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'Pay as you own' or 'pay as you throw'? A counterfactual evaluation of alternative financing schemes for waste services

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ABSTRACT

Italian municipalities finance waste services by applying either a general property tax ("pay-as-you own" system, PAYO) or, less frequently, a fee calibrated to the waste produced by each household ("pay-as-you throw" system, PAYT). The aim of this paper is to estimate what would be the impact of a massive implementation of PAYT schemes. We gather information for a panel of Italian municipalities, covering a ten years time span, in order to assess the impact of switching from PAYO to PAYT on both the amount of waste generated by households and the cost for waste services. Our empirical strategy is based on a IV 3SLS cost model in a counterfactual setting and deals with the simultaneous determination of the demand and supply side of waste services, also taking into account the cross dependency among sorted and unsorted waste. Our results show that the adoption of PAYT schemes brings a simultaneous significant reduction in both quantity and cost, especially for unsorted waste.

1. Introduction

The challenges posed by climatic change can be addressed by a comprehensive strategy, aimed at reducing net emissions of greenhouse gases and at the same time transforming production processes so as to decouple economic growth from resource use. As for European countries, the strategy for a climate neutral economy is embedded in the "Circular economy package" which was followed by the European Green Deal, committing Member States to achieve zero net greenhouse emissions by 2050.[2] Consistently with this goal, the European policy response to the pandemic crisis set up by NextGenerationEU has devoted 30 per cent of its resources to fight climate change.

Waste management plays a crucial role in the green agenda. Waste is the fourth largest source of emissions, accounting for more than 3 per cent of greenhouse and one fifth of methane global gas emissions respectively. Most of such emissions arise from the anaerobic decomposition of the organic fraction of solid urban waste in landfills. According to the most recent data, of the 4.8 tonnes generated yearly by an EU inhabitant, roughly one third is disposed on landfills and only 40 per cent is recycled: changing the treatment of municipal waste – by enhancing differentiation, composting and recycling – is therefore a key policy action towards achieving a more environmentally friendly society.[3]

Within this framework the debate among public finance scholars has increasingly focused on how taxation could contribute to climate neutrality. Waste services are usually financed by applying either a general tax (often similar to a property tax) or a specific fee. In the first case the tax is in some way calibrated to real estate wealth, giving rise to a "pay-as-you own" (PAYO) system; in the second case the fee is commensurate with the amount and the type of waste generated by each household in accordance with a "pay-as-you throw" (PAYT) principle. Under PAYO schemes households face a zero marginal cost for generating waste while the cost borne by the whole community (and arising from pollution) is positive: this misalignment leads to an excessive production of waste. Under PAYT households have to pay for each additional unit of waste sent to disposal; the effect is similar

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[1] The views expressed in the articles are those of the authors and do not involve the responsibilities of the employing institutions. Any mistake or inaccuracy is the sole responsibility of the authors.

[2] The package is composed of four directives approved on June 2018: Directive 2018/849 on end-of-life vehicles; Directive 2018/850 on landfills; Directive 2018/851 on municipal waste; Directive 2018/852 on packaging and packaging waste

[3] See https://ec.europa.eu/eurostat/statistics-explained. Also the paper by Lombardi et al. (2021) emphasises that *the collection method emerges as a crucial issue in ensuring the transition towards circular economy.*

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to a Pigouvian tax, which realigns the individual and social costs and delivers an optimal amount of waste generation. Switching from a PAYO to a PAYT system in the local financing system would hence provide the more suitable economic incentives to contain pollution, emerging as a top policy priority in the green agenda.

Over the last two decades PAYT have supplanted PAYO schemes in many industrialised countries, becoming widespread. Supported by a heightened public consciousness about environmental concerns, they have been widely applied also by EU countries and are providing a valuable contribution to meet the ambitious targets set by European directives in terms of waste differentiation and disposal. But unlike other major European countries, Italy still lays far behind in implementing PAYT schemes: out of 7,900 municipalities roughly 1,000 have so far adopted financing schemes that directly or indirectly price each unit of garbage sent to disposal (these systems are also labelled "unit pricing" schemes and in what follows we use this expression interchangeably with PAYT).

The objective of our work is to assess the benefits of a massive implementation of unit pricing by Italian municipalities. The advantages of a radical change in the methods of financing waste services could be twofold: from the point of view of environment sustainability, the switch from PAYO to PAYT systems is expected to reduce waste generation whilst increasing differentiation and recycling (demand side effects); from the point of view of local finance, the cost for waste services could consequently be reduced (supply side effects) thus promoting a more efficient use of public resources.

Our empirical exercise is conducted on a panel of more than 6,100 municipalities from 2010 to 2020. We follow a quasi-experimental approach built on a difference-in-difference strategy, which provides evidence that the demand and the supply of waste services respond not only to demographic, social and institutional variables, as predicted by the theory, but also to the financing schemes adopted by municipalities. The methodology innovates with respect to previous studies since it deals with the simultaneous determination of the demand and supply side of waste services – addressing endogeneity issues between cost and quantity – and takes into account the cross dependency among sorted and unsorted waste in the municipal cost function; furthermore, it explores the heterogeneity of the response over time. Our results show that the adoption of PAYT brings a statistically significant reduction in the amount of waste generated which is in turn associated with a decrease in the total cost for waste services. The latter is equal to approximately −17% in terms of cost (and about −13% in terms of quantity), in line with the findings of Valente (2023) and Bucciol et al. (2015), and is more sizeable in the case of unsorted waste (for which the impact is already detectable in the short run).

The rest of the paper is organised as follows. Section 2 describes the theoretical background and reviews the main contributions of the economic literature. Section 3 focuses on the Italian framework and the financing options for waste services currently adopted by municipalities. Section 4 outlines our empirical strategy, while Section 5 illustrates the data set and the main findings of the econometric analysis. Section 6 summarises and discusses future lines of research.

2. Literature review and research hypothesis

The academic debate on the optimal way of financing waste services is longstanding. Since late seventies of the last century a prolific line of research, fuelled by Wertz (1976), has highlighted the benefits of PAYT as opposed to PAYO systems. The central argument is that PAYT provides a market signal that enables households to produce an efficient amount of waste, improving environmental sustainability. Waste is a by-product of individual consumption choices and hence is a normal good, whose demand rises with income levels and reacts negatively to increasing costs for disposal facilities; models of waste generating processes and recycling decisions have been developed, among others, by Smith (1972), Richardson and Havlicek (1978), Morris and Holthausen (1994), Fullerton and Kinnaman (1996). These models suggest that producing waste involves significant negative externalities and social costs (arising from landfill congestion, disamenities, reduction in the real estate values and release of greenhouse emissions). If disposal activities are financed through general taxation the social cost of generating an additional unit of garbage is systematically higher than the individual marginal cost, whereas social and individual costs become comparable if unit pricing is applied. In this way PAYT systems reduce the amount of garbage produced by households and consequently the demand for waste services. This efficiency-enhancing effect extends similarly to the supply side of local waste services. Also unit pricing provides a yardstick for voters to evaluate local administrators' performance and thus induces them to contain costs and make the best possible use of scarce public resources (Ferraresi et al., 2018). Issues of waste financing also have implications for equity, as pointed out by Wright et al. (2018). In PAYO systems the disposal costs for high-income households, that produce large quantities of rubbish, are partially subsidised by low-income households, which generate lower amounts of waste. This circumstance was documented for the Italian framework, where waste is financed mostly through property tax revenues. The work by Messina et al. (2018) indeed showed that households in the lower decile of consumption distribution pay for waste taxes twice as much (in terms of income shares) that as households in the upper decile.

In practice, various implementations of PAYT financing schemes are possible. Kinnaman (2006) has identified three main types of unit pricing systems: bag- or tag-based systems, requiring households to purchase specific bags for disposal or stickers that identify the bins where waste is collected; weight-based systems, where trucks for collection are provided with scales to weigh a household's waste; and subscription or can systems, where residents subscribe to a given number or size of cans and are billed accordingly. Taleb and Al Farooque (2021) show how the volume-based PAYT method leads to lower costs and better incentives for households in terms of economic, social and environmental benefits. Morlok et al. (2017) provide a thorough discussion of the advantages and disadvantages of each one of these options. The common element is that the transition to PAYT may require massive investments, arising from the need to prompt plants for selecting, composting, and processing materials and technological devices for measuring the disposal of waste by each user. Initial fixed investment costs may be overwhelming for some municipalities, and only partially compensated in the short term by savings in waste management operating costs. Also additional administrative costs should be taken into consideration, arising from activities such as distribution of bags or stickers, user assistance, or taking stock of waste containers. All these factors considered together may discourage some local governments from adopting unit pricing. Another perceived barrier could be the risks of illegal dumping or waste tourism towards neighbouring municipalities, but the prevailing consent among scholars is that the scale of such behaviours would be small if compared with the overall positive impact of PAYT: see Linderhof et al. (2001), Card and Schweitzer (2016), and, for a different point of view, Kinnaman (2006).

