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Morbidity and mortality of people who live close to municipal waste landfills: a multisite cohort study

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Abstract

Background: The evidence on the health effects related to residing close to landfills is controversial. Nine landfills for municipal waste have been operating in the Lazio region (Central Italy) for several decades. We evaluated the potential health effects associated with contamination from landfills using the estimated concentration of hydrogen sulphide (H_2S) as exposure.

Methods: A cohort of residents within 5 km of landfills was enrolled (subjects resident on 1 January 1996 and those who subsequently moved into the areas until 2008) and followed for mortality and hospitalizations until 31 December 2012. Assessment of exposure to the landfill (H_2S as a tracer) was performed for each subject at enrolment, using a Lagrangian dispersion model. Information on several confounders was available (gender, age, socioeconomic position, outdoor PM_{10} concentration, and distance from busy roads and industries). Cox regression analysis was performed [Hazard Ratios (HRs), 95% confidence intervals (CIs)].

Results: The cohort included 242 409 individuals. H_2S exposure was associated with mortality from lung cancer and respiratory diseases (e.g. HR for increment of 1 ng/m^3 H_2S: 1.10, 95% CI 1.02–1.19; HR 1.09, 95% CI 1.00–1.19, respectively). There were also associations between H_2S and hospitalization for respiratory diseases (HR = 1.02, 95% CI 1.00–1.03), especially acute respiratory infections among children (0–14 years) (HR = 1.06, 95% CI 1.02–1.11).

Conclusions: Exposure to H_2S, a tracer of airborne contamination from landfills, was associated with lung cancer mortality as well as with mortality and morbidity for respiratory diseases. The link with respiratory disease is plausible and coherent with previous studies, whereas the association with lung cancer deserves confirmation.

Key words: waste, landfills, residential cohort study

Key Messages

- The evidence on the health of people living close to landfills is still controversial; most of the published studies are characterized by poor exposure assessment, use of health data at the aggregate level and limited possibility of adjusting for socioeconomic status.
- We evaluated the potential health effect of living near nine landfills (Lazio region, Italy), using a residential cohort approach and a dispersion model for exposure assessment.
- Exposure to landfills was associated with mortality from lung cancer and respiratory diseases and with hospitalizations for respiratory diseases, both in adults and in children.

Introduction

People who live close to municipal solid waste (MSW) landfills could be exposed to air pollutants emitted by the plants (landfill gas containing methane, carbon dioxide, hydrogen sulphide and other contaminants including volatile organic compounds, particulate matter and bioaresols) or to contaminated soil and water. The possible health effects related to residence close to these sites have been assessed in several original papers[1–9] and evaluated in systematic reviews.[10,11] Excess of mortality for some cancer sites (e.g. liver, pancreas, kidney, larynx) and non-Hodgkin lymphoma has been noted in some studies,[1–3] but the results have not been confirmed in other investigations.[4–6] In addition, some studies have indicated an increase of respiratory symptoms among residents close to biodegradable waste facilities.[12] In 2009, Porta *et al.*[10] concluded that evidence of an association between living close to a landfill and adverse health effects is inconclusive. Most of the published studies have methodological problems, including poor exposure assessment based only on distance from the source, use of health data at the aggregate level and limited possibility of adjusting for socioeconomic status. The quality of the epidemiological studies and scientific knowledge about the issue would be improved by using a residential cohort approach[13] and applying dispersion models to provide a better exposure assessment.[14]

This study aimed at evaluating the association between estimated exposure to hydrogen sulphide (H_2S, produced by anaerobic decomposition of sulphur-containing organic matter in landfills) and mortality and morbidity of a cohort of residents living within 5 km of the nine MSW landfills of the Lazio region (Central Italy, about 5 million inhabitants including the city of Rome). The study was part of a larger project on the characteristics of municipal solid waste treatment plants, their emissions and potential health effects in Lazio (www.eraslazio.it).

Methods

Study areas

Nine municipal solid waste landfills have been operating in Lazio for several decades. Only in the past two decades they were equipped with containments (including leachate collection and treatment, landfill cap construction and landfill gas collection and treatment). The main characteristics of the landfills (together with other potentially relevant environmental factors in the areas, e.g. arsenic contamination)[14] are described in Supplementary Table 1, Landfill characteristics, and in Supplementary Figure 2, Study areas, (available as Supplementary data at *IJE* online). The study area was defined for each landfill as a 5-km radius from the boundary of the landfills assessed using GIS software and regional technical maps with a scale of 1:5000. The World Geodetic System of 1984, with the Universal Transverse Mercator zone 33Nord projection (WGS84_UTM33N) was the reference for the geographical coordinates.

