Inventory parameters for regionalised mixes of municipal waste disposal in ecoinvent v3.5

Technical report
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Title picture Waste container probably near Nei Pori Platamonas, Greece, in September 2017. The picture illustrates the boundary between collected and uncollected waste. The collection rate of waste plays a crucial role in the estimation of waste fates elaborated in this report. From https://pixabay.com/de/m%C3%BCll-m%C3%BCllcontainer-abfall-2729608/

Significant digits Figures in this report often feature several digits. This is not to imply that all the shown digits are really significant or that the data displayed is very precise. Showing several digits helps to minimise the avoidable accumulation of rounding mistakes along the chain of calculations performed here, and in possible future studies referring to this data.

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Contents

1 Summary

In the present report, the raw data necessary to inventory regionalised disposal mixes of municipal waste in the ecoinvent database are presented. On one hand, new material-specific **disposal activities** need to be created, like open burning of wood, or inventories for unsanitary landfilling. This is basically the application of the regionalised waste tools presented previously in (Doka 2017a–c). On the other hand, regionalised **disposal treatment markets** need to be created that describe which kind of technology mix is employed in for waste disposal in a particular geographical region.

For the first part of creation of new disposal activities, selections are made on a) which materials and their disposal are useful to have in a backgrounds database like ecoinvent and b) which disposal technologies are employed. As materials of interest a range of **generic packaging materials** are selected, which are bound to be generated in a large number of activities, as opposed to very specific waste materials which are only applicable to one particular kind of process. Waste material composition, i.e. elemental ultimate analysis, is not regionalised here and the available data already compiled in (Doka 2003) is used. Employed disposal activities in the model encompass a selection of unmanaged activities (open burning, open dumping), and activities managed to different degrees (unsanitary landfill, sanitary landfill, municipal incineration). Inventories for the latter two (sanitary landfill, municipal incineration plant) already exist in the database (for Swiss conditions) and are not regionalised at this time, in order to keep the number of new datasets at a low level. **New activities are open burning, open dumping and unsanitary landfill**. The influence of the local climate on dumps and unsanitary landfills is heeded in the models of (Doka 2017b). Again in an effort to keep the number of new datasets manageable, we decided to create **five different climate classes** based on annual water infiltration to discern the different local conditions, instead of inventorying the activities of each country with their specific climate.

For the second part of regionalised disposal treatment markets, a methodology is devised that allows the calculation of a disposal market mix (waste annual production volume) based on a country's available statistical data and extrapolations. This framework is set up so that even in a country with nothing more than a figure for its Gross National Income per capita (GNI) an educated guess on its disposal market mix can be obtained. Available statistical data on actual waste disposal management are of course used with preference. From the present project, ecoinvent inventories for market mixes for 37 European countries are created, plus five focus countries of the Sustainable Recycling Initiative SRI (Brazil, Colombia, Peru, India, South Africa). The devised methodology allows to create additional market mixes for other countries in the future as well as inputs of updated statistical data. The elaborated data is available as supplemental Excel table for 218 countries and territories.

2 Introduction

In many world regions waste disposal consists to a large degree of very basic and very detrimental technologies. Uncontrolled open dumping and open burning of waste is common especially in economically less wealthy regions[1]. Although this situation has improved, such basic disposal technologies still abound. In the ecoinvent LCI database, which was at its very initial origin in 1992 focused on the Swiss consumption situation (see e.g. Suter et al 1992), any disposal activities were heeded with Swiss disposal technologies: municipal incineration with elaborate flue gas cleaning, well-engineered sanitary landfills with landfill gas capture and leachate treatment, or well buffered

[1] The word "technologies" applies only in a loose sense to these normally unplanned ad hoc activities. But as man-made activities they plainly belong to the technosphere of LCA.

residual material landfills for polluted inorganic waste. In lieu of other data these Swiss activities were usually used also for disposal processes abroad as approximations. As ecoinvent grew, disposal remained based on these rather high-tech Swiss disposal technologies, although the scope of activates in ecoinvent kept expanding into very diverse geographic regions.[2]

In (Doka 2017a–e) the calculation tools to create waste-specific disposal LCIs were expanded to include also more low-tech disposal processes as they occur in many areas of the world: Open burning, open dumping, unsanitary landfills.[3] This report provides a framework and obtains the user-defined information required to create country-specific disposal LCIs.

The waste fates elaborated in this report are for *mixed municipal waste* and their component waste fractions. This is a waste mixture from households, small businesses, offices and possibly also street sweepings which is disposed as a mixed conglomerate. Source-separated waste that goes to recycling is not part of this report's fate model, since such recycled waste depends strongly on the original material usage. It is important to realize that recyclability is not a mere material property, but also a characteristic of the *specific product application*[4]. When a material is recycled it will usually be binned differently in the real world at the waste-producing location and thus for LCI must also be inventoried separately from the mixed waste stream which goes to another bin altogether.

The waste materials targeted in this report's model are common, generic materials usually used in packaging going to mixed municipal waste. Specific wastes of specific industries, e.g. inorganic residues from manufacture of product X must be inventoried separately with their specific composition and their likely treatment route.

3 Municipal waste disposal technology mix

In (Doka 2017a–e) several tools were elaborated that allow the creation of material-specific and country-specific waste disposal inventories. Following waste disposals were targeted:

Index	**Technology**
(d)	Open dump (unmanaged)
(b)	Open burning (unmanaged)
(u)	Unsanitary landfill (minimal management)
(s)	Sanitary landfill (managed plant)
(m)	Municipal incineration (managed plant)

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2 For some wastes also disposal technologies were inventoried early on, which were not based in Switzerland, i.e. storage of hazardous waste in deep underground salt mines in Germany, or "landfarming" which is spreading waste sludges on land for accelerated degradation.

3 At the same time the Swiss disposal models for municipal waste incineration and sanitary landfills received an interface which allowed the user also to define certain plant-specific technology parameters like energy yields or DeNOx technology mix, not only define a specific waste composition. The wastewater treatment tool remains not updated and is still representing Swiss WWTPs of the year 2000 (Doka 2003-IV).

4 For instance *glass bottles* might well be recycled and put into a glass recycling bin, if the consumer chooses so. Recycling of glass in *fibreglass-reinforced polymers* cannot be recycled via such a glass recycling bin, since the consumer will hardly be able to separate the two combined materials. In this case the recyclabilty of glass is entirely determined by the *specific product application*, and not by composition or intrinsic properties of the glass itself.

To depict the waste treatment in a country accurately, the technology mix of those disposal pathways must be known. Good statistics of waste management are often difficult to obtain – especially for unmanaged and uncontrolled processes.

A procedure is elaborated here to estimate waste disposal mix based on available statistics and extrapolations, cf. Fig. 3.1 below. The overview of the procedure is as follows:

- Generated waste must be distinguished from waste collected. Uncollected waste can be assumed to be disposed in an unmanaged fashion, i.e. in **open dumps** and **open fires**.
- Some collected waste can still end up in unmanaged disposals, in regions where funds are low to finance collection together with a managed disposal.
- Even in managed landfills, **landfill fires** can occur. It is proposed here that the waste burned in landfills shall ultimately be inventoried as open burning, not as landfilling.
- A large part of managed waste disposal will usually be **unsanitary landfills**. In (Doka 2017b) these were managed landfills where waste is compacted and a daily cover is applied. This mitigates the direct unhygienic effects of dumps, but emissions to air or water remain unmitigated.
- To mitigate environmental effects further, **sanitary landfills** capture some landfill gas and treat the leachate. In LCA results the flaring or utilization of landfill gas is the most relevant difference compared to unsanitary landfills. Where information is available on landfill gas utilisation, it can be incorporated into the technology mix.
- **Municipal incineration** plants are costly investments and are currently only observed in countries with a Gross National Income (GNI) above 10'000 $/capita.yr. In countries below that threshold incineration can very likely be excluded.

So the fate of waste is seen here as the result of the interplay of several stages: Collection, management of collected waste, and occurrence of fires in dumps/landfills. These stages will now be elaborated. The compiled country-wise data is available as a supplementary Excel table "WasteDisposalMix+APV_v0.3.xls".

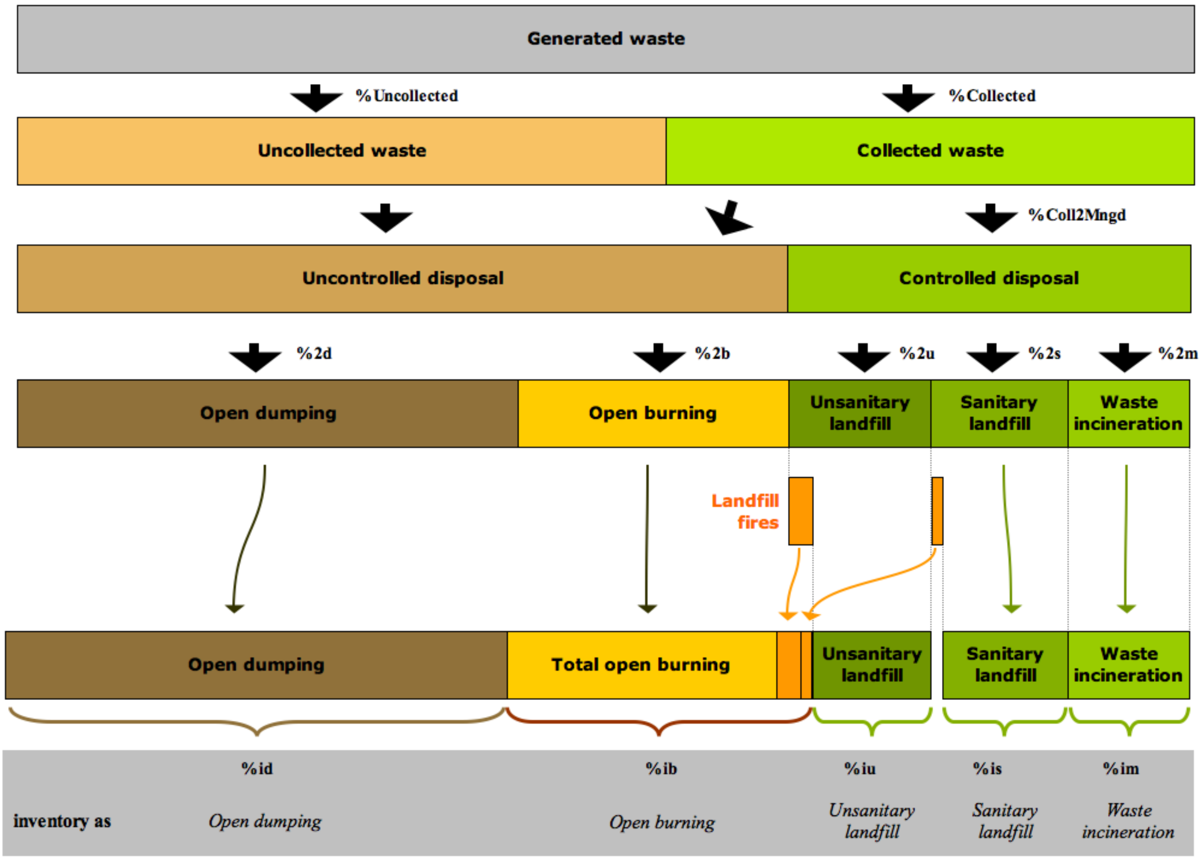

Fig. 3.1 **Scheme of calculation of an inventoried waste disposal mix. Arrows indicate waste material flow.**

3.a Collected waste

Data on percentage of the population being served by waste collection is compiled for example in UN statistics for 149 nations.[5] This data includes both waste collected by municipalities and the private sector. In absence of better data this figure is taken to be identical to the rate of mixed municipal waste being collected regularly.[6] Uncollected waste can reasonably be assumed to be disposed in an uncontrolled manner, as it fails to enter a proper waste management already at the waste generator. So the waste collection rate gives a starting point.

