Application of UAV orthophoto and thermal imaging for municipal solid waste landfills monitoring

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Abstract

Monitoring municipal solid waste (MSW) landfills is essential for understanding surface dynamics, vegetation changes, and temperature anomalies that may indicate environmental risks. Traditional ground-based methods are often labor-intensive and spatially limited, making unmanned aerial vehicle (UAV) remote sensing an efficient alternative. This study employs UAV-based RGB and thermal infrared (TIR) imaging to assess landfill conditions in two Czech MSW sites. The first objective is to map the distribution of the invasive plant cotton thistle *(Onopordum acanthium L.)* using UAV RGB imagery data and a convolutional neural network classifier. The second objective is to analyse apparent temperature variations across landfill zones using repetitive UAV TIR imagery. Results demonstrate that UAV RGB imagery effectively detects vegetation patterns, while UAV TIR imaging identifies temperature anomalies that may be associated with landfill processes. Zones with mixed waste and soil remain the warmest over time, suggesting potential hotspots for gas emissions. UAV-based monitoring offers a multi-dimensional approach to landfill assessment with the early detection of environmental concerns. Future work should focus on mapping other landfill plant species, refining temperature corrections, and integrating additional ground-truthing for emissivity adjustments for precise thermal measurements.

1. Introduction

One of the challenges in municipal solid waste (MSW) landfill monitoring is the understanding dynamics of the landfill surface, its associated vegetation, and the temperature variations that occur across different parts of the landfill. This requires efficient, high-resolution tools. Traditional ground-based monitoring methods are often time-consuming, labor-intensive, and spatially limited, making UAV remote sensing technologies an efficient alternative for landfill assessment.

Herbaceous vegetation plays a key role in stabilizing landfill surfaces and preventing erosion. Additionally, landfills can act as spreaders for invasive species (Vaverková 2023), particularly herbaceous ones, as the disturbed and nutrient-rich environment often provides ideal conditions for their growth. Vegetation also helps detect potential landfill issues, such as methane leaks (Bean et al. 2018) or unstable decomposition areas. While herbaceous vegetation can grow more in response to moderate landfill heat, excessive heat and gas emissions can stress or inhibit plant growth. By creating vegetation maps or performing image segmentation (Wyard et al. 2022, Pei et al. 2025), UAVs can help monitor changes in vegetation coverage over time, and observe how specific vegetation types expand or diminish in response to landfill conditions. Bruch et al. (2024) focused on using UAVs to map vegetation density on urban MSW landfill sites. A review by Sliusar et al. (2022) discussed how UAVs are revolutionizing waste management, including monitoring landfill vegetation health and distribution.

Similarly, the thermal anomalies across the landfill surface can provide information about subsurface processes such as gas emissions, microbial activity, and decomposition, which can have direct impacts on the environment. UAV thermal infrared (TIR) data can be useful for identifying such hotspots. The surface temperature calculated from TIR data relies on the assumption of the emissivity value of the surface (Zin et al. 2020, Wu et al. 2022). If this is not corrected, the derived temperatures may not be accurate in an absolute sense, but relative differences can still be identified (Kelly et al. 2019). Tanda et al. (2020) explored the use of UAV-mounted thermal cameras to identify subsurface fires and monitor their migration within landfills, highlighting the effectiveness of thermal infrared imagery in detecting landfill gas leakages. Sedano-Cobrián et al. (2023) discussed the integration of UAV thermal imagery with photogrammetry to create 3D thermal models, facilitating the identification of thermal anomalies and providing spatial context for detecting landfill gas emissions.

In this study, we employ two distinct UAV-based remote sensing techniques to monitor and assess landfill conditions. The first task involves using UAV RGB imagery to map the distribution of the partly invasive herbaceous vegetation cotton thistle (*Onopordum acanthium* L.) on the landfill surface. The second task utilizes UAV TIR imagery to capture apparent temperature differences across various zones of the landfill at different times of the year.