The empirical research on PAYT was pioneered by studies concerning the US. Wertz (1976) compared San Francisco, where a PAYT volume-based system had been adopted (*i.e.* a fee was charged on the number of bins put out for collection), with other urban areas and estimated a negative price elasticity of −0.15 in the amount of household generated garbage. This estimate is in line with the one found by Skumatz and Breckinridge (1990) for a similar system implemented years later in Seattle. According to Fullerton and Kinnaman (1996), the attempt of households to compress rubbish in order to fill fewer bags or bins without any reduction in the amount of garbage produced (an effect known as the 'Seattle stomp') may have reduced the effectiveness of such systems. Elasticities of the price of waste upon waste quantities close to −0.30 were estimated by Morris and Byrd (1990) for the bag-based system implemented in Perkasie (Pennsylvania) and Ilion (New

York), by Van Houtven and Morris (1999) and Morris and Holthausen (1994) for the PAYT system implemented in the city of Marietta (Georgia) and by Kinnaman and Fullerton (2000) in a cross-section of 114 US municipalities.

The evidence on the European experience is limited to a few countries. One prominent study is that carried out by Linderhof et al. (2001) on the implementation of a weight-based system in a Dutch municipality (Ostzaan): using a panel data set with individual observations on each household, the authors find significant short-run as well as long-run price effects for the amount of both compostable and non-recyclable waste, with the elasticity of the former being nearly four times greater than the elasticity of the latter and long-run elasticities about 30 per cent larger than short-run ones.

More recently, Allers and Hoeben (2010) applied a difference-in-difference approach to control for unobservable local characteristics on a sample of 458 Dutch municipalities and found a significant effect for unit pricing in reducing waste generation and increasing recycling, even after controlling for endogeneity. The authors found that the unitary price effect (user fee) depends on the pricing system: weight-based systems reduce waste quantities more than volume-based systems (for compostable waste the estimated elasticity is −1.77). Similar evidence was provided more recently by Morlok et al. (2017) for Germany, by Carattini et al. (2018) for Switzerland and by Vorobeva et al. (2022) for Portugal.[4] Finally, Ukkonen and Sahimaa (2021) developed a model to implement weight-based PAYT schemes, that would encourage efficient source separation and a significant decrease in the price of household waste; this financing scheme would turn out to be an important part of the policy mix aimed at reaching the EU targets.

Overall, the common findings of this very prolific field of empirical research can be traced by following (Bel and Gradus, 2016), who performed a meta-regression analysis on a database of 25 studies. They found that the elasticity of the price of waste upon household waste quantities is negative and in the order of 0.3 in magnitude, and estimates are not influenced by endogeneity issues. There is a slight indication that municipal data provide higher estimates for price elasticities with respect to individual data and that the elasticities found in studies focused on US experiences tend to be higher. As for the design of PAYT schemes, the systems whereby compostable waste is collected and charged separately seem to be more effective; in the same way, the elasticities derived for weight-based systems are considerably greater than those derived for volume-based programmes (whereas it does not make any significant difference if the latter are built upon the collection of bins or bags).

With reference to Italy, the empirical evidence is rather sparse and often focuses on the experience of small territories. Bucciol et al. (2015) estimate that the adoption of PAYT by 95 municipalities in the district of Treviso leads to an increase in the sorted to total waste ratio by 17 percentage points and found spatial as well as time effects associated with learning processes. Bueno and Valente (2019), using the synthetic control method, prove that unit pricing policies have been effective in reducing by 37.5 per cent unsorted waste generation in the municipality of Trento (with an impact statistically weaker of −8.6 per cent on total waste). Compagnoni (2020) follows a difference-in-difference approach with multiple treatment and time periods and assesses the impact of PAYT in 81 out of 331 municipalities in Emilia-Romagna, highlighting a 9.6 per cent decrease in total waste production and a non significant increase in sorted waste. Lombardi et al. (2021) use a non-parametric approach to measure the efficiency of municipal waste systems in 78 large Italian cities between 2014 and 2018, showing significant heterogeneities among municipalities. Waste management services are found to be more efficient in cities located in the North and in the Centre compared to Southern ones, in more densely populated areas and where a higher proportion of elderly people in the resident population. Finally, Romano et al. (2021) identify corruption as one of the key factors in the deterioration of municipal solid waste management in terms of quantity for around sixty Italian provinces for which relevant data was available over a three-year period.

Only a few studies, as far as we know, adopt a national perspective. Messina and Tomasi (2021b) evaluate the effectiveness of PAYT fees in a cross section of 6.100 municipalities by applying different estimation strategies, from standard OLS regressions to propensity score matching and spatial discontinuity techniques; their results show that PAYT schemes deeply affect user behaviour: unsorted waste halves and total waste decreases by roughly 10 per cent. Overall, the costs incurred by municipalities adopting PAYT financing schemes fall by roughly 10 per cent in per capita terms, reflecting a reduction of 20 to 40 per cent in the cost of managing undifferentiated waste. Taken at face value, this evidence implies Italian municipalities would save €0.6 billion per year on solid waste management if they all adopted PAYT schemes. Colussi et al. (2022), making use of a longitudinal municipal data set covering the period 2010–2019, found that PAYT programs reduce unsorted waste by 43 per cent and total waste by 9 per cent (while the effect on sorted waste is statistically not significant); unit pricing also seems to contain waste management costs by 6 per cent in per capita terms and to generate positive spillover effects on pro-environmental citizens' behaviour. More recently, Di Foggia and Beccarello (2023) show that the adoption of unit pricing is a stimulus for reducing waste and improving the quality of the separated collection. Unit pricing is associated with higher environmental performance (+4 per cent increase in the share of sorted waste) and lower per capita generation of waste management system (−12 kg, around −3 per cent).

Our work contributes to the evidence on the Italian case by taking a national perspective. Compared to Messina and Tomasi (2021b) we add a time dimension, which enables us to assess the short and long term effects of PAYT systems on the demand and the supply for waste services, while a distinguishing feature of our empirical approach with respect to Colussi et al. (2022) is that we explicitly take into account the interdependence between the different types of waste produced. More specifically, our empirical exercise aims at testing the following research hypothesis:

Hypothesis 1. Households respond to monetary incentives associated with a switch from PAYO to PAYT systems.

The first hypothesis refers to the demand side of waste services and specifically to how the sorting behaviour of households is affected by the introduction of PAYT. Following the theoretical literature from Wertz (1976) onward we expect households to adopt actions aimed at reducing the overall quantity of waste produced as well as the fraction of unsorted waste after the adoption of a PAYT.

Hypothesis 2. Changes in household behaviour affect the costs of providing waste services by municipalities.

The second hypothesis relates to the supply side of waste services. We assume that the behavioural response to the introduction of monetary incentives affect the production function of waste services and are reflected in a reduction of the costs incurred by municipalities. Unlike previous analysis that have explored this issue (such as Colussi et al., 2022) we explicitly take into account the mutual interactions that may arise between the provision of collection and disposal services for unsorted and sorted waste.

Hypothesis 3. The effects triggered by the switch from PAYO to PAYT are growing over time.

[4] Vorobeva et al. (2022) show that PAYT is effective in improving waste generation of people with low perceived pro environmental behaviour.

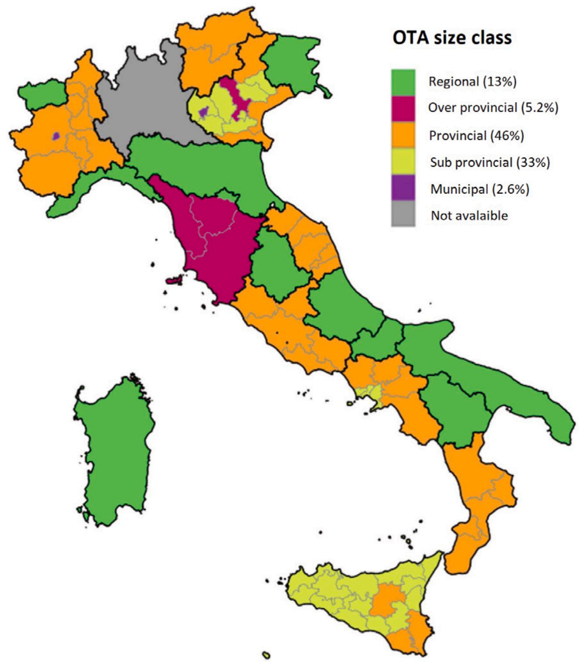


Fig. 1. Geographical boundaries of OTAs.
Source: Invitalia (2019).

The third and final hypothesis concerns the time profile of the response to PAYT. Our a priori is that there may be learning processes as envisaged by Bucciol et al. (2015) as well as administrative difficulties in the implementation of unit pricing or need to make fixed investments which in the short term could hinder the full unfolding of the effects of the adoption of PAYT.

3. Institutional framework

Waste services include a wide range of collecting and disposing activities (including street sweeping). In Italy, these services are performed at municipal level, but municipalities act as the final providers in a complex chain of responsibilities involving several tiers of government up to the European institutions. According to the Italian environmental code (d.lgs. 152/2006) each municipality has to join an Optimal Territorial Area (OTA) *i.e.* a territorial district whose scale is suitable for managing waste services in an efficient as well as environmentally sustainable way. The OTA delimits the perimeter within which the whole cycle of waste collection and disposal has to be completed, following a proximity principle. OTAs boundaries are set up by Regions under the constraint that the territorial scale is at least coincident with that of provincial districts, although different choices are allowed in order to preserve cost-effectiveness in presence of specific features such as high population density. Regions also appoint OTAs governing bodies: the latter are responsible for the organisation of waste services, the definition of managing methods, the outsourcing to publicly or privately owned companies.

Italian municipalities are currently aggregated into 76 OTAs (Fig. 1). In almost half cases OTAs boundaries overlap with that of provincial districts, while a share of one sixth has a supra-provincial or even a regional size; roughly one third of OTAs has a sub-provincial scale (for instance in the provincial district of Naples – the most densely populated area in Italy – three different OTAs are at stake). For the needs related to the organisation of specific activities within the waste cycle (in particular the collection of garbage) some regional administrations have partitioned OTAs in smaller districts, thus leading to the identification of 243 sub-OTAs.

