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Article

A multi-scale approach to quantifying metropolitan innovation and recycling behaviour

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Abstract: Urban infrastructures and services—such as public transportation, innovation bodies and environmental services—are important drivers for the sustainable development of our society. How effectively citizens, institutions and enterprises interact, how quickly technological innovations are implemented and how carefully new policies are pursued, synergically determine development. In this work, data related to urban infrastructure features such as patents and recycled waste referred to 106 province areas in Italy are investigated over a period of twenty years (2001–2020). Scaling laws with exponents characterizing the above mentioned features are observed and adopted to scrutinize whether and how multiple interactions within a population have amplification effects on the recycling and innovation performance. The study shows that there is a multiplication effect of the population size on the innovation performance of territories, meaning that the dynamic interactions among the elements of the innovation eco-systems in a territory increase its innovation performance. We discuss how to use such approach and the related indexes for understanding metropolitan development policy.

Keywords: sustainable development; urban and regional policy; data mining

1. Introduction

The shift towards a sustainable economy is identified as a necessary change to significantly reduce the negative impact of human activities on the environment (Van Mierlo and Beers, 2020). A main goal is to achieve marked reduction and reuse of waste, which in turn would reduce the amount of input resources needed for human activities. Recovering materials, saving resources and reducing carbon footprint are pressing challenges for policy-makers to improve the recycling performance of territories (Svennevik, 2022). Innovation is at the same time a key indicator and a driver of sustainable behaviour (Aldieri et al., 2019; Platon et al., 2022). In addition to active participation and responsible behaviour, innovative technological solutions need to be developed and integrated to foster sustainable development. Some studies have demonstrated that the interactions between citizens can be paradigmatic in changing recycling and innovation performances. "Social nudging" arising from the knowledge that other neighbours recycle is particularly powerful (Cheng et al., 2022). Hence, to quantify and understand how territories behave with respect to innovation and recycling phenomena is a necessary step for improving the environmental performance of human activities.

Population habits are featured by several interactions of physical, social and institutional origin (Adams et al., 2016). Hence, understanding population behavior requires a complex systems science approach. The high complexity degree of social interactions gives rise to nonlinear dynamics and highly correlated phenomena. The innovation dynamics should be interpreted as a complex phenomenon where bunches of citizens, inventors and innovators do not operate in isolation. The emergence of new ideas and technologies involves integrating and recombining knowledge from different individuals and institutions (Adams et al., 2016; Aldieri et al., 2019; Bettencourt et al., 2007; Carbone et al., 2022, 2023; Keuschnigg et al., 2019; Mayona and Sutriadi, 2024; Stanley, 1999).

In this work, we study the relationship existing between innovation and recycling and the impact of population size. The analysis has been implemented on data referred to the 106 Italian provinces population, innovation and recycling performance, by taking a complex systems perspective. The study highlights whether and how innovation and recycling behaviours correlate regarding the population groups involved in both processes. We measure innovation through patents, geo-localized according to the specific province where the company or individual inventor resides. Patents are one of the main fingerprints of innovation in a territory and thus are widely used as a measure of innovation (Ponta et al., 2020; Vanderlei et al., 2020). As far as recycling is concerned, we have collected data on the amount of recycled waste, for each province, breaking them down by merceological fractions. Glass, organic, paper and plastic have been chosen as the most relevant merceological fractions according to the quantity of tons produced. The database generated for this study is novel and constitutes an important contribution to this area of research "per se". The availability of large amounts of curated data could allow interested scholars and professionals to analyze correlation and anticorrelation regarding innovation and recycling in a very diverse population behaviour over a nation-wide context.

We investigate whether and how the increasing complexity of the interactions related to the increasing population size might boost performances in innovation and recycling, aimed at answering the question: "How and to what extent are innovation and recycling capabilities linked to each other at multiple metropolitan scales and over an extended temporal horizon?" and ultimately aims at clarifying: "Whether a positive or negative feedback effect, generated by population interactions, emerges in innovation and recycling". To address these issues, innovation and recycling features have been gathered for a population of about 60 million individuals with a breakdown over 106 metropolitan areas (Alcamo et al., 2024). We investigate the relationship between the number of patents and the amount of recycled waste and then these same features versus population size over twenty years (2001–2020) for the whole population of Italy amounting to around 60 million citizens. Italy stands out in Europe as a leader for the rates of waste recycling (68%), demonstrating remarkable capabilities in waste management and reprocessing of recycled resources (21.6%) (Circular Economy National Report 2022—CircularEconomy Network). Importantly, Italy takes the lead in innovation performances, particularly when small and medium enterprises (family enterprises) are concerned (Marseguerra et al., 2016). The availability of patent data referred to small circles of employees is of specific relevance for the feasibility of the multiple scale analysis which needs data referred to the micro, meso and mega scales of the analysed population. The remarkable quantity of collected data, regarding several features of patents and recycled waste, matters from the methodological point of view and makes the analysis statistically significant.

The added values of our analysis to the current knowledge in the field are:

- **Multi-scale dimension**. Our study is implemented on municipalities or provinces of any size at all scales, thus it goes beyond existing studies set on either whole countries or single cities. The inclusion of features of relevant phenomena at the intermediate scales (mesolevel) allows to understand the system behaviour with a multi-scale perspective.
- **Data quality**. Our study is implemented on urban areas (region, provinces and municipalities) of the same country, thus it goes beyond existing studies set on data for different countries, where different policies and regulatory instruments are enacted hence avoiding misleading results due to heterogeneous regulatory interventions.
- **Complex systems perspective**. Our study goes beyond the current analysis of patenting and recycling mostly performed in terms of linear modelling and superposition laws and highlights that the interactions among citizens involve nonlinear features.

The paper is structured as follows: section 2 gives the literature background; section 3 summarizes the methodology which revolves around the main concepts of power-law scaling; section 4 describes the details of the database built on purpose for this research; section 5 illustrates the results. Discussions are provided in section 6, whereas conclusions and suggestions for further developments are reported in section 7.

