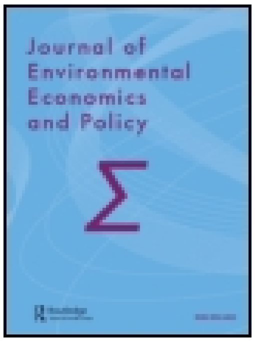

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Waste reduction and waste spillovers: evidence from unit-based pricing of municipal solid waste in Taiwan

Yu-Kai Huang[a], Reid B. Stevens[b] and W. Douglass Shaw[b]

[a]Department of Agricultural Economics and the Center on Conflict and Development, Texas A&M University, College Station, Texas, USA; [b]Department of Agricultural Economics, Texas A&M University, College Station, Texas, USA

ABSTRACT
This study evaluates the effects of unit-based pricing (UBP) of municipal solid waste and a mandatory recycling (MR) policy on waste reduction, recycling, illegal dumping, and garbage tourism incidents in major municipalities of Taiwan by using a quasi-experimental framework. The results suggest that the UBP policy curbed the quantity of unsorted waste and increased disposal of biodegradable waste but did not significantly increase recycling. In contrast, the MR policy effectively boosted biodegradable waste and recycling but did not necessarily decrease the amount of unsorted waste. There was a temporary increase in illegal dumping following the UBP policy. No evidence indicates that waste was shipped to nearby urban municipalities that had no UBP policy but likely to a neighbor rural municipality. The efficiency of the UBP in Taiwan is also discussed and compared with similar programs in other countries in this study.

KEYWORDS
Unit-based pricing; waste management; illegal dumping; quasi-experiment; recycling

SUBJECT CLASSIFICATION CODES
Q5

1. Introduction

A poorly designed waste management policy can have negative impacts on local water quality, the environment, human health, and biodiversity. Wilson et al. (2015) forecasts that the global population will increase to nine billion by the end of the 21st century. Eighty percent of the world's population will live in cities with sufficient disposable income to generate a significant volume of waste, necessitating advances in waste management. Traditionally, waste management strategies have relied on command and control (C&C) approaches which set specific laws/standards specifying behaviors. Alternatively, a unit-based pricing (UBP) policy or pay-as-you-throw, which charges residents a per-unit disposal fee for waste, potentially allows policymakers to both curb waste and promote recycling. A UBP can be practically implemented by using either trash bins, trash bags, or official tags/stickers. Units of waste can be measured or quantified by volume, weight, frequency, or some combination of these measures. The pay-as-you-throw approach follows the 'polluter pays' principle, providing residents with economic incentives to reduce waste and is a potentially efficient approach to reduce the quantity of collected waste (Callan and Thomas 1999; Dijkgraaf and Gradus 2009; Huang, Halstead, and Saunders 2011; Bel and Gradus 2016). In this paper, the effectiveness of a UBP policy is examined using data from Taiwan. Waste management is an important issue in Taiwan, a country with one of the highest population densities[1] in the world, and its waste management policies have received considerable attention worldwide[2].

CONTACT Yu-Kai Huang laurencehuang@tamu.edu Department of Agricultural Economics and the Center on Conflict and Development, Texas A&M University, College Station, Texas, USA

Taipei City, the capital in Taiwan, first implemented a UBP policy in July 2000. New Taipei City[3], which surrounds Taipei City, introduced a UBP pilot program in July 2008, which gradually expanded until December 2010, when the policy was adopted city-wide. Taiwan's UBP policy charges residents a waste-disposal fee based on their volume of garbage. Residents must dispose of waste using authorized garbage bags, which are sold in retail stores and priced according to the size of the bag. In New Taipei city, the price per authorized garbage bag varies from US $0.04 for the smallest bag to US $1.60 for the largest bag and is almost identical to the price in Taipei City (see Panel A of Table 1).

The introduction of a UBP policy in Taipei City and New Taipei City provides a nice quasi-experimental setting in which to evaluate the effectiveness of the UBP policy relative to neighboring municipalities and other major cities in Taiwan that have no municipality-wide UBP policy: these include Keelung City, Yilan County, Taoyuan City, Taichung City, Tainan City, and Kaohsiung City. These other municipalities constitute the experimental control group for the study. The map in Figure 1 shows that municipalities in the control group vary in their distances from the greater Taipei area. Spatial and intertemporal variation in UBP policies allows us to estimate whether there are policy spillovers, wherein residents of municipalities with UBP policies avoid unit-pricing fees either by disposing of garbage in neighboring cities without UBP policies (i.e., the practice sometimes referred to as "garbage tourism") or by illegally disposing of garbage in public. The overall effect of UBP is ambiguous if there are unintended side effects (e.g. garbage tourism or illegal dumping) (Kinnaman 2006; 2008), and this ambiguity sparked our research interest.