Exposure assessment

H_2S has been considered a surrogate measure of all contaminants emitted by landfills, and the airborne concentrations were predicted using a dispersion model. Dispersion models, such as the one we have been using here, have been recently used to assess the health effects of waste management processes.[15–17] We followed a process in three steps. First, yearly H_2S emissions from each sector of the landfills were estimated using a Landfill Gas Emissions Model.[18] Using several variables (the start and end dates of operations for each sector of the landfills, the waste capacity and waste acceptance rate), the annual emission rates for H_2S were calculated by means of a first-order decomposition rate equation:

$$Q_{H_2S} = \sum_{t=1}^{n} \sum_{j=0.1}^{1} KL_0 \left(\frac{M_t}{10}\right) e^{-kt_{ij}}$$

where:

QH_2S = annual emission rate (m^3/year)

t = age of the jth section of the landfill

i = 1 year time increment

n = (year of the calculation) – (initial year of waste acceptance)

j = 0.1 year time increment

K = hydrogen sulphide generation rate (year-1)

L_o = potential hydrogen sulphide generation capacity (m^3/Mg)

M_t = mass of waste accepted until t (in Mg)

tij = age of the waste mass accepted until the ith year (M_t) at the jth section

Mg = Megagram.

We used inventory defaults parameters derived from the US Environmental Protection Agency (EPA) Compilation of Air Pollutant Emission Factors[19] to define hydrogen sulphide generation rate (K) and potential hydrogen sulphide generation capacity (L_o), and Mt and tij were defined by the Lazio Environmental Protection Agency (EPA) using local data. Second, the EMMA software was used for the temporal and spatial modulation of the estimated emissions. EMMA approximates landfills shape as a regular grid with a resolution of 125 m x 125 m.[20] Finally, we used a Lagrangian particle model (SPRAY ver.5, ARIANET Srl, Italy) to simulate H_2S concentrations around the landfills and to produce maps of annual average concentrations around the sites; 2008 was chosen as the reference year for all the sites. The meteorological data were derived from regional measurements made by Lazio EPA in 2005 (that year is considered representative of the meteorological conditions in the area), and used in connection with RAMS data.[21] The Lagrangian model simulates the transport, dispersion and deposition of pollutants emitted using the orography, the meteorological data, the turbulence and the hourly spatial distribution (horizontal and vertical) of the emissions, based on the characteristics of the single source and on the mass fluxes. The model follows the path of fictitious particles in the atmospheric turbulent flow, and it is able to take into account complex situations, such as the presence of obstacles, breeze cycles, strong meteorological non-homogeneities and non-stationary, calm wind conditions.

Each subject in the cohort (see below) was assigned an H_2S exposure value corresponding to the estimated annual average value from the dispersion model at the baseline address. In other words, no exposure variation over time was considered and each person remained at the same exposure level during the all study period.

Enrolment of the cohort and follow-up procedures

All residents living within 5 km of the borders of the landfill on 1 January 1996, or those who later moved to the areas until 31 December 2008, were enrolled; datasets from 16 municipalities were used. Vital status was assessed using local registries until 31 December 2012. We considered subjects at risk until they died or moved out of the municipality.

Health outcomes

We analysed natural and cause-specific mortality and hospital admissions for cardiorespiratory diseases. The underlying cause of death for deceased subjects was retrieved from the Regional Registry of Causes of Death, and hospital admissions were obtained from the Regional Hospital Information System which collects information related to all hospital admissions that occur each year in public and private hospitals. Causes of death and diagnoses of hospitalization were coded according to the ICD 9 revision. For each subject, only the principal diagnosis that was the reason for the hospitalization was used and the event (i.e. failure in the Cox model) was defined at the time of the first hospitalization for a specific cause that occurred in the study period. Respiratory hospital admissions for children (residents under 14 years) were also analysed.