Eq. 3.1 $$Collected\% = between\ 0\ and\ 1$$

Collected% percentage of generated waste being collected, in mass-percent of generated waste.[7] (see Fig. 3.1)

If collection rates are not available, an extrapolation can be used which was developed in (Doka 2017a) based on the Gross National Income per capita (GNI) using the following formula. Data on

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5 See (UNstats 2016). Some data gaps were filled with data from (Hoornweg et al. 2012), but only when referring to a country-averages, and not urban collection rates. For India and South Africa collection rates were calculated from data in (Chalmin & Gaillochet 2009).

6 This ignores differences in waste production in the population.

7 As always, 100% equals 1. "%" is not a physical unit, but only a way to write a number.

GNI is from World Bank using the Atlas method and expressed in current US$.[8] The GNI approximation for the waste collection rate is only used for 55 countries/territories covering 11.4% of the world's population, while statistical data on the waste collection rate is available for 171 countries representing 88.2% of the world's population. In all a waste collection figure can be obtained for 226 countries covering 99.6% of the world's population.

Eq. 3.2 $$Collected\% = 1 - e^{(-0.000332 \cdot GNI)}$$

Collected%	Estimation for percentage of generated waste being collected
GNI	Gross National Income per capita in $/cap.yr

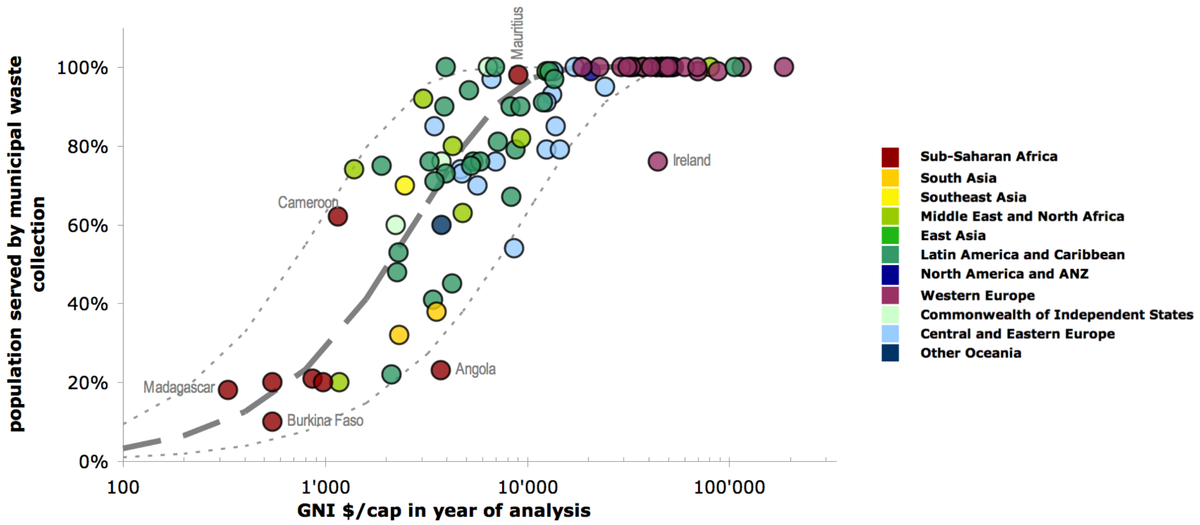

Fig. 3.2 **Municipal waste collection in various countries plotted against Gross National Income (GNI) per capita.[9] Colours indicate world regions. Lines indicate a logistic growth according to Collected% = 1–exp(–k* GNI) with a median of k=2.75E-4. Some data relating to urban areas only was not included (Kenya, Tunisia)**

3.b Uncontrolled vs. controlled disposal

It is assumed that uncollected waste will be disposed in an uncontrolled manner. Additionally, also some part of the collected waste can be assumed to end up in uncontrolled, unmanaged disposals. To model this effect, it is assumed that this occurs increasingly so in countries with low collection rates. The rationale for this is the tendency that municipalities which have (usually financial) problems in performing waste collection will tend to have problems in performing managed disposals. See Fig. 4.1

8 http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators (10 Dec 2016). Data gaps for some smaller countries are filled with estimates based on GDP (for the Vatican and some small islands: American Samoa, Aruba, Cayman Is., Curacao, Guadeloupe, Guam, Northern Mariana Is., Reunion, Sint Maarten, Somalia, St Martin, Turks & Caicos, Virgin Is. (Brit)).

9 Data on MSW collection is from UN Statistics Division, based on UN questionnaires, EU or OECD statistics, "Total population served by municipal waste collection" (https://unstats.un.org/unsd/ENVIRONMENT/Time%20series.htm#Waste, released Sept 2016). GNI data was matched to the year the collection data was measured. Data on GNI is from World Bank using the Atlas method and expressed in current US$ http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators (10 Dec 2016).

in (Doka 2017a) for an illustration of this for the member states of India, detailing the percentage of open dumping of *collected* waste. In the present study the fraction of collected waste being delivered to a managed, at least minimally controlled disposal is estimated using following expression:

Eq. 3.3 $$Coll2Mngd\% = 1 - \left(1 - Collected\%^{\,3}\right)^4$$

Coll2Mngd% part of collected waste going to managed disposals (unsanitary landfill, sanitary landfill, incineration) (see Fig. 3.1). Please note the two exponents 3 an 4 in the formula.

For large collection rates, the fraction of collected waste going to managed, controlled disposals is large: e.g. for a 90% collection rate the managed fraction is 99.5%. If the collection rate in a country is for instance 70%, Coll2Mngd% equals 81%, which means only 56% of the generated waste will be going to managed disposals (=70% · 81%). The formalism itself and the exponents in the formula are tentative guesses and rather uncertain.

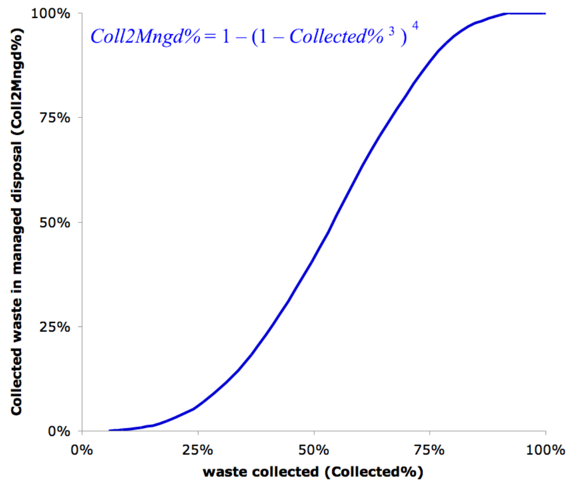

Fig. 3.3 Fraction of collected waste being delivered to a managed, at least minimally controlled disposal, in dependence of the waste collection rate

Eq. 3.4 $$Mngd\% = Collected\% \cdot Coll2Mngd\%$$

Mngd% part of generated waste going to managed disposals (unsanitary landfill, sanitary landfill, incineration)

With this we can now determine the part of the generated waste going into *unmanaged, uncontrolled disposals*: this is simply the remainder of the generated waste not going to managed disposals. This is also equal to the sum of uncollected waste and the part of collected waste *not* going to managed disposals.

Eq. 3.5 $$Unmngd\% = 1 - Mngd\%$$

Unmngd% part of generated waste going to unmanaged disposals (open burning , open dumping)

As unmanaged waste disposals only open dumping and open burning are considered in this report.[10]

3.c Open burning

Open burning of waste will be one option of unmanaged waste disposal. It is not surprising that information on open burning rates are hard to obtain.[11] Fortunately some helpful information can be found in (Maxson 2009). There, open burning rates of waste were determined for global subregions based on expert judgment, see Tab. 3.1 below. The original purpose of Maxson's study was to estimate global mercury emissions and it was used in the UNEP Global Mercury Assessment (UNEP 2013:105).

In the present study the Maxson's waste burning rates were compared with Gross National income per capita (GNI) in those global subregions and a rather reliable correlation was found (see Fig. 3.4 and Eq. 3.6 below). In absence of better information it is therefore suggested here to use available GNI data of countries to derive waste-burning rates. This can be seen as a kind of formalised educated guess, in absence of proper country-specific statistical data on burning rates. Please note that the basis of the rates provided below ($\%b_u$, $\%b_r$) is the mass of waste in *uncontrolled disposal*, not the total waste mass generated. So to apply these rates, the fraction going to unmanaged, uncontrolled disposal needs to be first determined, using Eq. 3.5 above.

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10 Other fates in uncontrolled disposal are imaginable. The open dumping model assumes waste stays on land. In the real world waste can also be windblown, eroded or dumped directly into rivers and sea (see chapter 'Outlook' in Doka 2017b). Some organic and food waste might be consumed by wild or domesticated animals (cows, pigs, donkeys etc). These effects are not covered in the present inventory model.

11 National greenhouse gas inventories feature emissions of CO_2 from open burning of waste under the entry "5.C.2. Open Burning of Waste" for the 43 different Annex I countries (UNFCC 2018). But only six of those countries report non-zero emissions of open burning of municipal waste (United Kingdom, Denmark, Estonia, Ireland, Turkey, Liechtenstein) which are mostly high-income countries. In contrast low-income countries where – according to the following elaborations – open burning might be suspected to occur with some regularity like Ukraine, Bulgaria, or Belarus report the issue to be "not observed" or "not applicable". So this seems to be rather a lack of reporting diligence. In the 73 non-Annex I countries of UNFCC only the coarser category "6.A Solid Waste Disposal on Land" exists, not allowing to derive any information on open burning.

Tab. 3.1 Rates of open burning in uncontrolled disposal for urban and rural regions, differentiated into world sub-regions from (Maxson 2009) and corresponding GNI data.

	Open burning in uncontrolled disposal, urban *(Maxson 2009)*	Open burning in uncontrolled disposal, rural *(Maxson 2009)*	Gross National Income GNI, $/capita.yr *World Bank data*
East and Southeast Asia	8%	24%	8'980
South Asia	12%	36%	1'534
European Union	4%	12%	39'893
CIS & other European countries	8%	24%	11'568
Middle Eastern States	8%	24%	11'282
North Africa	12%	36%	3'757
Sub-Saharan Africa	15%	45%	1'664
North America	4%	12%	54'211
Central America & Caribbean	8%	24%	7'980
South America	8%	24%	9'484
Australia N. Zealand & Oceania	4%	12%	51'840

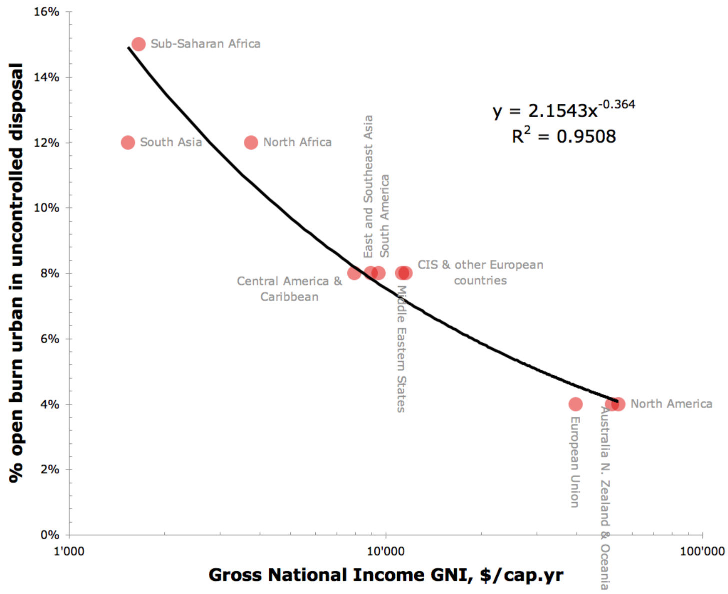

Fig. 3.4 Open burning rates in uncontrolled disposal urban areas plotted against the Gross National Income GNI of the sub-regions and fitted regression.

