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Evaluating ecological impacts of landfill gas dispersion on Hyrcanian forest habitat quality (Saravan landfill, Rasht, Iran)

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ABSTRACT
Landfill sites are significant sources of greenhouse gases (GHG) that may affect surrounding ecosystems, particularly when located close to sensitive forest environments. This study evaluates the ecological impacts of landfill gas dispersion on habitat quality in the Hyrcanian forests of Northern Iran, focusing on the Saravan landfill. A combined Source-Transport-Impact framework was applied by integrating field-based emission monitoring, atmospheric dispersion modeling (AERMOD), and habitat quality assessment (InVEST). Field survey were conducted at 25 gas venting points and 12 surface locations using the static flux chamber method. Gas samples were analyzed using gas chromatography (Agilent 7890A) with flame ionization and thermal conductivity detectors to determine the methane (CH_4) and carbon dioxide (CO_2) concentrations. The measured data provided input parameters for the AERMOD dispersion model. Spatial concentration patterns were incorporated as environmental pressure layers in the InVEST Habitat Quality model. Results indicated substantial variability in gas concentrations, with methane ranging from several thousand to several hundred thousand ppm. Dispersion modeling revealed spatial gradients of gas exposure extending into adjacent forest areas. Integration of dispersion outputs into the habitat quality model indicated that areas closer to the landfill and along prevailing wind directions experienced higher levels of habitat degradation. The combined modeling approach highlights the spatial relationship between landfill gas emissions and habitat quality patterns in the Hyrcanian forest landscape. The proposed framework demonstrates how integrating emission measurements, dispersion modeling, and ecological assessment can support environmental impact evaluation and inform management strategies for landfills beside ecologically sensitive forests.

Keywords: Landfill gas emissions, Methane and carbon dioxide, Habitat quality assessment, AERMOD dispersion modeling, InVEST model, Hyrcanian forests.

INTRODUCTION

Municipal solid waste landfills are recognized as significant sources of greenhouse gases, particularly methane and carbon dioxide, which are produced through the anaerobic decomposition of organic waste. These gases contribute substantially to climate change and may also affect local environmental conditions around landfill sites. Methane is especially important, since its global warming potential is considerably higher than that of carbon dioxide, making landfill emissions an important environmental concern (Bogner *et al.* 2022). In addition to their atmospheric impacts, landfill gases may influence surrounding ecosystems when dispersion occurs beyond the

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landfill boundary, particularly in environmentally sensitive areas such as forest ecosystems. To assess the environmental consequences of pollutant emissions, atmospheric dispersion models have been widely used. Among these models, AERMOD is a steady-state Gaussian plume dispersion model designed for near-field applications, typically within distances of less than 50 km from emission sources. It has been extensively applied to simulate the dispersion of pollutants from industrial facilities and estimate ground-level pollutant concentrations in surrounding areas. For instance, Saghafi & Hajiabdollahi Mamaghani (2024) applied AERMOD to model pollutant dispersion from the Tabriz thermal power plant (Northwest Iran) and demonstrated that maximum concentrations of pollutants could occur in nearby residential areas under certain meteorological conditions. Such studies highlight the capability of AERMOD to identify areas potentially exposed to higher environmental risk and to support environmental impact assessments. In addition to atmospheric dispersion modeling, spatial tools for evaluating ecosystem conditions have become increasingly important in environmental studies. The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model is widely used for mapping ecosystem services and assessing habitat quality under different environmental pressures. The Habitat Quality module of InVEST produces spatially explicit outputs that represent habitat quality on a scale from 0 to 1, allowing researchers to distinguish between degraded and high-quality habitats (Sharp *et al.* 2020). Previous studies have demonstrated that the model can effectively identify habitat sensitivity to various threats and help determine which anthropogenic pressures have the greatest impacts on biodiversity. The InVEST model has been widely applied in habitat quality assessment (Zhang *et al.* 2022). As a result, the InVEST model has become an important decision-support tool in ecosystem management and conservation planning. Recent studies have also focused specifically on greenhouse gas emissions from landfill sites (Njoku *et al.* 2025; Gavrila *et al.* 2025). Research on municipal solid waste landfills has shown that methane, carbon dioxide, and nitrous oxide are among the main greenhouse gases produced during waste decomposition (Wei *et al.* 2024). These gases originate from microbial processes occurring under anaerobic conditions within landfill bodies (Njoku *et al.* 2025). Field measurements in landfill environments have similarly shown that methane and carbon dioxide concentrations are typically highest near gas venting points and decrease with increasing distance from the landfill, confirming landfills as significant emission sources influencing surrounding environments (Naveen *et al.* 2023). Despite the growing body of research on landfill gas emissions and habitat quality assessment, relatively few studies have attempted to integrate atmospheric dispersion modelling with habitat quality evaluation to assess the ecological impacts of landfill emissions on forest ecosystems. This gap is particularly evident in the Hyrcanian forests of Northern Iran, which represent one of the most valuable and sensitive forest ecosystems in the region. Therefore, the present study aims to investigate the spatial effects of greenhouse gas dispersion from the Saravan landfill on the surrounding forest ecosystem by integrating field measurements, AERMOD atmospheric dispersion modelling, and the InVEST Habitat Quality model.

MATERIALS AND METHODS

Study Area

This study was conducted at the Saravan landfill and its surrounding landscape in Guilan Province, Northern Iran (Fig. 1). The landfill is situated within the Hyrcanian forest belt, characterized by a humid subtropical climate, complex topography, and dense forest cover. The climate is influenced by the Caspian Sea, with high annual precipitation (approximately 1,300 mm) and average temperatures ranging from 10 °C in winter to 28 °C in summer (Ahmadi Orkomi & Ameri 2024). The surrounding landscape comprises a mosaic of forest patches, agricultural lands, orchards, and residential areas. The landfill has been operational since 1984, spans approximately 21 hectares, and receives approximately 800 to 1,000 tons of municipal solid waste daily from Rasht and surrounding cities (Ahmadi Orkomi & Malekpour 2021). For this analysis, a 50-km buffer zone around the landfill was defined for the AERMOD dispersion modeling, while a 10-km buffer zone was used for the InVEST habitat quality assessment to capture the potential influence of landfill gas dispersion on the adjacent habitats.

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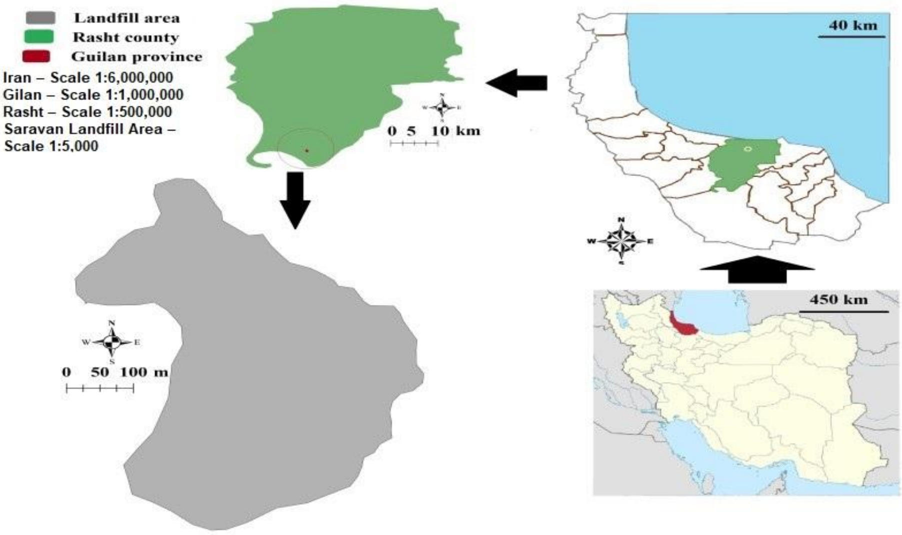

Fig. 1. Location of the Saravan landfill and the Hyrcanian forest landscape in Guilan Province, Northern Iran

Landfill gas emission measurement and flux calculation

Direct field measurements were conducted to quantify CH_4 and CO_2 emissions from the Saravan landfill. A total of 25 active gas venting points were detected, of which one was closed. Additionally, the landfill surface was divided into 12 individual subsections according to age, surface cover, and accessibility. All 12 surface locations were surveyed using the static flux chamber method. Gas temperature, CH_4 concentration, CO_2 concentration, and gas velocity were recorded at each point using a KIMO FG110 device, TESTO 535, and a hot-wire anemometer (TENMARS TM 4001).