Covariates

We considered for each subject an area-based socioeconomic position (SEP) index, based on several characteristics at the census tract level (around 400 inhabitants) such as education level, occupation, housing conditions, family size and country of origin, classified into five levels (high, middle-high, medium, middle-low, low).[22] Modelled outdoor PM_{10} concentrations ($\mu g/m^3$) from primary emissions were assigned to the residential addresses of the cohort participants as a measure of background air quality.[23] The dispersion model was based on the integration between the meteorological Regional Atmospheric Modelling System [21] and the Eulerian Flexible Air Quality Regional Model (FARM, ARIANET Srl, Italy). As an additional indicator of long-term exposure to traffic-related air pollution at the baseline address, we used the Functional Road Class (FRC) (included in the TeleAtlasMultiNet road network) to classify the type of street: motorway (FRC = 0) and major traffic roads (FRC = 1–5). Presence of an industrial plant in the 2-km buffer from the residence was also considered. Information on individual lifestyle factors was not available.

Statistical analysis

The association between landfill H_2S exposure and mortality and hospital admissions was evaluated using Cox proportional hazard regression models [hazard ratios (HRs), 95% confidence intervals (CIs)], with age as the underlying time variable.

For mortality we defined a latency period of 5 years; therefore we considered all cohort participants who were residents of the area on 1 January 1996 (and started the follow-up on 1 January 2001) and those who subsequently moved to the areaup until 31 December 2003 (starting the follow-up 5 years after enrolment). No latency was allowed for the analyses of cardiorespiratory hospitalizations. We first compared the mortality and hospitalization risk of residents according to quartiles of the H_2S distribution. We then considered H_2S as a continuous variable, using the value of the annual mean exposure at residence. A linear association was estimated for increments equal to 1 ng/m^3 of H_2S. We considered as potential confounders socioeconomic position (SEP), PM_{10} background concentrations, residence within 150 m of main roads, 500 m from highways and within 1 or 2 km of industrial plants. With the exception of PM_{10}, which was a continuous variable, all other covariates were considered in the model as categorical variables. In addition, the analyses were performed stratifying in the Cox analysis by landfill sites, to take into account the possible different background rates in the various local areas, by gender and by calendar period (1996–2000, 2001–04, 2005–08, 2009–12), to take into account possible time-related changes in background rates of mortality and hospitalization. Diagnostic tools were used to check the proportional-hazard assumption for all categorical covariates. If any variable in the individual cohort models violated this assumption, effect estimates were compared with a stratified Cox analysis for that covariate. SAS (SAS Institute, NC) and STATA ver. 12 (StataCorp, TX) software programs were used for the statistical analyses.

Results

A total of 242 409 individuals were enrolled in the cohort from 1996 to 2008 (50.4% females), and H_2S concentrations were estimated for each of them at the address of recruitment. The annual average H_2S exposure levels of the population was rather low, 6.3 ng/m^3 [standard deviation (SD) 22.5]; as expected, people living close to the larger landfills (Latina and Rome) had higher H_2S exposure levels [mean = 32.7 ng/m^3 (SD 76.3) and mean = 45.8 ng/m^3 (SD 59), respectively].

The main characteristics of the study cohort according to H_2S concentrations (divided by quartiles of exposure) are described in Table 1. The distribution of gender, age and vital status was rather similar across exposure categories. However, people living in areas with higher concentrations of H_2S were more likely to be of lower SEP compared with people living in areas with lower exposure. PM_{10} background concentrations were higher in the most exposed group compared with those in the low exposure category. People in the higher exposure category tended to live farther from high traffic roads (500 m) but closer to highways and industrial plants (0–1 km). There was a good correlation between distance from landfill and H_2S exposure.

At the end of the follow-up there were 18 609 deaths (7.7%), and for 40 740 subjects (16.8%) the follow-up ended at the time of move away from the municipality of residence.

Table 2 shows the association between H_2S concentrations and cause-specific mortality; effect estimates are given for the quartile distribution of H_2S (25–50, 50 75 and > 75 percentile of the distribution vs < 25 percentile) and for a linear increase of H_2S equal to 1 ng/m^3. There were associations between H_2S exposure and lung cancer (HR 1.34, 95% CI 1.06–1.71), and respiratory diseases (HR 1.30, 95% CI 0.99–1.70) when comparing residents in areas with H_2S concentrations greater than 75 percentiles to the reference group. These findings were confirmed when we consider H_2S exposure as linear (HR 1.10, 95% CI 1.02–1.19 for lung cancer and HR 1.09, 95% CI 1.00–1.19 for respiratory diseases). No other associations were noted.