2. Literature review

Nowadays, society aims to implement efficient resource management and a competitive economy to boost sustainable development (Köhler et al., 2019). The role of innovation in recycling and waste management has been studied by Aldieri et al. (2019); Platon et al. (2022); and Sumrin et al. (2021). How firms and policymakers are motivated to adopt and attain competitive advantage, how entrepreneurial innovation impacts the recycling rate of municipal waste is reported by Sumrin et al. (2021). The relations among innovation features such as business expenditure on research and development (R&D), private investments, Gross Domestic Product (GDP) expenditures on R&D, environmental taxes and recycling have been analysed (Aldieri et al., 2019). Business and GDP expenditure on R&D show a positive impact on the recycling rate of municipal waste, while any in- crease in environmental taxes seems to decrease the recycling rate of municipal waste and prevent potential investments in ecological projects. Platon et al. (2022) investigates how innovation intensity affects recycling by showing that eco-innovation has moderate delayed (about 2 years lag) influence and matters more at the initial stages of recycling.

In this context, populations behave as complex systems characterized by several interactions of physical, social, and institutional origin which manifest heterogeneous features about different activities (Cheng et al., 2022). Hence, nonlinear behavior may emerge due to the high number of interactions that impact social and organizational dynamics (Bettencourt and Lobo, 2016). These features must be explored with the quantitative understanding of how human dynamics try to successfully navigate and achieve specific goals.

Innovation challenges have to be tackled as complex phenomena because citizens, inventors and innovators do not operate in isolation. The onset of new ideas and technologies involves integration and recombination of knowledge from different individuals and institutions (Fleming, 2001). For this reason, population interactions are determinant and consequent of the socio-economic transformation occurring within urbanized areas, like cities, provinces, regions and whole countries. Large population groups may foster interpersonal interactions, thus creating opportunities for enhanced information, knowledge and technology flows (Jacobs, 1985; Jaffe et al., 1993; Ponta et al., 2021). Knowledge's creation increases the attractiveness of a territory towards educated, highly skilled, entrepreneurial and creative individuals who may in turn contribute to the generation of further knowledge spillovers (Audretsch and Feldman, 2004). This is the engine whereby regions sustain their continuous development through unfolding innovation.

To step in this direction and accelerate transformation, quantitative measures and indicators are required, whose definition might not be straightforward (Pavitt, 1985). Patents can be seen as one of the "footprints" of the inventive activity and can be taken as one of the most reliable sources of data to quantify innovation. Patent data and metadata are publicly accessible and represent an objective measure in contrast to self-reported/self-referenced ones (J. Acs and Audretsch, 1989). The relationship between population and patented innovation has shown that larger urban agglomerates give rise to increased patenting rates with increased returns to scale as expected for processes where social interactions matter (Gambardella, 1994). Social networks play a key role in spreading and diffusing information and knowledge by enabling both formal and informal connections through which ideas flow among individuals (Bettencourt et al., 2007).

Similarly, the behaviour of a population concerning recycling performance can be seen as a complex phenomenon with features of urban societies that foment, or hinder, population behaviour toward recycling. Citizens' attitude towards recycling is gaining increasing attention with the rate of recycling a relevant indicator for municipalities and population contribution toward environmental challenges and circular economy principles (Liu et al., 2023). Thus, drastic changes are requested to cities to improve municipal waste management and recycling capabilities. Studies have already highlighted that the interactions among citizens can be a main aspect in changing the rate of recycling. Active participation is indispensable and citizens' social relations seem to be highly correlated with region recycling performance. As Barr pinpoints, "Knowledge for action is a significant prerequisite for behaving appropriately and would be a significant barrier to action if levels were low" (Barr, 2007). The general awareness of environmental problems, the knowledge of the specific local services, the influence of family members, neighbours, friends and social networks act as guidance to enhance recycling actions, especially in places with high visibility of people's behaviour (Barr, 2007). The information flow among citizens may also contribute to the correct separation of recyclables at home, cleaning, storing and disposing of waste containers (Knickmeyer, 2020; Thomas and Sharp, 2013). Nevertheless, several learning barriers may arise, which limit the positive effect of the interactions. For example, a poor understanding of waste treatment and its value may give rise to obstacles reducing the positive impact of social interactions (Jesson et al., 2014; Miafodzyeva and Brandt, 2013).

In summary, the literature has widely recognised that innovation and recycling are linked to each other and both can contribute to sustainability.

3. Methodology

A variety of socio-economic features have been found to exhibit quite universal behaviour depending on population size *N*. Urban organization has been modelled as a hierarchy of closely connected interacting subunits similar to living organisms consisting of cells, tissues and organs. Such interpretation has led to formulate the fundamental scaling relation:

$$A \sim N^{\beta} \tag{1}$$

derived by generalizing the allometric scaling model between the metabolic rate of an animal and its body mass to city area A and population size *N* (Nordbeck, 1971). Exponents $\beta = 3/4$ and $\beta = 1/4$ respectively for the basal metabolic rate and the breathing rate have been reported for living organisms. Empirical results have suggested values $\beta < 1$ also for urban areas.