Chamber specifications and sampling protocol

The flux chamber was constructed by the Air Research Centre of the Environmental Research Institute at Tehran University of Medical Sciences. The chamber had an internal radius of 0.145 m and a height of 0.3 m, resulting in a volume of 0.0198 m^3 and a surface area of 0.066 m^2.

At each surface sampling point, the chamber was placed on a base inserted 1 cm into the soil, and the seal was ensured with water in the base groove to prevent ambient air infiltration. Gas samples were collected over a 5-minute period using Tedlar bags and glass vials. The gas flux (F) for each chamber was calculated from the change in gas concentration over time using the Eq. (1).

$$F = \text{Slope} \times \frac{V}{A} \times \frac{T0}{T} \times \frac{MW}{22.4} \times \frac{1}{1000} \times 60 \times 24 \quad (1)$$

where:

F = gas flux (g m^{-2} day^{-1})
Slope = rate of concentration changes over time (ppm/min), derived from linear regression of concentration vs. time ($R^2 > 0.99$)
V = chamber volume (0.0198 m^3)
A = chamber surface area (0.066 m^2)
T_o = standard temperature (273.15 K)
T = chamber temperature (K)
MW = molecular weight of the gas (16.04 g mol^{-1} for CH_4, 44.01 g mol^{-1} for CO_2)
22.4 = molar volume at standard conditions (L mol^{-1})

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Vents sampling protocol
For each vent the gas velocity, gases concentrations and temperatures were measured or sampled via the sample point on the pipe. Then the emission rate was calculated using the whole gas flow rate and each species concentration. For the 25 vent points, gas samples were first collected in Tedlar bags directly from each vent outlet. Immediately after collection, the samples were transferred from the Tedlar bags into glass vials using gas tight syringes under isolated conditions to prevent contamination and gas exchange with ambient air. The glass vials were then placed in an ice bath (maintained at approximately 4 °C) to minimize gas adsorption and preserve sample integrity during transport to the laboratory. All samples were stored in glass vials and analyzed within 24 hours of collection. Glass vials were used instead of polypropylene syringes to minimize gas adsorption and preserve sample integrity, as recommended by standard protocols (Rigon *et al.* 2017).

Gas chromatography analysis
Gas samples were analyzed using a gas chromatograph (Agilent 7890A) equipped with a flame ionization detector (FID) for CH_4 analysis and a thermal conductivity detector (TCD) for CO_2 analysis. The GC was calibrated before each analysis using certified standard gases (CH_4: 100 ppm, 1000 ppm, 5000 ppm; CO_2: 500 ppm, 2000 ppm, 5000 ppm). The detection limits were 0.5 ppm for CH_4 and 1.0 ppm for CO_2. Quality-control procedures included analysis of blank samples and replicate injections (three injections per sample) to ensure precision and accuracy.

Parameterization of sources in AERMOD
All 25 active vent points were parameterized as point sources in AERMOD. In addition, the 12 surface flux chamber locations were included as area sources in AERMOD, based on their measured flux values and the surface area of each of 12 subsections.

Atmospheric Dispersion Modeling (AERMOD)
The AERMOD model (Version 3.0) was employed to simulate the atmospheric dispersion of CH_4 and CO_2 from the landfill. AERMOD is a steady-state Gaussian plume model that requires meteorological data, emission rates, and terrain information (Wei *et al.* 2024; Njoku *et al.* 2025). Since reliable meteorological data were not available at the exact landfill location, the required parameters (including wind speed and direction, air temperature, relative humidity, cloud cover, and station pressure) were obtained from the nearest synoptic meteorological station. The Agricultural Meteorological Station (ID: 99272), at 49°38'39.56"E, 37°12'06.79"N, is 14.4 km from the landfill. The most recent 5-year data (2019–2023) from this station were collected and used as the meteorological inputs for this study. The wind rose analysis revealed that the dominant wind direction in the study area was from the northeast to the southwest (Fig. 2).

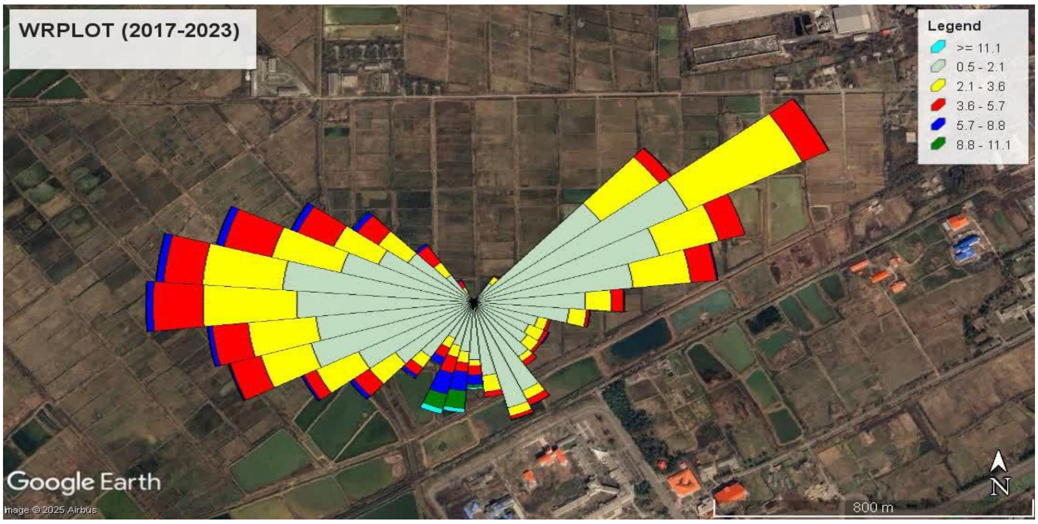

Fig. 2. Annual wind rose plot for the study area based on 5-year meteorological data.

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Emission rates for each gas were derived from the field measurements as described in the Landfill Gas Emission Measurement section. The physical parameters of the 25 active venting points (height, diameter, exit velocity, and temperature) were incorporated as point sources. The model was run on a grid with a 200 × 200 m^2 resolution and the output was produced as seasonal and annual average concentration surfaces for both CH_4 and CO_2 across the 50-km study domain.

Land Use/Land Cover (LULC) data preparation

A LULC map for the year 2023 was generated for the study area using Sentinel-2 satellite imagery with a spatial resolution of 10 m. Supervised classification was performed in GIS software to identify the following land cover classes: Dense Forest, Sparse/Modified Forest, Agricultural Land, Orchards, Residential/Urban Area, Landfill, and Masil (watercourse). The resulting LULC map was resampled to a 30-m resolution to match the other spatial input layers (Fig. 3). This LULC map provided the spatial framework for the InVEST model, defining both the habitat types present in the landscape and their relative suitability scores.

