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Waste fires in Poland and some of Their Environmental Implications – A Ten-Year Perspective

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ABSTRACT
Economic growth and development are connected with the increase in consumption. One of the side effects of progress is waste production. Sustainable development would also include proper management of waste, focusing on their recycling. However, the direct costs of recycling sometimes exceed the costs of waste storage. Therefore, waste storage in landfills is still widespread. Improper waste storage or deliberate actions can lead to waste fires. In the work, the statistics of landfill fires from the years 2012 to 2021 were analyzed. The work includes statistics of the parameters of fires reported in the reports of Polish State Fire Services. Additionally, the usage of the resources and materials for firefighting and their trends were discussed. It was shown that resources required for extinguishing waste fires were increasing in this period. The statistics are accompanied by spatiotemporal analyses of the location of fires based on Corine Land Cover which showed that approximately half of the fires are on arable land and non-continuous urban fabric while fires at dumpsites are relatively rare. The important concern is also that around 10% of very big waste fires are in forests. All these analyses lead to the assessment of some environmental impacts which are caused by waste fires.

Keywords: waste fires, environmental assessment, statistics, GIS analyses, landcover, wastewater, public health.

INTRODUCTION

Fire is an uncontrolled process of burning at a place that is not intended to burn, which is spreading in an uncontrolled way affecting the health and life of people and animals as well as causing material losses. According to ISO 8421-1:1987 (ISO, 1987), it is also characterized by heat release accompanied by emission of smoke and usually flame. Focusing on the burning process, the characteristic attributes of fires are the possibility of high-temperature occurrence, release of significant amounts of burning products, and spreading, i.e., increase of fire surface and volume (Pofit-Szczepańska, 1994). Until recently, fires were generally connected with direct threats to health, life, and property as well as direct exposure of firefighters during rescue action. However, for more than a decade, it is known that every fire causes environmental impact defined in time and space (Marlier et al., 2015; Martin et al., 2016; Nyamadzawo et al., 2013; Otrachshenko and Nunes, 2022; Williams, 2013). The environmental impacts comprise losses in a specific component of the environment as well as whole ecosystems (Hantson et al., 2022; Teixeira et al., 2022). Such impact causes indirect influence not only on the environment like soil, water, or air pollution but also on short- and long-term health effects (Fent et al., 2017, 2014; O'Hara et al., 2021; Rogula-Kozłowska et al., 2020a, 2020b), fatalities, economic losses, properties, etc., during fire and restoration, (Kiely et al., 2021; Milne et al., 2014; Molina Martínez et al., 2011) but also extinguishing expenditures like the cost of extinguishing agents, man-power and equipment which are used in the rescue.

There are many methods of reporting and assessment of fires and their impact. The most popular are the statistics provided by The International Association of Fire & Rescue Services CTIF. CTIF collects and assimilates data from the national fire reporting system and publishes it in form of yearly summaries (CTIF, 2022). The depicted statistics include, among others, the number and cause of fires, number of fatalities, the structure of employment at fire brigades, injuries and fatalities of firefighters as well as economic estimate of "fire costs". In Poland, State Fire Service (pol. Państwowa Straż Pożarna, PSP) is evidencing all fires in decision support system SWD-ST. SWD-ST is a system designed for the Polish State Fire in which every district (LAU-1 unit, (EUROSTAT, 2021)) or city (in larger cities) headquarters prepare an incident report and daily summaries of indictments of every type of action in which PSP is involved, i.e., support of notification of emergencies, coordination of actions, and reporting and evidencing fires (KG PSP, 2019).

Among many parameters which are reported in SWD-ST about each incident, there are physical dimensions of fire/object which are responsible for fires in four categories: small, medium, big, and very big. The parameter which is required in all reports is the area, but volume is also quite often reported. The database includes also geographical coordinates, type of event, location, classification of the object, of the owner, time of event: observation, notification, localization of units and end of the rescue action, number of engaged firefighters, rescuers, others, number of fire engines and equipment, use of extinguishing agents divided into water, foams and powders and many, many others (KG PSP, 2019). Such a comprehensive database could be successfully used in the assessment of the environmental impact of fires expressed as the usage of different resources for firefighting. It has been shown that these data can be used for the assessment of the total atmospheric emissions from fires (Bihałowicz et al., 2021a) and evaluation of the impact of these emissions on the atmosphere (Bihałowicz et al., 2021c) for different pollutants and green-house gases (Bihałowicz, 2021). Nonetheless, there are no studies in which SWD-ST is used for the environmental impact assessment of fires in sense of reducing resources, utilities, and the decrease of the value of some environmental resources. The most important parameters are consumption of water and other fire extinguishing agents, degradation of soil, and water ecosystems, fuel consumption in fire engines, as well as number of firefighters involved in the rescue. All of these elements are directly connected with impact of fires on environment and economic, health as well as ecological aspect, hence their analysis is very important from the social and environmental point of view.