Eq. 3.6 $$\%b_u = 2.1543 \cdot GNI^{-0.364}$$

$\%b_u$ Estimation for percentage of unmanaged waste going into open burning in an urban setting (index u)

GNI Gross National Income per capita in $/cap.yr

As a further refinement, Maxson distinguishes waste burning rates in *urban areas* and in *rural areas*, with the latter being three times the former (see Eq. 3.7). This information can also be used by assuming that the waste generated in urban areas is proportional to the percentage of the population living in urban areas.[12] See Eq. 3.8. Urban waste will be burnt less frequently and rural waste more frequently. Data on percentage of urban population ($\%pop_u$) is available from UN statistics for 172 nations (UNSD 2016a). In case proper statistical data on percentage of the urban population is not available, again a regression using a nation's GNI is used to estimate $\%pop_u$ (see Eq. 3.9).

Eq. 3.7 $$\%b_r = 3\cdot \%b_u = 6.4629\cdot GNI^{-0.364}$$

$\%b_r$ Estimation for percentage of unmanaged waste going into open burning in an rural setting (index r)

$\%b_u$ Estimation for percentage of unmanaged waste going into open burning in an urban setting (index u)

Eq. 3.8 $$\%2b = \%pop_u \cdot \%b_u + (1 - \%pop_u)\cdot \%b_r$$

%2b Percentage of unmanaged waste going to open burning (see Fig. 3.1)

$\%pop_u$ Percentage of a nation's population living in urban areas.

$\%b_u$ Estimation for percentage of unmanaged waste going into open burning in an urban setting (index u)

$\%b_r$ Estimation for percentage of unmanaged waste going into open burning in an rural setting (index r)

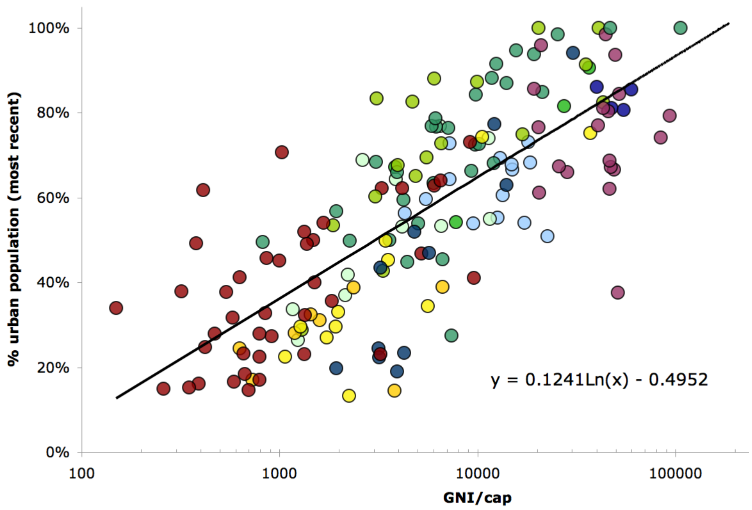

Fig. 3.5 **Percentage of urban population plotted against the Gross National Income GNI of the country and fitted regression. Each dot represent a single country.**

Eq. 3.9 $$\%pop_u = 0.1241\cdot \ln(GNI) - 0.4952$$

$\%pop_u$ Percentage of a nation's population living in urban areas.

GNI Gross National Income per capita in \$/cap.yr

ln Natural logarithm function

3.d Open dumping

In this report, uncontrolled disposal of waste has only two options: open burning or open dumping. With the extent of open burning established in Eq. 3.8, the remainder of the uncontrolled waste must therefore go into open dumping. The percentage of uncontrolled waste going into open dumping is therefore:

12 This ignores any differences in waste generation per capita of rural and urban populations.

Eq. 3.10 $$\%2d = 1 - \%2b$$

%2d Percentage of unmanaged waste going into open dumping (see Fig. 3.1)

%2b Percentage of unmanaged waste going into open burning (see Fig. 3.1)

3.e Unsanitary landfills

Within the modelling framework of this study, the unsanitary landfill is one of the possible destinations for controlled waste disposal (See dark green bar in Fig. 3.1 on page 7).

The percentage going to unsanitary landfill (%2u) is derived here as a *complement* to the other two controlled waste disposal activities of sanitary landfill and municipal incineration. I.e. whatever part of waste disposed in a controlled manner is *not* going either to sanitary landfill or to municipal incineration is assumed to be delivered to an unsanitary landfill. The flow to an unsanitary landfill in a country is therefore dependent on its flows to sanitary landfill (see chapter 3.g on page 15) and its flows to municipal incineration (see chapter 3.h on page 17).

Eq. 3.11 $$\%2u = 1 - \%2s - \%2m$$

%2u Percentage of managed waste going into unsanitary landfill (see Fig. 3.1)

%2s Percentage of managed waste going into sanitary landfill (see Fig. 3.1)

%2s Percentage of managed waste going into municipal waste incineration (see Fig. 3.1)

The mass landfilled in an unsanitary landfill will be further modified by subtracting an estimated amount of waste being burnt off in landfill fires (chapter 3.f on page 13).

The unsanitary landfill assumed in this study is a distinct abstraction and specification of the continuum of real-world characteristics that unsanitary landfills can or could have. The specifications made in (Doka 2017b:Tab 3.1) are adopted where an unsanitary landfill features a waste compaction and a daily waste cover, but neither landfill gas or leachate collection systems, bottom liners. The waste compaction and a daily waste cover leads to lower methane oxidation compared to open dumps and therefore larger methane emissions, which is modelled in the unsanitary landfill model.

3.f Landfill Fires

Maxson (2009) has not only provided estimates for uncontrolled open burning rates (see chapter 3.c 'Open burning' on page 10), but also for occurrence of fires in *managed* landfills. Even in managed landfills fires can occur, which will burn waste in a largely uncontrollable manner. For the purposes of this report it is suggested that the share of waste burnt in landfill fires is ultimately also inventoried with an open burning inventory, not a landfilling inventory (orange bars in Fig. 3.1 on page 7).

By using this inventory model of subtracting burnt waste from landfilled waste, one is implicitly assuming that landfill fires occur *immediately after* waste placement in the landfill, i.e. that no time is allowed for waste first sit in the landfill for a length of time, possibly contribute to landfill gas and leachate emissions, and only then being burnt off. This simplification is necessary due to lack of data on temporal dynamics of landfill fires. Landfill fires can theoretically affect newly placed, but also old waste. Not all landfill fires are well visible surface fires. Some landfill fires are slow burning, oxygen deficient smoulders deep within the landfill body, which are often hard to detect and difficult to extinguish by fire fighters (see e.g. Copping et al. 2007). The used data by (Maxson 2009) on landfill fires only provides a figure for the percentage of waste burnt in landfills, without a further differentiation on the kind of fire or the age of the waste affected. Until further discriminating information can be obtained, this data will have to suffice as a qualified estimate for landfill fire occurrence. The important effect is that the burnt waste will have very different emission patterns compared to being degraded in a landfill.

Tab. 3.2 Amount of waste burnt in managed landfills in open fires from (Maxson 2009) and corresponding GNI data.

	Percent of managed landfill burned *(Maxson 2009)*	**Gross National Income GNI, $/capita.yr** *World Bank data*
East and Southeast Asia	3%	8'980
South Asia	5%	1'534
European Union	1%	39'893
CIS & other European countries	2%	11'568
Middle Eastern States	2%	11'282
North Africa	4%	3'757
Sub-Saharan Africa	6%	1'664
North America	1%	54'211
Central America & Caribbean	2%	7'980
South America	2%	9'484
Australia N. Zealand & Oceania	1%	51'840

Similar to the observed for rates of uncontrolled open waste burning in chapter 3.c, also here a good correlation between burning rates and GNI can be drawn. This allows to extrapolate these findings from a global subregion granularity to a country-specific one, using a country's GNI.

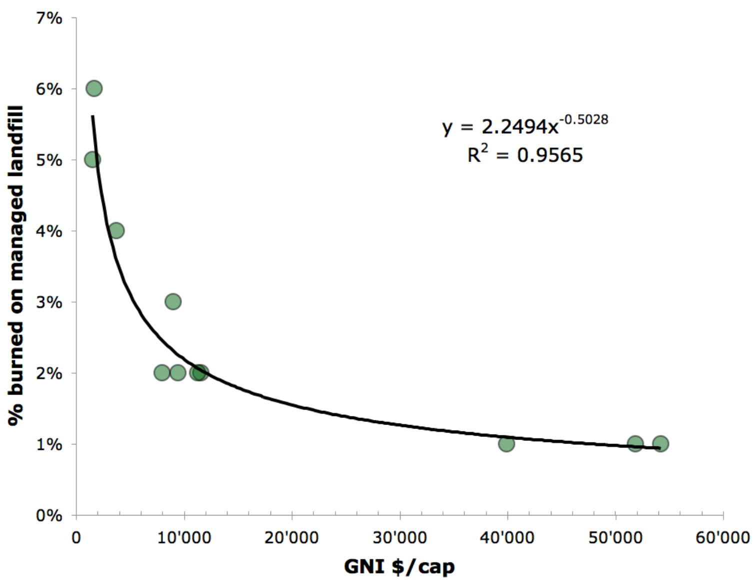

Fig. 3.6 Correlation between percentage of waste burnt in managed landfills in open fires from (Maxson 2009) versus corresponding GNI data for 11 global subregions.

Eq. 3.12 $$\%lff = 2.2494 \cdot GNI^{-0.5028}$$

%lff Estimation for percentage of waste in *controlled* landfills burnt in landfill fires

GNI Gross National Income per capita in $/cap.yr

3.g Sanitary landfills

In the sanitary landfill inventory model, landfill gas can be captured and flared or utilized and the leachate is captured and treated.

It would be imaginable to create country-specific activity datasets for sanitary landfills, using the various parameters in the sanitary landfill model. But for the present update work for ecoinvent v3.5 it was decided in advance to use the already existing sanitary landfill datasets and only update market datasets (cf. Fig. 5.1 on page 22).

But in distinguishing sanitary from unsanitary landfills, a problem arises. The term "sanitary landfill" is not clearly defined and used internationally for plants with various characteristics.[13] A crucial issue for LCA results will be the *capture and subsequent flaring or utilisation of landfill gas*, which reduces the direct methane emissions via emitted landfill gas, while the leachate treatment, operational and infrastructure aspects are usually of minor importance in these processes. For the present work it was therefore decided that only landfills with landfill gas utilization should be inventoried with the sanitary landfill datasets, and all other managed landfills should be inventoried with unsanitary landfill datasets. The inventoried sanitary landfill datasets have a capture of 53 w% of the produced lifetime landfill gas.[14]

> *For the purposes of this report, "sanitary landfills" are considered to be landfills with <u>capture of landfill gas</u>. The subsequent flaring or utilisation reduces methane emissions, which is the major difference between such landfills and unsanitary landfills or open dumps, which both have no capture.*

To accompany the simplification made here, the following picture lists some dump and landfill characteristics in the real world and the approximate delineations made in distinguishing open dumps, unsanitary landfills and sanitary landfills for the process inventory models in (Doka 2017a). The picture illustrates that in the continuum that real-world landfill characteristics represent, some rather arbitrary distinctions were made to separate three distinct models of land-based disposal technologies, namely open dump, unsanitary landfill and sanitary landfill. This illustration might also ease the irritation that some might feel over the fact that what some consider *sanitary* landfills are inventoried in this project with the process of an *unsanitary* landfill, *only* because of lack of landfill gas capture. To avoid any confusion: the characteristic of landfill fires is not heeded in the landfill models themselves, but must be inventoried as a separate open burning activity (see chapter 3.f 'Landfill Fires' on page 13).