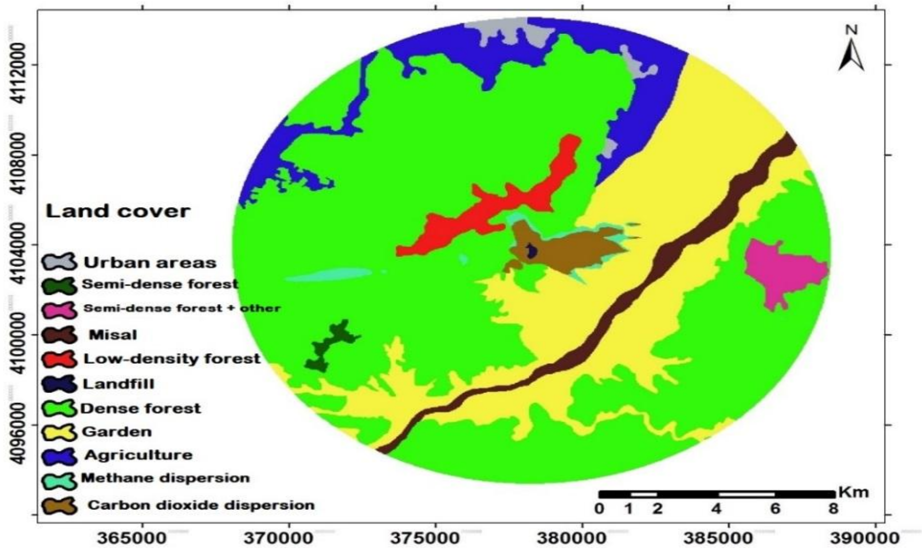

Fig. 3. Land cover map (LULC) of the study area showing the spatial distribution of major land cover classes.

An accuracy assessment of the LULC classification was performed to ensure the reliability of the map as an input to the InVEST model. The supervised classification, using the Random Forest algorithm, achieved an overall accuracy of 87.6% with a Kappa coefficient of 0.84, indicating substantial agreement with reference data. Detailed accuracy metrics are provided in Table S1(Supplementary Material).

Habitat quality assessment using InVEST

To assess the ecological consequences of landfill gas dispersion, the Habitat Quality module of the InVEST model was applied. InVEST estimates habitat quality by integrating land use and land cover data with spatially explicit threat layers and sensitivity parameters. In this study, the threat layers included landfill boundaries, the modelled CH_4 and CO_2 dispersion surfaces derived from AERMOD, residential areas, agricultural lands, and orchards. Each threat was assigned a maximum distance of influence, a relative weight, and a decay function to represent how its impact diminishes over space. The parameter values were established through a combination of expert judgment and previous studies (Asadolahi *et al.* 2018; Nematollahi *et al.* 2020; Abdollahi *et al.* 2024).

To convert the AERMOD outputs into threat layers suitable for the InVEST model, first the AERMOD outputs (annual and seasonal average concentrations in ppm) were extracted for the 10-km study domain, and then the concentration values were linearly normalized to a 0–1 scale using Eq. (2).

$$\text{Normalized Value} = (C - C_{min}) / (C_{max} - C_{min}) \quad (2)$$

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where C, C_{min}, C_{max} are the concentration in each pixel, the minimum and maximum background concentrations within the domain, respectively.

Pixels with values below the detection limit were assigned a value of 0; and the normalized layers were then used as spatially explicit threat layers in the InVEST model. A distinction should be made between the 6 threat layers and the 11 LULC classes used in the InVEST model. The threat layers (landfill boundary, CH_4 plume, CO_2 plume, urban areas, agriculture, and orchards) represent the environmental stressors that exert pressure on habitats. The LULC classes, by contrast, represent the habitat types that receive these pressures. Each LULC class is assigned a sensitivity score for each threat (Table 1), indicating how strongly that habitat type is affected by a given stressor. It is important to clarify the ecological rationale for including CH_4 and CO_2 dispersion surfaces as threat layers. While these gases are not typically classified as direct habitat threats in the same way as land conversion or infrastructure development, they serve as proxy indicators of landfill influence across the surrounding landscape. Elevated concentrations of CH_4 and CO_2 in soil and ambient air can affect soil redox conditions, root-zone oxygen availability, and plant physiological processes (Asadolahi *et al.* 2018; Nematollahi *et al.* 2020). Therefore, the spatial distribution of these gases provides a useful and spatially explicit indicator of zones where forest habitats may be under increased anthropogenic pressure, not as a proven cause of habitat loss, but as a proxy for potential stress. We emphasize that the outputs of the InVEST model in this study represent potential habitat degradation based on modelled pressure layers, and should not be interpreted as direct measurements of ecological impact.

Table 1. Habitat suitability and sensitivity scores for each land cover class.

LULC Class	Suitability	Sensitivity					
		Urban	Agriculture	Orchards	Landfill	CO_2	CH_4
Urban	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dense Forest	1.00	0.82	0.71	0.65	1.00	0.92	0.93
Agriculture	0.20	0.65	0.20	0.41	0.57	0.56	0.57
Sparse/Modified Forest	0.92	0.73	0.63	0.59	0.90	0.87	0.89
Mixed Modified Forest	0.94	0.74	0.58	0.51	0.92	0.89	0.91
Moderate Forest	0.97	0.75	0.56	0.56	0.95	0.90	0.92
Orchards	0.38	0.64	0.32	0.30	0.58	0.60	0.61
Masil (watercourse)	0.36	0.57	0.34	0.30	0.64	0.62	0.63
Landfill	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Habitat suitability scores (H_j) range from 0 (unsuitable) to 1 (most suitable). Sensitivity scores range from 0 (not sensitive) to 1 (most sensitive) for each threat type. The InVEST model produced two main outputs: habitat quality and habitat degradation. Habitat quality values ranged from 0 to 1, with higher values indicating better habitat conditions and lower levels of anthropogenic stress. Habitat degradation quantified the cumulative pressure imposed by all threat layers across the landscape. These outputs were used to identify areas of ecological concern and to evaluate the spatial relationship between landfill gas dispersion and forest habitat condition.

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Uncertainty analysis

Uncertainty in the present study arises from three main sources. First, emission estimation is influenced by the spatial heterogeneity of landfill gas generation and surface flux variability. Second, AERMOD outputs depend on the quality of meteorological inputs, emission assumptions, and the simplified representation of atmospheric transport. Third, InVEST results are affected by the accuracy of land cover mapping and by the selection of threat weights, decay functions, and sensitivity parameters. Therefore, the reported outputs should be interpreted as a spatially explicit assessment of potential ecological pressure rather than as an exact measurement of habitat loss. The selection and parameterization of threat layers were guided by previous studies on habitat quality assessment and ecosystem threats (Asadolahi *et al.* 2018; Nematollahi *et al.* 2020; Abdollahi *et al.* 2024; Shamsipour *et al.* 2024).

RESULTS

Gas measurement results

Field measurements showed substantial variability in landfill gas concentrations across sampling points. CH_4 concentrations ranged from 6,685 ppm at Vent 6 to 609,348 ppm at Vent 19 in the Tedlar bag sample. The mean and the median CH_4 concentrations were 158,225 ppm and 148,844 ppm respectively. The relationship between CH_4 and CO_2 fluxes measured at 12 flux chamber points was positive and statistically significant, with a Pearson correlation coefficient of $r = 0.64$ and $p = 0.034$. A summary of the estimated annual emissions (Mg/year) from the surface flux chamber measurements and vent point measurements is presented in Table 2. The detailed characteristics and individual emission rates for all 25 vent points are provided in Table S2. The measured CH_4 and CO_2 concentrations, and calculated fluxes for all 12 chambers for CH_4 and CO_2 concentrations are presented in Table S3.CH_4 and CO_2 emission values from each of the 12 zones were calculated and are reported in Mg/year (mega grams per year) in Figs. S1 and S2 (Supplementary Material).