From an operational point of view, following the decision of OTAs governing bodies, waste services can be outsourced to third parties through public procurement procedures or directly assigned to in-house companies; it is also possible that the service is awarded to a mixed public–private company through a specific type of tender. The management of waste services can encompass the whole integrated cycle of the refuse, including the realisation and operation of plants, or may be limited to single activities such as collection, transport, treatment, disposal. A recent survey involving 61 per cent of Italian municipalities identified 368 management companies (Invitalia, 2019). OTAs governing bodies are formally in charge of defining waste services financing schemes for municipalities falling within their jurisdiction. As mentioned above, there are two viable options. The most common is that waste services are financed through a property tax, which is owed by each family living in a house (either as an owner or a tenant) and is computed based on the house's area and the household size as presumptive indicators of waste production. The alternative is to apply unit pricing methods and charge households according to the quantity and the type of refuse they produce. The first financing scheme comes close to taxing households wealth ("pay as you own", PAYO), since house size can be considered as a rough indicator of real estate wealth. The impact of the tax is regressive since properties differing in their real estate values and households with heterogeneous standards of living are treated in the same way. More than 8 out of 10 Italian municipalities are currently adopting PAYO schemes. The corresponding tax burden borne by households is not negligible: we can estimate that a representative family pays €260 per year for waste services in Northeastern Regions and €380 in Southern Regions; these amounts have grown by almost a fifth on average since the beginning of 2010's (Fig. 2).

As opposed to PAYO, unit pricing PAYT schemes provide an application to the polluters pay principle and require the adoption of specific measurement methods when collecting waste. Different solutions have been implemented (Messina et al., 2018a). In some cases a partial unit pricing is applied, by fixing a flat 'first-tier' fee covering a given number of bags or bins to be collected and a 'second-tier' fee based on the additional amount of waste thrown away: such schemes ensure the coverage of a minimum level of service, at the same time does not encourage illegal dumping. Alternatively, the price for waste services can be specifically tailored to waste production: national law requires that at least the fraction of unsorted garbage generated by each user is measured, but municipalities frequently also measure organic, differentiated and/or green waste. Assessing the amount of garbage produced is an integral part of waste charges: the dry fraction can be measured either directly according to its weight or indirectly according to its volume. Some types of waste (such as green garbage) can be priced with a flat fee (if the service is activated by the user), according to the number of pieces collected (for bulky materials) or the frequency of collection. Finally, PAYT municipalities employ specific technological devices to measure the amount of waste generated by each user, such as bags endowed with microchips, bins with user recognition systems, and weighing scales placed on collecting trucks or installed in waste collection centres.

What matters most to the purpose of our analysis is that the decision to adopt a PAYT or a PAYO scheme is undertaken by OTAs governing bodies and municipalities simply have to comply with the decisions made for the entire area to which they belong. Thereby a potential source of endogeneity with which other studies on public policies effectiveness have to tackle with is in this case virtually absent. According to the most recent evidence, slightly more than a thousand Italian municipalities have been assigned by their OTA to a PAYT scheme and three quarters of them apply punctual measurement methods in order to calibrate waste charges on the quality and quantity of refuse produced. The great majority of PAYT municipalities has outsourced to waste management companies (the sector is highly concentrated since

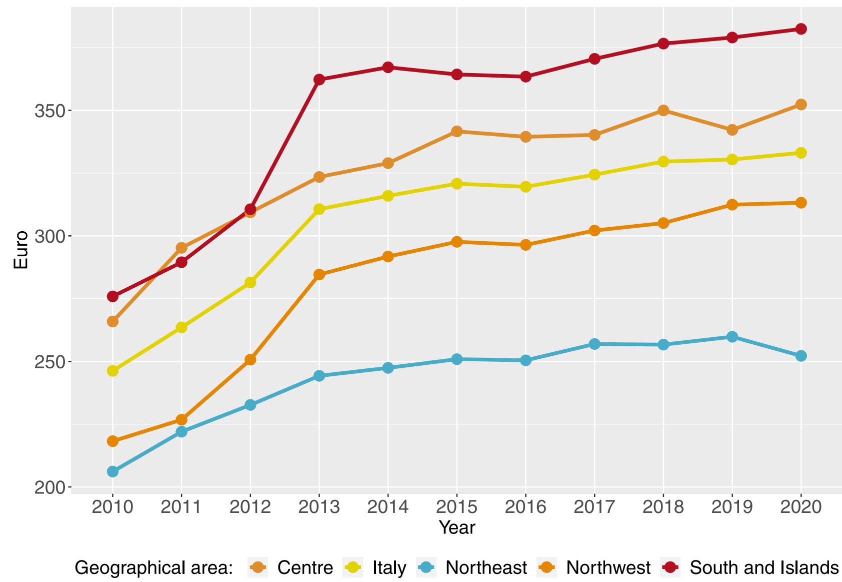


Fig. 2. Waste service taxes (PAYO) borne by households, Euro in real terms (base year 2020) per representative family. *Source:* Federconsumatori (2010-2016) and, for the years 2017–2020, municipal resolutions. Figures are computed for a three-member household resident in a provincial capital and living in a 100 square meter house.

less than ten companies provide the service for over a third of the municipalities considered).

To draw an exhaustive picture of the institutional framework we must finally take into account the additional tasks performed by upper tiers in the vertical hierarchy of general government. Regions are also responsible for outlining regional waste management plans where new plants or renovations of the existing ones are envisaged; Provinces are in charge of identifying the areas suitable for locating new disposal and treatment plants. The central government sets up the general rules and carries out supervisory activities, while regulation and enforcement powers are assigned to an independent national authority (the Regulatory Authority for Energy, Networks and Environment). At the highest level in the scale of responsibilities are the European institutions which formulate the guidelines for the environmental policy of the whole area. In particular, in June 2018 a "Circular economy package" was approved. The package set ambitious targets for member States, committing them to collect separately the organic fraction by 2024, increase the share of recycled urban waste to 55 per cent by 2025 (and then to 60 per cent by 2030 and 65 per cent by 2035) and reduce the incidence of land filling disposal to 10 per cent by 2035.

4. Empirical approach

The empirical cost function for the production of public services for a given time period t and a given municipality i may be expressed basically as a simultaneous system in which *(i)* the total unitary cost c depends on the level of production q (output), the prices of the productive factors p and any supply variable S that makes the service more expensive, and *(ii)* the level of production itself, which the local policy-maker must define taking into account the characteristics of his municipality in terms of local demand factors D, the level of income R and, of course, the unitary cost of the service under consideration itself (for a more detailed discussion please see *e.g.* Chambers, 1988; Blochliger et al., 2007).

$$\begin{cases} c_{it} = s(q_{it}, p_{it}, S_{it}) \\ q_{it} = d(D_{it}, R_{it}, c_{it}) \end{cases} \tag{1}$$

As is widely indicated in the literature (see *e.g.* Verbeek, 2008), OLS estimator can be inconsistent (*i.e.* the estimator may not converge to the true population parameter and thus produce biased coefficients) when there is an endogeneity problem (Wooldridge, 2002) and this occurs more precisely in presence of errors or omitted variables or – as in the present case – of simultaneous causality, *i.e.* when two variables (cost c and quantity q) influence/cause each other and have mutual feedback loops (reverse causality). The issue of endogeneity can be addressed using instrumental variables and two- or three-stages least squares approaches (Zellner and Theil, 1962) as well shown by Zaefarian et al. (2017).[5] More in particular, the first stage of a 3SLS model requires the identification of instrumental variables for the endogenous variables of the system: these estimates can be derived as predictions from a linear regression of each endogenous regressor on all the exogenous variables in the system. Given these instrumental variables (second stage) a generalised least squares (GLS) estimator can be identified. Finally, the residuals of the 2SLS estimates of each equation in the system (third stage) can be used to obtain a consistent estimator for the variance and covariance matrix of errors.

To deal with endogeneity in the output q we follow an instrumental variable approach, that makes more explicit the counterfactual setting – the comparison between PAYT municipalities (treated) and PAYO municipalities with similar characteristics (untreated) – and estimate the causal effects of the PAYT policy when treatment assignment is non-random (see Section 5.2 for a more comprehensive discussion).