Table 3 shows the results for cardiorespiratory hospital admissions. No association was detected for cardiovascular diseases. There was an association between the highest quartile of exposure to H_2S and hospitalizations for respiratory diseases (H 1.05, 95% CI 0.99–1.11) also when considering H_2S exposure as linear (HR 1.02, 95% CI 1.00–1.03). H_2S exposure was linked with respiratory diseases and acute respiratory infection hospital admissions among children (for the highest quartile, HR 1.11, 95% CI 1.01–1.22; HR 1.20, 95% CI 1.04–1.38, respectively) also when we considered H_2S exposure as a linear term in the model. We found an association with paediatric admissions for asthma but with wider confidence intervals.In both mortality and hospitalization analyses, we did not find effect modification by gender (data not shown).

Because of the peculiarity of the urban site in Rome ('Malagrotta') (where a large landfill, an incinerator of medical wastes, and a petrochemical refinery are located within just a few kilometres of each other[3]), we repeated the analyses excluding the subjects who live close to the Malagrotta landfill. There were no important changes in the results (See Supplementary Tables 3 'Mortality excluding Malagrotta landfill' and 4 'Morbidity excluding Malagrotta landfill', available as Supplementary data at *IJE* online). We did perform the same sensitivity analysis excluding each landfill at the time, and again the results were similar (see Supplementary Figures 7 'Lung cancer mortality', 8 'Respiratory mortality', 9 'Respiratory morbidity' and 10 'Respiratory morbidity in children', available as Supplementary data at *IJE* online).

Table 1. Descriptive individual and environmental characteristics of the cohort members by hydrogen sulphide (H_2S) exposure

	Total		H_2S exposure levels (ng/m^3)							
			<25° perc (<0.77)		25°–50° perc (0.77–2.1)		50°–75° perc (2.1–4.2)		>75° perc (>4.2)	
	No.	%	No.	%	No.	%	No.	%	No.	%
Total	242 409	100	60 927	100.0	60 775	100	63 962	100	56 745	100
Gender										
Males	120 232	49.6	29 781	49.0	30 137	49.6	31 979	50.0	28 335	49.9
Females	122 177	50.4	31 146	51.0	30 638	50.4	31 983	50.0	28 410	50.1
Vital status										
Alive	183 060	75.5	48 306	79.3	45 948	75.6	44 673	69.8	44 133	77.8
Migrant	40 740	16.8	8 169	13.4	10 228	16.8	14 446	22.6	7 897	13.9
Dead	18 609	7.7	4 452	7.3	4 599	7.6	4 843	7.6	4 715	8.3
Age at recruitment (years)										
0–14	53 082	21.9	12 246	20.0	13 011	21.4	16 266	25.4	11 559	20.4
15–44	112 754	46.5	27 380	45.0	28 383	46.7	30 661	47.9	26 330	46.4
45–64	50 146	20.7	13 296	22.0	12 584	20.7	11 727	18.3	12 539	22.1
>65	26 427	10.9	8 005	13.0	6 797	11.2	5 308	8.3	6 317	11.1
Area-based socioeconomic position										
High	23 589	9.7	10 012	16.0	6 033	9.9	4 779	7.5	2 765	4.9
Middle-high	41 955	17.3	7 843	13.0	8 834	14.5	9 548	14.9	15 730	27.7
Medium	42 286	17.4	7 447	12.0	8 588	14.1	13 958	21.8	12 293	21.7
Middle-low	50 394	20.8	5 364	9.0	16 816	27.7	17 563	27.5	10 651	18.8
Low	62 157	25.6	22 806	37.0	15 206	25.0	11 906	18.6	12 239	21.6
Missing	22 028	9.1	7 455	12.0	5 298	8.7	6 208	9.7	3 067	5.4
PM_{10} (μg/m^3)										
< 11.99 (<50° perc)	121 222	50.0	44 371	73.0	29 696	48.9	23 986	37.5	23 169	40.8
11.99–17.69 (50°–90° perc)	96 369	39.8	16 556	27.0	28 967	47.7	31 661	49.5	19 185	33.8
> 17.69 (>90° perc)	24 818	10.2	0	0.0	2 112	3.5	8 315	13.0	14 391	25.4
Distance from major roads (metres)										
<= 150 m	114 698	47.3	31 842	52.0	25 876	42.6	34 506	53.9	22 474	39.6
> 150 m	127 711	52.7	29 085	48.0	34 899	57.4	29 456	46.1	34 271	60.4
Distance from highways (metres)										
<= 500 m	9 428	3.9	2 908	5.0	1 087	1.8	744	1.2	4 689	8.3
> 500 m	232 981	96.1	58 019	95.0	59 688	98.2	63 218	98.8	52 056	91.7
Distance from industrial plants (km)										
0–1 km	12 863	5.3	376	1.0	2 676	4.4	1 130	1.8	8 681	15.3
1–2 km	50 503	20.8	1 138	2.0	9 589	15.8	28 809	45.0	10 967	19.3
> 2 km	179 043	73.9	59 413	98.0	48 510	79.8	34 023	53.2	37 097	65.4
Distance from landfill (km)										
0–1 km	5 187	2.1	0	0.0	3	0.0	19	0.0	5 165	9.1
1–2 km	21 475	8.9	2	0.0	4 225	7.0	5 835	9.1	11 413	20.1
2–3 km	65 386	27.0	8 372	13.7	20 588	33.9	23 627	36.9	12 799	22.6
3–4 km	77 722	32.1	19 739	32.4	18 787	30.9	20 217	31.6	18 979	33.4
4–5 km	72 639	30.0	32 814	53.9	17 172	28.3	14 264	22.3	8 389	14.8