Many empirical studies conducted over the past 40 years pointed out that several urban quantities, *Y*, vary continuously with the population size *N* (Ribeiro and Rybski, 2023). Such quantities are mathematically described by power-law relations of the form:

$$Y = Y_0 N^{\beta} \tag{2}$$

where Y_0 and β are constant in *N*. In particular, rates of social quantities (innovations or gross domestic product) have been found to increase superlinearly with the population size *N*, i.e., with an exponent $\beta > 1$ in Equation (2). Conversely, features related to urban infrastructures per capita (such as transportation, services, etc.) have been found to increase sublinearly with the population size *N*, i.e., with an exponent $\beta < 1$ in Equation (2). Features related to individual needs (such as water consumption, and waste production) generally vary according to a linear relationship, i.e., with an exponent $\beta \approx 1$ in Equation (2):

$$\begin{cases} \beta > 1 \text{ socioeconomic features} \\ \beta < 1 \text{ infrastructural features} \\ \beta \approx 1 \text{ individual needs} \end{cases}$$

Values of the exponent $\beta > 1$ are in line with the expectation that larger population agglomerates (cities, urban areas) are more productive and creative compared to smaller ones (Bettencourt et al., 2008, 2007; Carbone et al., 2022; Keuschnigg et al., 2019; Rybski et al., 2019). On the other hand, values of the exponent $\beta < 1$ indicate that physical urban infrastructures contribute to reduce cost and congestion in urban areas with large population size *N* compared to smaller ones (Bettencourt and West, 2010; Samaniego and Moses, 2008). By plotting the data of the relevant feature *Y* vs. the pertinent population size *N* in log-log scales, a linear regression provides the value of the exponent β to be used as an indicator of the overall quality of the feature *Y* given the population size *N*.

The described methodology will be used for analysing data related to innovation and recycling as a function of the population size. The dataset, referring to the whole

Italian country over twenty years, has been built on purpose for this research. The granularity and significance level of the data, i.e., the spatial unit of analysis both for patent and recycled waste, are the metropolitan areas (provinces). The dataset is described in section 4. The results of the analysis, the exponents β, and the discussion are reported in the next sections.

4. Data

In this section, we describe the main features of the dataset built on purpose for this study addressed to investigating innovation and recycling performances at the scale of the population of metropolitan urban areas (provinces) over the whole territory of Italy. Innovation performances can be quantified in terms of patents, R&D expenditure, new technologies and products (Furman et al., 2002; Narin et al., 1984). In this paper, we have chosen patent data as a proxy of innovation. Patents data are public and quite accurately recorded, hence able to capture novelty, market acceptance, quality and evolution of the innovation features (Ponta et al., 2020). Recycling performances are analyzed in terms of total recycled waste. Merceological fractions breakdown is also considered to complement and support the analysis of the total recycled waste. Patent and recycling data refer to the 106 Italian provinces and over a temporal range of twenty years from 2001 to 2020 (Alcamo et al., 2024).

4.1. Innovation data

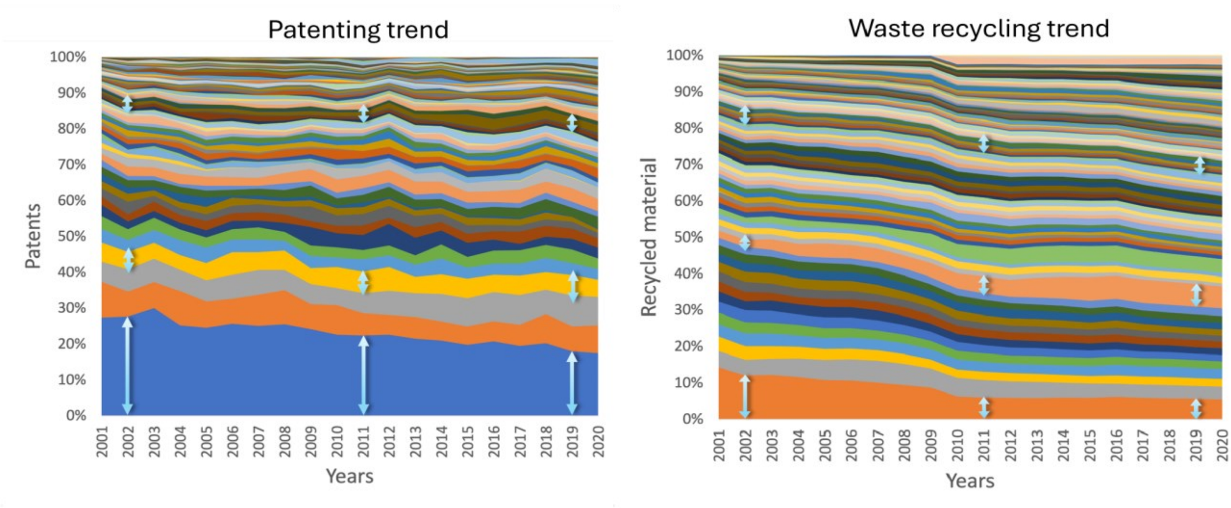
Patent data are publicly collected in several databases (Bonino et al., 2010). For the current analysis, the Orbit Intelligence database, provided by Questel (www.questel.com), one of the world's leading intellectual property management companies, is used as data source. A total of 408,770 patents for the 106 provinces have been collected. Data are collected with a temporal resolution of a year. The analysed database includes 59,045 patent families defined as "a collection of patent documents that are considered to cover a single invention. The technical content covered by the applications is considered to be identical. Members of a simple patent family will all have exactly the same priorities and then have been extended in different countries." Patents are assigned to each province by indexing the postal code of the assignee considering the address of either the firm registered office or the inventor's residence. Twenty provinces, that are also regional capitals, are listed in the first column of **Table 1**. The related population size, averaged over the years from 2001 to 2020, is reported in the second column. The population size is measured in terms of number of resident people. The total number of patents issued over the same period is reported in third column of **Table 1**. The fourth column reports the patents issued per year. Columns 5 and 6 report respectively the total number of patent families over the period 2001–2020 and the number of patent families per year. The total number of patents collected for the whole set of 106 provinces is reported by Alcamo et al. (2024).

Table 1. Data for twenty main provinces.

