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Classification of fires in coal waste dumps based on Landsat, Aster thermal bands and thermal camera in Polish and Ukrainian mining regions

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Abstract A self-heating intensity index (SHII) based on the highest (pixel max.) and lowest (pixel min.) values taken from satellite thermal maps of burning coal waste dumps are proposed. The index enables the classification of such fires in Ukrainian- and Polish coal waste dumps. Both in Ukraine and in Poland, varying thermal intensities during 1985–2019 are revealed, using the SHII and following thermal intensity threshold values, namely, extreme thermal activity (> 7), advanced (3–7), moderate (3–1.5), initial (1.5–1), no activity (< 1). The SHII shows decreasing thermal activity in the selected Ukrainian coal waste dumps during 2017–2019. It aids in reconstructing the thermal history of the dumps. Analysis of satellite images revealed a large number of burning coal waste dumps in the Donetsk Coal Basin (Ukraine) with high thermal activity. Such burning likely reflects large amounts of organic matter and sulphides in the dumped material subjected to self-heating and self-burning processes, lack of compaction of the coal waste and/or high methane contents. Comparison of SHII values calculated from satellite- and drone thermal-camera images were compared to show that SHII from drone thermal images have much higher values than those from satellite images; the former have better resolution. Thus, SHII from Landsat- and drone images should be used separately in dump heating studies.

Keywords Self-heating · Coal waste dump · Landsat · Self-heating intensity index (SHII) · Drone

1 Introduction

Coal mining worldwide is associated with the production of waste mostly composed of claystones, mudstones, sandstones, conglomerates, carbonates, carbonaceous shales, and pyrite-bearing carbonaceous rocks. The waste material usually contains 5%–30% of organic matter from very thin, workable or poor-quality uneconomic coal seams, rock partings, and dispersed organic particles (Skarżyńska 1995). The waste material begins to weather immediately after deposition due to organic matter oxidation and other processes which, later, may lead to self-heating.

Carbonaceous rocks are usually in thermodynamic equilibrium with their geological environment at depth. This balance is disturbed by their relocation during mining into an oxygen-rich environment. As carbonaceous matter may undergo self-heating at these conditions due to the fact that heat is not adequately dissipated. This occurs independently of pyrite weathering and oxidation. With the participation of thionic bacteria, the pyrite oxidation process can be faster. The oxidation reaction is highly exothermic as the pyrite oxidizes to sulphuric acid. This significantly increases the rate of low-temperature oxidation (Kaymakçı and Didari 2002; Melnikov and Grechanovskaya 2004; Pone et al. 2007; Onifade and Genc 2018). In the initial stages of self-heating subjected for high volatile bituminous coals or sub-bituminous coals, the temperature increases slowly until a threshold temperature

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of 60–80 °C is attained. When that threshold is exceeded, the temperature rises fast and self-ignition and burning of the waste follow. Heating inside a coal waste dump is typically highly variable with temperatures ranging from ambient to > 500 °C. However, at the end stages of heating in the subsurface, self-combustion temperatures can reach up to 1000–1300 °C (Carras et al. 1994, 1999; Skarżyńska 1995; Heffern and Coates 2004; Querol et al. 2008; Ribeiro et al. 2010; Jendruś 2016). Several factors influence self-heating occurrence and progress. The self-ignition temperature is strongly rank-dependent, increasing with increasing rank of the organic matter, i.e., ~ 150 °C for subbituminous coals, ~ 200 °C for bituminous coals and ~ 300 °C for anthracites (Sokol 2005). In general, lower rank coals such as lignites and subbituminous coals are more susceptible to self-heating than higher rank coals (Chandra and Prasad 1990; Bell et al. 2001; Suárez-Ruiz and Crelling 2008; Ribeiro et al. 2010; Vice et al. 2019). However, self-heating occurs in coals and coal waste of all ranks (e.g., Stracher et al. 2010, 2012, 2015; Stracher 2018).

Apart from the organic-matter rank, the susceptibility of coal waste to self-heating is dependent on the number of other factors. Internal factors are the content of organic material, its maceral composition, mineral-matter content and composition, moisture, and oxygen content. External factors are air temperature, wind direction, size and distribution of coal waste particles, and the shape, layer structure, and compaction of a dump (Skarżyńska 1995; Saghafi and Carras 1997; Lohrer et al. 2005; Pone et al. 2007; Zhang and Kuenzer 2007; Carras et al. 2009; Masalehdani et al. 2009; Misz-Kennan and Fabiańska 2010, 2011). Poor compaction of coal waste, common in the past, allows easier penetration of air and rainwater into the dump, promoting the self-heating process (Bell et al. 2001). For all the above reasons, the heating is very complex. It occurs in coal seams, coal dumps, and coal waste dumps everywhere coal is mined (e.g., Stracher et al. 2010, 2012, 2015; Stracher 2018). The phenomenon is very dynamic with temperatures fluctuating in any individual place over time. The thermal processes occur under oxygen-limited conditions and commonly without flames (Misz-Kennan 2010; Misz-Kennan and Tabor 2015).

Self-heating coal wastes emit copious amounts of major greenhouse gases, i.e., CO_2, CH_4. Apart from these, other harmful compounds in self-heating gases include NO_x, NH_3, SO_x, and H_2S from the decomposition of sulfide minerals, HCl, aromatic compounds such as benzene and its alkyl derivatives, styrene, alcohols, polycyclic aromatic hydrocarbons (PAHs), heavy metals, e.g., Hg, As, Pb, and Se, halogenated organic compounds, e.g., chlorobenzene, dichloromethane and dichloroethane, sulfur-, oxygen-, and nitrogen heterocyclic compounds such as furane, thiophene, and pyridine (Davidi et al. 1995; Stracher and Taylor 2004; Pone et al. 2007; O'Keefe et al. 2010; Ribeiro et al. 2010; Querol et al. 2011; Borisovskaya et al. 2013; Fabiańska et al. 2013a, 2019; Kruszewski et al. 2018). During self-heating, one ton of coal waste can generate 0.84 kg of SO_2, 0.61 kg of H_2S, 0.03 kg of NO_x, 99.7 kg of CO, and 0.45 kg of smoke (Liu et al. 1998).

In Poland and Ukraine, coal waste dumps are often surrounded by settlements (Fig. 1). They are used as meeting places, touristic viewpoints, sites for cultural exhibitions, and sport events, including climbing, cycling and extreme sports (Ivchenko and Lebezova 2012). Dump emissions adversely affect human- and animal life. Emitted dust damages the central nervous and circulatory systems, kidneys, livers, and contributes to the development of cancer (Glushkov et al. 2010; Petrov et al. 2014; Privalov 2015). Apart from this permanent influence, large disasters such as explosions can occur during dump exploitation as e.g., in case of the coal waste in the Dymytrov town (now Myrnohrad) in 1966 in Donbas area. Part of the dump torned appart and the burning material slumped on to the Nakhalovka settlement (Skrypnik and Tretyakova 2015). Witnesses compared this event to a volcanic eruption. Several similar accidents have occurred in the Donetsk Coal Basin (Gayvoronsiy and Yugov 2015).