An additional analysis was performed using distance from the landfills (0–2 km, 2–3 km vs 3–5 km), instead of estimated H_2S concentration, as the exposure variable. Although the results for mortality using distance were not similar to what has been observed using H_2S concentrations (see Supplementary Table 5 'Mortality by distance', available as Supplementary data at *IJE* online) the results for hospitalizations were similar to those obtained using H_2S concentrations (see Supplementary Table 6 'Morbidity by distance', available as Supplementary data at *IJE* online).

Our final concern was that migration outside the areas could bias the results in the case of migration being associated with the exposure and if residents with pre-existing diseases were more likely to migrate. We compared the characteristics of people who migrated outside the study

Table 2. Associations between hydrogen sulphide (H_2S in quartiles and continuous) and cause specific mortality: number of deaths (No.) hazard ratios (HR) and 95% confidence intervals (95% CI)

Cause of death (ICD-9-CM)	H_2S concentrations														
	<25° percentile[a]	25°–50° percentile				50°–75° percentile				>75° percentile				Linear trend	
	No.	No.	Crude HR	HR	95% CI	No.	Crude HR	HR	95% CI	No.	Crude HR	HR	95% CI	HR	95% CI
Natural causes (001–799)	3 701	3 946	0.98	1.01	(0.96–1.06)	4 254	1.00	1.02	(0.97–1.08)	4 104	0.96	0.98	(0.91–1.05)	1.00	(0.98–1.02)
All cancers (140–239)	1 282	1 307	0.97	0.99	(0.91–1.08)	1 493	1.03	1.05	(0.95–1.16)	1 452	1.00	1.03	(0.91–1.16)	1.01	(0.98–1.05)
Stomach (151)	75	88	1.03	0.98	(0.70–1.37)	108	1.27	1.23	(0.84–1.79)	105	1.00	0.88	(0.54–1.42)	1.00	(0.87–1.16)
Colorectal (153–154,159)	154	170	0.99	1.00	(0.79–1.27)	176	0.96	0.97	(0.74–1.28)	159	0.93	0.91	(0.64–1.28)	0.97	(0.87–1.08)
Liver (155–156)	102	89	0.86	0.83	(0.61–1.13)	106	0.89	0.77	(0.53–1.11)	89	0.74	0.76	(0.48–1.2)	0.90	(0.78–1.05)
Pancreas (157)	68	64	0.92	0.93	(0.64–1.35)	69	0.92	0.95	(0.61–1.49)	72	0.69	0.73	(0.41–1.32)	0.93	(0.77–1.11)
Larynx (161)	17	15	0.81	0.72	(0.33–1.56)	11	0.38	0.40	(0.14–1.14)	23	0.43	0.26	(0.07–0.95)	0.64	(0.43–0.97)
Lung (162)	276	281	0.98	1.06	(0.89–1.27)	360	1.09	1.18	(0.97–1.45)	361	1.19	1.34	(1.06–1.71)	1.10	(1.02–1.19)
Bladder (188)	54	48	0.88	0.89	(0.59–1.36)	56	1.22	1.33	(0.81–2.16)	50	1.01	0.94	(0.5–1.80)	1.03	(0.85–1.26)
Kidney (189)	36	30	0.76	0.85	(0.51–1.43)	36	0.87	0.94	(0.52–1.70)	31	0.70	0.86	(0.41–1.83)	0.96	(0.75–1.22)
Brain (191)	23	29	1.26	1.25	(0.70–2.26)	38	1.63	1.63	(0.84–3.17)	41	1.70	1.76	(0.81–3.81)	1.22	(0.95–1.56)
Lymphatic and haematopoietic tissue (200–208)	108	115	1.03	1.16	(0.87–1.54)	106	0.94	0.96	(0.68–1.35)	102	1.06	1.12	(0.74–1.17)	1.02	(0.89–1.16)
Cardiovascular diseases (390–459)	1 457	1 681	1.02	1.05	(0.97–1.13)	1 676	0.96	1.00	(0.91–1.09)	1 641	0.90	0.91	(0.81–1.02)	0.98	(0.94–1.01)
Ischaemic heart diseases (410–414)	512	570	0.99	1.00	(0.88–1.14)	574	0.86	0.91	(0.78–1.06)	530	0.77	0.78	(0.64–0.95)	0.93	(0.87–0.99)
Respiratory diseases (460–519)	256	244	0.88	0.92	(0.76–1.11)	279	1.15	1.13	(0.90–1.40)	264	1.30	1.30	(0.99–1.70)	1.09	(1.00–1.19)
Digestive diseases (520–579)	158	163	0.93	0.97	(0.77–1.24)	218	1.06	1.09	(0.83–1.41)	186	0.94	0.97	(0.69–1.35)	1.01	(0.91–1.12)
Urinary system diseases (580–599)	58	92	1.49	1.54	(1.08–2.21)	74	1.25	1.28	(0.83–1.97)	67	1.26	1.42	(0.84–2.40)	1.11	(0.94–1.30)