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[13] In Brazil for instance in a large statistical collection of 2473 dumps and landfills sites, 679 landfills were categorised as sanitary (*"Aterro sanitário"*) (SNIS 2017). But out of these sanitary landfills, only 317 (47%) reported to have landfill gas drainage systems in place (*"Drenagem de gases"*) and only 37 (6%) reported to have landfill gas recovery (*"Aproveitamento dos gases"*). Further, only 374 (55%) reported leachate capture, only 406 (60%) had even a base seal, either of which would be a prerequisite of a sanitary landfill in Switzerland. A further 37 (6%) sites even report to operate without an environmental license. Six sanitary landfills in operation even report to have no compacting tractors or any other equipment on site. Even ignoring the roughly 100 non-answering sanitary landfills sites, it is clear from this that in Brazil a "sanitary landfill" can have very low standards which might not go beyond waste compaction and waste cover. Such basic features can have important effects for local hygiene and sanitation. But for the purposes of this report such minimally managed landfills would be considered unsanitary landfills.

[14] These datasets were created in ecoinvent v1 for Switzerland, based on the reference year 2000.

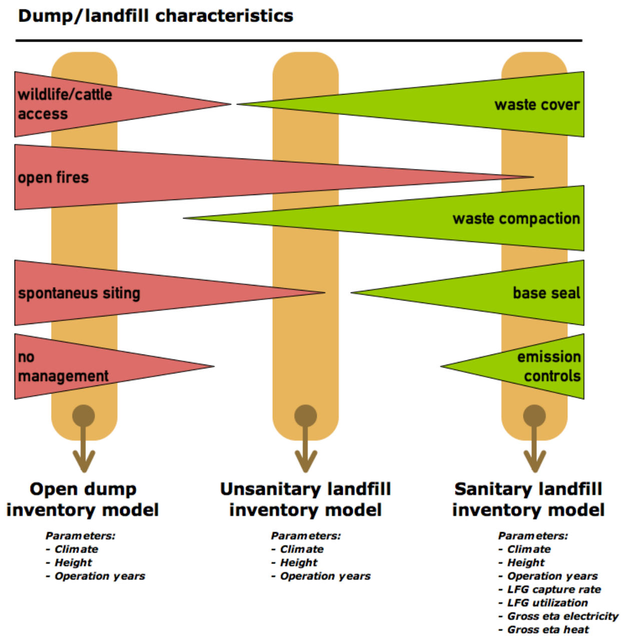

Fig. 3.7 The continuum of characteristics of dumps/landfills real world and their distinction into three isolated landfill inventory models (bottom). The thickness of the wedges illustrates the approximate probability of occurrence of that characteristic.

Country-wise information on the quantitative extent of landfill gas capture is difficult to obtain. National greenhouse gas reports (UNFCC 2018) would heed landfill gas capture and the subsequent oxidation of methane. But the capture information itself is not disclosed. And from methane emission timelines it is not possible to determine capture rates, as a decline in methane emissions can also be caused by a reduction in waste being landfilled. Changes from open dumps to unsanitary landfills will *increase* methane emissions and can mask capture efforts.

EurOberv'ER, a site collecting statistical data on various renewable energies in Europe, has some current information on *annual landfill gas primary energy production* for 29 European countries (EurObserv'ER 2017).[15] This is taken to be the energy in landfill gas harvested prior to utilisation. This is converted to an amount of MSW landfilled[16] and then divided by the total generated MSW amount in that country to obtain a technology mix rate of MSW going to sanitary landfill. This approximation is considered weak, but was the best quantifiable data to be found.[17] The obtained rates

[15] Unfortunately, its international counterpart "Observ'ER" does not present isolated figures for landfill gas only, but presents it as energy from biogas in general, summing up also biogas from agricultural and wastewater treatment sludge digesters. This information can only be used to determine if a country has zero landfill gas utilisation.

[16] The landfill gas primary energy data in EurObserv'ER is in Mtoe, which is first converted to megajoules (1 Mtoe = $4.1868 \cdot 10^9$ MJ), and then reversing the calculation performed in the sanitary landfill model: megajoules are converted to kg CH_4 (1 kg CH_4 = 40 MJ, which is the conversion factor used in the sanitary landfill model) which then represents the methane prior to utilisation. Dividing by the share of utilized gas in captured gas (66%) gives the amount of *captured* CH_4. Dividing by the capture rate (53%) gives the total amount of CH_4 generated. At 56 w% methane in landfill gas and for average municipal waste in the sanitary landfill datasets one kg of MSW produces 40.687 grams of CH_4 raw landfill gas. With this calculation chain, landfill gas primary energy can be converted to a mass of average municipal waste. This procedure ignores however any time lags in methane generation. Thus the calculated waste mass is a weighted average result of several decades. Nevertheless in absence of better data (i.e. current waste masses going into landfills with gas recovery) this amount is taken to be indicative of the mass of waste currently going into sanitary landfills.

[17] Some older data on the mere number of plants performing landfill gas utilization by Willumsen is available (Willumsen 2002). This suggests that outside Europe, in 2001 USA had 385 such plants, and Canada and Australia had 25 each, Brazil 6

of sanitary landfilling have further to be corrected as in some cases the found rates of were larger than the remainder of waste after waste going to municipal incineration is subtracted. Rates for municipal incineration are considered more reliable here (see following chapter), so the sanitary landfill data is adjusted.

If better international statistics on country-averages of effective landfill gas capture percentages or waste masses per country going into landfills with gas recovery are publicly available, the author would welcome a hint (gabor@doka.ch).

3.h Municipal incineration

Information on municipal waste masses going into waste incineration plants is available from Eurostat for 37 European countries, also non-EU countries (Eurostat 2018). Identical parameters are listed for 39 OECD countries in (OECD 2018). In total data on incineration for 49 countries is available. From this the share of municipal waste going to incineration is calculated.

Both sources distinguish incineration with and without energy recovery (in Eurostat labelled with D10 and R1 respectively). But no information is given on the *extent* of energy recovery made in incineration.[18] For the purposes of LCA of waste disposal treatment markets, it is more important to distinguish incineration versus landfilling. The differences occurring from different incineration technologies, like extent of energy recovery, are of secondary importance. For LCIA results it is more relevant that waste has been diverted from landfills to incineration, than the exact extent of energy recovery in incineration. Both incinerations with and without energy recovery are added together to obtain a figure for total waste incineration. Also, for this project no new incineration datasets were targeted. Thus, both types of incineration activity, with and without energy recovery, are combined here and inventoried with the same, already existing dataset.[19] For the present update work for ecoinvent v3.5 it was decided in advance to use the already existing waste incineration datasets and only update market datasets (cf. Fig. 5.1 on page 22). The statistical data shows that in most countries practically 100% of incinerators also perform energy recovery. Countries with high fractions of non-recovering incinerators are countries with rather low shares of incinerated waste (Albania, Italy, Iceland). This means that the quantitative error of subsuming non-recovering and recovering incinerators will be limited.

4 Data reduction: Infiltration classes

With the tools provided in (Doka 2017) it is possible to calculate dump and landfill disposal of specific materials *heeding the local climate*. In the model, scarcity of available precipitation water can influence the amount of landfill gases. The rate of water infiltrating the landfill body determines the speed of weathering of the landfill and influences inventoried emissions from the landfill body.

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and China 3. For Brazil these figures seem doubtful, as the Brazilian GHG report states that prior to 2003 no methane was recovered in Brazilian landfills (MCTI 2016-III:189).

18 Strictly speaking, also the "incinerators without energy recovery" (D10) *might* produce some usable energy in the real world, since to qualify as a energy-recovering incinerator (R1) under the rules of the EU/OECD data collection, the extent of energy recovery has to surpass a certain threshold.

19 The appropriate update (Doka 2013) represents Swiss incineration for 2006-12, as a proxy for modern incinerators, with a gross electric efficiency of 27.8% and gross thermal efficiency of 13.5%.

While it is advantageous to have a detailed, climate-sensitive landfill model, there can be practical limitations for the use in a backgrounds database like ecoinvent: there are roughly 250 separate countries in the world and potentially for almost each country distinct dumping and landfilling disposal datasets could be made.[20] With even only a few specific waste materials, this would result in thousands of new disposal datasets, each one tailored to the specific climate of the originating country.[21]

To avoid an excess of new landfilling datasets for each country, a reduction of datasets is achieved by creating climate classes, or more precisely **infiltration classes**. Each country or region can be assigned to a class of five infiltration rates. Infiltration in the landfill model is annual precipitation minus annual actual evapotranspiration. [22]

Eq. 4.1 $$I = P - E$$

where,

I Mean annual infiltration rate (mm/m^2a)

P Mean annual precipitation, MAP (mm/m^2a)

E Mean annual actual evapotranspiration (mm/m^2a)

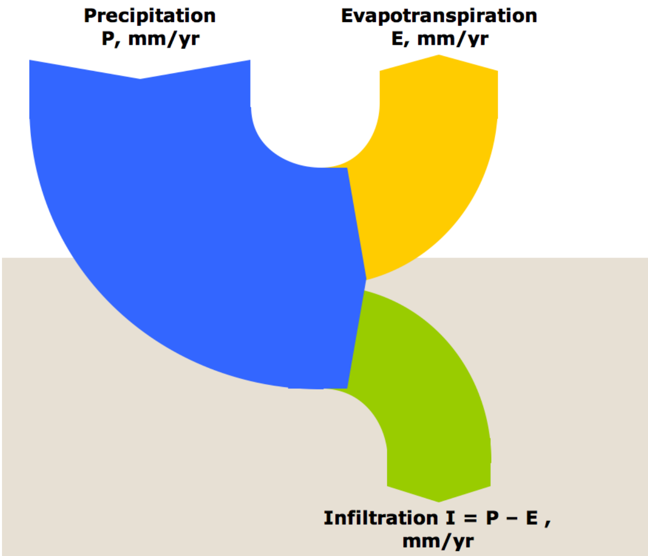

Fig. 4.1 Illustration of the simplified concept of infiltration water generation for the landfill model from precipitation P minus evapotranspiration E.

To classify the countries, a further aspect is heeded: the infiltration should be applicable to landfill and dump sites. Mean infiltration rates over the *whole* area of a country might be misleading for this purpose. Therefore, when calculating mean annual infiltration of a country, a weighting according to **population density** is employed. In general, landfills will tend to be close to population centres and

[20] Some countries could be excluded where landfilling of municipal waste is not practiced anymore, like for instance Switzerland.

[21] Ecoinvent currently (April 2018, v.3.4) features processes in a multitude of geographic regions, including nations, global sub-regions, national provinces (for India, China, Canada), electricity grid areas. In total 261 different regions are distinguished.

[22] In the landfill model, surface runoff and therefore mechanical erosion, is assumed to be zero.

areas with large populations will also tend to have more municipal landfills or dumps than sparsely inhabited areas.

For each country a population-weighted mean infiltration was derived using gridpoint data on precipitation, evapotranspiration, and population. For each gridpoint the expected infiltration I = P – E at that gridpoint was calculated. The mean infiltration value for a country was then derived by aggregating all gridpoints belonging to a country, but weighting each gridpoint with the population at that gridpoint c_p.