Due to its adverse impact on the environment and health, it is important to detect the self-heating process as early as possible using satellite remote sensing and drones to prevent spreading of self-heating affected areas and to extinguish zones subjected to self-combustion. Hot spots in self-heated coal waste are commonly located 2–3 m below the surface. They usually appear as high-temperature surface anomalies, which can be detected by Thermal Infrared Sensors (TIRs) used by Landsat 4–5 TM (120 m resolution resampled to 30 m), 7 ETM+ (60 m resolution resampled to 30 m), 8 OLI (100 m resolution resampled to 30 m), and ASTER (90 m, resampled to 30 m) satellite images or by Thermal Infrared Cameras (details of satellite images in Table 1S in the Supplementary Material). Typically the migration, intensification, and disappearance of such hot spots can be recognized on thermal maps (Nádudvari 2014).

The aim of the research is to create a classification index for self-heating intensity in coal waste dumps in different regions using Landsat-, ASTER- and thermal-infrared camera acquisition from a drone using Landsat 4–5 TM, ETM+, and ASTER images. The other aim is to use this index to compare the self-heating intensity of burning dumps from different coal basins and provide a reconstruction of the thermal history of coal waste dumps. As, in most cases, there are no records of dump history, such a method could help better understand the initiation, development, migration, and waning of dump heating.

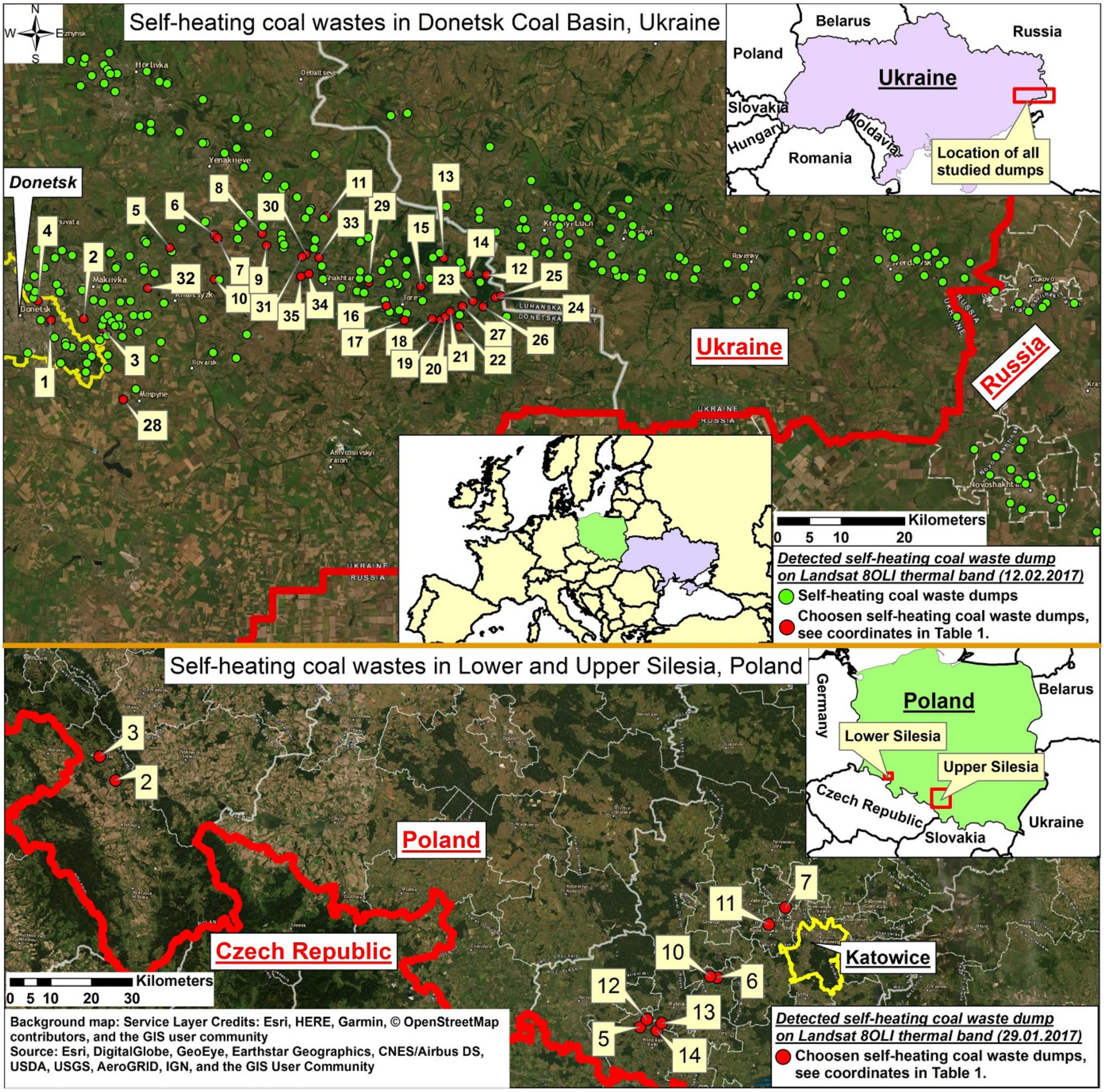


Fig. 1 The location of the study area with detected self-heating coal waste dumps in Ukrainian and Polish coal mining regions. The Landsat, ASTER images were downloaded from https://earthexplorer.usgs.gov/ website. Not all coal waste dumps are indicated in Poland, just the thermally active dumps in 29.01.2019. The location (coordinates) of all dumps see in Table 1

2 The scope of investigation

For the present studies, 35 coal waste dumps in Ukraine and 14 in Poland were selected. The coal waste dumps represent the mined coal-rank types except for their lower carbon content.

2.1 Coal waste dumps in Ukraine

Most ($<$ 95%) of Ukrainian hard-coal deposits are located in the Donetsk Coal Basin spreading over Donetsk, Lugansk, and Dnipropetrovsk. The coal is generally of anthracite (2.5%–3.5% random vitrinite reflectance R_r) and meta-anthracite ($>$ 3.5% R_r) rank in the central part of the basin. Bituminous coals (0.6%–2.5% R_r) are concentrated on the western- and northern basin margins (Levenshtein et al. 1991; U.S. EPA 2002; Savitsky 2015). The coal basin hosts about 300 coal layers (typically thin with wide lateral distribution), where 130 seams reaching a thickness of > 0.45 m, but only 12 are > 1.0 m thick. Seams > 2.0 m thick are rare. Recoverable coal resources extend up to 1.5 km depths (Sachsenhofer et al. 2003; Antsiferov et al. 2004; Privalov et al. 2007; Sachsenhofer et al. 2012; Dychkovskyi et al. 2014; Savitsky 2015).

