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RESEARCH ARTICLE

Circular Economy and Core–Periphery Relations: Territorial Inequalities in Waste Management through Agglomeration, Proximity, and Structural Effects

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Abstract

This article examines the territorial effects of the circular economy (CE) through the lens of waste management in France, using the core-periphery model from economic geography. Relying on a unique dataset of 62 million tons of waste flows (IREP), we combine spatial analysis with regression, gravity and shift-share models. Results confirm a concentration of high-value recovery operations in urban centres, while disposal operations remain dominant in rural and peri-urban areas. However, we also highlight emerging complementarities, including energy and material recovery in small towns and rural areas. These findings prompt a reevaluation of territorial justice in the transition towards a circular economy.

Keywords Waste · circular economy · core-periphery model · economic geography · France

1. Introduction

Over the past two decades, the circular economy (CE) has evolved into both a significant academic field of research (Kircherr et al., 2023) and a central focus in practice. In the face of environmental issues, CE is viewed as part of a necessary shift towards more virtuous ways of production and consumption, even if its contributions are not always clear (Corvellec et al., 2022). Because of its quick diffusion, the concept of CE is increasingly used by diverse stakeholders, making unclear its definition and contours (Ghisellini et al., 2016). Based on an analysis of 114 definitions, Kirchherr et al., (2017, p.229) propose their own: “economic system that replaces the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes” that operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation) with sustainable objectives. The application of geographic economy and spatial planning can, in particular, facilitate the acquisition of insights into the macro perspective of the CE, to close the loops, but the geographical issues of CE have long been ignored (Bourdin and Torre, 2024).

In practice, CE has been promoted by the European Union, by several national governments, and by many businesses around the world for more than a decade (Korhonen et al., 2018). Thus, the "new Circular Economy

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Action Plan For a cleaner and more competitive Europe" adopted by the European Commission in March 2020 is part of continuity concerning regulatory action to support a change of economic practices towards a sustainable way. The 2008 directive on waste management had already integrated it into a circular economy perspective.

In the academic field, there are thousands of publications and dozens of journals on CE (as the present one) in different disciplines (economy, but also management, natural sciences, engineering, etc.). Several bibliometric studies have taken stock of the contribution made by these publications, focusing on CE in general (Alcalde-Calonge et al., 2022, Goyal et al., 2021, Ruiz-Real et al., 2018; D'Amato et al., 2017), or with a specific focus, eg. The link between CE and sustainability (Schöggl et al., 2020) or industry (Hora et al., 2023). While the number of themes is increasing, waste management and recycling remain one of the most important (Schöggl et al., 2020), revealing that it is still a major issue.

Economic geography (EG) is a discipline that primarily concerns itself with the location and connectivity factors of economic activities. It has evolved, in part, into environmental economic geography (EEG), which is concerned with resources and environmental effects of R&D, production, trade, and other aspects of the economic cycle (He, and al., 2022; Hayter, 2008). One of the key objectives is to gain insight into the environmental impact and/or contributions of diverse economic activities at the city and regional levels - depending on their economic structure, stakeholders' action, etc. Thus, EG can explain the existence of local disparities in the context of climate and environmental challenges. More specifically, concerning CE practices, EG has elucidated the role of geographical and organized proximity in facilitating resource sharing, innovation in recycling technologies, and the development of local and regional policies (Arfaoui et al., 2024; Chembessi et al., 2024). We think that EG could also provide a framework for assessing the differentiated socio-economic impacts of CE (and potential) new inequalities. Our article sheds some light on this issue.

Does EC prompt a re-evaluation of the relationships between territories, with a particular focus on the dynamics between major urban centers and their hinterland? If so, how? To answer these questions, we use the core-periphery model and direct our analysis towards the subject of waste treatment in France. By seeing waste as a resource, at the end of the chain, to close the loops, CE helps transform what was previously regarded as a scrap into a catalyst for local economic activity.

This study mobilises a central concept in economic geography, as well as spatial analysis methodologies, to analyse the influence of CE on territorial relations. It is based on a case study of waste management in France, utilizing an original database from the National Pollutant Release and Transfer Register.

2. Theoretical Background

2.1. The core-periphery model, "core" of economic geography

The core-periphery model has long been employed in the social sciences as a means of elucidating disparities between places and/or social groups. Among the theoretical concepts of economic geography, this model remains one of the most frequently used frameworks for studying economic disparities between regions. The model analyzes the imbalanced relationships between central places and their hinterlands, which can be observed at the local level between the urban core and rural and surrounding areas, as well as at the global level between northern and southern regions.

From neoclassical approaches to recent theories of regional development, research conceptualises and measures the socio-economic asymmetries between areas. To illustrate, Friedman's core-periphery model (1967) posits that knowledge and innovation are attributes of the core, whereas backwardness and dependence are attributed to the periphery at all geographical scales. Similarly, regional development theories in economic geography draw on the fundamental work of Porter (2000) on clusters, Perroux (1955) on growth poles, and Freeman and Lundvall (Freeman, 1995; Lundvall, 1995) on models of national innovation systems. Such approaches facilitate a more nuanced comprehension of the heterogeneous development processes that are shaped by innovation dynamics. In the view of Shearmur (2017), innovation is invariably regarded as emerging or being produced in large cities, which are regarded as clusters (the core), with the periphery being regarded as residual spaces. Three narratives have been developed to explain these unbalanced relationships over time: 'no innovation in the periphery', 'innovation despite the periphery', and 'innovation because of the periphery' (Glückler et al., 2023).

In Krugman's model (1991), it is assumed that industries will locate in a single place, taking into account the trade-off between economies of scale, which generate concentration, and transport costs, which favour dispersion. The context of low transport costs favours a circular process whereby industries seek locations where local demand is strong, while local demand is further reinforced by the presence of numerous industries in the area. Large markets, such as metropolitan areas, derive benefit from this process and become progressively "cores". These discrepancies between the core and the periphery are contingent upon immaterial and material flows of resources from the peripheries to the core economies (Tonts et al., 2013), which in turn engender political, cultural, and technological dependence for peripheries (Mytelka, 1978). The model proposed by Krugman and the subsequent developments in new economic geography have been effectively employed to elucidate and comprehend the phenomenon of global metropolisation.

The core-periphery model, therefore, has a long history and has been the subject of extensive research and regional policy in the European Union (Barca, 2009). It remains efficient for comprehending unequal dynamics of regional development. A significant part of scientific research in economic geography is devoted to quantifying economic redistribution from metropolitan areas to the peripheries. Despite the solidarity fostered by the flows of wealth between these areas (Davezies, Talandier, 2014), unbalanced relations still exist, as shown by empirical research on places that have been left behind (MacKinnon et al., 2022) or the pitfalls of development (Diemer et al., 2022). Recent developments in evolutionary economic geography have brought a dynamic perspective to the traditional core-periphery model, emphasizing that spatial economic structures are not static but shaped by long-term processes such as institutional change, innovation diffusion, and path dependence. Rather than viewing core and peripheral areas as fixed entities, this approach underscores their mutual co-evolution over time. For instance, Capello and Lenzi (2018) highlight how regional innovation systems evolve differently depending on their historical and institutional contexts, reinforcing or mitigating core-periphery dynamics. Similarly, Chu and Hassink (2023) argue that the application of a critical spatial ontology within evolutionary frameworks enables a more nuanced understanding of spatial inequality and agglomeration processes. These contributions suggest that integrating an evolutionary lens into the discussion of core-periphery relationships enhances our ability to account for spatial transformation and regional differentiation in economic geography.

2.2. Geography of waste management in a linear economy

In the field of waste management geography, two models are typically employed to elucidate the mechanisms of regional development, waste production, and alterations in territorial disparities. Firstly, in economic geography, waste management is often analysed using the Kuznets environmental curve. This is a hypothetical relationship between various indicators of environmental degradation and economic dynamics. The Kuznets curve has received considerable attention for its ability to elucidate the interrelationships between per capita income and waste production at the regional or national level (Dinda, 2004; Mazzanti et al., 2012; Bao & Lu, 2023; Gui et al., 2019). The model postulates a positive correlation between the two variables up to an inflection point, beyond which the curve inverts and seeks to identify the explanatory factors. When a country reaches a certain level of wealth, the negative impacts on the environment start to decrease. This occurs because the country now has sufficient financial, technological, and institutional resources to better protect the environment and invest in cleaner technologies. However, this relationship is increasingly questioned. Many studies show that high-income countries often reduce local pollution by outsourcing polluting industries abroad (Copeland & Taylor, 2004; Cole, 2004). Moreover, while the Kuznets curve may apply to local pollutants, it does not hold for global and persistent issues such as CO_2 emissions or biodiversity loss (Stern, 2004; Dinda, 2004). In addition, the 'new toxics view' suggests that the substitution of new chemicals for existing pollutants can lead to a positive relationship between economic growth and environmental degradation

(Stern, 2004). The curve also overlooks social and territorial inequalities: environmental improvements often benefit central regions, while peripheral areas bear residual pollution (Boyce, 1994; Martinez-Alier, 2002). Therefore, this Kuznets curve should be viewed as a context-dependent hypothesis, not a universal pattern.

Secondly, the core-periphery model has been powerful in understanding the spatial relationships generated by waste management at two levels. At the sub-national level, the objective has historically been to relegate waste management to the outskirts of urban areas (Berdier & Deleuil, 2010). Consequently, the core-periphery model has been instrumental in elucidating the interrelationships between urban and rural areas. At the international level, waste flows between countries, with illegal trade and landfill from developed to developing countries leading to relationships of domination, despite the existence of regulatory mechanisms designed to limit them. Wastes are secondary resources for lower-income countries; harvesting them is a significant economic activity, and consequent resource recovery is a key part of the global economy (Gregson and Crang, 2015; Gregson, 2023).

The reintegration of waste into circular loops can shake up this geography and invite us to re-examine these classic core-peripheries relationships.

2.3. Waste management as a pillar of the circular economy

EC places significant emphasis on the reduction of waste, the reuse of materials and the recycling of resources. This approach is designed to minimise environmental impacts and promote sustainable economic growth (Geissdoerfer et al., 2017; Hachaichi and Bourdin, 2023). The objective is therefore to reduce the necessity for new resources and to close the loop in the utilisation of products and materials, to transition from a linear economy to a circular one.

According to the definition of the French Agency for Ecological Transition, waste management is one of the three pillars of EC (with the offer of economic stakeholders and the consumer demand). To support changes in this field, already well-established, the European Waste Framework Directive (WFD) (2008) defined the waste hierarchy, and since 2016, it has been included in the Sustainable Development Goals (SDG). In terms of priority, the recommended order for waste management and treatment operations is as follows: prevention, preparation for reuse, recycling, other forms of recovery (including energy recovery), and disposal. Energy recovery through incineration is regarded as a superior alternative to disposal, yet it is accorded the lowest priority in a circular economy, given that it contributes to the single-use of materials (Potting et al., 2017). While prevention is arguably the most effective means of achieving a more environmentally virtuous economy (lower consumption, eco-design, etc.), waste management is nevertheless a crucial aspect in organising reuse, recycling, and energy recovery. Consequently, in the long term, disposal operations are likely to diminish or even disappear, with the preceding stages becoming the dominant approach.

