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Approaches to measuring extent and impacts

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Glossary

Brownfield (BF) sites:

- are 'derelict and underused or even abandoned former industrial or commercial sites, which may have real or perceived contamination problems' (EC, 2012, p. 40);
- have been affected by former uses of the site or surrounding land, are derelict or underused, and occur mainly in fully or partly developed urban areas; they require intervention to bring them back to beneficial use, and they may have real or perceived contamination problems (CABERNET, 2007).

Brownfield redevelopment: 'bringing brownfield land back into use. This involves one or more of the following: bringing the site back into market without change in land use, changing existing or past land use by integrating the site into planning strategy for the local or regional area (this includes also renaturalisation and de-sealing of brownfield land) and cleaning up existing soil pollution' (BIO, 2014, p. 15).

Functional urban area (FUA): 'The functional urban area (FUA) consists of the city and its commuting zone' (Eurostat, 2015).

Greenfield (GF): usually land located in a (semi-)rural area that is undeveloped apart from agricultural use, especially land considered as a site for expanding urban development.

Land recycling: 'redevelopment of previously developed land (brownfield) for economic purpose, ecological upgrading of land for the purpose of soft-use (e.g. green areas in the urban centres) and renaturalisation of land (bringing it back to nature) by removing existing structures and/or desealing surfaces' (BIO, 2014, p. 16). In this report, this is referred to as 'land recycling in its narrow sense'. Whenever urban densification, or infilling, is included in the term, we refer to it as 'land recycling in its broad sense'. In this report we distinguish between 'grey' and 'green' land recycling. 'Grey' land recycling is understood as the re-use of built areas; whereas 'green' land recycling is understood as the creation of green or open urban areas. 'Green' land recycling has the potential to contribute to urban green infrastructure, while such potential is limited in the case of 'grey' recycling.

Land take: the amount of agriculture, forest, semi-natural/natural land, wetlands or water taken by urban and other artificial land development, as defined in the EEA Land take indicator (CSI 014/LSI 001; EEA, 2005). This indicator provides information on the change from agricultural, forestry and semi-natural/natural land, wetlands or water to urban land cover as a consequence of urban residential development, development of economic sites and infrastructures (including the creation of industrial, commercial and transport units, but excluding the conversion of previously developed land to sport and leisure facilities) and development of green urban areas on previously undeveloped land. To this end, the indicator uses Corine Land Cover (CLC) data, containing a hybrid of land cover and land use data. Land take is also referred to as 'land consumption' in some cases, although the actual meaning may differ from the EEA's definition of land take.

Life cycle assessment (LCA): a method for quantifying the potential environmental impacts of a product or service over its entire life cycle. The most important applications are (1) analysing the contribution of different life cycle stages to the overall environmental impact, in order to prioritise improvements in products or processes; and (2) comparing products and services in terms of their overall environmental impact.

Life cycle thinking (LCT): describes a process that considers environmental impacts over the entire life cycle of a product. The key aim of LCT is to avoid burden shifting. This means minimising impacts at one stage of the life cycle, or in a geographical region, or in a particular impact category, while avoiding increasing impacts elsewhere.

Site actuation: activities performed at a site with the purpose of developing it for a new use.

Soil sealing: 'the permanent covering of an area of land and its soil by impermeable artificial material (e.g. asphalt and concrete), for example through

buildings and roads' (EC, 2012, p. 36) or 'the covering of the soil surface with impervious materials as the result of urban development and infrastructure construction', as defined in the EEA Imperviousness indicator (LSI 002; EEA, 2016a).

Urban sprawl: 'Urban sprawl is a phenomenon that can be visually perceived in the landscape. A landscape [is affected by urban sprawl] if it is permeated by urban development or solitary buildings and when land uptake per inhabitant or job is high. The more area built over in a given landscape (amount of built-up area) and the more dispersed this built-up area in the landscape (spatial configuration), and the higher the uptake of built-up area per inhabitant or job (lower utilisation intensity in the built-up area), the higher the degree of urban sprawl' (Jaeger and Schwick, 2014, in EEA, 2016c, p. 22).

Abbreviations

7th EAP	Seventh Environment Action Programme
BF	brownfield
CLC	Corine Land Cover
CTUe	comparative toxic unit for ecosystems
CTUh	comparative toxic unit for humans
EEA	European Environment Agency
Eionet	European Environment Information and Observation Network
ETC/ULS	European Topic Centre on Urban, Land and Soil Systems
EU	European Union
FUA	functional urban area
GF	greenfield
GHG	greenhouse gas
ILCD	International Reference Life Cycle Data System
ISO	International Organization for Standardization
LCA	life cycle assessment
LCF	land cover flow
LCIA	Life cycle impact assessment
LCT	life cycle thinking
LEAC	land and ecosystem accounts
MMU	minimum mapping unit
NRC LUSP	National Reference Centre for Land Use and Spatial Planning
PAF	potentially affected fraction of species
SOM	soil organic matter
UA	Urban Atlas

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Chapter 3, 'The wider environmental impacts of land recycling', was developed largely under the service contract 'Study on land recycling' (Negotiated procedure EEA/NSV/14/003): Jordi Boronat (MediTerra), Karen Van Geert (Arcadis), Paul Nathanail (LQM) and Carme Hidalgo (Leitat); Geertrui Louwagie and Rastislav Staník (EEA).

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Executive summary

Land take, or the change from non-artificial to artificial land cover, reflects on-going and often conflicting claims on land. Some of the land that is 'taken' for urban development is covered with an impervious surface, which severely hampers ecosystem functioning and the related delivery of ecosystem services. However, when land is 'recycled', land that was developed in the past and has become available for redevelopment again is reused. Urban densification, or infilling, can also prevent the consumption of land that may be very valuable for food production or recreation.

In this report, the processes of recycling and densification are jointly referred to as 'land recycling in its broad sense'. Land recycling can be considered a response to the on-going pressures we as a society apply to our land resources, particularly in the urban fringe.

The recognition that our land resources need conservation is articulated in the EU's Seventh Environment Action Programme (7th EAP). The 7th EAP also recognises the need to improve the knowledge base.

Our knowledge of various aspects of land recycling is generally limited. In this report, we focus on the environmental dimension of land recycling, presenting two approaches:

- an accounting approach to monitoring land recycling (Chapter 2);
- a life cycle assessment (LCA) approach to evaluating the environmental impact of land recycling across a wide range of environmental domains (Chapter 3).

Considering the larger framework of sustainable land management, with its multiple dimensions, we reflect upon the findings of our test cases within the broader context of a green economy (addressing ecological scarcity, resource efficiency and social equity) in the last chapter (Chapter 4).

Pan-European monitoring of land recycling has in the past been based on estimates calculated from Corine Land Cover (CLC) change data, covering 39 countries (and the urbanised areas within). Recently, Urban Atlas (UA, part of Copernicus land monitoring) change data have become available, and they facilitate more accurate estimates, as they have a higher spatial and thematic resolution than CLC data. UA data are available for almost 700 main urban areas and their commuting zones in the EU. In this report, we present a set of indicators to estimate land recycling based on UA data; they look at land recycling in its broad sense, but also focus on its components: urban densification; and 'grey' and 'green' land recycling (reuse of built areas versus creation of green or open urban areas). Monitoring urban densification and 'grey' recycling responds to resource efficiency concerns, while monitoring 'green' recycling makes sense in the face of increased policy attention for green infrastructure and the well-being of European citizens in general.

Analysing a wide range of environmental impacts of land recycling sheds light on why it makes environmental sense as a response measure, beyond the consideration of the land use aspect. Global (climate change, land use, etc.), regional (freshwater ecotoxicity, eutrophication, etc.) and local (e.g. ionising radiation) effects are calculated across the life cycle stages of brownfield and greenfield developments. Life cycle stages in our calculations comprise (pre-development) site condition, site actuation or development, and operation or use of the site. The accompanying sensitivity analysis shows that the results are critically dependent on the choice of the functional unit (i.e. the unit to which impacts are related, such as the area of built surface). Nevertheless, our test findings illustrate that the use phase creates the greatest environmental impact, largely because of the mobility generated once citizens live at a site. Overall, they also indicate that reuse of a brownfield site should be favoured over construction on a greenfield site. Life cycle assessment (LCA) studies from the United States show that a similar conclusion can be drawn on cost grounds (even when a brownfield site is contaminated and needs remediation).

The land monitoring and LCA approach can add value and both can have limitations; exploring these issues contributes to expanding our knowledge of

land recycling. The proposed land recycling indicators resulting from the monitoring are well suited to evolving into an EEA indicator with regular assessment, following which trends in land recycling in functional urban areas in the EU could be tracked on a 6-yearly basis. The LCA approach, on the other hand, is better suited to use as a local or regional decision-making tool. Both approaches can provide policymakers and citizens with valuable insights about the consequences of their choices on land resources.

1 Introduction

This chapter will:

- explain why we need to reduce land take;
- introduce the concept of land recycling and other key terminology;
- discuss the gaps in implementation of the indicators proposed for measuring land recycling;
- explain why we need to consider the wider environmental implications of land recycling;
- explain how land recycling fits within the concepts of the circular and green economies.

1.1 Why is it important to reduce land take?

Land is a finite resource, on which conflicting demands are putting an unprecedented strain. The resulting degradation of land reduces its potential to supply ecosystem services.

Land take, or the increase in the area of land under artificial cover, is an on-going process across Europe (EEA, 2016d). Across all EEA member and cooperating countries (EEA-39), for the 2006–2012 period, land take was 1 065 km^2 annually, or 6 390 km^2 in total. Although this is slightly less than during the previous 6-year period, 2000–2006 (1 120 km^2 annually or 7 258 km^2), it still represents a substantial amount of land being taken for development each year. A similar pattern of land take can be seen across the EU (from 930 km^2 annually in 2000–2006 to 845 km^2 annually in 2006–2012; data for 27 Member States (EEA, 2016d)).

Not all of the land included in land take figures is actually covered with an impervious surface (soil sealing), which is one of the most detrimental effects of land take in terms of its environmental impact. However, between 2006 and 2009, soil sealing increased at an average rate of 1 454 km^2 per year across the EEA-39 (EEA, 2016a), which corresponds to a total of 4 364 km^2 (EEA, 2016a).

When soil is sealed, i.e. covered with an impervious surface, the four ecospheres (geosphere, hydrosphere, atmosphere and biosphere) become disconnected. As they constitute the earth's ecosystem, soil sealing disrupts the functioning of the ecosystem, in terms of nutrient and water cycling, and affects its ability to supply ecosystem services — which includes everything from provision of food and water to climate regulation and improving our quality of life.

Therefore, on-going land take and soil sealing have long been a cause for concern (EC, 2002; EEA, 2005). Bearing in mind the negative impact of these processes, how can we manage land resources to protect their potential to deliver ecosystem services? To address this, the EU made a commitment in its Seventh Environment Action Programme (7th EAP) to limit land take by setting the goal of 'no net land take, by 2050' (EU, 2013a). One of the key responses to the question of land governance that can reduce the pressure on land resources by limiting land take and soil sealing is land recycling (EC, 2012; EEA, 2015a; EC, 2016b).

1.2 What is land recycling and how can it be measured?

A study supporting potential land targets in preparation for the European Commission's planned Communication on land use (as announced in the Roadmap to a Resource Efficient Europe (EC, 2011a))

defined land recycling as the 'redevelopment of previously developed land (brownfield) for economic purpose, ecological upgrading of land for the purpose of soft-use (e.g. green areas in the urban centres) and renaturalisation of land (bringing it back to nature) by removing existing structures and/or desealing surfaces' (BIO, 2014, p. 16). It also proposed a set of indicators for monitoring land recycling (BIO, 2014, p. 89):

- the area of brownfield land (m^2 or other unit of area);
- the total area of land within the existing urban fabric that is available for inner development (m^2 or other unit of area);
- the brownfield land that is redeveloped (m^2 or other unit of area/time unit, or %);
- development on brownfield land as a proportion of total new development (%);
- land recycling as a proportion of total land consumption by artificial development (%);
- land recycling as a proportion of total land consumption by artificial development in functional urban areas covered by the Urban Atlas (%).

One of the above indicators refers to 'inner development', or 'development within the existing urban fabric through densification and recycling' (BIO, 2014). In this report, we use the term 'densification', or 'infilling', to denote a process that is related to, but distinct from, land recycling in its narrow sense. However, our definition of land recycling in its broad sense includes densification.

The last two proposed indicators are derived from Copernicus land-monitoring products: Corine Land Cover (CLC) and Urban Atlas (UA), respectively. CLC provides medium-resolution mapping of all land cover and land use in the EEA-39, whereas UA provides high-resolution mapping of land cover and land use in cities and their commuting zones, known as functional urban areas (FUAs) (Eurostat, 2015). The latter's high resolution and more detailed classification of, and greater sensitivity in detecting, artificial land cover make it ideally suited to developing indicators for measuring land recycling.

The quality of the proposed indicators can be assessed using the 'RACER' framework ([1]), which rates the last two as partially relevant (for policy), acceptable (i.e. ready to be implemented — only the indicator using CLC data), fully credible (i.e. easy to understand) and easy to monitor but not based on robust methodology. The absence of a clearly identified methodology and a lack of transparency regarding how the indicators are calculated have been acknowledged for the entire set of proposed indicators and represent crucial limitations on their use in practice.

In order to report the state of land recycling accurately, we need European-level indicators based on a harmonised methodology and harmonised datasets. In this report, we aim to fill the 'methodological gap' in the proposed indicators identified above by presenting a set of indicators for estimating land recycling and densification that is underpinned by just such a harmonised methodology and such harmonised datasets.

1.3 How can land recycling contribute to a sustainable future?

Looking at the 'bigger picture', how we use and manage land has impacts on parts of the environment other than land, e.g. depletion of water resources, greenhouse gas (GHG) emissions. Therefore, we also need a methodology for capturing such impacts. The life cycle thinking (LCT) approach allows the estimation and evaluation of the wider environmental impacts of brown- or greenfield development, i.e. impacts (both on and off site) not directly related to the land used. By looking at the environmental implications of land take and land recycling, we can identify potential improvements in how we use land in the form of reduced environmental impacts and reduced consumption of resources across all stages of the life cycle of a development, including the remediation of land and its use in the future.

Land recycling could be key to improving land management to maintain and develop the green infrastructure that is so important for the provision of ecosystem services. It could also make an important contribution to fulfilling the EU's aim of achieving a circular economy, in which maximum value is derived from resources by recycling and recovery of materials, and a green economy, which extends the concept of the circular economy to encourage economic development that is resource efficient and socially equitable and that respects the limits of the environment.

([1]) RACER framework: the criteria are (policy) relevance, acceptability (or indicator implementation), credibility (for non-experts, i.e. easy to understand), easiness (to monitor, including data availability) and robustness (of methodology across EU Member States).

1.4 Scope and structure of this report

This report aims to raise awareness and explain the importance of land recycling and densification in the context of the need to reduce land take.

Chapter 2 looks at the development of a robust methodology for measuring land recycling and densification.

Chapter 3 looks at the wider environmental implications of land recycling for policymaking, using the LCT approach, and reports the key findings of three case studies.

Chapter 4 discusses the implications of land recycling for governance — what difference can it make in 'real life'? — for both decision-making at the local level and society in general.

Detailed methodological approaches are presented in the Annex.

2 The extent of land recycling and densification

This chapter will:

- describe the harmonised datasets that can be used to estimate land recycling regularly;
- introduce a set of land recycling indicators based on a harmonised methodology;
- present the results of testing these indicators at country and FUA level.

2.1 The databases

Copernicus is an EU-wide earth observation programme: among other things, it provides the Corine Land Cover (CLC) and Urban Atlas (UA) databases. These are updated every 6 years, making them ideal for measuring changes in land cover and land use.

2.1.1 Corine Land Cover

CLC ([2]) provides medium-resolution wall-to-wall mapping of land cover and land use in the EEA-39, covering a total area of about 6 million km^2. CLC status layers (to date, these are available for 1990, 2000, 2006 and 2012) are produced with a minimum mapping unit (MMU) of 25 ha, whereas change layers have an MMU of 5 ha. CLC's positional accuracy is ± 100 m. Its current and planned temporal resolution, or 'revisit period', is 6 years.

CLC has 44 different land cover classes at the highest level of detail (level 3), which, for example, breaks down the major class 'Artificial surfaces' into 11 subclasses.

2.1.2 Urban Atlas

UA ([3]) is a high-resolution land cover and land use map for so-called FUAs. It is produced at a scale of 1:10 000, with an MMU of 0.25 ha for urban classes and 1 ha for the rural ones. Its positional accuracy is ± 5 m. Like CLC, its (planned) temporal resolution is 6 years.

UA 2006 is currently the only complete set available, covering up to 301 FUAs (with more than 100 000 inhabitants). UA 2012 is still under production, and will cover 695 FUAs (301 existing FUAs from UA 2006 and 394 new FUAs, including most cities with more than 50 000 inhabitants in the EU-28).