Eq. 4.2 $$I = \frac{\sum_p c_p \cdot \left(P_p - E_p\right)}{\sum_p c_p}$$

where,

I	Mean annual Infiltration rate (mm/m^2a)
p	Index for gridpoint
c_p	Population at gridpoint p (capita)
P_p	Mean annual Precipitation at gridpoint p (mm/m^2a)
E_p	Mean annual Actual evapotranspiration at gridpoint p (mm/m^2a)

Data used for precipitation is from (Hijmans et al. 2005), for actual evaporanspiration from (Mu et al. 2011), for population from (CIESIN 2005).

At the 1-degree-resolution employed, data for countries encompassing 98.5% of the world's population could be derived. Missing are some small states and islands.

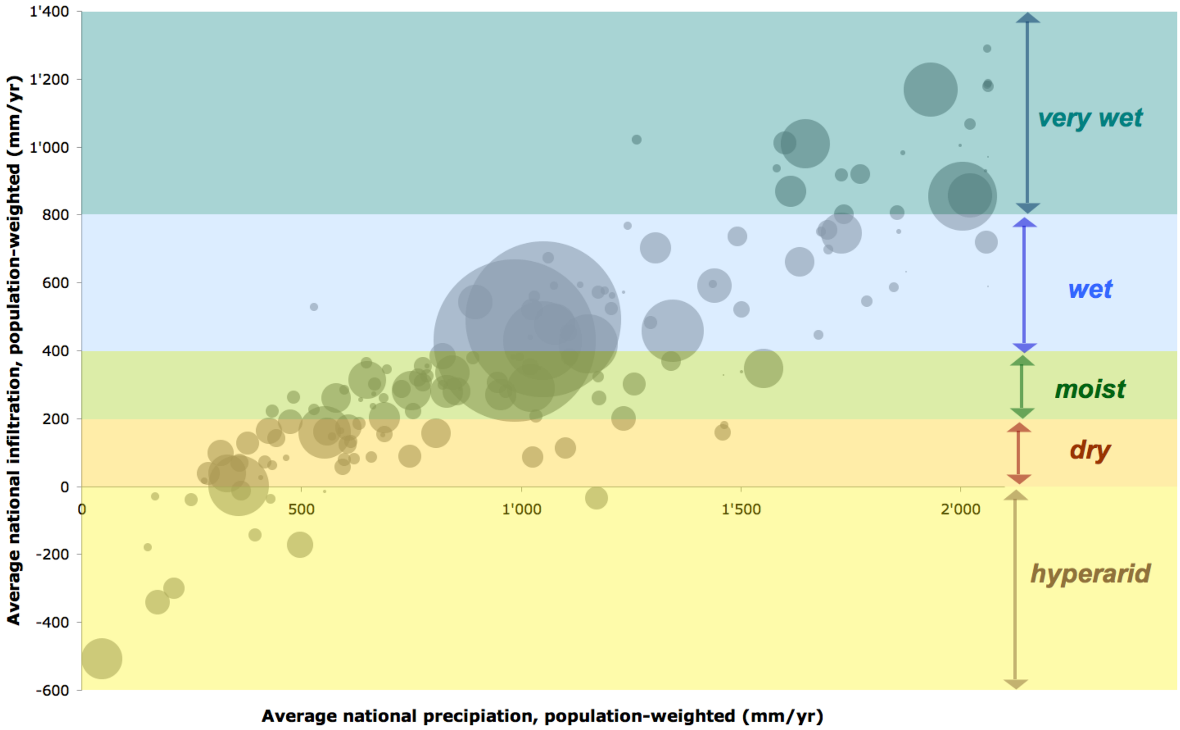

Fig. 4.2 Infiltration classes of 154 countries of the world. Displayed is the population-weighted precipitation (x-axis) vs. the population-weighted infiltration (y-axis), both in mm/yr. Each country is represented with a circle whose area represents the total population of that country. The infiltration classes (see right side) are set so that number of countries in each class is roughly balanced.

From the resulting infiltration data for each country, five infiltration classes were designed that would contain countries with a defined range of population-weighted infiltration. The boundaries of the classes were chosen so that the number of countries in each class is roughly balanced. The class boundaries are shown in columns 2 and 3 of Tab. 4.1 below. The typical, mean infiltration in that class was calculated (again weighing populous countries more), which would serve as the representative infiltration figure for that class, shown in column 3. In the same manner rounded figures for precipitation and evaporation were derived for each class (column 4 and 5). They will serve as input to the landfill model.

Descriptive names are given to the infiltration classes. These names shall not be confused with similar adjectives in climatology that usually refer to precipitation only. The classes here are based on infiltration.

Tab. 4.1 Five infiltration classes to reduce the diversity in landfill-relevant climates and thus amount of datasets in the database.

Infiltration class #	Infiltration class boundaries		Mean infiltration I in class	Mean precipitation P in class	Mean evaporation E in class	Countries in this class
	lower	upper	mm/yr	mm/yr	mm/yr	n
5) very wet	800		**1000**	1900	900	20
4) wet	400	800	**500**	1100	600	41
3) moist	200	400	**300**	900	600	46
2) dry	0	200	**100**	550	450	35
1) hyperarid		0	**-250**	350	600	12

\# Descriptive names are given to the infiltration classes. These names shall not be confused with similar adjectives in climatology that usually refer to precipitation only. The classes here are based on infiltration.

The obtained data on country-specific, population-weighted precipitation, evapotranspiration, and infiltration is shown in the 'Appendix A' on page 29.

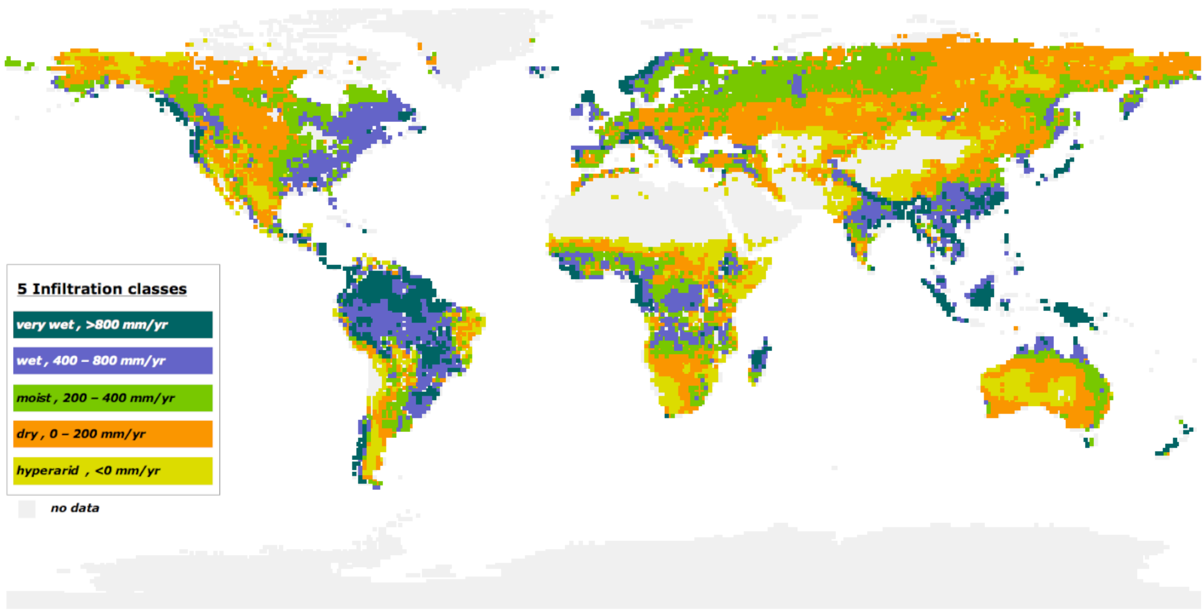

Fig. 4.3 World map with local infiltration classes. Shown are gridpoints where precipitation *and* evaporation data was available to calculate the local infiltration and from that the infiltration class that gridpoint falls into.

For the mean annual temperature (MAT) a value of 8°C is used for all infiltration classes. This corresponds to the global mean temperature.

Please note that a hyperarid site does not necessarily mean a hot desert. There are also *cold* hyperarid sites: see Fig. 4.3, e.g. in Alaska.

5 Municipal waste treatment markets

5.a Treatment technology mix

The introduction of infiltration classes (see previous chapter) is aimed at reducing the number of necessary datasets to depict a treatment situation. To represent a country's disposal situation, the market dataset must (quite normally) heed the different shares of the employed technology, but for dumps and landfilling also the infiltration class of the country.

The general structure of the modelled municipal waste treatment markets is shown below.

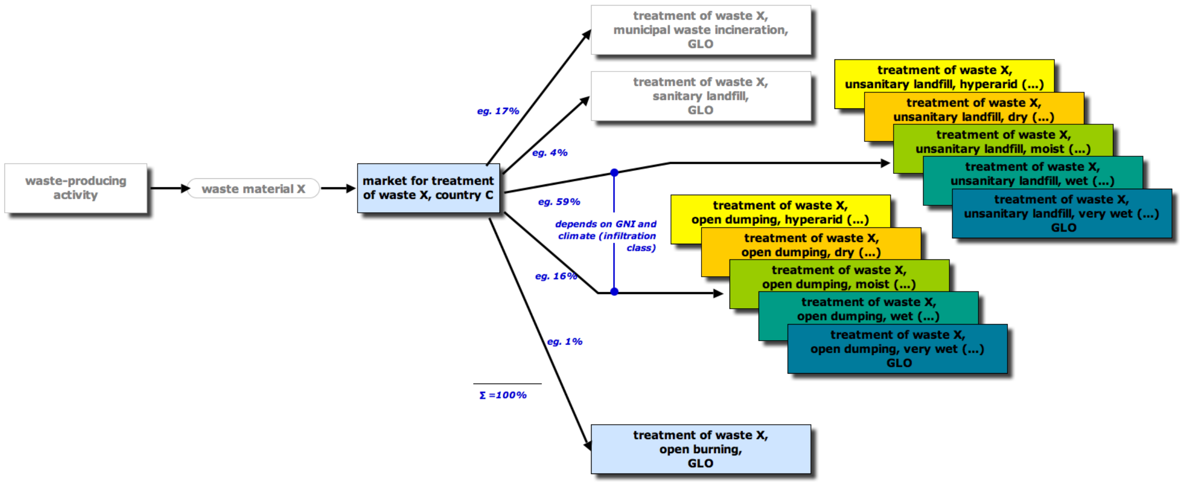

Fig. 5.1 Waste treatment markets and the connection to disposal processes. Arrows indicate the flow of waste material. Datasets with a colour fill are newly created ones based on the information given here; Datasets with grey text are already existing ones and will not be further differentiated within this project.

The waste treatment market (in the middle of Fig. 5.1) connects waste-producing activities (on the left) with disposal processes (on the right). For each considered waste material and each infiltration class a GLO treatment dataset for unsanitary landfilling and open dumping is created.[23] These are the yellow to blue-green datasets represented on the right. Open burning of the material is created as well, but since this process is not dependent on climate, one GLO process per material suffices. Also needed for the treatment markets in some countries are the municipal incineration and sanitary landfill datasets (top middle). In this project it was decided to use the already existing datasets for this, which are based on Swiss processes and exist as GLO copies.

A special feature of this arrangement is that a *country-specific* treatment market ("country C") but the links go out to *GLO* datasets. The country-specifity will be heeded on one hand by the market shares of the treatment technologies and on the other hand by heeding the infiltration class the country belongs to. Depending on the infiltration class a country, one of the five variants of disposal datasets are linked up in the case of open dumps and unsanitary landfills.