Table 2. Summary of estimated annual emission rates (Mg/year) from surface flux chambers and vent points at the Saravan landfill.

Parameter	Surface (Mg/year)		Vent (Mg/year)	
	CH_4	**CO_2**	**CH_4**	**CO_2**
Max	1783	2958	428	1554
Min	0	0	5	392
Mean	484	653	126	799
Median	276	243	105	757

Wind Rose Analysis

The wind rose analysis revealed that the dominant wind direction in the study area was from the northeast to the southwest (Fig. 2). Key wind characteristics included: mean wind speed of 1.19 m s^{-1}, calm conditions (wind speed < 0.5 m s^{-1}) accounting for 53.74% of total hours, and the most frequent wind speed range of 0.5 to 2.1 m s^{-1}.

Spatial dispersion of landfill gases

Annual dispersion

The spatial distribution of methane and carbon dioxide dispersion zones around the landfill was determined by applying point and area sources in the AERMOD model. The resulting dispersion patterns are presented in Figs. 4a and 4b. AERMOD simulations indicated that both methane and carbon dioxide plumes were transported predominantly toward the southwest of the landfill (Figs. 4a and 4b). This directional pattern was consistent with the dominant wind regime in the study area. Concentrations decreased with increasing distance from the landfill; however, detectable influence persisted over several kilometers. The spatial pattern suggests that the southwest corridor is the most exposed zone in terms of landfill gas dispersion.

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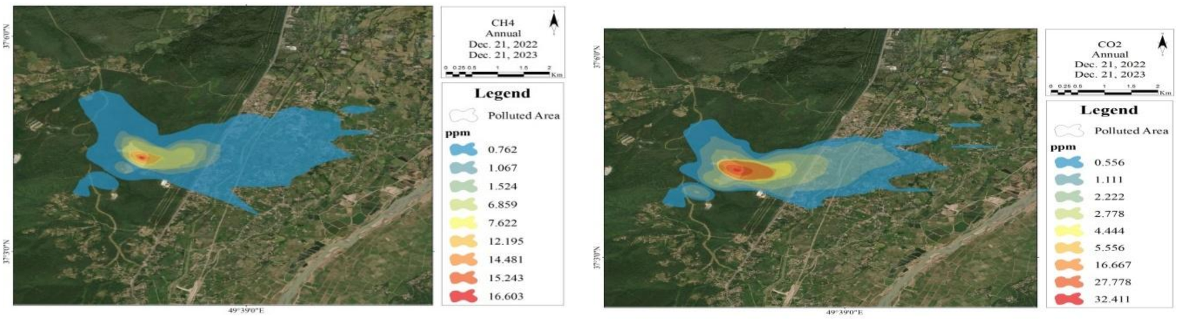

a. Annual average dispersion of CH_4 **b.** Annual average dispersion of CO_2

Fig. 4. Annual average dispersion pattern of a) CH_4 and b) CO_2 concentrations (ppm) simulated using the AERMOD model.

Seasonal dispersion

Seasonal analysis revealed significant variation in concentration patterns for both gases. According to Figs. 5 and 6, the maximum concentrations of CH_4 and CO_2 were observed in spring (19.67 ppm and 39.38 ppm, respectively), followed by autumn (18.32 ppm and 33.08 ppm). The lowest concentrations were recorded in summer (12.55 ppm for CH_4 and 22.31 ppm for CO_2), while winter showed moderate values (15.79 ppm for CH_4 and 29.70 ppm for CO_2).

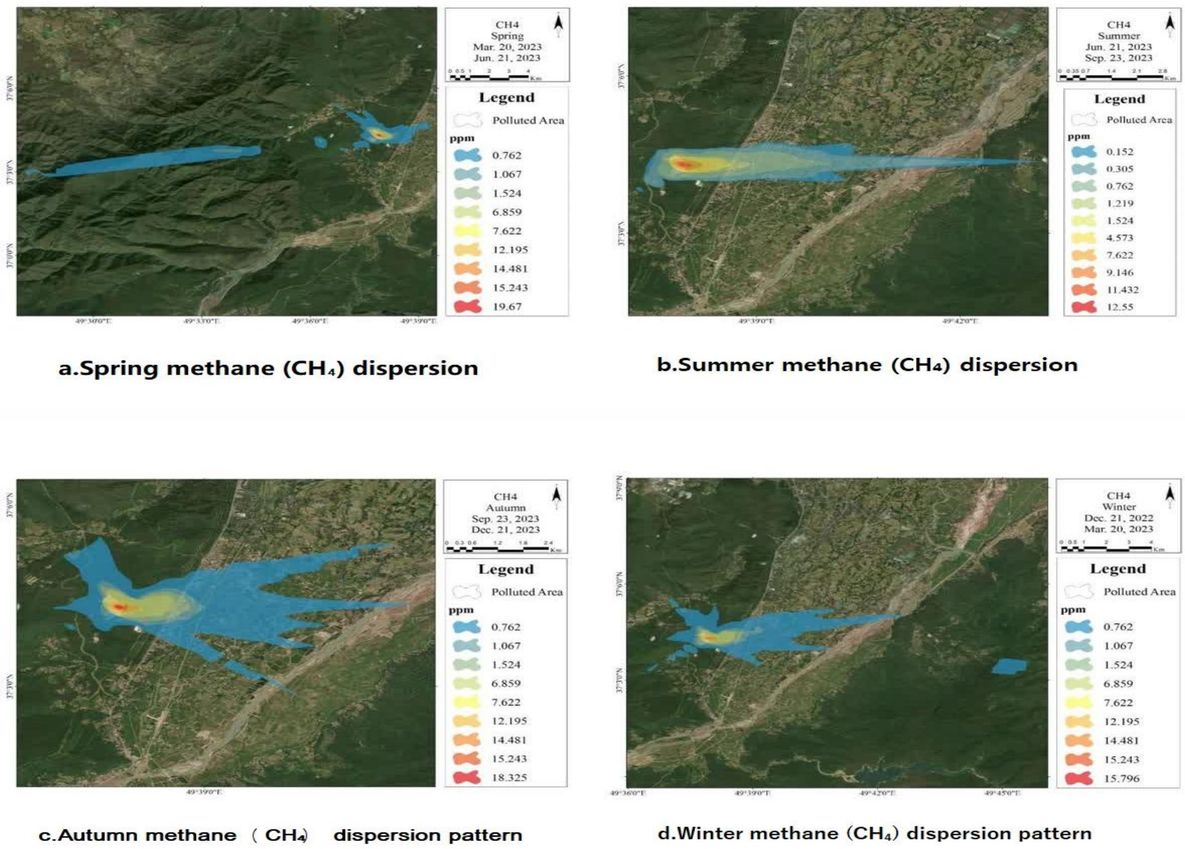

Fig. 5. Seasonal dispersion patterns of methane concentrations (ppm): (a) spring, (b) summer, (c) autumn, and (d) winter.

