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"The Effect of Door-to-Door on Separate Collection of Plastic Packaging: Evidence from Catalonia"

Germà Bel and Joël Bühler

UBIREA Institut de Recerca en Economia Aplicada Regional i Pública

Institut de Recerca en Economia
Aplicada Regional i Pública
UNIVERSITAT DE BARCELONA

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Abstract

In this article, we estimate the causal effect of the Door-to-Door waste collection policy on the separate collection of plastic waste in Catalonia. We use municipality-level data on the share of separately collected plastics and apply a Difference-in-Differences framework. We can demonstrate that Door-to-Door increased the share of separated plastics by around 75% compared to untreated units at the end of the sample period. Furthermore, our suggestive evidence indicates that there are no differences of Door-to-Door designs with source-separation of plastics from other recyclable waste components compared to those where plastics are collected with other materials and separated post-source. These findings highlight that Door-to-Door can be a highly effective measure to increase separate collection of plastics, a precondition for ambitious plastics recycling goals legislated by policy makers.

Keywords: Plastic waste; Door-to-Door; Recycling; Catalonia

JEL Classification: K23; L65; Q53

Authors:

Germà Bel. Department of Econometrics, Statistics and Applied Economics (Public Policy Section) and GiM-IREA. Universitat de Barcelona, Barcelona. gbel@ub.edu

Joël Bühler (corresponding author). Department of Econometrics, Statistics and Applied Economics (Public Policy Section) and GiM-IREA. Universitat de Barcelona, Barcelona. joel.l.buehler@gmail.com

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1 Introduction

Environmentally sound waste management can have beneficial effects on climate change in several ways. These include reducing methane emissions from landfills; reduced industrial energy use and associated pollution; energy recovery from waste; and reduction of energy use in waste transport (Ackerman, 2000). Reducing waste generation has long been recognized as a primary strategy for reducing environmental damage caused by waste. In addition to this, increased recycling -which reduces waste for disposal- was adopted as a major goal in the first systematic environmental programs for waste management, such as the Action Plan for Increased Recycling in Denmark in 1989 (Thøgersen, 1994), the Solid Waste Master Plan in Massachusetts in 1990 (Callan and Thomas, 2001), or the Container and Packaging Recycling Law enacted in Japan in 1995 (enforced in 1997; Kumamaru and Takeuchi, 2023).

Indeed, waste management is directly mentioned in the Sustainable Development Goals (SDGs) defined by United Nations (UN, 2015): goal 12 includes reduction of food waste (target 12.3) and environmental management of all waste by means of prevention, reduction, recycling, and reuse (targets 12.4 & 12.5). The guiding principles of the UN SDGs are analogous to those of solid waste management (SWM) based on the circular economy -CE- (Sharma et al, 2021). In the same vein, the current policy in the European Union (EU) is based on ambitious targets for waste recycling established in 2018 (EC, 2018), and requires EU Member States to increase the recycling target of municipal waste to 55% of all waste generated by 2025, 60% by 2030 and 65% by 2035.

Most studies in the literature find that recycling is generally superior to incineration in terms of social costs, i.e. including environmental externalities in costs and benefits (e.g., Morris, 1996; Ferreira et al, 2017), which is consistent with the fact that recycling is promoted by public policy around the world, as noted above. In this sense, the separation of waste is the most efficient way to increase effective recycling and reuse, and source-separated waste collection increases the efficacy of separation (Di Maria et. al, 2020; Degli Esposti, Magrini and Bonoli, 2021), and avoids a significant amount of greenhouse emissions (Wünsch and Simon, 2018).

Plastic waste is of particular concern, due to its extraordinary environmental damage, both when it comes to climate change and local pollution (e.g., Li and Takeuchi, 2023). Consequently, increasingly stringent regulations regarding plastic waste are spreading around the world. In that regard, the European Commission also introduced ambitious targets specifically for the recycling of plastics (EC, 2018), which should reach a minimum of 50% by 2025, and 55% by 2030 (art 6 Directive). Furthermore, the EU adopted in 2019 the 'Single-Use Plastic Directive' (EC, 2019), which contains a wide range of measures intended to reduce plastic waste (see a detailed overview in Kiessling et al., 2023). In addition to the reduction of plastic litter, other measures are being taken to encourage increased recycling of plastic waste. Moreover, the European Commission published its Circular Economy Action Plan (EC, 2020) in which it was announced that further targeted measures will be taken to address the sustainability challenges posed by plastic waste.

However, there is intense debate as to whether in the specific case of household plastic, waste recycling it is superior to incineration, when all benefits and costs are considered (e.g. Merrild, Larsen and Christensen, 2012; Gradus et al., 2017).[1] In addition to this, there is no unanimous agreement on the superiority of source separation of packaging plastics with respect to post-separation. According to Klingenberg et al (2024), the separation system -whether source or post-source- has only limited impact on the waste stream quality, although technological differences in the post-source separation - whether manual or automated - can play a role in the quality obtained (Cecon, Curtzwiler and Vorst, 2023). From a more general approach, Dijkgraaf and Gradus (2021) suggest that post-source separation of plastic may be preferable to source separation both economically and environmentally. In fact, Albizzati, Tonini and Gaudillat (2024) have recently noticed that in countries with most advanced recycling policies and waste management, the question may be arising whether there is a limit to sorting and separation (whether source or post-source), and whether there is an optimum, instead of a maximum, level of waste separation.

Regardless of the intense academic debates about the optimal extent and form of separation of household plastic waste, institutional policy pushes towards ambitious plastic recycling targets in the near future. In the case of the EU, discussed previously, debates also revolve around the appropriate policy measures to bring the laggard member states closer to the leaders (EEA, 2023). Against this backdrop, the Door to Door (DtD) collection system is attracting attention and interest, (e.g., Degli Esposti, Magrini and Bonoli, 2023). One of many advantages of this system is that it facilitates a more effective segregation of waste, thus making possible an increase in the recycling rate. In fact, Abeshev and Koppenborg (2023) found, by means of linear regression analysis, that promoting DtD bio-waste collection increased sorting of dry recyclables in several European cities.

There are good reasons to expect that expanding DtD will especially increase plastics sorting: Existing empirical evidence on household waste sorting behavior shows a high preference for plastics sorting, because it is recognized as an important environmental problem (see, e.g., Niangolan et al., 2019 for Denmark; Mielinger and Weinrich, 2024, for Germany). This is¡ the hypothesis that we test in this article by empirically analyzing the effect of the expansion of DtD on the separation of plastic waste.

Environmentally sound management plays a relevant role in waste collection in Catalonia (see, Bel and Elston, 2024; Montseny and Sorribas-Navarro, 2024). We take advantage of a large database with information on the adoption of DtD by municipalities in Catalonia between 2000 and 2021 (both the time of adoption and the degree of extension within each jurisdiction) and data for the same period for the detailed distribution (fractions) of different waste components that are collected in each municipality. We adopt a quasi-experimental approach, using Differences-in-Differences estimators in the setting of staggered adoption. Our main results reveal that DtD increases the share of separated plastics in total waste by about 2.5 percentage points, an increase of around 80% over

[1] As explained in Gradus et al. (2017: 22), the main benefit of recycling plastics is the avoidance of CO2 emissions that would otherwise occur during incineration and the production of virgin (new) plastic material, while the main benefit of incinerating plastic waste is the energy that can be recovered, which reduces emissions in the conventional energy production sector. On the other hand, the main costs associated with recycling are related to collection, separation, sorting, and recycling, and the main cost associated with incineration is that it requires a capital-intensive waste-to-energy plant.

non-treated municipalities *at the end of the period*.[2] Furthermore, we find that DtD schemes that include user-based plastic sorting have marginally larger effects than DtD schemes that did not include user-based sorting of light packaging, but that these effects are not statistically significant.

With this article we make a two-fold contribution to the literature on waste management. First, we use the most up-to date quasi-experimental techniques to estimate the effect of DtD on plastics sorting, pointing out the potential contribution of DtD to plastics recycling. Second, we provide evidence on the difference in the effect of DtD depending on whether plastic separation is included in the DtD scheme or not.

2 Institutional, regulatory and policy background for waste management

2.1 Institutions

Our analysis of the effect of DtD collection on the separation of plastic packaging is conducted on data from the municipalities of Catalonia. Municipalities are the lowest level of elected government and are required by Spanish law (Law 7/1985) to provide waste management services. Municipalities are responsible for both waste collection (which includes transportation) and treatment. Because of the type of facilities and equipment required, the treatment has become usually managed by supra-municipal local entities (such as the counties, or the metropolitan area of Barcelona -AMB-). Collection, however, remains a municipal responsibility. In that regard, it is the municipal government who decides how the service is provided (by the municipality itself, or cooperating with other municipalities), and how it is organized (whether public delivery is used, or it is contracted out, instead; also, the type of collection techniques). All this happens within the framework of environmental regulations.

2.2 Regulations

The Catalan legislator is responsible for the regulation of waste management, subject to European directives on environmental policies that affect waste management. *Agència de Residus de Catalunya* (ARC, Catalan Waste Agency) is the regulatory agency, which is in charge of regional monitoring and supervision of municipal compliance with regional regulations. Therefore, all municipalities in our study are subject to the same legislation and regulatory framework.

Among the legal norms passed in recent times that have relevant effects on environmental management of waste management, two are worth mentioning for our purposes.[3] Firstly, with Law

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[2] We use this conservative comparison because comparing to the untreated at the beginning of the period risks inflating the effect; baseline plastics separation rates were almost, zero and there was a general upwards trend independently of the DtD policy.

3 While Unit-Based Pricing (UBP) is being used in a variety of countries, with effective results in reducing waste generation (see Bel and Gradus, 2016). However, it is only marginally used in Catalonia, where the only experience properly designed as UBP was that of the small municipality of Torrelles de Llobregat, started in January 2003, and terminated in September 2003, after the local elections in May of that year changed the local government (Puig Ventosa, 2008).

16/2003 (on the financing of waste treatment infrastructures and the creation of a landfill tax) a landfill tax was introduced. Secondly, Legislative Decree 1/2009 (which integrated the previous legislation in force on waste management) made compulsory the establishment of a system that allows selective collection, and a tax on incinerated solid waste was created in the same year.

2.3 Environmental management of waste collection

Since 2009, municipalities in Catalonia must have selective collection schemes. To that purpose, they can choose into what categories users separate their waste. Street collection with containers is the most common technique, and it requires residents to drop their sorted waste outside of their homes, usually within a few minutes of walking distance. The most widespread system consists of five components (glass, paper/cardboard, organics, light packaging, and refuse).[4] Therefore, there is no separate collection of plastic only in Catalonia. Instead, light packaging such as milk packages, cans, PET bottles and other plastic materials are sorted into the same bins by households. Further sorting is then done manually or mechanically at industrial waste selection plants. Finally, those components suitable for recycling are sent to recycling plants. The process of interest for our research is selection by households into the light packaging category.