Referring to Y_t as the dummy variable indicating the year when the treatment started and as $treated$ the dummy variable identifying the group exposed to the treatment, the interaction (called did) between time and treated has been calculated in order to enhance a before–after

[5] Please note that other approaches can be also used in this case such as the Generalised Method of Moments as a system (System GMM, Arellano and Bond, 1991; Blundell and Bond, 1998) which corrects for all three types of endogeneity ("*unobserved heterogeneity, simultaneity and dynamic endogeneity*", Wintoki et al., 2012) not relying on external exogenous instruments, but using the lagged levels of the dependent variable as instruments; but such approaches, albeit with very interesting formal properties, are only suitable in the presence of long time series *i.e.* when it is possible to construct lagged variables of order two without loosing too much information – please note that in our case we also need to define a pre-treatment period and, therefore, the time-span of our panel are even more reduced – and when it is not possible to obtain instrumental variables that are appropriate also from an economic point of view.

comparison for the treatment and control group[6]; Eq. (2) thus shows the did term (the terms Y_t and $treated$ are omitted for simplicity of exposition) and the instrumented output:

$$\begin{cases} c_{it} & = s(q_{it}^{IV}, p_{it}, D_{it}, did) \\ q_{it}^{IV} & = d(S_{it}, R_{it}) \end{cases} \tag{2}$$

A final step is necessary in the context of cost analysis for waste services. There are, in fact, two interconnected parts of the same production function: the first one concerning sorted and the second one unsorted waste. It is, therefore, necessary to make explicit both the two cost functions (and their relative instruments) and their mutual interrelations as in Eq. (3) (for the sake of simplicity subscripts i and t have been omitted from the notation of the equation):

$$\begin{cases} c_{sort} & = s_1(q_{sort}^{IV}, c_{unsort}, p, D_{sort}, did_{sort}) \\ c_{unsort} & = s_2(q_{unsort}^{IV}, c_{sort}, p, D_{unsort}, did_{unsort}) \\ q_{sort}^{IV} & = d_1(S, R) \\ q_{unsort}^{IV} & = d_2(S, R) \end{cases} \tag{3}$$

This setting allows to separately model the treatment for sorted and unsorted waste (did_{sort} and did_{unsort}) having, at the same time, controlled for the interaction between the two cost components and the endogeneity of the quantities collected.

Eq. (3) can be finally described making explicit the relationships in linear terms as a system of simultaneous linear equations using instrumental variables that can be jointly estimated using three-stage least squares (3SLS) estimator.

$$\begin{cases} c_{sort} & = \alpha + \beta_1 q_{sort}^{IV} + \beta_2 c_{unsort} + \beta_3 p + \beta_4 D_{sort} + \beta_5 did_{sort} + \epsilon_1 \\ c_{unsort} & = \gamma + \delta_1 q_{unsort}^{IV} + \delta_2 c_{sort} + \delta_3 p + \delta_4 D_{unsort} + \delta_5 did_{unsort} + \epsilon_2 \\ q_{sort}^{IV} & = \lambda_1 Pop + \lambda_2 Dens + \lambda_3 Size + \lambda_4 Tourist + \epsilon_3 \\ q_{unsort}^{IV} & = \mu_1 Pop + \mu_2 Dens + \mu_3 Size + \mu_4 Tourist + \epsilon_4 \end{cases} \tag{4}$$

where, in particular, the demand factors (instrumental variables) that affect the waste generation are `Pop`, the resident population, `Dens`, the population density, `Size`, the size of the municipality in terms of area (km2) and `Tourist`, the tourist beds per inhabitant, representing the instrumental variables of the waste quantity (q_{sort}^{IV} sort and q_{unsort}^{IV} unsort).

Please note that, in order to ensure that the 3SLS estimator is consistent and efficient, and to provide valid statistical inference on the estimated parameters, the assumptions on the error terms (in addition to the usual assumptions concerning OLS models) concern the exogeneity hypothesis (the error terms in each equation are uncorrelated with the explanatory variables in that equation, and with the error terms in the other equations in the system), the absence of serial correlation (there is no autocorrelation or serial correlation among the error terms in each equation) and of endogeneity (the explanatory variables are not correlated with the error terms in any equation in the system).

5. Application to the Italian municipalities

5.1. Data

The empirical application was conducted using yearly data from different sources. A first set of information concerns the characteristics related to the demand and supply for waste services and to how the system is financed. More specifically we collected from ISPRA (the Italian Institute for Environmental Protection and Research) data on: the year of introduction of PAYT; the amount and the composition of municipal waste (*i.e.* unsorted and sorted, further subdivided into paper, glass, metal, plastic and so on); the main cost components for waste functions (*i.e.* for the treatment of the sorted and unsorted component, as well as for administrative activities); the location of waste treatment facilities; the organisational aspects of waste services (*i.e.* if such services are provided individually or in association with other municipalities, to what OTA a single municipality belongs). Furthermore we have drawn from the archives of municipal regulations managed by the Ministry of Economy and Finance information on the features of the PAYO or PAYT financing schemes adopted by each municipality.[7] A second subset of information is aimed at controlling for the structural characteristics of each municipality, such as population, area, family size, location (*i.e.* latitude and longitude coordinates, dummies for coastal municipalities), cadastral rent: such variables were taken from official data released by the National Institute of Statistics and the Ministry of Economy and Finance (Revenue Agency).

Gathering all this information we have set up a panel dataset not fully balanced of more than 6.000 of municipal observations[8] from 2010 to 2020; it should be noticed, however, that missing data do not represent a major problem for our analysis, since 90% of the observations have full data, 7% have a missing for one year and only the 3% have two or more missing years.

Since the main purpose of our analysis is to estimate differences in waste generation and in waste services costs between PAYT (treated) and PAYO (untreated) municipalities, we built a counterfactual framework, matching each treated municipality with a set of non-treated ones with the most similar characteristics (see the method more fully described in Section 5.2).

The matching procedure led us to select 1020 observations (350 treated and 670 non treated), of which 915 with full panel. It should be emphasised that the year when the treatment has started is different for each municipality and we considered in our subsample only municipalities having adopted PAYT from 2013 onward (in order to have a pre-treatment period of at least three-years to carry out the matching).

In the following we provide a more detailed discussion on how the variables used in the analysis relate to the literature and to the empirical model set up in Eq. (3).

- *Dependent and output variables*: costs are expressed in per capita real terms and refer to current expenditures for the management of the unsorted and sorted shares of waste.[9] Output variables are expressed by the quantities of waste generated, both sorted and non sorted, expressed in kilograms per capita.
- *Demand and supply variables*: some municipal characteristics shape waste generating processes (the demand side, see Hypothesis 1) while some others may constrain the provision of waste services (supply side). A large literature has analysed the impact of such factors (see *e.g.* Picchio, 2022; Grazhdani, 2016; Johnstone and Labonne, 2004; Greco et al., 2015). Population is the main driving force of urban solid waste generating processes. Scale factors can be relevant in such processes, as well as in the supply of waste

[6] With regard to the empirical strategy to calculate the DiD parameter, i.e. the difference in the average outcome between the treatment and control group before and after the implementation of the policy, it is necessary to correctly identify the control group: Section 5.2 discusses this step in detail.

[7] Italian law requires each municipality to issue a regulation on waste charges, usually by the end of May, and to publish it on the website of the Ministry of Economy and Finance.

[8] This number clearly represents the total universe of municipalities offering the waste collection service in Italy: from this, the set of municipalities that have introduced the PAYT service and the corresponding set of matched ones have been extracted.

[9] In the case of missing information most recent available data have been used. In a small number of cases, in which costs are available only for aggregations of municipalities, the data have been broken down on the basis of demographic weights. We excluded from the analysis capital expenditure for waste services because this information is inaccurate and is not representative of managing costs for waste services, but rather of fixed investment costs related to barriers to entry.

services by municipalities, as shown by Dijkgraaf and Gradus (2003), Goodman and Leland (2013) and Simões et al. (2010) (who included in their analysis also a quadratic form for which they found a negative sign). Population density can also be considered as a proxy of the degree of urbanisation, as in Soukiazis and Proença (2020), and, together with municipal area, may capture the urban sprawl effect: the wider is the area of provision of a given public service, the higher are the expected management costs for collecting and disposing waste, as shown among others by Fregolent and Tonin (2016), RERC (1974) and Burchell et al. (2005).

Family size is correlated with waste generation because of its influence on eating and consuming behaviour. Several studies have emphasised that larger households are associated with a lower amount of wasted food on a per capita basis (Canali et al., 2014 and Jörissen et al., 2015). To capture the extent of the demand for waste services arising from non resident population we included an indicator of the intensity of touristic flows (number of bed places in touristic facilities per inhabitant) as (Fasano et al., 2021) (who found that touristic flows can increase the annual production of waste up to 80 annual kg per capita).

Among the supply variables, we considered as a driving factor for the cost of providing waste services the average distance of each municipality from disposal plants, since the distance impacts on transportation costs as shown by Callan and Thomas (2001).[10]

The touristic connotation of a municipality can also influence the supply side of waste services, as costs may be subject to seasonal peaks which may affect the way the service is organised (see Espinosa Lloré et al., 2008; Bel et al., 2014 and, for the Italian case, Greco et al., 2018 who found a significant positive correlation of touristic activity with the collections costs of multi-material, paper and undifferentiated waste). To capture the effects due to the seasonality we further included in our analysis a dummy variable which signals whether or not the municipality is located on the coast.

- *Local prices and income* As an indirect proxy of the local price conditions in the provision of waste services we consider a dummy signalling whether a municipality belongs or not to an association. As a matter of fact the participation in associative formulas can lead to particularly advantageous price conditions for those services characterised by economies of scale. Finally, as a further qualification of the demand for service,s we consider an income variable, specifically per capita average cadastral value of residential property. Such variable is more reliable in describing the variation in local economic conditions than recorded income tax, which is more severely affected by under-reporting as argued by Richardson and Havlicek (1978). The fact that waste is a by-product of consumption and that individuals usually consume normal goods generates the presumption that the demand for waste services is increasing in income and, therefore, the coefficient for the variable should be positive.

To sum up Table 1 reports the descriptive statistics of the variables taken into account together with the role they play in the estimation model; note in particular the demand and the population variables, which are also referred to as instruments for the output variable.

[10] More specifically, the variable included in our analysis corresponds to the average of the distances of the municipality from the closest disposal plant specific for each category of waste (composting plants, anaerobic digestion, integrated aerobic and anaerobic biotreatment mechanical biological treatment, incinerator, co-incinerator and landfill).