[a]Reference category

Table 3. Associations between hydrogen sulphide (H_2S, in quartiles and continuous) and cardiorespiratory morbidity: number of people hospitalized (No.), hazard ratios (HR) and 95% confidence intervals (95% CI)

Diagnosis (ICD-9-CM)	H_2S concentrations													
	<25° percentile[a]		25°–50° percentile			50°–75° percentile			>75° percentile			Linear trend		
	No.	No.	Crude HR	HR	95% CI	No.	Crude HR	HR	95% CI	No.	Crude HR	HR	95% CI	HR	95% CI
Total cohort															
Cardiovascular diseases (390–459)	6 666	6 090	0.99	0.99	(0.95–1.03)	6 291	0.99	1.00	(0.96–1.04)	6 677	1.03	1.02	(0.97–1.07)	1.00	(0.99–1.02)
Cardiac diseases (390–429)	3 991	3 585	0.99	0.98	(0.93–1.03)	3 580	0.97	0.98	(0.92–1.04)	4 022	1.05	1.04	(0.97–1.11)	1.01	(0.98–1.03)
Ischaemic heart diseases (410–414)	1 393	1 347	1.03	1.02	(0.94–1.10)	1 288	0.94	0.94	(0.85–1.03)	1 426	1.01	0.99	(0.88–1.10)	0.99	(0.95–1.02)
Cerebrovascular diseases (430–438)	1 635	1 482	0.98	0.98	(0.91–1.06)	1 466	0.97	0.97	(0.89–1.06)	1 543	0.97	0.98	(0.88–1.10)	0.99	(0.96–1.03)
Respiratory diseases (460–519)	4 372	4 249	0.98	0.97	(0.92–1.01)	5 628	1.02	1.01	(0.96–1.06)	4 837	1.06	1.05	(0.99–1.11)	1.02	(1.00–1.03)
Acute respiratory infections (460–466,480–487)	1 447	1 441	1.00	0.96	(0.89–1.04)	1 721	1.00	0.97	(0.89–1.05)	1 509	1.09	1.07	(0.97–1.18)	1.02	(0.98–1.05)
COPD (490–492,494,496)	654	592	0.96	0.94	(0.84–1.06)	535	0.92	0.90	(0.78–1.04)	577	1.09	1.06	(0.90–1.25)	1.00	(0.95–1.05)
Asthma (493)	332	355	1.01	1.00	(0.86–1.17)	594	1.16	1.17	(0.99–1.38)	365	1.11	1.09	(0.90–1.33)	1.04	(0.98–1.11)
Children 0–14 years old															
Respiratory diseases (460–519)	1 457	1 522	1.00	0.99	(0.92–1.07)	2 420	1.07	1.08	(0.99–1.17)	1 499	1.10	1.11	(1.01–1.22)	1.04	(1.01–1.07)
Acute respiratory infections (460–466,480–487)	573	669	1.10	1.02	(0.91–1.15)	925	1.15	1.10	(0.97–1.25)	617	1.25	1.20	(1.04–1.38)	1.06	(1.02–1.11)
Asthma (493)	257	267	0.98	0.99	(0.83–1.19)	506	1.23	1.29	(1.06–1.55)	276	1.11	1.13	(0.91–1.41)	1.07	(0.99–1.14)