Province (1)	Population (2)	Patents (3)	Patents (4)	Patents (5)	Patents (6)	Recycled Tons (7)
Ancona	469,043	4235	212	818	41	100,863
Aosta	125,374	614	31	100	5	31,162
Bari	1,401,469	1373	69	315	16	149,772
Bologna	978,806	27,147	1357	3975	199	226,208
Cagliari	583,137	889	44	143	7	93,413
Campobasso	227,247	174	9	34	2	17,231
Catanzaro	363,198	382	19	86	4	33,676
Firenze	982,317	12,959	648	1640	82	268,237
Genova	863,771	5301	265	960	48	125,363
L'Aquila	302,113	1322	66	134	7	37,537
Milano	3,478,603	95,133	4757	11,610	581	850,211
Napoli	3,078,379	3441	172	565	28	411,022
Palermo	1,245,994	649	32	146	7	66,456
Perugia	648,136	2521	126	405	20	142,977
Potenza	379,343	329	16	56	3	30,526
Roma	4,088,771	29,245	1462	4035	202	586,092
Torino	2,249,981	21,328	1066	3219	161	499,060
Trento	520,607	4146	207	653	33	153,933
Trieste	235,749	2388	119	339	17	28,979
Venezia	509,906	2291	115	417	21	174,892

Note to **Table 1**: (1) Twenty main provinces out of the 106. (2) Population size: Average value over the years from 2001 to 2020. The population size is measured as the number of resident people in the metropolitan area. The data are extracted from the telematic national registers created and updated by the Istituto Italiano di Statistica (ISTAT) (https://www.istat.it/). (3) Total number of patents over the years from 2001 to 2020. (4) Average number of patents per year. (5) Total number of patent families over the years from 2001 to 2020. (6) Average number of patent families. The patent family" is a collection of patent documents that are considered to cover a singl e invention. The technical content covered by the applications is considered to be identical. Members of a simple patent family will all have exactly the same priorities" and have then been extended in different countries. Full details of the variation of the number of patents and patent families over the years 2001–2020 are reported in Figure 1a for all 106 metropolitan areas. (7) Total amount of recycled material (tons) averaged over the years 2001–2020.

Figure 1a shows the number of registered patents filed in the 106 provinces referred to the total number of patents registered in Italy per year from 2001 to 2020. The trends of the patent data in **Figure 1a** shows an overall increase of the innovation performances in the whole country. This effect can be appreciated by observing that the patent percentages are more uniformly distributed among the 106 provinces as time progresses from 2001 to 2020.



(a) **(b)**

Figure 1. (a) Number of registered patents filed in the 106 provinces to the overall quantity of patents registered in Italy over the years 2001–2020; **(b)** amount of recycled material collected in Italy in the different provinces to the overall quantity of recycled material collected in Italy over the years 2001–2020.

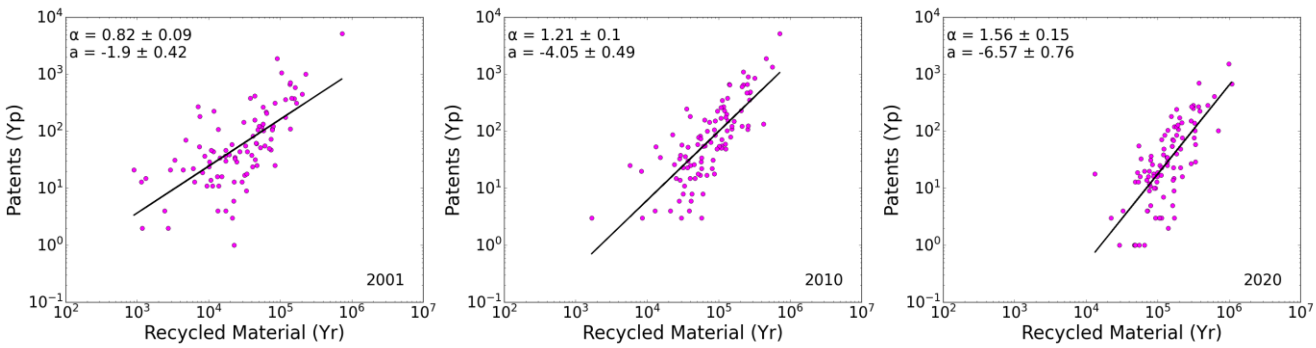
4.2. Waste management data

Recycling data refers to the production and sorting of urban waste. These data are extracted from the telematic national registers curated by the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), published by the Italian Ministry of the Environment. The adoption of a national database allows to access a complete and detailed framework for the production and management of recycled resources over the Italian territory with high detail level. Data are provided at different spatial scales (national, regional, provincial and municipal). The granularity of the database changes over time: from 2010 data are available at the municipal level of details, before 2010 the minimum level of details is the provincial scale. The information available in the database is related to the production of recycled material and related fractions. For each Italian province, the amount of urban recycled resources per waste fraction (Ton) is defined. Several merceological fractions are provided by the ISPRA database: paper, glass, plastic, organic, wood, metal, electrical and electronic equipment, textile, selective waste, construction and demolition activities, and street cleaning waste. In this paper, the fractions of paper, glass, plastic, and organic waste have been considered, as collected at the level of blocks or individual buildings for several years. Hence, data of these fractions can provide more robust and statistically significant outcomes.

The total amount of recycled material collected by the 20 main provinces (capitals of regions) is reported in the last column of **Table 1**, while the total amount of recycled material collected by all 106 provinces is reported by Alcamo et al. (2024). **Figure 1b** shows the amount of recycled material collected in Italy in the different provinces to the overall quantity of recycled material collected in Italy over the years 2001–2020. The effect, noted for patent data in **Figure 1a**, is even more evident for recycling data shown in **Figure 1b**. A convergence towards a more proactive behaviour is observed as indicated by a more equally distributed ratio between the recycled material at the end compared to the first years of the analysed period (2001–2020).