The coal waste generated during exploitation and beneficiation is deposited in about 1200 stockpiles containing ~ 1.5 billion m^3 of coal waste and < 120 million tons of waste are produced annually by coal preparation plants (Fig. 1). The waste material consists of argillites, siltstones, limestone rocks, sandstone, coal, and mineral pyrite aggregates showing various degrees of metamorphism (Kochetov and Konischeva 1994; Omelchenko 2011; Voloshyna et al. 2014). It is estimated that the Donbas coal waste dumps may contain 10%–46% of organic matter, < 20% of silica and iron oxides. As the Ukrainian coal deposits have high (1.5%–5.5%) sulphide contents, the waste dumps are also rich in sulphides (Vasileva 2015; Perov et al. 2016).

The coal wastes in Ukraine were not properly compacted, which accentuates water erosion, especially on conical dumps. Significant annual temperature amplitudes promotes the fragmentation of coal waste particles (Vasileva 2015). As the material is typically loose, gravel- and stony fractions predominate. Even on the oldest dumps, fractions < 1 mm rarely exceed 30% (Torokhova 2007). The coarseness will result in greater oxygen availability which, combined with a large amount of organic material, will promote self-heating.

These dumps located in the Donetsk Coal Basin annually emit > 500,000 tons of harmful gases into the atmosphere (Kochetov and Konischeva 1994; Omelchenko 2011). Each year, from the surface of a single dump, ~ 400 t of dust is generated and ~ 8 t of salt is washed out (Kuzyk 2009). It is estimated that 15,000 t of CO_2 and < 5000 of CO are emitted annually. Other environmental issues linked to coal mining in the Donetsk Coal Basin are water supply disruptions, increased salinity of groundwater and enormous accumulations of solid waste, resulting in land degradation, air pollution and dust, as well as mudslides (Savitsky 2015). Coal production declined during the 1990s due mainly to the collapse of domestic demand and the plant closures in heavy industry. Between 1990 and 2004 there were 119 underground coal mines abandoned without remediation or in the process of mine closure. In addition, ~ 77% of abandoned mines in the region reported elevated methane contents released from coal (U.S. EPA 2002; Privalov et al. 2004; Oprisan 2011; Savitsky 2015).

2.2 Coal waste dumps in Poland

In Poland, self-heating in coal waste occurs in two mining areas, i.e., the Upper Silesian Coal Basin (USCB) and the Lower Silesian Coal Basin (LSCB). The ~ 7400 km^2 USCB is the largest coal basin in Poland and one of the largest in Europe (Jureczka and Kotas 1995; Kędzior 2009). Coal seams are generally thin (< 1–1.5 m). About 60 seams are typically 4–8 m thick but can reach up to 24 m (Fabiańska et al. 2013b). The coals are hard coals varying in rank from subbituminous to high-volatile bituminous coals that are mostly humic, rarely sapropelic. In their composition, vitrinite-group macerals predominate (> 80%). Their content is lowest in the eastern part of the basin and increases westwards. The coal rank in the western part of the basin is much higher (R_r > 1.0%) than in the eastern part ($R_r \approx$ 0.50%) (Gabzdyl 1994; Jureczka and Kotas 1995; Kotarba et al. 2002; Fabiańska et al. 2013b). Coal waste deposited in the Upper Silesian Coal Basin comprises claystones, mudstones, sandstones, and smaller amounts of conglomerates and carbonates. The organic matter content is commonly 7%–15%, but it may exceed 30% (Skarżyńska 1995). Sulphide contents in the coals range from 0.32% to 2.82% (Sobczyk et al. 2016). This, and pyrite (< 8% content) mixed with coal gangue, has generated favorable conditions for long-lasting coal waste fire that remains hard to control (Jendruś 2017).

Self-heating intensity and its frequency vary considerably within the Upper Silesian Coal Basin. The area most definitely affected by heating is the Rybnik Region in the south-western part of the basin, where almost all coal waste dumps were or are undergoing self-heating (Fig. 1; coal waste dumps Nos. 5, 6, 10, 12–14). In the western part, where rank is higher than in the eastern, self-heating is more frequent. In the eastern part, self-heating temperatures can be extremely high, e.g., 1300 °C as registered in the Szarlota dump near Rydułtowy town, where thermal processes affect large parts of the dump (Fig. 1; dump No. 12; Misz-Kennan 2010; Misz-Kennan and Fabiańska 2010; Misz-Kennan and Tabor 2015). In the northern part of the basin occupied by the highly populated cities of Bytom, Ruda Śląska, and Katowice, tens of dumps show lower intensities of heating than those in the Rybnik Region (Misz-Kennan and Tabor 2015). However, self-heating is common there and difficult to extinguish. Heating is least intense in the eastern part of the basin.

This regional pattern of heating in the Upper Silesian Coal Basin is explained by differences in the rank of organic matter within the waste rocks. Average present-day geological temperatures within the Mudstone Series in this basin ranging from 24.9 °C (eastern part) to 58.9 °C (west-southern part) approximately coincide with the pattern of mean random vitrinite reflectance (Karwasiecka 2001;

Kędzior 2015). These temperature differences reflect the geological history of the basin (Kędzior et al. 2007; Kędzior 2015). It is not surprising that organic matter in coal waste shows a similar pattern of thermal maturity. A higher coalification stage means higher self-heating intensities in the dumps. Moreover, the sapropelic coals deposited there are highly reactive.

In the smaller 350 km^2 Lower Silesian Coal Basin, hard-coal seams cover an area of $\sim$ 350 km^2. Large quantities of natural gas (mainly CO_2 and CH_4) constitute a CH_4 explosion hazard. The quality of the coals varies considerably; in the Wałbrzych area, the coal R_r ranges from 1.10% to 4.28%, in the Nowa Ruda area from 1.08% to 1.56% (Bossowski 1995; Kotarba and Rice 2001).

In this basin, three dumps were subjected to self-heating during the period 1987–2017, namely, Wałbrzyc, Słupiec, and Nowa Ruda (Fig. 1, dump No. 1–3); all displayed continuous thermal activity. For instance, the fire had mostly vanished in Wałbrzych in 2017. Though thermally-altered red clinker indicated earlier intensive fire at another dump (Fig. 1, No. 4), the dump was not thermally active at all during 1987–2017 (Fabiańska et al. 2019).

Except for sulphide contents, there is no significant difference between Ukrainian- and Polish coal deposits in terms of coal quality, i.e., gross heating values and remaining ash contents (U.S. EPA 2013; Małkowski and Tymoshenko 2018).

3 Methodology

For this study, 35 representative coal waste dumps with different shapes, e.g., conical and trapezoidal from the Donetsk Coal Basin in Ukraine from 1985 to 2019 (dates of acquired data in Table 1S) were selected. For comparison, 14 coal waste dumps from the Upper- and Lower Silesian Coal Basins between 1985 and 2018 were also selected (Table 1S; Fig. 1; Table 1).