The main aim of this work was to evaluate the environmental impact of waste fires in Poland in a relatively long perspective of ten years from 2012 to 2022. The landfill fires are causing many social anxieties, hence it is important to evaluate them precisely, including all the impacts of water consumption, and its run-off to the environment, diesel fuel consumption connected with the machine-hour of the fire engines, and man-force estimates required to extinguish waste fires. The next, but equally important aspect is the evaluation of fire locations to better understand the structure and assess the plausible causes and mechanisms causing waste fires as well as evaluate the relationship between location and the population density, namely whether the waste fires are more likely at populated or non-populated areas, which is a concern for public health.

MATERIALS AND METHODS

SWD-ST

The SWD-ST database provides the information on every fire incident in Poland. Every incident has data about the dimensions of the object. While the burning area is always provided in the report, the length, width, height or volume of the object are commonly reported as zero. It is mainly caused by the fact that during the rescue the precise assessment of the dimensions of the object is not crucial for the rescue. The location of fire reported in SWD-ST can be both the GPS location of the place of arrival of the first fire engine as well as the location of the object. Since the fire engines have to be relatively close to the fire, it can be assumed that the uncertainty of the GPS device can be similar to this uncertainty, while the number of decimal places provided in coordinates has a greater impact on precision. The expenditure of fire extinguishing agents is also written by the firefighter involved in the action.

All the data have data precision is increasing with the size of the fire since reports of larger events are objects of more careful verification. One of the measures which can be derived from the data from SWD-ST is the "man-force", defined for the purpose of assessment as a product of the reported number of people and reported time of rescue. This measure should be not confused with man-hour, since they are equal only in the cases, where the whole personnel arrives almost simultaneously at the beginning, and leaves finish at the end; however, it is a good measure of the total cost in man-force needed to extinguish the waste fire.

The next derived measure of the cost of fire can be the “engine-force”, similarly defined as the number of fire engines multiplied by the duration of the fire. It also has similar limitations as “man-force”, since it should not be confused with machine-hour but it evaluates the fire engines usage caused by fires. Since the fire engine pumps are powered by truck engines, and hence the engines are running during the whole extinguishing process, this measure can be also used to evaluate total fuel consumption during the fire extinguishing. On the basis of the idle truck consumption in (Gaines et al., 2006) it can be assumed that fuel consumption is 4.5 L/h and hence total consumption. These derived measures can be also affected by the reporting policy of the number of people involved by the given firefighting headquarters. Generally, the uncertainty occurs for fires that last more than 24 hours or are lasting during the shift change – the fire engine can return to the fire station, can be replaced with other or remains at the fire site and firefighters are only changed by other means of transport. It also affects the reported number of people. However, there are no possibilities of investigating it for every fire and the proposed measures are not very precise but are the best possible.

The SWD-ST database used in this work covered the fires reported between 1st April 2012 and 1st December 2021, the object code of which, according to the (KG PSP, 2019), was 801 standalone waste shelters, and landfills. In order to remove fires of dustbins, only the fires which met one of following conditions were analyzed: fires larger than 71 m^2; fires larger than 351 m^3 (according to SWD-ST database theses fires are marked with three fire size flags medium, big, and very big). The time dependence of total usage of resources was evaluated using Spearman rank correlation r_S (Spearman, 1904) and tested for significance p using the values from (Glasser and Winter, 1961).

Location of waste fire

The landcover in the European Union is monitored as a part of the Copernicus Land Monitoring Service. One of the results of the service is the Corine Land Cover (EEA, 2021). It provides the data about landcover in a 100 m x 100 m grid with thematic accuracy higher than 85% and updated every six years since 2000. The data are obtained through satellite observations of the Earth. The landscape is divided into 5 first-level (first-order) categories: artificial surfaces; agricultural areas; forest and semi-natural areas; wetlands and water bodies which are divided into second and third-level landcover codes. The landcover codes of the third level are used to evaluate at which landcover type the waste fire occurs. The 100x100m raster layer of CLC for 2012 and 2018 was used to assess the landcover code at the waste fires coordinate. It leads to empirical distributions of the location of medium waste fires, big waste fires, and very big waste fires. The assessment of locations was conducted in order to determine what the most common locations of waste fires are, do the waste fires at the dumpsites, and landfills are common, and which ecosystems are affected by landfill fires.