In addition to the UBP policy, Taiwan also implemented a nationwide C&C practice that is essentially a mandatory recycling (hereafter MR) policy in January of 2006. Based on the MR policy, people who dispose of recyclable waste along with ordinary waste will be fined NT $1,200–6,000 (US $1 = NT $30), and waste-collection crews can refuse to collect mixed wastes. Details of the waste collection system in Taiwan are discussed in Section 2.2. The objectives of this research are to quantify the effect of UBP policy on the levels of unsorted garbage, biodegradable waste[4], and recyclable waste[5] relative to municipalities in the control group. This is accomplished by

Table 1. Information of the UBP policy, Taichung City, and summary statistics.

Panel A: Information of unit-based pricing in Taipei city and New Taipei City

			Taipei City			New Taipei City		
Bag size (liter)	Max. load / bag (kg)	Bags/pack	US$/pack	US$/bag	US$/liter	US$/pack	US$/bag	US$/liter
3	0.6	20	0.70	0.04	0.01	0.80	0.04	0.01
5	1	20	1.20	0.06	0.01	1.33	0.07	0.01
14	2.9	20	3.33	0.17	0.01	3.73	0.19	0.01
25	5.1	20	6.00	0.30	0.01	6.67	0.33	0.01
33	6.9	20	7.90	0.40	0.01	8.80	0.44	0.01
76	15.9	10	9.10	0.91	0.01	10.13	1.01	0.01
120	25.1	5	7.20	1.44	0.01	8.00	1.60	0.01

Panel B: Comparison between Taichung City and Shigang Town

		Population		Density (Pop./km^2)	
	Area (km^2)	2001	2016	2001	2016
Taichung City	2214.9	2,485,968	2,767,239	1122.38	1249.37
Shigang Town	18.2	15,290	15,174	839.63	833.26
Share of Taichung City	0.0082	0.0062	0.0055	-	-

Panel C: Summary statistics

Statistic	*N*	Mean	St. Dev.	Min	Max
Unsorted waste (kg per capita)	1536	16.56	5.73	6.38	70.04
Biodegradable waste (kg per capita)	1152	2.62	1.23	0.02	5.98
Recycling (kg per capita)	1632	9.07	4.2	0.74	18.23
Illegal dumping incident (count/1000 ppl)	1296	0.64	0.66	0.01	3.74
Income (NTD 1000)	1632	1163.46	207.05	874.4	1697.89
Percentage of babies	1632	0.04	0.01	0.02	0.06
Household size	1632	2.94	0.25	2.45	3.49

Figure 1. Geographical illustration of Taiwan.

using a difference-in-differences (DID) model in the quasi-experimental setting described above. Besides that, this study also investigates possible evidence of illegal dumping and garbage tourism induced by the UBP policy and further compares the effectiveness of UBP policy and nationwide MR policy. This paper contributes to the understanding of the effect of implementing the UBP policy in the short and long run, its unintended side effects, and its waste reduction mechanisms by investigating changes in the quantity of different waste sources. These experiences and lessons can guide policymakers interested in addressing waste management problems in other areas, especially in other emerging economies with severe waste management issues.

The remainder of the paper is structured as follows. Section 2 reviews waste management literature and describes the waste management in Taiwan. In Section 3, the data used in this study are described. In Section 4, the empirical strategies for estimating the effect of UBP policy and investigating spillover effects are described. Section 5 presents the estimates of static and dynamic policy effects of UBP and the analysis of the UBP policy side effects. Section 6 discusses the welfare effects of the estimated policy effects. Finally, the conclusions and policy implications are summarized.

2. Waste management review

2.1. Literature review

Several previous studies have investigated the demand for garbage collection and evaluated the effect of UBP policies. The data used in these studies can be simply classified as falling into two types: (i) household survey, and (ii) city-level aggregate data. Household survey data studies are reviewed first. Fullerton and Kinnaman (1996) estimate household responses to the implementation of a UBP policy in Charlottesville, Virginia, and find that the policy reduces the number of garbage bags and increases the weight of recycling, but does not necessarily decrease the weight of households' garbage. Hong and Adams (1999) investigate the effects of a change in the price of waste disposal services on recycling in Portland, Oregon. They conclude that households respond to a waste disposal price increase by increasing recycling to avoid extra charges for waste generation above the contracted volume. Hong (1999) investigates the effect of an increase in waste collection fees on recycling in South Korea, finding that households do not decrease demand for waste collection services after fee increase because demand for waste is relatively inelastic. Linderhof et al. (2001) find significant and sizeable price effects of weight-based pricing on compostable and non-recyclable waste for households in Oostzaan, the Netherlands. A nationwide households study in the U.S. by Jenkins et al. (2003) estimates the effect of curbside recycling, MR program, and unit pricing implemented in 20 U.S. metropolitan areas finding that a curbside recycling program increases household recycling more than a unit pricing program and this effect varies across different recyclable materials. They also suggest that MR programs have an insignificant effect on recycling.