2. Data and Methods

2.1 Study sites

The MSW sanitary landfill in the town of Strážnice and the MSW landfill in the town of Klobouky u Brna are located in the Moravian region of the Czech Republic (Figure 1). The Strážnice landfill has been in operation since 1993 and is currently expanding. It also includes a closed reclaimed section. The total site area is a 2 ha. The Klobouky u Brna landfill has been in operation since 1994 and is also undergoing expansion. It includes a reclaimed section that has been under monitoring for 15 years. The total site area is a 8 ha with complex terrain.

Figure 1. Location of MSW landfills Klobouky u Brna (1) and Strážnice (2).

2.2 UAV data

UAV TIR imagery was acquired using a DJI Matrice 600 Pro hexacopter equipped with a WIRIS Pro camera, which includes a TIR sensor operating in the 7.5–13.5 µm spectral range. The imagery was collected over the Klobouky u Brna landfill at a thermal resolution of 640 × 512 pixels and with a field of view ranging from 6.9° to 58.2°. For TIR data acquisition, flights were conducted at an altitude of 100 meters above ground level to achieve a ground sampling distance of 9 cm. Image overlap was set to 80% in the flight direction and 60% in the lateral direction. Due to the high overlap, approximately 1,200 images were acquired in total. Simultaneously, RGB imagery was captured using a DJI Phantom 4 Pro, which offers a resolution of 5472 × 3648 pixels and a field of view of 84°. The RGB images were used to support both the interpretation and georeferencing of the thermal data through the application of ground control points (GCPs) in Agisoft Metashape. These datasets were used to analyze apparent surface temperature differences across various zones of the landfill. RGB dataset acquired at the Strážnice landfill was specifically used to map the distribution of cotton thistle. UAV data acquisition parameters are provided in Table 1.

Type of UAV data	Date	Time CET	Spatial resolution [cm]	Landfill site
RGB	15. 6. 2023	12:00	1.6	Strážnice
	15. 5. 2024	11:00	0.8	Strážnice
	31. 5. 2023	4:00	1.6	Klob. u Brna
	21. 3. 2024	13:00	1.6	Klob. u Brna
	6. 11. 2024	13:00	1.6	Klob. u Brna
TIR	31. 5. 2023	13:00	9.0	Klob. u Brna
	21. 3. 2024	13:00	9.0	Klob. u Brna
	6. 11. 2024	13:00	9.0	Klob. u Brna

Table 1. UAV data acquisition parameters.

A standard data processing workflow in Agisoft Metashape (version 2.0.1) was applied. Ground control points were collected to ensure accurate georeferencing and were surveyed using the CZEPOS GNSS RTK system. These GCPs were incorporated during the image alignment phase. Camera calibration was carried out automatically through self-calibration as part of the bundle adjustment process. Image alignment followed standard settings, with optimization of both internal and external camera parameters. The subsequent generation of a dense point cloud, followed by the creation of a 3D mesh and orthophoto, was performed in accordance with the software manufacturer's recommended procedure.

An orthomosaic was then generated from the individual thermal images. Thermal contrast in the UAV TIR imagery was enhanced by referencing low-temperature mirror targets using Thermolab v.2.4 software. The resulting orthomosaics were exported in GeoTIFF format (Figure 2).

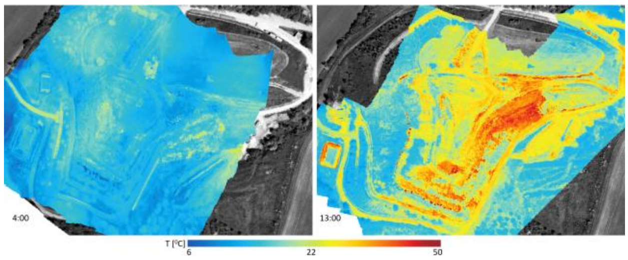

Figure 2. Example of an orthomosaic of UAV TIR data acquired at the MSW landfill in Klobouky u Brna on May 31, 2023, at 04:00 CET (left) and 13:00 CET (right).