Recent research has underscored the significance of spatial and territorial considerations in the context of the EC, long overlooked (Bianchi and al., 2022; Bourdin and al., 2021; Bahers and al., 2022). Several factors have been identified as key influence on the attainment of the sector's economic and environmental objectives (Arfaoui and al., 2024). In particular, proximity and territorial governance (Chembessy and al., 2024; Bolger and Doyon, 2019) have emerged as pivotal elements in the advancement and growth of this economy (Niang et al., 2020; 2024). Six territorial factors have been identified by Tapia et al. (2021): (1) structural factors related to material endowments; (2) agglomeration factors; (3) proximity, accessibility, and connectivity factors; (4) access to advanced technologies; (5) knowledge; and (6) governance. They argue that urban and industrial agglomerations represent the most important carriers for an integrated and organized circular economy. Nevertheless, seeking to understand the operationalization of the "proximity principle" (promoted by EC legislation, and longer ago for waste management), Bahers and al. (2017) highlight six interpretations of proximity: spatial, interpersonal, organizational, environmental, politico-administrative, and socio-economic. These proximities reflect various dimensions—ranging from geographical distance and institutional coordination to social trust, local development goals, and industrial logic—that shape how actors implement circular economy practices at different scales.

Thus, the advent of "circular territorial ecosystems" has opened up new avenues for policy-makers and researchers alike (Bourdin and Torre, 2024), but the question of the transformation of the geography of waste management due to the rise of CE remains open.

2.4. Critical views about circular economy practices

In a circular economy perspective, waste is no longer conceived solely as a residual output but increasingly as a potential resource (Gregson et al., 2015; Ghisellini et al., 2016). However, this reframing remains highly uneven across spaces and waste types. The localization of waste treatment infrastructure—particularly for more polluting or hazardous forms of waste—continues to follow logics of negative externalities, often displacing environmental burdens toward peripheral or less politically influential regions (Zorpas & Lasaridi, 2013). These spatial decisions reflect cost-benefit rationalities that prioritize minimizing nuisance and resistance, rather than fostering local circular ecosystems. In this sense, the current organization of waste flows and facilities may act as a structural barrier to the transformation of core-periphery relations. While urban centers accumulate the technological and institutional capacity to valorize certain waste streams, peripheral territories often bear the material costs of a system that still largely externalizes the dirty side of circularity (Lepawsky, 2015).

The classification of waste as "recoverable" or "non-recoverable" is not purely technical; it is shaped by legal, economic, and territorial considerations (Hultman & Corvellec, 2012). For instance, recyclable plastics or metals are often deemed valuable due to existing markets and regulatory incentives, while contaminated organic waste or certain industrial by-products are excluded from recovery schemes, despite their potential. These distinctions are also spatialized: urban areas tend to concentrate high-value waste streams and the infrastructures capable of processing them, whereas rural or peripheral zones receive lower-value or hazardous waste, with limited capacity for local valorization. Zapata Campos & Hall (2013) emphasise how the notion of waste, and the narratives and discourses associated with it, have been socially constructed with corresponding implications for waste governance and local waste handling practices. This asymmetry reinforces spatial inequalities in how the "resource" potential of waste is distributed and recognized, complicating the inclusive implementation of circular economy principles.

While the circular economy is often presented as a sustainable alternative to the traditional linear economy, several researchers caution against an overly idealistic or simplified view of this model. This 'umbrella concept', as Blomsma and Brennan (2017) have named it, is the subject of debate. For instance, Bahers (2014) highlights that the circular economy concept sometimes overlooks the material and geographical limitations of recycling loops, concealing material flows that remain highly energy-intensive and polluting. Similarly, Desvaux (2017) emphasizes that the circular economy, as a dominant institutional and political discourse, risks serving as greenwashing for unchanged industrial practices, relying primarily on technological innovation without questioning consumerist logic or underlying socio-economic dynamics. Thus, focusing on recycling and energy recovery from waste may obscure the imperative to drastically reduce consumption and hinder a profound reevaluation of existing economic models. These authors therefore call for a critical reflection on the real conditions for implementing the circular economy to prevent it from becoming a strategy of avoidance in the face of the urgency of a genuine ecological transition.

2.5. Hypothesis

The core-periphery model could provide a valuable analytical framework for understanding the spatial logics underpinning waste management systems. Urban centers, as hubs of economic activity and consumption, are the primary generators of waste, while peripheral areas—often rural or less densely populated—tend to host waste-related infrastructures such as landfills, incinerators, and sorting facilities. This spatial distribution reflects a pattern of externalizing environmental burdens to the margins, frequently driven by asymmetric power relations between territories (Gregson & Crang, 2010). Although simplified, the model highlights dynamics of environmental injustice and territorial inequality, particularly in terms of access to infrastructure, exposure to environmental risks, and participation in decision-making processes.

In a context of ever-increasing promotion of the circular economy, this paper examines the geography of waste treatment and relationships that it creates between territories. Is the increase in waste recovery creating new disparities between urban centres and their peripheries?

To respond to our question, we formulate three hypotheses, testing three territorial factors of CE highlighted by Tapia et al. (2021):

Agglomeration or size effect hypothesis: The capacity of territories to implement a CE approach is contingent on their size (bigger production and treatment capacity linked to availability of financial and technical resources). Urban centers (cores) would be well placed to host waste recovery centres.

Geographical proximity effect hypothesis: Spatial proximity would remain determinant in organising the waste circulation between cores and peripheries.

Structural effect hypothesis: The type of treatment implemented in spaces is influenced by the type of waste that they treat (technological issues). These structural effects could reinforce territorial disparities.

3. Data and methods

The present study is based on the French case. In 2020, France adopted an anti-waste law for a circular economy, which included several quantitative targets. These are as follows: the end of disposable plastic by 2040; 10% of reused packaging on the market by 2027; a 50% reduction in food waste in the catering and agri-food sectors by 2030; and so on. Annually, France generates over 300 million tons of waste (including mineral waste), equating to approximately 5 tons per inhabitant (in line with the European average). 4% of waste produced is exported, while 96% is processed within the country. The production and treatment of this waste is not uniformly distributed across the country. This section presents our original database on waste treatment (3.1), the scale and spatial classification we use to analyse the core-periphery relationships (3.2), and the methods (3.3).

3.1. The construction of a waste treatment database

The Pollutant Emissions Register in France (IREP) provides annual open data on pollutant releases and transfers, as well as on waste produced and treated by facilities classified for environmental protection purposes or by operators of urban water treatment plants. Among the available data, we focus our analysis on facilities reporting that they treat waste, whether household or from economic activities (eg. incinerators, recycling plants, etc.). The database is more complete than for waste production (because of the concentration of treatment activity between a smaller number of units), and this avoids double-counting (the inclusion of waste produced by establishments that process waste). For our analysis, we selected five types of variables giving information on the location of the establishment, the sector classification of the establishment, the geographical origin of waste, the type of waste, and the waste treatment (Table 1). Regarding the latter two, we proposed our classification to increase the analytical scope of our study (see respectively Appendix A and B to obtain information about the construction of our classification).

Table 1. Variables available in the database (source: authors)

Object	Variable	Source
Location of the establishment	X, Y coordinate	IREP
Sector classification of the establishment	NACE code (615 classes)	IREP
Geographical origin of waste	Department and country code	IREP
Type of waste	Waste Code	IREP
Waste treatment	Treatment code	IREP

About the types of waste taken into accountdata pertaining to minerals are excluded, given that the mechanisms involved are already well documented and relatively well known by local stakeholders. The subject of numerous scientific studies (Amarasinghe, 2024; Geldermans, 2016; Bastin, 2023; Augiseau and Barles, 2017) and studies carried out by consultants for local authorities, the aim of these studies is to improve the circularity of management, for example through urban mines (Krause and Hafner, 2022 ; Kleeman, 2016). This waste is extremely heavy, inexpensive and therefore never travels long distances. Mineral waste generated by urban centers is processed locally, in periurban and rural areas.

We are therefore focusing our analysis on all other types of waste, organised into 12 classes: Chemicals, Metal, Glass, Paper and cardboard, Rubber, Plastic, Wood, Textile, Animals and plants, End-of-life equipment, Mixed, Other.

Based on the treatment code, we focus on 3 categories of treatment:

- Material recovery (eg. recycling, spreading on the ground for plant materials)
- Energy recovery (eg. methanization, heat network)
- Disposal (eg. storage, incineration)

Thus, our database provides information on the type of waste, the type of treatment, and the department of origin of the waste streams processed in each facility for the year 2022. With 62 million tons studied, the database covers almost 75% of all dangerous and non-dangerous waste treated in the country, excluding construction waste and sludge. Not all tonnages are included, as not all companies are covered by these annual declarations. The discrepancy can be attributed to two factors. Primarily, the database is reliant on company-submitted declarations, which may be susceptible to inaccuracies. To address this, a comprehensive cleaning, consolidation, and completion process was undertaken, aligning with the guidelines set forth by the French Agency for Ecological Transition (ADEME, 2020). Secondly, unclassified establishments are not legally obligated to declare the waste they process.

3.2. Scale and spatial classification to analyze the core-periphery pattern

Given the very large number of municipalities in France (more than 34,000 in 2024), and the institutional responsibilities for waste management, we define our spatial scale of analysis at the inter-municipal scale (or EPCI for public establishments for inter-municipal cooperation). By Article L. 2224-13 of the French General Local Authorities Code (CGCT), and in light of the 2015 New Territorial Organisation of the Republic law, the management of household and similar waste is a mandatory responsibility of inter-municipalities. This responsibility may be transferred to a syndicate for the entirety of waste collection and treatment, or solely for the operations about treatment and its associated processes (article L. 2224-13 of the CGCT). At the request of EPCIs that wish, the department may assume responsibility for treatment and related transport operations through the establishment of an agreement. There are 1232 inter-municipalities in France. On average, they count 50,000 inhabitants, but they are highly diverse from 6000 inhabitants (including only 4 municipalities) to 7,000,000 inhabitants (with 130 municipalities in the case of Grand Paris).

To analyze the core-periphery relationship through waste treatment, we operate in two steps to obtain a spatial classification of these inter-municipal areas. Firstly, we use the number of inhabitants of each area (urban inter-municipalities are more populated than rural ones). Secondly, to enhance the precision of our analysis, we combine the number of inhabitants with the functional areas zoning produced by the French National Institute for Statistics and Economic Research (INSEE) to obtain four categories of inter-municipalities (Table 2 - map available in Appendix C). A functional area is a group of municipalities, in one piece and without an enclave, made up of a population and employment centre, or urban pole, and surrounding, peri-urban municipalities, where at least 15% of the working population works in the hub. Functional areas are classified according to the total number of inhabitants in the area.

Table 2. Classification of inter-municipalities (source: authors, data from INSEE)

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="3">The majority of the population of the inter-municipality is part of a functional zone which has:</td></tr>
<tr><td>More than 200000 inhab.</td><td>Between 50 000 and 200000 inhab.</td><td>Less than 50 000 inhab.</td></tr>
<tr><td rowspan="2">The inter-municipaliy</td><td>Includes the city center of the functional zone</td><td>Urban center (48)</td><td>Small and medium sized towns (107)</td><td rowspan="2">Rural (729)</td></tr>
<tr><td>Doesn’t include the city center of the functional zone</td><td>Periurban (348)</td><td></td></tr>
</table>

These 4 types of area can be seen through a core-periphery gradient:

- Urban center: main core;
- Periurban: periphery spatially close to core;
- Small and medium-sized towns: more hybrid status, periphery to the urban centre but core to rural areas;
- Rural: periphery of all other categories.