Allers and Hoeben (2010) suggest that there are two disadvantages of using survey data to evaluate UBP policies. First, studies which use household-level survey data may suffer from sample-selection bias because environmentally conscious or well-educated people may have a higher tendency to respond to environmental policy surveys. The bias may well distort results, misleading policymakers as to the true effectiveness of a UBP policy. However, statistical corrections to such potential bias can overcome this criticism. Second, these survey studies typically focus on a short study period and may not capture the long-term policy impact. This also may be overcome, if panels of households are developed. It is also worth noting that developing one's own survey allows response to thoughtful questions to be integrated into the analysis.

Several recent studies use the second type of data (city-level aggregate data) to evaluate the effect of UBP policy. Kinnaman and Fullerton (2000) use community-level cross-sectional data to address potential issues associated with endogeneity of the local government's decisions regarding garbage fees and curbside recycling programs. Their results show that the effect of local waste management programs may be underestimated by assuming the policy is exogenous. Dijkgraaf and Gradus (2004; 2009) also use municipal-level panel data, evaluating the effect of UBP policy on a reduction of waste in the Netherlands. They find that a UBP policy reduces the amount of unsorted waste, compostable waste, and increase the quantity of recyclable waste. The authors also note that administrative costs are significantly lower for bag-based pricing. Usui and Takeuchi (2014) estimate a fixed effects model to examine the effect of a UBP in cities of Japan finding a long-lasting effect of UBP on recycling and that the policy effect differs by income groups. The higher income groups are more likely to engage in recycling activities without economic incentives. Carattini, Baranzini, and Lalive (2018) use both administrative data and survey data to estimate the effect of a UBP policy in Switzerland and find that people accept 70% higher garbage taxes after pricing garbage by the bag compared to before the pocliy came into effect.

In spite of a considerable amount of literature evaluating the effectiveness of UBP policies, the effectiveness of these policies remains mixed, especially in terms of welfare impacts. Dijkgraaf and Gradus (2004) find a large welfare gain from the UBP policy that reduces waste in the Netherlands because of a higher marginal cost of garbage collection and disposal. To the contrary, Kinnaman (2006) and Kinnaman (2008) claim that net benefits of introducing the UBP policy could be small or even negative given the high administrative cost of implementing the policy and the increase in illegal garbage dumping. Kim, Chang, and Kelleher (2008) also estimate that a 1% increase in the unit price of a trash bag led to a 3% increase in the number of reports of illegal dumping in South Korea. Likewise, a small amount of disposal spillover to adjacent municipalities was identified when municipalities introduced their pricing schemes in Japan (Usui and Takeuchi 2014). Miranda and Aldy (1998) examine UBP of residential solid waste in US communities and find that illegal disposal does not appear to be evident. Given that estimated policy impacts vary in individual countries, more carefully done studies of differences in the impacts of country-specific UBP policies are needed, to explore why they seem to work fairly well in some countries, but not others (e.g. the U.S.).

There are several previous waste management studies conducted in Taiwan. For example, Lu et al. (2006) overview the waste management measures in Taiwan and highlight the importance of MR policy among waste management measures in Taiwan. Yang and Innes (2007) investigate the impact of the UBP policy in Taipei City using a fixed-effects pooled model and a seemingly unrelated regression, but they do not estimate the side effects of the policy or the long-term policy effects. The authors also study a regional MR program (only in Kaohsiung City not nationwide one). As noted above, there is no previous study to estimate effects of the UBP policy in New Taipei City and the national MR policy in Taiwan or in similar emerging economies in a quasi-experimental framework, nor do previous studies with administrative data quantify the amount of illegal dumping in terms of actual weight caused by relevant policy interventions.

2.2. Waste management systems in Taiwan

The waste collected by municipalities in Taiwan is composed of four components: unsorted waste, biodegradable waste, recycling, and large recyclable waste. Large recyclable waste is primarily large-sized durable goods (e.g., sofas, mattresses, air conditioners, and refrigerators) and is not subject to the UBP policy. Hence, we exclude large recyclable waste in this study.