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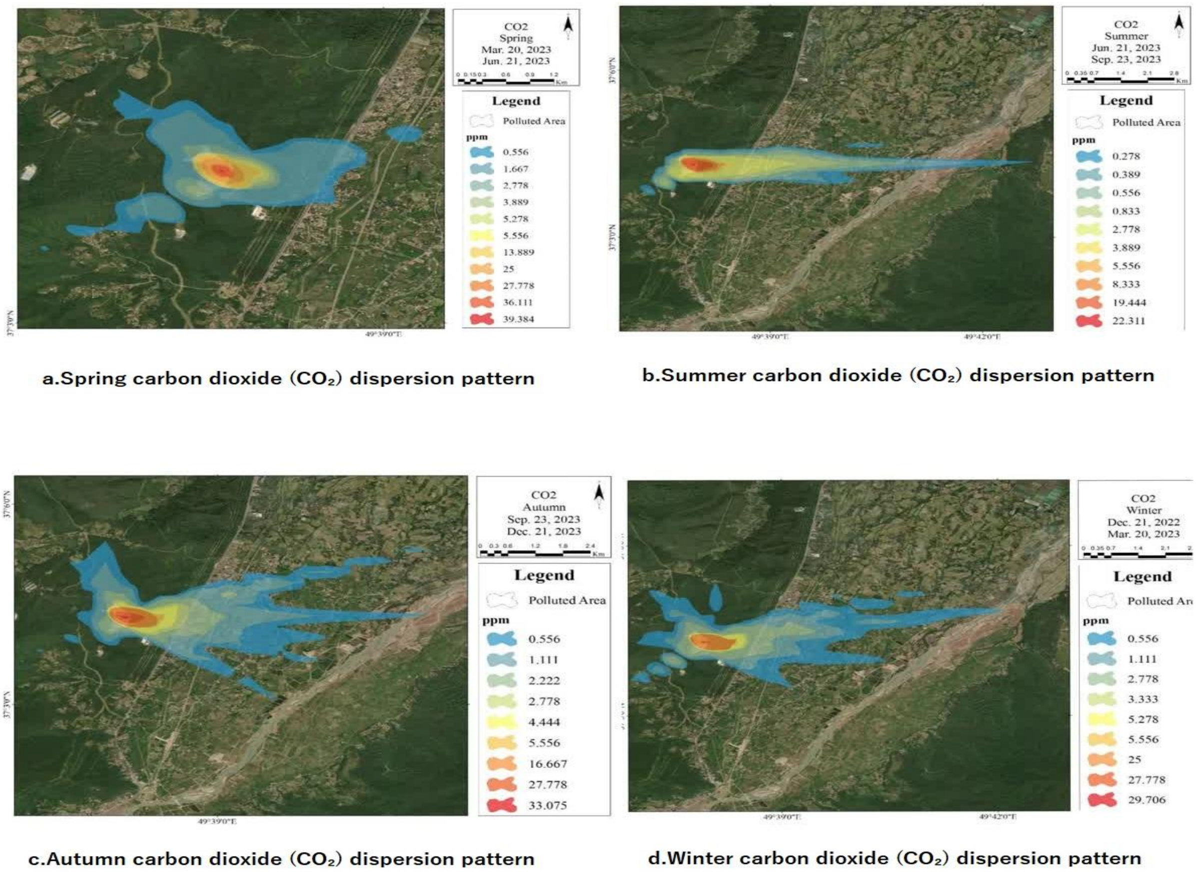

Fig. 6. Seasonal dispersion patterns of CO_2 concentrations (ppm): (a) spring, (b) summer, (c) autumn, and (d) winter.

Habitat quality patterns

The InVEST model incorporated six threat layers: landfill boundary, methane dispersion plume, carbon dioxide dispersion plume, urban areas, agricultural lands, and orchards. The parameter values for each threat, including maximum distance of influence, relative weight, and decay function, are summarized in Table 3.

Table 3. Threats, their maximum distance of influence, weight, and decay type used in the InVEST Habitat Quality model.

Threat	**Maximum distance (km)**	**Weight**	**Decay type**
Landfill	3.0	1.00	Exponential
CH_4 emission	4.5	1.00	Exponential
CO_2 emission	3.5	0.92	Exponential
Urban area	4.0	0.90	Exponential
Agriculture	2.8	0.61	Linear
Orchards	2.5	0.42	Linear

For the gas plumes, the maximum influence distance and weight were calibrated based on the spatial extent of the modeled plumes from AERMOD and the relative importance of each gas as a stressor. Methane was assigned a weight of 1.0 and a maximum distance of 4.5 km, since it is the primary landfill gas with high global warming potential and its dispersion pattern extends further downwind. Carbon dioxide was assigned a weight of 0.92 and

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a maximum distance of 3.5 km, reflecting its slightly lower relative impact per unit concentration. All decay functions were selected based on the spatial behavior of each threat (exponential for point-source or concentrated threats, linear for diffuse threats), consistent with standard InVEST applications (Sharp *et al.* 2020).
The InVEST Habitat Quality model revealed clear spatial variation in ecological condition across the study area. The model incorporated six threat layers: (i) landfill boundary, (ii) methane dispersion plume, (iii) carbon dioxide dispersion plume, (iv) urban areas, (v) agricultural lands, and (vi) orchards (Fig. 7).

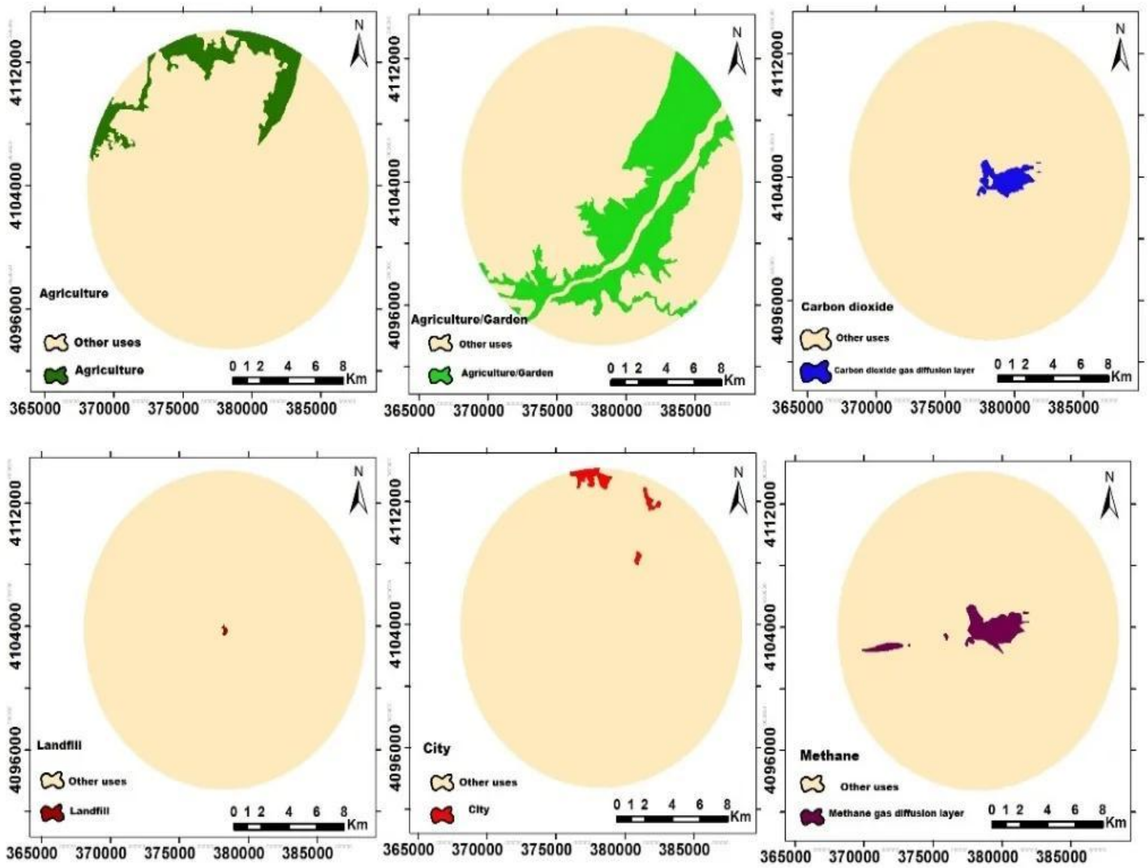

Fig. 7. Spatial distribution of all six threats within the 10 km buffer zone.