2.3 Field and weather data

GPS measurements of selected point positions (XY) and their elevation (Z) were conducted using geodetic equipment (Topcon HiPer HR) at Klobouky u Brna and Strážnice landfills. The selected points were those that could be clearly identified on UAV data and remained unchanged in all coordinates (X, Y, Z) during repeated data acquisition. The points were used as ground control points (GCPs) to improve the georeferencing accuracy of the orthophoto and achieve precise alignment between different UAV datasets. Mirror-surfaced targets were distributed on landfill site Klobouky u Brna during UAV TIR data acquisitions to enhance thermal contrast and improve image processing. The coordinates of these targets were measured as well (Figure 3).

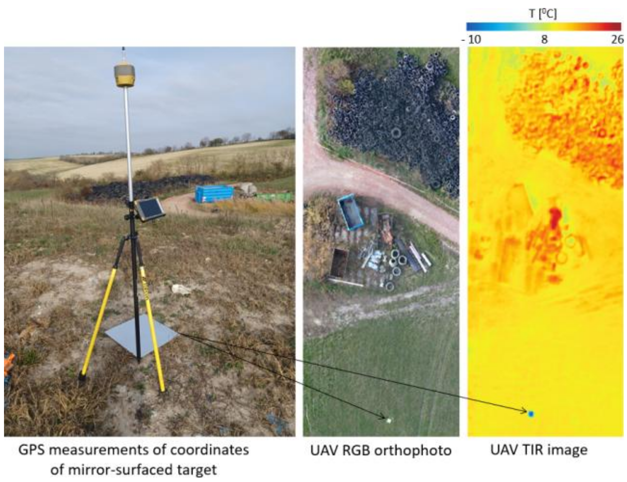

Figure 3. Example of a mirror-surfaced target located on the MSW landfill Klobouky u Brna from the campaign on March 21, 2024 (13:00 CET). From left to right: field photograph, UAV RGB orthophoto, and UAV thermal image.

Weather data were recorded to support the interpretation of UAV TIR data. On May 31, 2023, air temperature ranged from 10°C (4:00 CET) to 22°C (13:00 CET), with wind speeds of approximately 3 m/s. On November 6, 2024, at 13:00 CET, the air temperature was 8.5°C, with wind speeds of 2.0 m/s. On March 21, 2024, at 13:00 CET, the air temperature was 15°C, with wind speeds of 1.1 m/s. No precipitation was recorded for at least eight days prior to each UAV data acquisition (https://www.meteocentrum.cz/archiv-pocasi).

2.4 Mapping cotton thistle (*Onopordum acanthium* L.) using UAV RGB data

MSW landfill active areas are covered with a very heterogeneous plant community (Vaverková et al. 2019), more than hundred species of herbs and shrubs, which are so densely interwoven/overlapping both horizontally and vertically that the identification of individual species is only possible for taxa that have a robust, homogeneous leaf surface (large, broad leaves in a horizontal position) and are either solitary or form a homogeneous stand. Among these species, cotton thistle (*Onopordum acanthium* L.) (Figure 4) stands out as a particularly robust plant native to Southern Europe and Southwest Asia. Due to its high competitiveness and phytotoxic effects, it negatively impacts field crops and pastures and is considered invasive in some countries (Watanabe et al. 2014). In landfills, cotton thistle can form extensive, dense stands and effectively colonize newly covered waste sections with potential spreading into surrounding agricultural areas.

Figure 4. Cotton thistle (*Onopordum acanthium* L.) during a botanical survey on the MSW landfill in Strážnice.

