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Use of genetic algorithms to improve the solid waste collection service in an urban area

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ABSTRACT

Increasing generation of Urban Solid Waste (USW) has become a significant issue in developing countries due to unprecedented population growth and high rates of urbanisation. This issue has exceeded current plans and programs of local governments to manage and dispose of USW. In this study, a Genetic Algorithm for Rule-set Production (GARP) integrated into a Geographic Information System (GIS) was used to find areas with socio-economic conditions that are representative of the generation of USW constituents in such areas. Socio-economic data of selected variables categorised by Basic Geostatistical Areas (BGAs) were taken from the 2000 National Population Census (NPC). USW and additional socio-economic data were collected during two survey campaigns in 1998 and 2004. Areas for sampling of USW were stratified into lower, middle and upper economic strata according to income. Data on USW constituents were analysed using descriptive statistics and Multivariate Analysis. ARC View 3.2 was used to convert the USW data and socio-economic variables to spatial data. Desk-top GARP software was run to generate a spatial model to identify areas with similar socio-economic conditions to those sampled. Results showed that socio-economic variables such as monthly income and education are positively correlated with waste constituents generated.

The GARP used in this study revealed BGAs with similar socio-economic conditions to those sampled, where a similar composition of waste constituents generated is expected. Our results may be useful to decrease USW management costs by improving the collection services.
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1. Introduction

In many developing countries, increasing generation of USW has exceeded action plans and collection programs of local governments, and has become an issue of concern to public health (Al-Khatib et al., 2007; Fauziah and Agamuthu, 2012). Additionally, USW is not characterised as frequently as required because most funding is allocated to collection service, which affects the recycling and collection processes. Furthermore, information regarding the management of USW is dispersed amongst different sources and generally lost with successive changes in government administration (Buenrostro et al., 2008). The selection of appropriate sites within the collection process is key to urban planning, as it may affect regional economic balances (Chang et al., 2008; Uyan, 2014). Therefore, modern streamlined collection systems are vital to ensure better management of USW, to reduce operational costs, and to improve the coverage and efficiency of collection services (Rada et al., 2013).

GIS can be used to make informed decisions relevant to USW management. Information from maps such as roads and settlements may be used to select the most appropriate sites to locate landfills (Delgado and Sendra, 2010; Rada et al., 2010; Demesouka et al., 2014). For instance, Vijay et al. (2005) input population density, demography, employment and communication

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routes into ArcGIS to forecast the generation of USW in India and improve the efficiency of collection routes by relocating USW containers. Nas et al. (2010) identified appropriate sites for landfills in Konya, Turkey, using ArcGIS with a multi-criteria evaluation analysis (MCEA). MCEA was used to weight the importance of urban settlements, roads, railways, agricultural land class, archaeological sites, wells, irrigational canals and land slope. The limitations of GIS were concluded to be the availability of relevant data.

The integration of USW data into GIS affords better designed and constructed models of urban areas to calculate variations in the generation of USW, which may result in reduced service costs (Karadimas and Loumos, 2008; Rada et al., 2013). Higgs (2006) combined GIS techniques with MCEA to accelerate decision making by including public opinion in the selection of programs to manage USW (De Feo and De Gisi, 2010; Castagna et al., 2013). By contrast, Chang et al. (2008) integrated environmental, bio-physical, ecological and socio-economic variables into ArcGIS to establish a spatial decision support system to select optimal sites to dispose of USW. A fuzzy multi-criteria algorithm using information on environmental impact, public transportation, aesthetic deterioration, and economic and public opinion, was run to select a landfill site.

GAs are widely used to automatically generate rules according to Fuzzy Rule Based Systems (FRBS) (Mohatar and Barranquero, 2007). Stockwell and Peters (1999) established that GAs represent a stochastic strategy to search in a space of potential solutions for a problem, such as modelling the laws of evolution with hereditary and environmental adaptations. The GARP has been used to model the ecological niche of a species, representing environmental conditions that are suitable to maintain their population.

Vioti et al. (2003) introduced a GA to solve the so-called "Travelling Salesman's Problem" (TSP), which is a typical approach to optimise waste collection routes. GAs are an alternative to traditional heuristic algorithms used to resolve the TSP, which lack precision and have long execution times. Vioti et al. (2003) referred to the projected algorithm as the Minimum Length Route (MLR), which requires several input parameters: number of nodes, distance between nodes, time required to empty the first waste container and to empty all the other containers, number and starting time of each time interval, costs of fuel and labor in each time interval, and name of street. The MLR algorithm was able to find faster solutions than the exact algorithm, and provided an improvement of 21% when compared with the heuristic algorithm. It was also applied to find the optimum collection route in a bourhood of Rome, Italy, and provided a 2% improvement compared with traditional algorithms.

Multi-Criteria Analyses (MCA) are required to make informed decisions due to the high number of variables and complexity of the management of USW. Karadimas et al. (2007) implemented GAs to simulate scenarios to optimise USW collection routes in Athens, Greece. They focused on optimising the collection and transportation of USW in containers by using six parameters to find possible solutions: iterations, population, children per generation, mutation policy and probability, and diversity threshold. It was concluded that GAs afforded a significant reduction of 9.62% of the waste collection route distance by comparison with the empirical method currently used by the municipality of Athens.