The nomenclature developed for UA used the CLC nomenclature as a starting point (see Section A.1 in the Annex). Therefore, the nomenclature used in the products is similar, although not identical, given the differences in their thematic resolution and the level of detail of the geospatial information that they provide. On that point, UA 2012 covers 27 different land cover and land use types, whereas UA 2006 covered only 20 classes. The difference arises from the further subdivision, in UA 2012, of the former classes 'Forest' and 'Agricultural areas, semi-natural areas and wetlands'. Nevertheless, comparing UA with CLC, the latter still has a higher thematic resolution within the non-artificial classes (agriculture and forest), while UA gives more detailed descriptions of the artificial classes.

2.2 The methodology

2.2.1 From land cover changes to land cover flows

Land accounting is based on organising land cover changes into different land cover flows (LCFs) (EEA, 2008). These LCFs are based on grouping land cover

([2]) CLC data are available at: http://land.copernicus.eu/pan-european/corine-land-cover/view (accessed 6 May 2016).
([3]) UA data are available at: http://land.copernicus.eu/local/urban-atlas/view (accessed 6 May 2016).

changes according to the underlying processes or drivers (described in detail in Section A.2 in the Annex). LCFs therefore correspond to land cover change drivers, such as urban land management, urban residential development, and development of economic sites and infrastructures, and they facilitate the reporting and assessment of changes in land cover over time.

The definition of land cover flows in Corine Land Cover

For the purpose of land accounting, the EEA has developed LCFs based on the CLC nomenclature as part of the land and ecosystem accounts (LEAC) approach (EEA, 2006b; EEA, 2008).

All the potential CLC changes (44 × 43 = 1 892) are grouped into LCFs; these are organised into three different levels, similar to the CLC levels. The methodology and logic developed using the CLC nomenclature can, with some adjustment, be applied to the more recently developed, yet more spatially and thematically accurate, UA land monitoring and mapping database. For full details of the methodology, please refer to Section A.2 in the Annex.

2.2.2 The indicators

The EEA has developed a set of indicators (Table 2.1) for measuring land recycling and/or urban densification, which are calculated using the LCFs defined above and in Section A.2 in the Annex. Although the two processes were considered as one under the generic name of land recycling in an EEA report on land accounts (EEA, 2006b), a distinction is made in this report between densification (lcf 11) and land recycling in the narrow sense (lcfs 12, 13 and 38 — the last two only on developed land). Furthermore, within the land recycling flows, those that involve the creation of open or green space (lcfs 13 and 38 — only on developed land) are highlighted separately, as they have the most potential to contribute to urban green infrastructure, hereafter referred to 'green' land recycling. Land recycling that does not have that potential is referred to as 'grey' recycling.

Indicators 1 and 2 are calculated with both CLC and UA data, whereas indicators 3–13 are calculated with only UA data (see section 2.3 'Results of testing the indicators'). For full details of how the indicators are calculated, please refer to Section A.3 in the Annex.

2.2.3 Testing the indicators

The aim of testing was to:

- compare estimates of land recycling and densification using datasets with different spatial and thematic resolutions, and in particular to

Table 2.1 The indicators

Indicator no	Description of indicators
	General indicators
1	'Grey' land recycling and densification (CLC-based)
2	'Grey', 'green' land recycling and densification (Land recycling in its broad sense, CLC-based)
3	'Grey' land recycling and densification (UA-based)
4	'Grey', 'green' land recycling and densification (Land recycling in its broad sense, UA-based)
Land recycling components	
5	Densification
6	'Grey' land recycling
7	'Green' land recycling
Land recycling components related to urban land management	
8	Densification related to urban land management
9	'Grey' land recycling related to urban land management
10	'Green' land recycling related to urban land management
Land recycling components related to land take	
11	Densification related to land take
12	'Grey' land recycling related to land take
13	'Green' land recycling related to land take

compare the use of CLC data with the use of UA data to calculate indicators 1 and 2 over the same spatial extent (defined by the Urban Audit boundary);

- assess the thematic meaningfulness of the indicators.

Indicators were calculated for 23 FUAs, namely those capitals in the EU for which UA change data between 2006 and 2012 were available at the time of writing.

Indicators 1 and 2 were calculated for all the selected FUAs with both the CLC 2006–2012 changes (version 18.5) and the UA change data (2006–2012), using exactly the same territorial extent (the FUA boundary).

2.3 Results of testing the indicators

This section assesses the test results, starting with the densification and land recycling indicators, which were calculated using both CLC and UA datasets. However, to provide a framework for interpreting these results at FUA level, combined densification and land recycling estimates (i.e. land recycling in its broad sense) at country level using CLC data from the time series 1990–2000–2006–2012 are presented in Table 2.2.

These data show that, on average, land recycling in its broad sense increased steadily between 1990 and 2012 on an annual basis. However, the values vary considerably between countries, and, within countries, increasing or decreasing trends in land recycling are not necessarily detectable.

Table 2.2 Densification and land recycling (indicators 1 and 2) as a percentage of total land consumption at country level, based on CLC time series data

Country	Indicator 1			Indicator 2		
	1990–2000	2000–2006	2006–2012	1990–2000	2000–2006	2006–2012
Albania (AL)	ND	0.23	0.00	ND	0.27	0.00
Austria (AT)	2.03	0.99	0.23	3.77	0.99	0.23
Belgium (BE)	4.90	2.99	4.82	5.13	2.99	4.82
Bosnia and Herzegovina (BA)	ND	0.74	0.27	ND	0.74	0.27
Bulgaria (BG)	0.48	2.81	2.71	0.48	4.07	2.71
Croatia (HR)	0.00	1.33	0.88	0.00	1.48	1.01
Cyprus (CY)	ND	0.37	0.53	ND	0.74	0.62
Czech Republic (CZ)	8.82	1.60	1.80	10.52	2.44	2.43
Denmark (DK)	0.89	1.01	0.99	1.62	2.33	2.57
Estonia (EE)	0.59	0.81	8.83	0.59	0.81	8.83
Finland (FI)	ND	3.48	3.53	ND	4.28	3.79
France (FR)	2.04	0.71	0.87	2.63	0.72	0.93
Germany (DE)	2.10	1.29	3.57	2.34	1.96	3.79
Greece (EL)	0.11	4.40	1.17	0.23	5.42	1.17
Hungary (HU)	1.54	5.18	1.35	2.27	5.23	1.40
Iceland (IS)	ND	0.97	5.51	ND	0.97	5.51
Ireland (IE)	1.96	2.25	0.16	1.97	2.25	0.16
Italy (IT)	0.19	1.00	1.51	0.19	1.03	1.54
Kosovo [(a)] (XK)	ND	0.00	3.14	ND	0.00	3.55
Latvia (LV)	0.00	2.26	6.07	0.00	2.26	6.26
Lithuania (LT)	0.35	1.78	1.06	0.35	1.78	1.06
Luxembourg (LU)	2.33	1.34	11.91	2.33	1.34	11.91
Macedonia, former Yugoslav Republic of (MK)	ND	0.32	0.00	ND	0.32	1.50
Malta (MT)	0.00	0.00	0.00	0.00	0.00	0.00
Montenegro (ME)	5.03	0.00	13.07	5.03	0.00	15.64

Table 2.2 Densification and land recycling (indicators 1 and 2) as a percentage of total land consumption at country level, based on CLC time series data (cont.)

Country	Indicator 1			Indicator 2		
	1990–2000	2000–2006	2006–2012	1990–2000	2000–2006	2006–2012
Netherlands (NL)	1.81	2.21	1.17	1.87	2.37	1.41
Norway (NO)	ND	2.47	1.22	ND	2.54	1.22
Poland (PL)	1.72	1.26	1.71	1.91	1.31	1.73
Portugal (PT)	2.68	0.61	0.55	2.80	0.66	0.73
Romania (RO)	0.29	0.00	0.09	0.29	0.00	0.09
Serbia (RS)	0.55	2.11	0.61	0.55	2.11	0.61
Slovakia (SK)	0.59	0.18	0.09	0.59	0.18	0.09
Slovenia (SI)	3.46	0.00	3.90	3.46	0.00	3.90
Spain (ES)	1.83	1.12	1.47	1.97	1.20	1.57
Sweden (SE)	ND	3.50	1.56	ND	4.11	1.63
Switzerland (CH)	ND	7.62	3.85	ND	7.62	4.46
Turkey (TR)	1.02	1.86	4.14	1.06	1.90	4.20
United Kingdom (UK)	5.54	7.56	4.21	6.29	9.37	5.06
European average	**1.96**	**1.85**	**2.66**	**2.23**	**2.10**	**2.93**
Minimum	0.00	0.00	0.00	0.00	0.00	0.00
Maximum	8.82	7.62	13.07	10.52	9.37	15.64

Note: ND, no data available for that particular period; the first period was 10 years, as opposed to 6 years for the two subsequent periods.

([a]) Under UNSCR 1244/99.

Source: EEA Land and Ecosystem Accounting Cube based on Corine Land Cover 2012, version 18.5.

2.3.1 A comparison of Corine Land Cover-based densification and land recycling indicators calculated with Corine Land Cover and Urban Atlas data — indicators 1 and 2

Indicator 2 is similar to indicator 1; the difference is that it adds the flows lcf 13 (development of green urban areas) and lcf 38 (sprawl of sport or leisure facilities) to the calculation of land recycling — in both cases only on previously developed land.

For the majority of FUAs selected, the FUA-level recycling rates are higher than the rates at country level (comparison based on CLC data; Table 2.3); this is to be expected, as, at country level, land recycling, which commonly takes place in urbanised areas, is averaged over the entire territory. Nevertheless, the opposite can be observed for a number of FUAs; this is the case particularly for those with no observable land recycling (in its broad sense). In some countries, such as Estonia, Italy, Sweden and Germany, there seem to be other FUAs that have higher recycling rates than those of the capital.

Furthermore, the results show important differences between the indicators obtained using CLC data and UA data (Table 2.3). Generally, the figures obtained from CLC data are lower than those from UA data. Nevertheless, there are two clear exceptions: in Luxembourg and Brussels, the proportions of densification and land recycling are much higher when calculated with CLC data than when calculated with UA data. Looking at the underlying data for these two FUAs, these high percentages are due to many artificial land cover classes transitioning into the 'Construction sites' class in 2012. The results indicate that CLC overestimates changes to this transitional class (intermediate rather than final use) as a consequence of more aggregated changes (MMU of 5 ha for CLC changes versus MMU of 0.25–1 ha for UA changes). For Copenhagen, the land recycling rate calculated with CLC data exceeds that calculated with UA data only for indicator 2, i.e. the estimate including 'green' recycling. The sub-flow 'Sprawl of sport and leisure facilities' (lcf 38) is almost entirely responsible for this change.

Using CLC data, and apart from three FUAs (Luxembourg, Brussels and Riga), the densification and land recycling rates are ≤ 5 % (lower than or equal). Furthermore, according to CLC data there was no land recycling in its broad sense (indicator 2)

Table 2.3 Densification and land recycling (indicators 1 and 2) as a percentage of total land consumption for selected FUAs based on CLC and UA change data

FUA	Indicator 1			Indicator 2		
	Country	FUA		Country	FUA	
	CLC data	CLC data	UA data	CLC data	CLC data	UA data
Bratislava (SK)	0.09	0.00	2.30	0.09	0.00	2.54
Nicosia (CY)	0.53	0.00	2.96	0.62	0.44	3.00
Luxembourg (LU)	11.91	21.61	3.21	11.91	21.61	3.21
Lisbon (PT)	0.55	2.35	4.49	0.73	3.16	4.52
Ljubljana (SI)	3.90	4.17	4.58	3.90	4.17	4.89
Prague (CZ)	1.80	4.37	5.01	2.43	4.37	5.16
Athens (EL)	1.17	1.44	5.29	1.17	1.44	5.29
Copenhagen (DK)	0.99	2.58	4.62	2.57	14.73	5.31
Bucharest (RO)	0.09	0.00	5.36	0.09	0.00	5.43
Tallinn (EE)	8.83	5.12	5.38	8.83	5.12	6.04
Rome (IT)	1.51	1.15	6.06	1.54	1.15	6.26
Vienna (AT)	0.23	0.00	6.14	0.23	0.00	6.28
Vilnius (LT)	1.06	2.37	6.21	1.06	2.37	6.43
Dublin (IE)	0.16	0.00	6.47	0.16	0.00	6.47
Brussels (BE)	4.82	20.24	8.82	4.82	20.24	8.88
Budapest (HU)	1.35	1.50	9.85	1.40	1.50	9.93
Sofia (BG)	2.71	4.02	18.13	2.71	4.02	18.13
Stockholm (SE)	1.56	0.39	16.91	1.63	0.39	19.78
Berlin (DE)	3.57	1.74	22.26	3.79	1.74	22.62
Amsterdam (NL)	1.17	3.40	24.96	1.41	4.64	25.42
Paris (FR)	0.87	2.32	33.88	0.93	2.45	34.17
Riga (LV)	6.07	20.96	34.73	6.26	23.30	34.73
Valletta (MT)	0.00	0.00	43.72	0.00	0.00	43.72
Minimum	0.00	0.00	2.30	0.00	0.00	2.54
Maximum	11.91	21.61	43.72	11.91	23.30	43.72

Note: FUAs are presented in order of increasing land recycling (in its broad sense) percentages based on UA data (indicator 4).

Sources: Corine Land Cover 2006–2012 changes (version 18.5), Urban Atlas changes 2006–2012 (Copernicus Programme, 2016).

in Bratislava, Bucharest, Vienna, Dublin and Valletta between 2006 and 2012, whereas, using UA data, the rate of land recycling was between 2.54 % and 43.72 %. The situation in Nicosia is similar, but the CLC data indicate some 'green' recycling (difference between indicators 2 and 1).

Based on UA data, there is considerable variability in densification and land recycling rates between FUAs (2.30–43.72 % and 2.54–43.72 % for indicators 1 and 2, respectively).

Compared with indicator 1, indicator 2 includes two additional LCFs. This results in slight increases in the proportions of densification and land recycling, generally below 10 % when using UA data. However, Bratislava (10.4 %), Tallinn (12.2 %), Copenhagen (14.9 %) and Stockholm (17 %) show greater increases resulting from 'green' recycling, according to UA data. If any difference between indicators 2 and 1 can be detected with CLC data, the differences tend to be higher: from 5.5 % for Paris to 36.4 % for Amsterdam (ignoring the exceptional case of Copenhagen, with a 471.3 % increase).

Focusing on the comparison between using CLC and using UA data, changes that could not be detected with CLC data (including the absence of changes) can be

detected using UA data. This is in line with expectations, given the differences in spatial and thematic resolution between CLC and UA. On the other hand, including 'Construction sites' as a destination class of change seems to indicate that CLC data overestimate this transitional class, thereby also overestimating the rates of densification and land recycling. Finally, UA data seem to detect 'green' recycling more accurately and reliably.

2.3.2 *Urban Atlas-based densification and land recycling indicators — indicators 3–13*

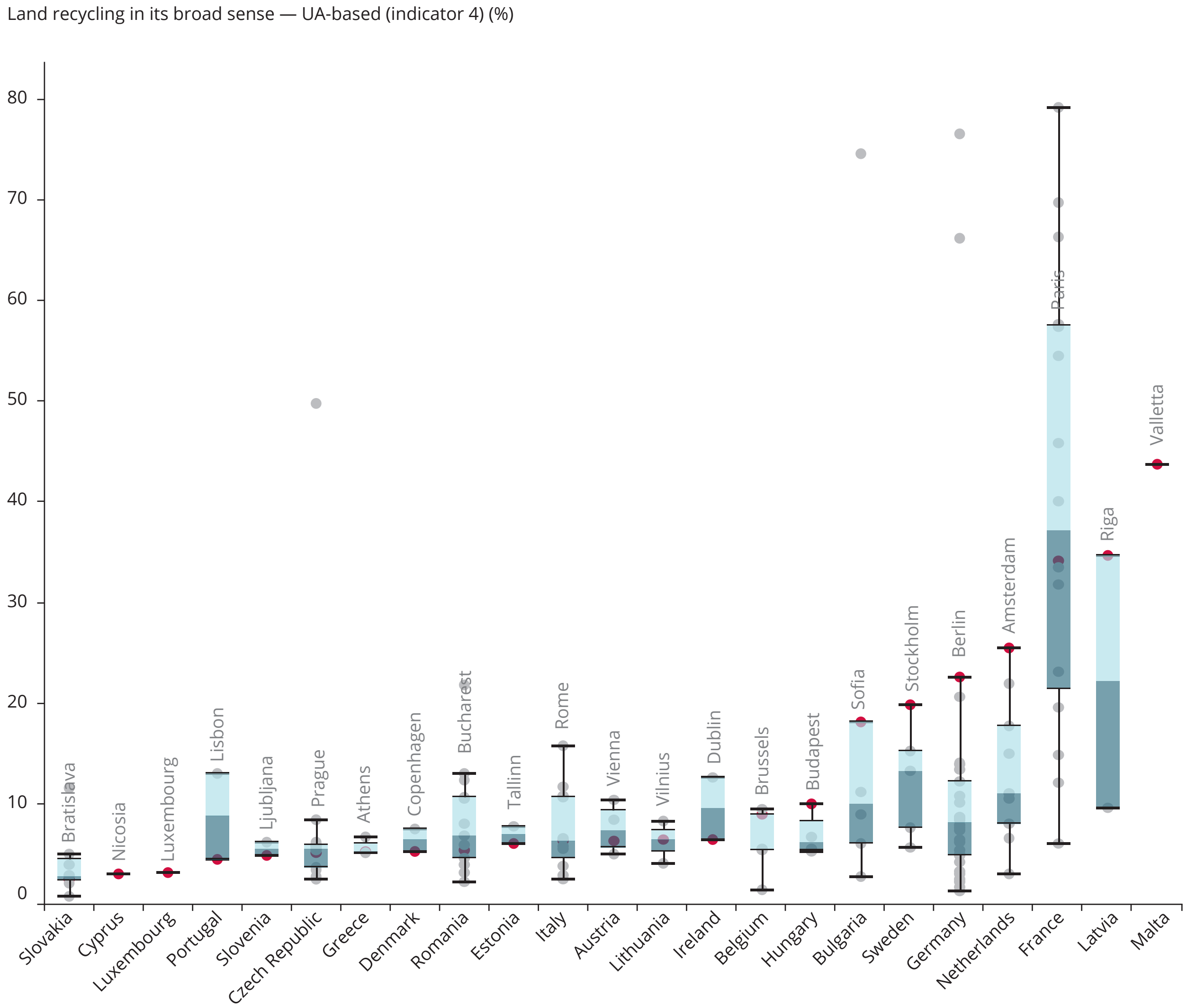
Indicators 3–13 are based on UA characteristics. As UA differs from CLC in its spatial and thematic (i.e. nomenclature) resolution, some of the land cover changes are attributed to an LCF that is different from that to which it would be attributed based on CLC characteristics (see Section A.2 in the Annex).