Municipal solid waste in Taiwan is typically collected by garbage trucks five days a week. These trucks broadcast music to notify inhabitants of their arrival at a designated location. Usually, two different types of trucks arrive to collect waste: an open-bed recycling truck and a garbage truck. The recycling truck arrives 10 minutes before the garbage truck, which collects unsorted and biodegradable waste. The recycling truck departs to the next pick-up area once the garbage truck arrives. The system makes it difficult for households to avoid paying the disposal fee. Because residents have to personally deposit their waste in a garbage truck that is monitored by the collection crew, it is relatively easy to inspect whether residents use officially authorized garbage bags or not. This collection system also allows collection crews to inform residents of the policy details and the recycling options.

In addition to the truck system, there are a few stationary waste collection locations in two cities, which are also managed and monitored by collection crews and video cameras. Some apartments also have a centrally managed waste space that is also monitored by video cameras and managed by an outsourcing environmental service company. Finally, some residents sell their recyclable waste to private waste collection services. Although residents can earn money using these services, the private collector's irregular visits are considered an inconvenience by residents and the payments are relatively low, so the services are not typically used to dispose of recycling waste.

The Taiwanese EPA also creates an incentive for residents to be involved in monitoring any illegal dumping. Residents can upload evidence of violators in a form of videos or pictures on an EPA online platform and earn up to half of the value of any fines collected as a reward for providing evidence of violations. For instance, people who dispose of recyclable waste along with ordinary waste or do not use government-issue trash bags for ordinary waste will be fined NT $1,200–6,000 (US $1 = NT $30), and waste-collection crews can refuse to collect those wastes.

Though all municipalities in Taiwan charge garbage fees, only Taipei City and New Taipei City charge a variable fee by government-authorized garbage bags. The other municipalities in Taiwan assess residents a flat garbage fee that is distributed along with water bills. These flat fees do not cause residents to internalize external collection and disposal costs. Some other major cities in Taiwan have expressed interest in a variable rate waste management policy. For example, a small town, Shigang Town, in Taichung City also has implemented the UBP policy since 2000. However, Taichung City faced considerable opposition to a proposal to have a city-wide policy. Opposition from the local congress and residents was because of political considerations as well as the possibility of increased illegal dumping, which has been discussed by Kinnaman (2006; 2008). Note that although there is the small town in Taichung City implementing the UBP policy, we still use Taichung City as one of our control municipalities. Shigang Town comprises only 0.82% of the total area in Taichung City, and only 0.62% of the total population, of Taichung City in 2001 [and only 0.55% of the total population in 2016 (see Panel B of Table 1)]. Because town-level data are not available, we use different subsets of data to conduct our analysis to address potential confounding.

3. Data

This study uses both waste and municipal characteristics data, each of which are observed at the municipal level at a monthly frequency. The variables of interest are the quantity (by weight) of unsorted waste, biodegradable waste, and recycling. Waste data are collected by the Taiwan EPA and publicly available as an administrative dataset. Unsorted waste is collected five days a week and is either sent to incineration plants or sent to landfills after being collected. Municipal level data on garbage collection are available from January 2001 to December 2016. Biodegradable waste data are available from January 2003 to December 2014. Illegal dumping data, which provide the number of illegal dumping violations, are collected by the major municipalities (Taipei City, New Taipei City, Taoyuan City, Taichung City, Tainan City, and Kaohsiung City) and are available from January 1998 to December 2015. These data are based on the number of citations to illegal waste dumpers which are assessed by inspection crews in Environmental Protection Bureaus of local governments or, as are reported by residents.

The municipal characteristic data include annual household income, monthly city population, percentage of babies (below 3-years-old), and the annual average household population. These data are available from January 1998 to December 2016. Annual household income, available from the Statistical Bureau of Taiwan, consists of annual household salary, rents from other properties, and other transferred income. Monthly population data from the EPA records the monthly number of residents in each municipality. Household population data, including the population distribution by age, are provided by the Ministry of the Interior database. Summary statistics for the waste and municipal characteristic data are shown in Panel C of Table 1.

4. Empirical strategies

This study first uses a difference-in-differences model to estimate the effect of the UBP policy, using monthly municipal data. Taipei City is included as a treated control, and six other municipalities in Taiwan without UBP policies are included as controls. The empirical approach of a static DID model is presented in detail in section 4.1, and a dynamic DID model is introduced in section 4.2. Spillover effects on neighboring municipalities without UBP policies are also investigated. In particular, we estimate whether municipalities adjacent to New Taipei City experienced an increase in waste disposal following the policy implementation using a regression discontinuity method. This spillover part of the empirical strategy is discussed in section 4.3.

