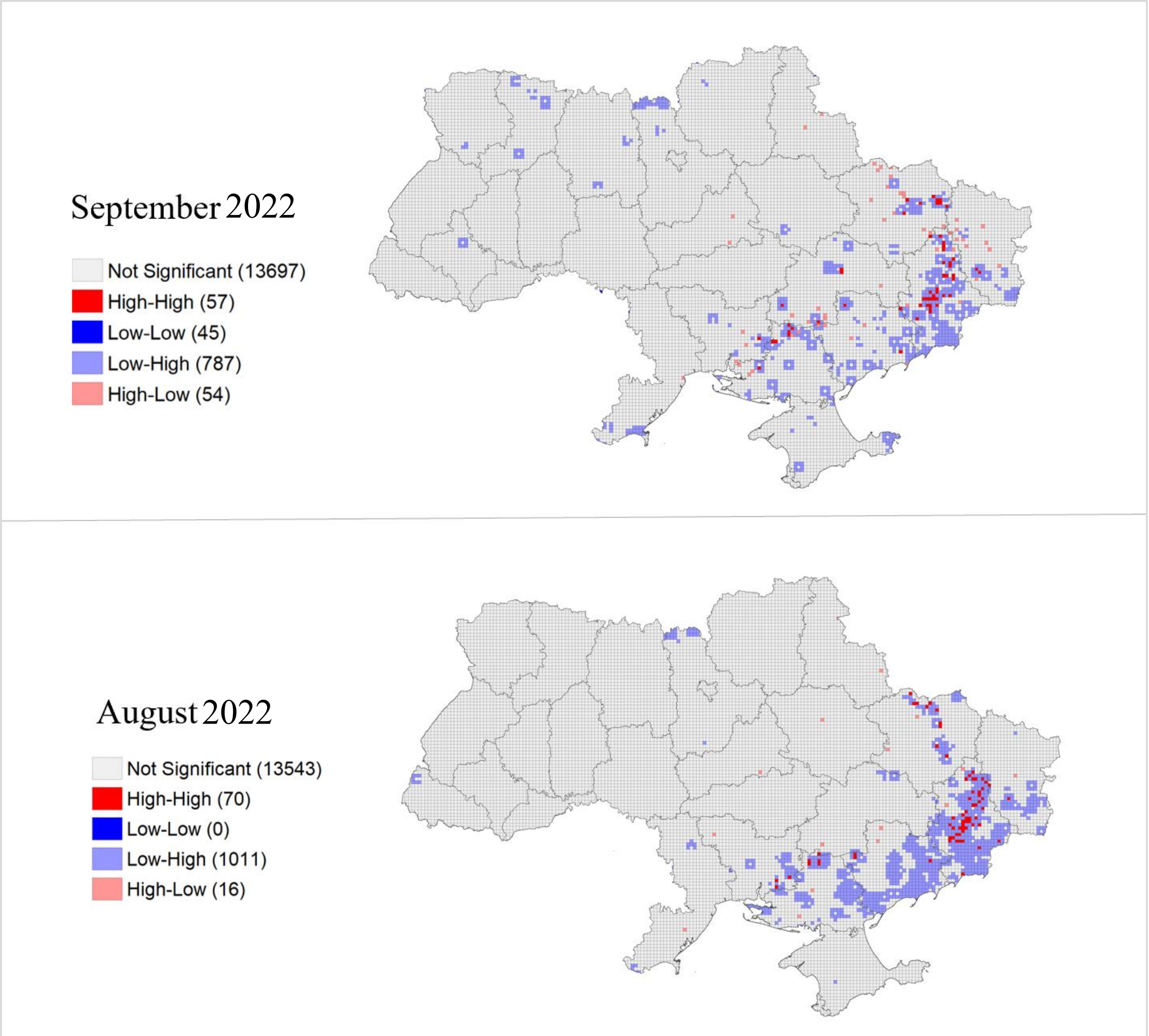


Figure A1. The BiLISA Analysis for armed conflict and vegetation fire for the months April, May, July, August, and September 2022. High-high corresponds to high conflict and high fire, low-low is low conflict and low fire and low-high to low conflict and high fire and vice versa.

Appendix B - Gross Primary Productivity (GPP) (2022, 2021, 2020)

Table B1. The average GPP (Kg C/ m² / yr) and standard deviation in 2022, 2021, and 2020 in the regions Kharkiv, Luhansk, Donetsk, Zaporizhzhia, Mykolayiv, and Kherson.

Administrative Regions with conflict and fire	Average GPP in 2022 (Kg C/ m² / yr) ± std. dev.	Average GPP in 2021 (Kg C/ m² / yr) ± std. dev.	Average GPP in 2020 (Kg C/ m² / yr) ± std. dev.
Donetsk	0.653 ± 0.212	0.697 ± 0.219	0.605 ± 0.201
Kharkiv	0.760 ± 0.192	0.733 ± 0.181	0.745 ± 0.193
Kherson	0.641 ± 0.229	0.729 ± 0.247	0.659 ± 0.242
Luhansk	0.698 ± 0.182	0.685 ± 0.177	0.671 ± 0.179
Mykolayiv	0.675 ± 0.216	0.785 ± 0.131	0.626 ± 0.129
Zaporizhzhia	0.637 ± 0.186	0.718 ± 0.203	0.636 ± 0.190
Total	**0.677 ± 0.188**	**0.724 ± 0.193**	**0.657 ± 0.189**