Figure 1 corroborates the positive correlation between the four types of area and the population, while also elucidating the core-periphery relationships that connect them.

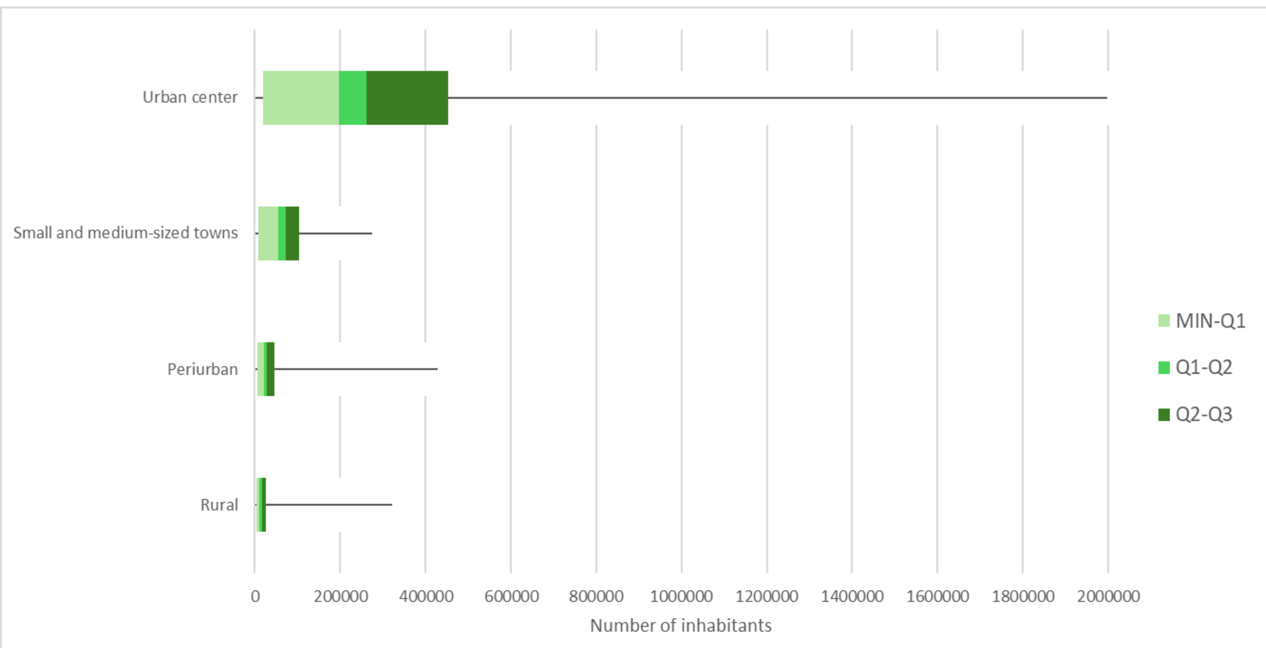

Figure 1. Number of inhabitants by type of areas (source: authors, data from INSEE)

3.3. Methodology

Massive geographic and origin-destination flows data analyses are always a challenge due to the complexity of the phenomenon to study and the high dimensionality of the data reflecting it (Andrienko et al. 2017). Here, three different methodological approaches are implemented to analyze the geographical patterns of the waste treatment.

Following the initial hypothesis (agglomeration effect), the total quantity of waste treated is proportional to the number of inhabitants of inter-municipalities. As the population increases, the amount of waste treated also rises. This relationship is quantified through the utilisation of a log-linear regression model, wherein the volume of waste is correlated with the population of the inter-municipalities.

$$log\ (Mi)\ = \alpha\ log\ (Pi) + b$$

In this context, Mi represents the aggregate quantity of waste treated by each inter-municipality, while Pi denotes the number of inhabitants. The objective of this preliminary model is to elucidate the hypothesis regarding the relationship between area population and waste, conceptualised here as a potential resource for the circular economy. Furthermore, the relationship can be refined according to the type of treatment. The hypothesis is that major urban centres, due to their financial resources and the quantities of waste they treat, have an advantage over the peripheries in terms of waste recovery. Conversely, the question of waste disposal in peripheral areas arises. The analyses focus on waste from households and activities. Although industrial waste production is not strictly correlated with population size, the spatial allocation of treatment infrastructure is often influenced by the availability of technical expertise, energy demand, and regulatory oversight — factors more prevalent in urban areas. Furthermore, the study of deviations from the model allows us to identify and discuss cases for which this relationship is not necessarily observed. The analysis of the model's residuals allows for the identification of areas that are over-represented and under-represented in relation to their population. The analysis of residues is detailed according to the four categories of territory presented above.

The second hypothesis (spatial proximity effect) is tested using a geographical method known as the gravity model, which assumes that a regional system comprising populated areas in close proximity encourages exchanges between the two geographical entities in question. This approach thus introduces the distance of flows between inter-municipalities. The study of waste flows is conducted using a gravity model in which the relationships between two locations are proportional to the volumes of waste processed in the departure and arrival locations, and inversely proportional to the distance separating them. A more precise adjustment of the role of distance is obtained with a Pareto form of the gravity model (Baccaïni and Pumain, 1998).

$$Fij = Mi.Mj.D_{ij}^{\alpha}$$

Where Fij is the predicted flow between area i and area j (with i $\neq j$). The inter-municipality j receives and processes waste from department i. The origin of the waste is only available at department level. Mj corresponds to the tons of waste treated by the inter-municipality j, while Mi corresponds to the tons of waste treated by department i.

Dij is the euclidean distance between i and j , and α a parameter expressing the dissuasive effect of the distance. The model is computed with a Poisson generalised linear regression (Flowerdew and Aitkin, 1982):

$$log\ (Fij)\ =\ \beta 0 + \alpha\ log\ \ (Dij)\ +\ \beta 1\ log\ \ (Mi) +\ \beta 2\ log\ \ (Mj)\ +\ \varepsilon$$

All variables in the model are significant. The model acts as a filter to highlight repellent and desire lines where waste flows are less or more numerous than expected based on the distance and the amounts at both origin and destination. We cross-reference these results with our four functional categories to complete the analysis.

The third hypothesis introduces the structural effects, as the method of treatment is partly determined by the type of waste (eg. metals are recycled much more than chemical waste – see Appendix D). Inspired by the shift-share analysis, widely used in economic geography, we isolate the role of waste structure in rendering a particular (under)performance or (under)specialisation for each treatment and for each four territorial categories. Shift-share analysis is a decomposition technique widely used in regional studies to identify sectoral effects - the one resulting from the sectors' weights in the economy and the other from the sectors' growth rates - leading to inequality in employment growth across regions (Murray 2010). We adapt this method to our data and the subject of our article, by considering:

The national effect as the treatment rates per waste item on a national scale.

The waste mix effect as the proportion of treatment attributed to a specific type of waste in a given area. It is equivalent to the theoretical rate observed in the local area if the same treatment rate per type of waste as at national level were applied.

The local share effect as the proportion of change attributable to regional influences. It is equivalent to the actual change in the regional variable, minus the preceding effect.

$$Nij = T\,i * Wj$$

$$Rij = ti * wj$$

$$TRij = (wj * TiWj)$$

$$LRij = TRij - Rii$$

$$i = 1 \text{ to } 3 \text{ (type of treatment, Appendix B)}$$

$$j = 1 \text{ to } 12 \text{ (type of waste, Appendix A)}$$

Where N*ij* is the national rate or national effect, with R*i* is treatment rates by D*j* = type of waste. R*ij* corresponds to the regional type of treatment (t*i*) by type of waste (w*j*). TR*ij* is the theoretical rate of treatment or waste mix effect, and, LR*ij* the local share effect.

4. Results

Following the presentation of descriptive statistics on waste treatment and its geographical distribution, we discuss the results obtained by following our three hypotheses, which are associated with the three methodological stages.

4.1. Breakdown of waste treatment by type of area

One-third of waste is disposed of, while the remaining two-thirds is recovered in the form of materials (35%) or energy (32%) (Table 3).

Table 3. Volume of waste for each operation of treatment (source: authors, data from IREP).

Operation of treatment	Quantity concerned (thousands of tons/year)	Share (%)
Material recovery	17 302	35 %
Disposal	16 464	33 %
Energy recovery	16 171	32 %
Total	49 933	100 %

The type of treatment varies greatly depending on the type of waste (Appendix D):

Metal waste (100%), glass (98%), paper and cardboard (96%), disused equipment (97%), and to a lesser extent, plastic (76%), animal and vegetal (76%), rubber (61%) are totally or mainly subject to material recovery.

Wood is equally recycled (50%) and used for energy production (50%)

Mixed waste is more disposed (49%) than used for energy production (42%), like other waste (respectively 60% and 37%).

But as the volume of different types of waste differs widely, they more or less “feed” the three treatments. Almost all the waste disposed of is mixed waste (90%). Material recovery is largely composed of animal and vegetable waste (30% of total volume), metal waste (18%) and mixed waste (15%). Energy production is mainly fueled by mixed waste (80%), followed by animal and vegetable waste (10%).

Geographically, the database contains 1,861 treatment facilities in France, distributed across 676 intermunicipalities. Consequently, 54% of intermunicipalities have at least one treatment unit, with the proportion varying considerably depending on the type of area:

- 100% of urban centres are equipped;
- 85% of small and medium-sized towns;
- 57% of periurban areas
- 46% of rural areas.

Furthermore, the treatment capacity of equipped areas exhibits considerable variation, from 0.001 to 775,865 tons of waste treated annually. 34% of waste is treated in urban centres, 26% in rural areas, 25% in periurban areas and 15% in small and medium-sized towns.

If we consider spatial repartition in terms of types of treatment, two-thirds of waste disposed of is made in periurban and rural areas and half of waste destined to recovery (either for energy or materials) is in urban centres.

Spatial specificities can also be observed for different types of waste. 40% of chemical waste, 44% of metal waste and 56% of disused equipment are treated in urban centres. Rubber and paper and cardboard waste are mainly treated in periurban areas (41% and 33% respectively), and to a lesser extent in rural areas (34% and 32% respectively). Rural areas process 70% of textile waste, 51% of animal and vegetable waste, 55% of plastic waste, 45% of wood and 42% of glass waste. In small and medium-sized towns, there is no specificity.

When we cross type of treatment, type of waste and type of spaces, we can see that the great majority of waste disposed of are mixed waste, disposed of in peripheries areas (either periurban or rural areas) (Figure 2). Regarding energy recovery, a very large proportion of waste is mixed waste recovered in urban and peri-urban areas (Figure 3). Animal and vegetal waste are widely used in rural areas for energy recovery (for them, they represent the same volume as mixed waste). For material recovery, spatiality is less clear. Animal and vegetable waste represent the biggest volume and are used in all types of areas, but in particular in rural areas. For material recycled, chemical, metal and disused equipment are mainly treated in urban areas but we can see that for these materials and even more for wood and glass, rural areas also stand out. Periurban areas and small and medium sized towns are more in intermediate situations.