Densification and land recycling — indicators 3 and 4

As for indicators 1 and 2, the difference between indicators 3 and 4 is the exclusion and inclusion, respectively, of flows lcf 13 and lcf 38.

Despite the small difference in approach for calculating indicators 3 and 4 on the one hand and indicators 1 and 2 on the other, there is no difference in the results obtained. For the selected FUAs, the specificities

Figure 2.1 Boxplots of UA-based land recycling in its broad sense (indicator 4) per country



Note: Functional urban areas (grey dots) are presented in order of increasing land recycling (in its broad sense) percentages of the capitals covered in this report. The red dots show where the capitals (covered in this report) are positioned with regard to their respective country variation (based on FUAs available at the time of writing).

Source: Urban Atlas changes 2006–2012 (Copernicus Programme, 2016).

introduced by the UA-based approach are not reflected in the results because there were no changes between 2006 and 2012 that correspond to those particular transitions. However, this does not mean that, when considering other periods or other FUAs, there will be no differences between the UA-based and the CLC-based calculation.

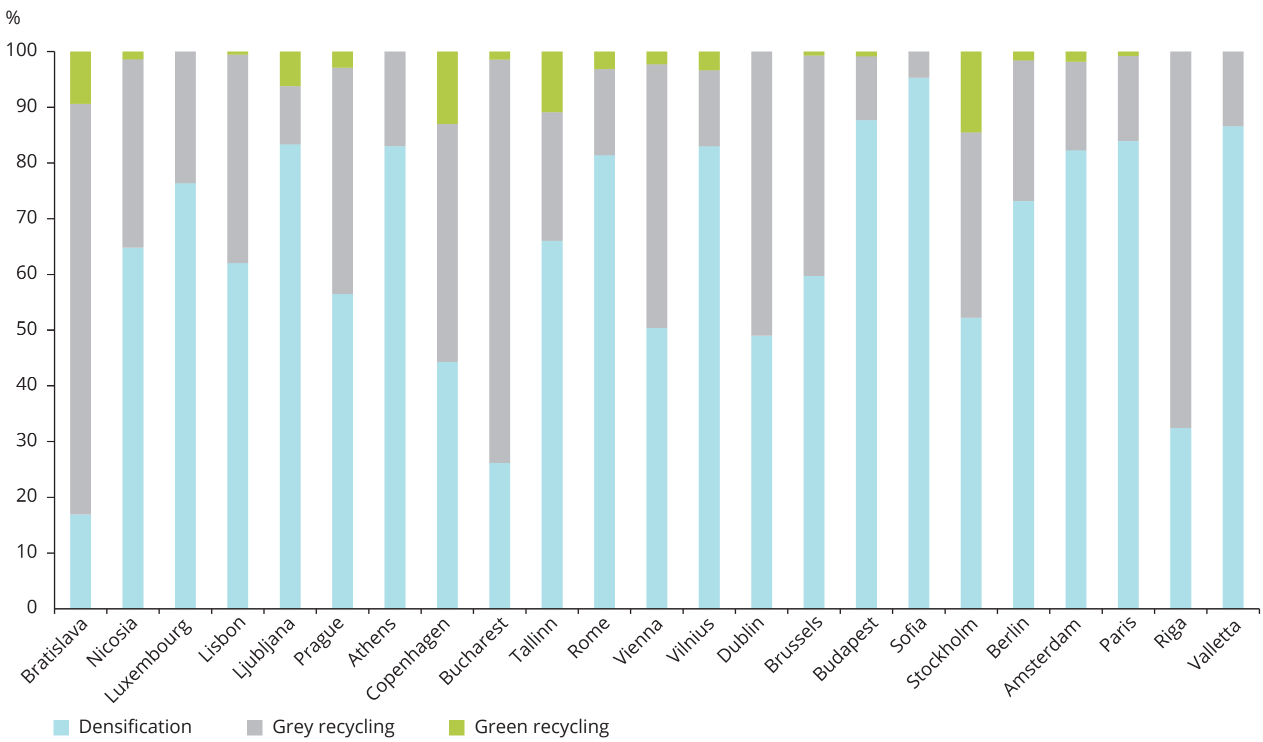
Figure 2.1 shows where the land recycling (in its broad sense) values (indicator 4) of the capitals covered in this report are positioned with regard to their country variation (based on the FUAs available at the time of writing). Cyprus, Luxembourg and Malta clearly have too few observations at this stage to contribute to a meaningful boxplot. In Hungary, Bulgaria, Sweden, Germany, the Netherlands and Latvia, the capitals seem to lead by example in adopting land recycling. At the other end of the spectrum, the Portuguese and Irish capitals are land recycling laggards compared with their peer FUAs. However, this does not mean that they do not perform well compared with other capital FUAs.

Densification versus land recycling as a proportion of total land consumption — indicators 5–7

Indicators 5, 6 and 7 distinguish between densification processes (lcf 11) and land recycling processes (lcfs 12, 13 and 38) as part of total land consumption. Indicator 5 includes only transitions that imply densification, whereas indicators 6 and 7 are intended to cover changes that can be referred to as land recycling (without densification). Indicator 6 is limited to lcf 12, whereas indicator 7 (lcfs 13 and 38) captures the creation of green and open space in urbanised areas, which is relevant to green infrastructure and the delivery of ecosystem services. Taken together, therefore, these three metrics indicate the prevailing urban land management processes in the selected FUAs.

In most FUAs, densification is more common than land recycling, with the clear exception of Bratislava, Bucharest and Riga, where the rate of land recycling is at least double that of densification (Figure 2.2, Table 2.4). In Copenhagen and Dublin, recycling rates are higher than densification, but the difference is less pronounced. In Vienna and Stockholm, they are more or less on a par. The proportion of recycling to create green urban areas or sport and leisure facilities (included in indicator 7) is very small in most cases, and non-existent in Luxembourg, Athens, Dublin, Sofia, Riga and Valletta., Copenhagen, Tallinn and Stockholm have over 10 % 'green' recycling, and Bratislava has close to 10 %. Stockholm and Copenhagen were winners of the European Green Capital Award in 2010 and 2014,

Figure 2.2 The components of land recycling (%) in European capitals



Note: Capitals (FUAs) are presented in order of increasing land recycling (in its broad sense) percentages based on UA data (indicator 4).

Source: Urban Atlas changes 2006–2012 (Copernicus Programme, 2016)

Table 2.4 Densification (indicator 5) and land recycling (indicators 6 and 7) as a percentage of total land consumption for selected FUAs based on UA change data

FUA	Population ([a]) (inhabitants)	Indicator 5	Indicator 6	Indicator 7
		Densification	'Grey' land recycling	'Green' land recycling
Bratislava (SK)	603 975	0.43	1.87	0.24
Nicosia (CY)	ND	1.95	1.01	0.04
Luxembourg (LU)	7 484	2.45	0.76	0.00
Lisbon (PT)	2 728 605	2.80	1.69	0.03
Ljubljana (SI)	532 297	4.07	0.51	0.30
Prague (CZ)	2 190 927	2.91	2.10	0.15
Athens (EL)	ND	4.39	0.90	0.00
Copenhagen (DK)	1 854 191	2.35	2.27	0.69
Bucharest (RO)	2 182 648	1.42	3.93	0.08
Tallinn (EE)	535 969	3.98	1.39	0.66
Rome (IT)	3 958 564	5.09	0.97	0.20
Vienna (AT)	2 689 474	3.16	2.97	0.14
Vilnius (LT)	688 107	5.33	0.88	0.22
Dublin (IE)	1 788 291	3.17	3.30	0.00
Brussels (BE)	2 517 101	5.31	3.51	0.07
Budapest (HU)	2 880 111	8.71	1.13	0.09
Sofia (BG)	1 533 052	17.27	0.85	0.00
Stockholm (SE)	2 088 982	10.33	6.58	2.87
Berlin (DE)	4 861 473	16.55	5.70	0.36
Amsterdam (NL)	2 453 622	20.91	4.05	0.47
Paris (FR)	11 688 389	28.67	5.21	0.28
Riga (LV)	643 436	11.26	23.47	0.00
Valletta (MT)	376 496	37.85	5.87	0.00
Minimum	7 484	0.43	0.51	0.00
Maximum	11 688 389	37.85	23.47	2.87

Note: FUAs are presented in order of increasing land recycling (in its broad sense) percentages based on UA data (indicator 4). ND, no data.

([a]) Calculated for the FUA in question based on a population grid.

Sources: Urban Atlas changes 2006–2012 (Copernicus Programme, 2016); population, Geostat Population Grid 2011.

respectively, whereas Bratislava and Tallinn have never even been finalists (EC, 2016a).

In terms of densification, Sofia stands out from the rest, with a rate of densification 20 times greater than that of recycling. In descending order, Valletta, Paris, Ljubljana, Athens, Vilnius and Rome, have rates of densification about five times greater than recycling.

The densification and recycling patterns described are seemingly unrelated to the number of inhabitants of the FUAs. A more advanced analysis in which land recycling indicators are calculated separately for high- and low-density population zones within FUAs could be more revealing.

Densification and land recycling in relation to urban land management — indicators 8–10

Indicators 8, 9 and 10 also treat densification and land recycling separately. However, these indicators relate to urban land management processes (LCF 1), rather than overall land consumption.

As the numerators in the indicator sets 5–7, 8–10, and 10–13 are the same — expressing urban densification, 'grey' and green land recycling, respectively — the relative proportions of these processes are also the same for the three sets of indicators (see Figure 2.2). However, land recycling expressed in relation to urban land management (LCF 1) is between 1.9 and 7.0 times

higher than land recycling expressed in relation to total land consumption.

Densification and land recycling in relation to urban residential, industrial, commercial and infrastructure sprawl' — indicators 11–13

Indicators 11, 12 and 13 also deal with densification and land recycling separately. However, these indicators relate to urban residential, industrial, commercial and infrastructure development processes (LCFs 2 and 3), or land take, rather than overall land consumption. Therefore, the proportions show the ratio of land densification or recycling occurring for every hectare of urban development on undeveloped land (i.e. expansion of the 'artificial' land cover class).

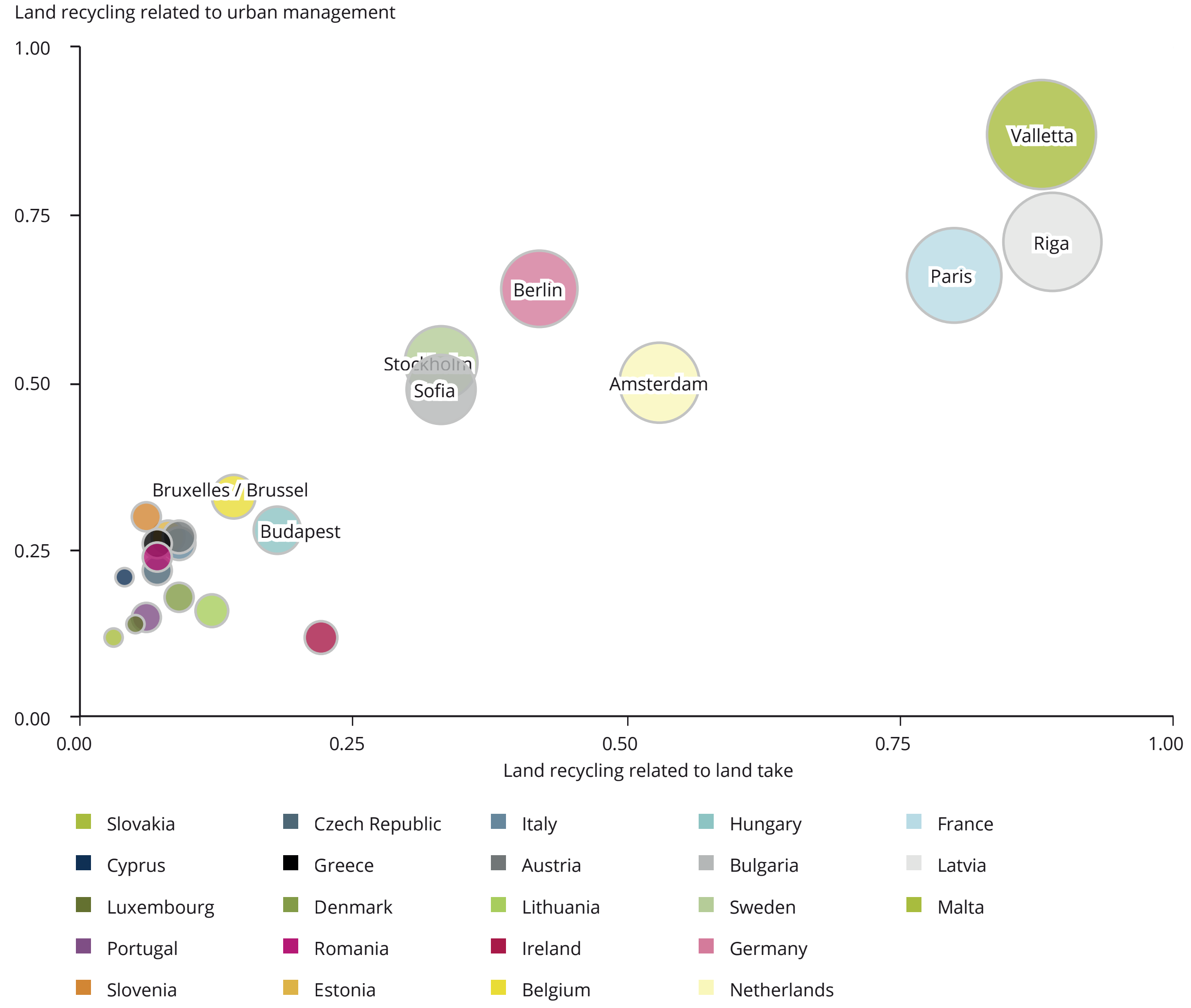
Land recycling expressed in relation to land take (as approximately defined by LCFs 2 and 3) is between 1.2 and 3.4 times higher than land recycling expressed in relation to total land consumption. In addition, when looking at individual FUAs, land take is clearly a stronger driver for land cover changes than urban land management (given the higher total values for the land recycling indicators related to urban management). However, Dublin, Riga, Paris, Amsterdam and Valletta show the opposite trend (the sum of indicators 10–13 is higher than that of indicators 7–9); Valletta, Riga and Paris also have the highest rates of land recycling in relation to total land consumption (Figure 2.3).