The location of the fires was also analyzed in the context of the distance to the population (WorldPop and Bondarenko, 2020). The population density in circular buffers around the location of the waste fire was evaluated. The results can indicate whether waste fires occur at the sites where population density is average, higher than average, or lower than average. All the spatial analyses were prepared using QGIS software (QGIS Development Team, 2021).

RESULTS

Water and extinguishing resources

During the landfill fires, extinguishing agents, mainly water and firefighting foams, are consumed. Moreover, extinguishing involves both humans and equipment. The substances which are produced during burning and pyrolysis, generally, fires, can be water-soluble or non-water soluble. The most common resource used for extinguishing fires is water with the addition of surfactants. Although the heat released in the fire causes evaporation of water, some amount of water is flushing the products of combustion. Hence, the substances soluble in water and soluble in the water-surfactant mixture are directed to the environment: soil and water (Campos and Abrantes, 2021; Isaacson et al., 2021; Ré et al., 2021; Solomon et al., 2021). Moreover, surfactants are treated as emerging contaminants and their transport to the environment should be limited (Ali et al., 2022). The distribution of the water expenditure for firefighting of waste fires is provided in Figure 1. The plot shows that in the case of medium fires although the median values are not growing over the years, the maximum consumption increases. It can be observed that larger fires require greater amounts of water. The total water consumption in the years 2012–2021 was 357.5 thousand m^3 water, with a peak 137.5 m^3 in 2019. To evaluate whether there is a positive correlation between the total yearly water usage for waste fire extinguishing and year, the Spearman rank coefficient r_S was calculated. The obtained value r_S=0.58 (p<0.05) shows that the water usage is increasing with time and the environmental impact of waste fires is increasing. On the basis of the average wastewater treatment costs in 2021 (cena-pradu.pl, 2021), it can be estimated that cost of this water utilization at the wastewater treatment facilities would be of the order of 500 k€. Nevertheless, the main problem is that this water could not be directed to wastewater treatment facilities, and having an unknown load of substances was directed into soil and river ecosystems.

The second most often used extinguishing agent corresponds to firefighting foams. Foams are made of foaming agents, organic solvents, glycols, and other substances which are intended to ensure good fire extinguishing properties of foam (Jakubiec, 2018; Mizerski and Sobolewski, 2007; Węsierski and Eszer, 2018). The foams can be persistent pollutants in soil and water environment (Kärrman et al., 2011) and have impact on plants (Tureková and Balog, 2011). The presence of the organic solvents causes the hydrocarbons from soot and ashes effective removal and transport to the environment. This is one of the causes that firefighting foams are subjects of waste management and are planned to be landfilled or incinerated (Carignan and Clukey, 2020). The distribution of foam consumption is presented in Figure 2. The medians of foam consumption are not visible on the graph for medium fires, and big fires, except in 2017 and 2020 and are visible only for a few very big fires. It is worth noticing that in 2014 and 2016 there were no very big fires that were extinguished using foam. The total foam consumption in the investigated period was 202.5 m^3 which is comparable to the water consumption, although the distributions of foam consumption in Figure 2 are significantly different from water in Figure 1. The total yearly foam consumption correlation coefficient with time was r_S=0.48 (p<0.1); hence, it is quite possible that the consumption of the foam increased during the investigated period.