4.1. Difference-in-differences analysis of UBP in NTC

This research estimates the average treatment effect (ATE) of a unit pricing policy on waste disposal using the following specification:

$$\begin{aligned} Y_{it} = {} & \alpha \cdot X_{it} + \beta_{TT} \cdot TT_t + \beta_{TC} \cdot TC_i + \tau \cdot TT_t \cdot TC_i + \rho \cdot MR_t + \theta \cdot MR_t \cdot UBP_{it} \\ & + \gamma \cdot Trend_t + \mu_i + \lambda_t + u_{it} \end{aligned} \tag{1}$$

where Y_{it} is the variable of interest (quantity of unsorted waste, biodegradable waste, and recycling per person). X_{it} is a set of controls for municipality i at time t, such as the percentage of babies, household size, and income. The indicator variable TT_t is equal to 1 following the implementation of the UBP policy, and equals 0 before the policy. The indicator variable TC_i is equal to 1 if the observation belongs to a treated municipality and equals 0 otherwise. The coefficient τ accounts for the ATE of the UBP policy. Since the unit price of the UBP policy is almost identical in Taipei City and New Taipei City (refer to Panel A of Table 1), using the dummy variable to estimate the effect of the UBP policy in both cities is not problematic. The indicator variable MR_t, which is 1 if an observation is after January 2006, represents the presence of a nationwide mandatory waste recycling policy. Note that there is no control group to conduct a DID analysis for the national MR policy because the MR policy was implemented to all municipalities in Taiwan. Thus, the simple dummy variable is employed to analyze the MR policy in Equation (1). UBP_{it} is a dummy variable which is equal to 1 if the observation is in the period of implementing the UBP policy in Taipei City or New Taipei City. The coefficient θ captures differential effects of the MR policy on the non-UBP and UBP municipalities. $Trend_t$ is a time trend which captures nationwide growth of environmental awareness and increasing familiarity with recycling behavior over the study period. μ_i and λ_t represent municipality-specific fixed effects and monthly fixed effects, which respectively control for unobserved geographical and seasonal factors. u_{it} denotes the idiosyncratic error term.

4.2. Potential dynamic effects of the UBP

In addition to quantifying the average effect of the UBP on our variables of interest, the effect of the policy change over time is also relevant to policymakers. In order to address the dynamic aspect of the policy, we conducted an alternative DID model (Equation (2)) with dynamic treatment effects as follows:

$$Y_{it} = \alpha \cdot X_{it} + \sum_{k=1}^{K} \beta_k \cdot LTT_k + \beta_{TC} \cdot TC_i + \sum_{k=1}^{K} \tau_k \cdot LTT_k \cdot TC_i + \delta \cdot Trend_t + \mu_i + \lambda_t + u_{it} \quad (2)$$

where Y_{it} is the variable of interest (quantity of unsorted waste, biodegradable waste, and recycling per person). X_{it} denotes a matrix of characteristics of municipality i in time t, which is the same as defined in Equation (1). LTT_k denotes a set of indicator variables for kth lagged year after the implementation of the UBP policy. For instance, the UBP policy was first implemented in July 2008 in New Taipei City, so LTT_1 is 1 if an observation is in the first year lag (i.e. 2009) and is zero otherwise. Other year lag length indicator variables use the same notation except for the indicator variable 2008 which is equal to 1 if an observation is in the period from July to December of 2008 and is zero otherwise. τ_k is a treatment effect of the UBP policy in kth lagged year. μ_i represents municipality-specific fixed effects. Note that we cannot include the MR policy dummy and yearly fixed effects simultaneously because of issues associated with multicollinearity. To estimate yearly dynamic treatment effects, we need to include yearly dummy variables instead of incorporating the MR policy dummy. Thus, λ_t is a set of month and year dummies, which control unobserved seasonal effects and nationwide impacts of the MR policy over time.

4.3. Potential spatial spillover effects of UBP

This section describes the identification strategy for spatial waste spillovers (or garbage tourism) caused by the UBP policy. Given that waste disposal policies vary at the municipal level, it is possible for Taipei City and New Taipei City residents to avoid waste disposal fees by disposing of waste to nearby municipalities without UBP. By moving waste from the treated to control municipalities, garbage tourism would bias the estimated average treatment effect upward, making the policy appear effective even if the nationwide garbage disposal levels were unchanged.