For municipal waste incineration some country datasets do exist, but only for average municipal waste, not single specific waste materials, and also these datasets are just copies of Swiss processes. For specific waste materials, incineration will have to be covered by the GLO processes also.

The following table list all the market datasets/disposal mixes for Europe and the SRI focus countries.

[23] A differentiation of *sanitary* landfills would be correct too, but this will not yet be performed for ecoinvent v3.5.

Tab. 5.1 The derived technology mix for the disposal of mixed municipal waste for Europe and the SRI focus countries. Not all digits significant, but shown to avoid accumulation of rounding errors.

Country		Infiltration class	Open dump	Open burning	Unsanitary landfill	Sanitary landfill (with LFG capture)	Municipal incineration
Poland	PL	2 - dry	23.0392%	4.091%	14.6103%	32.6208%	25.6386%
Romania	RO	2 - dry	62.4024%	11.3764%	23.8636%	0.801799%	1.55584%
Czech Rep.	CZ	2 - dry	0%	1.22605%	74.0401%	n.a.	24.7338%
Hungary	HU	2 - dry	6.34704%	2.16911%	45.1852%	25.2313%	21.0674%
Serbia	RS	2 - dry	35.7519%	8.97695%	55.2711%	0%	0%
Bulgaria	BG	2 - dry	2.61158%	2.75938%	89.235%	0%	5.39407%
Slovakia	SK	3 - moist	0%	1.43534%	84.8434%	n.a.	13.7212%
Croatia	HR	4 - wet	0.869107%	2.0547%	70.3137%	26.6856%	0.0768037%
Bosnia Herzegovina	BA	3 - moist	28.6272%	8.71242%	62.6604%	n.a.	0%
Lithuania	LT	3 - moist	8.32381%	2.03629%	8.85384%	47.4264%	33.3597%
Albania	AL	4 - wet	13.6414%	5.89998%	76.5381%	n.a.	3.92054%
Latvia	LV	3 - moist	15.0754%	3.30013%	4.44997%	77.1745%	0%
Macedonia	MK	2 - dry	30.4973%	8.60012%	60.9026%	n.a.	0%
Slovenia	SI	4 - wet	4.47969%	0.966044%	0%	27.5351%	67.0191%
Estonia	EE	3 - moist	23.635%	2.78904%	0%	12.575%	61.0011%
Montenegro	ME	4 - wet	26.9518%	6.34286%	66.7053%	n.a.	0%
Kosovo	XK	3 - moist	72.813%	19.0205%	8.16652%	n.a.	0%
Germany	DE	3 - moist	0%	0.00636128%	0%	0.617249%	99.3764%
France	FR	3 - moist	0%	0.417187%	0%	38.0706%	61.5122%
United Kingdom	GB	4 - wet	0%	0.369092%	0%	34.8271%	64.8038%
Italy	IT	3 - moist	0%	0.674379%	0%	55.2179%	44.1077%
Spain	ES	3 - moist	0%	1.04398%	31.6018%	48.0172%	19.337%
Netherlands	NL	3 - moist	0%	0.0301607%	3.02713%	n.a.	96.9427%
Portugal	PT	3 - moist	0%	1.07373%	0%	69.2492%	29.677%
Greece	GR	2 - dry	0%	1.52657%	3.05664%	94.8089%	0.607834%
Belgium	BE	3 - moist	0%	0.018209%	0%	1.73861%	98.2432%
Sweden	SE	3 - moist	0%	0.0111927%	0%	1.22249%	98.7663%
Austria	AT	4 - wet	0%	0.0668777%	0.497642%	6.08672%	93.3488%
Switzerland	CH	4 - wet	0.947393%	0.0526841%	0%	n.a.	98.9999%
Denmark	DK	3 - moist	0%	0.0174344%	0%	1.91722%	98.0653%
Finland	FI	3 - moist	0%	0.0565773%	0%	5.52443%	94.419%
Ireland	IE	4 - wet	29.1427%	2.64594%	0%	25.4367%	42.7747%
Norway	NO	5 - very wet	0.952916%	0.0986036%	7.18163%	n.a.	91.7669%
Cyprus	CY	4 - wet	0%	1.35771%	98.6423%	0%	0%
Luxembourg	LU	3 - moist	0%	0.260975%	32.9636%	0%	66.7754%
Malta	MT	2 - dry	0%	1.50318%	98.0731%	0%	0.423729%
Iceland	IS	4 - wet	0%	0.917396%	92.828%	0%	6.25465%
Brazil	BR	4 - wet	8.40658%	2.91928%	88.1137%	n.a.	0.560402%
Colombia	CO	4 - wet	20.0311%	4.87659%	75.0923%	0%	0%
Peru	PE	2 - dry	28.9881%	6.24725%	64.7646%	0%	n.a.
India	IN	4 - wet	50.5164%	28.4308%	21.0528%	0%	n.a.
South Africa	ZA	2 - dry	3.38346%	3.34239%	93.2741%	0%	n.a.

n.a. data not available, presumed to be zero for this study

0% actually zero, backed up by data or modelling results.

5.b Waste treatment production volumes

The percentages given in the previous chapter define the treatment mix for mixed municipal waste (Tab. 5.1). Unless the mixed municipal waste is separated further downstream into distinct waste fractions – like separating out metals – the shown treatment mix applies to all constituent waste fractions of the mixed municipal waste.

The ecoinvent Association used this info to create market datasets for the treatment mixes of different waste materials in different regions.[24] Although relative percentages are sufficient to create a treatment or market mix, the *absolute production volumes* – or rather disposal volumes – for individual materials in the mixed municipal waste were requested additionally by ecoinvent Association as well. So the absolute masses of disposed waste materials per year are required, or at least estimates of them. In the following the assumptions made to derive those absolute annual

[24] See ecoinvent documentation (Moreno et al. 2018, ecoinvent 2018)

production volumes (APV) are described. The APV describes how much of a certain waste material is disposed annually with the pertaining process, heeding also the specified region and time period of the process. For waste disposal the physical unit of APVs is "kilogram of wet waste per year".

A graphical overview of the procedure employed here to arrive at APVs is shown in . The procedure is explained in more detail in the text sections below.

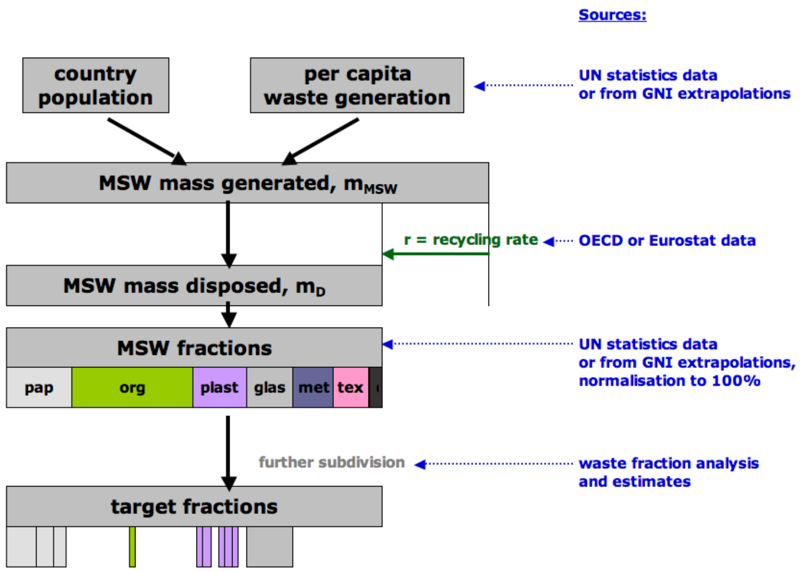

Fig. 5.2 **Scheme of the calculation procedure to obtain country-specific annual production volumes of municipal waste fractions to disposal. All steps are country-specific, except the last one of "further subdivision".**

Since in ecoinvent activities in a large number of countries and regions can be inventoried, it is efficient to have a framework that allows data generation with a large global coverage. That means that compiled statistical data for the world's countries is helpful in obtaining the desired data in a consistent manner, as opposed to trying to find pertinent country data case by case.

Fortunately, several organisations provide such data, which allows to obtain information on disposed waste mass and disposed composition. The data sources and the procedure and assumptions to obtain the annual production volumes of different specific waste materials in mixed municipal waste are presented below.

5.b.1 Discerned waste materials

For ecoinvent v3.5 several individual waste materials were discerned for created the new climate-specific waste disposal activities. Some omnipresent, generic materials were chosen that will frequently be produced as waste in a large range of different activities. These will tend to be generic packaging materials. Although it is still perfectly possible – and in cases necessary – to generate inventories of the disposal of *very specific* waste materials with the tools of (Doka 2017a–e), for the ecoinvent backgrounds database only these frequent and generic waste materials are used to create new disposal activities for now. These generic waste materials used are listed below.

Tab. 5.2 List of generic waste materials in mixed municipal waste used to generate new disposal activities in ecoinvent v3.5.

graphical paper packaging paper cardboard	plastic, mixture polyethylene polyethylene terephtalate polypropylene polystyrene polyurethane polyvinylchloride	glass	wood, untreated

In order to provide absolute annual production volumes of these different waste materials in mixed municipal waste, two questions must be answered:

1. **Disposed mass:** How large is the amount of disposed mixed municipal waste in a country?
2. **Disposed composition:** What percentage of the different materials is in mixed municipal waste in a country?

5.b.2 Country-specific mass of disposed mixed municipal waste

Generated mass

The annual mass of *generated* mixed municipal waste in a country can be derived from statistical data on per-capita waste generation m_{MSW} and a country's population by simple multiplication (UNstast 2016, ISWA 2017). In case statistical data on waste generation m_{MSW} is not available, an extrapolation can be made, using a regression based on the gross national income (GNI) per capita. The regression follows a logarithmic growth, $m_{MSW} = a*\ln(GNI) - b$, with a = 79.345 and b= 349.29. Data for gross national income is available from statistical sources (Worldbank 2016).

Recycling rate

The *generated* waste mass m_{MSW} is not necessarily identical to the *disposed*, non-recycled waste mass m_D. For the disposal activities described in chapter 3 the latter is required. This means that in order to obtain the disposed, non-recycled waste mass any waste mass that is recycled should be discounted from the generated waste.

Statistical information on formal recycling is available for OECD countries in (OECD 2018)[25] and for European countries in (Eurostat 2018)[26]. For the compilation of country-specific recycling rates *r* both sources were used, and priority was given to the OECD data, since for a few countries with diverging figures, OECD has the more recent data (Ireland, UK, Slovenia).

With data on the generated waste and the recycling rate it is now possible to calculate the non-recycled disposed waste mass as $m_D = m_{MSW} \cdot (1 - r)$.

25 From data for 45 OECD countries the entries for 'Recycling', 'Composting' and 'Other recovery' were added and then divided by the 'Municipal waste generated' figure to obtain a recycling rate. Latest reported data was used which is from the period 2010 to 2016 for the large majority of the countries.

26 From data for 40 European countries (including non-EU) the entries for ' Material recycling' and 'Composting and digestion' were added and then divided by the 'Waste generated' figure to obtain a recycling rate. Latest reported data was used which is for the year 2016 for the large majority of the countries.

5.b.3 Country-specific composition of disposed mixed municipal waste

How much of the different waste materials discerned in chapter 5.b.1 above are present in the non-recycled disposed waste mass? Waste fraction analysis for around 100 countries is available from UN statistics (UNSD 2016b), which is based on UN questionnaires, EU or OECD statistics with the majority of data originating in the period 2000-2013. This UN data however only discerns the following waste fractions: "Paper, paperboard", "Organic material", "Plastics", "Glass", "Metals", "Textiles", "Other inorganic material".