Qualitative assessment of habitat quality

Quantitative analysis of the InVEST outputs revealed that within the 10 km study domain, approximately 6,000 hectares (38%) of the Hyrcanian forest fell into the high-quality category ($Q > 0.8$), while approximately 1,800 hectares (12%) were classified as low-quality habitat ($Q < 0.3$), concentrated predominantly in the southwest direction along the modeled dispersion pathway. The mean habitat quality score for forest patches within the southwest plume corridor (downwind) was approximately 0.4, compared to approximately 0.7 for patches located northeast of the landfill (upwind). The mean degradation score for forest patches within 1 km of the landfill was approximately 0.5, which was substantially higher than the mean degradation score observed at distances greater than 5 km (approximately 0.2). These estimates are consistent with the spatial patterns shown in the habitat quality maps (Fig. 8). The highest methane emission was observed in Zone 11 (1782.56 Mg/year) and Zone 8 (1353.35 Mg/year), while the highest CO_2 emission was recorded at Zone 8 (2957.93 Mg/year). In contrast, Zones 4 and 12 showed no detectable emissions, corresponding to the higher habitat quality in those areas.

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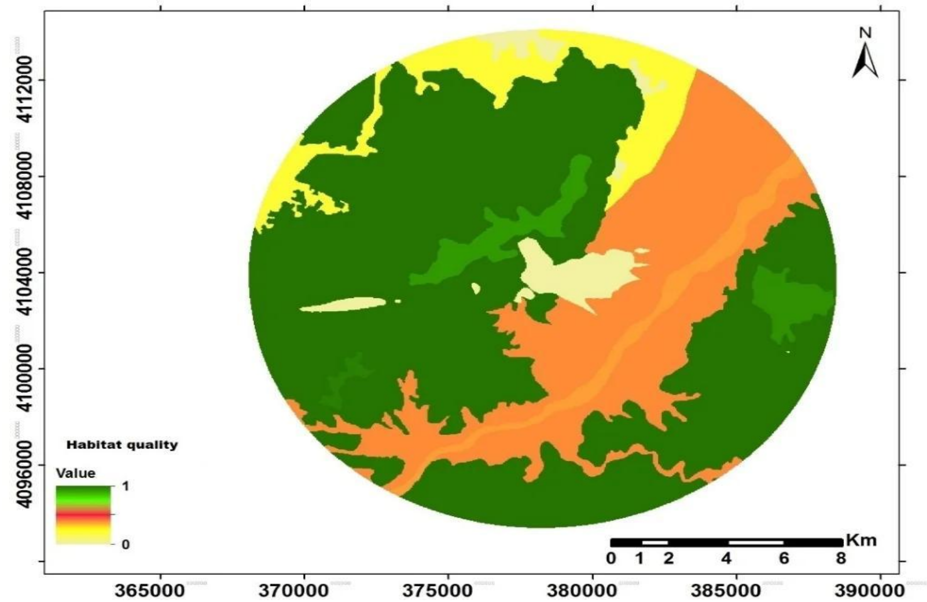

Fig. 8. Habitat quality map generated by the InVEST model for the 10 km buffer zone.

Spatial gradient analysis

A distinct spatial gradient in habitat quality was observed from the landfill outward. Forest patches located within the southwest dispersion plume (downwind) exhibited substantially lower habitat quality compared to patches located northeast of the landfill (upwind, outside the main plume influence). This difference indicates a clear spatial correspondence between gas dispersion patterns and habitat degradation.

Habitat degradation patterns

Habitat degradation scores, which quantify the cumulative pressure imposed by all threat layers, showed a strong distance-dependent pattern. The highest degradation values were recorded in forest patches immediately adjacent to the landfill (within 1 km), where the combined influence of landfill boundary, gas plumes, and surrounding anthropogenic land uses created a zone of intense environmental pressure. Degradation levels decreased progressively with increasing distance from the landfill, with the lowest values observed in forest patches beyond 5 km.

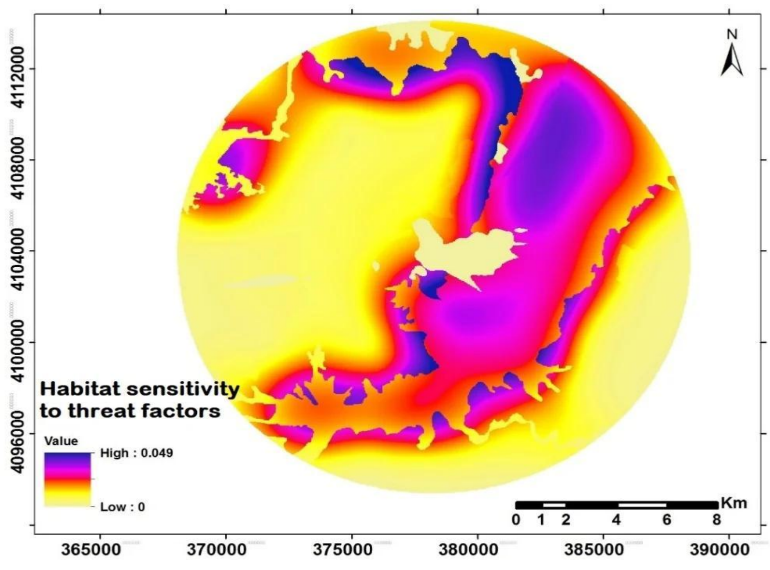

Fig. 9. Habitat sensitivity map showing the vulnerability of different land cover classes to the identified threats.

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The degradation surface reflected the combined influence of all six threat layers, with the gas plumes (CH_4 and CO_2) contributing significantly to the degradation signal in downwind forest patches. The highest degradation values were concentrated along the southwest dispersion axis, indicating that landfill-derived gases act as effective spatial stressors in this direction.