When conducting studies of USW generation, due to economical, logistic and operative constraints, the number of samples is typically the minimum statistically significant required. The use of GARP allows BGAs to be selected with socio-economic conditions within urban areas similar to those where analyses of USW generation are performed. It also allows the distribution of USW to be mapped within the urban areas. In this study, a GARP was used to find areas with socio-economic conditions that are representative of the generation of USW constituents in such areas.

2. Materials and methods

2.1. Study site and sampling campaigns

This study was carried out in Morelia, the capital city of the Michoacán state in western Mexico (Fig. 1). Morelia lies at an altitude of 1950 m above sea level, and covers an area of 1336 km^2. The climate is mild with an annual average rainfall of 770 mm and an annual average temperature between 14 and 18 °C. The population of the city is about 729,279 inhabitants (INEGI, 2010).

At Morelia, the collection, treatment and disposal of USW are co-ordinated by the municipal authority. The collection service is divided into municipal and private collection routes, which operate from Monday to Saturday and the whole week, respectively. USW is collected in plastic containers and plastic bags that are left outside dwellings, and in some neighbourhoods, at other designated sites, such as street corners according to established timetables. USW is commonly not separated, and only in few areas of the city are two fractions distinguished: (i) dry fraction (paper, cardboard, steel and plastic), and (ii) wet fraction (food and garden waste).

Two sampling campaigns were carried out in 1998 and 2004 to characterise the generation of USW in 229 and 269 dwellings, respectively. In each campaign, only dwellings with one family were found. Socio-economic data were obtained by conducting surveys. The sampled dwellings were chosen according to monthly income categorised into three socio-economic strata defined by INEGI (1990):

(i) Lower stratum: Up to 1 minimum wage monthly (Approx. $90.00 and $115.00 USD in 1998 and 2004, respectively).
(ii) Middle stratum: 1 to 2 minimum wages monthly (Approx. $182.00 and $230.00 USD in 1998 and 2004, respectively).
(iii) Upper stratum: 2 to 5 minimum wages monthly (Approx. $450.00 and $575.00 USD in 1998 and 2004, respectively).

Non-separated samples of USW generated at dwellings during the previous day were taken for further analysis in labelled plastic bags of size 60 × 90 cm. Sampling was carried out during 7 continuous days (one-week) according to the Official Mexican Standard (NMX-AA-061-1985; SECOFI, 1985). The collected plastic bags were weighed before separating the samples into individually weighed waste constituents (SECOFI, 1985). 65 different waste constituents were identified during both sampling campaigns (Table 1).

2.2. GARP description

GARP is an expert-system, machine-learning approach to predictive modelling (Stockwell and Noble, 1992; Stockwell and Peters, 1999). It uses an iterative process of rule selection, evaluation, testing, and incorporation or rejection. A method is chosen from a set of possibilities (e.g. logistic regression and bio-climatic rules), applied to training data, and a rule (which take the form of IF/THEN statements) is developed or evolved. Rules may evolve by several means that mimic DNA evolution: point mutations, deletions, crossing over, etc. Change in predictive accuracy from successive iterations is used to evaluate whether a certain rule should be incorporated into the model, and the algorithm either converges or runs 2560 iterations. When this process ceases, the model is projected back onto the landscape to predict geographical distributions in the form of a raster data grid, in which each square cell is designated as present or absent. Two types of data input are required to develop the spatial distribution: (i) location data points, which are the centroids of the study areas (BGAs), and (ii)