2.4 Conclusions

The indicators for land densification and recycling developed for the UA database were calculated and tested for a selected set of FUAs. These indicators — using the earlier methodology applied to CLC, but modified to take account of the differences in the thematic and spatial resolution of UA — were compared with the results obtained from CLC. The results point to some interesting conclusions:

- ***Higher spatial resolution of Urban Atlas data is critical for monitoring land recycling and densification.*** Because of its higher thematic and spatial mapping resolution, UA is much better suited than CLC to analysing urban phenomena as well as changes and trends in the urban environment and can be recommended to calculate land densification and recycling indicators. Land recycling processes are generally underestimated by CLC data, basically because of CLC's less accurate MMU compared with UA. Whereas UA maps show any change bigger than 0.25 ha (core urban areas) or 1 ha (peripheral areas), CLC change maps record only changes over 5 ha. In many cases, land within urban areas is reused in small parcels; if these are less than 5 ha, they will not be detected by CLC. Similarly, densification in residential areas may affect only one or a few blocks; again, such changes are not detected or recorded in CLC because of its higher MMU.
- ***Construction sites are overestimated by CLC data, and this may mean that land densification and recycling is overestimated.*** As observed for e.g. Luxembourg and Brussels, when we look at the biggest changes occurring within FUAs using CLC, many cases involve the 'Construction sites' class, whereas in UA the same changes are either much smaller or there are no 'Construction sites' (or similar transitional classes such as 'Land without current use') involved.
- ***Indicators based on land recycling and densification could be suitable for comparing and benchmarking of different cities.*** The selected FUAs have different proportions of land densification and recycling, which reflect different trends in urban management and planning. Although we analysed only a few FUAs to test the data, the results are promising and will be useful for comparing and benchmarking urban areas in the future.
- ***General indicators of land recycling and densifications provide much more nuanced understanding when complemented with more detailed indicators (Table 2.1).*** Additional indicators calculated from UA (indicators 5–13) are very useful to allow better characterisation of urban land management processes in FUAs. They allow differentiation between the proportions of densification and recycling in the narrow sense, particularly 'grey' and 'green' recycling. They also facilitate the assessment of urban sustainability when comparing those processes with urban development or land take phenomena, which in some cases represent urban sprawl. Urban sprawl is critically important because of its major impacts in terms of increased consumption of energy, land and soil (EEA, 2006a).
- ***The indicators defined and tested in this report have good potential for urban assessments and wider land systems assessments.*** Combining this information with data on urban typologies could prove very useful in future urban assessments. Within FUAs, distinguishing between high- and low-density populated areas, and calculating the land recycling indicators for those areas separately, would further enrich the analysis.

Figure 2.3 Relationship of land reycling ([a]) related to urban management (*y*-axis), land take (*x*-axis) and total land consumption (size of bubbles)



Notes: ([a]) Land recycling in its broad sense.

The size of the bubbles indicate land recycling in its broad sense as part of total land consumption (indicator 4).

'Urban land management' (LCF 1, the denominator of the indicator on the *y*-axis) concerns the internal transformation of urban areas; it includes all transitions from 'Construction sites' and 'Land without current use' classes to any other artificial classes. As deviation from the LCF1 concept, it also includes the creation of green urban areas from non-artificial classes, but it does not include the creation of sport and leisure facilities (lcf 38) on developed land.

'Urban residential, industrial, commercial and infrastructure sprawl' (LCFs 2 and 3, the denominator of the indicator on the *x*-axis) concerns conversions from non-artificial (undeveloped) to artificial land classes for urban development purposes (to meet residential, economic — such as industry and commerce — and infrastructure needs); As deviation from the LCF2+3 concept, it also includes the creation of sport and leisure facilities from artificial classes.

Source: Urban Atlas changes 2006–2012 (Copernicus Programme, 2016).

- ***Development of tested indicators should continue and become part of EEA reporting.*** Further work should include calculating UA indicators for all FUAs available, plus statistical analysis to find correlations in trends and clusters of FUAs with similar land recycling, densification and/or urban sprawl processes (as defined by specific indicators for urban sprawl or land take). The indicators presented here offer significant advantages over other proposed indicators and could be developed and adopted as EEA indicators.

- ***More attention should be put on calculating life cycle costs***, although this was not considered in our case studies. Hendrickson et al. (n.d.) have developed a model for estimating the life cycle costs and emissions of residential brown- and greenfield developments in the United States. The activities included are brownfield remediation, residential building construction, infrastructure costs, residential building utilities and maintenance, and residential travel. They conclude that brownfield developments have on average slightly lower costs — despite significant remediation costs in some cases — resulting from reduced travel costs, as brownfield sites tend to be closer to urban centres than greenfield sites. As is the case for environmental impacts, the operational stage makes by far the greatest contribution to the overall cost impact.

The methodology and tested indicators presented in this report provide a solid foundation for the assessment of land recycling and densification within European urban areas (FUAs). The expected completion of UA 2012 data and the 2006–2012 change data for 301 FUAs (and in future for the 697 FUAs covered since 2012) offers an excellent opportunity to undertake a comprehensive assessment of sustainable urban management practices across Europe.

3 The wider environmental impacts of land recycling

This chapter will:

- explain the life cycle thinking (LCT) approach and the life cycle assessment (LCA) methodology;
- demonstrate how LCA can be applied to brown- and greenfield developments by reporting the key findings of three real-world case studies;
- discuss how LCA can be of use to support policymakers in decision-making.

3.1 Introduction

In this chapter, we will shift the focus from the immediate impact of land recycling on land use to the wider environmental impacts of brown- and greenfield development and how they can be measured.

To make environmentally sound decisions about urban development, policymakers need to be able to understand and compare the environmental impacts of different options for development. To provide them with that essential information, we need to be able to quantify the environmental impact of, for example, land recycling and densification (brownfield development) versus greenfield development. What is the outcome likely to be in the 'real world'? If it can be clearly demonstrated that land recycling and densification can reduce the wider environmental impacts of development, as well as limiting land take, these measures will become key to sustainable urban development in future.

How can the wider environmental impacts of land recycling be quantified? LCA is a methodology that first became popular in the 1990s. In recent years, it has led to the development of the wider concept of LCT, which has become the cornerstone of environmental thinking. As part of this approach, the next use of the land is taken into consideration during planning for its redevelopment, thereby encouraging planning for more sustainable urban development far into the future.

3.2 The life cycle thinking approach and life cycle assessment

The LCT approach sets out to identify potential improvements in goods and services in terms of reduced environmental impacts across all life cycle stages of a process.

LCA is a method for quantifying the potential environmental impacts of a product or service over its entire life cycle. The most important applications are (1) analysing the contribution of different life cycle stages to the overall environmental impact, in order to prioritise improvements in products or processes; and (2) comparing products and services in terms of their overall environmental impact.

Applying LCA to green- and brownfield developments is an innovative approach that requires special considerations to obtain reliable results on the direct and indirect environmental impacts of brownfield developments.

3.3 The methodology

The LCA methodology used in this study is based on the standard International Organization for Standardization (ISO) framework (ISO 14040:2006 and ISO 14044:2006; see Figure 3.1) and the recommendations of the International Reference Life Cycle Data System (ILCD) Handbook (JRC, 2012). The standard method was adapted to align it with the goals of the study, which allows recommendations to be made regarding the environmental evaluation of brown- and greenfield

developments. Calculations were done using SimaPro 8 software, based on the Ecoinvent database version 3 and the ILCD impact assessment method, as well as site-specific data for each case study.

The four phases of the methodology are shown in Figure 3.1 and summarised in the following section.

3.3.1 Phase I — Defining the goal and scope

Goal

The goal of this LCA study was to evaluate the potential environmental impacts of the development or reuse of brownfield sites across all stages of development. The results will allow us to identify the stages and parameters that have the greatest impacts and will allow comparison with other development options, including extending urban development into greenfield sites.

Scope and boundaries

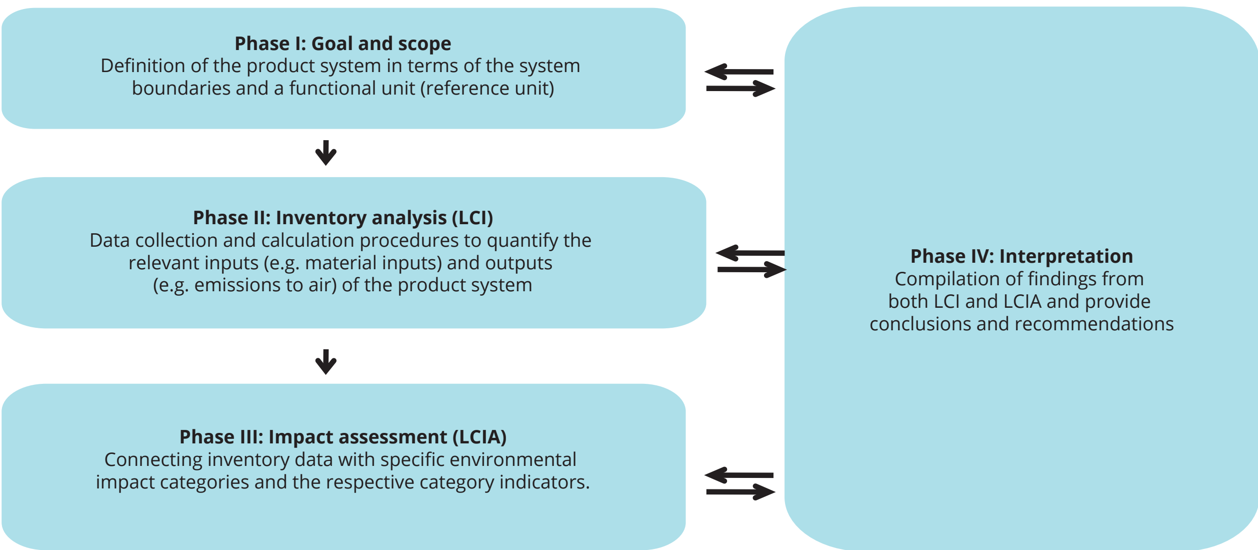
We took an innovative approach in order to include the different life stages of brown- and greenfield developments and their associated impacts, as shown in Figure 3.2 (based on Lesage et al., 2007). This approach takes a holistic view across the three life stages, whereas conventional studies assess only impacts related to the intervention stage (secondary impacts) and exclude the primary and tertiary impacts.

The impacts

Primary impacts are associated with the state of the site (site condition) and consider existing soil and groundwater contamination that may, for example, have an impact on human or ecosystem health.

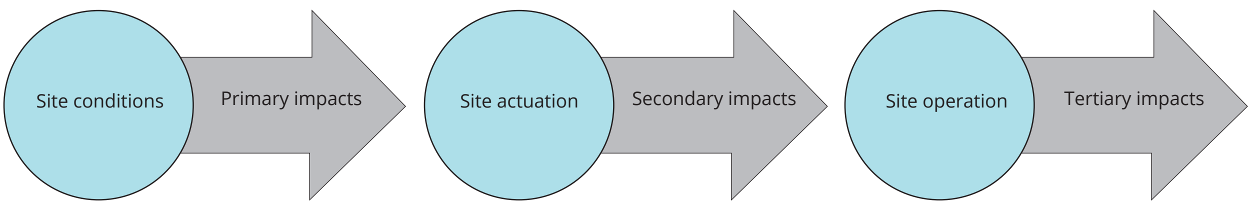
Secondary impacts arise from (re)development to (re) use the area for urban purposes (site actuation) and

Figure 3.1 Methodology for LCA studies



Source: ISO, 2006.

Figure 3.2 Flowchart of the life stages of a brownfield development and their associated environmental impacts



include land occupation (in the case of greenfield developments), soil and groundwater investigations, soil remediation, deconstruction, construction of new buildings and construction of new infrastructure.

Tertiary impacts are associated with the operation or use of the site after development and include energy and water consumption, waste production, wastewater production and the impacts associated with user mobility. Decommissioning stages are not included in our cases.

The lifespan

The lifespan is a key assumption for LCA of brown- and greenfield developments, because it has such an important influence on the final results. For most LCAs of buildings, the lifespan is considered to be 50 years (UN, 2011), but some LCAs of brownfield developments have used 20 or 40 years (Lange and Mashayekh, 2003; Lesage et al., 2007; Brecheisen and Theis, 2013). Given the importance of the operational stage, and in order to present the results of the different life stages proportionally, this study used a lifespan of 20 years, in order to give a balanced view of all parameters.

Local versus regional or global components

All assessed impacts have a local component (i.e. impacts inside the limits of the developed site) and a regional or global component (impacts outside the developed site); both were assessed in this study.

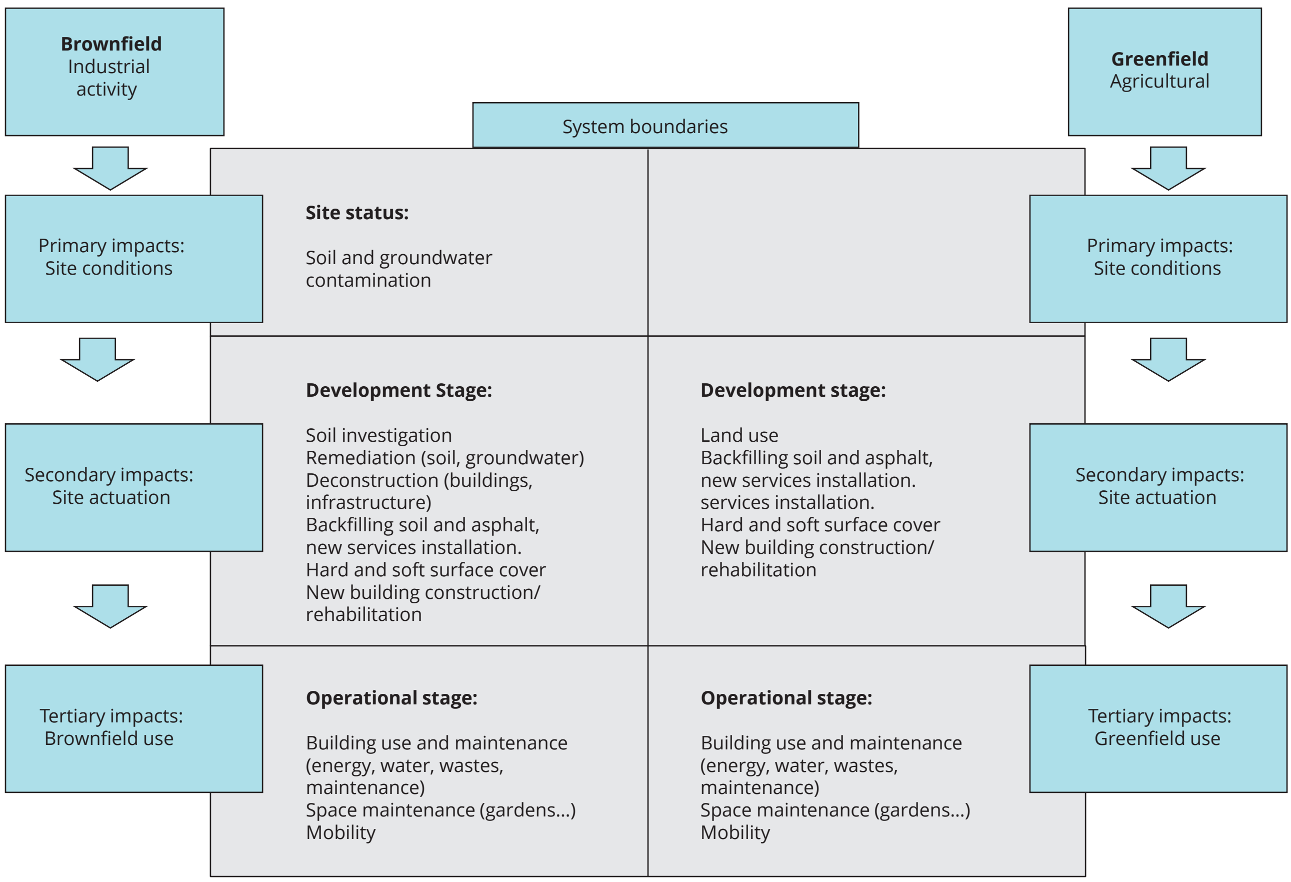
Figure 3.3 shows the activities assessed for each life stage of each site.

The functional units

The functional unit of a development project is the reference unit for the results of the impact assessment. Three functional units were defined:

- hectare of managed brownfield/greenfield (reference functional unit);

Figure 3.3 Flowchart showing the activities assessed for each life stage of each site



- square metre of constructed area (or built surface);
- number of residents (inhabitants and habitants are used interchangeably).

The use of a specific functional unit is crucial to allow comparisons between different sites. All the results were referenced to a functional unit of 1 ha in order to compare results within a case study. The other two functional units (constructed area and number of residents) were applied to specific impacts to allow comparisons between different case studies.

3.3.2 Phase II — Inventory analysis

In this phase, each activity at each life stage is analysed to determine the relevant input flows (energy and materials entering the system) and output flows (emissions and waste from the system to the environment). For the case studies, most information was obtained from urban planning documents and from authorities, consultants and developers involved in urban development. Primary data were prioritised, and secondary data from databases and literature were used when required. Ecoinvent version 3 was the main database used (Ecoinvent, n.d.). In each phase, the selected inputs (parameters) were indicated, along with their associated input and output flows.