The measure of involvement of the firefighters, i.e., "man-force" defined in chapter 2 is presented in Figure 3. The medians of "man-force" required for extinguishing waste fires was increasing with time for all fire sizes, from less than 20 h in 2012 to around 30 h in 2021 for medium fires, and from around 500 h to around 1000 h for very big fires in the same period. The correlation of total yearly effort with time was r_S=0.76 (p<0.01). It proves that the waste fires were consuming more and more human resources, and work, during the investigated period. The estimate of the "engine-force" during waste fires in

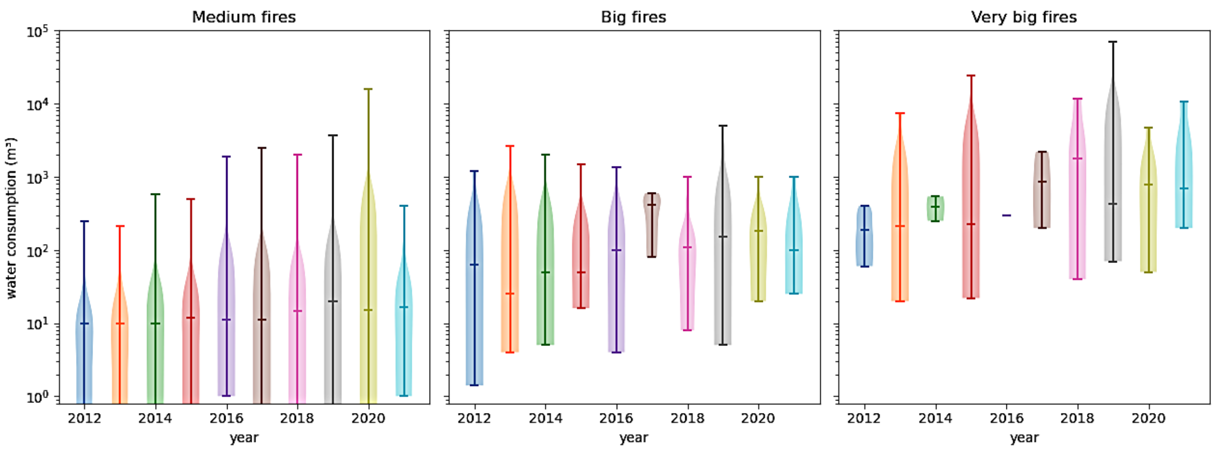

Figure 1. Distribution of water consumption for medium, big, and very big waste fires in the years 2012–2021. The whiskers of the violin plot are from the minimum to maximum while the horizontal line represents the median water consumption

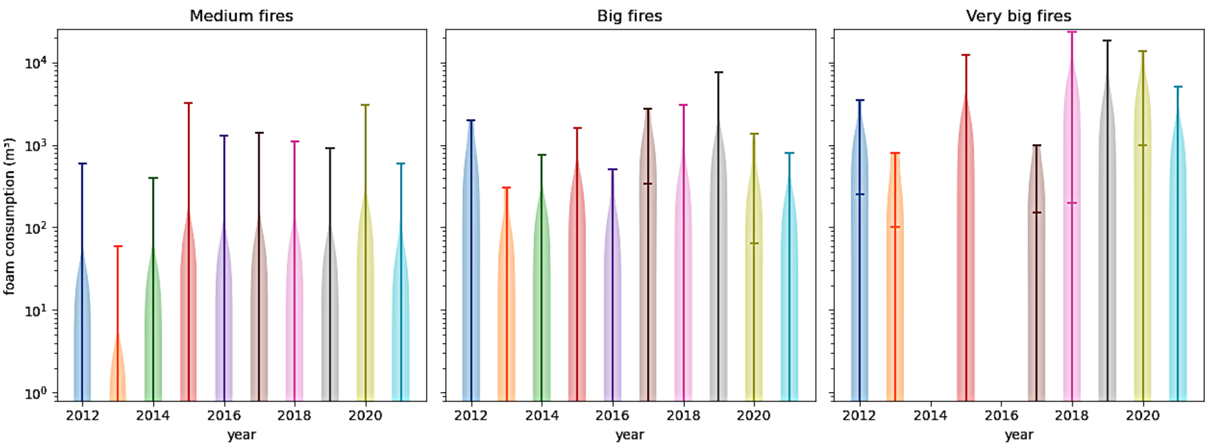

Figure 2. Distribution of firefighting foam consumption for medium, big, and very big waste fires in the years 2012–2021. The whiskers of the violin plot are from the minimum to maximum while the horizontal line represents the median foam consumption