As previously mentioned, environmentally sound management of waste has been promoted in Catalonia in the last two decades. Local governments in charge of waste management have increased their ambition for selective collection and recycling (Bel and Elston, 2024), and the regional regulator has introduced and expanded fiscal measures to encourage recycling (Jofre-Monseny and Sorribas-Navarro, 2024). Consequently, waste separation has increased in the period under study, as shown in figure 1. While overall separation (right vertical scale) was less than 15% of total municipal waste at the beginning of the century, it had grown to nearly half of the total waste collected in 2021. In the same line, the category including plastic packaging (left vertical scale) experienced rapid growth, particularly also compared to the growth of other waste components. Separated light packaging grew from just above 0.5% to 5% of all waste.

2.4 Door to Door collection

While street containers are the dominant collection technique in Catalonia, DtD collection has experienced a remarkable growth since its recovery began in the early 2000s. Under DtD, separated waste is collected directly at the households' doorstep, in distinct household-size containers for the different components and at specified times. According to Figure 2, the share of municipalities adopting the DtD waste collection technique has increased steadily from 2000 to about 2017. In the two periods between 2017 and 2018, and between 2021 and 2022, there were jumps of about 7 and 6 percentage points, respectively. The same qualitative pattern can also be seen for those municipalities adopting a Door-to-Door version which includes source-separation of collection of light packaging. Notably, the share of these municipalities more than doubled after 2017.

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4 Some municipalities, however, collect light packaging together with cardboard, and some collect it in the same bins as refuse (ARC, 2024). For purposes of recycling, these municipalities later sort out light packaging manually or mechanically (ARC, 2022). The interpretation of the data may vary slightly depending on the configuration applied in a municipality.

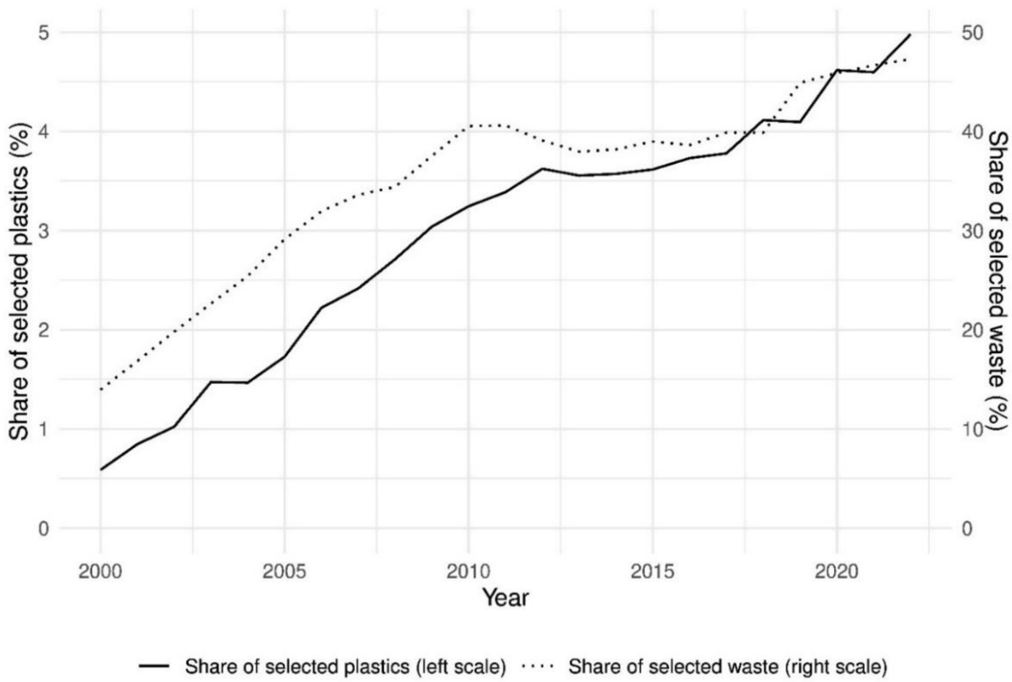

Fig 1 Evolution of overall sorted and plastic packaging sorted collection

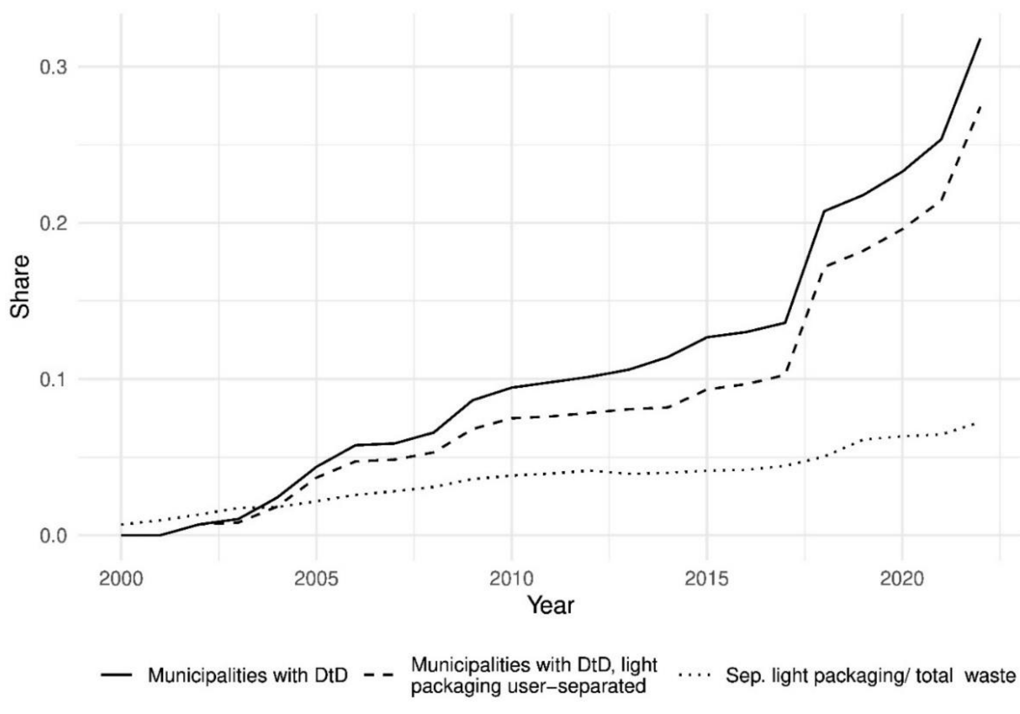

Fig 2 Trends in Door-to-Door policy adoption and separation of light packaging in the period

An early study with linear panel regression by Saldivia Gonzatti et al. (2022) found that DtD increases the share of separated waste by about 27 percentage points compared to street bins. Jofre-Monseny and Sorribas-Navarro (2024) find even larger effects of about 35 percentage points or a 90% increase compared to the mean in 2013. Jofre-Monseny and Sorribas-Navarro (2024) use the

DtD policy in their identification strategy of the effect of landfill tax increases on waste volume and separation. It is interesting to notice that while the share of separated collection of light packaging in overall waste also increased steadily over time, it grew faster before 2010, while DtD was adopted particularly fast after 2017.

3 Data

We use a panel of 943 municipalities in Catalonia from 2000 to 2022: Due to a separation and merger, 948 municipalities existed at one point during the sample period (today 947). We exclude three municipalities that were already treated at the beginning of our sample period, and two where we do not observe the outcome variable. Our data set includes the variables documented below.

Door-to-Door collection. The non-profit "porta a porta" publishes on its website an updated list of all municipalities applying a DtD waste collection policy, including the implementation date and treatment intensity (the share of the population served by "door-to-door" collection). The earliest implementations were in June 2000, the most recent ones in 2023 (Porta a Porta, 2023).

Door-to-Door of light packaging. The data set by Porta a Porta (2023) also provides information on the different types of waste collected through "door-to-door" collection, namely all "five components", light packaging together with paper / cardboard, or light packaging collected with refuse. We use this information to identify municipalities that have implemented "door-to-door" versions where light packaging is collected separately by users ("source separation of plastics").

Share of separated light packaging in overall waste. This variable can be calculated from a variable which measures volume of separately collected light packaging (plastic bottles and packaging, cans, wooden fruit containers) in tons per municipality. The data set is provided by Agència de Residus de Catalunya (ARC, 2023) and covers all municipalities in Catalonia ranging from 2000 to 2022. Note that the volume of light packaging in those municipalities applying "five fractions" is measured after user selection and before further sorting (post-source selection). In contrast, where light packaging is collected together with cardboard or refuse, it is measured right before entry into recycling plants, and therefore after manual or mechanical sorting (ARC, 2022).

Separated light packaging per capita. We calculate tons per capita using the light packaging and population data from the same dataset (ARC, 2023), which are used to calculate other per capita metrics in the data set.

We document descriptive statistics in Table 1 below. There are 21667 *time* × *municipality* pairs, of which 2452 periods got DtD treatment (1797 of which including light packaging collection at the user). Those units with user-based light packing sorting were treated a bit later on average than those without light packaging.

Table 1: Descriptive statistics

Variable	n	min	max	med.	q1	q3	iqr	mean	sd
Per capita plastics volume, tons	21667	0	0.255	0.016	0.009	0.026	0.018	0.019	0.014
Separated plastics/total waste	21667	0	0.446	0.03	0.016	0.051	0.035	0.037	0.029
DtD	21667	0	1	0	0	0	0	0.113	0.317
DtD, source separated	21667	0	1	0	0	0	0	0.083	0.276
Treatment year	6900	2001	2022	2018	2009	2020.25	11.25	2014.8	6.507
Treatment year, source separated	5658	2002	2022	2018	2010	2021	11	2015.7	6.246
Population	21667	19	1664182	912	313	3516	3203	7692	55451

In Figure 3, the two treatment groups are compared to the control group in terms of population, surface area of the municipality and population density (table 1.A in the Appendix A1 displays the corresponding data). In general, the control group tends to be somewhat skewed towards municipalities with lower population and higher surface area, resulting in lower densities than in the treatment groups. Those municipalities which implemented DtD with user-based light packaging sorting are mostly at intermediate levels of population density, whereas those with DtD collection but no separation of light packaging are quite diverse and present at the lower and upper end of density, mainly because they are quite heterogeneous with respect to their population size.