3.3.3 Phase III — Impact assessment

In this phase, the potential environmental impacts associated with inventory flows are calculated. This is the phase during which the quantified input flows (of energy and materials) are expressed and quantified as output flows (of emissions and waste). The base methodology chosen for this study was the ILCD 2011 midpoint method (JRC, 2011), which specifies the impact assessment categories (see Table A.4 in the Annex) and the units for the categories identified (see Table A.5 in the Annex).

3.3.4 Phase IV — Interpretation of results

The final step in LCA is the interpretation and critical review of the results to verify their reliability. The completeness, sensitivity and consistency of the data collected and the results obtained are assessed to ensure that they are representative and suitable for inclusion in the LCA. These iterations and a sensitivity analysis were carried out during the LCA as an internal control on the quality of the data.

3.4 Key findings of the case studies

3.4.1 Case study characterisation

Table 3.1 summarises the main characteristics of the case study sites, which were selected to illustrate and compare different development scenarios — brownfield versus greenfield and level of brownfield contamination.

The different life stages and development and operational activities considered for the three case studies are presented in Table A.6 in the Annex.

Table 3.1 Characteristics of the case study sites

Site characteristic	Brownfield site, Nottingham (BF_UK)	Brownfield site, Terrassa (BF_Spain)	Greenfield site, Terrassa (GF_Spain)
Total surface (ha)	7.7	3	47.5
Residents	700	1 269	13 356
Residential units	600 (2 floors)	423 (5 floors)	4 452 (5 floors)
Construction surface (m^2)	40 000	22 638	130 641
Residents/100 m^2 construction surface	1.75	5.60	10.2
Former use	Opencast coal mine	Industrial (textile factory)	Agricultural (greenfield)
Existing contamination and remediation	Yes	Yes	No
Existing buildings	No	14 443 m^2 (10 industrial units)	16 970 m^2 of rural houses

3.4.2 Key findings

Choice of the functional unit

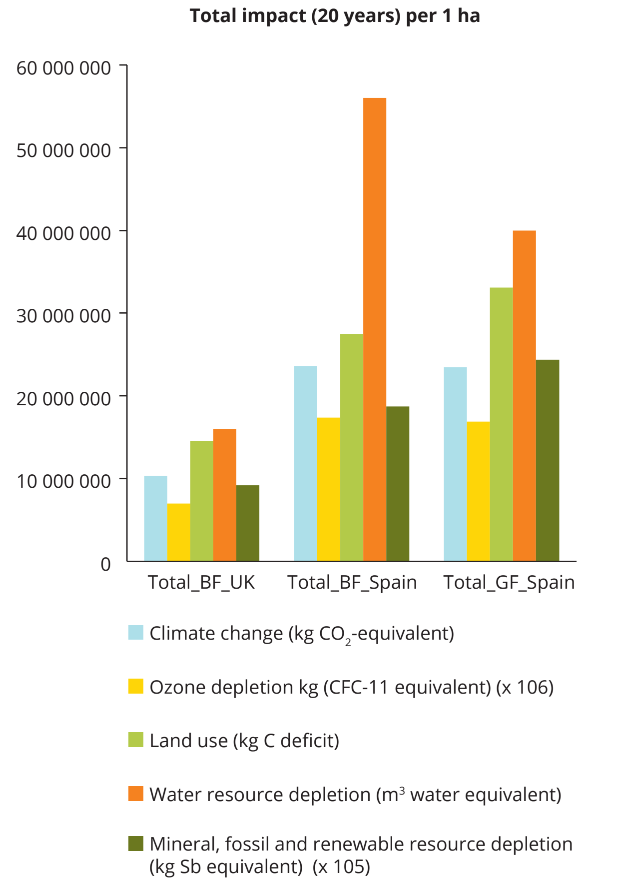
Looking at the impact categories with global implications (climate change, ozone depletion, land use, depletion of water resources, and depletion of minerals, fossil fuels and mineral resources) using the reference functional unit (Figure 3.4), the brownfield site in Nottingham has the least impact in all categories. The brownfield site in Terrassa has the greatest impact in terms of depletion of water resources, and the greenfield site has the greatest impact in terms of land use.

However, analysing the global impacts using a different functional unit (1 m^2 of built surface) changes the results and their interpretation (Figure 3.5). In this case, the brownfield site in Nottingham still has the least impact across all categories, but the greenfield site now has the greatest impact in all categories, particularly in terms of depletion of water resources and land use. The impact on climate change of the greenfield site is approximately three and four times greater than that of the brownfield sites in Terrassa and Nottingham, respectively.

To investigate this difference properly, we carried out a sensitivity analysis to look at the effect of choice of functional unit on the impacts with global implications (Figure 3.6).

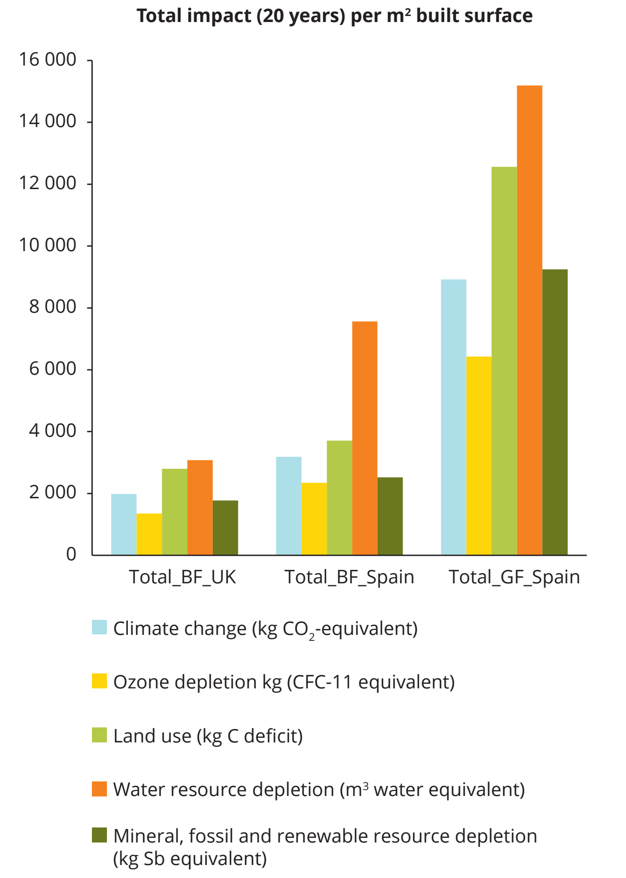
When the impacts are compared on a per hectare basis, the Terrassa brownfield site has the greatest impact in all categories, except for land use and use of materials (mineral, fossil and renewable resources). This is because of its small size (only 3 ha) compared with the other two sites. Although the greenfield site is by far the biggest, its impacts, especially in terms of land use and resource depletion, are still greater than those of the two brownfield sites.

Figure 3.4 Comparison of global environmental impacts across the three case studies



Note: 20-year lifespan, functional unit 1 ha.

Figure 3.5 Comparison of global environmental impacts across the three case studies

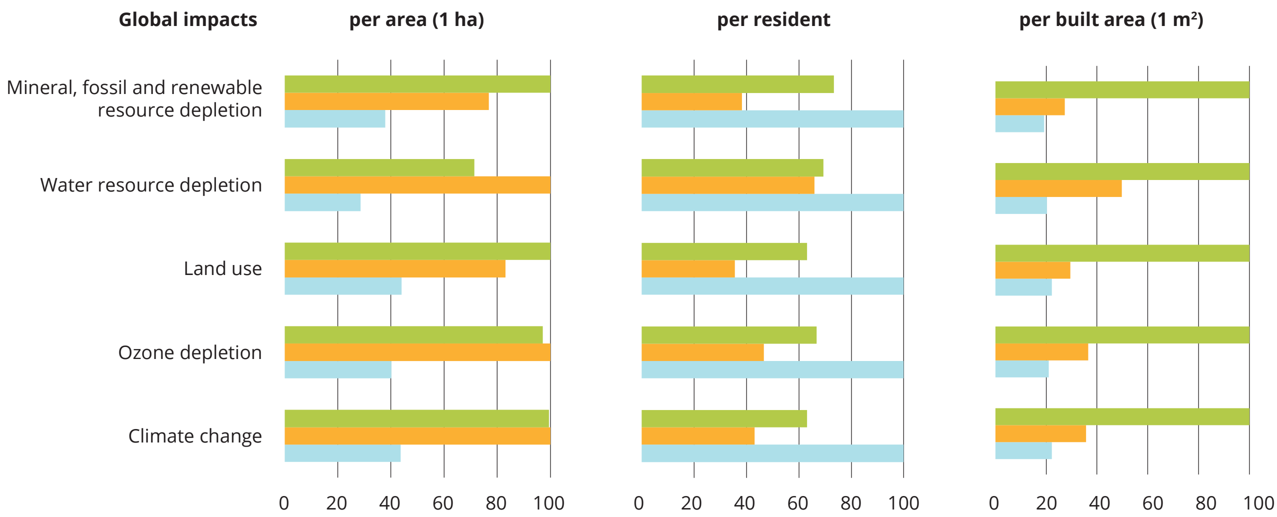


Note: 20-year lifespan, functional unit 1 m^2 of built surface.

Figure 3.6 Results (normalised) of sensitivity analysis comparing global environmental impacts in the three case studies using the three functional units

Life cycle analysis — sensitivity analysis

Comparison of global environmental impacts (relative importance, maximum 100) across life cycle stages and activities of the **three test cases** (20-year use scenarios)



Site characteristic	GF_Spain	BF_Spain	BF_UK
Total surface (ha)	47.5	3	7.7
Residents	13 356	1 269	700
Built surface (m^2)	130 641	22 638	40 000

On a per resident basis, the Nottingham brownfield site has the greatest impact across all categories, which is because of the small number of residents (only 700) compared with the Terrassa brownfield and the greenfield sites. Comparing the two sites in Terrassa, the greenfield site has a considerably greater impact in most categories, despite a population more than 10 times that of the brownfield site.

On the basis of per unit of built surface (1 m^2), the Terrassa greenfield site has by far the greatest impact across all categories, even though it also has by far the greatest built area (approximately three and nearly six times bigger than the Nottingham and Terrassa brownfield sites, respectively).

These results show that the choice of functional unit is critical for the interpretation of the LCA, as it can result in marked variations in the final results. The functional unit is particularly important when comparing brownfield sites with different characteristics in terms of surface, use, buildings and infrastructure, and numbers of anticipated residents or users. It is also particularly relevant when comparing brown- and greenfield sites. Expressing impacts on a per hectare or per resident basis can distort the results. Therefore, a functional unit of built surface area is the most appropriate for comparing the environmental impacts of different approaches to urban development, as, in this study, it resulted in the greenfield site having the greatest global environmental impacts despite also having by far the greatest built surface area.

Impacts across different life cycle stages

Considering the effects of the different stages of development of the site, the operational or use stage has the greatest environmental impacts across the three case studies, i.e. across brown- and greenfield sites (Figures 3.7, 3.10 and 3.11).

Tertiary impacts arising from the use stage are responsible for the greatest impacts at all three sites (use impacts ranging from 8 % to 96 % across impact categories and sites). This also applies to climate change impacts, particularly at the greenfield site — where 88 % of all GHG emissions arise during the use stage (Figure 3.9). This is largely related to the mobility of

Figure 3.7 Environmental impacts across life cycle stages and activities at the Terrassa brownfield site (20-year lifespan, functional unit 1 ha)

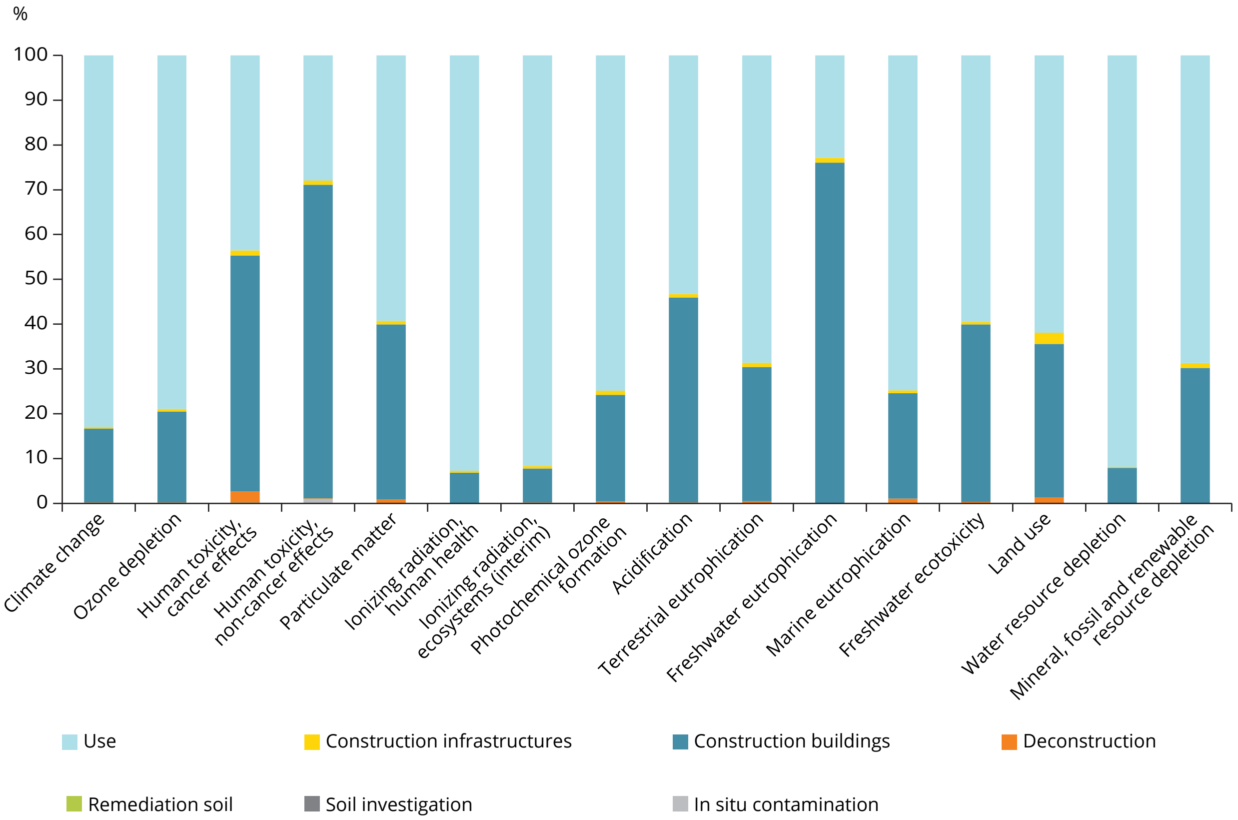
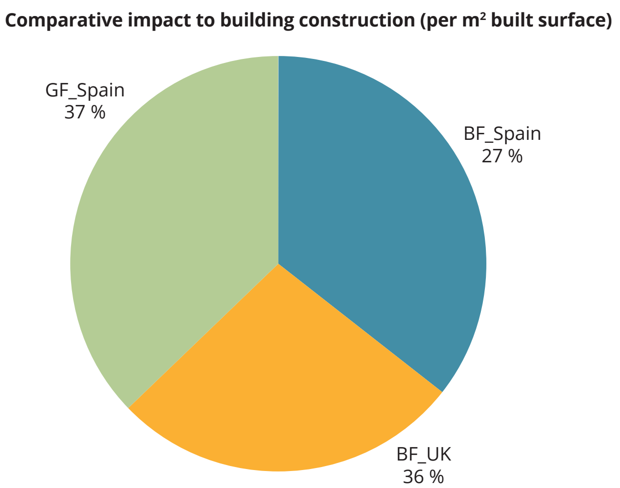


Figure 3.8 Climate change impacts of the building construction phase across the three case studies (20-year lifespan, functional unit 1 m² of built surface)



residents and other users, as the greenfield site has the highest number of residents, also per unit of constructed area (Table 3.1). Comparing the two brownfield sites, the Terrassa site has a greater density of residents than the Nottingham site, which explains the former's greater contribution to GHG emissions during the operational stage (83 % of GHG emissions versus 61 % for the Nottingham site). As the lifespan of the site is directly correlated to its impact during the operational stage, a longer and more realistic period of use of up to 50 years would increase the impact of this stage proportionally.