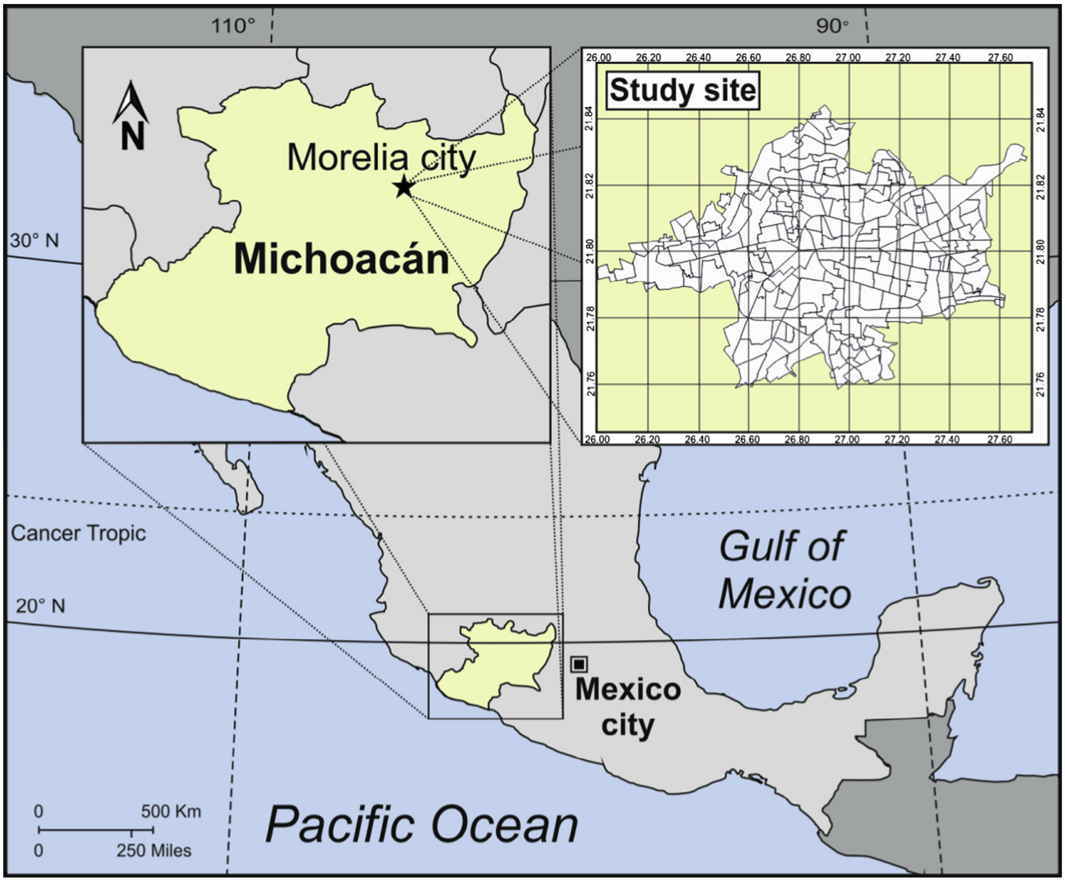

Fig. 1. Location map of the study site. The upper right panel shows the distribution of the BGAs sampled and surveyed as defined by INEGI in the 2000 NPC.

a set of socio-economic variables, that describe the geographic area, and are stored as a grid of cells (raster data).

2.2.1. Location data points

The centroid of a polygon is generally defined as the mean position of all points within that polygon. Centroids were calculated using the procedure of Jenness (2006), which requires a polygon layer theme, i.e. the BGAs. This method generates a point layer that was used as the location data. Centroids were calculated for two socio-economic strata: lower and middle.

2.2.2. Socio-economic raster data layers

Table 2 shows the 32 socio-economic variables chosen from the 2000 NPC (INEGI, 2000) to construct the models. ArcView 3.2 software (ESRI, 1996) was used to construct the raster data set, with each variable associated to the BGAs vector theme and rasterized to a cell size of 0.000278° × 0.000278° (about 30 × 30 m). Socio-economic layers were transformed to a raster grid format of 590 columns × 363 rows, and saved in ASCII arcraster format, with geographic co-ordinates in decimal degrees and WGS84 datum.

2.3. GARP spatial distribution model

The spatial distribution of USW was modelled using the GARP (Stockwell and Noble, 1992). GARP predictions were generated using Desktop GARP v1.1.6 (Scachetti-Pereira, 2001). 100 prediction maps were generated for each stratum using 50% of the location data point set, with a convergence limit of 0.01 and a maximum of 1000 iterations per model. The ten best subsets were chosen using a soft extrinsic measure of 20% omission and 50% commission. The geographic predictions of these 10 models were summed to provide a summary of potential geographic distributions for the areas of similar USW. This consensus map has a value range from zero (no model predicted suitability) to 10 (all best subset models predicted). Model predictability was assessed and validated via the coincidence of 50% random subsets of available information from model building and geographic predictions. This coincidence was evaluated using a chi-square statistical analysis that summarizes the predictive performance of the model above and beyond that expected at random (Peterson, 2001). The models generated were cross tabulated against data from sampled dwellings to produce the spatial distribution of USW.

2.4. Data analyses

The dataset was analysed extensively with the JMP®, software version 8. SAS Institute Inc., Cary, NC, 1989-2007.

Firstly, a correspondence analysis (CA) was performed to verify whether the monthly income data from sampled dwellings agreed with the socio-economic data reported for each stratum in the NPC (2000). This was necessary as in Mexico the physical location of some dwellings does not necessarily correspond with their official socio-economic classification (Buenrostro et al., 2001). Secondly, a rank in one criterion analysis of variance (Kruskal–Wallis) was carried out to examine the statistical relation between each waste constituent and socio-economic data. Then, a MANOVA was performed with the waste constituents that presented individual statistical differences to determine whether statistically significant differences were observed relative to the total generation of USW. Finally, a principal component analysis (PCA) was carried out using

Table 1
Daily production of identified by-products during the 1998 and 2004 sampling campaigns.