5. Results

In this section, we investigate analogies and differences between the area's capabilities in terms of innovation and recycling behaviour, by implementing the methodology of section 3 on the dataset described in section 4. The first step of the analysis is concerned with the relationship between data features of patents (Y_p) and of recycled material (Y_r) for the 106 Italian provinces over 20 years (i.e., a total of about 408,770 patents and 230,015,242.487 tons of recycled waste for 60 million citizens). **Figure 2** show the relations between Y_p and Y_r respectively for the year 2001, 2010 and 2020. Data are plotted in log-log scales. The regression line yields the exponent α of the slope. It is found that α increases continuously from 0.82 to 1.56 from 2001 to 2020.



(a) **(b)** **(c)**

Figure 2. Patents vs. recycled material (dots) for the years **(a)** 2001; **(b)** 2010; **(c)** 2020.

Note to **Figure 2**: Linear regression (continuous line). R^2 and adjusted R^2_{Adj} for years 2001, 2010 and 2020 are 0.45, 0.59, 0.54 and 0.45, 0.59, and 0.54, respectively. The correlation coefficient ρ for years 2001, 2010 and 2020 is equal respectively to 0.89, 0.79, and 0.80.

To unravel the role of the individual interactions regarding the different activities, the data features related to innovation (namely patents Y_p and patent families Y_{pf}) and to recycling (namely total recycled waste Y_r, glass Y_{rg}, plastic Y_{rp} and others) have been analysed as a function of N, the population size referred to each of the 106 metropolitan areas, taken as an independent variable. The general outcomes of the analysis confirm the onset of power-law relationships between patents vs. population size N and recycling vs population size N as shown in **Figure 3a–l**. By plotting the data vs. population in log-log scales, a linear regression allows to estimate the value of the exponent β entering Equation (2). Each graph reports the value of the exponent β and the intercept q with the regression errors. Both a single year and the average over 20 years (2001–2020) have been considered.

As far as innovation is concerned, the analysis has been implemented on patents and patents' families issued in the 106 metropolitan areas. **Figure 3a–c** show the relations between the number of patents Y_p, as a function of the population size N of the 106 metropolitan areas for the years 2001, 2010 and 2020. **Figure 3d–f** show the relations between the number of patents' families Y_{pf}, as a function of the population size N of the 106 metropolitan areas for the years 2001, 2010 and 2020. The quantity of patent data satisfactorily allows the visualization of robust trends over the investigated period as a function of the population size. The relations show that β is always larger than one for patents and patent families.

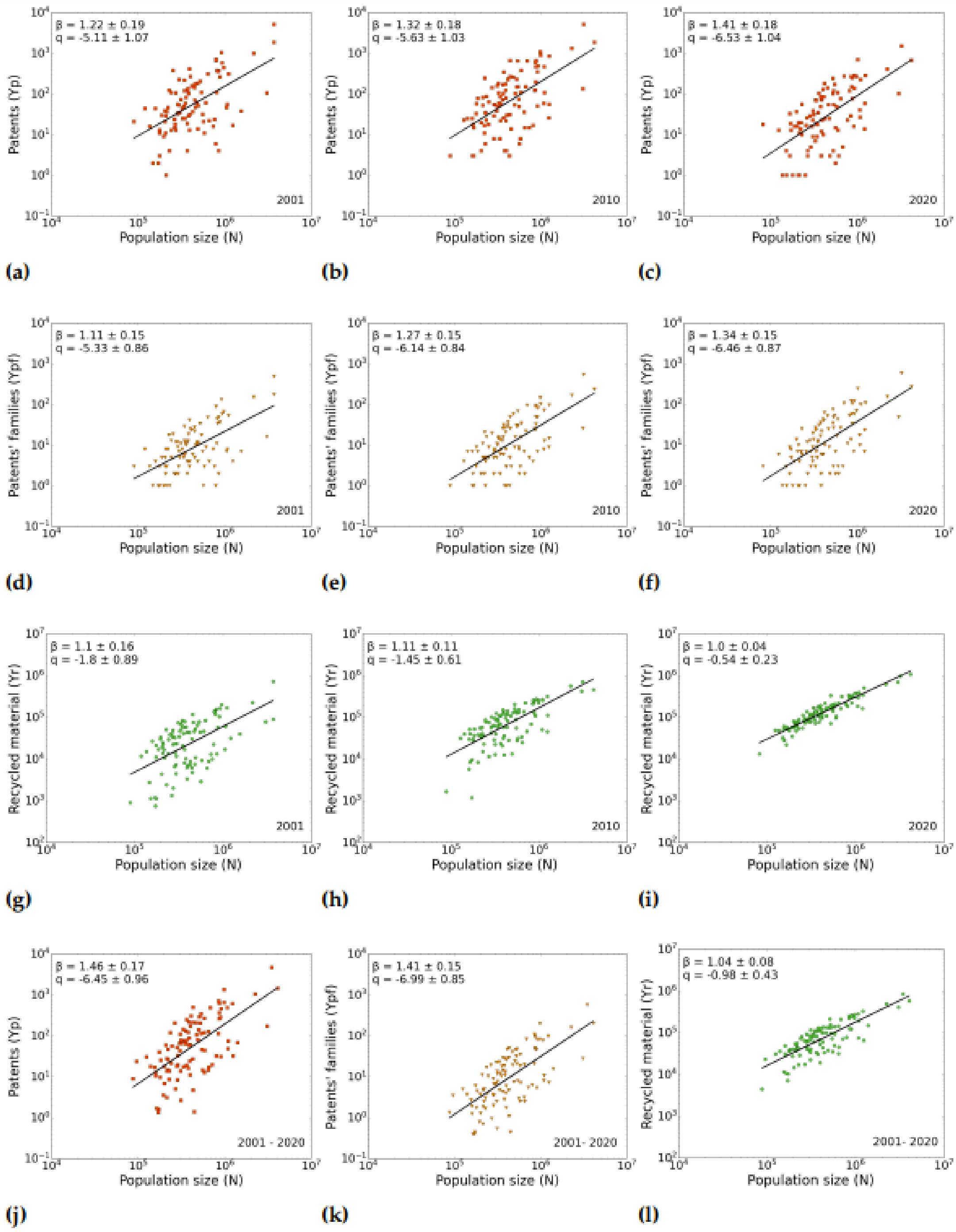


Figure 3. Patents vs. population size for the years **(a)** 2001; **(b)** 2010; **(c)** 2020. Patents' families vs. population size for the years **(d)** 2001; **(e)** 2010; **(f)** 2020. Recycled material vs. population size for the years **(g)** 2001; **(h)** 2010; **(i)** 2020. **(j)** Patents; **(k)** patents' families; **(l)** recycled material for the whole analyzed period from 2001 to 2020.