5.2. Treatment and matching design

Difference-in-differences (DiD) is one of the most frequently used methods in impact evaluation studies. It has an intuitive appeal and has been widely applied in economics, public policy, management and other research streams. As stated by Athey and Imbens (2006) "*these methods are used in problems with multiple subpopulations – some subject to a policy intervention or treatment and others not – and outcomes that are measured in each group before and after the policy intervention*".

Despite the simplicity of the methodological setting, this framework hides two assumptions that are particularly important in practical applications: *(i)* the policy has to be unrelated to outcome at baseline (the allocation of policy is not determined by outcome) and *(ii)* the treated and control groups have parallel trends in outcome before the treatment.

The first underlying assumption is, therefore, related to the problem of self-selection bias of PAYT municipalities. Adopting a PAYT program could, in fact, depend on municipal characteristics. It may be the case, for example, that environmentally aware municipalities, generating lower amounts of garbage and more accustomed with separate collection of waste, are more prone to introduce unit pricing systems, or conversely that communities with structurally higher levels of refuse per capita and lower recycling rates expect sizeable gains from PAYT policies and hence are more likely to adopt them. This endogeneity in the selection of the treated sample could lead to overestimate or underestimate policy effectiveness. But as already mentioned in Section 3, the risk of self selection in the sample of treated municipalities is absent in the Italian case as a consequence of an institutional framework which substantially deprives municipalities of any decision-making power on how to finance waste services. Specifically the choice between PAYO or PAYT systems belongs to ATOs, a supramunicipal administrative unit with its own representative bodies and to which each municipality is compulsorily assigned by the region to which it belongs.

The second assumption must be verified directly on the data by comparing the treated group with a control group, which must be constructed to be as similar as possible in the pre-treatment period in terms of structure and cost.

It is, therefore, crucial to choose a matching method that identifies the matching set of treated as precisely as possible especially in the present case in which the year of treatment is not the same for all units; Fig. 3 shows separately for the whole of Italy and for the Veneto Region only (the Region with the highest number of municipalities that have chosen the PAYT tariff over time) the time series of the treatment (for the units in red) and of the remaining units (in blue) from which the control group has been extracted.

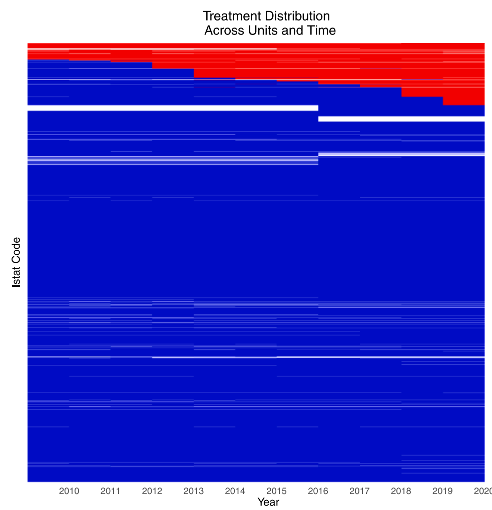
The ability of estimating causal effects with time-series cross-sectional data (TSCS) proposed by Imai et al. (2022) differs from most of these approaches designed specifically for cross-sectional data as it allows for the control of multiple treatments[11] occurring in different time periods.

More in detail, the method proposed by Imai et al. (2022) allows as a first step to derive a subset of potential control observations with identical treatment history at time t - for this reason, units that were already treated in the years 2010, 2011 and 2012 have been excluded from the analysis in order to derive two groups of untreated units prior to 2013; secondly, the initial control group is further narrowed down according to different weighting methods – the Panel Matching with Mahalanobis Distance in our case – based on control variables - in the case under consideration *population*, *demographic density* and *touristic flows* (beds for tourists per inhabitant) lagged for the previous three years on the outcome variable *total cost per inhabitant*. This refinement

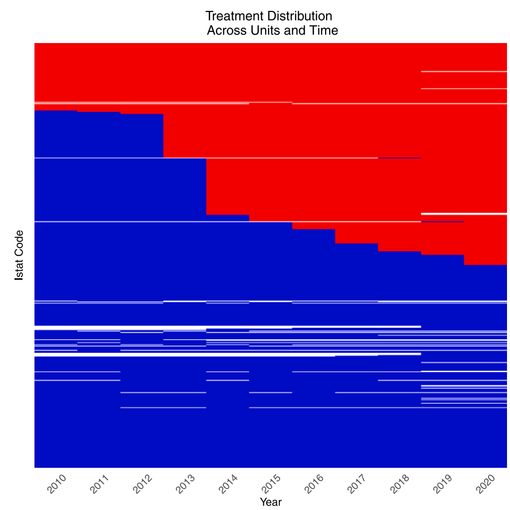
[11] It should be noted that, although possible from a regulatory point of view, no treated units have left treatment in the years following the decision to change tariff.

Table 1
Main descriptive statistics and their relative role in analysis, year 2010–2020, N. of units=1,020 per year.

Statistic	Role	Mean	St. Dev.	Min	Max
Total waste cost (Euro p.capita)	Dependent variable	123.095	37.485	17.730	248.280
Unsorted waste cost (Euro p.capita)	Dependent variable	45.803	25.888	0.000	210.220
Sorted waste cost (Euro p.capita)	Dependent variable	43.939	22.380	0.020	185.890
Total waste quantity (kg/inhab)	Output	122.396	37.266	17.730	248.280
Unsorted waste quantity (kg/inhab)	Output	182.075	122.174	1.656	1,161.512
Sorted waste quantity (kg/inhab)	Output	264.728	116.787	0.000	885.660
Resident population (N)	Returns to scale (IV)	9,077	20,272	38	214,198
Population density (inhab/km^2)	Demand (IV)	305.162	394.634	0.728	2,804.456
Average N. of household members (N)	Demand (IV)	2.359	0.233	1.260	3.700
Area of the municipality (km^2)	Demand (IV)	38.594	44.045	1.895	653.822
Tourist beds per inhab. (N. p.capita)	Demand (IV)	0.141	0.412	0.000	6.529
Coastal municipality (0/1)	Supply	0.056	0.229	0	1
Average distance to waste disposal plant (km)	Supply	48.643	36.362	8.284	254.271
Average cadastral rent (Euro)	Income	251.649	131.976	79.297	1,765.578
Municipality in Union (0/1)	Prices	0.211	0.408	0	1



(a) Italy



(b) Veneto Region

Fig. 3. Treated (red) and untreated (blue) municipalities by year. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

process is crucial, as it allows for the control of relevant confounding factors, such as past performance and other time-varying factors that are expected to influence the treatment.

The parallel hypothesis, in particular, holds when the treatment and control groups have similar trends in the outcome variable over time prior to the introduction of the treatment. If the parallel hypothesis holds, it suggests that any differences in the outcome variable between the treatment and control group after the introduction of the treatment can be attributed to the treatment itself, rather than pre-existing differences in the outcome variable between the two groups. In our application this hypothesis before treatment is more likely to be fulfilled, as well shown in Fig. 4 for total waste in terms of cost and quantity after the matching phase.

5.3. Results for total waste cost

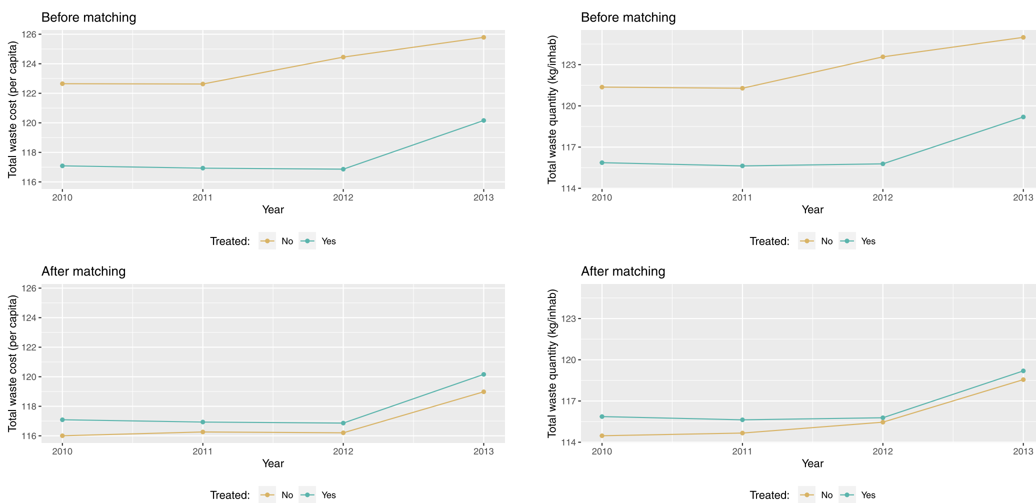
Once the treated group (350 municipalities having adopted PAYT from 2013 onward) and the control group (670 municipalities[12] that have never adopted it) have been defined, the cost model made explicit in Eq. (4) can be estimated. We will do it in successive steps in order to make the path of analysis more understandable and show more clearly the improvements of our approach over a simple baseline cost model.

More specifically in this section, the assessment of the PAYT policy will be overall evaluated on total costs (Table 2), separately by year after implementation (Table 3) and using the method of instrumental variables to instrument the amount of total waste (Table 4). Section 5.4, instead, will go beyond this approach by taking into account also the diversified but complementary effect of the type of waste on cost showing the results of the three-stage estimation model for systems of simultaneous equations (Tables 5 and 6).