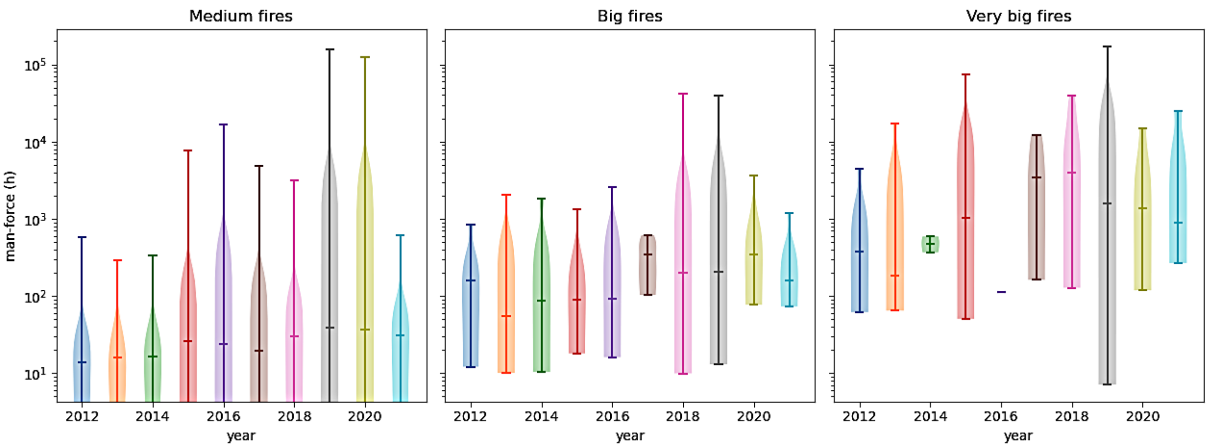

Figure 3. Distribution of "man-force" for medium, big, and very big waste fires in the years 2012–2021. The whiskers of the violin plot are from the minimum to maximum while the horizontal line represents the median "man-force"

the years 2012–2021 shows that 2.1 million liters of diesel fuel could have been consumed during waste fire extinguishing. This estimate does not take into account the fuel consumed for arrival at the fire site and possible shift changes during very long fires. Hence, the extinguishing of waste fire can release additional 5.5 Gg of CO_2 into the atmosphere, creating an approximate cost of 2.5 M€, assuming the price of diesel fuel 1.2 €/L.

Location of fires

Spatial distribution

The summary of the spatial distribution of the waste fires in Poland is presented in Figure 4. The locations of the fires show that there are two main tendencies. Firstly, the waste fires are more common for the western part of Poland while there are few in the east, north-east part. Secondly, the waste fires are concentrated at agglomerations with over 200 fires in Katowice metropolitan area, almost 100 in Warsaw urban area, and in general, those waste fires are closer to the settlements.

Corine land cover

The important question is also where waste burns. For each fire, the landcover presented in the Corine Land Cover (CLC) raster was assigned (EEA, 2022, 2021), for the fires in the years 2012–2017 the CLC2012 set was used while for the remaining CLC2018. Afterward, the empirical distribution of landcover, where waste fires were reported, was created for each fire size