By-product*	Stratum					
	Lower		Middle		Upper	
	1998	2004	1998	2004	1998	2004
Cotton	2.5	1.7	0.0	1.7	0.5	3.3
Cardboard	61.2	77.4	53.1	299.5	62.5	344.5
Leather	0.8	2.3	4.0	3.8	0.4	1.6
Fine residues	0.0	2.7	0.0	1.8	0.0	1.8
Unidentifiable material	0.0	45.1	0.0	30.5	0.0	24.7
Wax cardboard	0.0	0.2	1.0	5.7	0.4	3.3
Tetra pack	2.5	12.0	19.3	65.1	30.1	82.2
Tetra brick	0.9	2.7	8.6	17.5	0.1	20.4
Waxed paper	1.4	1.3	0.0	2.2	0.3	3.2
Hard plant fibre	6.9	177.2	3.9	173.0	17.6	203.3
Synthetic fibre	6.6	12.6	4.2	31.5	0.8	25.4
Bone	11.5	2.8	32.2	4.7	17.3	5.8
Rubber	1.6	2.5	4.3	18.7	0.8	5.7
Ceramic and shreds	22.0	10.4	13.2	7.6	5.4	10.0
Wood	40.6	14.0	0.0	8.5	4.6	18.7
Construction/ demolition material	6.7	3.1	0.9	41.2	0.0	52.1
Aluminium	1.0	3.3	6.5	18.0	1.9	16.8
Tin	1.6	12.4	1.9	85.9	0.3	80.2
Ferrous material	38.3	9.5	36.6	14.7	36.7	18.0
Paper	75.7	70.0	90.0	411.4	140.0	405.6
Toilet paper	50.9	99.1	118.2	290.4	103.7	346.2
Baby Diaper	317.7	371.0	183.6	201.1	84.4	246.4
Adult Diaper	0.0	7.4	0.0	33.1	0.0	42.5
Feminine towels	0.0	9.9	4.3	10.1	5.8	10.8
Faeces	9.2	0.2	4.8	18.2	3.8	23.4
Snack packaging	9.2	14.3	3.0	21.5	2.5	24.0
Plastic film	109.6	83.1	74.3	138.0	76.5	150.8
Foil pouch	1.7	1.9	0.2	11.3	1.3	11.1
Rigid plastic	26.6	44.8	41.1	83.0	30.5	99.5
PET	36.1	56.5	35.1	182.7	26.8	199.9
HDPE	8.5	10.0	31.3	131.2	37.5	122.7
Polyvinylchloride	6.9	2.5	0.5	4.9	5.6	3.6
Carboy	3.8	8.4	0.2	5.8	2.3	6.6
Polyurethane	2.0	3.1	0.5	18.6	0.2	5.5
Polystyrene	3.2	9.5	7.1	26.1	11.9	29.7
PP	3.8	3.7	9.1	16.4	8.1	20.2
Food waste	942.2	852.8	1372.6	2383.2	1520.3	2743.7
Garden waste	0.0	102.5	77.9	405.5	313.0	362.5
Clothing	94.5	32.1	7.7	40.8	28.2	38.9
Unstained glass	88.3	57.1	121.8	147.4	125.9	171.7
Stained glass	2.1	5.0	10.7	42.5	1.9	49.1
Batteries	2.3	1.3	1.9	1.7	0.0	1.3
Dust	286.2	74.3	29.1	25.5	17.1	24.4
Cellophane	11.7	0.3	7.0	3.1	7.5	1.2
Electronic waste	5.9	1.9	0.0	1.8	0.0	1.4
Butts	0.0	0.3	0.7	4.2	0.6	0.6
Stone	0.0	6.2	0.1	0.2	3.3	0.0
Clay	0.0	0.1	0.1	0.1	0.0	0.0
Washing powder	0.0	0.0	0.0	2.1	0.0	2.5
Viscera	0.0	0.0	4.6	1.1	7.0	1.4
Hazardous waste	0.0	3.9	0.4	9.3	1.6	9.9
Shoes	0.0	15.4	2.0	9.4	0.0	5.6
Hair	0.0	0.1	0.0	0.5	0.0	0.6
Wax	0.0	1.1	0.0	0.8	0.0	0.5
Feathers	0.0	0.0	0.0	0.1	0.0	0.0
Filters	0.0	0.0	0.0	0.0	0.0	0.0
Broom	0.0	0.2	0.0	1.6	0.0	2.7
Ash	0.0	8.6	0.0	0.0	0.0	0.0
Coal	0.0	1.7	0.0	0.0	0.0	0.0
Latex gloves	0.0	0.0	0.0	0.1	0.0	0.2
Flour	0.0	0.7	0.0	1.2	0.0	1.5
Straw	0.0	0.0	0.0	0.0	0.0	0.0
Eraser	0.0	0.0	0.0	0.0	0.0	0.0
Total	2304.1	2354.3	2429.3	5517.5	2746.9	6089.0

* Daily production is expressed in grams of fresh weight d^{-1}.

the 65 waste constituents observed during both sampling campaigns to identify those that showed minimum significant differences (MSD) among strata and linear relationships between the generation of waste constituents and socio-economic variables.

3. Results and discussion

3.1. Correspondence analysis

229 and 267 sampling bags were recovered from the selected dwellings in the 1998 and 2004 sampling campaigns, respectively, which represented 71.0% and 81.7% of recovery (at least 70% of recovery was required to validate the analyses). Samples were discarded when data from the surveys showed that dwellings did not correspond to their official socio-economic classification. Table 3 shows results of the CA performed. The numbers in brackets show the percentage of dwellings that corresponded to their official allocated socio-economic stratum. In the 1998 campaign, correspondence of 50.8% in the lower stratum and 64.3% middle stratum is evident, with 72.4% and 52.0% of correspondence observed during the 2004 campaign.