Against this background, the baseline model has been drawn in order to verify the functional relationships between *total waste cost* and the supply, demand, prices and income variables as defined in Table 1. Table 2 and Fig. 5 highlight[13] the statistical significance together with the sign of the covariates. As expected, the size of resident population is positively correlated with per capita costs for waste services; nevertheless, population density has a negative sign, confirming that sprawling the service on a wider territorial scale has an increasing impact on costs. Household size is negatively associated with costs and this effect is likely mediated by the impact on the amount of waste generated (decreasing in per capita terms as households become larger). The distance to disposal plants is a driving factor of waste services costs,

[12] For increased robustness, the matching algorithm allowed to choose the number of the matched unit similar to the treated one; it was, therefore, chosen to obtain two untreated units for each treated one.

[13] Results for the *total quantity of waste* are very similar to the cost ones and are, therefore, reported in the Appendix A as a robustness check.



(a. Total waste cost) (b. Total waste quantity (kg/inhab))

Fig. 4. Parallel trends before and after matching.

Table 2
Baseline OLS model — dependent variable: Total waste cost.

	Coefficient	Std. err.	t	$P > t$	[95% conf. Interval]	
Constant	−0.038	0.023	−1.65	0.098	−0.082	0.007
Resident population	0.220	0.010	21.24	0	0.200	0.241
Population density	−0.132	0.011	−11.99	0	−0.154	−0.111
Average number of household members	−0.150	0.012	−12.44	0	−0.174	−0.126
Average distance to waste disposal plant	0.079	0.011	7.07	0	0.057	0.101
Coastal municipality (0/1)	0.177	0.0109	16.26	0	0.155	0.198
Cadastral rent	0.115	0.011	10.09	0	0.093	0.137
Municipality in Union (0/1)	0.0002	0.024	0.01	0.993	−0.047	0.048
Treated (0/1)	0.070	0.039	1.81	0.07	−0.005	0.146
Y_t Year of treatment	0.077	0.026	2.94	0.003	0.026	0.129
did	−0.137	0.044	−3.07	0.002	−0.224	−0.049

in the same way as the touristic vocation of a municipality (captured by the coastal dummy). The cadastral rent, a proxy for household income, is positive as expected, while the effect of belonging to a municipal union does not clearly emerge from the baseline model. Finally, the did coefficient between the treated municipalities and the control group clearly stands out: the negative and statistically significant coefficient shows a clear per capita cost reduction effect[14]

But an interesting aspect is to verify – again respect to the baseline model on total costs – the trend over time of the marginal effect of the variable did; in other terms, the question is if this effect on costs remains constant over time or if specific trends emerge following the adoption of the new pricing scheme.

Table 3 and Fig. 6 show the results of the model in which the variable did has been correlated with the year of analysis (compared to the control group, $did = 0$, and the $year = 2020$); it is easy to note a substantial invariance over the years of the effect of the tariff change while maintaining a very good statistical significance.

The baseline model, while useful for correctly defining the identification part, as highlighted in Section 4, presents two main critical issues: *(i)* the first one motivated by the fact that "*heterogeneity of policy effects on municipal budgets is driven by both demand and cost effects*" (Valente, 2023) that is, in econometric terms, the inclusion of the output and the related endogeneity problem to be dealt with by instrumental variables and *(ii)* the second one concerning the differentiated, but interdependent treatment between costs due to sorted and unsorted collection. We will cover the two issues step by step to make it easier and more informative for the reader.

As a first step, therefore, the quantity of waste produced has been introduced among the covariates: to do this properly it was necessary to instrument the quantity of produced waste (in terms of its per capita weight) for demand factors that affected the waste generation itself (*resident population, population density, size of the municipality in terms of area (km2), tourist beds per inhabitant*) and adopt a two-stage least squares (2SLS) estimator which is useful when there are feedback loops in the model. Table 4 reports the results of the instrumented model and the statistical tests related to the chosen instrumental variables: as for the latter, the IV tests show that an IV estimate was necessary,[15] that the instruments used are significant (not weak) in explaining the endogenous variable.[16] and that all the instruments used were valid and necessary.[17]

[14] The wide confidence interval is clearly also due to the limited number of units under analysis, a limitation due to the low adoption of this policy across the country.

[15] In the Anderson underidentification test the null hypothesis states that the endogenous regressors are orthogonal to the error term: in this case a small p-value shows that it can be rejected so IV estimation is required.

[16] The Stock and Yogo test provides critical values for the Cragg–Donald statistic. The null hypothesis (H0) is that the instruments are weak and the Cragg–Donald has to be compared with the 5, 10, 20 or 30% of the bias of OLS. In our case, a Cragg–Donald statistic of 183.439 is significantly higher than all the critical values. As such, there is sufficient evidence to reject the null hypothesis that the instruments are weak in this case.

[17] In Sargan test of overidentifying restrictions the null hypothesis implies all instruments are valid: so a p-value greater than 5% implies that all instruments used are valid.

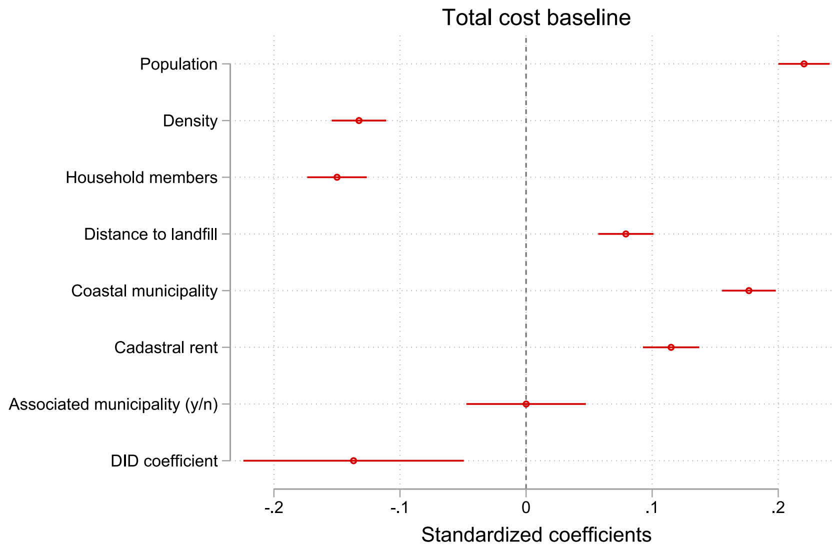


Fig. 5. Baseline OLS model — dependent variable: Total waste cost, marginal coefficients.

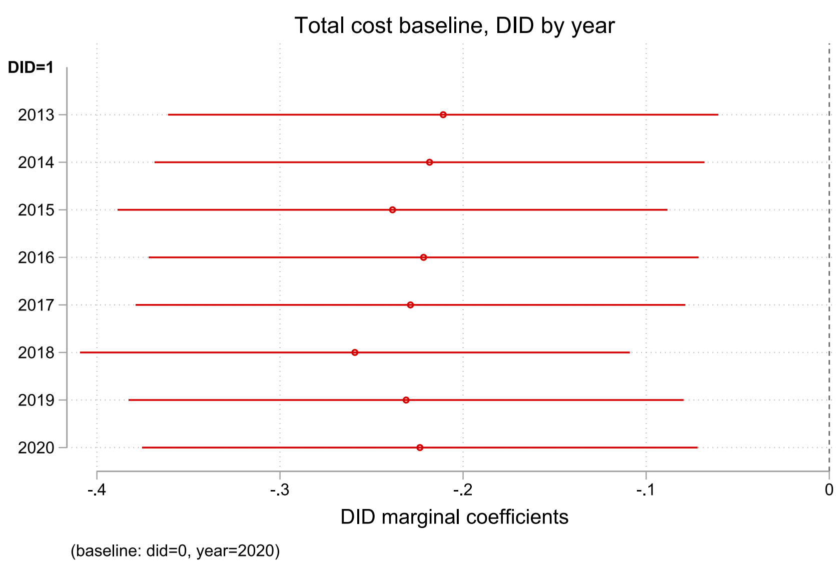


Fig. 6. Baseline OLS model — dependent variable: Total waste cost, did marginal coefficients by year (baseline: did=0, year=2020).