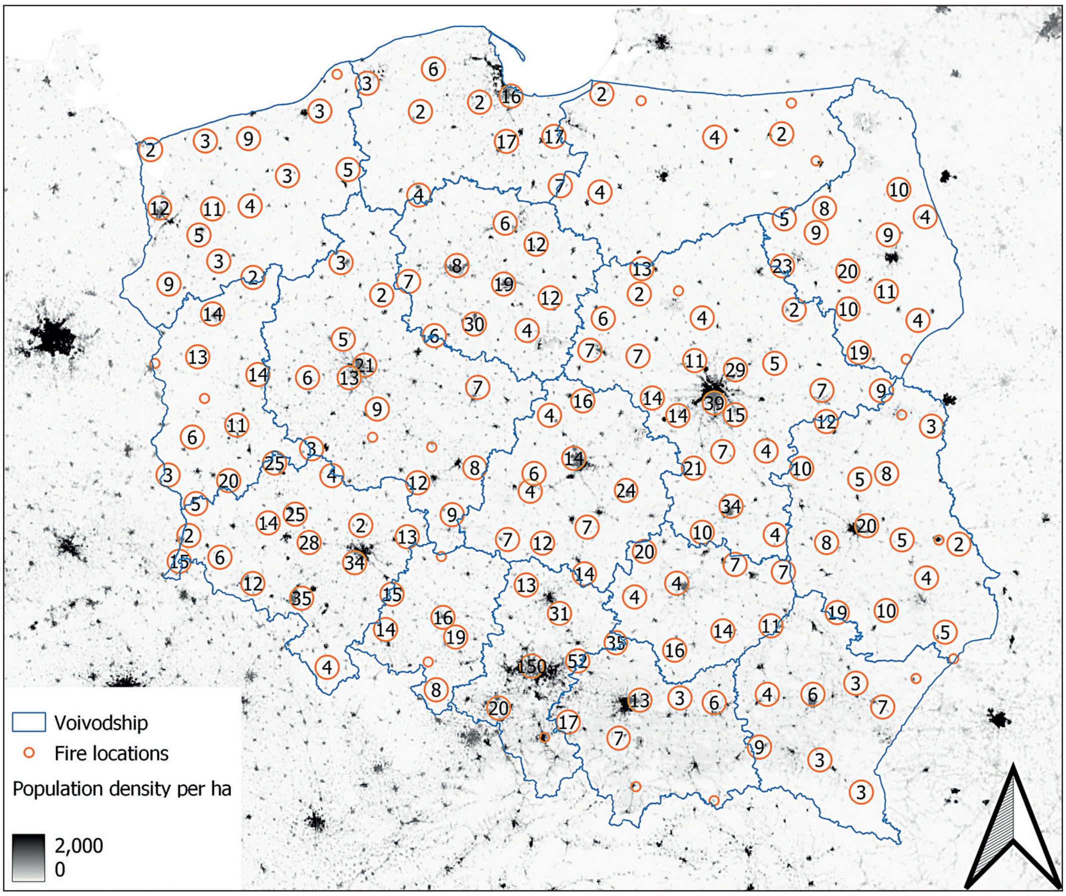

Figure 4. Map of the locations of the medium, big, and very big waste fires in Poland in 2012–2021

category separately. Table 1 presents these distributions. They are similar since the comparison of Spearman rank correlation between empirical distributions is at least 0.868. For each fire size highest share of fire, locations were reported at 2.1.1 Non-irrigated arable land, over 30% in each category. This class includes land which is fallow for less than 3 years. It can be concluded that wastes that are stored on arable land which is currently not used are most often burned, intentionally or accidentally. In each fire size, the second most popular site was the 1.1.2 Discontinuous urban fabric, while there are almost no fires at 1.1.1 Continuous urban fabric. The reason for it is simple since 1.1.1 represents urban areas, while 1.1.2 is rather suburbs. The waste fires are more likely to occur in the suburban areas where the waste management practices include waste burning (Bihałowicz et al., 2021b) which can lead to uncontrolled burning – fire. In the case of medium fires, all fires were distributed along with landcover types with a share of less than 10%; however, the most important landcover was 1.2.1 Industrial or commercial units. This landcover cannot distinguish between the industries, for example, recycling industries and commercial areas and hence it is impossible to draw clear conclusions about the fires at this landcover code. In the case of big fires, the third most frequent fire site is also 1.2.1; however, the share is significantly higher than in the case of medium fires. The possible reason is that the waste fires at the industrial sites develop rapidly into big fires. The third most popular site of very big waste fires is not as in the previous case, 1.2.1 which became fourth, but 1.3.1 – mineral extraction sites. The mineral extraction sites – open-pit mines are vulnerable to illegal waste storage and deliberate burning of them. Some people perceive such sites as ideal for discarding problematic waste. Subsequently, the waste is ignited and the problem is "solved" by fire (Chmielewski et al., 2020). Another possible reason is that sites classified in CLC as 1.3.1 can be under transformation to 1.3.2 since it has been discussed that former extraction sites can be transformed in this way (PIG, 2005). It is worth noticing that around 10% of very big fires are located in forests or shrubs under transition. Waste fires at 1.3.2 – Dumpsites are a quite rare phenomenon; hence, it confirms that law regulations

Table 1. The distribution of locations of the medium, big, and very big fires across land covers