3.1 Application of Landsat images for detecting self-heating dumps

Using the Thermal Infrared (TIR) sensors of satellite images, i.e., Landsat series, ASTER is the cost-effective and time-saving technique for monitoring coal waste fires and detecting their thermal anomalies. Several authors have successfully applied Landsat, ASTER night-time and winter-time images for localizing such coal- or coal-seam fires worldwide (e.g., Voigt et al. 2004; Gangopadhyay et al. 2005; Chatterjee 2006; Zhang and Kuenzer 2007; Prakash et al. 2011; Guha and Kumar 2012). The image data were obtained from night-time and snow-covered images with zero cloud-, haze- and fog cover from https://earthexplorer.usgs.gov (2019). The calculations were performed according to the methodology given in https://www.usgs.gov/land-resources/nli/landsat/using-usgs-landsat-level-1-data-product (2019). First, the radiance was calculated and then the brightness temperature was converted from Kelvin to Celsius according to $T_{Celsius} = T_{Kelvin} - 273.15$ (TS: temperature at satellite). To obtain the Land Surface Temperature (LST), a thermal emissivity map first had to be generated based on the spectral absorption properties of the surface materials as surface temperatures are directly related to surface physical properties.

Firstly,

$$\text{Proportion of vegetation } (\mathbf{Pv}) = ((\text{NDVI} - \text{NDVI min})/(\text{NDVI max} - \text{NDVI min}))^2 \tag{1}$$

where NDVI min and NDVI max = minimum and maximum values of the NDVI (Normalised Difference Vegetation Index) image. This helped to separate the surface materials.

Secondly,Thermal emissivity (e) was calculated as follows:

$$\text{Emissivity (e)} = 0.004Pv + 0.986 \tag{2}$$

where Pv = Proportion of vegetation.

Land Surface Temperature (LST) was calculated as follows:

$$\text{LST} = \text{TS}/[1 + (\text{DN}_{\text{TIR}} \times \text{TS}/P) \times \ln(\text{e})] \tag{3}$$

using the thermal (e) and (TS) values proposed by Weng et al. (2004), Jiménez-Muñoz et al. (2009), and Suresh et al. (2016). TS = temperature at satellite, DN_{TIR} = DN values of original thermal band of Landsat image used, and $P = 1.438 \times 10^{-2}$ m K = 14,388 µm K;

P was calculated according to:

$$P = h \times C/S \tag{4}$$

where h = Planck's Constant (6.626×10^{-34} J s), $C = 2.998 \times 10^8$ m/s, i.e., velocity of light, $S = 1.38 \times 10^{-23}$ J/K, i.e., Boltzmann Constant.

All calculations were performed in ENVI 5.3 software.

The self-heating intensity was calculated from the highest (pixel max) and lowest (pixel min) values according to:

$$\text{Self heating intensity index (SHII)} = (\text{pixel max} - \text{pixel min})/2 \tag{5}$$

For the index, the required pixel values were taken from the area of a coal waste dump, taking care to avoid any man-made structures, lakes, or ponds during delineation. These ratios should be used only for night-time images with cold weather ($\sim$ <10–15 °C), and daytime snow-

Table 1 Location of the coal waste dumps studied with coordinates (coordinate system: WGS 84)

Item	No. of studied coal waste	North	East
Polish coal waste dumps from Upper and Lower Silesia	1	50.747285	16.279807
	2	50.535132	16.570566
	3	50.585383	16.515785
	4	50.601605	16.558627
	5	50.045529	18.422059
	6	50.159808	18.679582
	7	50.319759	18.908264
	8	50.280512	19.034497
	9	50.277346	18.778163
	10	50.161664	18.655705
	11	50.281069	18.851763
	12	50.062717	18.442718
	13	50.056748	18.494442
	14	50.038264	18.479252
Ukrainian coal wastes dumps from Donetsk Coal Basin	1	47.995299	37.877937
	2	47.998358	37.947571
	3	47.985010	37.986945
	4	48.022835	37.850213
	5	48.100832	38.128460
	6	48.119112	38.222327
	7	48.114734	38.226793
	8	48.121673	38.322375
	9	48.105511	38.332173
	10	48.056762	38.223272
	11	48.147650	38.459162
	12	48.065677	38.797696
	13	48.089767	38.707232
	14	48.067482	38.760917
	15	48.048607	38.659061
	16	48.021404	38.585819
	17	48.000728	38.626036
	18	48.002794	38.682964
	19	48.000930	38.701527
	20	48.005927	38.710700
	21	48.012636	38.721825
	22	48.020497	38.747001
	23	48.027718	38.769620
	24	48.033640	38.816757
	25	48.036027	38.828260
	26	48.019787	38.790525
	27	47.991903	38.740795
	28	47.884687	38.032245
	29	48.054846	38.548280
	30	48.093108	38.415214
	31	48.089270	38.407331
	32	48.042455	38.083386
	33	48.088212	38.443541
	34	48.065776	38.421659
	35	48.061854	38.405310

covered images. The ratio values increase when thermal activity is high.

Differences in albedo and features such as slope and aspect can significantly impact the thermal anomalies. Hot spots of low thermal activity are usually visible on Landsat thermal map with 2–3 °C difference between pixel max (hot spot)—pixel min (cold snow covered surface with no thermal activity). Also hot surfaces on burning dumps with small extensions (the area of a hot spot is smaller than the satellite sensor of TIR) are difficult to detect and distinguish from the surrounding pixel values. Furthermore these pixel values are also disturbed by the sun effect (same for the thermal camera images). However the thermal camera images are more sensitive for the sun influence. Therefore, any disregard for the manner of the impact of solar radiation on the surface can lead to significant distortion of thermal information from a surface. Even partial sunshine significantly disturbs the temperature values obtained (Zhang and Kuenzer 2007; Nádudvari 2014; Usamentiaga et al. 2014; Nádudvari and Ciesielczuk 2018).

3.2 Thermal images taken by a drone

Infrared low-altitude aerial photogrammetry is currently one of the most popular methods for thermal-data collection (Sawicki 2012; Usamentiaga et al. 2014; Wasilewski and Skotniczy 2015). The current state of the technology allows acquisition of data with very good resolution; their accuracy is already measured in centimeters—much better than the TIR sensors of satellite images (Landsat series, ASTER). Unfortunately, there are a number of limitations. First of all, weather requirements strictly include no rain or fog, clean air, no wind, stable air temperature and full cloud cover (Bernard et al. 2014). The omission of any of the requirements significantly affects the accuracy and reliability of the thermal data.

Appropriate planning of a drone flight and the fieldwork requires much more time than is expended using one of the satellite databases at a desk. Moreover, the data obtained are usually difficult to compare with the historical state of a dump. As high-resolution thermal drone photographs became popular only in the last decade, archival data are not available. Unfortunately, there are currently no open-access databases collecting thermal images from drones (McCarley and Wickens 2004; Abramowicz and Chybiorz 2017).

The method presented here is based on two thermal maps made using the DJI S900 drone with a FLIR Vue Pro R336 thermal imaging camera (matric 336 × 256, lens 9 mm, spectral range 7.5–13.5 μm). The maps cover the area of the burning coal waste dump in Ruda Śląska (Table 1, No. 11). The first flight performed in March 2018 (479 thermal images) was treated as a trial. Thus, its range was limited to fire spots visible on the surface. Unfortunately, the final image shows that the range was too small to fully cover all burning zones and sites. The second flight was in October 2018, when 650 thermal images were taken that represent the variability of the fire over a period of 7 months. The second flight was based on the first flight. The range of the flight was extended to include fragments missed earlier in the western part of the dump.