The distribution of *Onopordum acanthium* L. was mapped using a classifier that was iteratively trained on the UAV RGB data acquired at the MSW landfill in Strážnice in 2023 and 2024. For training, a map of the occurrence of the target species was first created based on visual interpretation of the image and field survey data. Both the RGB mosaic and the training map were divided into contiguous tiles of 256×256 pixels. For model training, the tiles containing the target species were split into training and validation datasets in a 75:25 ratio. A binary convolutional neural network classifier with a U-Net architecture was used for classification. The U-Net had five convolutional levels and a convolutional window size of 3 pixels with “relu” activation. Each U-Net layer contained “drop-out” step to reduce overfitting. Adam optimizer with combination of Dice_loss and CategorialFocal_loss as loss function was used to train the model. The classifier was implemented using the TensorFlow library (Abadi et al. 2015). The classification map from the first iteration was manually corrected, and the existing model (first iteration) was retrained based on these corrections. The model output is a continuous variable ranging from 0 to 1, representing the confidence level with which the model identifies a given class. The final occurrence map of *Onopordum acanthium* L. was obtained by thresholding values above 0.99. The model's transferability was verified by applying it to RGB data from 2023. For the classification map of 2023, a threshold value of 0.8 was chosen.

2.5 Extraction of apparent temperature in selected landfill zones using UAV TIR data

Apparent temperature values from 14 zones of MSW landfill Klobouky u Brna were extracted from each UAV TIR dataset, including waste mixed with soil (5 zones), waste mixed with soil and vegetation (2 zones), vegetation (3 zones), soil, a dirt road, concrete, and shaded part of tree crowns (Figure 5). All zones were located on the same southeast landfill slope to ensure uniform sun exposure and minimize temperature variations caused by shading and differences in heat absorption due to changing sun angles. The landfill slope, featuring various land covers and experiencing mostly sunny conditions throughout the day, was selected for the analysis of potential hot spots related to waste biodegradation and landfill gas emissions. The area of each zone on UAV TIR image ranged from 2,000 to 3,000 pixels, which were used to calculate statistics and visualize the mean zone apparent temperature and confidence intervals on a graph (Figure 7).

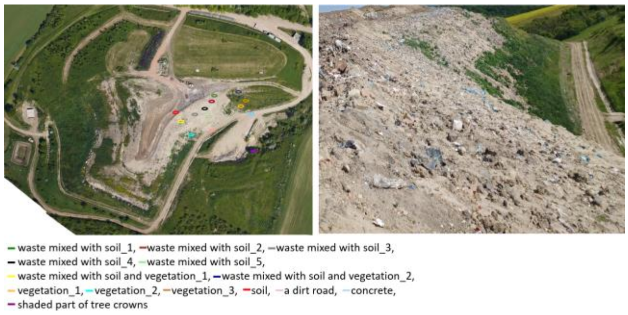

Figure 5. UAV orthophoto of Klobouky u Brna landfill with highlighted zones to analyse apparent temperature from UAV TIR (right). Photograph of the southeast landfill slope where the zones are located (left).

3 Results

3.1 Mapping cotton thistle *Onopordum acanthium* L. using UAV RGB data

In the training phase (50 epochs) the best model reached 0,96 accuracy which resulted in the f1-score of 0.87 when applied to the whole study area. When applied to data from 2023 the f1-score slightly decreased to 0.84. The lower final threshold in case of 2023 classification corresponds with slightly lower overall accuracy which is probably result of applying model to data with lower spatial resolution. Based on the classification results the cotton thistle covered 461 m2 in 2023 and increased its coverage to 494 m2 in 2024. The area of 209 m2 was covered during both years (Figure 6). Relatively the area covered by cotton thistle represented around 2.4% of the MSW landfill.