Regarding recycling data, the analysis has been carried out on features such as the total amount of recycled resources Y_r and the amount of recycled waste fractions Y_{rg}, Y_{rp}, … with respect to the population size N. **Figure 3g–i** show the relationships between the amount of recycled resources collected in a territory and its population size N respectively for the years 2001, 2010 and 2020. It is worth noting that the exponent β is always close to one for recycling. As a further confirmation of data robustness, **Figure 3j–l** show the values of β and q evaluated as the average values over the 20 investigated years for the patents, patent families and recycling material.

Table 2 reports the values of the exponent β and dispersion $\Delta\beta$ for all the investigated years. The first column reports the year. The exponent β and the dispersion $\Delta\beta$ are reported for patents and for patent families respectively in columns 2 and 3. The fourth column reports the exponent β and the dispersion $\Delta\beta$ for recycled resources. Values of $\beta > 1$ for patents and patents families indicate superlinear scaling, as expected for socioeconomic features. As the population size of a territory increases, the patenting rate increases even more, indicating an amplification of the innovation outcome of the region with the number of residents. Values of $\beta \approx 1$ for recycled material indicate linear scaling, as expected for individual features. As the population size of a territory increases, the recycling rate simply increases as the sum of the individual contributions. For the sake of completeness, the relation between the amount of glass, organic, paper and plastic fraction and population size has been also investigated. The scaling behaviour is approximately linear and similar to those of the total amount of recycled material. In all cases, a concentration of the data along the regression line can be observed. The decreasing value of the dispersion $\Delta\beta$ in column (4) clearly indicates the trending alignment towards a virtuous recycling behaviour. The relation between the amount of recycled resources of the analyzed waste fractions (paper, glass, plastic and organic waste) and the population size is similar to the whole amount of recycled resource. In particular, the value of the exponent is close to 1. Data concentrate along the regression line indicating an increasing attitude towards recycling.

Table 2. Exponent β, dispersion $\Delta\beta$, R^2, adjusted R^2_{Adj} and correlation coefficient ρ for patents' families (2), for patents (3) and for recycled material (4) per each investigated year (1). The exponent β and its dispersion $\Delta\beta$ averaged over the whole investigated period (years from 2001 to 2020) are reported in the last row.

Year (1)	Patents' families (2)				Patents (3)				Recycled material (4)			
	$\beta \pm \Delta\beta$	R^2	$R^2_{Adj.}$	ρ	$\beta \pm \Delta\beta$	R^2	$R^2_{Adj.}$	ρ	$\beta \pm \Delta\beta$	R^2	R^2_{Adj}	P
2001	1.11 ± 0.15	0.37	0.36	0.73	1.22 ± 0.19	0.31	0.30	0.72	1.10 ± 0.16	0.32	0.31	0.66
2002	1.19 ± 0.18	0.32	0.31	0.69	1.38 ± 0.21	0.31	0.30	0.68	1.09 ± 0.14	0.33	0.32	0.67
2003	1.06 ± 0.17	0.31	0.31	0.69	1.11 ± 0.21	0.25	0.24	0.68	1.06 ± 0.14	0.32	0.31	0.71
2004	1.26 ± 0.15	0.42	0.41	0.74	1.36 ± 0.19	0.37	0.36	0.73	1.06 ± 0.13	0.33	0.32	0.74
2005	1.29 ± 0.16	0.40	0.40	0.74	1.47 ± 0.20	0.36	0.36	0.73	1.05 ± 0.12	0.40	0.39	0.76
2006	1.30 ± 0.14	0.47	0.47	0.73	1.50 ± 0.18	0.44	0.43	0.72	1.08 ± 0.12	0.42	0.41	0.76
2007	1.31 ± 0.15	0.46	0.45	0.74	1.40 ± 0.19	0.38	0.37	0.74	1.06 ± 0.12	0.41	0.40	0.77
2008	1.39 ± 0.14	0.49	0.49	0.76	1.57 ± 0.17	0.46	0.46	0.76	1.06 ± 0.11	0.44	0.43	0.79
2009	1.30 ± 0.15	0.44	0.44	0.74	1.35 ± 0.18	0.38	0.38	0.70	1.07 ± 0.11	0.49	0.49	0.84
2010	1.27 ± 0.15	0.43	0.42	0.72	1.32 ± 0.18	0.35	0.35	0.68	1.11 ± 0.11	0.52	0.51	0.83
2011	1.19 ± 0.16	0.36	0.35	0.69	1.25 ± 0.21	0.28	0.27	0.64	1.10 ± 0.10	0.57	0.56	0.87

Table 2. (*Continued*).