To eliminate the influence of insolation on temperature measurements, all the photographs were taken just before sunrise, in conditions close to the benchmark. The air temperature during the flights was − 2 °C (March 2018) and + 9 °C (October 2018). Drone flights were carried out at a height of 70 m. The final resolution of the thermal maps is 20 cm.

In preparation of a large-scale thermal map, it is necessary to make a whole series of photographs with appropriate transverse (minimum 50%) and longitudinal coverage (minimum 70%). Apart from the images, the data from the GPS receiver placed on the drone was also collected. This gives information on the exact location of each photograph and allows for subsequent georeferencing of every individual image. The next step was to create a mosaic using the AgiSoft PhotoScan software. Appropriate algorithms were used to search for the same points on every individual image in order to combine the images (Maes et al. 2017). Five ground control points with known coordinates were added. These were later used to register and georeference the image. Finally, the picture locations were optimized and the map created.

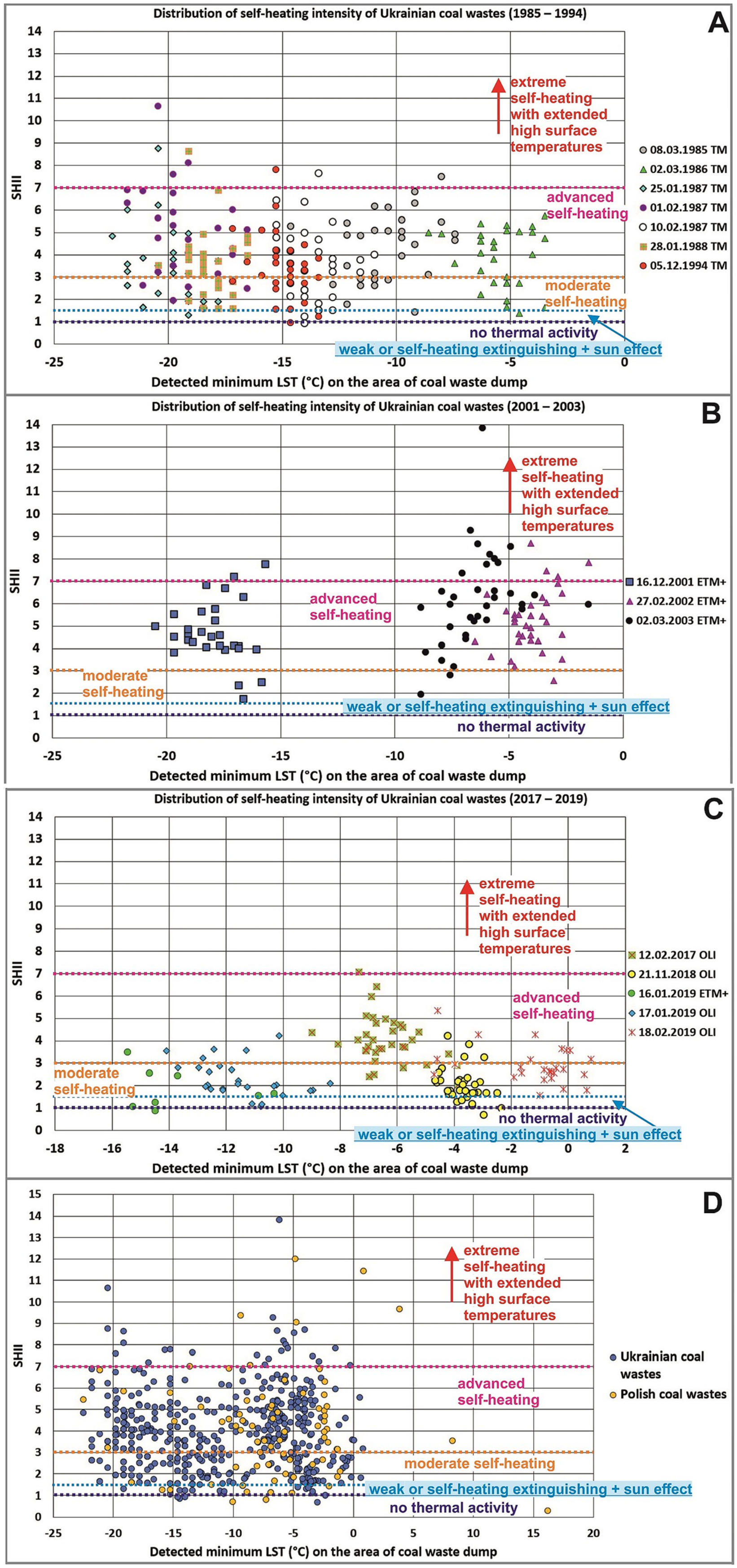
4 Results and discussion

In ~ 330 self-heating coal waste dumps in the Donetsk Coal Basin, compared to ~ 10 in Upper- and Lower Silesia, the size and heat intensity of the hot spots could be detected on satellite images in 2017 (Fig. 1). The estimated number of burning dumps is between 140 and 400. The exact number is unknown as fires in these dumps are activating and extinguishing continuously (Kochetov and Konischeva 1994; Omelchenko 2011; Voloshyna et al. 2014). Self-heating events are still a problem in the Upper Silesian Coal Basin. In 2000–2010, at least 21 fire occurrences were observed in original- and recultivated dumps. Between 2007 and 2013, 15 thermally active dumps were reported from among the 220 coal waste dumps in the Upper Silesian Coal Basin (Misz-Kennan and Fabianska 2010; Misz-Kennan 2010; Skręt et al. 2010; Zając and Zarzycki 2013; Fabiańska et al. 2013a). In the Lower Silesian Coal Basin, the self-heating problems with dumps are generally decreasing (Fabiańska et al. 2019).

Using the proposed SHII, the results indicated varying thermal activity on the studied Ukrainian dumps between 1985 and 2019 (Fig. 2a–c). The results helped to establish SHII threshold values, i.e., extreme (> 7), advanced (3–7), moderate (3–1.5), weak or waning (1.5–1), no thermal activity (< 1). During 2017–2019, compared to earlier periods, the thermal activity of major dumps could be seen to have changed, e.g., to a moderate- from an advanced state of self-heating or to have extinguished. However, 20–30 years ago, extreme thermal intensities were recorded in e.g., 1987, 2002 and 2003. Usually it happens when a coal waste dump is excavated for recover remaining coal particles as it has happened in Ukraine in 2000 years, see and example on Fig. 3—Makoszowy dump (Pilov et al. 2000). There is no difference in the pattern of heat intensities between the Polish and Ukrainian self-heating dumps (Fig. 2d).