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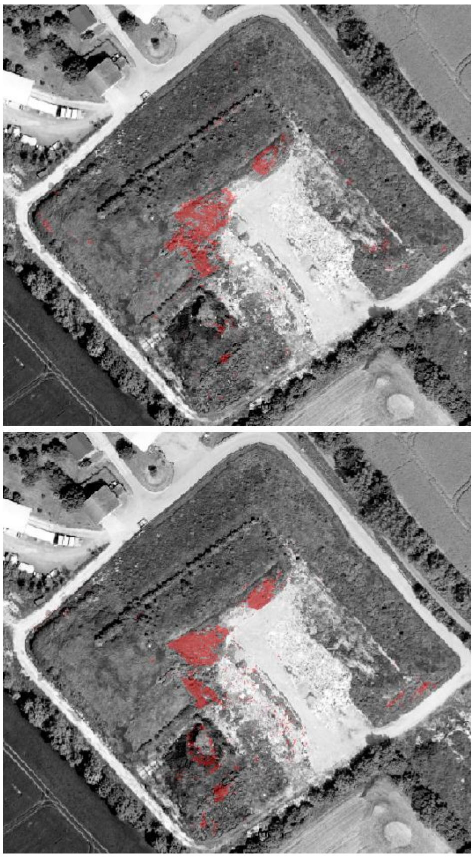

Figure 6. Dynamic of cotton thistle (*Onopordum acanthium* L.) distribution (red color) from processing of UAV RGB data on MSW landfill Strážnice in 2023 (top image) and 2024 (bottom image).

3.2 Analysis of apparent temperature in selected landfill zones using UAV TIR data

Given that all zones are on the same slope with the same sun exposure, the main factors influencing their temperature differences can be attributed to surface characteristics (Figure 7).

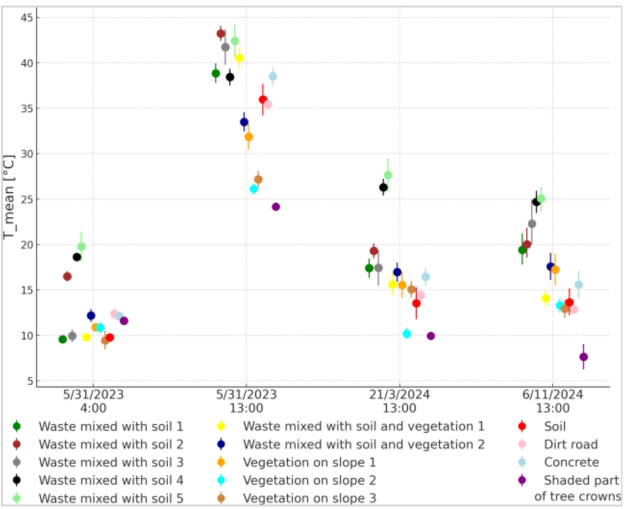

Figure 7. Apparent temperature of landfill zones in four terms of UAV thermal infrared data acquisition.

Vegetation and shaded tree crowns were the coolest due to the transpiration effect, where actively transpiring plants lose water and reduce surface temperature. Additionally, shaded tree crowns received minimal direct solar radiation, keeping their temperature close to air temperature. Concrete, soil, and dirt roads showed temperatures 1.5 times higher than shaded tree crowns at 13:00 on May 31, 2023, March 21, 2024, and June 11, 2024. However, at 4:00 on May 31, 2023, the temperatures of concrete, soil, and dirt roads were similar to those of shaded tree crowns. “Waste mixed with soil” zones showed variable temperature patterns across all four time points. However, “waste mixed with soil 4” and “waste mixed with soil 5” were the warmest at 4:00 on May 31, 2023, and at 13:00 on March 21, 2024, and June 11, 2024. On May 31, 2023, all “waste mixed with soil” zones had higher temperatures compared to other zones. The temperature of the "waste mixed with soil and vegetation" zones was approximately 1.2 times higher than that of the vegetation zones and 1.3 times lower than that of the "waste mixed with soil" zones for daytime points.