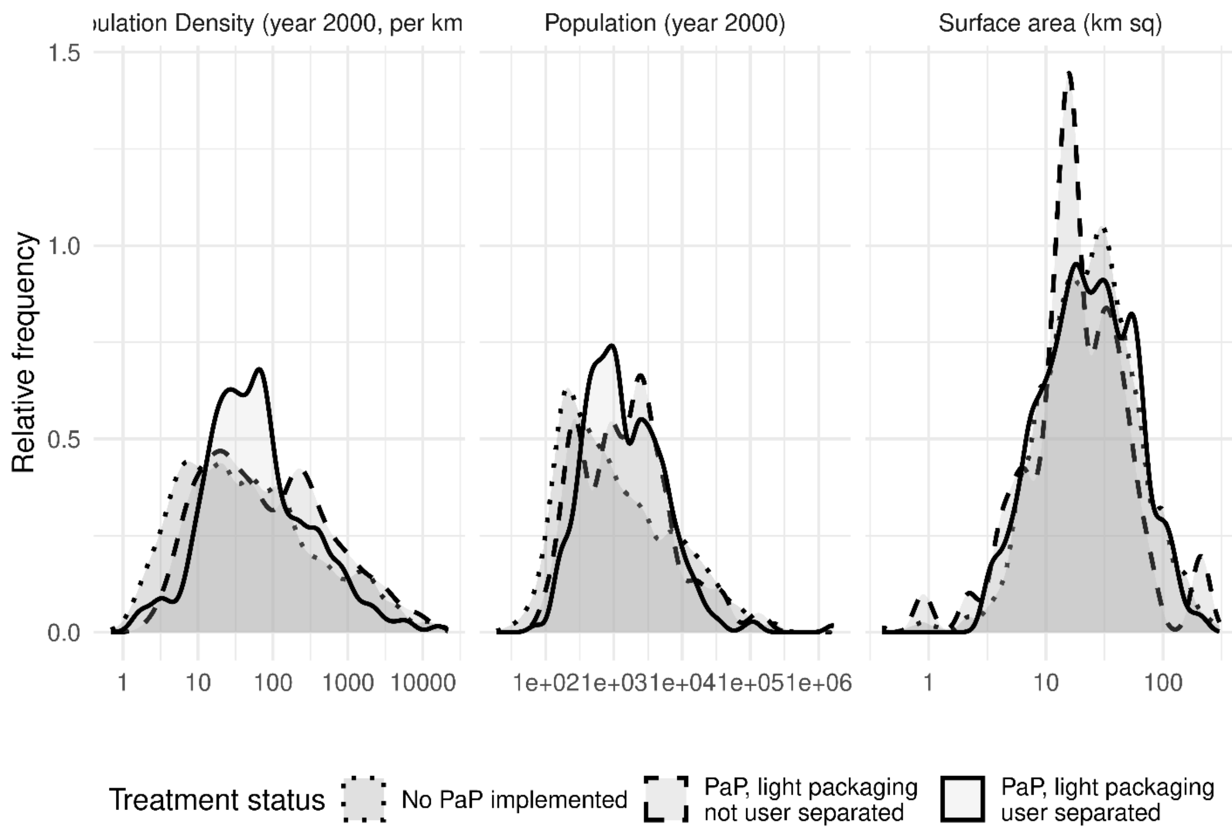

Fig 3 Treatment and control group balance with respect to demographic and geographic variables

4 Empirical Strategy

Our empirical setting is in the context of panel data with staggered adoption of DtD over time. Traditionally, researchers used static Two-Way Fixed-Effects (TWFE) estimators in these settings, where they controlled for unobserved time-invariant heterogeneity between individuals and individual-invariant heterogeneity over time. The reasoning for this strategy was that it was very similar (arguably identical) to the well-known Difference-in-Difference setting with a treatment and a control group (de Chaisemartin and D'Haultfoeuille, 2023). In this setting, under a parallel trend assumption (treated groups would have evolved the same as untreated groups after treatment), the researcher can identify the Average Treatment Effect on the Treated (ATT) (Butts and Gardner, 2022). Using our data, this would imply we could estimate the following equation,

$$p_{it} = \tau\, DtD_{it} + \beta X_{it} + \alpha_i + \gamma_t + \epsilon_{it} \qquad (1)$$

where p_{it} refers to the share of separately collected plastics in overall waste for municipality i at time t, τ is our parameter of interest, which measures the effect of Door-to-Door (with or without user-separated plastic, respectively) on the outcomes. X_{it} are time- and individual specific controls and α_i captures municipality and γ_t time fixed-effects.

The TWFE estimator τ from the equation above is only equivalent to a Difference-in-Difference estimator with just *one* treated and an untreated group under very strong conditions which are generally not met in the case of staggered adoption (Gardner, 2022; De Chaisemartin and D'Haultfœuille, 2020). A number of approaches have been developed to mitigate these problems (Sun and Abraham, 2021; Callaway and Sant'Anna, 2021; Borusyak et al., 2024, Gardner, 2022). These rely on slightly varying assumptions and differ in their strengths and weaknesses (see Butts and Gardner, 2022 for a nice illustration of some common estimators).

The following four assumptions are the key ingredients for DiD methods in staggered settings. (1) *The parallel trends assumption* which states that treated and control groups would have evolved in parallel absent the treatment.; (2) *No (or limited) anticipation.* It implies that the effect of the treatments cannot start before the treatment period, or that the anticipation horizon is known – that is, we know the maximum number of periods previous to treatment where effects of the policy could start to be present (Callaway and Sant'Anna, 2021); (3) *Stable unit treatment value assumption.* Typically, this assumption is violated when there are general equilibrium effects, spillovers or externalities between units. (4) *Correct model specification for Y (0).* Imputation methods for staggered DiD (Borusyak et al., 2024; Gardner, 2022) require an additional assumption: They apply a model to impute the counterfactual (untreated) outcome. To correctly identify the causal effect of the treatment, this model used for imputation must not be misspecified.

5. Main results

For our estimates to recover the ATT of the DtD collection policy on plastic selection, we need to make the following key assumption (de Chaisemartin and D'Haultfoeuille, 2023): Parallel trends between all groups (groups of municipalities where DtD was implemented at the same time) on the potential outcome without treatment for all *t*. Note that this assumption can only be scrutinized statistically to a very limited extent.[5]

5.1 Effect of DtD on the share of selected light packaging waste

Table 3 provides the results of DtD on the volume of light packaging separated. The four estimators suggest that there is an increase of about 2.43 to 2.66 percentage points in separately collected light packaging waste as share of all municipal waste. With t-statistics of between seven and 14, these effects are significant on the 1‰ level. Relative to the baseline of selected light packaging of 3.43% per capita in the untreated sample at the end of the observation period, this implies an increase in selection of between 71% and 77%. We compare the results to the end of the baseline period, because other municipalities have also been on an upward trajectory over the more than 20 years of our analysis. Comparing the effect to the start of the sample would thus inflate the possible impact in the real world.

Table 3: Average Treatment Effect on the Treated (ATT) of Door-to-Door on selected light packaging waste

	(1)	(2)	(3)	(4)
Estimator	Callaway & Sant'Anna	Sun & Abraham	Borusyak et al.	Gardner
Estimate	0.02492***	0.024341***	0.026603***	0.026603***
SE	(0.003118)	(0.002604)	(0.001897)	(0.002142)
t-statistic	7.991031	9.348187	14.021778	12.420881

Note: Standard Errors in parentheses. ***p<0.001; **p<0.01; *p<0.05; †p<0.10

The event study plot in Figure 3 indicates that there are no significant and systematic pre-trends in four of the five estimators. The only doubts remaining are about the Sun and Abraham (2021) estimator, where the pre-treatment coefficients are mostly slightly positive and significant. But since the pre-trends are calculated as long differences, the accumulated divergence between treatment and control group does never exceed a very narrow range.[6] The estimators also all agree on the dynamics of the effect post-treatment. They all show an effect of about 4 percentage points in the first periods right after treatment, and a decline to between 2 and 2.5 percentage points after about five years. These are economically meaningful effects, suggesting that introducing DtD collection in general is a highly effective measure to achieve increased rates of plastics separation.

[5] Pre-trends cannot be used to test for parallel trends in a direct way, as parallel trends is an assumption about unobserved potential outcomes. However, conceptually in line with formal test in De Chaisemartin and D'Haultfœuille (2020), we use a visual test on the pre-trends to test jointly for the presence of non-parallel trends pre-treatment and anticipation of the treatment. Once the treatment time is redefined to the earliest time where anticipation could arguably become a problem, still rejecting this "placebo test" would give us a serious warning about the presence of non-parallel trends.

[6] Comparisons of pre-trend estimates of different estimators must be taken with caution, because the way they are constructed differ markedly (Roth, 2024)

We estimated the effect of *any* type of Door-to-Door waste collection so far. However, some municipalities chose to implement DtD, but to require users to collect light packaging together with paper/cardboard or with refuse. We could expect light packaging separation to increase more strongly in municipalities where it is collected separately, as some studies show that more comprehensive separation in one waste component can spill over to others. This could imply that a stricter and more explicit separation of packaging also leads people to separate more of it from other waste components. We will estimate the effect for both types of DtD separately in a next step.

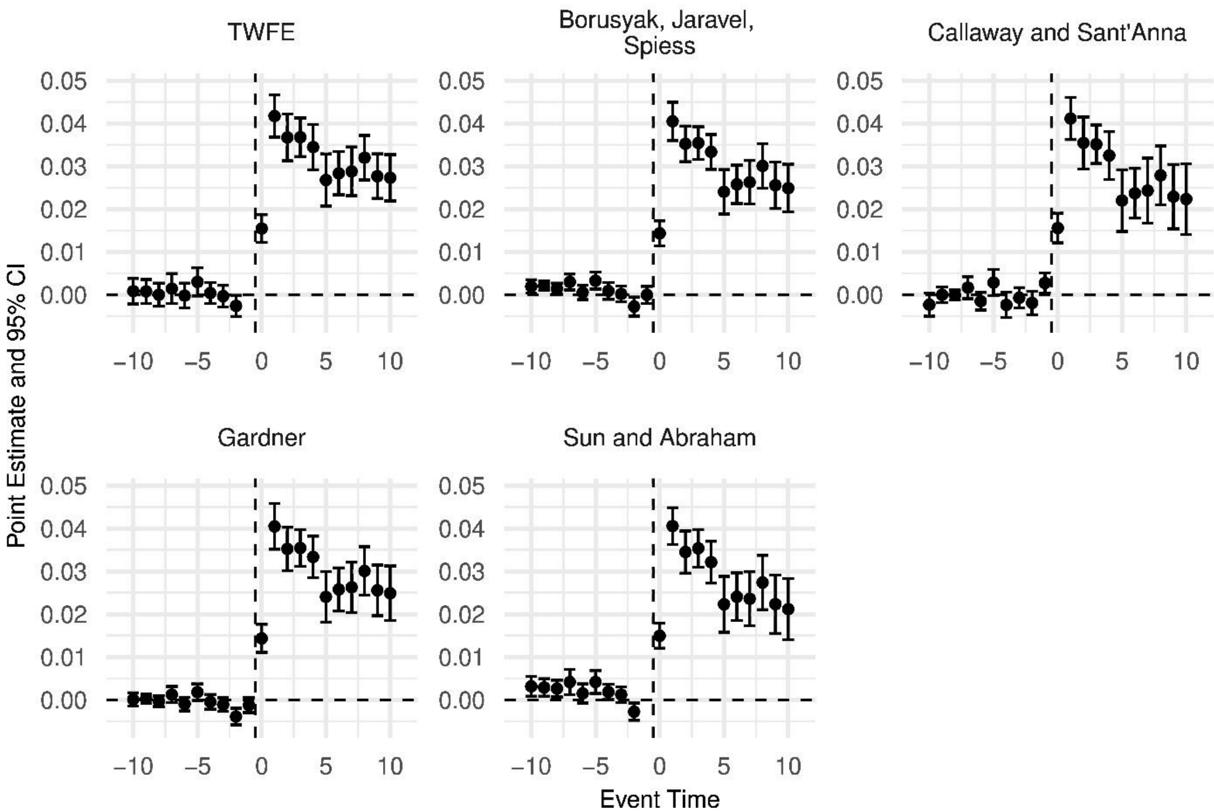

Fig. 4 Event-study plot of the effect of Door-to-Door collection on the share of separated light packaging

5.2 Effect with user-selected light packaging

Table 4 provides the results for DtD with user-separated light packaging on the volume of collected light packaging. The three estimators suggest that there is an increase of about 2.8 percentage points in separately collected light packaging waste as share of all municipal waste after adoption of DtD. With t-statistics of between 11 and 26, these effects are significant on the 1‰ level. Relative to the baseline of selected light packaging of 3.43% per capita in the untreated sample at the end of the observation period, this implies an increase in selection of 82%. However, the event study plot in Figure 5 suggests that there are some concerns about pre-trends, particularly in the Borusyak et al. (2021) and Sun and Abraham (2021) estimators, and in Gardner (2022) to a lesser extent. Since even accumulated (long differences) pre-trends such as those in Borusyak et al. (2021) are quite small compared to post-treatment long-differences, we think that we can still trust that parallel trends hold sufficiently pre-treatment for this estimator to provide an accurate estimate of the effect.