Tab. 5.3 Waste fractions in UN statistical data and extrapolations for their weight share in municipal waste.

Waste fractions in UN data	Extrapolation for share in municipal waste. [w%]. From (Doka 2017a)	Type of extrapolation
Paper, paperboard	0.009151 · (GNI)^0.320887	power law
Organic material	-0.047721 · LN(GNI) + 0.852361	logarithmic, natural
Plastics	0.028556 · (GNI)^0.14531	power law
Glass	0.002595 · (GNI)^0.302399	power law
Metals	0.003211 · (GNI)^0.254579	power law
Textiles	0.00000043149 · (GNI) + 0.03216152613	linear
Other inorganic material	-0.0196 · LN(GNI) + 0.3285	logarithmic, natural

In (Doka 2017a: Fig 2.3) this statistical data was used to derive extrapolations of waste composition based on a country's GNI. These extrapolations allow to generate best guess estimates of a country's waste composition based on an available GNI figure and are shown in Tab. 5.3. The extrapolations also allow to complete missing fraction information in a country's waste composition data[27]. The waste compositions extrapolated in this way usually add up reasonably well to 100 weight-percent. To avoid any specious mass loss or -generation, at this point the obtained composition is normalized to 100%.

Refining the UN statistics waste fractions

Only in the case of "glass" and "plastic mixture" do the waste fractions used in UN statistics data match the targeted waste fractions given in Tab. 5.2 on page 25. The UN fractions are more general and encompassing than the targeted waste fractions.

Subdividing Paper/board

The UN fraction "Paper, paperboard" subsumes the target fractions graphical paper, packaging paper, and cardboard. In order to convert the UN fraction into the more differentiated fractions a simple subdivision is performed, using 48.94% graphical paper, 17.50% packaging paper and 33.56% cardboard. These figures are based on a 2008 waste composition study for Danish waste discerning 43 different waste fractions in municipal waste (Riber & Christensen 2008: Tab 26). [28]

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[27] E.g. UN data for Nigeria lists only four figures (8% paper/board, 4.8% plastics, 3.1% glass, 11.3 textiles) not adding up to 100%. The missing fractions (Organic material, Metals, Other inorganic material) can be estimated with the extrapolations, using the country's GNI of 2820 $/capita.year to be 47.3%, 2.4%, 17.3% respectively.

[28] For graphical paper following fractions from the Danish study were added together: Newsprints; Magazines; Print Brochures; Books and phone books; Office paper; Other clean paper. For packaging paper following fraction was used: Dirty paper. For cardboard following fractions were added together: Paper and carton containers; Other cardboard (clean); Drink cartons wo Alu foil (Milk etc.); Drink cartons with Alu foil (Juice etc.); Dirty cardboard. It is assumed that drinks cartons are included in the UN fraction for "paper/cardboard". The small weight contributions from aluminium and plastic in drinks cartons are considered negligible.

No further distinction is made here, i.e. the fractional composition in Danish waste is used to differentiate the paper/cardboard fraction of all countries in the same way. If better statistical data becomes available, this can be changed.

Subdividing Plastics

The UN fraction "Plastics" corresponds to the target fraction "plastic, mixture". Therefore this can be applied directly.

In parallel, there are more differentiated target plastic fractions which are subsumed in the mixed plastic fraction (since MSW is a mixture anyway): polyethylene, polyethylene terephtalate, polypropylene, polystyrene, polyurethane, polyvinylchloride. In order to convert the UN fraction into the more differentiated fractions another subdivision is performed.

Waste fraction analysis according to plastic type is hard to come by; even the very differentiated Danish study used above has 43 different waste fractions, but plastics according to polymer type are not listed. Instead data on plastic *manufacture* is used here. Data from the European plastics manufacturers is available for types of polymers used by European plastics converters (PE 2018:p.22).

The derived profile is used to subdivide the UN waste fraction "Plastics" into several target waste fractions. Please note that while the profile in Tab. 5.4 adds up to 100%, not all fractions represent target fractions in this study (i.e. EPS and others) and those will not be used in the subdivision.

Tab. 5.4 Polymer types used in European plastics converters 2016 (based on PE 2018). Printed in bold are the figures used to derive target waste fractions.

Polymer Type		
Polyethylene	PE	**29.80%**
Polyethylene terephtalate	PET	**7.40%**
Polypropylene	PP	**19.30%**
Polystyrene [1]	PS	**6.00%**
Expanded polystyrene	EPS	0.7%
Polyurethane	PU	**7.50%**
Polyvinylchloride	PVC	**10%**
Others		19.30%

1 Given as 6.7% for the sum of PS and EPS, assumed 0.7% EPS.

This method of using *production* input data to estimate *waste* data is flawed with respect of assuming that all polymer types have the same short lifetime. In the real world product applications and therefore lifetimes differ, which means that certain product are turned more quickly into waste than others. In a market that has not reached a steady state or plateau this means that polymer shares in production are not the same as polymer shares in disposal.[29]

[29] If the plastics market were in a steady-state (zero growth and no shifts) the polymer shares in production would become identical to the polymer shares in waste after the period of the longest product lifetime has passed.

Deriving the wood target fraction

The target fraction "wood, untreated" is derived from the UN waste fraction "Organic material". A fixed share of 1.5% of organic material is estimated to represent untreated wood. This estimate is based on the Danish waste fractions study (Riber & Christensen 2008: Tab 26).[30]

[30] The corresponding organic waste fraction in (Riber & Christensen 2008) is derived from adding up the fractions "Vegetable food waste", "Animal food waste", "Garden & yard waste", "Animals and excrements", "Wood", and "Soil". The entry for wood makes up 1.5% in that sum.

Appendix A

Listed below are the county-specific data on **population-weighted rates of precipitation, evapotranspiration and resulting infiltration**. All in mm per year = liter per m^2.yr. The sources and the procedure to obtain the results see chapter 4 'Data reduction: Infiltration classes' on page 17.

The obtained population-weighted infiltration is used to grade countries into one of five infiltration classes, shown on the right side of the table. For reasons of conserving database space it is suggested that disposal in landfills and dumps are created for those five classes, instead of each country individually. It is not generally *compulsory* to use infiltration classes. For case studies outside the constraints of a large backgrounds database like ecoinvent, it is of course possible to create more accurate disposal datasets with the specific climate data of a country or location using the models in (Doka 2017b). For country data on precipitation and evapotranspiration the values listed below can be used.

Descriptive names are given to the infiltration classes. These names shall not be confused with similar adjectives in climatology that usually refer to precipitation only. The classes here are based on infiltration.

All countries are identified by their two-letter ISO country code.

The following table is sorted by 1. global region and 2. country population. The global regions are in following order:

1. Central and Eastern Europe
2. Commonwealth of Independent States
3. East Asia
4. Latin America and Caribbean
5. Middle East and North Africa
6. North America and Australia/New Zealand
7. Other Oceania
8. South Asia
9. Southeast Asia
10. Sub-Saharan Africa
11. Western Europe
12. Small Islands
13. Additional sub-territories already included above
14. Additional supra-regions made up of territories already listed above

This data is also listed for each country in the supplementary Excel table "WasteDisposalMix+APV_v0.3.xls".

country	ISO code	pop.w. Precipitation (mm/yr)	pop.w. Evapotranspiration (mm/yr)	pop.w. Infiltration (mm/yr)	infiltration class	
Poland	PL	608.12	435.42	172.7	2	dry
Romania	RO	605.38	483.52	121.86	2	dry
Czech Rep.	CZ	613.7	480.68	133.02	2	dry
Hungary	HU	597.36	512.82	84.54	2	dry
Serbia	RS	660.12	574.57	85.55	2	dry
Bulgaria	BG	620.83	539.15	81.68	2	dry
Slovakia	SK	821.19	521.76	299.43	3	moist
Croatia	HR	1189.79	615.73	574.07	4	wet
Bosnia Herzegovina	BA	997.31	616.06	381.25	3	moist
Lithuania	LT	662.49	427.19	235.31	3	moist
Albania	AL	1134.36	517.81	616.55	4	wet
Latvia	LV	666.13	392.97	273.16	3	moist
Macedonia	MK	685.27	532.9	152.37	2	dry
Slovenia	SI	1020.53	581.13	439.4	4	wet
Estonia	EE	636.11	388.16	247.94	3	moist
Montenegro	ME	1233.16	625.57	607.59	4	wet
Russia	RU	552.8	393.81	158.99	2	dry
Ukraine	UA	558.62	398.75	159.87	2	dry
Uzbekistan	UZ	288.3	250.22	38.08	2	dry
Kazakhstan	KZ	360.08	294.65	65.43	2	dry
Belarus	BY	631.29	447.44	183.86	2	dry
Azerbaijan	AZ	417.45	378.47	38.98	2	dry
Tajikistan	TJ	648.62	288.52	360.1	3	moist
Kyrgyzstan	KG	433.43	379.46	53.97	2	dry
Turkmenistan	TM	167.46	196.64	-29.19	1	hyperarid
Georgia	GE	1242.37	474.42	767.96	4	wet
Moldova	MD	569.47	424.21	145.26	2	dry
Armenia	AM	590.48	455.54	134.94	2	dry
China	CN	986.27	561.24	425.03	4	wet
Japan	JP	1646.54	637.83	1008.71	5	very wet
South Korea	KR	1305.89	622.79	683.1	4	wet
North Korea	KP	1025.36	505.17	520.19	4	wet
Taiwan	TW	1772.69	853.56	919.13	5	very wet
Mongolia	MN	279.79	263.6	16.19	2	dry
Brazil	BR	1345.8	896.55	449.25	4	wet
Mexico	MX	1022.14	761.21	260.94	3	moist
Colombia	CO	1633.6	970.09	663.51	4	wet
Argentina	AR	853.57	583.11	270.46	3	moist
Peru	PE	747.18	658.7	88.49	2	dry
Venezuela	VE	1171.49	1185.32	-13.83	1	hyperarid
Chile	CL	776.46	406.28	370.18	3	moist
Ecuador	EC	1109.82	730.28	379.54	3	moist
Guatemala	GT	1459.83	1301.79	158.04	2	dry
Cuba	CU	1204.84	682.01	522.83	4	wet
Bolivia	BO	965.18	683.15	282.02	3	moist
Dominican Rep.	DO	1295.34	813.81	481.53	4	wet
Haiti	HT	1729.84	813.81	916.03	5	very wet
Honduras	HN	1786.98	1220.95	566.04	4	wet
Paraguay	PY	1676.82	1230.81	446.01	4	wet
El Salvador	SV	1848.08	1262.32	585.76	4	wet
Nicaragua	NI	1682.56	938.85	743.71	4	wet
Costa Rica	CR	2060.52	877.98	1182.54	5	very wet
Panama	PA	2062.18	875.21	1186.96	5	very wet
Uruguay	UY	1207.01	643.04	563.97	4	wet
Guyana	GY	2057.01	1128.66	928.35	5	very wet
Suriname	SR	1875.65	1242.68	632.97	4	wet
Belize	BZ	1459.95	1133.06	326.89	3	moist
French Guiana	GF	2062.18	1092.53	969.64	5	very wet
Palestine	PS	528.5	301.26	227.24	3	moist
Egypt	EG	46.98	554.39	-507.41	1	hyperarid
Turkey	TR	650.28	339.36	310.92	3	moist
Iran	IR	331.49	300.41	31.07	2	dry
Algeria	DZ	427.23	283.69	143.54	2	dry
Morocco	MA	475.52	284.23	191.29	2	dry
Iraq	IQ	316.01	217.27	98.74	2	dry
Saudi Arabia	SA	173.64	515.87	-342.23	1	hyperarid
Yemen	YE	211.44	512.67	-301.23	1	hyperarid
Syria	SY	444.3	302.12	142.18	2	dry
Tunisia	TN	434.76	212.64	222.13	3	moist
Israel	IL	528.5	301.26	227.24	3	moist
Jordan	JO	249.38	289.43	-40.05	1	hyperarid
Lebanon	LB	694.3	349.37	344.93	3	moist