To examine the waste spatial spillovers, the following municipality-specific time-series model for municipality i is used:

$$Y_t = \alpha + \beta \cdot X_t + \gamma \cdot UBP_t + \rho \cdot MR_t + \delta \cdot Trend_t + \lambda_t + e_t \quad (3)$$

where Y_t denotes the quantity of unsorted waste per person in time t. X_t denotes a matrix of characteristics of neighboring municipality in time t, such as percentage of babies, household size, and income. The coefficients on the policy spillover effects (γ) are estimated using the policy dummy variables (UBP_t), which have a value of 1 if observation is after July 2008, and 0 otherwise. Long-term time-variant unobservable trends, such as environmentally conscious awareness and familiarity of recycling behavior, are controlled for using a linear time trend ($Trend_t$) in the model. λ_t is a set of month dummies, which control unobserved seasonal effects. Finally, e_t denotes the error term. Results of Equations (3) are estimated using a generalized least squares approach to make the results robust to serial correlation.

5. Empirical results

5.1. Results of UBP in NTC

The quantities of unsorted waste, biodegradable waste, recycling, and illegal dumping are plotted over time for each city in the sample in Figure 2, respectively. The first vertical dashed line in July 2000 marks the implementation of the UBP policy in Taipei City. The vertical dashed line in January 2006 and in July 2008 indicate the implementation of the nationwide MR policy and the beginning of the UBP pilot program in New Taipei City, respectively. The dashed line in December 2010 marks when the policy was expanded to cover the entire New Taipei City. Unsorted waste had a downward trend over the study period. Note that we excluded observations for unsorted waste in September 2001 because there is an extremely high amount of unsorted waste in that period in Taipei City. This outlier was caused by Typhoon Nari which led to catastrophic flooding in Taipei City and caused huge damage in residential and commercial areas. In fact, the UBP policy was temporarily suspended during a one-month cleanup period. Biodegradable and recyclable waste had an increasing trend over the study period (see Panel B and C of Figure 2). The number of illegal dumping incidences in New Taipei City increased sharply right after the

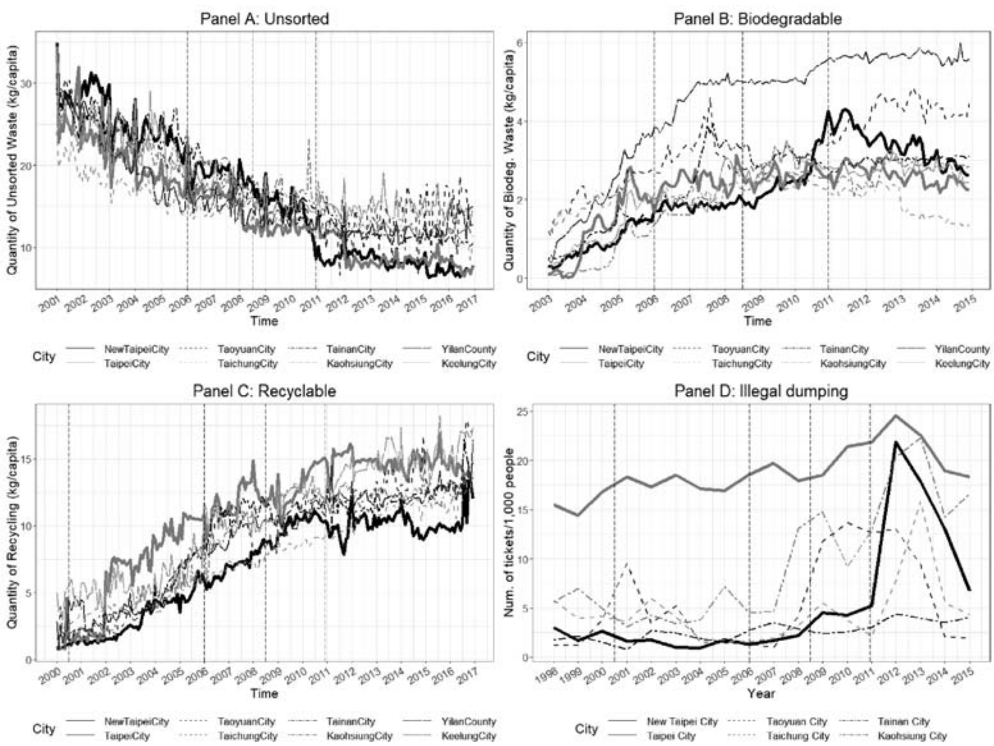

Figure 2. Trend for variables of interest. Note: The vertical line in July of 2000 indicates the implementation of the UBP policy in TPC; the vertical line in January of 2006 indicates the implementation of the nationwide MR policy; the vertical line in July of 2008 indicates the implementation of the pilot UBP policy in NTC; the vertical line in December of 2010 indicates the implementation of the city-wide UBP policy in NTC.