The studied dumps in the Upper Silesian Coal Basin can also attain extreme self-heating conditions (Fig. 3). Typically, intensive self-heating on the surface can start, when a dump with ongoing burning inside is opened by excavation. That is perfectly seen in the diagram (Fig. 3) for the Makoszowy dump, where coal waste excavation started in early 2000 and thermal activity stopped by about 2007. By 2013, all coal waste had been removed from Makoszowy dump (Nádudvari and Ciesielczuk 2018). A similar tendency is visible on a representative dump (Fig. 3—Ukrainian dump) from the Donetsk Coal Basin for the 2001–2003 timespan, where self-heating progressed from the initial/weak stage to the advanced stage in 1987–1994. The dump was probably opened for excavation or the self-heating spontaneously intensified. Such time-line diagrams can help to visualize the self-heating history of a dump.

In Fig. 4, the highest SHII values among the studied coal waste dumps (02.03.2003—Ukrainian coal waste dump No. 2, intensity 13.8) is shown. Also, the location of the lowest and highest temperatures used for the calculation of the self-heating intensity is also shown. The disadvantage of using different types of a satellite image with the different resolutions is illustrated by another coal waste dump (Polish dump No. 11; Fig. 4). The self-heating intensity is low (1.1–1.3) for both Landsat 8 OLI and for the hot spot perfectly identified with a better resolution at Landsat 7 ETM+; in this case, the index value (2.5) indicates moderate thermal activity. A heated spot on a dump usually shows a > 3 °C difference between the surface- and air temperatures. However, hot spots are commonly located 1.5–2.5 m below the dump surface with no surface indication of the presence of intensely hot zones even within a few meters of the dump surface (Urbański 1983; Walker 1999; Barosz 2002; Tabor 2002; Day et al. 2015; Jendruś 2017). That makes the detection of hot spots with low intensity or situated in a deeper part of a dump


Distribution of self-heating intensity of Ukrainian coal wastes (1985 – 1994)
A
extreme self-heating with extended high surface temperatures
advanced self-heating
moderate self-heating
no thermal activity
weak or self-heating extinguishing + sun effect
08.03.1985 TM
02.03.1986 TM
25.01.1987 TM
01.02.1987 TM
10.02.1987 TM
28.01.1988 TM
05.12.1994 TM
SHII
Detected minimum LST (°C) on the area of coal waste dump
Distribution of self-heating intensity of Ukrainian coal wastes (2001 – 2003)
B
16.12.2001 ETM+
27.02.2002 ETM+
02.03.2003 ETM+
Distribution of self-heating intensity of Ukrainian coal wastes (2017 – 2019)
C
12.02.2017 OLI
21.11.2018 OLI
16.01.2019 ETM+
17.01.2019 OLI
18.02.2019 OLI
D
Ukrainian coal wastes
Polish coal wastes

◀**Fig. 2** The application of SHII combined with detected minimum LST (°C) on the surface area of the dump in the classification of Ukrainian coal waste fires from the Donetsk Coal Basin (**a**–**c**) and Silesian coal basins in Poland from 1985 to 2018 (**d**)

complicated (Figs. 4 and 5). When hot spots occur at shallow depths or with low thermal activity and a limited extent, cold air temperatures can overcome the self-heating and any thermal response by the TIR sensor is diminished (Nádudvari and Ciesielczuk 2018). Therefore, on the drone TIR reacts in the same way. The self-heating spot is completely absent in Fig. 4 (Polish coal waste dump No. 10) as Landsat 8 OLI was unable to properly detect the hot spot; the exception was Landsat 7 ETM+, which seems to be the most effective sensor for such purposes.

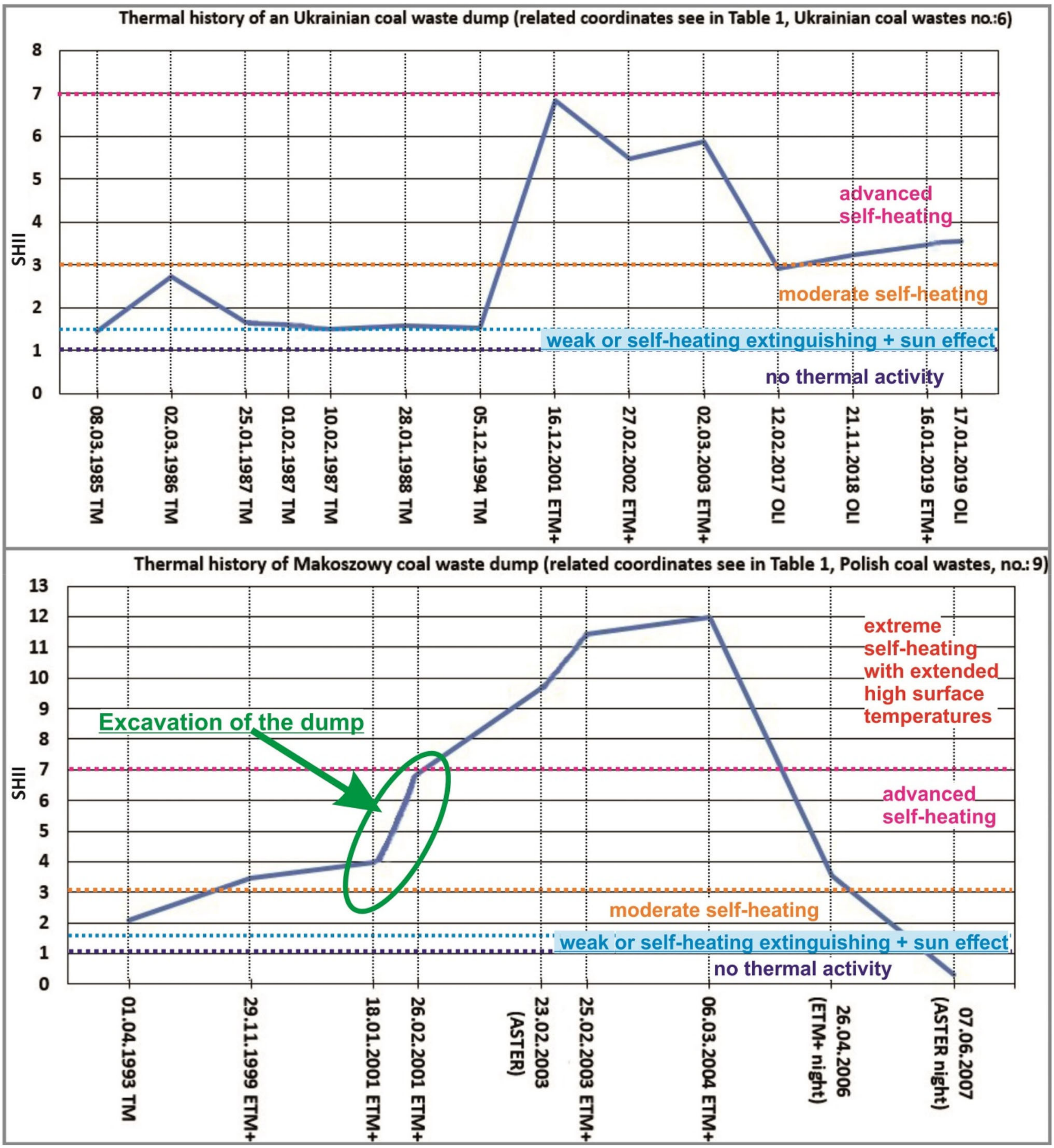


Fig. 3 Time-line diagrams for two representative coal waste dump in Poland and Ukraine