Following the operational stage, the next biggest contributor to environmental impacts is the construction of buildings during the development stage (see Figures 3.7 (for all environmental impacts, 3.10 (for climate change impacts) and to a lesser degree 3.11 (for land use impacts)). This is because all three sites would require new buildings regardless of their previous use. The impacts are mainly due to emissions arising from the production of the construction materials. Nevertheless, the climate change impact variation across the three sites can be considered irrelevant (Figure 3.8), as detailed information on construction materials for the

Figure 3.9 Contribution of each stage of development to GHG emissions ($t\ CO_2$ eq) across the three case studies (20-year lifespan, functional unit 1 m^2 of built surface)

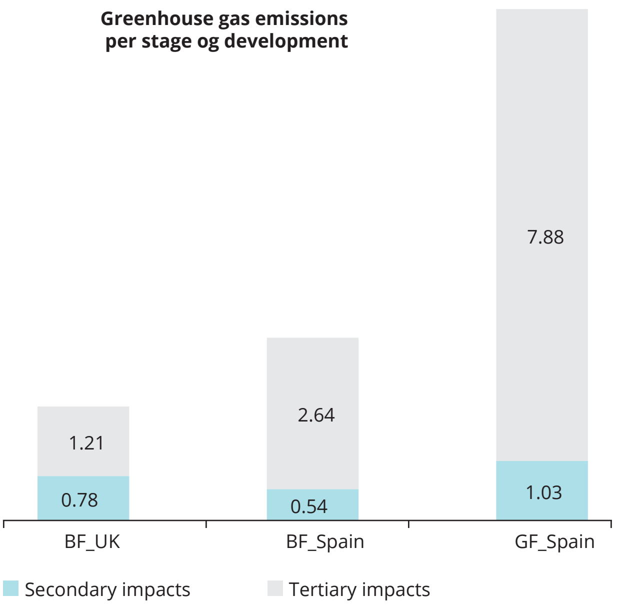
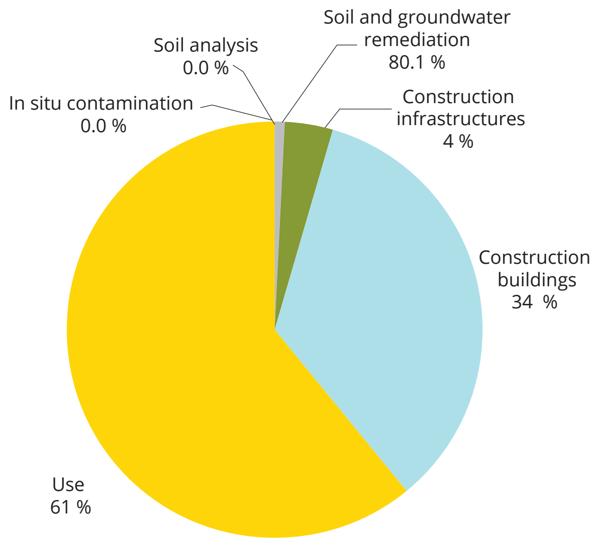


Figure 3.10 Contribution of each life stage to GHG emissions at the Nottingham brownfield site (20-year lifespan, functional unit 1 ha)

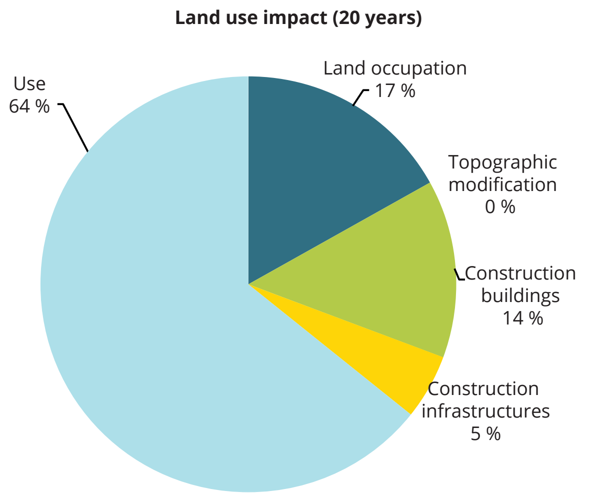


three sites was missing. Construction of infrastructure has the third greatest environmental impact, and in this case the greenfield site has by far the greatest impact because it required new roads, water supply and sewerage networks, and utility and communications networks.

Land use impacts

Land use impacts follow the general impact pattern, i.e. the greatest impacts are primarily linked to the use stage but are also linked to construction activities during the development stage (Figure 3.11). For greenfield development in particular, there is a land use impact during the site development stage, as undeveloped land is 'taken' from agricultural or (semi)natural use. Changes in topography during this stage may also result in considerable land use impacts. Nevertheless, additional land use impacts may also occur on brownfield sites, particularly when contaminated soil is dumped in landfill as part of the remediation (site development stage). On the plus side, the development of green areas has a positive impact on land use, as it results in an increase in soil organic matter and thus contributes to the system's carbon reservoir. This effect resonates with the importance of green infrastructure in mitigating negative land use impacts.

Figure 3.11 Land use impacts across life cycle stages and activities at the Terrassa greenfield site (20-year lifespan, functional unit 1 ha)



However, the model accounts only for the loss of organic carbon content from land use, whereas other impacts from (semi-)natural land occupation, such as the loss of diversity or the ecological role of the area occupied or taken, are not reflected in the results. The model thus ignores the value of land, and the fact that land is a finite and non-renewable resource. Indeed, it takes much longer to produce soil than it does to consume it.

3.5 Conclusions

In this chapter, we have introduced the concept of the LCT approach to environmental thinking and explained how LCA can be used to measure the wider environmental implications of brown- and greenfield developments across all life cycle stages. To demonstrate the approach, we reported the key findings of three case studies, selected to illustrate and compare different development scenarios. These findings allow us to draw the following conclusions:

- The choice of the functional unit is crucial to the interpretation of the results of LCA, as shown by the sensitivity analysis. The reference functional unit used in the case studies was unit of area (1 ha), but selected data were analysed on a per resident and per built surface (1 m^2) basis to look at the effect of the functional unit. This sensitivity analysis showed that, for comparing options for urban development, a functional unit of 1 m^2 of built surface area is the most appropriate.

- Taking a functional unit of 1 m^2 of built surface, the greenfield site had the greatest impact across all categories with global environmental implications, particularly depletion of water resources and land use. Its impact on climate change (measured by emissions of GHGs) was approximately three and four times that of the two brownfield sites, although the greenfield site was by far the biggest site.

- The operational stage had by far the biggest impact on climate change across all three sites — but particularly at the greenfield site, mainly arising from the mobility of that site's large number of residents and other users. Local and regional impacts followed the same pattern across the three sites. The impact of a site during the operational stage is directly correlated with its lifespan, and a more realistic period of use of up to 50 years, rather than the 20 years used in the case studies, would more than double the environmental impact of this stage.

- The second largest contributor to environmental impacts on every scale (local, regional and global) was the construction of buildings during the development stage, which did not vary much between the three sites. The third largest was the construction of infrastructure, for which the greenfield site had the greatest impact because it required a completely new infrastructure.

Despite the limitations of the methodology and the small sample size, the results are very encouraging, as they demonstrate that, using an appropriate functional unit, LCA is a useful tool for comparing different approaches to urban development in terms of their global, regional and local environmental impacts. However, it is limited in that it does not take any account of the socio-economic aspects of sustainable development, and it may simply be too complicated for some sites. Nonetheless, LCA will allow policymakers to weigh up the environmental impact of development options and provide them with the information they need to choose the route with the least environmental impacts.

Although they were not considered in our case studies, life cycle costs can also be calculated. Hendrickson et al. (n.d.) have developed a model for estimating the life cycle costs and emissions of residential brown- and greenfield developments in the United States. The activities included are brownfield remediation, residential building construction, infrastructure costs, residential building utilities and maintenance, and residential travel. They conclude that brownfield developments have on average slightly lower costs — despite significant remediation costs in some cases — resulting from reduced travel costs, as brownfield sites tend to be closer to urban centres than greenfield sites. As is the case for environmental impacts, the operational stage makes by far the greatest contribution to the overall cost impact.

The case study results also highlight greenfield developments as having, in these cases, the greatest environmental impacts, which supports the use of land recycling as a key measure to reduce the overall environmental impact of urban development, as well as to limit land take and help to protect a precious resource. However, it is important to emphasise the importance of context when interpreting the results of LCA, particularly when comparing brownfield developments, and to look at the results in the light of, for example, the size of the site, the number of residents or other users, and the existing infrastructure.

To sum up, this chapter shows that LCA is a useful tool to support policymakers in decision-making, as long as the results are considered in the context of the site. It also supports the use of land recycling as a key response to limit land take and promote more environmentally sustainable urban development.

4 Supporting land governance

This chapter will:

- discuss the added value of and limitations on the use and development of the approaches presented for estimating land recycling and its environmental impacts;
- present the future prospects for these approaches;
- explain how these approaches can be relevant to policy-making in land governance, for both society in general and decision-making at the local level in particular.

4.1 Added value and limitations of the approaches presented

In this report, we have proposed a set of indicators for land recycling in its broad sense, using harmonised data (arising from the harmonised UA mapping approach) and methods. Once the accounting framework has been set up, it does not require much resource to calculate the indicators. They also have the potential to provide a consistent, and thus comparable, picture of the extent of land recycling across FUAs with more than 100 000 inhabitants in Europe. From reference year 2018, the scope will be extended to include change data from FUAs with more than 50 000 inhabitants.

There would be merit in validating these estimates — in other words, assessing how far they represent the true potential for land recycling in an FUA. This would also bring the definition of land recycling and brownfield development used in this report (i.e. looking at land recycling from a mapping perspective) closer to the definitions used in practical brownfield application projects such as CABERNET (2007) and CircUse (2010). In these projects, the definition of brownfield development is based on the market availability of abandoned land (including buildings already on the land).

The above estimates of land recycling focus only on the mapping or geospatial characterisation of land recycling, i.e. the location of land recycling and how it can be quantified. Essentially, they focus only on the land use aspect and disregard other environmental impacts, such as climate change, ecotoxicity or water depletion. To quantify these impacts, a comprehensive environmental impact assessment is commonly applied to remediation or construction activities. However, environmental impact assessments of brown- and greenfield urban developments in Europe are generally not carried out in a holistic and systematic manner. To address this gap, this report applied the LCA approach to case studies of European brown- and greenfield developments, across all stages of redevelopment.

LCA can be thought of as a tool for performing comprehensive environmental assessments in a holistic manner, across all life cycle stages and addressing different thematic impact categories across spatial scales. The three case studies were only an exploration of how this streamlined methodology could be applied to brown- and greenfield developments. Nevertheless, they demonstrated the importance of considering all life cycle stages, as impacts can occur during all stages and can be transferred from one stage to another. This issue is especially important for large urban projects with several redevelopment stages taking place in the territory over a longer period of time. Furthermore, the case studies also identified options for minimising environmental impacts (local, regional, global) and reducing the use of resources across all life cycle stages. Thus, applying the LCA approach in a specific context allows recommendations to be made on how land recycling can be used to make the most efficient use of resources in that particular context.

However, the LCA approach requires a lot of input data. The case studies also showed that the choice of

the reference analytical unit (e.g. expressed per unit of area, per unit of built surface or per resident) can directly influence the results and their interpretation. Furthermore, three case studies are certainly too limited to represent the diversity of brown- and greenfield conditions and contexts across Europe. For example, whether a brownfield is contaminated or not, or whether a greenfield is located on the edge of an already urbanised area, as opposed to having a more remote location (with transport and energy implications), will have a direct bearing on the environmental impact of the site's development. Finally, it also needs to be acknowledged that, although the LCA approach broadens the scope from looking at only land use impacts to assessing a range of the environmental impacts of land recycling, it still addresses only environmental impacts. Other tools are needed to deal with other aspects of sustainability.

4.2 Prospects

Based on the current indicator results derived from UA, a Copernicus local component with an update cycle of 6 years, it is possible to illustrate the concept of land recycling using a set of operational indicators for a number of FUAs across Europe. By offering the response dimension, such a set of indicators would fit well within the EEA thematic cluster of land and soil indicators, which are being developed to address gaps in reporting on changes in land and soil (EEA, 2015b).

Given that land recycling also has a clear urban dimension, the land recycling indicators could also form part of the set of urban indicators currently being developed by the EEA. Additional analysis linking the land recycling indicators to indicators for other processes that take place in urban areas, such as land take, soil sealing or urban sprawl, could shed further light on patterns (in space) and (developing) trends (over time). Indicators based on land recycling and densification could also be suitable for comparing and benchmarking of different cities as they have different proportions of land densification and recycling, which reflect different trends in urban management and planning.

Looking at supplementary urban variables (e.g. population, population density, extent of the transport network) and how they change over time could support the interpretation of such an analysis. This type of combined analysis could also be approached by linking to urban typologies and calculating the land recycling indicators separately for areas of high- and low-density population within FUAs and comparing their patterns.

The LCA approach links land recycling directly to resource efficiency. However, given its context specificity, the LCA method is geared to local — possibly regional — applications and decision-making. The results of the case studies, in which the overall environmental impact of site development was assessed, suggest that LCA will be most useful as a decision-making tool for evaluating short-term impacts (e.g. evaluating different approaches to site remediation) or long-term impacts (e.g. focusing on optimising the timespan of the land use).

4.3 Supporting land resource efficiency across different scales and aspects of sustainability

Land is a multifunctional and multidimensional resource that delivers provisioning, regulating, supporting and cultural services to society. Land is also a finite and non-renewable resource. In recognition of the value of land, land recycling in its broad sense has been put forward as a response to avoid losing land's multiple functions for the sole purpose of urban development (EEA, 2015a).

Densification and 'grey' recycling both have a role to play in making the most efficient use of resources and reducing environmental impacts in FUAs. 'Green' recycling, which creates open and green space, directly contributes to green infrastructure and ecosystem functioning, and thus to well-being in urbanised areas (in line with the EU Biodiversity Strategy (EC, 2011b) and Green Infrastructure Strategy (EC, 2013)). In terms of use of materials and ecosystem functioning, the land recycling process also fits well within the concepts of the circular and green economies.

Land recycling in its broad sense thus responds to the three thematic priority objectives of the 7th EAP, 'Living well, within the limits of our planet': natural capital protection, preservation and enhancement; resource efficiency; and health and well-being (EU, 2013a). Development of green infrastructure and regeneration of brownfield sites are also explicitly mentioned as investment priorities for the EU Cohesion Fund (EU, 2013b) and the European Regional Development Fund (EU, 2013c). When viewed as part of the 'avoid — recycle — compensate' hierarchy (as, for example, advocated by the CircUse (2010) project), adopting a land recycling approach is also broadly in line with the globally agreed principle of land degradation neutrality, as part of the Sustainable Development Goals (Target 15.3) (UNGA, 2015).

Land recycling thus has a central role to play in sustainable land governance. However, to make land

recycling a reality, we need to move from a conceptual to a practical level. In this report, two approaches have been proposed: one for estimating land recycling in a harmonised (data and method) and geospatially explicit manner, and one for estimating the environmental impacts of land recycling, as opposed to land take, in regional and local contexts. Although the findings of testing the approaches that are presented are a useful contribution to the knowledge base on land recycling, they are, in themselves, not sufficient to recommend implementing land recycling at regional or local level, nor do they cover all aspects of sustainability.

The EU has implemented regulations that require environmental impacts to be taken into account in urban developments in Member States (the Environmental Impact Assessment Directive (EU, 2001) and the Strategic Environmental Assessment Directive (EU, 2011)). LCA can be a useful tool in urban planning when detailed alternative developments need to be assessed for a specific location, thereby supporting the decision-making process. LCA can also be used to determine the option(s) with the least environmental impact, in both the short and the long term.

Life cycle costs and emissions calculations for residential brown- and greenfield developments in the United States indicate that brownfield developments are on average also more cost-effective — despite considerable remediation costs in some cases. As is the case for environmental impacts, the use stage is by far the greatest contributor to the overall cost. Travel costs during the use stage tend to be lower for brownfield sites, which are commonly at a shorter distance from activity centres than greenfield sites.

In reality, true costs are seldom internalised in decision-making. Particularly in countries facing a financial crisis or in regions where the economy is shrinking, economic advantages (e.g. attracting investment, revenues from building or business taxation) are commonly prioritised over environmental impacts. Therefore, authorities avoid putting (environmental) constraints on such developments. A lack of understanding and appreciation of the value of soil (and landscape) as a limited resource may further influence decision-making (EEA, 2016b). However, the financial crisis has also forced some countries to develop new policies promoting the reuse and revitalisation of existing buildings because the stock has become too large compared with the demand.

Governance arrangements in Europe determine regional differences in land use patterns and intensity (e.g. how brownfield sites are developed). In regions with low urban density, the development of brownfield areas is restrained by contamination issues, as it is perceived that there is enough land available, and that it is thus cheaper to take new land than to invest in existing brownfield sites that would require remediation. By contrast, in regions with high urban density, the development of brownfield areas is driven by the scarcity of urban land for development, as well as by economic and social issues.

LCA is a tool that is based on modelling, and thus it is a simplification of reality; it implies a certain degree of user subjectivity, especially when there are different political and social priorities (e.g. in the selection of the functional unit). Involving stakeholders in using the tool, and in the planning and decision-making process overall, may have the effect of making the LCA tool less subjective. The outcomes of the CircUse project emphasise that 'circular flow land use management' can be achieved only through the active participation of a range of public and private individuals (planners, property owners, land developers, citizens) influencing land use (Preuß and Verbücheln, 2013).