Table 4: Average Treatment Effect on the Treated (ATT) of Door-to-Door including light packaging on the share of selected light packaging waste

	(1)	(2)	(3)	(4)
Estimator	Callaway & Sant'Anna	Sun & Abraham	Borusyak et al.	Gardner
Estimate	0.028032***	0.028032***	0.02768***	0.02768***
SE	(0.002367)	(0.002099)	(0.001953)	(0.002149)
t-statistic	11.841534	13.352144	14.173916	12.880233

Note: Standard Errors in parentheses. ***p<0.001; **p<0.01; *p<0.05; †p<0.10

The dynamics of the effect post-treatment are very similar across estimators. In line with our expectations, these estimates are on average a bit larger than those for all types of DtD.[7] In order to arrive at a more complete picture, we report the results for municipalities implementing DtD excluding plastics collection next, and then estimate the difference in effects between the two policy setups explicitly later, in section 7.

5.3 Effect with post-user separation of light packaging.

Some municipalities implemented DtD, but do report not collecting light packaging separately. Namely, these municipalities either use a "multi-product category" (paper / cardboard /light packaging) or collect light packaging with refuse. They therefore measure the separated light packaging only after further manual or mechanical separation. Since this step will remove some of the waste materials due to impurities, we might expect light packaging shares to increase less than where they are collected separately at source, at least in these municipalities which changed from "five fractions" street collection to a "multi-product" DtD. However, the extent of this is not obvious, as we do not possess information on what type of street bins were used previous to DtD. The same qualification also needs to be applied to the spillover-type explanation for differences between the systems, namely that waste separation which is stricter and into more different categories leads to more careful separation in general, increasing plastic separation.

[7] Note that while this allows us to say something about the effect in municipalities with different designs of the policy, we cannot reliably attribute this effect to the two types of DtD in a causal sense, as we do not observe any switchers from one DtD design to the other.

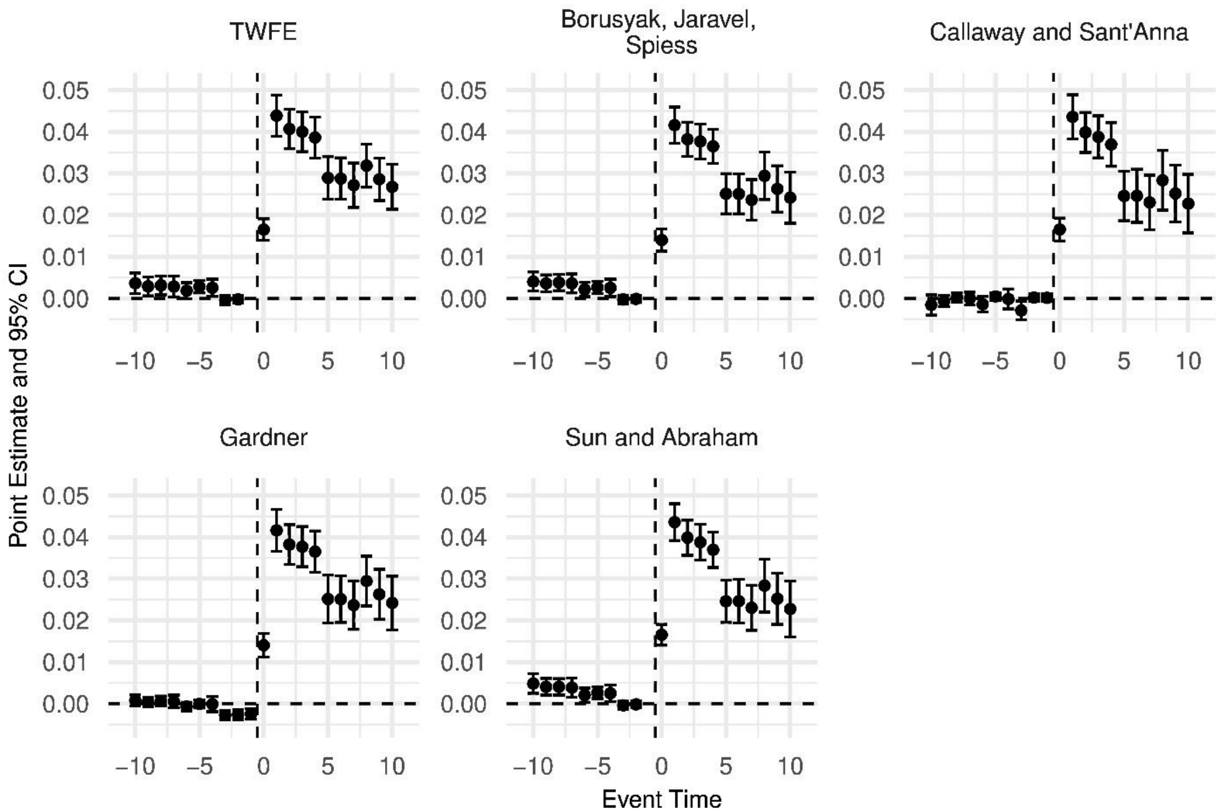

Fig 5 Event-study plot of the effect of Door-to-Door light packaging collection on the share of separated light packaging

According to Table 5, the t-statistics of the effects are between 1.7 and 6.6, and separated light packaging waste (after mechanical or manual industrial separation) increases between 1.38 and 3.9 percentage points, depending on the estimator. This results in an increase in selection of between 40% and 114% relative to the baseline of 3.43% per capita in the untreated sample at the end of the observation period. Note that all estimators report smaller effect sizes than for DtD where light packaging is already separated from paper/cardboard or refuse by the users.

Table 5: Average Treatment Effect on the Treated (ATT) of Door-to-Door without light packaging on the share of selected light packaging waste

	(1)	(2)	(3)	(4)
Estimator	Callaway & Sant'Anna	Sun & Abraham	Borusyak et al.	Gardner
Estimate	0.016382†	0.013818***	0.023451***	0.023451***
SE	(0.009475)	(0.003365)	(0.003546)	(0.005272)
t-statistic	1.728954	4.105728	6.61394	4.448532

Note: Standard Errors in parentheses. ***p<0.001; **p<0.01; *p<0.05; †p<0.10

As can also be seen in the event study in Figure 6, all estimators agree on the post-treatment pattern, with relatively stable treatment effects around 2-3 percentage points for all post-treatment periods. While the pre-trends are much noisier both compared to the previous estimations and the post-treatment period this time, they are mostly not systematically statistically significant. In the case of Callaway and Sant'Anna (2021), the short differences are neither systematically positive nor negative, implying that there is no strictly increasing or decreasing pre-trend present either.

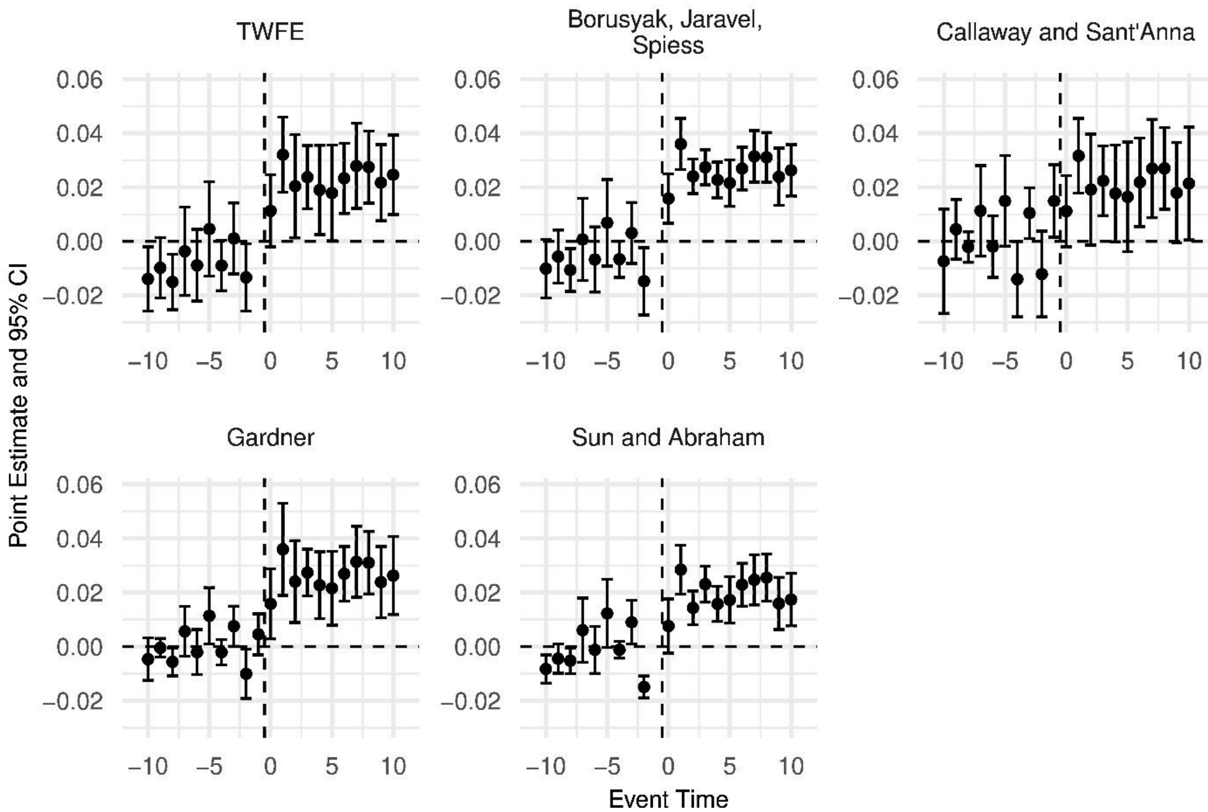

Fig 6 Event-study plot of the effect of Door-to-Door without collection of light packaging on the share of separated light_packaging.