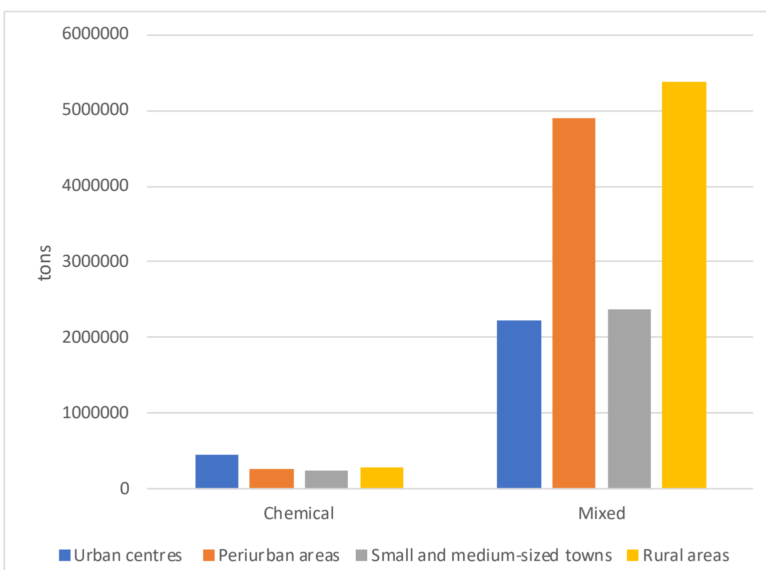

Figure 2. Volume of waste treated by type of waste and type of spaces for disposal (source: authors, data from IREP) (*NB: Chemical waste and mixed waste represent 98 % of the total waste treated.*)

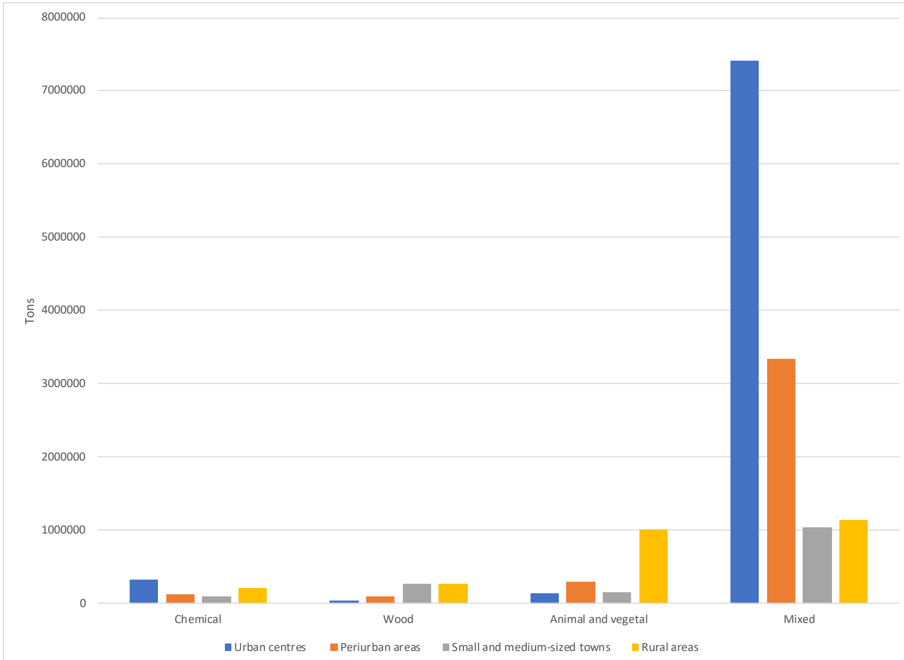

Figure 3. Volume of waste treated by type of waste and type of spaces for energy recovery (source: authors, data from IREP) (NB: *Chemical waste, mixed waste, wood, and animal and vegetal represent 98 % of the total waste treated.*)

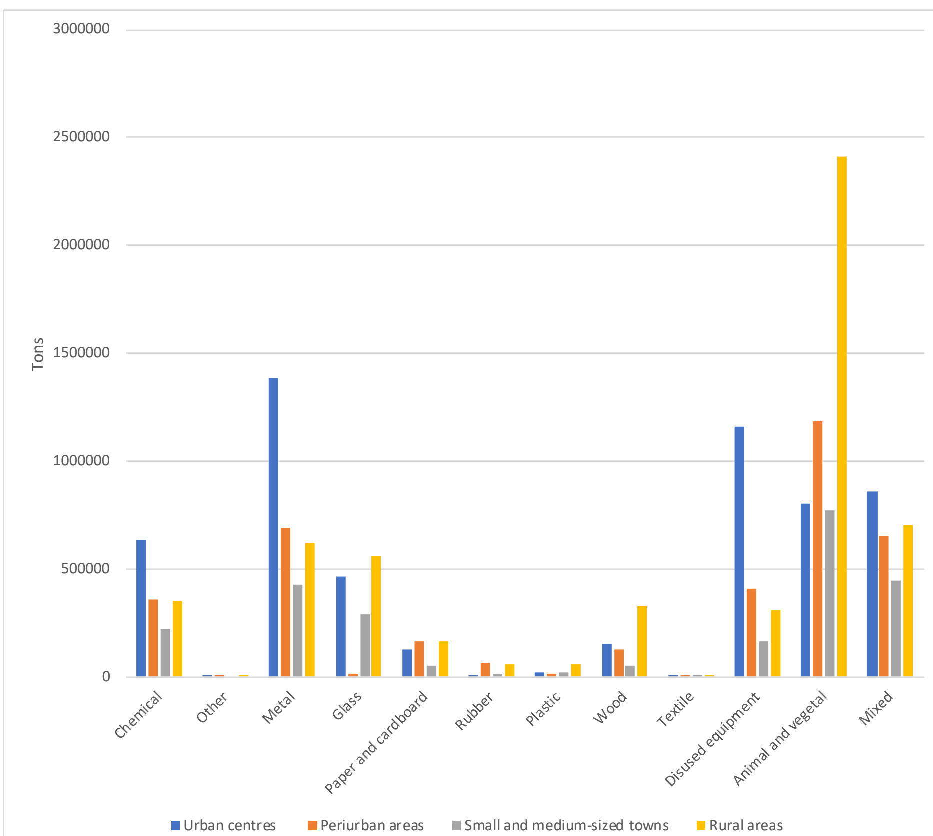

Figure 4. Volume of waste treated by type of waste and type of spaces for material recovery (source: authors, data from IREP)

4.2. The agglomeration effect on recovery capacity

The initial hypothesis posits that large urban centers, which are better equipped in terms of engineering and financial resources, but which also produce more waste, are the main treatment centers in terms of volume. This hypothesis is supported by an analysis of the three types of treatment (energy recovery, materials recovery, and disposal).

4.2.1. An agglomeration effect for energy and material recovery The waste management model demonstrates a hierarchy of inter-municipalities in terms of volume. While this is not the sole determining factor, the relationship is nevertheless significant. The agglomeration, measured by the number of inhabitants of the territory, accounts for nearly 18.5% of the total variance in waste management, and the dependent variable (quantity treated) is explained by the number of inhabitants (Appendix E).

Only 1% of inter-municipalities are responsible for treating 20% of the waste produced in France, and these are all urban centres. In order of ranking, the inter-municipalities responsible for processing the largest quantities of waste in France are those of Aix-Marseille-Provence, Grand Paris, Rouen Normandie, Lille, Lyon, and Roissy, close to Paris. The top ranking of Marseille, and the presence of Rouen, both of which are known in France for their productive profile, suggest that some industrial activities as chemical, metallurgy, or oil and gas sectors, concentrated in both areas, are associated with significant waste processing. In both cases, France has encouraged exchanges between companies in business parks, creating well-defined hubs of activity. Concerning Roissy, the inter-municipality hosts major waste processing platforms, close to the international airport and the national market (wholesalers). Conversely, the smallest waste treatment facilities are located in rural municipalities or on the outskirts of small towns.

When we distinguish the type of treatment, for waste recovery, the results of regression models corroborate the correlation between the number of inhabitants of the area and its capacity to recover waste, whether in the form of energy or materials (Appendix F). Even if the model is verified and there is indeed a relationship between the quantity of waste treated and the number of inhabitants for energy and materials, the variance explained by the models remains low (<15%). The analysis of the regression line's slope can provide insights into the elasticity or scaling coefficient for various categories of waste. Scaling exponents (or elasticities) are below 1, that reveal a sublinear relationship between the volume of the recycling activity and city size, meaning a relatively higher concentration in smaller places, even if this trend is not very strong according to the low value of the R2. We note that the elasticity is higher for energy (0,967) than for material (0,691). Energy recovery is more sensitive to the size (population) of the inter-municipality. When large cities process waste, they derive benefit from it, particularly as an energy resource, thereby contributing to the circular economy. Conversely, there is no notable correlation for disposal. Less populated areas are not systematic receptacles for waste disposal. The same findings are evident when population density is taken into account.

4.2.2. Analysis of residues for waste recovery Figure 5 illustrates the geography of deviations from the model. The data demonstrate that the inter-municipality Grand Paris is under-represented in comparison to its population. This can be explained by the concentration of waste management in different facilities in the second ring of Paris (eg. Roissy, Val d'Essonne, Coeur d'Yvelines). Except Rennes and Tours, all other major urban centers in France exhibit a positive residual. In the northern half of France, a considerable number of small and medium-sized and rural inter-municipalities process substantial quantities of waste relative to their respective populations. In the southern part, where industrial economic activities are less prevalent, these types of inter-municipalities exhibit a net negative balance in waste management.

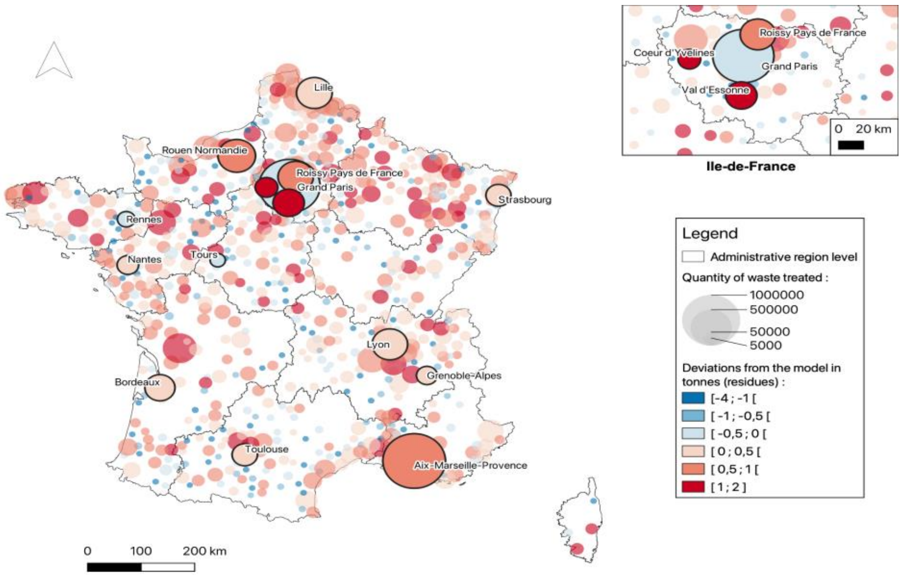

Figure 5. Regression model residuals from linear model between the volume of waste treated (Mass-Mi) and size of cities (Population-Pi) (source: authors, data from IREP)

4.2.3. Analysis of residues for energy recovery It's admitted that energy recovery is a technique that is particularly well suited to large urban centers in Europe (Calisto and al., 2023; Williams, 2022), because of their urban form and density (Talandier, 2018). In France, this is the case, for example, in Paris, Bordeaux, Marseille, Lyon, and Grenoble (Figure 6). In particular, it is used to supply district heating networks, which benefit the local population. Where known, we specify the type of energy recovery (e.g., heat networks, industrial steam production, biomethanisation). However, in many cases, the database does not allow for a distinction between these modes. Interpretations are therefore supported by secondary sources or known regional case studies by the authors.