UBP policy extended to the entire city, but it fell a few years later after the implementation of the policy. Overall, Figure 2 displays parallel trends for these variables of interest in the sample municipalities during the pre-treatment periods.

Table 2 presents the results of the basic DID model with and without including observations in Taichung City, and using only observations in post January 2006. Data in the post January 2006 period captures the effect of the UBP policy in New Taipei City after the MR policy has been implemented nationwide. Although the UBP policy in Taiwan is volume-based, our wastes are measured by weight, as opposed to volume. This is important for the following reasons. First, the volume of waste can vary based on household behavior because waste can be compacted, even if by hand. This potentially introduces endogeneity in volume. The weight of the waste does not depend on a change in volume. Second, the original units of our data are weights of the waste per month so that we do not need to do any conversion. Third, most relevant studies also estimated policy effects by weight of the wastes, facilitating comparisons. Finally, we can gauge possible illegal dumping by weight (refer to Section 6.2 for details) which is more precise compared to the number of illegal dumping citations.

We estimate that the UBP policy in New Taipei City reduces the quantity of unsorted waste by 2.59 kg per capita per month, or 14% decline relative to New Taipei City's 2007 level (19.08 kg per capita per month). The combination of the UBP policy and MR policy contributed 3.48 kg per capita per month reduction in unsorted waste, or 18% decline relative to New Taipei City's 2007 level. The MR policy alone had no statistically significant effect on reducing unsorted waste across all study municipalities. In addition, the MR policy had a more significant effect on increasing biodegradable waste in New Taipei City compared to the UBP policy. Biodegradable waste disposal increased by 0.62 kg per capita per month (a 34% increase relative to New Taipei City's 2007 level) under the MR policy. The UBP policy boosted recycling in Taipei City by 2.6 kg per capita per month (a 59% increase relative to Taipei City's 2000 level), but the UBP policy alone in New Taipei City did not significantly increase recycling. The interaction term between the UBP and MR policy in the model, implying the combination effect of both policies, accounts for an additional increase of 0.99 kg per capita per month (a 14% increase relative to New Taipei City's 2007 level). The MR policy alone also helped to stimulate recycling by 1.6 kg per capita per month (a 31% increase relative to New Taipei City's 2005 level). Our results also show that the UBP policy in New Taipei City increased illegal dumping by 0.27 violation incidences per 1,000 people relative to the control cities However, there is no statistical evidence showing that the MR policy increased illegal dumping.

There is a potential confound caused by the pilot UBP program in Shigang Town of Taichung City, and to address this we estimate the policy effects on four variables of interest with all data and again by excluding data in Taichung City. Due to the small scale of the town in terms of sizes and populations compared to entire Taichung City, the town barely affected the level of waste in Taichung City. Our estimation yields the similar result for all variables of interest with and without including data for Taichung City.

The identification assumption of DID in this study is based on the fact that in the absence of the UBP policy, municipalities' waste level in the treated municipalities would have remained similar to the municipalities yet to be treated. This is known as a common trend assumption. To check the robustness of the estimated average treatment effect, a falsification or Placebo test, which evaluates the common trend identification assumption required in DID models, was conducted. The aim of these robustness checks is to demonstrate that the estimated treatment effect in Table 2 is not simply the result of chance. Rather, our estimation is statistically different from counterfactual treatment effects which we estimate by creating artificial counterfactual policy interventions.

First, monthly counterfactual policy intervention dummies were created using data in the pre-treatment period. These policy dummies are equal to 1 from the time of counterfactual policy interventions through the end of the pre-treatment period and have zero values before the counterfactual policy interventions. Using the counterfactual policy dummies in Equation (1), rather than the

Table 2. Estimated effects of the UBP and MR policy on waste.