Year (1)	Patents' families (2)				Patents (3)				Recycled material (4)			
	$\beta \pm \Delta\beta$	R^2	$R^2_{Adj.}$	ρ	$\beta \pm \Delta\beta$	R^2	$R^2_{Adj.}$	ρ	$\beta \pm \Delta\beta$	R^2	R^2_{Adj}	P
2012	1.31 ± 0.18	0.36	0.35	0.67	1.56 ± 0.20	0.40	0.39	0.63	1.08 ± 0.09	0.57	0.57	0.88
2013	1.27 ± 0.15	0.44	0.43	0.67	1.42 ± 0.20	0.36	0.36	0.64	1.08 ± 0.09	0.64	0.64	0.91
2014	1.29 ± 0.18	0.35	0.34	0.66	1.42 ± 0.24	0.28	0.27	0.62	1.08 ± 0.09	0.60	0.60	0.91
2015	1.15 ± 0.16	0.36	0.36	0.66	1.25 ± 0.18	0.32	0.32	0.63	1.05 ± 0.08	0.64	0.64	0.92
2016	1.33 ± 0.16	0.42	0.41	0.65	1.38 ± 0.19	0.36	0.35	0.63	1.05 ± 0.07	0.65	0.65	0.93
2017	1.39 ± 0.16	0.45	0.44	0.67	1.48 ± 0.19	0.40	0.39	0.66	1.04 ± 0.06	0.73	0.73	0.94
2018	1.40 ± 0.17	0.41	0.41	0.71	1.39 ± 0.19	0.35	0.35	0.70	1.02 ± 0.05	0.80	0.80	0.95
2019	1.43 ± 0.16	0.45	0.45	0.71	1.43 ± 0.18	0.39	0.38	0.70	1.02 ± 0.04	0.83	0.82	0.95
2020	1.34 ± 0.15	0.45	0.44	0.73	1.41 ± 0.18	0.39	0.38	0.71	1.00 ± 0.04	0.85	0.85	0.95
2001–2020	1.41 ± 0.15	0.45	0.45	0.72	1.46 ± 0.17	0.41	0.41	0.69	1.04 ± 0.08	0.64	0.64	0.89

6. Discussion

The relationship between waste recycling and patenting performances at the scale of provinces for the whole Italian territory over a time scale of two decades has been investigated. People play a crucial role in increasing the number of filed patents and the amount of recycled waste also considering the complexity of local, national and international legislation, of innovation systems, waste types, and transformation processes just to mention a few (Kirchherr et al., 2017; Zisopoulos et al., 2022). The results of this study indicate a different attitude of the population towards recycling and innovation as it will be argued in the next paragraphs.

The urban scaling methodology, briefly recalled in section 3, has been implemented to analyse to what extent:

- Number of filed patents;
- Number of patents' families;
- Total recycled waste;
- Recycled fractions of glass, organic, paper and plastic vary as a function of the population size of the 106 analysed provinces over a time window of two decades.

To the aim of quantifying the relationships between recycling vs. population and between innovation performance (measured by patents) vs. population, the analysis leverages a large database of patents and recycled material covering the entire Italian country population in the period 2001–2020 at the municipality level as described in section 4. The whole database is accessible in Alcamo et al. (2024). There is a broad interest to exploit the predictive power of the urban scaling laws by using historical projections over extended time windows. For example, Burghardt et al. (2024) investigates data for urban agglomerates in USA over a time horizon of one hundred years.

The results of the analysis reported in section 5 outline the emergence of scaling laws of the form of Equation (2) with statistically significant values of the exponent β, dispersion $\Delta\beta$, correlation coefficient ρ and regressor significance R^2 and R^2_{Adj} for patents and municipality waste with respect to the population size N. Values of the exponents $\beta > 1$ (superlinear behaviour) and $\beta \approx 1$ (linear behaviour) are respectively found for patent features and recycled material as shown in **Table 2**. Values of the exponent $\beta > 1$ for patent and patent families are consistent with systems where interactions among innovation actors (companies, institutions, policies ...) play a major role (Bettencourt et al., 2008, 2007; Ribeiro and Rybski, 2023). In particular, for patents and patents' families data, β ranges from 1.3 to 1.4. The dispersion $\Delta\beta$ for patents and patent families takes values ranging from 0.14 to 0.24 with negligible trend over the investigated years. The large dispersion $\Delta\beta$ for patent and patents' families indicates that β strongly fluctuates around the regression line as reported in **Table 2** and visualized in **Figure 3a–f**. Overall, the results indicate a patenting system attitude heterogeneously distributed across the country.

For recycled waste, β takes values always close to 1.0 indicating linearity. Compared to patenting, the dispersion values for recycling are smaller and markedly decreasing over the investigated years. The dispersion $\Delta\beta$ exhibits steadily decreasing trend varying from 0.16 to 0.04 over the investigated decades. One can note from the results reported in **Table 2** and visualized in **Figure 3g–i** that recycling data for the 106 provinces steadily tend to accumulate onto the regression line. This indicates that on average each person recycles the expected quantity of waste per capita and the recycling attitude aligns across metropolitan areas. People in large municipalities have approximately the same performance as the ones in smaller municipalities with limited dispersion with respect to the expected values. The decreasing trend of the dispersion indicates that the policies put in place over the national territory are quite effective to boost a correct behaviour in terms of recycling, provided the correctness of the data published at the ISTAT website.