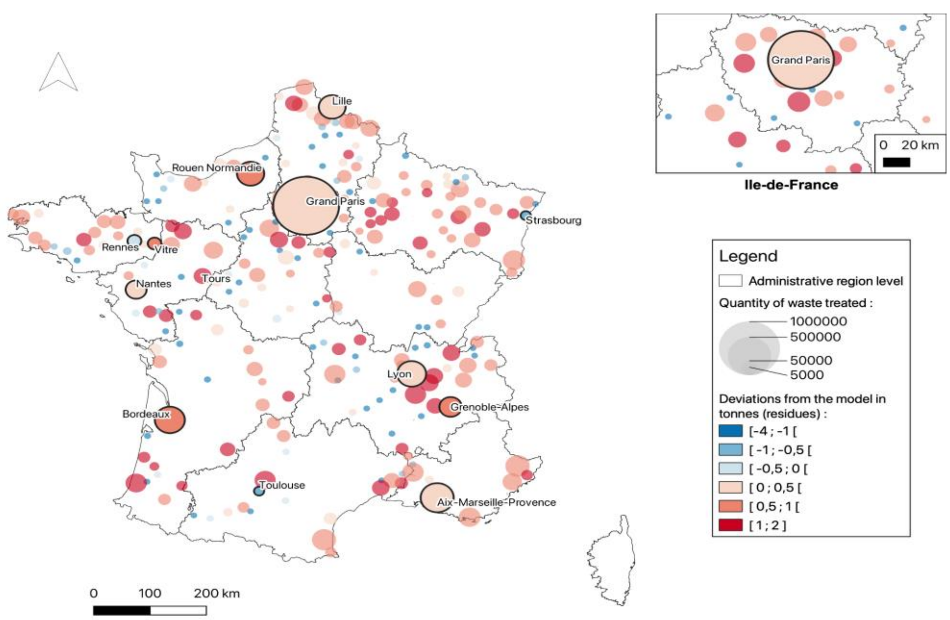

Figure 6. Regression model residuals from linear model between the volume of waste used for energy recovery (Mass-Mi) and size of cities (Population-Pi) (source: authors, data from IREP)

On the one hand, the analysis of residuals by type of area type (Appendix G) confirms that positive deviations from the model are over-represented in urban centres and also in periurban areas, even if it's not significant in the second case (Chi test). This type of recovery is therefore more developed in urban areas, including when we look at the residues of the model. The potential for expanding existing heating networks has been highlighted by a French public organization (Cerema, 2024). This potential partly relies on energy recovery from household, tertiary, and industrial waste. The publicly available maps provided by Cerema confirm the opportunities for implementing such projects in urban and peri-urban areas.

On the other hand, negative residues are over-represented in small and medium-sized towns and rural areas. The result is significant for small and medium-sized towns (SMS), but not for rural areas. This may be regarded as a potential resource that is not yet being fully exploited in these areas, particularly in the case of SMS towns. The gap is smaller in rural areas, which appear to be better equipped than SMS towns. Indeed, the use of waste for energy represents an opportunity for rural areas, particularly in conjunction with the continued prominence of agricultural and rural industrial activities (Gros-Balthazard and Talandier, 2023). The number of bio-methane projects, which are often subject of controversies (Dobers, 2019 ; Mazzanti and al., 2021; Bourdin, Delcayre, 2024) is growing. These results may also be linked to the fact that the French Agency for Ecological Transition provides significant funding for methanisation projects in rural areas. Other explanations can be found in energy recovery by industrial companies. For example, SAICA PAPER, a company located in a rural area in the Auvergne-Rhône-Alpes Region, needs a large amount of steam to produce recycled paper (Talandier et Loisel, 2025). To guarantee its supply while reducing its dependence on fossil fuels, the company built a waste-to-energy unit. The project was then carried out in collaboration with the local authorities, creating a network to supply heat to neighboring buildings.

4.2.4. Analysis of residues for material recovery The distribution of materials recovery units demonstrates a regional effect (Figure 7). The data indicates a notable concentration of materials processing units in the north-west (eg. Rouen), the north (eg. Dunkerque and Lille), and the north-east (eg. Ouest Vosgien). These areas of concentration align with regions that have developed industrial specialisation in metallurgy, manufacturing, chemicals, and wood. In the southern part of the country, the Aix-Marseille-Provence inter-municipality is notable (and relatively isolated) for the considerable quantities of materials it processes, which are linked to its industry.

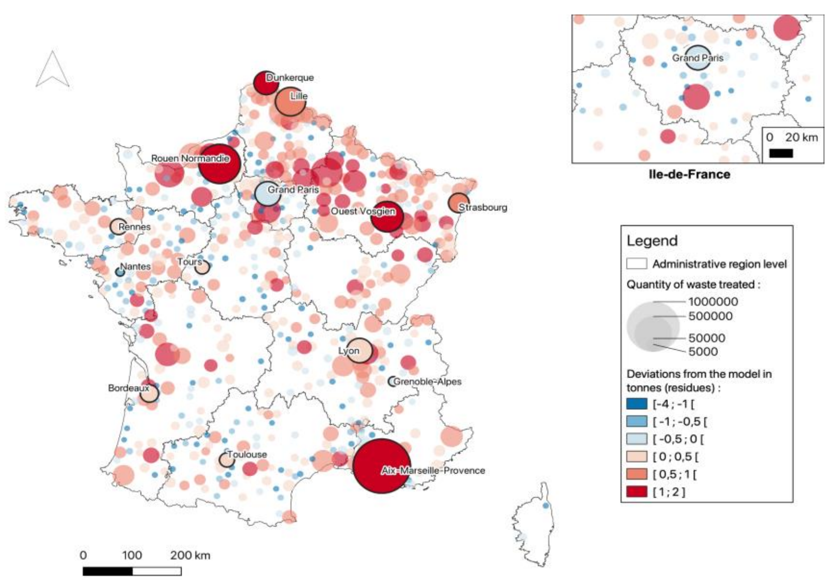

Figure 7. Regression model residuals from linear model between the volume of waste destined for material recovery (Mass-Mi) and size of cities (Population-Pi) (source: authors, data from IREP)

The results can be refined by cross-referencing the residues by type of zone (Appendix H). The results indicate that urban centres are now over-represented in negative terms, while periurban areas are over-represented in positive terms. In small towns and rural areas, there is no over-representation of positive or negative residues. Therefore, depending on the case and in particular on the region and its industrial specialisation, rural areas or small and medium-sized towns may also host this type of treatment unit.

4.3. The geographical proximity effect on recovery capacity

Our second hypothesis concerns the role of proximity in core-periphery interactions drawn by waste flows (Fij). Only the departmental origin of the waste (i) managed in the intermunicipalities (j) is known. The database indicates that 65% of the waste flows managed by the intermunicipalities originate from the same department, situated within a radius of less than 40 km. For urban centres, this proportion rises to 81% for energy recovery (Appendix I). Given the considerable volume of waste produced and the associated costs of transportation, geographical proximity, defined as the act of being situated in close geographical proximity to another entity (Torre, 2008, 2014), is determinant. However, Arfaoui and al. (2024) have also demonstrated that other rationales may prevail in certain circumstances, such as costs of treatments, removal of polluting waste… In several cases, waste treatment flows reflect not only geographical proximity but also institutional or organisational proximity (Torre & Rallet, 2005; Torre, 2014), through shared knowledge, values, and beliefs (Bahers and al., 2017). For example, public-private partnerships, such as those observed in Dunkirk or Fos-sur-Mer, structure inter-firm waste exchanges. These clusters, supported by the French government, act as hubs that transcend strict core-periphery logic. The gravity model we are currently testing concerns extra-departmental flows and enables us to reveal other forms of geographical proximity on a regional scale, for example. Conversely, our results highlight the existence of national waste management systems for certain sectors, suggesting the prevalence of organisational proximity, also referred to as industrial proximity by Bahers et al. (2017).

Table 4. Distance of extra-departmental flows by type of treatment (source: authors, data from IREP and IGN)

	Energy recovery			Material recovery			Disposal		
Quartile	**Km**	**Q treated (kg)**	**%Q**	**Km**	**Q treated (kg)**	**%Q**	**Km**	**Q eliminated (kg)**	**%Q**
Ql	[0 to 98[	3273868	722	[0 to 125[	3303078	545	[0 to 99[	4404438	676
Q2	[99 to 167[	535373	118	[125 to 235[	1300735	215	[99 to 185[	1623026	249
Q3	[185 to 309[	509715	112	[235 to 387[	802541	132	[185 to 350[	363667	56
Q4	[350 to 870[	214535	47	[387 to 1085[	654043	108	[350 to 939[	127986	20
Total	85	4533492	1,000	170	6060397	1,000	91	6519117	1,000

Table 4 shows the distance differences of extra-departmental waste flows according to the types of treatment. Material recovery involves an average transport distance of 170 km, and 50% of the observed flows travel more than 235 km, representing a quarter of the total tonnage. Energy recovery and disposal take place closer to the source, with average distances of 85 km and 91 km. These figures can also be related to the distances travelled by waste type. Glass, for example, travels nearly 150 km when recovered outside the department, metal travels 114 km, and end-of-life equipment travels around 112 km (Appendix N).

4.3.1. A significant effect of geographical proximity The relationship between the mass treated of waste per zone (Mi and Mj), the distance separating them (Dij), and the quantity of flows they exchange (Fij), as measured by the gravity model, has been verified. This indicates a strong link between these variables. The model explains nearly 44% of the variance for disposal and 25% for energy or material recovery (see Appendix J). The analysis revealed that distance has a significant negative impact on all three types of treatment, while treatment volumes have a positive impact: waste tends to circulate nearby, even if it comes from another department.

Figure 8 shows the waste flows and allows for the identification of the specific geography of extra-departmental waste flow management in France. In contrast with the majority of studies on urban systems in France, based on non-material flows (Berroir and al., 2017; Davezies and Talandier, 2014; Halbert, 2006), our findings do not indicate a dominant, centralising effect of Paris on the remainder of the national territory. In this regard, the core-periphery relationship between the capital of France and the rest of the country, which is a defining feature of the French model, is not evident when considering waste management.