6. Robustness checks

To investigate the robustness of our results, we restrict our sample in different ways; all results are provided in the Appendix. First, we remove some observations with implausibly high volatility in selection rates between years (see Appendix 2, Figures 8-10). Namely, we remove observations when selection rates increase (decrease) at least by factor five from *t-1* to *t*, and then decrease (increase) again by at least factor 5. We think that these observations are typically errors in the data collection process, most likely where a misplaced decimal comma changed plastic volumes by an order of magnitude. The magnitudes of the results are very similar.

Secondly, we also estimate the specification with a different outcome variable, the logarithm of the volume of plastics selected (in kg) per capita. This variable is less dependent on the accuracy of measurement in the overall collected waste volume. Instead, it only relies on population in the denominator, which typically evolves in a much steadier way. The downside is that it is a bit further away from what we are interested to measure, as an increase in per capita plastics could be driven just as well by increases in overall waste volumes, which also increase plastics. Figures 11, 12 and 13 in Appendix 3 show that the qualitative patterns remain the same. We noticed that when not excluding outliers (see previous paragraph), the results for DtD with post-source plastics selection are insignificant and all estimators report very unstable pre-treatment values. However, when again excluding observations with implausible variability analogously as in the previous paragraph, the results are in line with our baseline and the other robustness checks (see Appendix 4, Figure 14).

Lastly, Porta a Porta (2023) also includes a variable for the share of population served by DtD collection. We test whether excluding all municipalities with less than 25%, 50%, 75% or 100% of DtD treatment changes the results. The results remain qualitatively the same, as can be seen in Appendix 5, Figures 15-18.

7. Extension: Comparison of source and post-source separation in DtD systems

In a last step, we estimate also a TWFE event study specification including both treatments at the same time. That is, we estimate the following equation:

$$y_{it} = \alpha_i + \lambda_t + \sum_{k=T_0}^{-2} \beta_k^+ DtD_{ik}^+ + \sum_{k=0}^{T_1} \beta_k^+ DtD_{ik}^+ + \sum_{k=T_0}^{-2} \beta_k^- DtD_{ik}^- + \sum_{k=0}^{T_1} \beta_k^- DtD_{ik}^- + \epsilon_{it} \quad (2)$$

where α_i are individual fixed effects, λ_t are time fixed effects, DtD^+ , DtD^- indicator variables for the DtD policy with (indicated by +) and without (−) user-based light packaging separation in municipality i in period k relative to treatment. β^+, β^- are treatment effects for each time span before or after treatment k (β^+, β^- with negative k represent the pre-trends). Importantly, this specification allows the pre-treatment periods of the other not-yet-treated group to be included in the control. Figure 7 shows the estimated treatment effects for the DtD policy with and without user-based light packaging collection. There is a positive and persistent effect of DtD with user-separated light packaging on the share of separated light packaging, while the estimates of the effect of DtD policy without light packaging collection suffer from serious pre-trends. The effect is slightly smaller in municipalities where plastics are not user-separated, but the effect is not statistically significant.

It is important to note that the lack of significant differences between the two policy designs should be taken with caution, because our results are not proof that differences do not actually exist. Firstly, actual effect heterogeneity between the policy variants could be cancelled out by differences in the municipalities opting for one or the other policy, if these differences are also correlated with the general effect size of DtD. Furthermore, our plastic outcome variable is measured *before* further manual or mechanical processing in municipalities where plastics are separated at the user, but after sorting out unsuitable materials for recycling in those municipalities where it is collected with paper / cardboard or refuse. There could be slight differences in the actual composition of the packaging materials measured here, so that one method may outcompete the other in quality of the sorted material. However, the literature does not provide conclusive evidence that the quality of selected plastic is superior in any one of the two designs.

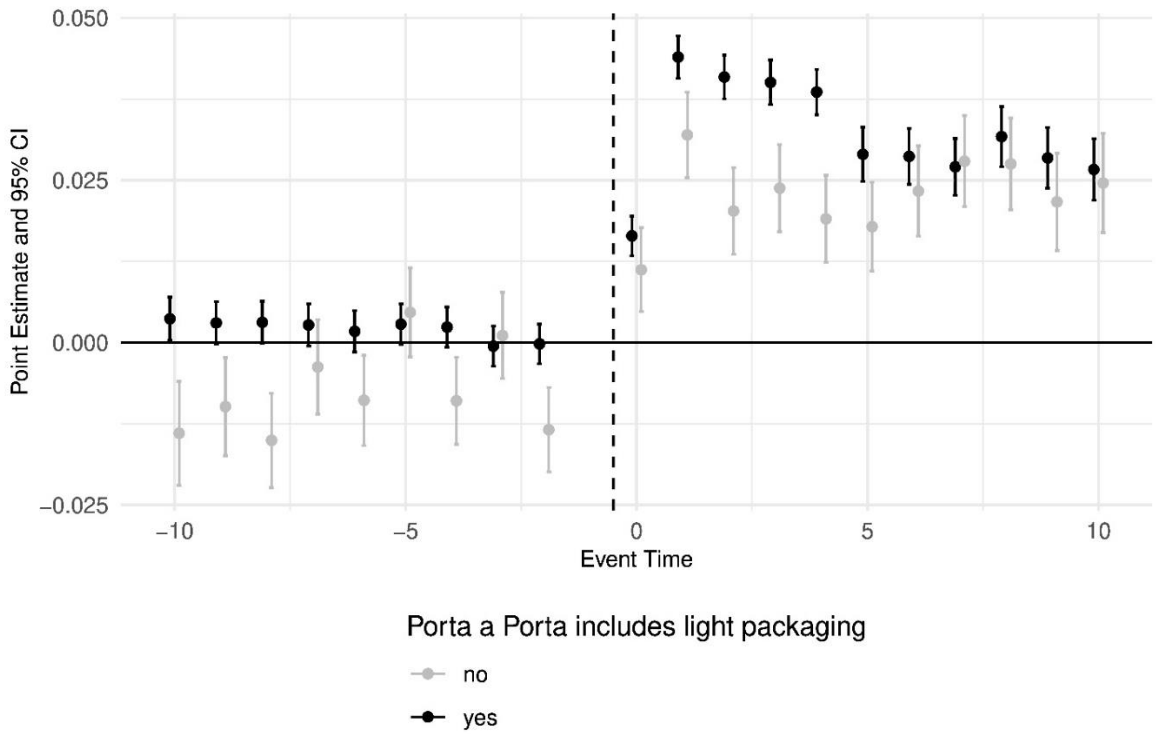

Fig 7 Event-study plot of the effect of Door-to-Door with and without collection on the share of separated light packaging.

8. Concluding Remarks

Our study shows very sizeable positive effects of Door-to-Door waste collection on the share of separately selected plastic, even where separate plastic collection is well-established. More precisely, we estimate that DtD is highly effective even in a setting where plastic separation had been promoted for a long time and was increasingly complied with even in the absence of DtD: Compared to untreated municipalities in 2021, DtD could further increase separate plastic collection by around 80%. We provide suggestive evidence that these results are in a similar ballpark regardless of whether plastics are collected with other materials and selected post-source, or already by the user pre-source. Thus, any type of DtD system seems to have large positive effects on the separate collection of plastics. As a consequence, policymakers may consider using it as an useful measure to reach current ambitious policy goals for plastic recycling and reduce environmental harm.

To further our understanding of the policy trade-offs, we see several avenues for further research: Future studies should consider the quality of the collected plastic material, particularly when further investigating different setups, for example those where different waste components are collected together. Furthermore, these insights also need to be combined with information on operating costs of the policy, because only an emerging complete cost-benefit picture can help policy makers decide whether DtD is the best measure both compared to other collection methods, and also compared to interventions further up- or downstream like packaging regulations, unit-based pricing or technological solutions in incineration or other waste treatment.

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Appendix

A1 Descriptives: Table

Table 1A: Descriptive statistics for treatment and control, standard deviation in parentheses

	No PaP implemented	PaP, light packaging not user separated	PaP, light packaging user separated
Population	5442.138	5221.538	9042.214
	(19374.59)	(16195.62)	(96973.12)
Density	375.4000	410.4903	248.4422
	(1547.275)	(1075.190)	(1110.232)
Surface area	34.65165	29.72115	33.04444
	(35.91997)	(40.37671)	(31.32891)
#obs.	637	52	243

A2 Excluding observations with likely errors in the outcome (outcome: share of separated plastics)

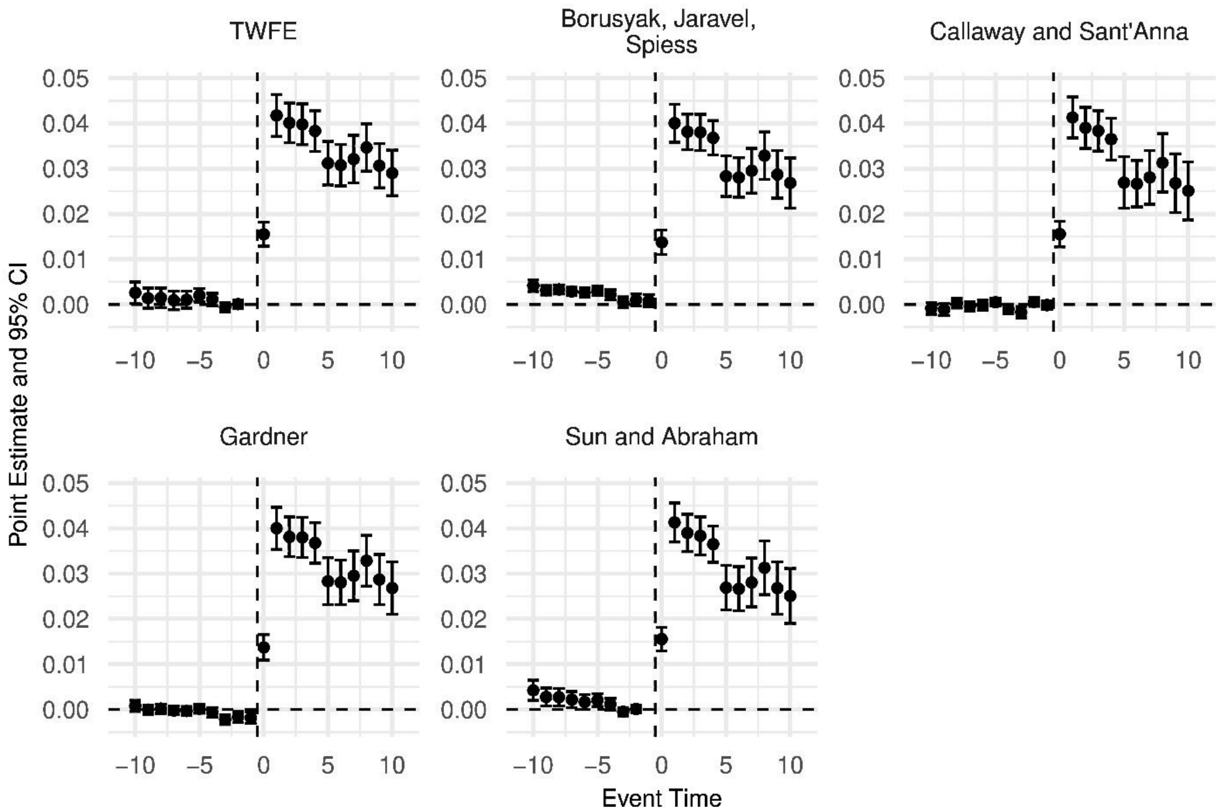

Fig 8 Event-study plot of the effect of Door-to-Door with and without light packaging collection on the share of separated light packaging, excluding likely outliers