country	ISO code	pop.w. Precipitation (mm/yr)	pop.w. Evapotranspiration (mm/yr)	pop.w. Infiltration (mm/yr)	infiltration class	
United States	US	1048.65	621.79	426.86	4	wet
Canada	CA	822.59	444.83	377.76	3	moist
Australia	AU	946.15	684.44	261.71	3	moist
New Zealand	NZ	1581.31	646.09	935.22	5	very wet
India	IN	1050.01	565.4	484.61	4	wet
Pakistan	PK	358.12	358.52	-0.4	1	hyperarid
Bangladesh	BD	1932.87	798.17	1134.71	5	very wet
Afghanistan	AF	379.06	252.83	126.23	2	dry
Nepal	NP	1601.11	589.54	1011.57	5	very wet
Sri Lanka	LK	1698.22	941.95	756.27	4	wet
Bhutan	BT	553.21	569.52	-16.31	1	hyperarid
Indonesia	ID	2005.71	1127.73	877.98	5	very wet
Philippines	PH	2021.15	1123.64	897.52	5	very wet
Viet Nam	VN	1728.79	996.8	731.99	4	wet
Thailand	TH	1439.52	886.05	553.46	4	wet
Myanmar	MM	1614.2	771.67	842.53	5	very wet
Malaysia	MY	2058.4	1338.43	719.97	4	wet
Cambodia	KH	1502.75	986.94	515.81	4	wet
Laos	LA	1698.48	1038.73	659.75	4	wet
Papua New Guinea	PG	2021.75	956.19	1065.56	5	very wet
Timor-Leste	TL	1502.59	1165.27	337.32	3	moist
Brunei	BN	2062.18	1472.8	589.37	4	wet
Nigeria	NG	1153.6	737.93	415.67	4	wet
Ethiopia	ET	1077.01	599.44	477.58	4	wet
Congo (Kinshasa)	CD	1551.7	1211.42	340.29	3	moist
South Africa	ZA	688.58	502.09	186.49	2	dry
Tanzania	TZ	953.24	694.12	259.13	3	moist
Kenya	KE	807.1	652.19	154.92	2	dry
Sudan	SD	496.69	668.05	-171.36	1	hyperarid
Uganda	UG	1233.09	1051.59	181.5	2	dry
Ghana	GH	1258.55	957.72	300.84	3	moist
Mozambique	MZ	1101.78	1006.9	94.88	2	dry
Madagascar	MG	1491.69	772.55	719.14	4	wet
Cote d'Ivoire	CI	1342.37	973.9	368.47	3	moist
Cameroon	CM	1735.16	934.77	800.39	5	very wet
Angola	AO	1026.22	937.24	88.98	2	dry
Burkina Faso	BF	728.62	437.07	291.55	3	moist
Niger	NE	363.49	375.96	-12.47	1	hyperarid
Malawi	MW	1109.28	717.29	391.99	3	moist
Mali	ML	765.86	446.27	319.59	3	moist
Zambia	ZM	1020.76	669.22	351.54	3	moist
Senegal	SN	593.55	536.89	56.67	2	dry
Zimbabwe	ZW	689.87	535.15	154.72	2	dry
Rwanda	RW	1177.59	917.38	260.21	3	moist
Chad	TD	753.73	541.46	212.27	3	moist
Guinea	GN	1855.66	1064.34	791.32	4	wet
Burundi	BI	1176.66	606.18	570.48	4	wet
Somalia	SO	395.44	537.77	-142.33	1	hyperarid
Benin	BJ	1034.7	827.33	207.37	3	moist
Togo	TG	1175.32	853.79	321.53	3	moist
Eritrea	ER	431.25	468.07	-36.83	1	hyperarid
Sierra Leone	SL	2062.18	898.57	1163.61	5	very wet
Cent. Afr. Rep.	CF	1461.95	1281.63	180.32	2	dry
Congo (Brazzaville)	CG	1436.54	1077.95	358.59	3	moist
Liberia	LR	2061.57	768.58	1292.99	5	very wet
Mauritania	MR	151.14	330.36	-179.21	1	hyperarid
Namibia	NA	466.32	382.85	83.48	2	dry
Botswana	BW	408.1	381.63	26.47	2	dry
Lesotho	LS	785.83	431.84	353.99	3	moist
Guinea-Bissau	GW	1868.25	885.19	983.06	5	very wet
Gabon	GA	1859.03	1109.81	749.22	4	wet
Swaziland	SZ	1041.18	693.51	347.66	3	moist
Equatorial Guinea	GQ	2000	995.82	1004.18	5	very wet
Germany	DE	750.47	468.56	281.91	3	moist
France	FR	844.01	515.85	328.16	3	moist
United Kingdom	GB	936.67	410.09	526.57	4	wet
Italy	IT	831.53	564.1	267.43	3	moist
Spain	ES	580.36	320.2	260.16	3	moist
Netherlands	NL	777.11	491.07	286.04	3	moist
Portugal	PT	890.04	516.1	373.94	3	moist
Greece	GR	591.06	444.56	146.5	2	dry
Belgium	BE	786.89	491.08	295.81	3	moist

country	ISO code	pop.w. Precipitation (mm/yr)	pop.w. Evapotranspiration (mm/yr)	pop.w. Infiltration (mm/yr)	infiltration class	
Sweden	SE	666.25	379.87	286.38	3	moist
Austria	AT	1030.22	469.79	560.43	4	wet
Switzerland	CH	1061.27	388.41	672.86	4	wet
Denmark	DK	687.81	428.54	259.27	3	moist
Finland	FI	598.72	322.72	276	3	moist
Ireland	IE	1075.31	483.58	591.74	4	wet
Norway	NO	1263.58	250	1013.58	5	very wet
Cyprus	CY	943.01	300	643.01	4	wet
Luxembourg	LU	860.1	573.22	286.88	3	moist
Malta	MT	580	560	20	2	dry
Iceland	IS	950	250	700	4	wet
Greenland	GL	445.6	307.53	138.06	2	dry
Kosovo	XK	982.09	601.13	380.97	3	moist

Appendix B

Results for waste disposal rates in 219 different countries, according to the procedure outlined in chapter 3 'Municipal waste disposal technology mix' on page 5ff.

Fig. B.1 below gives a graphical overview of the elaborated waste disposal rates (first x-axis) with the countries sorted according to ascending Gross National Income GNI, which is indicated as a dot (•) on a second, logarithmic x-axis. Countries are indicated on the y-axis with their ISO country codes.[31]

It is apparent that open burning and landfill fires, indicated as orange bars, are frequent in countries with low GNI, which is premeditated by the estimates used (cf. Fig. 3.4 on page 11 and Fig. 3.6 on page 14).

It is also well visible that waste incineration in controlled plants (MSWI, indicated as purple bars) is not common in countries with a GNI below 10'000 $/cap.yr. This is based on statistical country data and not a modelling precept.

The elaborated data for each country is listed in the supplementary Excel table "WasteDisposalMix+APV_v0.3.xls".

[31] One outdated ISO code (GB-CHA) is used here to indicate the Channel Islands. The Channel Islands consist of Guernsey and Jersey, which would form separate entities, but for which individual statistical data was not available.

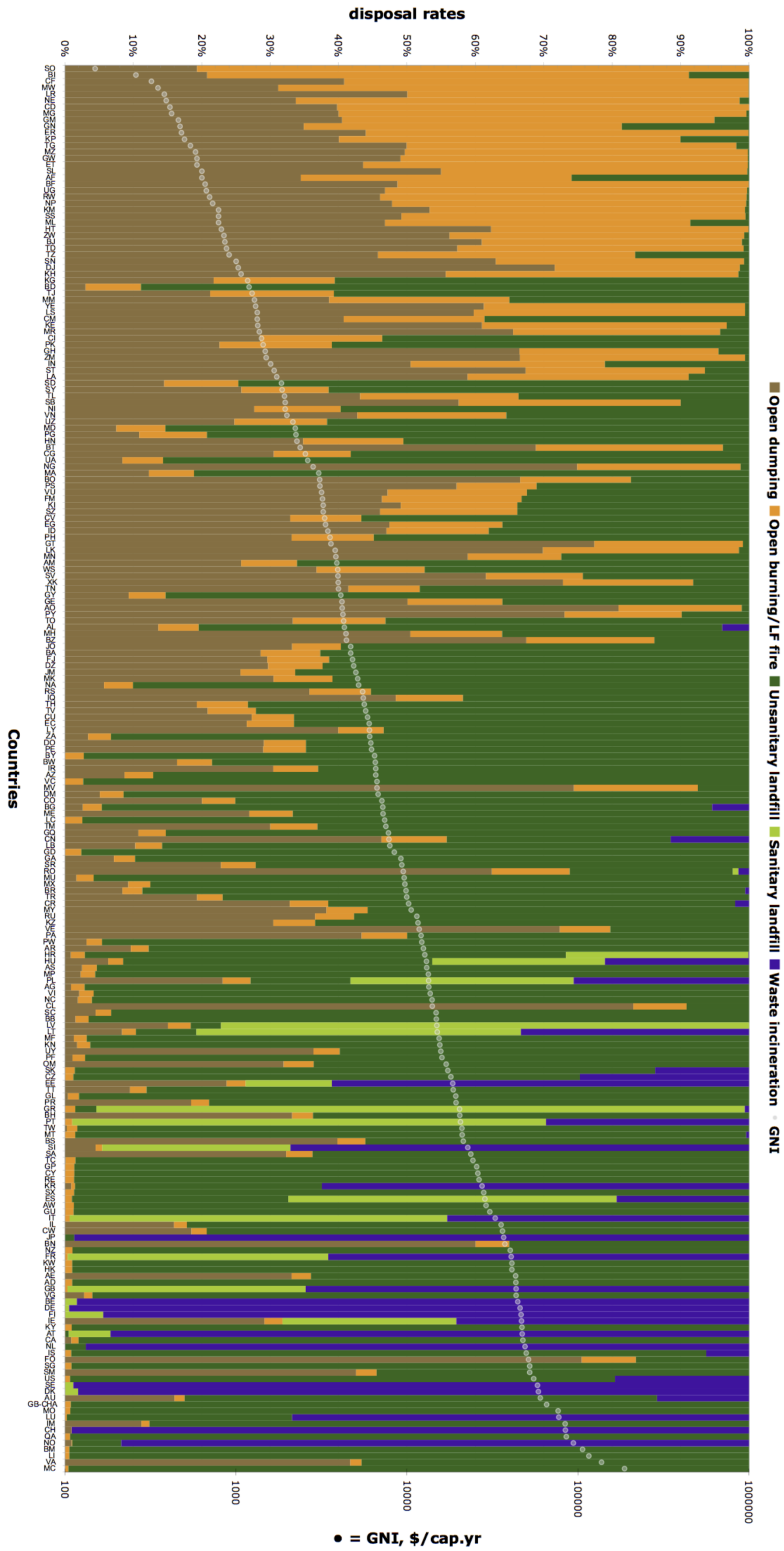

Fig. B.1 Waste disposal in 219 countries, sorted according to Gross National income GNI

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