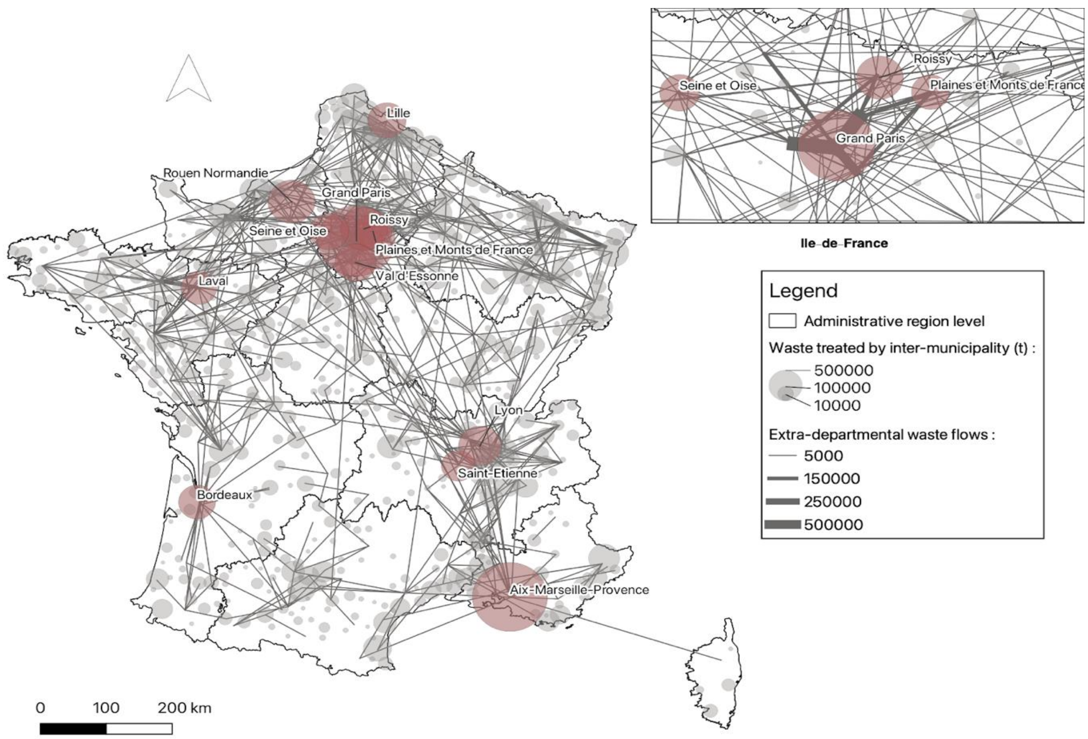

Figure 8. Volume of waste treated by each inter-municipality and extra-departmental flows of waste (over 5500 tons) (source: authors, data from IREP)

A geographical analysis of these flows by type of treatment reveals different types of proximity.

4.3.2. Energy recovery: geographical proximity and industrial opportunities for peripheries The regression results obtained for energy recovery indicate that Mj is significant, while Mi is not. This means that, regardless of their size (number of inhabitants) and treatment capacity, the departments tend to send their waste to the nearest waste-to-energy centres. We calculate that extra-departmental waste flows are organised over a distance of 85 km for energy recycling. In this model, the major conurbations capture and recycle part of the resources of their hinterland, both near and further afield, as is the case for Paris, Bordeaux, and Toulouse (Figure 9). However, we are also seeing the emergence of inter-municipalities centred on small and medium-sized towns, as well as peri-urban and rural areas. Positive residuals are overrepresented in these three types of areas. The results of the Chi-squared test on the model's residuals (Appendix K) confirm this over-representation to their population.

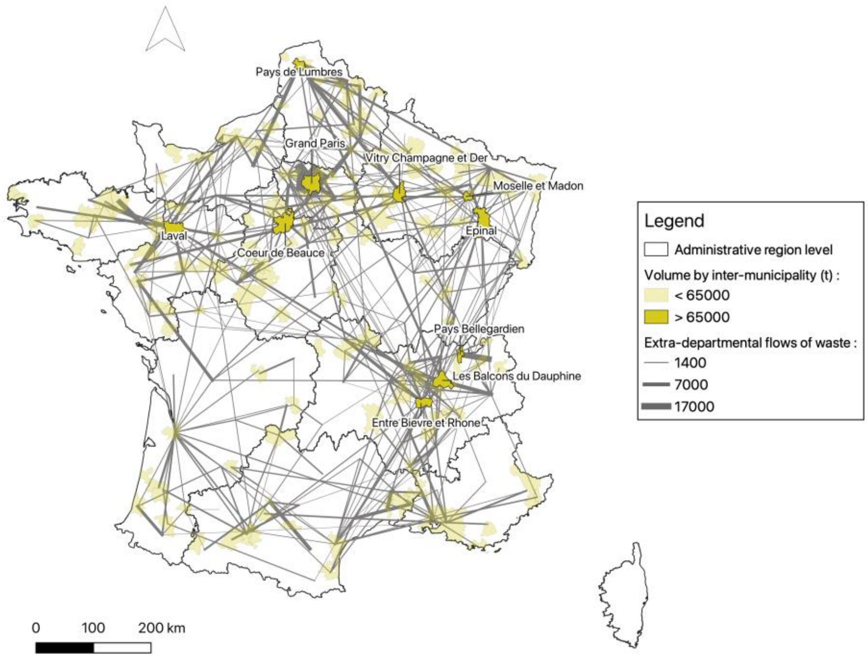

Figure 9. Extra-departmental flows of waste for energy recovery (over 1000 tons) (source: authors, data from IREP).

By focusing on these cases, the database allows for the identification of industrial energy recovery units, for collective or individual, public or private purposes.

Collective and public processes are carried out by intermunicipal unions, which oversee the energy recovery of household waste for rural populations or those living in medium-sized and small towns. To illustrate, SIVALOR, situated within the rural intermunicipality "Pays Bellegardien", recycles 120,000 tons of household waste, generating 68,000 megawatt hours of energy. This is sufficient to meet the energy requirements of over 55,000 inhabitants. Such processes are also observed in industrial contexts. The inter-municipality "Entre Bièvre et Rhône" hosts a facility that transforms chemical waste into energy. This is one of the most substantial thermal treatment and recovery centres for hazardous waste in France. The heating network provides a source of energy for 16 industrial plants situated in the business park.

Additionally, energy recovery is employed by industrial enterprises, which require substantial quantities of energy for their production processes. Such industrial and private processes can be observed, for instance, in the cement and paper industries. The Lafarge plant in Laval Agglomeration, which is responsible for the highest level of CO_2 emissions in France, utilises specific materials to generate the energy it requires. The utilisation of tyres and their associated health implications have prompted a series of protests from residents. In the case of the paper mill, on-site biomass cogeneration (Norske Skog, Golbey, Vosges), which is less polluting, has been met with less opposition. In Vitré, in the Brittany Region, the private company Paprec operates the household waste-to-energy center. It produces hot water (intended for public and private structures) and steam to supply industrial processes.

4.3.3. Material recovery: industrial opportunity and inter-regional relations

The regression results now indicate that Mi and Mj are positive and significant, while the distance remains negative and significant (Appendix L). However, in the case of material waste, the distance travelled is now 170 km on average for extra-departmental recovery. While geographical proximity remains an essential factor in understanding the flow of this type of waste, other factors are also important.

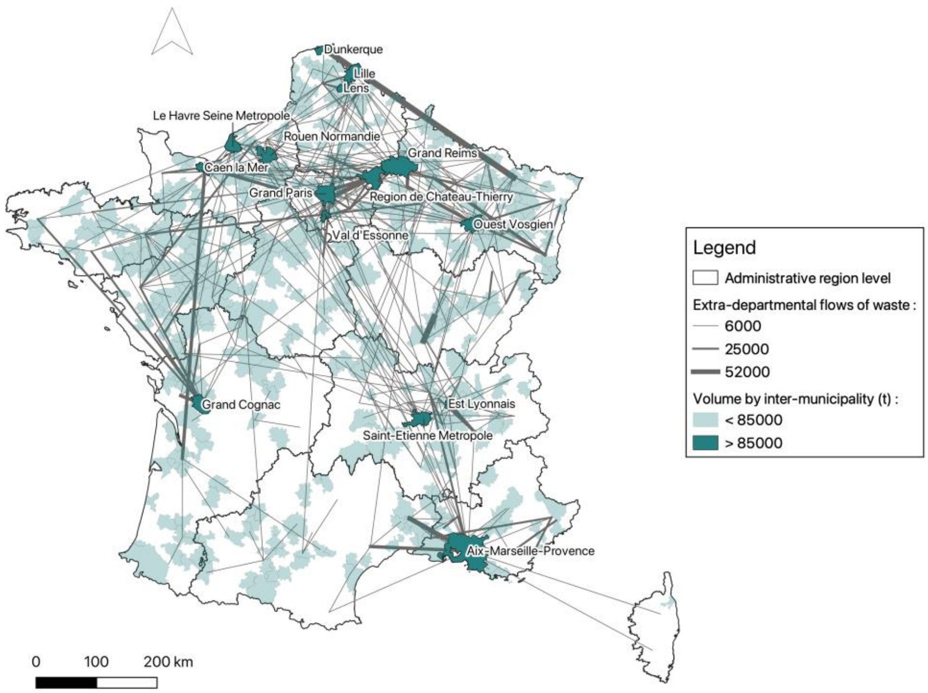

Figure 10. Extra-departmental flows of waste for material recovery (over 4000 tons) (source: authors, data from IREP).

Figure 10 reveals that these flows are evidently extra-regional, establishing connections between inter-municipalities with a predominantly industrial or agricultural base and the department responsible for the production of material waste. In this manner, the implementation of a genuine sub-national management of waste management is being organised around sectors, suggesting industrial proximity (based on industrial logic as defined by Bahers and al. 2017), contingent on the type of waste and the treatment capacity of the units. The northern regions of France are particularly well represented, as are Auvergne-Rhône-Alpes and Marseille. These regions are notable for their high levels of industrial production, which generate a considerable amount of material waste, including some hazardous materials. They have, at least in part, taken steps to develop the necessary infrastructure to facilitate the recycling of this waste.

In the intermunicipality of Dunkerque, metal and chemical waste is imported from neighbouring departments, as well as from all over France and Europe (including Germany, Belgium, Finland, and Italy). The historic presence of metallurgy and chemicals has enabled the development of unique treatment capabilities. Hydropale, for example, treats and recovers special waste from maritime and industrial activities, while BEFESA Valera, which initially specialised in the manufacture of ferrochrome, expanded its business in 1995 to include the recycling of residues from the manufacture of stainless steel. The presence of Arcelor Mittal also explains the specific profile of this area. National public programmes also support exchanges between companies in this territory.

But the results of the Chi-square test on the model's residuals (Appendix L) show an over-representation of rural areas about their population, and an under-representation of urban centres. When we focus on rural cases, a link with territorial resources and the history of the area becomes apparent. For example, in the Ouest-Vosgien intermunicipality, Sibelco Green recycles approximately 250,000 tons of glass bottles in the form of cullet on an annual basis. This process provides glassmakers with 90% of the material they require to manufacture other bottles in France. The recycling plant is situated in a small community with a strong historical connection to the industrial sector. It was in this location that the Gironcourt-sur-Vraine glassworks was established in 1905 by the Bouloumié family, who were the proprietors of the Vittel water company (a famous water source in the Vosges). The plant processes waste from all over France and from neighbouring countries such as Switzerland and Luxembourg. In terms of the glass industry, Cognac has become a significant recycling hub too, reflecting its history. Notably, it was in Cognac in 1898 that Claude Boucher developed the first semi-automatic machine for shaping glass bottles, which had previously been mouth-blown. In the Cognac inter-municipality, there is also the REVICO company, founded in 1969, which treats waste from the cognac industry.

4.3.4. Disposal: infra-regional proximity organized around cities As for the precedent case, Mi and Mj are positive and significant, while the distance remains negative and significant. The distance travelled is now 91 km on average for extra-departmental disposal.