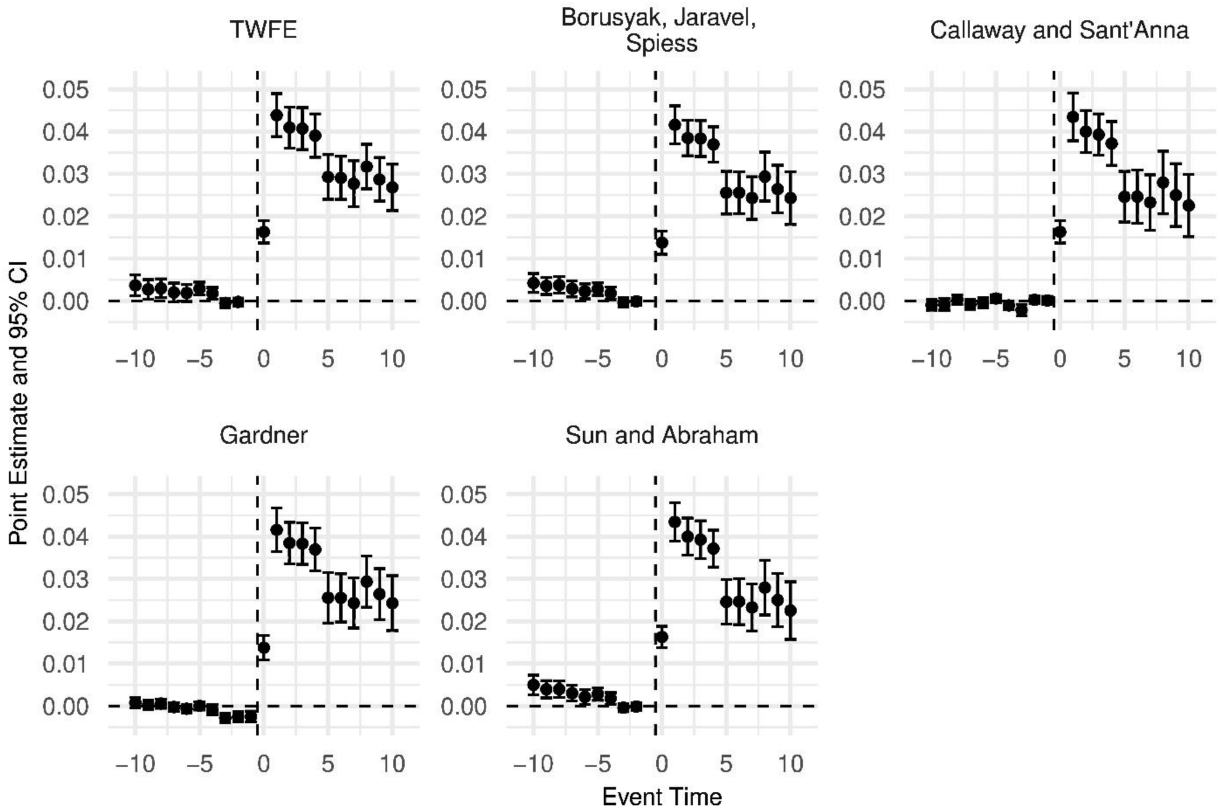

Fig 9 Event-study plot of the effect of Door-to-Door with and without light packaging collection on the share of separated light packaging, excluding likely outliers

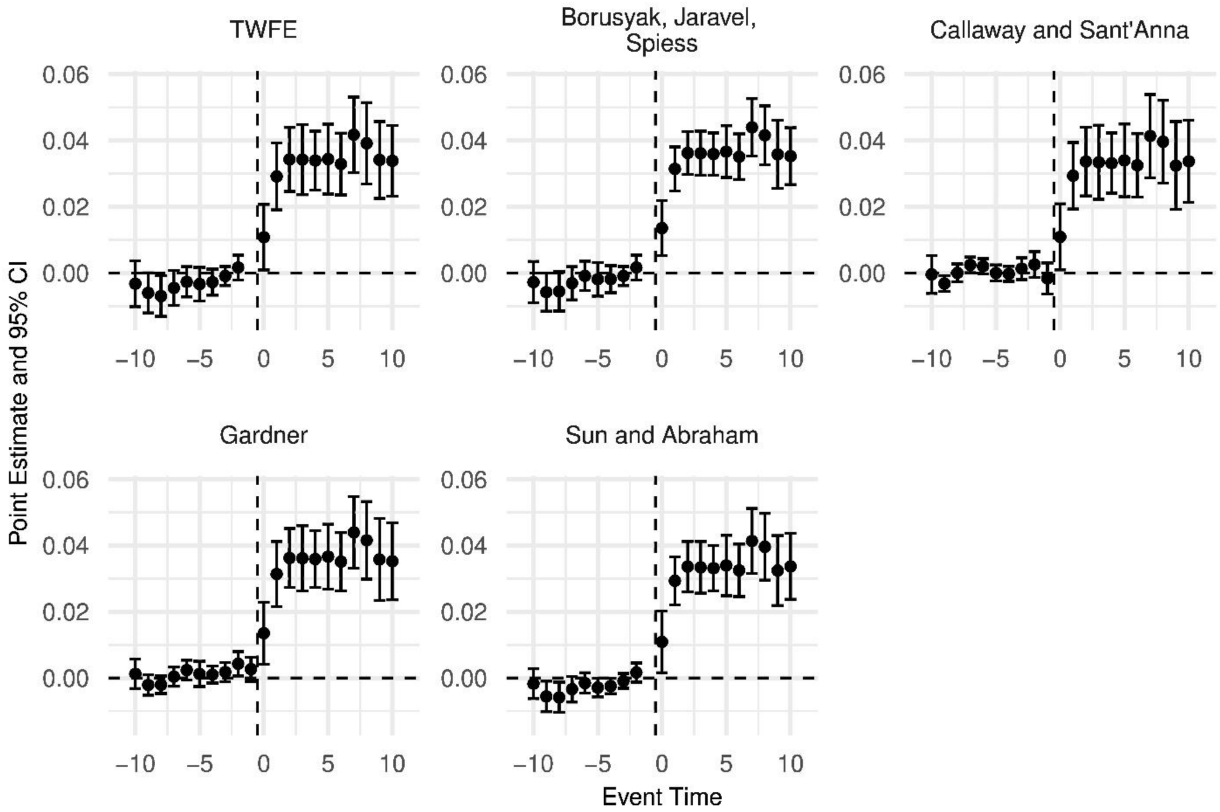

Fig 10 Event-study plot of the effect of Door-to-Door with and without light packaging collection on the share of separated light packaging, excluding likely outliers

A3 Using plastics per capita as an outcome

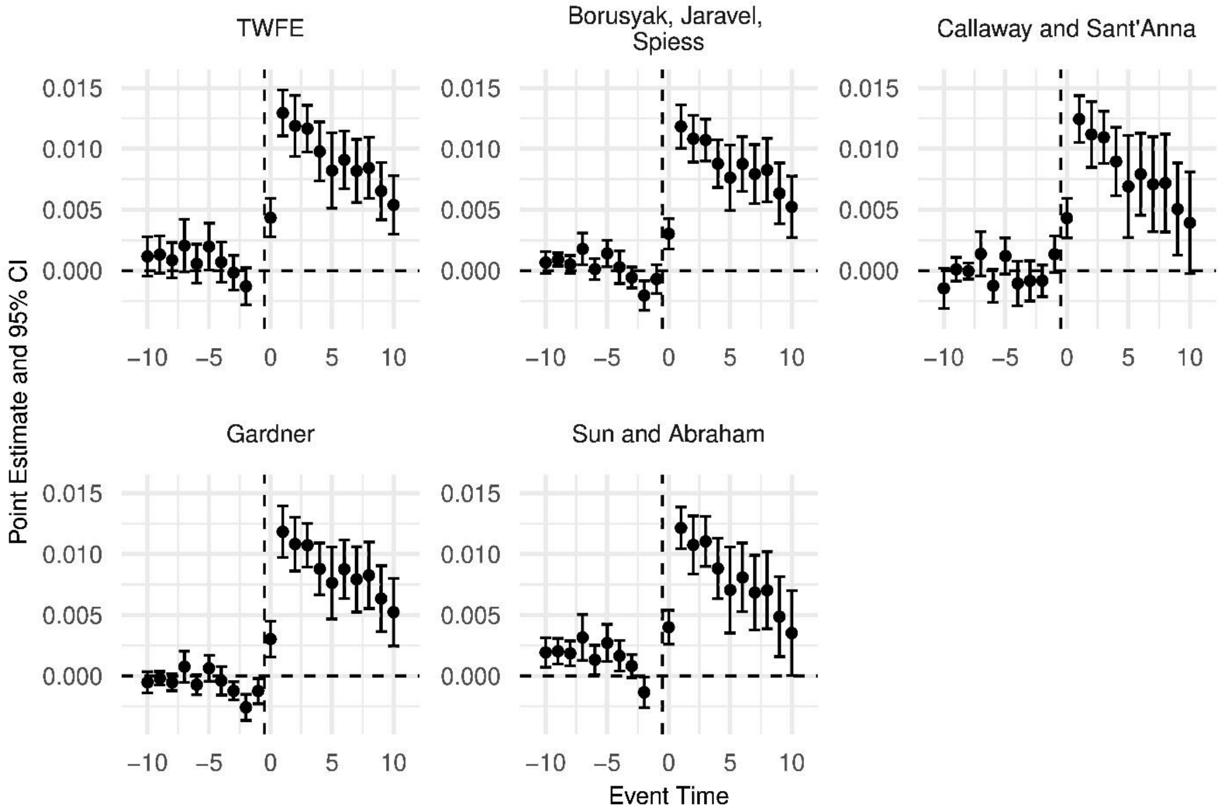

Fig 11 Event-study plot of the effect of Door-to-Door with and without light packaging collection on the per capita separated light packaging