Table 3
Baseline OLS model — dependent variable: Total waste cost, did marginal coefficients by year (baseline: did=0, year=2020)

	Coefficient	Std. err.	t	P>t	[95% conf. Interval]	
Constant	0.077	0.034	2.29	0.022	0.011	0.144
Resident population	0.221	0.010	21.31	0	0.200	0.241
Population density	−0.132	0.011	−11.97	0	−0.154	−0.110
Average n. of household members	−0.149	0.012	−12.3	0	−0.172	−0.125
Average distance to waste disposal plant	0.081	0.011	7.21	0	0.059	0.102
Coastal municipality (0/1)	0.177	0.010	16.28	0	0.155	0.198
Cadastral rent	0.115	0.011	10.08	0	0.093	0.137
municipality in Union (0/1)	0.012	0.024	0.51	0.609	−0.035	0.060
Treated (0/1)	0.071	0.039	1.85	0.064	−0.004	0.147
Y_t Year of treatment	0.050	0.053	0.95	0.342	−0.053	0.155
Coefficient did by year						
did=1, year=2013	−0.211	0.077	−2.75	0.006	−0.361	−0.061
did=1, year=2014	−0.218	0.077	−2.85	0.004	−0.368	−0.068
did=1, year=2015	−0.238	0.077	−3.11	0.002	−0.388	−0.088
did=1, year=2016	−0.221	0.076	−2.89	0.004	−0.371	−0.071
did=1, year=2017	−0.228	0.076	−2.99	0.003	−0.379	−0.079
did=1, year=2018	−0.259	0.077	−3.38	0.001	−0.409	−0.109
did=1, year=2019	−0.231	0.077	−2.99	0.003	−0.383	−0.079
did=1, year=2020	−0.224	0.077	−2.89	0.004	−0.375	−0.072

Table 4
IV (2SLS) model — dependent variable: Total waste cost, did marginal coefficients by year (baseline: did=0, year=2020)

	Coefficient	Std. err.	z	$P > z$	[95% conf. interval]	
Constant	0.118	0.002	57.91	0	0.114	0.122
IV waste (kg/inhab)	0.990	0.003	347.5	0	0.985	0.996
Average distance to waste disposal plant	0.002	0.0009	2.26	0.024	0.0003	0.004
Cadastral rent	0.004	0.001	3.41	0.001	0.002	0.007
Coastal municipality (0/1)	0.002	0.001	2	0.045	4.87E−05	0.004
Municipality in Union (0/1)	−0.016	0.002	−7.71	0	−0.020	−0.012
Treated (0/1)	−0.002	0.003	−0.49	0.624	−0.008	0.005
Y_t Year of treatment	−0.186	0.002	−75.88	0	−0.190	−0.181
Coefficient did by year						
did=1, year=2013	0.049	0.006	8.47	0	0.038	0.060
did=1, year=2014	0.043	0.006	7.46	0	0.032	0.054
did=1, year=2015	0.040	0.006	6.92	0	0.028	0.051
did=1, year=2016	0.043	0.006	7.51	0	0.032	0.055
did=1, year=2017	0.001	0.006	0.11	0.91	−0.011	0.012
did=1, year=2018	−0.041	0.006	−7.05	0	−0.052	−0.029
did=1, year=2019	−0.061	0.006	−10.42	0	−0.072	−0.049
did=1, year=2020	−0.054	0.006	−9.37	0	−0.066	−0.043
Underidentification test (Anderson canon. corr. LM statistic):						679.655
				Chi-sq(5) p-value =		0.000
Weak identification test (Cragg–Donald Wald F statistic):						183.439
Stock-Yogo weak ID test critical values: 5% maximal IV relative bias						16.85
10% maximal IV relative bias						10.27
20% maximal IV relative bias						6.71
30% maximal IV relative bias						5.34
10% maximal IV size						24.58
15% maximal IV size						15.09
20% maximal IV size						13.96
25% maximal IV size						10.26
Source: Stock-Yogo (2005)						
Sargan statistic (overidentification test of all instruments):						6.967
				Chi-sq(3) p-value =		0.073

Finally, notice how the did coefficients are no longer negatively stable, but exhibit positive coefficients in the early years and then turn negative again in the later years. Can this be a result to be considered definitive, or does this result hide heterogeneous effects among different cost components? The next section tries to answer this question by separately considering the cost of sorted and of unsorted waste.

5.4. Results for cost split by unsorted and sorted waste

Considering the total cost of waste (not separately by type of waste) is an obvious limitation, as the cost of waste collection and disposal depends on waste composition.

For this reason, the impact of adopting different pricing systems is to be considered separately with an important caveat: while it is true that collection and disposal follow different industrial routes, it is also true that – for the individual municipality – these costs are interdependent. This is due both to budgetary constraints, common managerial costs and because the industrial choices of one sector impact on the other one (as suggested by Bucciol et al., 2015 on the quantity side, too). In econometric terms, this evidence means that the cost of the sorted waste sector certainly depends on the quantity produced – instrumented for appropriate demand drivers – and on supply and price variables, but also on the cost level of the unsorted waste sector and vice versa.

It is, therefore, useful (see Eq. (4) and the model estimated in Table 5) set up and then estimate a system of simultaneous equations with cross dependency between costs, to take into due account the simultaneous and separate estimations of costs for sorted and unsorted waste. Therefore, a 3SLS estimator has been chosen, which is more efficient than a 2SLS estimator especially in the presence of strong interrelationships between the error terms. Also in this case, the output produced, the produced waste (kg/inhabitant), has been instrumented – this time separately by type of waste – with the instrumental demand variables identified earlier (please see Table 4).

Table 5, thus, highlights the positive marginal effect of the quantities (instrumented for the demand factors) of waste produced with respect to cost, but above all the negative marginal effect of the other type of cost; in other terms, the more the cost relating to sorted waste increases, the more the cost for unsorted waste decreases, and vice versa, showing a substitution effect between the two sectors. They are, thereby, interdependent areas, often managed by the same municipal company, which set each time where and in what percentage to invest within a common budget that, therefore, constrains the costs of the two sectors.

The treatment effects are, as a result, indirectly conditioned by the constraints on the total cost showing a marked and significant improvement for municipalities opting for PAYT charging on the cost for unsorted collection and a non-significant effect for the remaining sorted part. But with one major caveat: the latter result is an apparent effect as is clearly shown in Table 6 and Fig. 7 where the did coefficient – similar to some previous models – was interacted with the year of analysis. In this alternative case, that is, when the instrumented amount of waste and the cost of the other service, the impact of the PAYT tariff reform turns out to generate clear cost savings immediately for unsorted waste and in the long run for sorted waste (see assumption H3). Clearly, the coefficients for the differentiated part are not fully statistically significant, but what – in our opinion – is more important is the clear trend of cost-efficiency gains that the adoption of the PAYT tariff entails.

Thus, the answer to the question of whether the adoption of the PAYT tariff promotes cost efficiency is differentiated and the proposed cross dependency cost model among sorted and unsorted waste allows us to respond positively to the three research hypotheses previously formulated.

First of all, the introduction of PAYT schemes reduces the overall quantity of waste produced (hypothesis H1) (see Figs. A.1 and A.2); secondly, the introduction of PAYT schemes also reduces the cost incurred by municipalities (hypothesis H2) as suggested by Valente (2023) and by Lombardi et al. (2021); finally, the evaluation of results

Table 5
Three-stage estimation for systems of simultaneous equations — dependent variables: Sorted and unsorted waste cost.

	Coefficient	Std. err.	z	$P > z$	[95% conf. interval]	
Dependent variable: Unsorted waste p.capita cost						
IV unsorted waste (kg/inhab)	0.112	0.004	25.34	0	0.103	0.120
Sorted waste cost	−0.431	0.110	−3.92	0	−0.646	−0.216
Average distance to waste disposal plant	2.435	0.243	10	0	1.958	2.913
Coastal municipality (0/1)	0.629	0.248	2.54	0.011	0.143	1.115
Municipality in Union (0/1)	4.874	0.792	6.15	0	3.322	6.427
Treated (0/1)	0.029	1.019	0.03	0.977	−1.969	2.027
Y_t Year of treatment	−0.209	0.872	−0.24	0.811	−1.917	1.500
did	−2.47	0.983	−2.52	0.012	−4.403	−0.547
Constant	46.388	4.511	10.28	0	37.545	55.231
Dependent variable: Sorted waste p.capita cost						
IV sorted waste (kg/inhab)	0.060	0.013	4.76	0	0.035	0.085
Unsorted waste cost	−0.182	0.041	−4.36	0	−0.264	−0.100
Average distance to waste disposal plant	2.487	0.625	3.98	0	1.263	3.712
Coastal municipality (0/1)	1.023	0.268	3.82	0	0.498	1.548
Municipality in Union (0/1)	4.823	0.533	9.04	0	3.778	5.869
Treated (0/1)	−0.578	1.253	−0.46	0.645	−3.034	1.878
Y_t Year of treatment	−0.648	1.267	−0.51	0.61	−3.137	1.841
did	−0.103	0.951	−0.11	0.914	−1.967	1.761
Constant	37.804	2.346	16.11	0	33.206	42.402

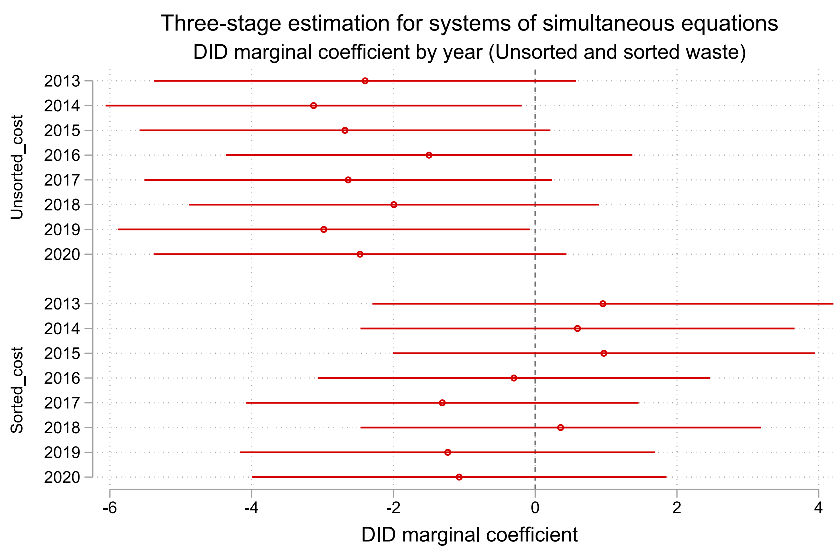


Fig. 7. IV 3SLS model — dependent variables: Sorted and unsorted waste cost, did marginal coefficients by year and by type of waste (baseline: did=0, year=2020).

in terms of cost must take into account the medium and long term effects since cost saving depends on the time horizon with which they are analysed (hypothesis H3), as also underlined by Valente (2023) ("*in year 3, PAYT generates cost savings in all municipalities*"). Monitoring the progress of subsequent adoption by municipalities over time, therefore, remains a priority exercise to understand the pros and cons of such a policy.