CLC code	Share of the location of		
	Medium fires	Big fires	Very big fires
1.1.1 Continuous urban fabric	0.6%	0.7%	0.0%
1.1.2 Discontinuous urban fabric	29.9%	18.5%	16.7%
1.2.1 Industrial or commercial units	9.8%	17.8%	9.7%
1.2.2 Road and rail networks and associated land	0.2%	0.0%	0.0%
1.2.4 Airports	0.2%	0.0%	0.0%
1.3.1 Mineral extraction sites	2.2%	5.5%	15.3%
1.3.2 Dump sites	1.7%	4.8%	2.8%
1.3.3 Construction sites	0.1%	0.0%	0.0%
1.4.1 Green urban areas	0.7%	0.0%	0.0%
1.4.2 Sport and leisure facilities	1.5%	3.4%	0.0%
2.1.1 Non-irrigated arable land	32.0%	30.8%	34.7%
2.2.2 Fruit trees and berry plantations	0.9%	0.0%	0.0%
2.3.1 Pastures	4.9%	3.4%	4.2%
2.4.2 Complex cultivation patterns	5.6%	4.8%	2.8%
2.4.3 Land principally occupied by agriculture, with significant areas of natural vegetation	3.7%	4.8%	4.2%
3.1.1 Broad-leaved forest	0.9%	1.4%	0.0%
3.1.2 Coniferous forest	2.7%	1.4%	5.6%
3.1.3 Mixed forest	1.2%	0.7%	1.4%
3.2.1 Natural grassland	0.1%	0.0%	0.0%
3.2.4 Transitional woodland/shrub	1.2%	1.4%	2.8%
5.1.1 Water courses	0.0%	0.7%	0.0%
5.1.2 Water bodies	0.1%	0.0%	0.0%
SUM	100.0%	100.0%	100.0%

Note: the table skips CLC land codes where no waste fires were reported.

for waste storage and waste prevention at dumps are adequate and the problem of waste fires is not a problem of landfills, contrary to some other studies (Ibrahim et al., 2022).

Atmospheric emissions

The data in the SWD-ST contains the size of the object. The landfill fires in Poland in 2018 were analyzed in detail (Bihałowicz et al., 2021a). This work presented a comprehensive methodology of assessment of the contribution of landfill fires to air pollution including validation data from SWD-ST. Applying the methodology presented there, under the assumption that there the emission factors from all waste fires are the same, regardless of the type of waste stored there, the atmospheric emission from waste fires can be estimated using values of emission factors and bulk densities presented in (Bihałowicz et al., 2021a) based on (EEA, 2016; Futures, 2010; Pansuk et al., 2018; US EPA, 1995). The time dependence of reported volumes is presented in Figure 5. Since it is required to assign the area to each fire report, the volume is not required; hence, the volume has to be estimated in some cases. The volume was assumed as for general waste fires in (Bihałowicz et al., 2021a). The emission factors were assumed to be the same for all waste, the curves of the emissions of CH_4, CO, CO_2, NO_x, PM_{10}, and SO_2 dependence on time have the same shape as in Figure 5, only the values are scaled by emissions factors (Bihałowicz et al., 2021a). During the investigated ten-year period, the estimated emissions of these substances from waste fires were: 6.7±1.8 Gg for CH_4, 315±84 Gg for CO_2, 58±15 Gg for CO, 3.19±0.85 Gg for NO_x, 4.7±1.2 Gg for PM_{10}, 207±55 Mg for SO_2. The uncertainty for fires with reported volume was 5 m^3 since the volumes in the database were reported by fire officers with such resolution, while for the fires without reported volume it was assumed 20%. The emissions for ten year period estimated here are not ten times higher than reported for 2018 in (Bihałowicz et

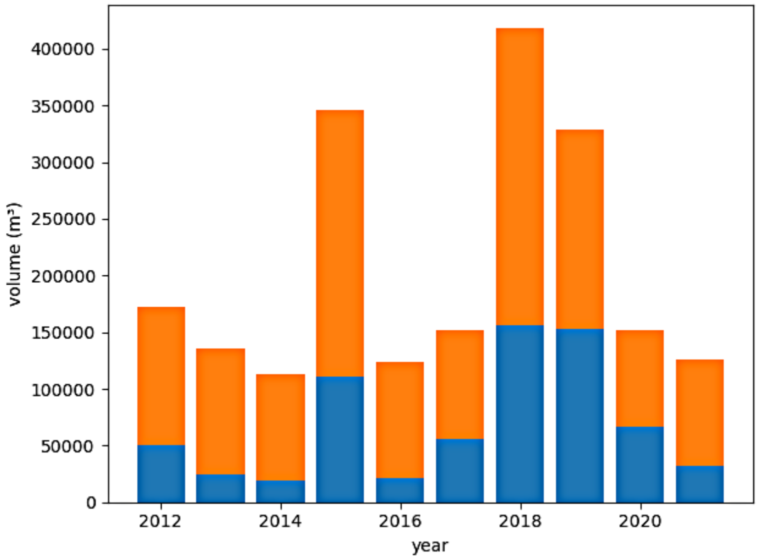

Figure 5. Time dependence of the reported volume of waste fires. The blue color represents the volume reported in SWD while orange represents the volume calculated based on the SWD-ST report

al., 2021a). It is caused by two factors, firstly, the volume of fires in 2018 was over 20%, secondly the emission factors for general waste are different, mainly lower, than for different types of waste and the deep analysis of the types of waste according to in (Bihałowicz et al., 2021a) would yield probably significantly higher emissions.