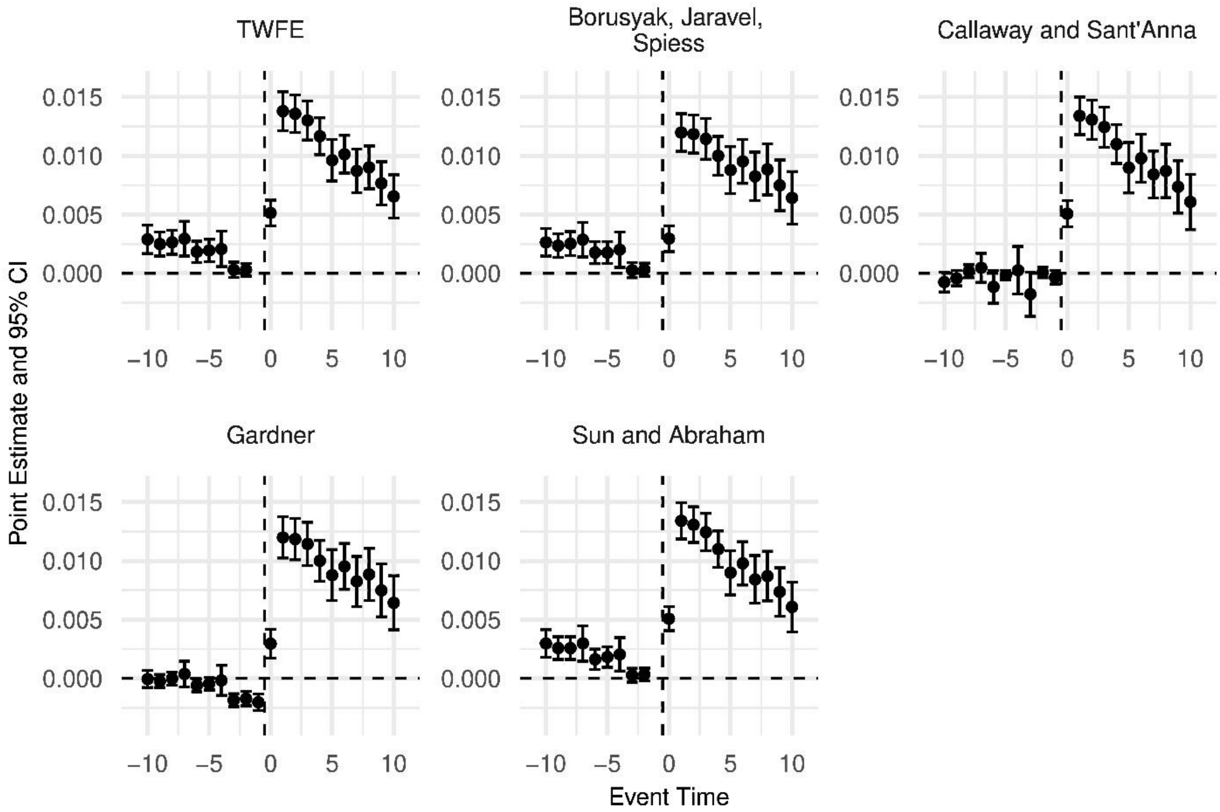

Fig 12 Event-study plot of the effect of Door-to-Door with light packaging collection on the per capita separated light packaging

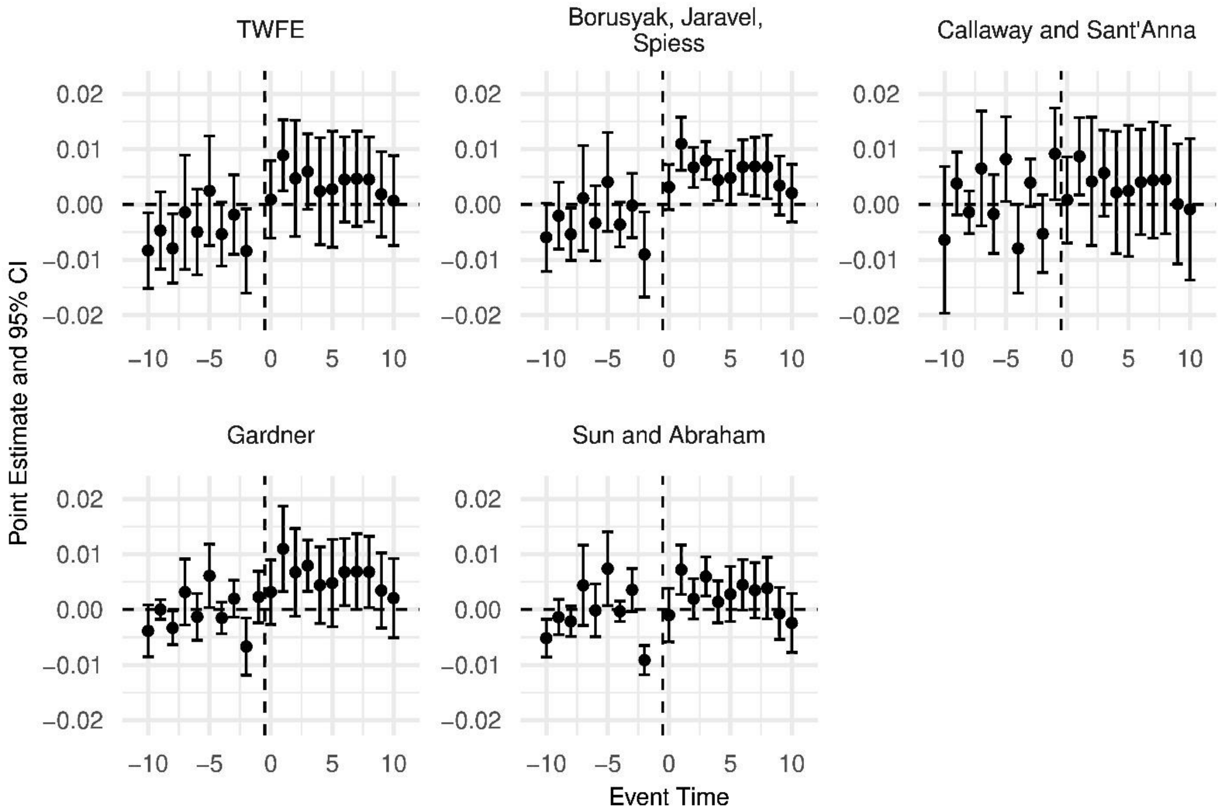

Fig 13 Event-study plot of the effect of Door-to-Door without light packaging collection on the per capita separated light packaging

A4 Plastics per capita, excluding high-volatility observations

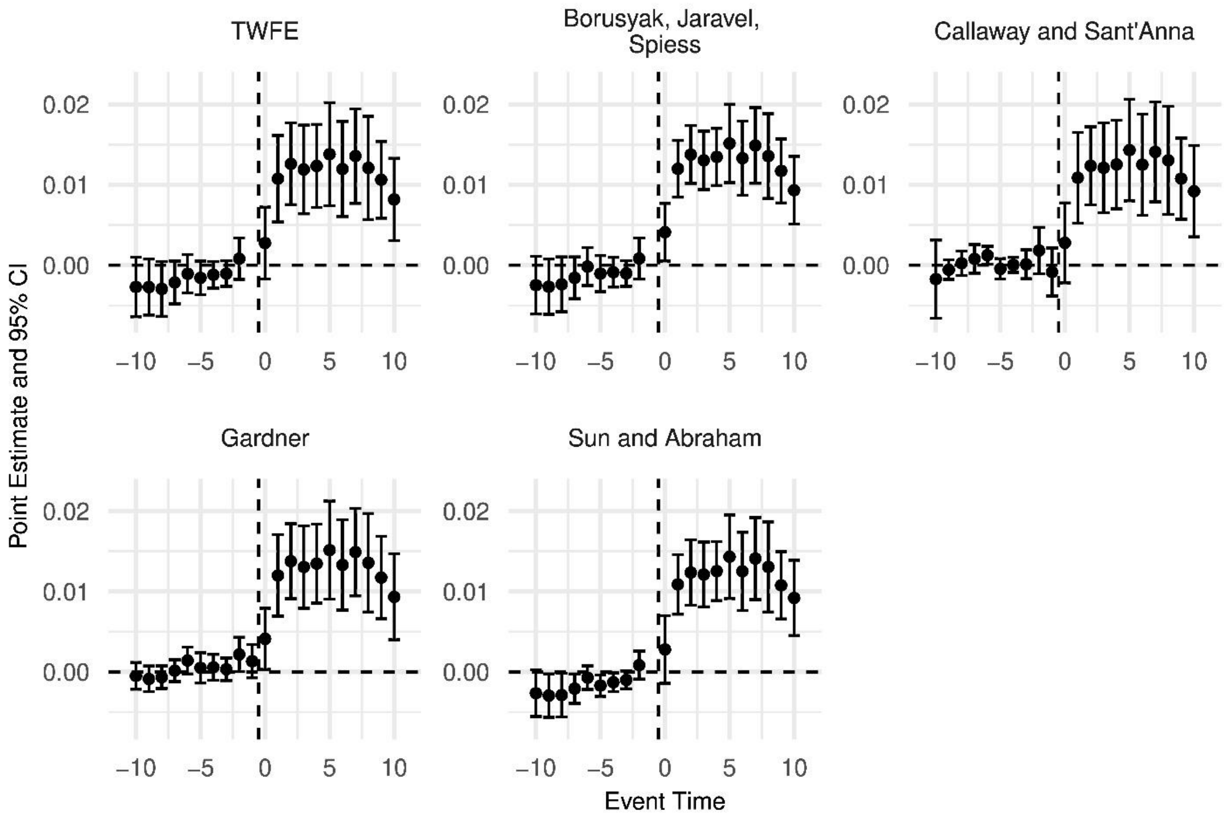

Fig 14 Event-study plot of the effect of Door-to-Door on sorted per capita plastics waste, excluding observations with very high volatility.

A5 Only including municipalities serving at least a certain threshold

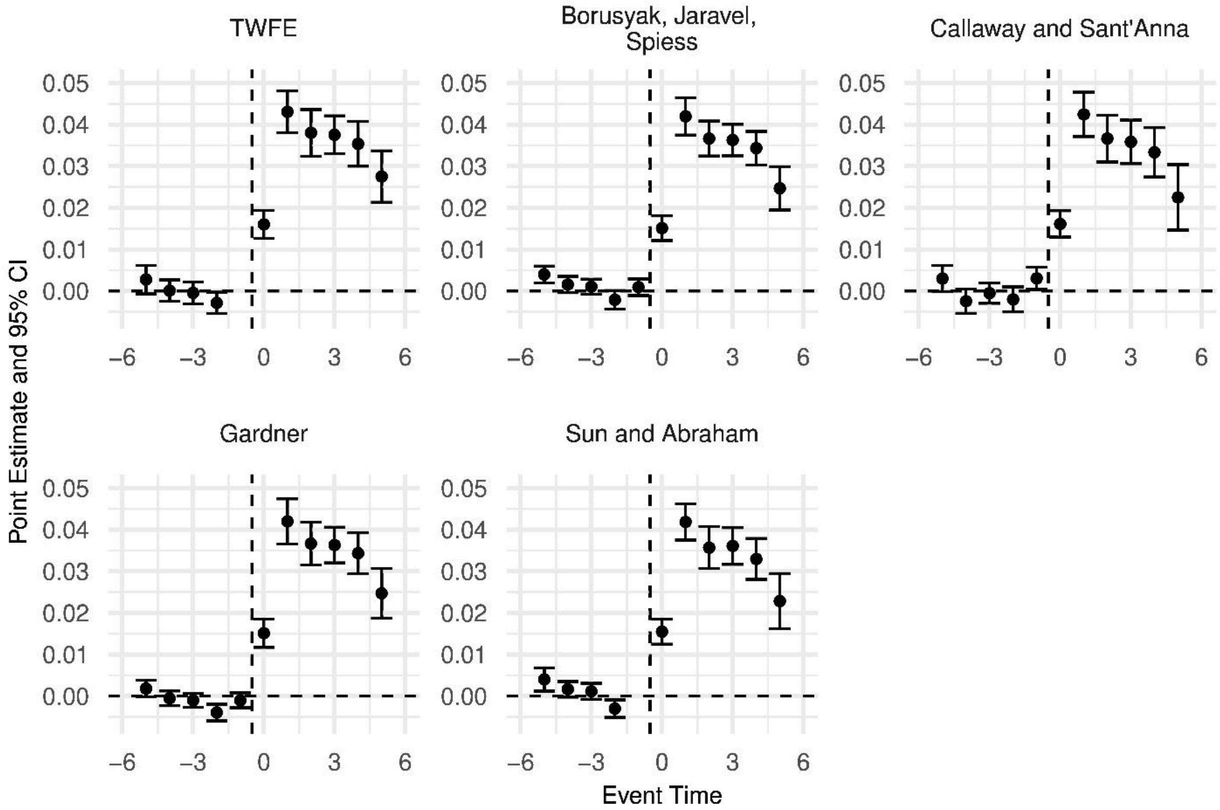

Fig 15 Event-study plot of the effect of Door-to-Door serving at least 25% of the population on selected light packaging