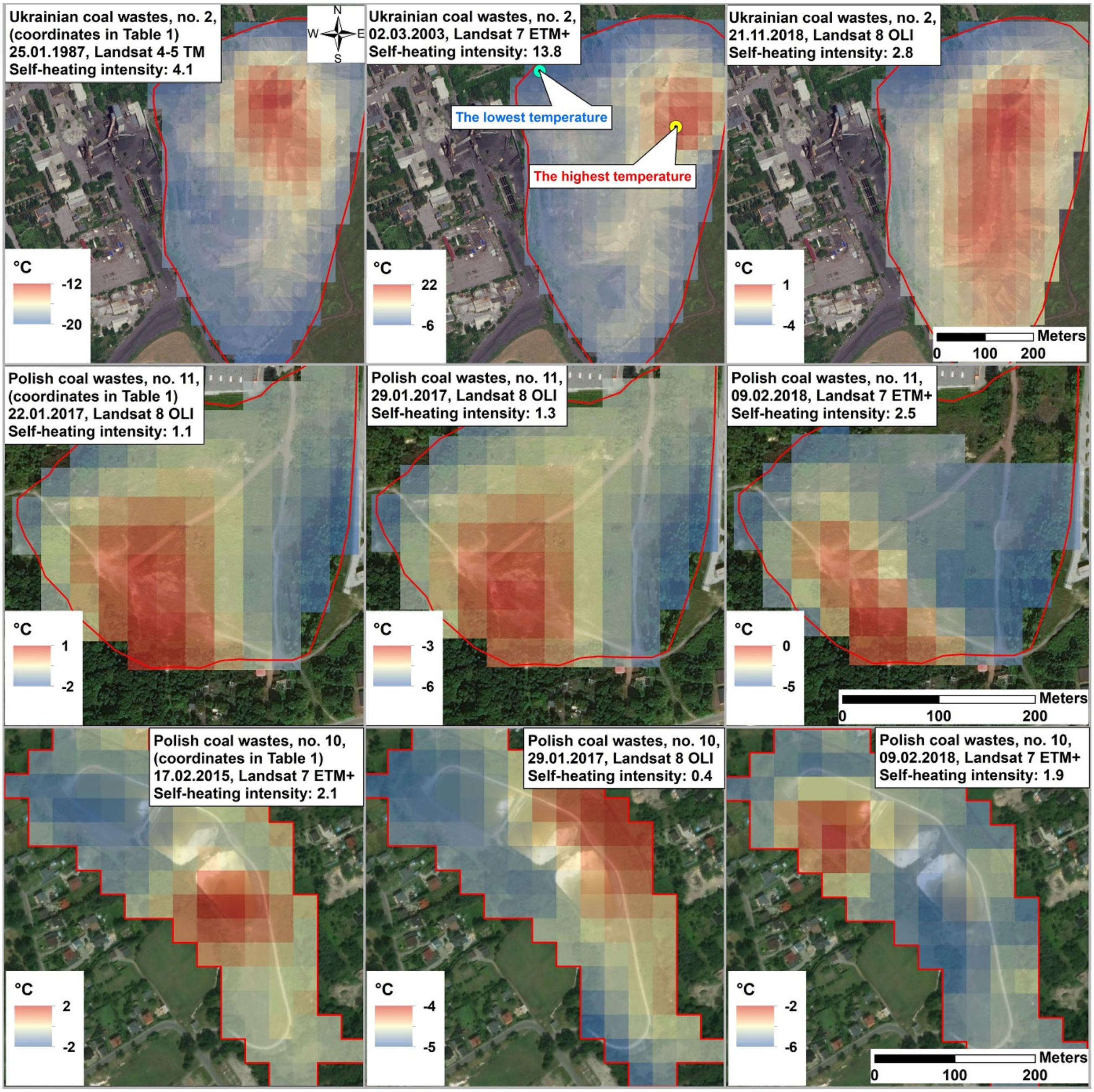


Fig. 4 Three representative coal waste dumps as examples of how the SHII index was calculated and to show the drawbacks of the method

In Fig. 5, a thermal camera image and a Landsat 7 ETM+ image of Polish coal waste dump no. 11 are compared. The SHII was calculated for each pixel and classified according to Fig. 2. The values are corresponding to moderate self-heating stage on the dump. The SHII was calculated for the thermal-camera image. With increasing resolution, the index value also increases because of the better resolution of drone images. Therefore, SHII should be applied, and trends described separately, for Landsat and drone images. The dump was established in 1992 on the site of the former Bielszowice brickworks. Waste material from the nearby Wawel coal mine was delivered there for the duration of 8 years. Gradually, vegetation was introduced onto the surface of the stored material to provide a recreational area. Unfortunately, the content of organic matter was so high that the waste material started to burn in 1995 (Laczny et al. Laczny et al. 2012a, b). Initially, heating involved only a small area in the south-western part of the dump. Over the years, the fire has spread and migrated north-eastwards. In the 2010s, fire sites also appeared in the eastern part of the dump along the technical road. In the following years, slow migration and