Population

The map of landfill fires imposed on the map of population density (Figure 4) reveals a pattern in which locations of waste fires are correlated with population density. To investigate quantitatively, whether the waste fires occur in densely populated areas or in less densely populated areas, the population density in circular buffers – annuli or colloquially donuts – around the reported coordinates of waste fire was analyzed. The boxplots presenting the average density are presented in Figure 6. The result shows that the highest average, median, maximum, and third quartile of population density is in the first annulus – just a circle of radius 1 km and center at fire coordinates. The average population density in the annulus can be successfully modeled by the

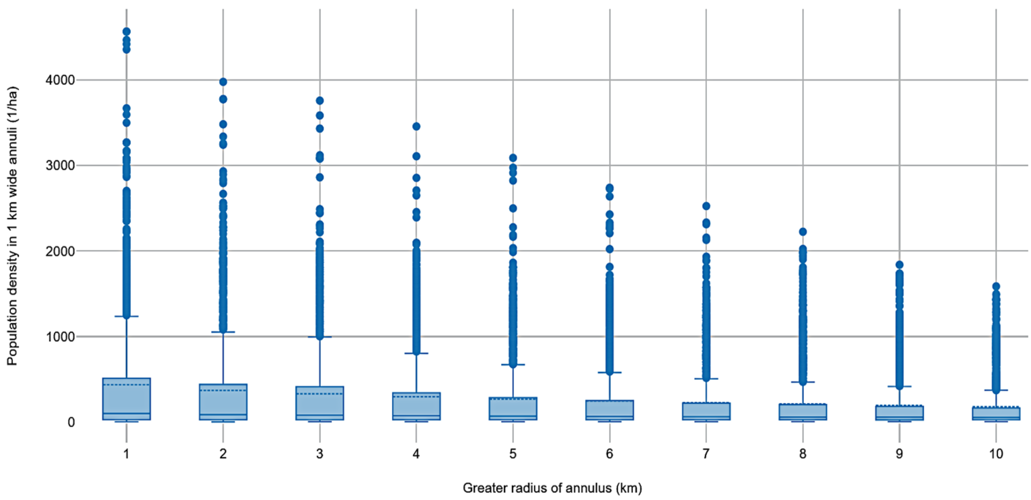

Figure 6. The average population density in equally-spaced annuli with the center in reported coordinates of waste fire. The average is denoted with the dashed line. The whiskers are standard whiskers of length 1.5 times the interquartile range. The box is from the first quartile to the third quartile with the median denoted as a continuous line

equation where is average population density, is grater radius of annulus, , are fit coefficients equal , with Pearson's correlation coefficient . The average population density in Poland in the grid as presented in Figure 4 based on (WorldPop and Bondarenko, 2020) is roughly 76 per pixel. This value would be could be obtained at , based on extrapolation. Hence, it can be concluded that landfill fires are not at "average" site, which can be found at a distance (donut) of radius 27 km.

CONCLUSIONS

In the article, some environmental impacts of the waste fires were discussed based on the 10-year database of fires in Poland. It was shown that the extinguishing waste fires are consuming high resources, from tens of thousands of cubic meters of water per year, the run-off of which transports water-soluble substances to soil and water ecosystems, through few to tens of cubic meters of extinguishing foam, which contains non-polar solvent and can act as medium transferring carbon products of burning to the environment, finally to the effort of firefighters and the equipment wear. All of these parameters were positively correlated with time; hence, the analysis of the ten years, 2012–2021, revealed that the waste fire problem was increasing in this period, and the resources, extinguishing, human, and equipment demand was increasing in these years. The investigation of locations of waste fires according to CLC showed that the most popular site for waste fires is arable land, but the second most popular one corresponds to loose settlements – suburbs, and villages. Investigation of the population in circular buffers around fires showed that waste fires occur in densely populated areas. Hence, waste fires cause a negative impact on the environment, lead to unneeded resource consumption, and cause concern for public health.

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