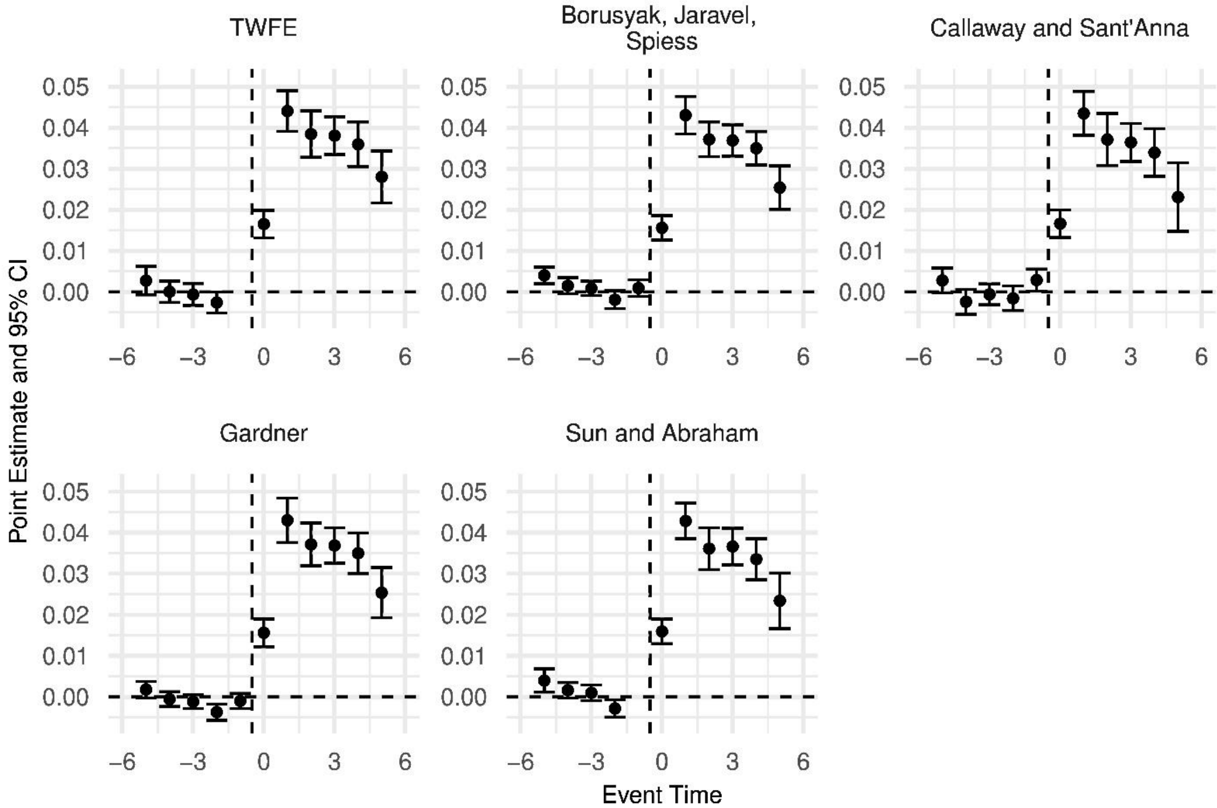

Fig 16 Event-study plot of the effect of Door-to-Door serving at least 50% of the population on selected light packaging

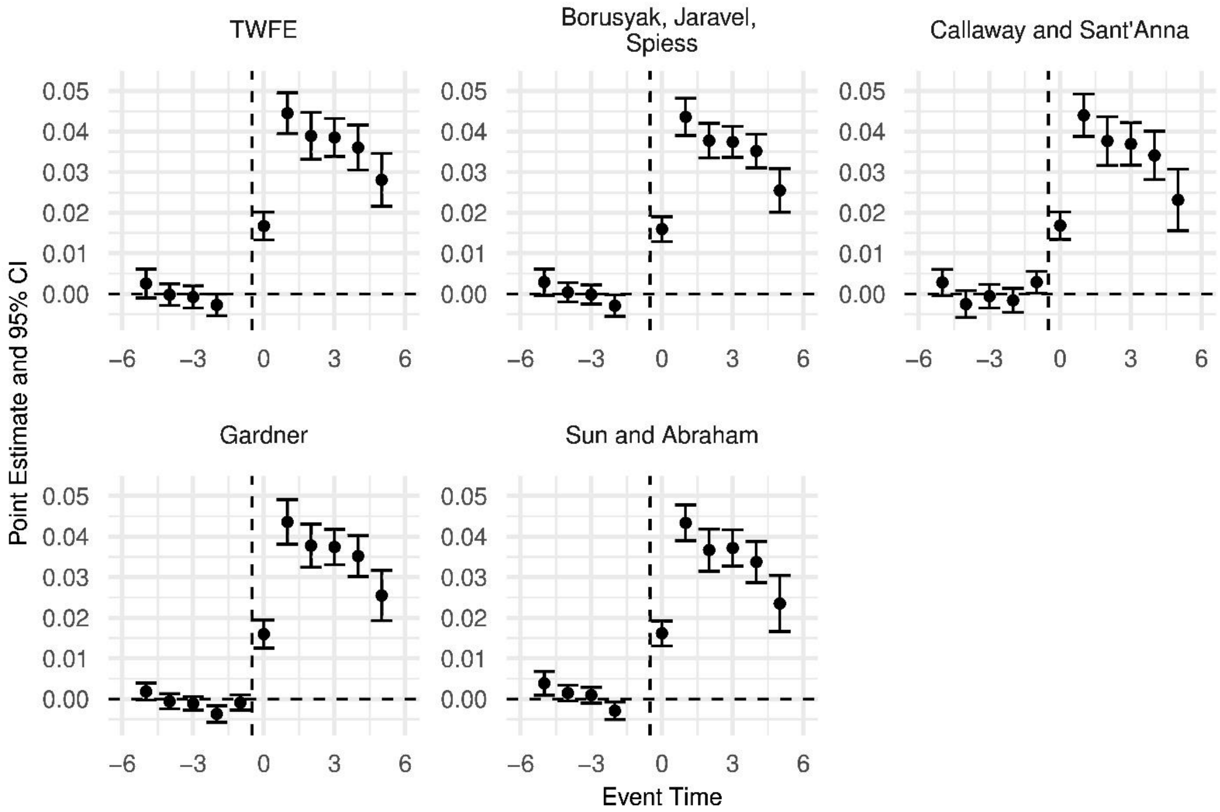

Fig 17 Event-study plot of the effect of Door-to-Door serving at least 75% of the population on selected light packaging

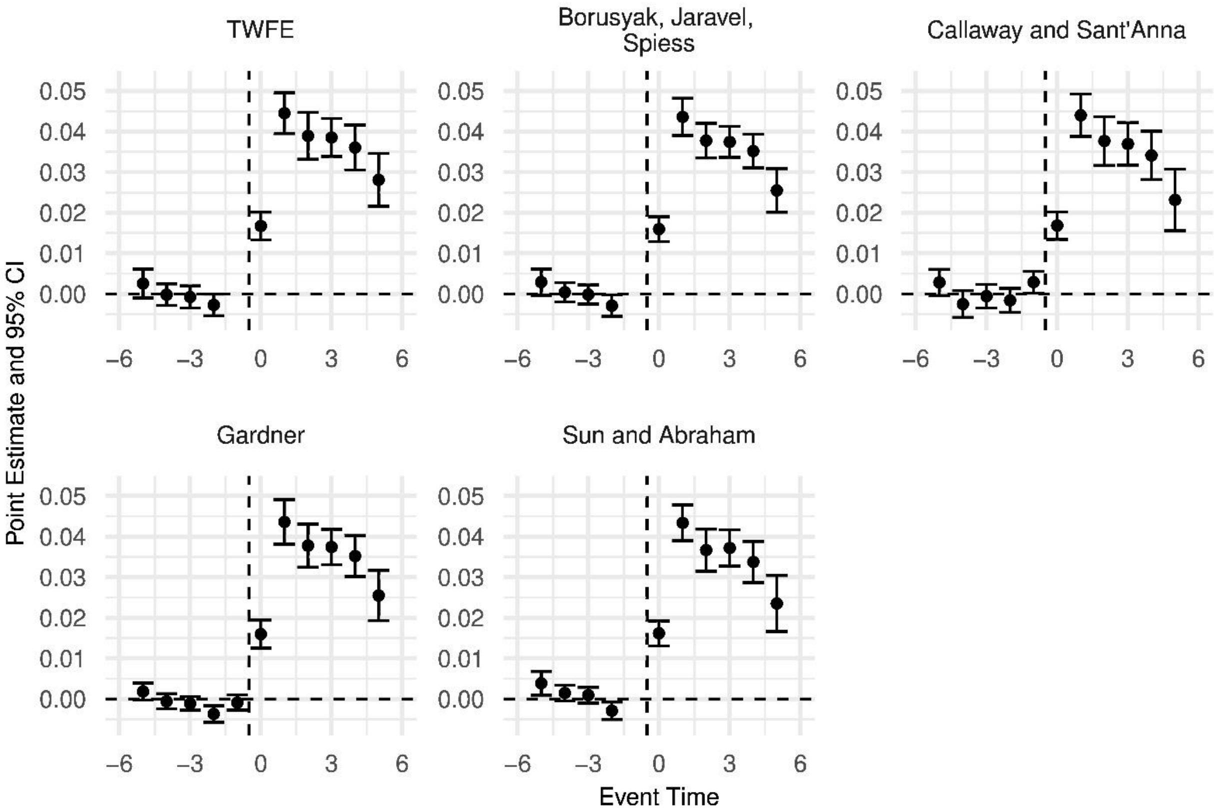

Fig 18 Event-study plot of the effect of Door-to-Door serving 100% of the population on selected light packaging

UBIREA
Institut de Recerca en Economia Aplicada Regional i Pública
Research Institute of Applied Economics
Universitat de Barcelona
Av. Diagonal, 690 • 08034 Barcelona

WEBSITE: www.ub.edu/irea/ • **CONTACT:** irea@ub.edu