[a]Reference category

areas (40 740 subjects) with those who remained in the areas until the end of the follow-up (201 669 subjects) See Supplementary Table 11 'Comparison between migrant and not migrant', available as Supplementary data at *IJE* online). We considered gender, age, socioeconomic status and H_2S exposure as fixed variables. Since occurrence of hospitalizations before migration is a time-dependent variable, we compared subjects migrating in the period 2004–12 (19 695 subjects) with all subjects who did not migrate before that period (189 560 subjects), evaluating the occurrence of cardiorespiratory hospitalizations during1998–2003. Migration was associated with male gender, younger age and lower exposure to H_2S; no clear differences of migrants compared with non-migrants were found for socioeconomic status. In a multinomial logistic regression(data not shown), we found no major differences between the two groups for respiratory diseases, whereas migrants were less likely than non-migrants to suffer from two or more hospitalizations for cardiovascular disease (OR, 0.74, 95% CI 0.57–0.95) before migrating. All these results indicate that bias due to increased susceptibility of migrants is unlikely given that migrants are less exposed and tend to be healthier than non-migrants.

Discussion

We found a positive association between exposure to hydrogen sulphide (H_2S), that we used as a surrogate for all the pollutants co-emitted from the landfills, and mortality for lung cancer and respiratory diseases as well as hospital admissions for respiratory diseases, especially in children.

Previous studies have investigated the association between residence close to landfills and cancer incidence or cause-specific mortality, with conflicting results. A Canadian cohort study compared cancer incidence in males living close to a landfill with that of residents of farther away areas.[1] The distance from the landfill was assigned to each person based on the residential address at diagnosis. Excess risks for non-Hodgkin lymphoma and liver, pancreas and kidney cancers were found in male residents close to the site. Malagrotta (Rome) residents who lived near (in an area about 2 km^2) a large landfill of municipal solid waste, an incinerator and a petrochemical refinery showed an association between proximity to landfill and laryngeal cancer.[2] A more recent residential cohort study of the same area found that H_2S exposure from the landfill was related to higher risk of mortality from laryngeal cancer and bladder cancer in women, as well as hospitalizations for cardiorespiratory diseases.[3] Jarup *et al.* compared cancer incidence (bladder, brain and hepatobiliary cancers and leukaemias) in the population resident within 2 km of 9565 landfills in UK with cancer rates of

those who lived more than 2 km away.[4] Despite the large statistical power, the study did not show excess cancer risk associated with proximity to landfill sites. An ecological study compared mortality, hospital admissions and reproductive health of a population living near a landfill site in Wales with another population matched for socioeconomic status.[5] No differences between the two populations were found. A study in Brazil evaluated the association between residence close to solid waste landfill sites and cancer mortality.[6] The exposed areas were defined using a 2-km buffer radius around 15 sites. Standardized mortality ratios were analysed in Bayesian spatial models. The results did not indicate any excess risk for people close to landfills. Some elevated risks of bladder and liver cancer, and death due to congenital malformation were found, although they did not have statistical significance.