3.2. Principal component analysis

Table 4 shows the results of the PCA performed. In 1998, high density polyethylene (HDPE), polypropylene (PP) and dust showed MSD ($p < 0.05$). Interestingly, the generation of HDPE and polypropylene was highest in the middle stratum, which may be due to widespread use of plastics for packaging in the food and liquid cleaner industries. Most dust was generated in the lower stratum and is attributed to dwellings without hard floors frequently found in large areas under development within the city (Buenrostro et al., 2001). Aluminium was more abundant in 1998 than in 2004 possibly due to substantial increases in cost and recycling in relation to HDPE. In 2004, MSD ($p < 0.05$) were observed for cardboard, non-identifiable material, ceramics, paper, polyethylene bag, PET (Polyethylene Terephthalate), rags and stained glass. HDPE and polypropylene production was more significant during 1998 than in 2004, when the volume of plastic bags and PET increased, probably due to their use as packaging for snack foods.

The predominance of plastic bags in the lower stratum reflects consumption patterns in shops that usually provide free plastic bags. Conversely, people from the middle and upper strata tend to buy in wholesale shops with goods moved directly from shopping carts to cars. Thus, there are relationships between the generation of cardboard and polyethylene bags with socio-economic strata. Paper is observed predominantly in the upper stratum, and is related to higher levels of education with at least one family member studying, and to a greater proportion of families that have access to information and communication technologies.

The highest generation of rags was observed in the lower stratum, which is attributed to limited opportunities to acquire good quality clothing which may lead to the wearing of second-hand clothing that is not long-lasting. By contrast, families in the upper stratum tend not to discard their clothes, but donate them to collection centres or sell them at flea markets.

The PCA analysis in Table 5 shows that five socio-economic variables were related to different waste constituents in 1998 and 2004. Household size, number of children in the household, and car ownership were related to HDPE, PP and dust in 1998. By contrast, in 2004, household size, adults in the household and monthly income were related to cardboard, LDPE (Low-Density Polyethylene) and PET.

Table 2
Socio-economic variables chosen to construct the models derived from the 2000 NPC.

Socio-economic raster data layers
Total population
Male population
Female population
Population 15 years and over without instruction
Population 15 years and over with incomplete primary school
Population 15 years and over with complete primary school
Population 15 years and over with secondary education or technical or commercial studies with primary school
Population 15 years and over with complete studies of secondary school
Population 15 years and over with incomplete studies of secondary school
Population 18 years and over without high school studies
Population 18 years and over with high school studies
Population 18 years and over without college education
Population 18 years and over with college education
Average level of education
Economically active population
Economically inactive population
Unemployed population
People employed as an employee or worker
People employed as a laborer or pawn
Self-employed population
Employed population who worked up to 32 h in the reference week
Employed population who worked 33–40 h in the reference week
Employed population who worked 41–48 h in the reference week
Employed population that does not receive income from work
Employed population receiving less than the minimum monthly salary
Occupied population receiving 1 and up to 2 minimum monthly salaries
Occupied population receiving 2 and up to 5 minimum monthly salaries
Occupied population receiving more than 5 minimum monthly salaries
Total occupied dwellings
Total occupied dwellings by owners
Private dwellings with own car or truck
Average occupants in private homes

Table 3
CA of samples carried out during the 1998 and 2004 campaigns.

Year	1998			2004		
Stratum	Lower	Middle	Upper	Lower	Middle	Upper
Low	33 (50.8)	17 (17.3)	7 (10.6)	55 (72.4)	33 (26.0)	6 (9.4)
Middle	20 (30.8)	63 (64.3)	25 (37.9)	15 (19.7)	66 (52.0)	16 (25.0)
High	12 (18.5)	18 (18.4)	34 (51.5)	6 (7.9)	28 (22.0)	42 (65.6)
Total	65	98	66	76	127	64

Columns correspond to the number of dwellings sampled divided by socio-economic stratum according by INEGI. Rows classify dwellings from data obtained during the conducted survey. The numbers in brackets indicate the percentage of dwellings that corresponded to their official allocated socio-economic stratum.

Table 4
Waste constituents that showed MSD according to socio-economic stratum within the PCA analysis (Generation in grams of fresh weight week^{-1}).