6. Final remarks and policy implications

Over the last 20 years a lively academic and institutional debate has pointed to the optimisation of waste management as a key step towards the development of more environmentally sustainable societies. In this framework PAYT policies have emerged as a relevant economic tool that, by sending clear market signals on the social cost of polluting, could contain waste generation from urban agglomerations while improving differentiation and recycling.

In Italy the implementation of PAYT schemes is still at an early stage. Our work seeks to provide empirical evidence on the impact of a wide diffusion of such policies among Italian municipalities.

In order to assess the impact of the introduction of the new financing scheme, a counterfactual approach has been adopted in order to compare the costs for waste services borne by PAYT municipalities with respect to PAYO ones. Within this setting, the differences in municipal costs have been analysed by also taking into account the composition of waste (sorted and unsorted) by means of a 3SLS linear system that allowed the interaction of the costs of collecting differentiated and undifferentiated waste and the endogeneity of the quantities of waste produced to be assessed. Clear, but heterogeneous results emerge: when the PAYT system is introduced, costs decrease for the unsorted fraction in the short term, whereas it takes longer for the sorted fraction, although a clear increase in efficiency is observed in the long term.

The policy implications of our analysis are clear-cut: through PAYT schemes Italian municipalities could contribute to the green transition, speeding towards the achievement of EU green goals (the introduction of PAYT charging in municipalities has reduced the total quantities collected by about 13%), while at the same reducing the cost for waste services provision (reduced by approximately 17%) and enhancing local public finance efficiency. Such advantages do not display all at once, but they unfold over the years. It is thus crucial that municipalities are from the onset provided with adequate financial resources and organisational skills in order to meet all the changes implied by the switch from PAYO to PAYT systems: a profound renovation of fixed capital endowment, the adaptation to new technologies, the eventual

Table 6
Three-stage estimation for systems of simultaneous equations — dependent variables: Sorted and unsorted waste cost, did by year (baseline: did=0, year=2020)

	Coefficient	Std. err.	z	P > z	[95% conf. interval]	
Dependent variable: Unsorted waste p.capita cost						
Constant	46.285	4.534	10.21	0	37.399	55.171
IV unsorted waste (kg/inhab)	0.112	0.005	25.43	0	0.103	0.121
Sorted waste cost	−0.428	0.110	−3.88	0	−0.644	−0.212
Average distance to waste disposal plant	2.437	0.243	10.01	0	1.960	2.914
Coastal municipality (0/1)	0.630	0.248	2.54	0.011	0.144	1.117
Municipality in Union (0/1)	4.866	0.796	6.11	0	3.305	6.427
Treated (0/1)	0.009	1.018	0.01	0.993	−1.987	2.005
Y_t Year of treatment	−0.233	0.870	−0.27	0.789	−1.938	1.472
Coefficient did by year						
did=1, year=2013	−2.399	1.519	−1.58	0.114	−5.376	0.577
did=1, year=2014	−3.126	1.497	−2.09	0.037	−6.061	−0.192
did=1, year=2015	−2.684	1.479	−1.82	0.069	−5.582	0.214
did=1, year=2016	−1.498	1.463	−1.02	0.306	−4.366	1.370
did=1, year=2017	−2.638	1.467	−1.8	0.072	−5.513	0.237
did=1, year=2018	−1.994	1.475	−1.35	0.177	−4.886	0.898
did=1, year=2019	−2.987	1.483	−2.01	0.044	−5.890	−0.075
did=1, year=2020	−2.471	1.486	−1.66	0.096	−5.383	0.440
Dependent variable: Sorted waste p.capita cost						
Constant	37.838	2.364	16	0	33.204	42.472
IV sorted waste (kg/inhab)	0.058	0.013	4.59	0	0.033	0.083
Unsorted waste cost	−0.176	0.041	−4.27	0	−0.257	−0.095
Average distance to waste disposal plant	2.391	0.623	3.84	0	1.170	3.612
Coastal municipality (0/1)	1.000	0.267	3.74	0	0.476	1.525
Municipality in Union (0/1)	4.862	0.536	9.07	0	3.811	5.913
Treated (0/1)	−0.427	1.252	−0.34	0.733	−2.88047	2.0267
Y_t Year of treatment	−0.467	1.267	−0.37	0.713	−2.949	2.017
Coefficient did by year						
did=1, year=2013	0.955	1.659	0.58	0.565	−2.297	4.207
did=1, year=2014	0.597	1.562	0.38	0.703	−2.466	3.659
did=1, year=2015	0.968	1.518	0.64	0.523	−2.007	3.944
did=1, year=2016	−0.301	1.412	−0.21	0.831	−3.068	2.466
did=1, year=2017	−1.311	1.413	−0.93	0.354	−4.079	1.458
did=1, year=2018	0.359	1.441	0.25	0.803	−2.465	3.182
did=1, year=2019	−1.234	1.493	−0.83	0.409	−4.161	1.693
did=1, year=2020	−1.072	1.492	−0.72	0.472	−3.997	1.852

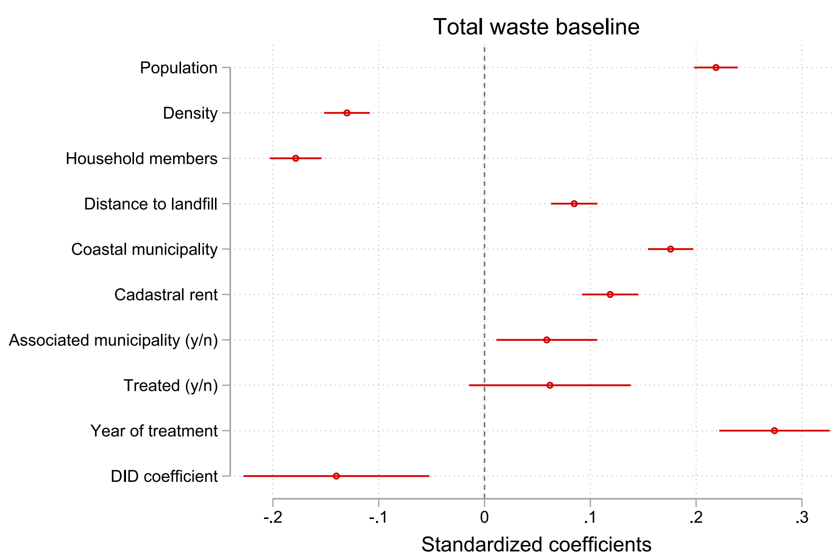


Fig. A.1. Baseline model — dependent variable: Total waste quantity, did marginal coefficient.

rescaling of waste services on a wider territorial perimeter and the implementation of strong enforcement mechanisms. The new season for economic policies opened by Next-Generation EU offers a wide range of instruments to seize this unmissable opportunity.

Finally, future developments of our research will be directed towards exploring the spatial correlation of policy choices among neighbouring municipalities and with spatial latent factors (Di Pillo et al., 2023), as well as evaluating the interactions between public and private actors; further analysis of consumption patterns and overall socioeconomic effects following the adoption of PAYT schemes would also deserve to be analysed in depth, but this would require more detailed and micro-level data.

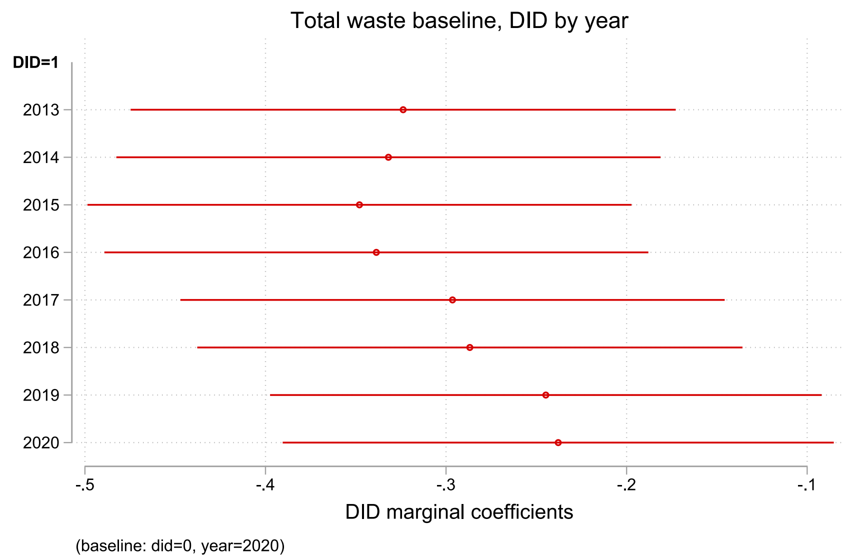


Fig. A.2. Baseline model — dependent variable: Total waste quantity, did marginal coefficient by year, baseline: did=0, year=2020.

CRediT authorship contribution statement

G. Messina: Conceptualization, Methodology, Validation. **A. Tomasi:** Data curation, Investigation. **G. Ivaldi:** Data curation, Investigation. **F. Vidoli:** Conceptualization, Methodology, Software, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Robustness checks

See Figs. A.1 and A.2.

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