DISCUSSION

The results of this study suggest a spatial association between landfill-derived greenhouse gas dispersion and patterns of potential habitat degradation in the surrounding Hyrcanian forest habitats. The high methane and carbon dioxide concentrations detected near vent points confirm that the Saravan landfill acts as a significant emission source. The significant correlation observed between CH_4 and CO_2 fluxes also indicates that these gases are co-emitted during the decomposition processes occurring within the landfill body. Similar emission patterns and environmental pressures associated with landfill gas release have been reported in previous studies (Njoku *et al.* 2025; Gavrila *et al.* 2025). The southwest-oriented plume pattern observed in the AERMOD simulations corresponds closely with the dominant wind regime of the study area. As a result, forest patches located downwind of the landfill are more exposed to atmospheric pollutants originating from the landfill. This spatial pattern is ecologically significant, since the InVEST habitat quality outputs show a decline in habitat quality within the same corridor where the dispersion plume was predicted. In other words, the atmospheric transport pathway modelled by AERMOD spatially coincides with the areas where increased habitat degradation was detected. This spatial correspondence highlights the value of integrating atmospheric dispersion models with habitat-quality assessments to identify ecological risk zones. The InVEST results revealed that relatively intact forest patches maintained higher habitat quality scores, whereas areas closer to the landfill and within the gas dispersion pathway experienced lower habitat quality values and higher degradation levels. This finding is consistent with landscape-ecology theory, which suggests that habitat degradation is driven not only by direct land-use changes but also by the spatial influence of anthropogenic stressors across the landscape (Nematollahi *et al.* 2020). Although greenhouse gases are not typically classified as direct habitat threats in the same way as land conversion or infrastructure development, their inclusion in the threat framework is justified in this context. The dispersion of CH_4 and CO_2 can serve as an indicator of landfill influence across the surrounding landscape, representing zones where environmental stress may affect vegetation health and ecological stability. The spatial patterns suggest that landfill emissions may contribute to potential ecological stress in sensitive forest ecosystems, but further empirical studies are required to establish causality and quantify actual impacts on forest health. It should be acknowledged that other anthropogenic and environmental factors including road construction, agricultural expansion, urban development, and natural topographic conditions may also contribute to habitat degradation patterns in the study area. While the spatial overlap between gas plumes and degraded areas is consistent with a potential link, the current study cannot establish a definitive causal relationship. The observed patterns should therefore be interpreted as spatial association, and independent field-based ecological observations are needed to confirm direct impacts. The ecological significance of these findings is particularly important in the Hyrcanian forests, which are internationally recognized as a biodiversity hotspot and a UNESCO World Heritage ecosystem. Previous studies in Iranian landscapes have demonstrated that habitat quality models are effective tools for identifying priority conservation areas and ecological hotspots (Asadolahi *et al.* 2018; Nematollahi *et al.* 2020; Zhang *et al.* 2022). Within this context, the present study contributes new insights by linking landfill emission dispersion to spatial patterns of habitat degradation in a sensitive forest ecosystem. Another important aspect highlighted by this research is the usefulness of integrated spatial modelling approaches in environmental impact assessment. The combination of field emission measurements, atmospheric dispersion modelling, and habitat quality analysis allows for a more comprehensive understanding of how anthropogenic sources influence ecological systems. This integrated framework therefore offers a powerful tool for identifying environmentally vulnerable areas and supporting evidence-based environmental management. From a management perspective, the results emphasize the need for stronger landfill management and environmental protection strategies in the Saravan region. The spatial analysis clearly indicates that forest areas located downwind of the landfill are potentially more vulnerable to environmental stress. Therefore, conservation and restoration efforts should prioritize these zones. Based on the findings of this study, several management actions are recommended. First, the establishment of an ecological buffer zone around the landfill, particularly toward the southwest, could help reduce the spread of pollutants and mitigate edge effects on adjacent forest ecosystems. Second, the installation

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of an effective landfill gas collection and treatment system would significantly reduce greenhouse gas emissions and limit further environmental impacts. Third, a long-term ecological monitoring program should be implemented in the surrounding forest areas to track key indicators such as vegetation health, soil conditions, and biodiversity trends.

Limitations and future research

Despite the valuable insights provided by this study, several limitations should be acknowledged. First, the assignment of threat weights and habitat sensitivity scores in the InVEST model was based on literature review and expert judgment, which is a common approach but may introduce subjectivity. A formal sensitivity analysis was not performed, and future studies should evaluate the robustness of model predictions under different parameter scenarios. Second, this study assessed potential ecological pressure rather than demonstrated ecological impact. The InVEST outputs are based on modelled threat layers that serve as proxy indicators of landfill influence, and no independent field-based ecological data (e.g., vegetation health, soil respiration, or biodiversity surveys) were collected to validate the predicted degradation patterns. Therefore, the results should be interpreted as spatially explicit estimates of potential pressure. Third, this study focused exclusively on CH_4 and CO_2 emissions, while other landfill-generated pollutants (VOCs, NH_3, H_2S) were not considered, potentially underestimating the overall ecological pressure. Future research should incorporate field-based ecological surveys, physiological studies on forest species responses, and scenario-based simulations (e.g., land-use change, gas collection systems, or buffer zones) to support adaptive management and conservation planning in the Hyrcanian forests.

CONCLUSION

This study investigated the ecological implications of landfill greenhouse gas emissions on the surrounding Hyrcanian forest ecosystem near the Saravan landfill by integrating field measurements, atmospheric dispersion modelling (AERMOD), and habitat quality assessment using the InVEST model. The results showed that methane and carbon dioxide emissions from the landfill are spatially dispersed predominantly toward the southwest, creating a corridor of increased environmental pressure in adjacent forest areas. The habitat quality analysis indicated that forest patches located within this dispersion pathway experienced lower habitat quality values and higher degradation levels compared with more distant forest areas. These findings suggest that landfill emissions may contribute to spatially localized potential ecological stress in sensitive forest ecosystems, even when direct land-use change is not evident. It is important to emphasize that the results should be interpreted as indicators of potential pressure rather than proven ecological impact. The InVEST habitat quality outputs are based on modelled threat layers that serve as proxy indicators of landfill influence, and independent field-based ecological observations are needed to establish direct causal links between gas exposure and habitat degradation. Future studies should integrate field-based ecological surveys to validate the predicted degradation patterns. The observed seasonal peak in gas concentrations during spring has practical implications for management and conservation planning. The higher concentrations are likely associated with increased microbial activity and decomposition rates due to rising temperatures and moisture after winter. From a management perspective, this suggests that ecological monitoring and mitigation efforts should be intensified during spring, particularly in downwind forest areas where the influence of landfill emissions is expected to be greatest. Seasonal planning of restoration activities, such as planting or soil improvement, should consider this temporal pattern to minimize potential stress on forest ecosystems. The integration of emission measurements, atmospheric transport modelling, and habitat quality assessment provides a comprehensive framework for evaluating environmental impacts of landfill systems. Such an approach can support more informed environmental management and conservation planning in regions where waste disposal sites are located near ecologically valuable landscapes. Considering the ecological importance of the Hyrcanian forests, the results highlight the need for improved landfill management strategies, including effective gas collection systems, ecological buffer zones, and long-term environmental monitoring programs. Implementing these measures can help mitigate the potential ecological impacts of landfill emissions and contribute to the sustainable management of both waste infrastructure and forest ecosystems in northern Iran.

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Future studies should consider scenario-based modelling to assess the long-term implications of landfill emissions under different land-use trajectories, such as urban expansion, agricultural intensification, or reforestation scenarios.

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Table S1. Accuracy assessment of the LULC classification for the 2023 land cover map of the study area.

LULC Class	Producer's Accuracy (%)	User's Accuracy (%)
Dense Forest	94	92
Sparse/Modified Forest	88	85
Moderate Forest	90	87
Mixed Modified Forest	86	83
Agriculture	82	80
Orchards	83	81
Urban	91	89
Masil (watercourse)	85	82
Landfill	93	91
Overall Accuracy	87.6%	
Kappa Coefficient	0.84	

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Table S2. Physical characteristics and emission rates of CH_4 and CO_2 for the 25 active vent points in the Saravan landfill.