Waste constituent	Low stratum		Middle stratum		High stratum	
	1998	2004	1998	2004	1998	2004
Aluminium	56.5		571		104	
HDPE	520		2833		1905	
Polypropylene	214		870		429	
Dust	12,590		3617		605	
Cellophane	476.05		758.5		428	
Cardboard		43,639		50,307		76,722
Non-identifiable material		25,200		9145		5667
Ceramics		5892		4825		2073
Paper		39,461		65,133		92,365
Polyethylene bag		46,885		37,698		34,716
PET		31,875		33,024		41,987
Rag		18,116		11,921		8997
Stained glass		2799		18,464		8319

The studies of USW generation carried out in 1998 and 2004 covered the intermission of the NPC conducted by INEGI in 2000. Therefore, geographic information available from the 2000 NPC was included to correspond with the 2004 sampling campaign. Based on the statistical analyses of samples collected in both campaigns, it was observed that USW composition was different because some waste constituents were observed in 1998 but were absent in 2004. According to Buenrostro et al. (2008), these changes are result of urbanisation and changes in consumption patterns that yield wastes with a higher level of industrialisation. A hallmark of the two periods is that highly recyclable waste constituents such as HDPE, PP, PET and cardboard become more important for the packaging industry, as they showed MSD among strata. Results also showed that the socio-economic stratification from INEGI (2000) were in good agreement with patterns of the generation and composition of USW.

3.3. Multivariate analysis of variance

MANOVA was used to investigate statistical differences within socio-economic strata during 1998 and 2004. Results showed MSD ($p < 0.05$) for waste constituents generated in the three strata

Table 5
Socio-economic variables that showed positive correlation with the generation of waste constituents during 1998 and 2004.

Socio-economic variables	Waste constituent	
	1998	2004
Household size	HDPE	Cardboard
Children in the household	Polypropylene	
Car possession	Dust	
Adults in the household		LDPE
Monthly income		PET

in both sampling campaigns. Interestingly, USW composition was related to patterns of household income, education and number of family members (Table 5), with paper and PET production ascribed to the middle and upper strata.

3.4. Relationship between waste constituents and socio-economic variables

PCA was used to investigate relationships between waste constituents and socio-economic variables for the 1998 and 2004 sampling campaigns. In 1998, the lower stratum showed positive correlation ($p < 0.05$) between dust production and the number of children per household without a car. By contrast, a weaker correlation was observed ($p > 0.05$) between the generation of polyethylene and polypropylene with monthly income. In 2004, education and monthly income were positively correlated ($p < 0.05$) with polyethylene bags, PET and cardboard in the middle stratum. Conversely, a weaker correlation ($p > 0.05$) was observed between the generation of PET and the number of adults per household in the lower stratum.

3.5. Spatial analysis of USW generation

Maps of the spatial generation of waste constituents by BGA and socio-economic stratum were produced using information from the 2000 NPC (INEGI, 2000). In 2004, non-separable material, rags and polyethylene bags were the largest waste constituents generated in the lower stratum. Fig. 2a shows the map for non-separable material by BGA. The BGAs with the largest daily production rate of non-separable material up to 59.3 g fresh weight d^{-1} were located on the outskirts of the city. This is due to the lack of a regular USW collection service that causes accumulation of a heterogeneous mix of waste. By contrast, at the city centre and BGAs of the upper stratum, the daily production of non-separable material ranged from 0 to 0.15 g fresh weight d^{-1}. At BGAs of the upper stratum, the waste collection service operates regularly, and inhabitants tend to separate waste prior to collection.

The production of rags by BGA is shown in Fig. 2b, and ranged from 0 to 49.1 g of fresh weight d^{-1}, with the largest production at the lower stratum. People in the lower stratum on low incomes tend to discard relatively poor quality damaged clothes, which leads to an increase in the generation of rags. Interestingly, non-separable material showed similar generation patterns to rags and was also related to socio-economic variables. Polyethylene bags were predominantly generated in the lower stratum as shown in Fig. 2c. In this stratum, householders tend to buy goods frequently in small quantities, and are given free polyethylene bags, which increases waste generation.

In the middle stratum, coloured glass was the prevalent waste constituent generated, as shown in Fig. 3a. The generation of coloured glass was concentrated at BGAs located within the city centre, and was minimal at BGAs of the lower stratum. Fig. 3b shows the spatial generation of ceramics, which is similar to that of coloured glass, and is probably due to the high density of hotels and restaurants in the city centre that dispose of old and broken ceramics. Fig. 3c shows that paper generation by BGA was widely distributed and that the largest production was around the city centre. This contrasts with the production of other waste constituents such as polyethylene bags and coloured glass, which were produced mostly in specific strata.

The generation of PET was positively associated to the number of inhabitants by BGA (Fig. 4a). Finally, Fig. 4b shows that the generation of paper and cardboard was concentrated at the city centre and decreased towards the outskirts. This could be attributed to the presence of departmental shops and supermarkets that produce large quantities of such waste constituents. Indeed, at some BGAs of the city centre where few or none of these shops are located, paper and cardboard generation was observed to be minimal compared with adjacent BGAs.