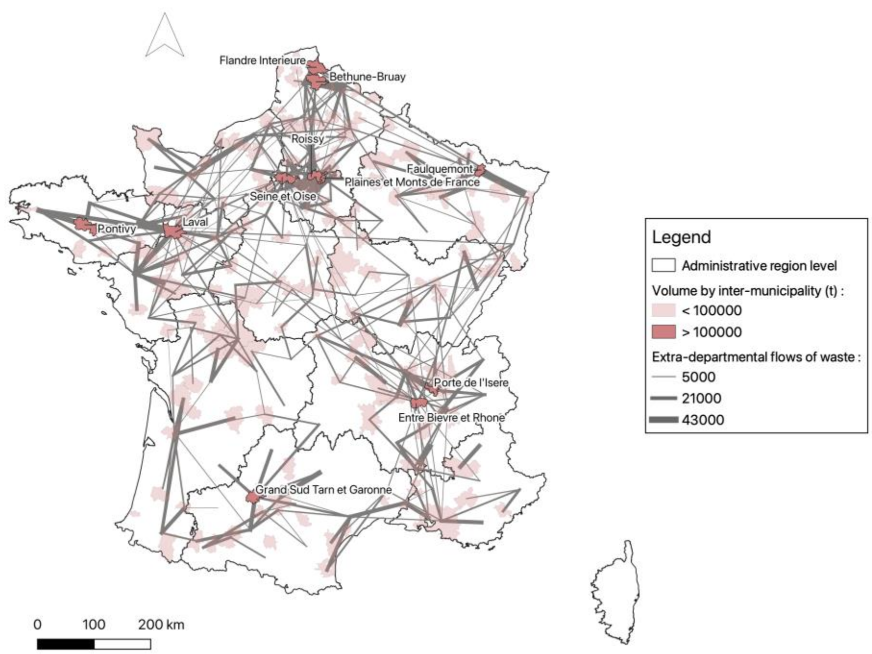

Figure 11. Extra-departmental flows of waste for disposal (over 2000 tons) (source: authors, data from IREP).

Figure 11 shows a more geographical proximity effect for disposal, which is much less qualitative and wealth-creating. It does not fall within the purview of the circular economy. However, it is enlightening to examine the locations to ascertain the remaining challenges. The geographical configuration of waste disposal structures is characterised by sub-regional systems, with relationships organised by periurban and rural units. The results of the Chi-square test on the model's residuals (Appendix M) confirm these two over-representations, for rural and periurban areas, about their population. The classical core-periphery logic still exists.

In terms of volume, the first system is organised in the Parisian region through periurban inter-municipalities (Plaines et Monts de France, Roissy, Seine et Oise). The second one is structured by hinterlands, either periurban or rural intermunicipalities, of large urban centers such as Lyon (Porte de l'Isère, Entre Bièvre et Rhône), Toulouse (Grand Sud Tarn et Garonne) and Lille (Flandre Intérieure, Bethune-Bruay).

The geographical proximity at the regional scale could be an opportunity to enhance circularity and gradually transition away from this linear model of waste treatment. In 2015, the French government delegated responsibility for planning waste management policy to the regions. To illustrate, the Auvergne-Rhône-Alpes regional waste prevention and management plan seeks to implement national and European waste regulations and targets at the local level. It establishes targets for waste reduction and recycling rates for a period of 6 years and 12 years, while also delineating the principles of equity and territorial proximity. It proposes a balanced distribution of treatment facilities across the region and the adaptation of incineration capacity to regional needs with the objective of reducing long-distance flows.

4.4. The structural effect on recovery capacity

Our third and last hypothesis to understand spatial differences in waste treatment seeks to investigate the role of structural effects.

As seen above, results suggest that type of treatment varies between types of area. Urban centres appear to be the preferred locations for energy recovery (50% of all waste recovered as energy is in urban centres, for 34% of waste treated in urban centres). Rural and periurban areas each receive more than a third of the waste disposed of, for ¼ of the waste treated (+10 points).

Shift-share analysis suggests that these results are not only due to the waste structure. Urban centres are over-specialised in energy recovery and under-specialised in disposal (particularly for mixed waste). This suggests a good capacity to recover waste, particularly mixed waste, for energy production. Material recovery could be more important, except for chemical waste, animal and plant waste, and end-of-life equipment. Periurban areas, like rural areas, dispose of more waste than is justified by the composition of the waste treated (mainly mixed waste). In addition, and more specifically, rural areas are over-specialised in the energy recovery of animal and vegetable waste, due to the proliferation of methanisation facilities. They are also over-specialised in the recovery of animal and vegetable matter (compost) and the recycling of wood, paper/cardboard, and glass. Periurban areas are less specialised in material recovery, but they are particularly good at recovering metals and paper, and to a lesser extent, animal and plant waste and end-of-life equipment. Finally, small and medium-sized towns are characterised by an under-representation of energy recovery (particularly animal and vegetable waste and mixed waste) and an over-specialisation in the recovery of metal waste and glass.

These results confirm partly our third hypothesis. It suggests that there is a complementarity between types of areas for the deployment of EC because of their specialization in certain types of waste.

5. Conclusion

This paper provides an overview of the impacts of the EC on territorial economic disparities through the case of waste management in France, using the centre-periphery model. The results suggest that a combination of agglomeration, geographical proximity, and structure effects interact to explain the spatiality of waste treatment. In particular, in cases where waste is transformed into resources to be recycled, whether for energy or materials, the core-periphery model appears to be strengthened. The development of the circular economy for waste is primarily concentrated in urban centres, raising concerns about the risk of increasing inequalities between cores and peripheries, confirming recent findings in economic geography (Rodriguez-Pose and Bartalucci, 2024).

However, a more detailed analysis of deviations from the model reveals the mechanisms of cooperation (for energy recovery) and complementarity (for materials recovery) between the centre and the periphery in urban areas. In rural areas and SMS towns, the significance of the agricultural and industrial sectors underscores the potential for the expansion of the circular economy of waste. In these areas, we have been able to highlight the role played over time by local resources, mobilised in the past by traditional, linear industry, which can now be recycled in circular loops. Moreover, these cases are most often located in economically depressed regions, characterised by what Rodriguez-Pose et al. 2024 call 'development traps'. This is a development opportunity for these 'peripheral' areas. A detailed analysis, categorised by treatment type, sector, and geographical area, yielded several key conclusions for action.

Concerning waste disposal, traditional core-periphery relations persist and are projected to remain dominant. Our analyses show that these relationships are most often organised at a regional level. Here, efforts must focus on reducing non-recyclable waste (NRW) and ensuring a "fair" spatial distribution of disposal centers. Regional public policies are central to the implementation of the circular economy (Niang et al., 2023), and for waste management in particular, regions are key prevention and planning actors.

With regard to material recycling, our results show that CE is rarely synonymous with geographical proximity. It confirms the role played by other economic and technical considerations generating inter-regional organisational and industrial proximity (Bahers et al., 2017). This is therefore no longer strictly a matter of core-periphery logic: there are intermunicipalities with an industrial profile that stand out, whether urban, rural, or peri-urban. The development of the circular economy can breathe new life into the economies of these territories, which are sometimes hard hit by deindustrialization, provided that the decarbonization of these industrial sites is supported (for example, by using the Just Transition Fund). Actions (regulatory constraints) could also be taken to reduce flows when several facilities can accommodate waste recycling. Moreover, some flows continue to be exported and are not covered by our analyses. As Bahers et al. (2017) noted for waste electrical and electronic equipment, eco-organizations managing WEEE flows tend to minimize spatial considerations, prioritizing cost and regulatory compliance over geographic location when selecting service providers. This approach runs counter to locally rooted dynamics, particularly those promoted by the social and solidarity economy.

Concerning energy, it appears that urban centres are currently the primary beneficiaries of the surge in waste-to-energy initiatives, in conjunction with their peripheral areas. However, there are projects in rural areas and in small and medium-sized towns that underscore the potential for these regions. These projects include methanisation (recovery of agricultural waste or green household waste), projects run by industrial companies (recovery of economic waste), and/or public projects (recovery of household waste). In the context of rising energy costs (gas and electricity), geopolitical turbulence, and incentives for decarbonisation (to meet net zero carbon targets by 2050), CE is creating development opportunities for peripheral areas. Concurrently, the question of energy dependence on waste (potentially contradictory with the desire to reduce waste, given the investment costs of these recovery processes) remains unresolved. The decarbonisation of industry and the aspiration to cultivate a circular economy are projected to expedite these processes (Psomopoulos et al., 2022), necessitating regulatory measures for environmental purposes, as well as, as evidenced in the context of spatial equity.

Three main limitations to this work could give rise to further research. Firstly, after waste reduction, reuse is the second priority of the circular economy. However, the paucity of available data hinders our ability to ascertain the impact of its development on the core-periphery relationship, leaving us to hypothesize that it is over-represented in consumption centres. Secondly, the absence of distinction between household, economic, and hazardous/non-hazardous waste further complicates our understanding. However, the territorial systems they engender are likely to differ due to their unique characteristics (e.g., public policies, regulations, treatment complexity). Further quantitative research is necessary to elucidate these discrepancies. Thirdly, our analysis mostly reflects ‘formal’ circularity — i.e., the redirection of material flows. Further work is needed to assess whether these changes are part of a deeper transformation of production-consumption models, or simply a logistical optimisation that leaves core industrial structures intact. Future qualitative research could focus more specifically on stakeholders to better understand the levers that have been used to initiate its deployment (public action, private funding, etc.).

Finally, the geography of the circular economy cannot be reduced to a reconfiguration of flows alone. It raises fundamental questions about territorial justice, access to infrastructures, and the redistribution of value across space. While large urban centers remain dominant, this research reveals the hidden potential of peripheral regions, whose contribution to CE could be pivotal if properly supported. Moving beyond proximity logics and agglomeration effects, a truly transformative circular economy calls for new institutional arrangements, robust local governance, and inclusive innovation strategies that explicitly address socio-spatial inequalities. Ultimately, a truly transformative circular economy must go beyond spatial optimisation: it requires deliberate institutional choices to redistribute value, infrastructure, and decision-making power across space — including to the peripheries.

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Data Availability The data are available in the IREP databases online.

Declarations

Competing interests The authors declare no competing interests.