Vent Name	**Latitude**	**Longitude**	**Velocity-mean (m/s)**	**Inner diameter (m)**	**Q (m^3/s)**	**Emission CH_4 (g/s)**	**Emission CO_2 (g/s)**
Vent 1	4103510	378301	0.23	0.280	0.0138	0.24	23.34
Vent 2	4103533	378287	0.24	0.280	0.0145	0.55	23.63
Vent 3	4103530	378323	0.24	0.280	0.0145	3.64	15.24
Vent 4	4103561	378316	0.22	0.270	0.0126	0.48	20.63
Vent 5	4103558	378351	0.37	0.265	0.0204	0.85	33.33
Vent 6	4103588	378314	0.56	0.280	0.0345	4.01	49.28
Vent 7	4103584	378351	0.32	0.265	0.0174	0.17	30.07
Vent 8	4103590	378381	0.65	0.280	0.0397	13.56	32.48
Vent 9	4103623	378328	0.37	0.28	0.0228	8.72	16.28
Vent 10	4103652	378331	0.29	0.270	0.0163	1.36	25.00
Vent 11	4103618	378368	0.38	0.280	0.0234	3.43	31.86
Vent 12	4103649	378365	0.33	0.280	0.0200	2.36	28.80
Vent 13	4103621	378398	0.20	0.280	0.0123	1.56	17.43
Vent 14	4103648	378395	0.40	0.270	0.0229	3.63	30.70
Vent 15	4103652	378423	0.37	0.28	0.0228	3.25	31.48
Vent 16	4103674	378398	0.32	0.280	0.0197	3.09	26.57
Vent 17	close	—	—	—	—	—	—
Vent 18	4103701	378381	0.20	0.280	0.0120	2.12	15.56
Vent 19	4103695	378413	0.30	0.280	0.0182	7.25	12.43
Vent 20	4103722	378394	0.25	0.280	0.0154	3.23	18.33
Vent 21	4103736	378423	0.31	0.275	0.0181	6.00	15.26
Vent 22	4103743	378462	0.33	0.280	0.0200	4.25	23.46
Vent 23	4103716	378460	0.37	0.270	0.0212	4.64	24.36
Vent 24	4103690	378460	0.50	0.280	0.0305	12.05	20.37
Vent 25	4103665	378461	0.57	0.270	0.0323	5.27	42.50

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Table S3. Summary of calculated CH_4 and CO_2 emissions from the 12 flux chamber locations at the Saravan landfill.

Row	Chamber Area(m^2)	Emission (Mg/year)-CH_4	Emission (Mg/year)-CO_2	Emission CH_4 (g/s.m^2) ×10^3	Emission CO_2 (g/s.m^2) ×10^3
1	12998	456.96	307.21	1.11	0.75
2	8048	149.07	100.18	0.59	0.39
3	7237	380.72	179.60	1.67	0.79
4	6253	0.00	42.79	0.00	0.22
5	3098	242.54	64.61	2.48	0.66
6	10964	179.42	60.69	0.52	0.18
7	6317	180.39	482.30	0.91	2.42
8	8263	1353.35	2957.93	5.19	11.35
9	14039	308.65	834.65	0.70	1.89
10	6893	309.70	695.63	1.42	3.20
11	17455	1782.56	741.61	3.24	1.35
12	20535	0.00	0.00	0.00	0.00

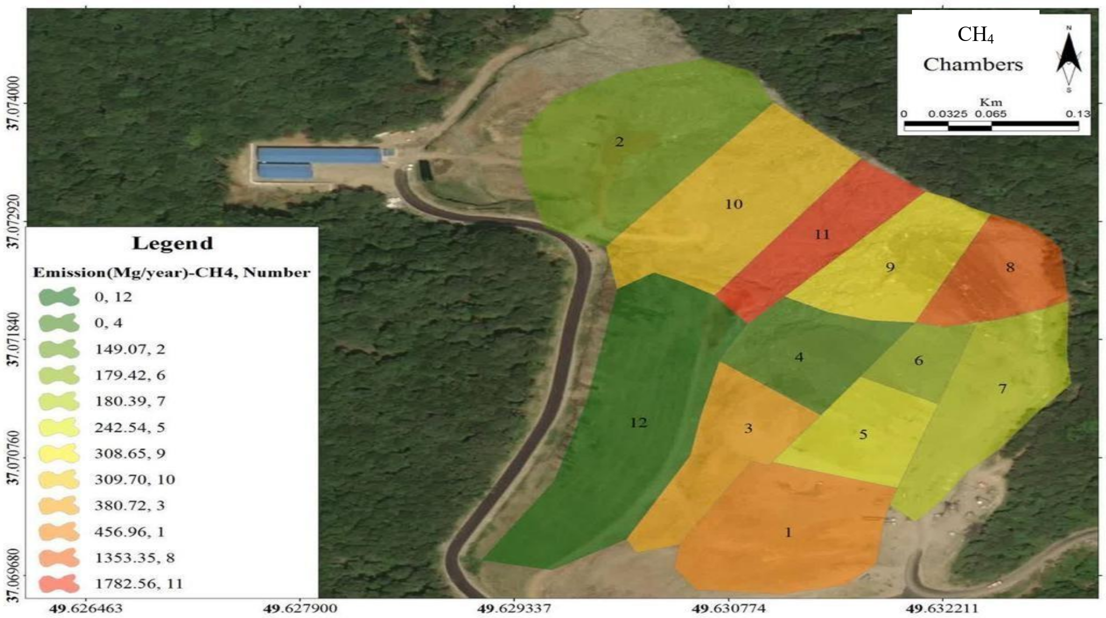

Fig. S1. Spatial distribution of methane emission zones (Mg/year) across the Saravan landfill surface, based on flux chamber measurements.

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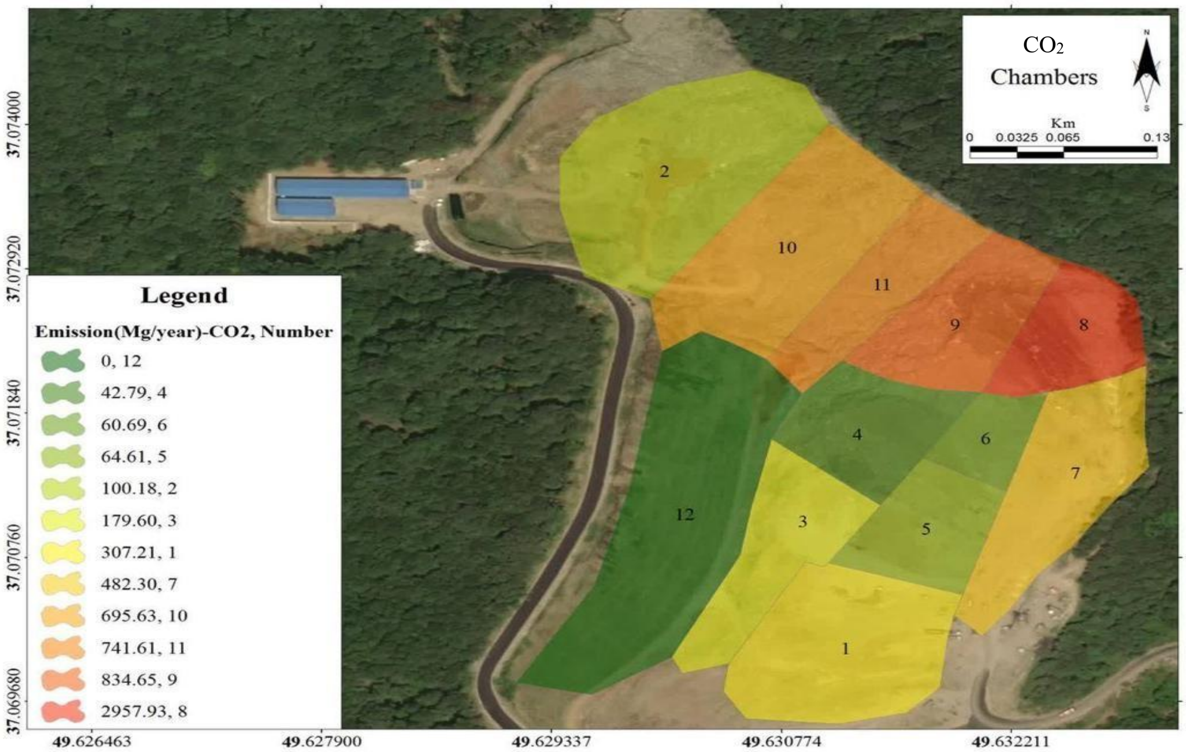

Fig. S2. Spatial distribution of carbon dioxide emission zones (Mg/year) across the Saravan landfill surface, based on flux chamber measurements.

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