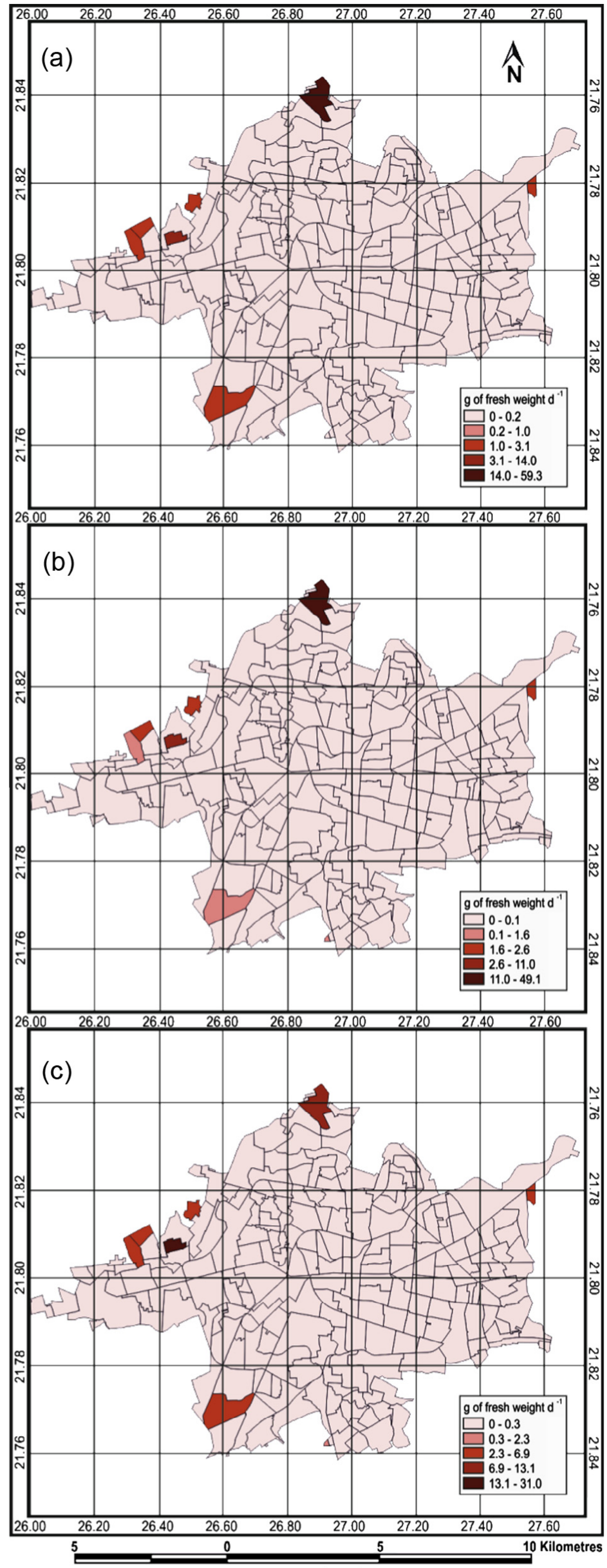

Fig. 2. Spatial representation by BGA in Morelia city of the generation of: (a) non-separable material, (b) rag, and (c) polyethylene bag. BGAs were defined from the 2000 NPC (INEGI, 2000).