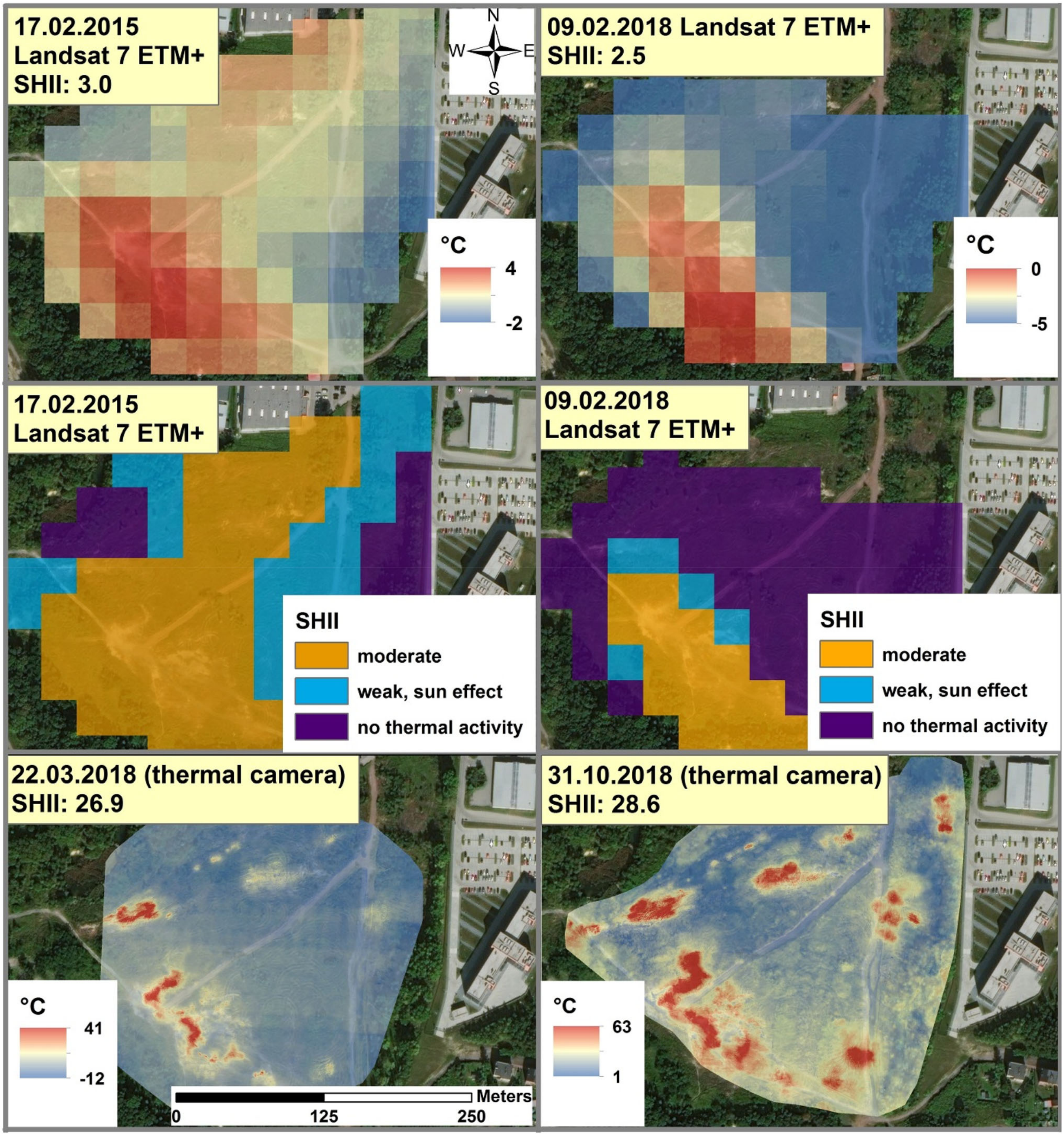


Fig. 5 Comparison of thermal data from Landsat 7 ETM+ and thermal camera mounted on a drone. Also the SHII distribution was calculated from Landsat 7 ETM+ using the Eq. (5) just replacing the pixel max. value with the raster image

segmentation of the fire zone took place. Currently, two large fire spots progressing towards the east are seen in the western part of the dump and, in the eastern part, three smaller spots progressing towards the north.

The application of the thermal bands of a Landsat image to coal-seam fires can cause problems, when the surface temperatures are extremely high. Usually, such fires have extended surface temperatures of 150–250 °C, or even higher, and emit more heat than a simple self-heating site on a coal waste dump (Cracknell and Mansor 1992; Chatterjee 2006; Huo et al. 2014). For example, a 30-cm-long crack emitting hot 400 °C gasses from a coal-seam fire might only raise the overall temperature of the 60 m× 60 m (Landsat 7 ETM+) thermal pixel by 3–10 °C against the background (Prakash and Gupta 1998; Prakash et al. 1995; Saraf et al. 1995; Zhang et al. 2004). The sensitivity of the thermal band (thermal infrared (TIR)) sensor of Landsat images is a maximum of 70–110 °C surfaces, occupying the major part of the pixel area. In the case of extreme coal waste fires, where high-temperature zones at the surface appear with mean temperatures of ≥ 50 °C, generally unaffected by air temperature or by the background temperature of the pixel, Landsat TIR bands are not effective (Chatterjee 2006). The short-wavelength infrared (SWIR) Landsat bands 5–7 can detect 160–277 °C hot spots, < 420 °C in the case of coal-seam fires, using nighttime images to avoid solar radiation (Rothery et al. 1992; Chatterjee 2006; Huo et al. 2014). The Landsat TIR bands are generally suitable for the detection of coal waste fire because surface temperatures of coal waste generally vary from 7 to 85 °C with larger areal extension. However open fires can extend to over 200 °C and tend to represent smaller spots (Misz-Kennan 2010). As night-time Landsat images are rare, the use of TIR cameras on drones are the most effective for localizing coal waste fires despite the restrictions.

The surface temperatures at thermally-inactive sites are lower than the hot-spot temperatures by 6–14 °C, on average, or even more depending on the heat intensity (Prakash et al. 2011; Nádudvari 2014; Abramowicz and Chybiorz 2019). Usually, in parts of dumps not affected by fire, ground- and air temperatures should be similar (Jendruś 2017; Abramowicz and Chybiorz 2019). The classification of coal waste fires proposed by Jendruś (2017) is based on the CO content in gases and the difference between the surface temperature of a dump and the surrounding temperature. Self-heating is deemed weak at most, if the difference between air- and surface temperatures is 0 ≤ 3 °C, slight if 3 ≤ 10 °C, moderate if 10 ≤ 20 °C and advanced if ≥ 20 °C. On thermally-inactive dumps, surface temperatures can exceed 3 °C due to intensive sunlight.

With regard to the SHII, the detected fire was classified as weak, or extinct (or a sun effect), where the difference between the highest and lowest surface temperatures was 3 °C. However, where such a difference occurred, where surface temperatures were ≥ 10 °C, the index classified the hot spot as an advanced- or extreme self-heating event according to the proposed SHII (Fig. 4). The proposed classification of Jendruś (2017) is based on time-consuming in situ measurements. However, for precise monitoring of hot spots below the resolution of Landsat images, the application of TIR satellite images can cover a wide range of dumps at one time and is effective for larger hot spots.

5 Conclusions

Especially in Ukraine, a large number of burning coal waste dumps pose a serious environmental-pollution threat. These dumps are not adequately compacted and contain high contents of sulphide as coals in the Donetsk Basin are sulphide-rich. They also comprise high levels of organic matter (10%–46%) and retain methane in elevated quantity; the Donetsk Basin is among the most gas-rich basins in the world. In the waste, the later serves as fuel for long term self-heating and smoldering (Nádudvari et al. 2020).

A large number of fires in the Donetsk Coal Basin reflect the nature of the waste deposited and the mode of storage.

Burning of various thermal intensities occurs in the coal waste dumps of both the Donetsk- and Silesian Basins Basins, especially in the former. A self-heating intensity index (SHII) classifying the thermal intensities of the dumps as extreme, advanced, moderate, weak or inactive helps to detect, monitor, and reconstruct the thermal history of the dumps. The proposed SHII classification may serve as a useful tool for monitoring of ongoing self-heating processes in active and abandoned coal waste dumps. The proposed SHII can be applied worldwide, wherever snow-covered or night-time Landsat, ASTER images are available.

For the difficult-to-detect self-heating areas of the small spatial extent or with low thermal activity at surface, a sensor resolution is important. Although, images from a thermal camera on a drone provide higher resolution images and, thus more detailed information of the location of hot spots in a dump, the long-termed thermal history and burning dynamics can be only discerned from satellite images.

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