Finally, from a governance point of view, implementing land recycling within an FUA — that is, an urban centre and its commuting zone — may be challenging because of the different administrative centres involved. Policy incentives for land recycling, such as voluntary targets on land take or attractive tax regimes (for brown- as opposed to greenfield developments), are likely to be more effective if agreed and implemented at national or regional level. In that way, synergies across spatial scales can be achieved. However, coordinating and integrating policy instruments across spatial scales need not be limited to the national level. From a cross-country comparison of cases, it has emerged that transnational exchange and cooperation can be equally conducive to implementing the land recycling concept (Preuß and Verbücheln, 2013).

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Annex Methodological approaches

A.1 Nomenclature for artificial surfaces used in Corine Land Cover and Urban Atlas

Corine Land Cover	Urban Atlas
1.1 Urban fabric	
1.1.1 Continuous urban fabric	11100 Continuous urban fabric
1.1.2 Discontinuous urban fabric	11210 Discontinuous dense urban fabric
	11220 Discontinuous medium density urban fabric
	11230 Discontinuous low density urban fabric
	11240 Discontinuous very low density urban fabric
	11300 Isolated structures
1.2 Industrial, commercial and transport units	
1.2.1 Industrial or commercial units	12100 Industrial, commercial, public, military and private units
1.2.2 Road and rail networks and associated land	12210 Fast transit roads and associated land
	12220 Other roads and associated land
	12230 Railways and associated land
1.2.3 Port areas	12300 Port areas
1.2.4 Airports	12400 Airports
1.3 Mines, dump and construction sites	
1.3.1 Mineral extraction sites	13100 Mineral extraction and dump sites
1.3.2 Dump sites	
1.3.3 Construction sites	13300 Construction sites
	13400 Land without current use
1.4 Artificial, non-agricultural vegetated areas	
1.4.1 Green urban areas	14100 Green urban areas
1.4.2 Sport and leisure facilities	14200 Sports and leisure facilities

A.2 Methodology for defining land cover flows relevant to land recycling indicators

A.2.1 Methodology based on Corine Land Cover data

The first level of the CLC nomenclature comprises nine major land use processes or drivers, which are subdivided into subclasses (lcfs):

- LCF 1: Urban land management;
- LCF 2: Urban residential sprawl ([4])
- LCF 3: Sprawl ([4]) of economic sites and infrastructures;
- LCF 4: Agriculture internal conversions;
- LCF 5: Conversion from forested and natural land to agriculture;
- LCF 6: Withdrawal of farming;
- LCF 7: Forests creation and management;
- LCF 8: Water bodies creation and management;
- LCF 9: Changes of land cover due to natural and multiple causes.

Land cover flows relevant to land recycling in its broad sense

To estimate land recycling and densification, we need to focus on those LCFs that refer to the internal transformation of urban areas, expressed by LCF 1, and part of LCF 3 — in particular lcf 38 (Sprawl of sport and leisure facilities) — when their sub-flows occur on already developed land. LCF 2 refers to the development of residential areas (new developments) and LCF 3 concerns the development of land for industrial, commercial and infrastructure purposes. Table A.1 shows the detail of LCFs 1, 2 and 3.

The corresponding relevant sub-flows (level 2) are defined as follows (EEA, 2006b, 2008):

LCF 1 — Urban land management: internal transformation of urban areas.

- **lcf 11** — Urban development/infilling: conversion from discontinuous urban fabric, green urban areas and sport and leisure facilities to dense urban fabric, economic areas and infrastructures.
- **lcf 12** — Recycling of developed urban land: internal conversions between residential and/or non-residential land cover types. Construction on urban greenfield sites is not included here but rather under lcf 11.
- **lcf 13** — Development of green urban areas: extension of green urban areas over developed land and, in the peripheral areas of cities, over other types of land use.

LCF 3 — Sprawl of economic sites and infrastructures: land uptake by new sites and infrastructures (including sport and leisure facilities) from non-urban land (extension into the sea may also take place).

- **lcf 38** — Sprawl of sport and leisure facilities: conversion from developed and non-urban land to sport and leisure facilities.

([4]) 'Urban sprawl is a phenomenon that can be visually perceived in the landscape. A landscape [is affected by urban sprawl] if it is permeated by urban development or solitary buildings and when land uptake per inhabitant or job is high. The more area built over in a given landscape (amount of built-up area) and the more dispersed this built-up area in the landscape (spatial configuration), and the higher the uptake of built-up area per inhabitant or job (lower utilization intensity in the built-up area), the higher the degree of urban sprawl' (Jaeger and Schwick, 2014, in EEA, 2016c, p. 22). Note that in this report we use the more neutral term '(urban) development', since not every application of LCFs 2 and 3 corresponds in practice to 'sprawl' (see also EEA, 2016b, 2016c).

Table A.1 LCF matrix detail for LCFs 1, 2 and 3

		111 Continuous urban fabric	112 Discontinuous urban fabric	121 Industrial or commercial units	122 Road and rail networks and associated land	123 Port areas	124 Airports	131 Mineral extraction sites	132 Dump sites	133 Construction sites	141 Green urban areas	142 Sport and leisure facilities
111	Continuous urban fabric	NC	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf13	lcf38
112	Discontinuous urban fabric	lcf11	NC	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf13	lcf38
121	Industrial or commercial units	lcf12	lcf12	NC	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf13	lcf38
122	Road and rail networks and associated land	lcf12	lcf12	lcf12	NC	lcf12	lcf12	lcf12	lcf12	lcf12	lcf13	lcf38
123	Port areas	lcf12	lcf12	lcf12	lcf12	NC	lcf12	lcf12	lcf12	lcf12	lcf13	lcf38
124	Airports	lcf12	lcf12	lcf12	lcf12	lcf12	NC	lcf12	lcf12	lcf12	lcf13	lcf38
131	Mineral extraction sites	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	NC	lcf12	lcf12	lcf13	lcf38
132	Dump sites	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	NC	lcf12	lcf13	lcf38
133	Construction sites	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	NC	lcf13	lcf38
141	Green urban areas	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	NC	lcf38
142	Sport and leisure facilities	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf13	NC
211	Non-irrigated arable land	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
212	Permanently irrigated land	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
213	Rice fields	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
221	Vineyards	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
222	Fruit trees and berry plantations	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
223	Olive groves	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
231	Pastures	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
241	Annual crops associated with permanent crops	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
242	Complex cultivation patterns	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
243	Agriculture mosaics with significant natural vegetation	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
244	Agro-forestry areas	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
311	Broad-leaved forest	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
312	Coniferous forest	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
313	Mixed forest	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
321	Natural grassland	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
322	Moors and heathland	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
323	Sclerophyllous vegetation	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
324	Transitional woodland shrub	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
331	Beaches, dunes and sand plains	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
332	Bare rock	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
333	Sparsely vegetated areas	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
334	Burnt areas	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
335	Glaciers and perpetual snow	lcf99	lcf99	lcf99	lcf99	lcf99	lcf99	lcf99	lcf99	lcf99	lcf99	lcf99
411	Inland marshes	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
412	Peatbogs	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
421	Salt marshes	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
422	Salines	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
423	Intertidal flats	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
511	Water courses	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
512	Water bodies	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
521	Coastal lagoons	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
522	Estuaries	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38
523	Sea and ocean	lcf21	lcf22	lcf31	lcf32	lcf33	lcf34	lcf35	lcf36	lcf37	lcf13	lcf38

Source: EEA, 2008.

The 'Urban development/infilling' sub-flow (lcf 11) is a proxy for land densification, and it includes the changes defined in Table A.1.

The sub-flows 'Recycling of developed urban land' (lcf 12), 'Development of green urban areas' (lcf 13 — if occurring over previously developed land) and 'Sprawl of sport and leisure facilities' (lcf 38 — if occurring over previously developed land) are all proxies for land recycling in its narrow sense. The changes that constitute these sub-flows are shown in Table A.1.

Estimating land recycling in its broad sense

The EEA report *Land accounts for Europe 1990–2000* (EEA, 2006b) includes estimates of land recycling (in its broad sense). According to that report, land recycling (%) is calculated as land consumption by internal conversion of artificial areas over **total land consumption** by artificial development and of artificial areas (in addition to those consumed by artificial development), for a given period, where:

- consumption by internal conversion of artificial areas is defined by lcfs 11 (Urban development/infilling), 12 (Recycling of developed urban land), 13 (Development of green urban areas) and 38 (Sprawl of sport and leisure facilities) on CLC class 1 (Artificial surfaces), excluding class 133 (Construction sites);

- consumption by artificial development corresponds to LCFs 1 (Urban land management), 2 (Urban residential sprawl) and 3 (Sprawl of economic sites and infrastructures) on all CLC classes;

- the consumption of artificial areas (in addition to those consumed by artificial development) corresponds to the parts of lcfs 5 (Conversion from forested and natural land to agriculture), 7 (Forests creation and management), 8 (Water bodies creation and management) and 9 (Changes of land cover due to natural and multiple causes) that affect artificial areas.

This can be expressed as follows:

Urban densification and land recycling

$$= \frac{lcf11^{(a)} + lcf12^{(a)} + lcf13^{(a)(b)} + lcf38^{(a)(b)}}{LCF1 + LCF2 + LCF3 + LCF5^{(b)} + LCF7^{(b)} + LCF8^{(b)} + LCF9^{(b)}} * 100$$

([a]) Excluding conversions from 'Construction sites' but including changes to these classes.

([b]) Only changes occurring on artificial land cover (previously developed land).

The denominator defines total land consumption by artificial development and of artificial areas (in addition to those consumed by artificial development) or, in short, 'total land consumption'.

A.2.2 Methodology based on Urban Atlas data

Considering the specificities of UA and its nomenclature, we need an adapted approach to defining LCFs and estimating land recycling in its broad sense. This involves identifying opportunities to refine the estimation of land recycling in its broad sense using the more accurate thematic resolution that UA offers.

Defining land cover flows relevant to land recycling in its broad sense

The definitions of LCFs developed for CLC can be applied to UA with some adaptation. To that end, individual UA land cover changes were grouped into LCFs that follow the logic of the CLC-based LCFs (Table A.2, where the changes are expressed in a change matrix). Nevertheless, particularly for the urban land management sub-flows, additional interpretation was needed to take account of the difference in thematic resolution between the CLC and UA databases:

- Class 13400, 'Land without current use', is treated similarly to class 13300, 'Construction sites', as both represent an intermediate rather than a final state. Flows from 'Land without current use' ([5]) were thus attributed to lcf 12, 'Recycling of developed urban land'. However, according to its definition in UA, this class can contain brownfield sites as well as areas that have streets and infrastructure but are not yet built up, meaning that it can include 'leftover land', the development of which would correspond to densification in the context of this methodology.

- Class 11300, 'Isolated structures' ([6]), has been treated similarly to class 11240, 'Discontinuous very low density urban fabric (S.L. < 10 %)', as it behaves like a very low density urban fabric area in terms of its function and potential flows towards other classes.

- Despite the different density levels in the discontinuous urban classes, all UA discontinuous urban classes (11210–11300) are treated similarly to CLC class 112, 'Discontinuous urban fabric'.

- All transitions towards class 14100, 'Green urban areas', from any other classes (except for 13300 and 13400) are listed as lcf 13, 'Development of green urban areas' (representing recycling when occurring on artificial land), keeping the coding from the CLC-based approach for ease of comparison and greater transparency.

- Transitions towards class 14200, 'Sport and leisure facilities', from other classes (except for 13300 and 13400) are treated in the same way, coded as lcf 38, 'Sprawl of sport and leisure facilities' (also including recycling if occurring on artificial land).

- Along with lcf 12, both lcfs 13 and 38 are seen as part of land recycling in its broad sense, rather than part of densification.

Estimating land recycling in its broad sense

To derive land recycling and densification indicators, the changes and flows needed to calculate the numerators and denominators of the equations defined in Section A.3 for use with CLC data need to be defined for use with UA data.

The denominator consists of the total land consumption. According to the definition of 'total land consumption' (see Section A.2.1), LCFs 5, 6, 7, 8 and 9 include only changes occurring on artificial land cover (previously developed land). Hence, land cover changes from classes 20000, 30000 and 40000 to classes 21000 to 50000 (see Table A.2) are not relevant for the calculation of total land consumption.

For defining the numerator, as for the CLC-based approach (Section A.1), class 13300, 'Construction sites', is important for calculating overall land consumption. However, as this class is only transitional or intermediate (rather than a final land consumption class), it is not included in the calculation of land recycling in its broad sense (numerator) if it is the original class of the change. The same approach is taken in the case of class 13400, 'Land without current use', because, as for 'Construction sites', the area of 'Land without current use' is in an intermediate state (Table A.2).

Refining the land cover flows for estimating land recycling in its broad sense

The LCFs for land densification and land recycling processes have been defined in accordance with the CLC nomenclature (Table A.2). However, given the higher thematic resolution of the UA classification and nomenclature, alternative definitions that make use of this are proposed (Table A.3). Using these, land cover

([5]) 'Land without current use' corresponds to 'Areas in the vicinity of artificial surfaces still waiting to be used or re-used. The area is obviously in a transitional position, “waiting to be used”. Waste land, removed former industry areas (“brownfields”), gaps in between new construction areas or leftover land in the urban context (“greenfields”). No actual agricultural or recreational use. No construction is visible, without maintenance, but no undisturbed fully natural or semi-natural vegetation (secondary ruderal vegetation). Also areas where the street network is already finished, but actual erection of buildings is still not visible' (EC, 2011a).

([6]) 'Isolated structures' are defined as 'isolated artificial structures with a residential component, such as (small) individual farm houses and related buildings' (EC, 2011a).

Table A.2 Identification of LCFs (following CLC-based LCFs) in the change matrix between UA 2006 and UA 2012

Code2006 \ Code2012	11100	11210	11220	11230	11240	11300	12100	12210	12220	12230	12300	12400	13100	13300	13400	14100	14200	21000	22000	23000	24000	25000	32000	33000	40000	31000	50000	
11100		lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf13	lcf38	lcf54	lcf54	lcf54	lcf54	lcf54	lcf911	lcf911	lcf911	lcf72	lcf81	11100
11210	lcf11		lcf12	lcf12	lcf12	lcf12	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf13	lcf38	lcf54	lcf54	lcf54	lcf54	lcf54	lcf911	lcf911	lcf911	lcf72	lcf81	11210
11220	lcf11	lcf11		lcf12	lcf12	lcf12	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf13	lcf38	lcf54	lcf54	lcf54	lcf54	lcf54	lcf911	lcf911	lcf911	lcf72	lcf81	11220
11230	lcf11	lcf11	lcf11		lcf12	lcf12	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf13	lcf38	lcf54	lcf54	lcf54	lcf54	lcf54	lcf911	lcf911	lcf911	lcf72	lcf81	11230
11240	lcf11	lcf11	lcf11	lcf11		lcf12	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf13	lcf38	lcf54	lcf54	lcf54	lcf54	lcf54	lcf911	lcf911	lcf911	lcf72	lcf81	11240
11300	lcf11	lcf11	lcf11	lcf11	lcf11		lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf13	lcf38	lcf54	lcf54	lcf54	lcf54	lcf54	lcf911	lcf911	lcf911	lcf72	lcf81	11300
12100	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12		lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf13	lcf38	lcf54	lcf54	lcf54	lcf54	lcf54	lcf911	lcf911	lcf911	lcf72	lcf81	12100
12210	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12		lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf13	lcf38	lcf54	lcf54	lcf54	lcf54	lcf54	lcf911	lcf911	lcf911	lcf72	lcf81	12210
12220	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12		lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf13	lcf38	lcf54	lcf54	lcf54	lcf54	lcf54	lcf911	lcf911	lcf911	lcf72	lcf81	12220
12230	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12		lcf12	lcf12	lcf12	lcf12	lcf12	lcf13	lcf38	lcf54	lcf54	lcf54	lcf54	lcf54	lcf911	lcf911	lcf911	lcf72	lcf81	12230
12300	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12		lcf12	lcf12	lcf12	lcf12	lcf13	lcf38	lcf54	lcf54	lcf54	lcf54	lcf54	lcf911	lcf911	lcf911	lcf72	lcf81	12300
12400	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12		lcf12	lcf12	lcf12	lcf13	lcf38	lcf54	lcf54	lcf54	lcf54	lcf54	lcf911	lcf911	lcf911	lcf72	lcf81	12400
13100	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12		lcf12	lcf12	lcf13	lcf38	lcf54	lcf54	lcf54	lcf54	lcf54	lcf911	lcf911	lcf911	lcf72	lcf81	13100
13300	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12		lcf12	lcf13	lcf38	lcf54	lcf54	lcf54	lcf54	lcf54	lcf911	lcf911	lcf911	lcf72	lcf81	13300
13400	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12		lcf13	lcf38	lcf54	lcf54	lcf54	lcf54	lcf54	lcf911	lcf911	lcf911	lcf72	lcf81	13400
14100	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11		lcf38	lcf54	lcf54	lcf54	lcf54	lcf54	lcf911	lcf911	lcf911	lcf72	lcf81	14100
14200	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf13		lcf54	lcf54	lcf54	lcf54	lcf54	lcf911	lcf911	lcf911	lcf72	lcf81	14200
20000	lcf21	lcf22	lcf22	lcf22	lcf22	lcf22	lcf31	lcf32	lcf32	lcf32	lcf33	lcf34	lcf35	lcf37	lcf37	lcf13	lcf38									lcf61	lcf81	20000
30000	lcf21	lcf22	lcf22	lcf22	lcf22	lcf22	lcf31	lcf32	lcf32	lcf32	lcf33	lcf34	lcf35	lcf37	lcf37	lcf13	lcf38	lcf51	lcf51	lcf51	lcf51	lcf51	lcf74	lcf74	lcf911		lcf81	30000
50000	lcf21	lcf22	lcf22	lcf22	lcf22	lcf22	lcf31	lcf32	lcf32	lcf32	lcf33	lcf34	lcf35	lcf37	lcf37	lcf13	lcf38	lcf53	lcf53	lcf53	lcf53	lcf53	lcf99	lcf99	lcf911	lcf72		50000
	11100	11210	11220	11230	11240	11300	12100	12210	12220	12230	12300	12400	13100	13300	13400	14100	14200	21000	22000	23000	24000	25000	32000	33000	40000	31000	50000	