The results we found regarding respiratory diseases are consistent with others suggesting a relationship between living close to landfill areas and damage to the respiratory system,[24,25] as highlighted in a recent systematic review.[26] Occurrence of respiratory symptoms was documented among residents living close to waste sites[12] and was linked to inhalation exposure to endotoxin, microorganisms, and aerosols from waste collection and land filling.[27]

Occupational exposure to organic dust, particulate matters from microbial, plant or animal origin, has been associated with an increased risk of lung cancer in a pooled analysis of case-control studies.[25] High lung cancer mortality was found among male residents of Italian National Priority Contaminated Sites with industrial waste landfills or illegal dumps[29] and among residents living near incinerators and landfills of hazardous waste in Spain,[30] but the overall evidence that residing near landfills is associated with increased risk of lung cancer is still inadequate.[10]

This study attempted to overcome some of the limitations of the previously conducted studies, which included issues of study design, exposure assessment and confounding.[11] We used a residential cohort approach to provide a more detailed estimation of the population at risk. To each subject in the cohort we assigned an H_2S exposure value(corresponding to the estimated H_2S concentration at the baseline address). It was not possible to consider indexes of average or cumulative exposure based on the different residences, because only a few municipality databases provided information about changes of residence during the follow-up. For this reason, individual exposure reflects residence at the beginning of the follow-up.

Previous studies have considered distance from landfills as a proxy of exposure.[4,7,9] Distance-to source is easy to understand because it assumes that people living near the landfill are more exposed than people living further away. We used modelled H_2S concentrations as an exposure measure of the landfill gases, on the assumption that the pollution from landfills does not spread uniformly around the site but depends on the quantity of incoming waste, the prevailing winds and the orography of the area.[3] Our results for hospitalizations were confirmed when we used distance from the source as the exposure variable instead of modelled H_2S concentrations. There are, however, several aspects in the exposure assessment process we used that should be considered. H_2S generation rates were taken from EPA published material, and waste acceptance capacity and waste acceptance rates were from derived from legal authorized values. It is likely, then, that the derived absolute emissions data were more accurate for the recent period and less certain for the past. On the other hand, we used the shape of the H_2S concentrations on the ground to rank subjects as more exposed or less exposed, and this shape is of greater importance than the exact absolute values. Of course, the major limitation of our exposure assessment is related to the lack of a validation study with *in situ* measurements. Nonetheless, SPRAY is a consolidated model that has been validated using a 'conventional' validation framework,[31] and its performances and efficiency have been evaluated and validated in multiple real conditions with different orography, size of domain, number of grid cells in the domain, meteorological conditions and emission types.[32–34] The model has been already used in other locations to study health effects of waste management.[3,17] Another aspect of concern is the use of meteorological parameters that greatly influence the dispersion of the pollutants. We considered the year 2005 as representative of the study area meteorological conditions because there were no particular meteorological anomalies in that year. Running the dispersion model with meteorological data for different years could change the landfills footprint only in presence of extreme weather conditions that strongly affect the annual average. In our opinion, the difference among years is generally minimal and the uncertainty associated with the use of specific meteorological data is negligible.

Our results were adjusted for several confounders: age, socioeconomic position and variables related to the environmental context (proximity to roads with heavy traffic, proximity to industrial sites, air quality) that might otherwise distort the study association. In particular, high level of PM_{10} (> 90 percentile of the distribution vs < 50 percentile) was associated in our model with cardiovascular and respiratory hospitalizations (HR 1.08, 95% CI 1.01–1.16 and HR 1.03, 95% CI 0.96–1.12, respectively). However, no data were available on the personal habits of the subjects, which could have had a role in the diseases investigated, especially cigarette smoking but also alcohol use, physical activity and obesity. The collection of this

information, through telephone interviews or home visits, would have been prohibitive for such a large cohort, and the lack of this information may have biased the results because of confounding not controlled in the analysis. It should be noted, however, that many personal habits are associated with socioeconomic position. It is therefore reasonable to assume that the analysis that adjusted for socioeconomic index also took into account others individual variables, including smoking. Moreover, excess of hospitalizations for respiratory diseases were found also in children, and no excess mortality/morbidity for cardiovascular diseases (indicative of most of the unmeasured lifestyle factors including smoking) was found, despite the larger statistical power than for respiratory diseases. Therefore, although residual confounding cannot be excluded, it is unlikely that the observed relationship between H_2S exposure and respiratory disturbances could be entirely due to unmeasured smoking habits and other factors.

In conclusion, we found associations between H_2S exposure from landfills and mortality from lung cancer as well as mortality and morbidity for respiratory diseases. The link with respiratory diseases has been observed in other studies and it is potentially related to irritant gases and other organic contaminants. The excess of lung cancer is a relatively new finding.

Supplementary Data

Supplementary data are available at *IJE* online.

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