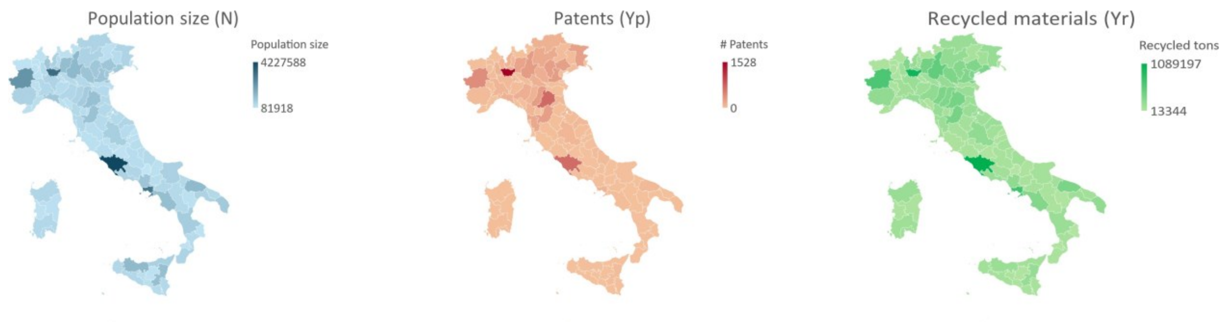
In the case of patents and patent families, larger urban agglomerates and municipalities generate more innovation with larger and constant dispersion $\Delta\beta$ around the regression line over the investigated period. The large values of the exponent and its variation indicate a variety of innovation attitudes across the country. Though a slight increase of the average number of issued patents has been observed, the dispersion among different territories is still remarkable hence pointing to the diverse efficacy of the innovation policy put in place across the country. The access to knowledge boosts creativity and productivity of individuals generating new inventions and wealth resulting in the tendency of firms with main activity related to R&D to locate their business in larger cities where the critical mass of well-educated individuals can flow in. Then, the emergence of a network of inventors plays an important role in fostering interactions and attracting other inventors and investment towards the same area. In accordance with the literature, it would be plausible to admit that the dynamic interactions within a population increase the innovation performance by attracting and leveraging on educated, highly skilled and entrepreneurial individuals (Audretsch and Feldman, 2004).

The results of the analysis can be summarized as follows:

- Values of the exponent $\beta \approx 1$ for recycling performance indicate no negligible multiplicative effect emerging from the interactions among citizens contrarily to the patenting attitude exhibiting exponents $\beta > 1$ for all the investigated years. For the case of recycling, the interactions are very likely limited at the smallest scales (i.e., within family, neighbours, and close friends) rather than involving larger population circles. Hence, behaviours do not differ much between large and small municipalities.

- Steadily decreasing values of the dispersion $\Delta\beta$ for recycling (from 0.16 to 0.04 over the investigated years) point to an increasing attitude towards recycling by the population regardless of the size of the urban agglomerates.
- Fluctuating values of the dispersion $\Delta\beta$ for patenting (randomly varying from 0.16 to 0.24 over the investigated years) indicate an unchanged attitude towards innovation by the metropolitan population ecosystem. The values of the dispersion $\Delta\beta$ for patenting are larger than for recycling, hence confirming the heterogeneous economic development across the country.

To better clarify the extent of the different attitudes towards patenting and recycling and shed light on the meaning of the urban scaling indicators reported in section 5, the maps in **Figure 4** show the distributions of the population size, number of patents and amount of recycled material for the 106 provinces for the year 2020.



(a) **(b)** **(c)**

Figure 4. Map of the distribution of **(a)** population size; **(b)** number of patents; **(c)** tons of recycled material of the 106 provinces of Italy.

Note to **Figure 4**: The different color intensity represents different values of each feature. The detailed scales of the values are shown in the upper right corner of each map. In particular the population size ranges from the minimum value 81,918 for Isernia to 4,227,588 for Roma, the number of filed patents ranges from 0 for the provinces of Agrigento, Enna, Grosseto, Matera, Nuoro, Oristano, Potenza, Ragusa, Trapani, Verbano Cusio Ossola to 1528 for the province of Milano. The amount of recycled material ranges from 13,344 (tons) for Isernia province to 1,089,197 (tons) for Roma province.

The reader can note the most populated metropolitan areas in map Figure 4a: Rome in the center, Milan and Turin in the north, Naples, Palermo, Bari in the south of the country. The diversity of population size of map Figure 4a is not exactly mirrored in the patent distribution shown in map Figure 4b. A flatter coloring in the central and southern part of the map Figure 4b indicates that the innovation outcomes are lower than expected compared to the population size shown in map Figure 4a. Conversely, by looking at the recycled material map Figure 4c, one can note that the variety of the population size shown in map Figure 4a is reflected more or less faithfully across the provinces shown in map Figure 4c, as expected with the exponent $\beta \approx 1$. The geographical differences shown in the maps point to a complementary interpretation of urban scaling as argued by (Keuschnigg et al., 2019). Superlinearity of the socioeconomic features, with values of exponent β larger than 1, points to a positive multiplication effect of the increased population and to an unambiguous divide across the analysed regions.

7. Conclusion and future development

The results of this study show a nonlinear relationship between the number of patents and the amount of recycled waste. The population behaviour is different when referred either to recycling or innovation for the 106 metropolitan areas pointing to a heterogeneity of attitudes. A larger population size, with increasing underlying interactions among citizens, institutions, and companies, acts with multiplier effect on innovation. In the case of recycling, the amplification effect is not evident.

The proposed study has theoretical and methodological implications, which can help the scientific community and the policy-makers to analyze and better understand complex systems behaviours, such as those of populations of a whole country. Specifically, when the analysed system, such as the one of the waste municipality, is regulated at the national and local level, the results evidenced a trends towards a general alignment of the attitude according to what expected on account of the linearity of the scaling laws and the decreasing dispersion values of the exponents. The converse is true for innovation which shows diverse performances across the country. For this reason, analyzing large database of facilities (technical subsystems) and corresponding behavioural patterns (social subsystems) is crucial for the optimization of their functionality and overall acceptance. The same population performs differently in terms of innovation and recycling, meaning that adequate policies should be put in place to achieve sustainable development goals in multiple social dimensions. The evolution of waste recycling performances is also determined by how society understands and participates and not only as a physical change. Urban policies act on knowledge-sharing and collaboration networks to break down cognitive, cultural, and linguistic barriers, improve overall performance, and enhance social subsystem's capability.

Future research directions of this study would deepen the knowledge and shed more light on these and related phenomena by including but not limited to the introduction of:

- Other innovation indicators, for example, the investments in R&D;
- Other waste sources, provided enough and reliable data be publicly accessible;
- Other countries, the current study refers to Italy, as a model of innovation and waste recycling at all scales;
- Other features in the database.

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