Note: LCF 1 — Urban land management: lcf 11 Urban development/infilling, lcf 12 Recycling of developed urban land, lcf 13 Development of green urban areas; LCF 2 — Urban residential sprawl: lcf 21 Urban dense residential sprawl, lcf 22 Urban diffuse residential sprawl; LCF 3 — Sprawl of economic sites and infrastructures: lcf 31 Sprawl of industrial and commercial sites, lcf 32 Sprawl of transport networks, lcf 33 Sprawl of harbours, lcf 34 Sprawl of airports, lcf 35 Sprawl of mines and quarrying areas (UA class 13100 also contains dump sites), lcf 37 Construction, lcf 38 Sprawl of sport and leisure facilities; LCF 5 — Conversion from forested and natural land to agriculture: lcf 51 Conversion from forest to agriculture, lcf 53 Conversion from wetlands to agriculture, lcf 54 Conversion from developed areas to agriculture; LCF 6 — Withdrawal of farming: lcf 61 Withdrawal of farming with woodland creation; LCF 7— Forests creation and management: lcf 72 Forest creation, afforestation, lcf 74 Recent felling and transition; LCF 8 — Water bodies creation and management: lcf 81 Water bodies creation; LCF 9 — Changes of land cover due to natural and multiple causes: lcf 91 Semi-natural creation, lcf 99 Other changes and unknown.

changes and the processes that drive them can be assigned to different LCFs. For instance, flows from 'Dense discontinuous urban fabric (50–80 %)' to classes such as 'Airports' can then be treated as recycling, given the often large proportion of green areas within airports, as opposed to taking the CLC-based approach, which treats this flow as infilling/densification. Nevertheless, the understanding of the underlying processes remains the same, meaning that lcf 11 still represents densification, whereas lcfs 12, 13 and 38 reflect different aspects of land recycling in its narrow sense.

The UA changes that are attributed to a flow different from that following CLC logic are highlighted in yellow boxes in Table A.3. The following changes are worth noting:

- The different density levels in the discontinuous urban classes (11210–11240) allow further distinction, e.g. the class with the highest density level in that range, class 11210, 'Discontinuous dense urban fabric (50–80 % sealing)', is similar to 'Continuous urban fabric (> 80 % sealing)'. Accordingly, changes from 'Discontinuous dense urban fabric (50–80 % sealing)' to any other artificial class (except 'Green urban areas' and 'Sports and leisure facilities', i.e. classes 11220–13400) are classified as land recycling (lcf 12) rather than densification (lcf 11), as these changes may not always represent densification.

- Changes from class 12220, 'Other roads and associated land', to class 12210, 'Fast transit roads and associated land', as part of lcf 11, 'Urban development/infilling', are interpreted as and attributed to densification. The same rationale can be applied to changes from class 12400, 'Airports', to classes 11100, 'Continuous urban fabric (S.L. > 80 %)', and 11210, 'Discontinuous dense urban fabric (S.L. 50–80 %)'.

A.3 The indicators

The meaning of ([a]) and ([b]) in the following formulas:

([a]) Excluding conversions from 'Construction sites' and from 'Land without current use' (UA only), but including changes to these classes, and calculating these flows as defined for CLC in the case of indicators 1 and 2, and as defined for UA for indicators 3–13.

([b]) Only changes occurring on artificial land cover (previously developed land).

Indicator 1

'Grey' land recycling and densification (CLC-based) =

$$\frac{lcf11^{(a)} + lcf12^{(a)}}{LCF1 + LCF2 + LCF3 + LCF5^{(b)} + LCF7^{(b)} + LCF8^{(b)} + LCF9^{(b)}} * 100$$

Indicator 2

'Grey', 'green' land recycling and densification (Land recycling in its broad sense, CLC-based) =

$$\frac{lcf11^{(a)} + lcf12^{(a)} + lcf13^{(a)(b)} + lcf38^{(a)(b)}}{LCF1 + LCF2 + LCF3 + LCF5^{(b)} + LCF7^{(b)} + LCF8^{(b)} + LCF9^{(b)}} * 100$$

Indicator 3

'Grey' land recycling and densification (UA-based) =

$$\frac{lcf11^{(a)} + lcf12^{(a)}}{LCF1 + LCF2 + LCF3 + LCF5^{(b)} + LCF7^{(b)} + LCF8^{(b)} + LCF9^{(b)}} * 100$$

Table A.3 Refined identification of LCFs relevant for land recycling and densification calculations (numerator) (UA-based methodology)

UA code 2006 \ UA code 2012	11100	11210	11220	11230	11240	11300	12100	12210	12220	12230	12300	12400	13100	13300	13400	14100	14200
11100	X	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf13	lcf38
11210	lcf11	X	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf11	lcf11	lcf13	lcf38
11220	lcf11	lcf11	X	lcf12	lcf12	lcf12	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf13	lcf38
11230	lcf11	lcf11	lcf11	X	lcf12	lcf12	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf13	lcf38
11240	lcf11	lcf11	lcf11	lcf11	X	lcf12	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf13	lcf38
11300	lcf11	lcf11	lcf11	lcf11	lcf11	X	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf13	lcf38
12100	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	X	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf13	lcf38
12210	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	X	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf13	lcf38
12220	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf11	X	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf13	lcf38
12230	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	X	lcf12	lcf12	lcf12	lcf12	lcf12	lcf13	lcf38
12300	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	X	lcf12	lcf12	lcf12	lcf12	lcf13	lcf38
12400	lcf11	lcf11	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	X	lcf12	lcf12	lcf12	lcf13	lcf38
13100	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	X	lcf12	lcf12	lcf13	lcf38
13300	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	X	lcf12	lcf13	lcf38
13400	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	lcf12	X	lcf13	lcf38
14100	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	X	lcf38
14200	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf11	lcf13	X

Note: LCF 1 — Urban land management: lcf 11 Urban development/infilling, lcf 12 Recycling of developed urban land, lcf 13 Development of green urban areas; LCF 3 — Sprawl of economic sites and infrastructures: lcf 38 Sprawl of sport and leisure facilities.

The differences from the CLC-based approach are highlighted in yellow.

Indicator 4

'Grey', 'green' land recycling and densification (Land recycling in its broad sense, UA-based) =

$$\frac{lcf11^{(a)} + lcf12^{(a)} + lcf13^{(a)(b)} + lcf38^{(a)(b)}}{LCF1 + LCF2 + LCF3 + LCF5^{(b)} + LCF7^{(b)} + LCF8^{(b)} + LCF9^{(b)}} * 100$$

Indicator 5

Densification =

$$\frac{lcf11^{(a)}}{LCF1 + LCF2 + LCF3 + LCF5^{(b)} + LCF7^{(b)} + LCF8^{(b)} + LCF9^{(b)}} * 100$$

Indicator 6

'Grey' land recycling =

$$\frac{lcf12^{(a)}}{LCF1 + LCF2 + LCF3 + LCF5^{(b)} + LCF7^{(b)} + LCF8^{(b)} + LCF9^{(b)}} * 100$$

Indicator 7

'Green' land recycling =

$$\frac{lcf13^{(a)(b)} + lcf38^{(a)(b)}}{LCF1 + LCF2 + LCF3 + LCF5^{(b)} + LCF7^{(b)} + LCF8^{(b)} + LCF9^{(b)}} * 100$$

Indicator 8

Densification related to urban land management =

$$\frac{lcf11^{(a)}}{LCF1}$$

Indicator 9

'Grey' land recycling related to urban land management =

$$\frac{lcf12^{(a)}}{LCF1}$$

Indicator 10

'Green' land recycling related to urban land management =

$$\frac{lcf13^{(a)(b)} + lcf38^{(a)(b)}}{LCF1}$$

Indicator 11

Densification related to land take =

$$\frac{lcf11^{(a)}}{LCF2 + LCF3}$$

Indicator 12

'Grey' land recycling related to land take =

$$\frac{lcf12^{(a)}}{LCF2 + LCF3}$$

Indicator 13

'Green' land recycling related to land take =

$$\frac{lcf13^{(a)(b)} + lcf38^{(a)(b)}}{LCF2 + LCF3}$$

A.4 Impact assessment categories and their units

Table A.4 Impact categories used in the ILCD LCA method

Impact category	Description	Model/method	Geographical scale
1. Climate change	Global warming potential calculating the radiative forcing over a time horizon of 100 years. GHGs such as CO_2 and CH_4 can cause climate change	IPCC, 2007	Global
2. Ozone depletion	Ozone depletion potential calculating the destructive effects on the stratospheric ozone layer over a time horizon of 100 years	WMO, 1999	Global
3. Human toxicity, cancer effects	Comparative toxic unit for humans (CTUh) expressing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogram). Specific groups of chemicals require further work	USEtox, n.d.	Regional, local
4. Human toxicity, non-cancer effects	CTUh expressing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogram). Specific groups of chemicals require further work	USEtox, n.d.	Regional, local
5. Particulate matter	Quantification of the impact of premature death or disability that particulates/respiratory inorganic compounds have on the population, in comparison with $PM_{2.5}$. It includes the assessment of primary (PM_{10} and $PM_{2.5}$) and secondary PM (including creation of secondary PM due to SO_x, NO_x and NH_3 emissions) and CO	Spadaro and Rabl, 2004	Regional, local
6. Ionising radiation HH (human health)	Quantification of the impact of ionising radiation on the population, in comparison with uranium 235	Frischknecht et al., 2000	Local
7. Ionising radiation E (ecosystems) ([a])	Comparative toxic unit for ecosystems (CTUe) expressing an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a radionuclide emitted (PAF m^3/year/kg). Fate of radionuclide based on USEtox consensus model (multimedia model). Relevant for freshwater ecosystems	Garnier-Laplace et al., 2009	Local
8. Photochemical ozone formation	Expression of the potential contribution to photochemical ozone formation. Only for Europe. It includes spatial differentiation. Volatile organic compounds react with nitrous oxides and form smog, which could have impacts on human health as well as ecosystems	van Zelm et al., 2008	Regional, local
9. Acidification	Accumulated exceedance characterising the change in critical load exceedance of the sensitive area in terrestrial and main freshwater ecosystems, to which acidifying substances deposit. European country dependent. Acids and some compounds that can be converted to acids emitted to the atmosphere can cause regional damage to ecosystems as a result of acid rain	Seppälä et al., 2006; Posch et al., 2008	Regional, local
10. Terrestrial eutrophication	Accumulated exceedance characterising the change in critical load exceedance of the sensitive area, to which eutrophying substances deposit. European country dependent. Nitrogen and phosphorus can lead to nutrient enrichment of ecosystems. Regarding soil, low-nutrient ecosystems could disappear	Seppälä et al., 2006; Posch et al., 2008	Regional, local
11. Freshwater eutrophication	Expression of the degree to which the emitted nutrients reach the freshwater end compartment (phosphorus considered as limiting factor in freshwater). European validity. Averaged characterisation factors from country-dependent characterisation factors. Nitrogen and phosphorus can lead to nutrient enrichment of ecosystems. In water, increased algal growth can eventually result in damaged ecosystems	ReCiPe, 2012	Regional, local
12. Marine eutrophication	Expression of the degree to which the emitted nutrients reach the marine end compartment (nitrogen considered as limiting factor in marine water). European validity. Averaged characterisation factors from country-dependent characterisation factors	ReCiPe, 2012	Regional, local
13. Freshwater ecotoxicity	CTUe expressing an estimate of PAF integrated over time and volume per unit mass of a chemical emitted (PAF m^3/year/kg). Specific groups of chemicals require further work	USEtox, n.d.	Regional, local

Table A.4 Impact categories used in the ILCD LCA method (cont.)

Impact category	Description	Model/method	Geographical scale
14. Land use	Soil organic matter (SOM) based on changes in SOM, measured in (kg C/m²/year). Biodiversity impacts not covered by the dataset	Milà i Canals et al., 2007	Global, regional, local
15. Water resource depletion	Freshwater scarcity: scarcity-adjusted amount of water used	Frischknecht et al., 2006	Global, regional, local
16. Mineral, fossil and renewable resource depletion	Scarcity of mineral resource calculated as 'Reserve base'. It refers to identified resources that meet specified minimum physical and chemical criteria related to current mining practice. The reserve base may encompass those parts of the resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics	van Oers et al., 2002	Global, regional, local

Note: ([a]) This method is classified as interim; see Garnier-Laplace et al. (2009) for explanation.

Source: ILCD impact method (JRC, 2011).

Table A.5 Impact categories and their units of measurement

Impact category	Units	Description of units
1. Climate change	kg CO_2 eq	Kilograms of CO_2 equivalent
2. Ozone depletion	kg CFC-11 eq	Kilograms of CFC-11 equivalent
3. Human toxicity, cancer effects	CTUh	CTUh expressing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogram)
4. Human toxicity, non-cancer effects	CTUh	Comparative toxic unit for humans expressing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogram)
5. Particulate matter	kg $PM_{2.5}$ eq	Kilograms of particulate matter less than 2.5 µm equivalent
6. Ionising radiation HH (human health)	kBq U-235 eq	Kilobecquerels of uranium 235 equivalent
7. Ionising radiation E (ecosystems)	CTUe	CTUe expressing an estimate of PAF integrated over time and volume per unit mass of a radionuclide emitted (PAF m³/year/kg).
8. Photochemical ozone formation	kg NMVOC eq	Kilograms of non-methane volatile organic compounds equivalent
9. Acidification	molc H^+ eq	Molcules of H+ equivalent
10. Terrestrial eutrophication	molc N eq	Molecules of nitrogen equivalent
11. Freshwater eutrophication	kg P eq	Kilograms phosphorus equivalent
12. Marine eutrophication	kg N eq	Kilograms nitrogen equivalent
13. Freshwater ecotoxicity	CTUe	Comparative toxic unit for ecosystems expressing an estimate of PAF integrated over time and volume per unit mass of a chemical emitted (PAF m³/year/kg)
14. Land use	kg C deficit	SOM based on changes in SOM, measured in (kg C/m²/year)
15. Water resource depletion	m³ water eq	Cubic metres of water equivalent
16. Mineral, fossil and renewable resource depletion	kg Sb eq	Kilograms of antimony equivalent

Source: ILCD impact method (JRC, 2011).

Table A.6 Different life stages and development use activities considered in the LCA of the three case studies

	Life stage/site status, and development and use activities	Considered in brownfield case study (BF_UK)	Considered in brownfield case study (BF_Spain)	Considered in greenfield case study (GF_Spain)
Primary	Remaining contamination	√ Included	√ Included	× Not applicable for this site study
Secondary	Soil and groundwater investigation	√ Included	√ Included	× Not applicable for this site study
	Soil remediation	√ Included	√ Included	× Not applicable for this site study, since no contamination is present on the site
	Deconstruction	√ Included	× Not included (not applicable)	× Deconstruction of the small huts has not been considered in this study
	Rehabilitation of existing buildings	√ Included	× Not included (not applicable)	× Existing buildings (16 970 m^2 of rural houses) are in good condition. Only minor rehabilitation activities have been carried out and they are not included in the study
	Land occupation: loss of natural land	× Not included (considered that it belongs to the previous economic activity system)	× Not included	√ Included as natural land occupation
	Construction of new buildings (including landscaping)	√ Included	√ Included	√ Included
	Construction of new infrastructures	√ Included	√ Included	√ Included
Tertiary	Mobility	√ Included	√ Included	√ Included
	Water supply buildings	√ Included	√ Included	√ Included
	Water supply facilities	√ Included	√ Included	√ Included
	Waste generation	√ Included	√ Included	√ Included
	Wastewater	√ Included	√ Included	√ Included
	Electricity building consumption	√ Included	√ Included	√ Included
	Natural gas consumption	√ Included	√ Included	√ Included

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