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Appendices

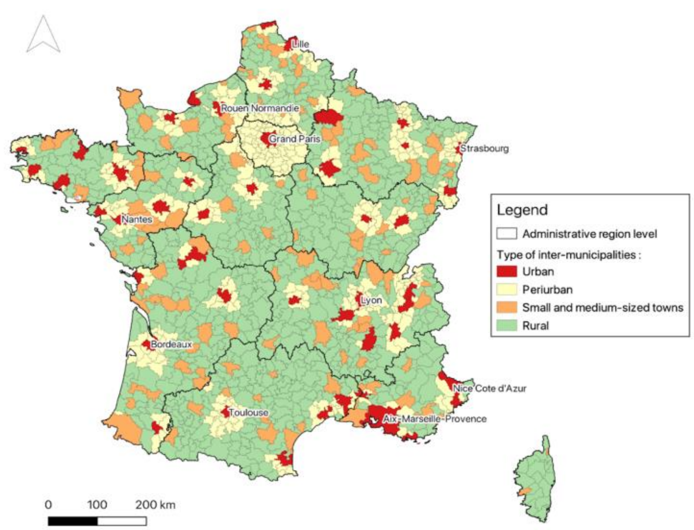
Appendix A: Type of waste classification

Code	Description	Own classification
01	Chemical compound waste	Chemicals
02	Chemical preparation wastes	Chemicals
03	Other chemical waste	Chemicals
05	Medical, veterinary and biological wastes	Other
06	Metallic wastes	Metal waste
07	*Non-metallic waste (See sub-categories)*	
07.1	Non-metallic waste - glass	Glass waste
07.2	Non-metallic waste - paper and cardboard	[Paper and cardboard waste
07.3	Non-metallic waste - rubber	Rubber waste
07.4	Non-metallic waste - plastics	Plastic waste
07.5	Non-metallic waste - wood	Wood waste
07.6	Non-metallic waste - textiles	Textile waste
07.7	Non-metallic waste – containing PCBs	Other
08	Discarded equipment	Discarded equipment
09	Animal and vegetable waste	Animal and vegetable waste
10	Mixed waste	Mixed waste
11	Ordinary sludge (aqueous)	Not conserved
12	Mineral waste	Not conserved
13	Solidified, stabilized or vitrified Waste	Other

Appendix B: Waste treatment classification

Treatment title	Treatment code	Treatment classification
Recycling or recovery of organic substances not used as solvents	R3	Material recovery
Recycling or recovery of metals and metal compounds	R4	Material recovery
Recycling or recovery of other inorganic materials	R5	Material recovery
Land treatment for agricultural or ecological purposes	R10	Material recovery
Regeneration or other reuse of oils	R9	Material recovery
Recovery or regeneration of solvents	R2	Material recovery
Regeneration of acids or bases	R6	Material recovery
Recovery of products from catalysts	R8	Material recovery
Recovery of products used to capture pollutants	R7	Material recovery
Primary use as a fuel or other means of generating energy	R1	Energy recovery
Specially engineered landfill	D5	Disposal
Incineration on land	D10	Disposal
Deposit on or in soil	D1	Disposal
Release into the aquatic environment except dumping	D6	Disposal
Permanent storage	D I2	Disposal

Appendix C: Map of inter-municipalities according their type (source: authors, data from INSEE)



Appendix D: Summary table

	Volume	% of total waste treated	% for each operation of treatment	Waste treatment rate	Number of areas
Material recovery	**17301779**	**35%**	**100%**		**587**
Chemical	*1564593*	*3%*	*9%*	*44%*	265
Metal	*3120481*	*6%*	***18%***	*100%*	192
Glass	*1330230*	*3%*	*8%*	*98%*	40
Paper and carboard	*503061*	*1%*	*3%*	*96%*	86
Rubber	*143404*	*0%*	*1%*	*61%*	30
Plastic	*109848*	*0%*	*1%*	*76%*	91
Wood	*658577*	*1%*	*4%*	*50%*	113
Textile	*4766*	*0%*	*0%*	*28%*	9
Disused	*2038001*	*4%*	*12%*	*97%*	342
Animal and vegetal	*5169474*	***10%***	***30%***	*76%*	331
Mixed	*2651430*	*5%*	*15%*	*9%*	253
Other waste	*7914*	*0%*	*0%*	*3%*	14
Energy recovery	**16171020**	**32%**	**100%**		**249**
Chemical	*726378*	*1%*	*4%*	*20%*	105
Metal	*1843*	*0%*	*0%*	*0%*	11
Glass	*1*	*0%*	*0%*	*0%*	3
Paper and carboard	*16561*	*0%*	*0%*	*3%*	24
Rubber	*84524*	*0%*	*1%*	*36%*	13
Plastic	*23093*	*0%*	*0%*	*16%*	28
Wood	*659529*	*1%*	*4%*	*50%*	69
Textile	*10488*	*0%*	*0%*	*61%*	12
Disused	*24272*	*0%*	*0%*	*1%*	27
Animal and vegetal	*1581814*	*3%*	*10%*	*23%*	104
Mixed	*12924990*	***26%***	***80%***	*42%*	162
Other waste	*117527*	*0%*	*1%*	*37%*	42
Disposal	**16464240**	**33%**	**100%**		**291**
Chemical	*1258799*	*3%*	*8%*	*35%*	149
Metal	*3595*	*0%*	*0%*	*0%*	25
Glass	*22919*	*0%*	*0%*	*2%*	23
Paper and carboard	*2677*	*0%*	*0%*	*1%*	15
Rubber	*8648*	*0%*	*0%*	*4%*	8
Plastic	*12352*	*0%*	*0%*	*9%*	52
Wood	*3031*	*0%*	*0%*	*0%*	16
Textile	*1983*	*0%*	*0%*	*12%*	16
Disused	*29923*	*0%*	*0%*	*1%*	39
Animal and vegetal	*33895*	*0%*	*0%*	*0%*	59
Mixed	*14898217*	***30%***	***90%***	*49%*	234
Other waste	*188202*	*0%*	*1%*	*60%*	27

Appendix E: Results of regression model between waste treatment (Mass-Mi) in tons and intermunicipalities number of inhabitants (Population-Pi)

Parameters of the regression model

	Model
Mi – Waste treatment	
Pi - Population	0,996***
	(0,0001)
Intercept	2,678***
	(0.0001)
Observations	745
R2	0,185
Adjusted R2	0,184

Appendix F: Results of regression models between the type of waste treatment (Mass-Mi) in tons and intermunicipalities number of inhabitants (Population-Pi)

	Model 1	Model 2	Model 3
	Mi – Energy recovery	**Mi – Material recovery**	**Mi –Disposal**
Pi - Population	0,967***	0,691***	0,338
	(0,0001)	(0,0001)	(0,0001)
Intercept	2,273**	3,644***	5,21***
	(0.0001)	(0.0001)	(0.0001)
Observations	249	587	291
R2	0,111	0,108	0,012
Adjusted R2	0,107	0,106	0,008

Appendix G: Residual ratios for energy recovery by type of intermunicipalities (residual from results of linear model)

	Urban center	Periurban	SMS towns	Rural	France
PRR	0,55	0,92	**1,38**	1,08	1,00
NRR	**1,21**	1,04	0,82	0,96	1,00

Chi-squared test significant

$$PRRj = \%\ PRj\ /\ \%\ PR$$

PRR = positive residual ratio

PR = positive residual

j = Type of intermunicipalities [urban center, periurban, SMS towns, rural]

$$NRRj = \%\ PRj\ /\ \%\ PR$$

NRR = negative residual ratio

NR = negative residual

j = Type of intermunicipalities [urban center, periurban, SMS towns, rural]

Appendix H: Residual ratios for material recovery by type of intermunicipalities (residual from results of linear model)

	Urban center	Periurban	SMS towns	Rural	France
PRR	0,75	**1,14**	1,01	0,95	1,00
NRR	**1,17**	0,90	0,99	1,04	1,00

Chi-squared test significant

$$PRRj = \%\ PRj\ /\ \%\ PR$$

PRR = positive residual ratio

PR = positive residual

j = Type of intermunicipalities [urban center, periurban, SMS towns, rural]

$$NRRj = \%\ PRj\ /\ \%\ PR$$

NRR = negative residual ratio

NR = negative residual

j = Type of intermunicipalities [urban center, periurban, SMS towns, rural]

Appendix I: Intradepartmental waste flows rate (%)

	TOTAL			Energy Recovery			Material Recovery			Disposal		
	Nb	**Mean**	**St. dev.**	**N b**	**Mean**	**St. dev.**	**N b**	**Mean**	**St. dev.**	**Nb**	**Mean**	**St. dev**
Urban center	114	**75%**	29%	40	**81%**	29%	45	66%	32%	29	**78%**	27%
Periurban	319	65%	37%	71	65%	40%	173	68%	34%	75	62%	37%
SMS towns	174	59%	41%	39	58%	42%	86	60%	39%	4'9	59%	42%
Rural	520	65%	39%	99	67%	40%	283	66%	38%	138	62%	38%
Total	**1127**	**65%**	**38%**	**249**	**67%**	**39%**	**587**	**66%**	**37%**	**291**	**63%**	**38%**

Appendix J: Results of gravity model between intermunicipalities waste treatments in tons and departmental waste treatments in tons

$$log\ log\ (Fij)\ =\ \beta 0 + \alpha\ log\ log\ (Dij)\ +\ \beta 1\ log\ log\ (Mi) +\ \beta 2\ log\ log\ (Mj)\ +\ \varepsilon$$

- Fij : Flow between area i and area j (with i≠j)
- Mj : the tons of waste treated by intermunicipalities
- Mi : the tons of waste treated by department
- Dij the euclidean distance between i and j

	Model 1	**Model 2**	**Model 3**
	Energy recovery	**Material recovery**	**Disposal**
Dij	-1.135***	-1.519***	-0.464***
	(0,0001)	(0,0001)	(0,0001)
Mj	0.580***	0.654***	0.724***
	(0,0001)	(0,0001)	(0,0001)
Mi	0.070	0.331***	0.217***
	(0,0001)	(0,0001)	(0,0001)
Intercept	2,273**	5.266***	8.720***
	(0.0001)	(0.0001)	(0.0001)
Observations	1179	5816	1699
R2	0,245	0,257	0,448
Adjusted R2	0,243	0,256	0,447

Appendix K: Residual ratios for energy recovery by type of intermunicipalities (residual from results of gravity model)

	Urban center	Periurban	SMS towns	Rural	France
PRR	0,172	**0,261**	**0,226**	**0,340**	1,000
NRR	**0,402**	0,204	0,146	0,246	1,000

Chi-squared test significant (>mean)

$$PRRj = \%\ PRj\ /\ \%\ PR$$

PRR = positive residual ratio

PR = positive residual

j = Type of intermunicipalities [urban center, periurban, SMS towns, rural]

$$NRRj = \%\ PRj\ /\ \%\ PR$$

NRR = negative residual ratio

NR = negative residual

j = Type of intermunicipalities [urban center, periurban, SMS towns, rural]

Appendix L: Residual ratios for material recovery by type of intermunicipalities (residual from results of gravity model)

	Urban center	Periurban	SMS towns	Rural	France
PRR	0,175	0,263	0,179	**0,382**	1,000
NRR	**0,218**	0,267	0,199	0,316	1,000

Chi-squared test significant (>mean)

$$PRRj = \%\ PRj\ /\ \%\ PR$$

PRR = positive residual ratio

PR = positive residual

j = Type of intermunicipalities [urban center, periurban, SMS towns, rural]

$$NRRj = \%\ PRj\ /\ \%\ PR$$

NRR = negative residual ratio

NR = negative residual

j = Type of intermunicipalities [urban center, periurban, SMS towns, rural]

Appendix M: Residual ratios for disposal by type of intermunicipalities (residual from results of gravity model)

	Urban center	Periurban	SMS towns	Rural	France
PRR	0,573	**0,430**	0,594	**0,602**	1,000
NRR	0,427	0,570	0,406	0,398	1,000

Chi-squared test significant (>mean)

$$PRRj = \%\ PRj\ /\ \%\ PR$$

PRR = positive residual ratio

PR = positive residual

j = Type of intermunicipalities [urban center, periurban, SMS towns, rural]

$$NRRj = \%\ PRj\ /\ \%\ PR$$

NRR = negative residual ratio

NR = negative residual

j = Type of intermunicipalities [urban center, periurban, SMS towns, rural]

Appendix N: Distance travelled by types of waste, extra-departmental flows

Type of waste	Km (extra-departmental flows)
Glass waste	147,7
Metallic waste	114,0
End-of-life equipment	112,4
Rubber waste	103,9
Chemical waste	93,3
Overall total	80,8
Plastic waste	75,0
Wood waste	71,4
Paper and cardboard waste	68,5
Animal and plant waste	62,5
Mixed waste	57,9
Other waste	34,7