4 Discussion

The model validation results for mapping *Onopordum acanthium* L. align with recent studies using similar methodologies. For instance, Badrouss et al. (2025) employed ultra-high-resolution UAV imagery combined with an enhanced U-Net architecture to map individual plant species, achieving a mean pixel accuracy (MPA) of 91.75%. However, the variability in plant size, shape, and distribution presents significant challenges for precise mapping, even with advanced deep learning methods, and additional efforts are needed (Zhang et al., 2020; Wyard et al., 2022). As a next step, practical task based on the created maps of *Onopordum acanthium* L. could involve determining the directional vectors of the spread of the observed species both within the area of the landfill and surrounding agricultural landscape since individual plants or small patches of cotton thistle can be observed near the surrounding roads and within neighbouring agricultural fields (Figure 8). The spatial/temporal transferability of the classification model should be further analysed to provide more universal tool with attention paid to the “transfer learning” approaches which can improve model results whereby the amount of data required is significantly lower compared to training new model (Zhu et al., 2021).

Figure 8. Expansion of cotton thistle (*Onopordum acanthium* L.) into surrounding field near the MSW landfill Strážnice.

The repeated UAV TIR data acquisition on the landfill led to observations that can be used to detect zones with potential LGF emissions by interpreting the apparent temperature of landfill area based on the period and time of UAV data acquisition. The temperature of "shaded deciduous tree crowns" can be considered close to air temperature, but not necessarily identical (Leuzinger et al. 2010, Shrmin et al. 2023, Li et al. 2024). At midday during warm months, shaded deciduous crowns may be cooler than the air temperature due to transpiration. In cooler seasons or at night, crown temperatures more closely approximate air temperature. In autumn, when transpiration is minimal, tree crowns may be slightly warmer than the air temperature due to minor heat retention. Due to their relative stability and close correlation with air temperature, "shaded deciduous tree crowns" temperature can be used as a proxy for air temperature when comparing the temperatures of other zones on the landfill.

Concrete, soil, and dirt roads had 1.5 times higher temperature than "shaded deciduous tree crowns" due to their high solar absorption, as these materials efficiently retain and re-radiate heat when exposed to direct sunlight. Their thermal inertia also contributes to slower cooling at night and faster warming in the morning. Due to the lack of precipitation for more than a week, we can suggest that dry soil conditions caused it to heat up rapidly during daytime points.

"Waste mixed with soil" zones displayed variable temperature patterns due to their heterogeneous composition; differences in percentage of organic and inorganic content, moisture retention, and reflectivity likely contributed to temperature variations. Two zones that consistently remained the warmest over time ("waste mixed with soil 4" and "waste mixed with soil 5") may indicate increased microbial breakdown of organic content, generating heat and potentially acting as hotspots for methane emissions. Fjelsted et al. (2019) showed that the UAV TIR method had some potential to indicate LFG emissions, albeit in the right conditions, at two Danish landfills. Tanda et al. (2020) presented an innovative method based on UAV TIR to identify significant biogas leakages from an urban landfill that could provide a preliminary evaluation of the methane production potential.

The temperature of the "waste mixed with soil and vegetation" zones was approximately 1.2 times higher than that of the vegetation zones and 1.3 times lower than that of the "waste mixed with soil" zones for daytime points, indicating the influence of vegetation in moderating the temperature in these zones. This finding aligns with recent studies. For instance, Ni et al. (2019) found that soil temperatures in vegetated areas were lower than in bare soils, with reduced temperature fluctuations.

UAV TIR can help identify areas of concern on MSW landfills, but for precise surface temperature values, further data processing with additional ground-truthing would be required to correct the apparent temperature for emissivity effects.

Conclusion

By applying UAV RGB and TIR imagery to monitor two separate landfills, this study highlights the effectiveness of UAV technology in advanced landfill monitoring. UAVs facilitate the collection of detailed spatial information necessary for the precise identification of individual plants in complex ecosystems like landfills, enhancing traditional field botanical surveys in waste environments. UAVs can also capture thermal anomalies over time, helping to identify areas of concern. However, for precise surface temperature values, further data processing with additional ground-truthing would be required to correct the apparent temperature for emissivity effects. The integration of these tasks offers a multi-dimensional approach to landfill management, enabling early detection of potential issues and supporting better environmental decision-making and landfill practices.

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