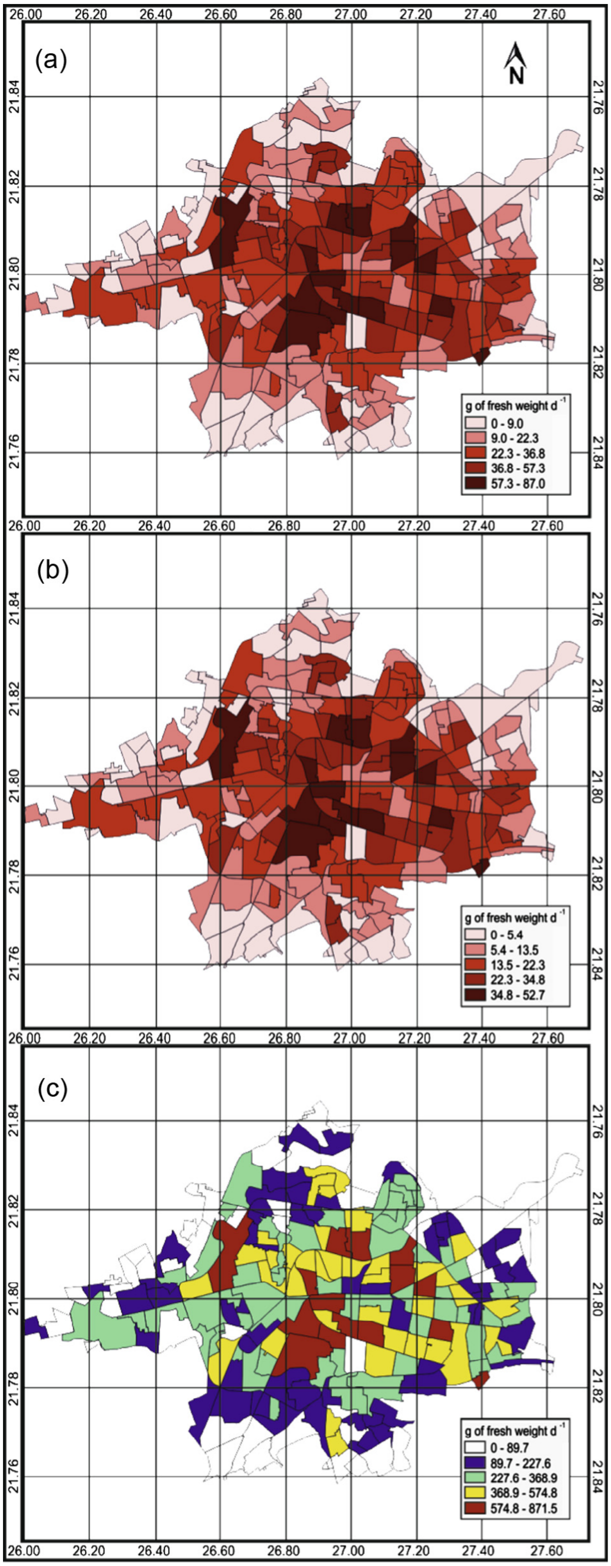

Fig. 3. Spatial representation by BGA in Morelia city of the generation of: (a) coloured glass, (b) ceramics, and (c) paper. BGAs were defined from the 2000 NPC (INEGI, 2000).

Dust generation was predominant in BGAs mainly of the lower stratum, where dwellings tend to lack solid floors, and inhabitants dispose of dust following daily floor sweeping. It is also related to the lack of basic services, such as potable water and street lighting,

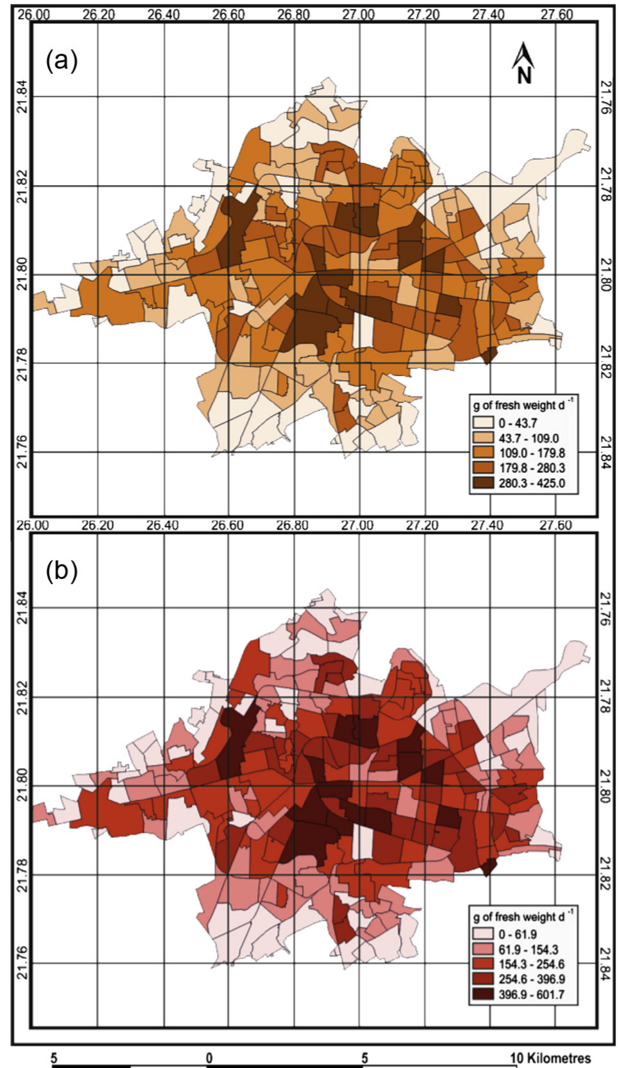

Fig. 4. Spatial representation by BGA in Morelia city of the generation of: (a) PET, and (b) cardboard. BGAs were defined from the 2000 NPC (INEGI, 2000).

which affects the operation of the USW collection service. A positive relationship between monthly income and waste constituents generated was also observed, and this may be because inhabitants from the middle and upper strata buy and dispose of larger quantities of highly industrialised products than inhabitants in the lower stratum. Finally, the same relationship was clearly observed in the production of PET.

4. Conclusions

In this study, a GARP was used to identify areas with particular socio-economic conditions that represent the generation of USW. The classification by socio-economic stratum for sampled households and collected USW was in good agreement with the 2000 NPC data. A positive relationship was observed between monthly income and volume and type of waste constituent generated by BGA. The spatial variations observed in waste constituents generated during the sampling campaigns carried out corresponded with the socio-economic stratification reported by INEGI. The socio-economic variables considered in the present study can be used to produce databases of USW in other cities with similar characteristics. Such databases may also be used to design and improve USW management and to increase recycling.

Increases in population are likely to affect services of USW management. Modelling USW generation by BGAs in maps can assist local authorities to forecast future needs. Maps of USW generation can also provide information of areas where environmental education must be improved in order to reduce the generation of USW. The GARP run in the present study successfully modelled the generation of USW according to socio-economic data recorded, and allowed meaningful comparison with data bases generated by the local authorities. The modelling of sampling data representative of spatial variations of USW generation in Morelia, Mexico, is relevant to improve the strategies and collection routes of USW.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.wasman.2015.03.026.

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