	Unsorted			Biodegradable		
	All data (1)	Exclude TCC (2)	Post Jan-2006 (3)	All data (4)	Exclude TCC (5)	Post Jan-2006 (6)
Percentage of babies	179.00**	183.74	-78.13	-54.07**	-44.56**	-69.45**
	(90.80)	(132.89)	(102.56)	(22.14)	(20.79)	(31.29)
Household size	-5.48	-8.27	-5.72*	-8.5	-7.94*	0.23
	(8.22)	(10.21)	(2.98)	(6.01)	(4.22)	(0.76)
Income (NTD 1,000)	0.01	0.01	0.01**	0.0003	0.002	0.001
	(0.01)	(0.01)	(0.00)	(0.00)	(0.00)	(0.00)
I(UBP in NTC)	-2.59***	-2.81***	-4.58***	0.18	0.38*	0.88***
	(0.31)	(0.23)	(0.59)	(0.34)	(0.22)	(0.11)
MR	-1.15	-1.4		0.62**	0.79***	
	(1.00)	(1.20)		(0.27)	(0.25)	
I(UBP in NTC) × MR	-3.48**	-2.59**		0.69	0.3	
	(1.36)	(1.15)		(0.50)	(0.24)	
Time trend	-0.08**	-0.09**	-0.07***	-0.02	-0.01	0.01
	(0.04)	(0.04)	(0.02)	(0.02)	(0.01)	(0.01)
Constant	27.4	35.77	32.48***	27.28	23.30*	2.49**
	(20.48)	(22.74)	(3.67)	(17.83)	(12.67)	(1.23)
Duration	Jan 2001 - Dec 2016	Jan 2001 - Dec 2016	Jan 2006 - Dec 2016	Jan 2003 - Dec 2014	Jan 1998 - Dec 2014	Jan 2006 - Dec 2014
Num. of municipalities	8	7	8	8	7	8
Observations	1,536	1,344	1,056	1,152	1,008	864
Municipal fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Monthly fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
	Recycling			Illegal dumping incident		
	All data (7)	Exclude TCC (8)	Post Jan-2006 (9)	All data (10)	Exclude TCC (11)	Post Jan-2006 (12)
Percentage of babies	-169.36***	-214.09***	-51.94	11.16	1.80	-18.26***
	(47.61)	(38.92)	(64.64)	(19.43)	(23.13)	(7.01)
Household size	1.4	5.94	-6.35***	-1.87	-0.6	-1.48***
	(5.64)	(4.43)	(1.66)	(2.87)	(3.79)	(0.11)
Income (NTD 1,000)	0.002	0.002	0.001	-0.0003	-0.001	-0.002
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
I(UBP in TPC)	2.60***	2.33***		0.35	0.27	
	(0.39)	(0.39)		(0.27)	(0.34)	
I(UBP in NTC)	-0.67*	-0.37	0.67*	0.27*	0.29	0.23
	(0.37)	(0.29)	(0.36)	(0.14)	(0.20)	(0.17)
MR	1.60***	1.79***		0.02	-0.001	
	(0.54)	(0.53)		(0.07)	(0.07)	
I(UBP in NTC) × I(UBP in TPC) × MR	0.99*	0.52		0.002	-0.1	
	(0.52)	(0.40)		(0.25)	(0.33)	
Time trend	0.04**	0.05***	0.01	-0.004	0.0002	0.002
	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)	(0.00)
Constant	5.69	-6.2	27.63***	6.40	3.54	7.77***
	(15.15)	(12.11)	(3.01)	9.55	(12.39)	(2.48)
Duration	Jan 2000 - Dec 2016	Jan 2000 - Dec 2016	Jan 2006 - Dec 2016	Jan 1998 - Dec 2015	Jan 1998 - Dec 2015	Jan 2006 - Dec 2015
Num. of municipalities	8	7	8	6	5	6
Observations	1,632	1,428	1,056	1,296	1,080	720
Municipal fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Monthly fixed effect	Yes	Yes	Yes	Yes	Yes	Yes

Note: *p<0.1; **p<0.05; ***p<0.01. The unit of income is NT$ thousands (US$ 1 = NT$ 30). The treatment effects of UBP and MR policies are in terms of kg per capita. All standard errors are clustered by cities. The results of municipal and monthly fixed effects are not shown in the table because of the limited space.

actual policy dummy, the new model can be written as

$$Y_{it} = \alpha \cdot X_{it} + \beta_{CTT} \cdot CTATU_t + \beta_{TC} \cdot TC_i + \tau_C \cdot CTATU_t \cdot TC_i + \rho \cdot MR_t + \mu_i + \lambda_t + u_{it} \quad (4)$$

where $CTATU$ is the average treatment effect on the untreated, namely a counterfactual treatment time dummy indicating counterfactual policy interventions in each month during the pre-treatment period. The coefficient on the interaction term is the counterfactual treatment effect (τ_C). The definitions of the rest of variables are identical to those used in Equation (1).

Iteratively replacing $CTATU$ in Equation (4) with different counterfactual policy interventions yields different counterfactual treatment effects (τ_C). The distribution of those counterfactual treatment effects using the same model specifications with Models (1), (4), (7), and (10) of Table 2 is shown in Figure 3, and its statistical summary is presented in Panel A of Table 3. The result of the Placebo test shows that the true ATEs are significantly different with the counterfactual placebo treatment effects (τ_C) for unsorted waste, biodegradable waste, and illegal dumping incidences, but the estimation in recycling appears to be less robust. In other words, except for the estimated effect

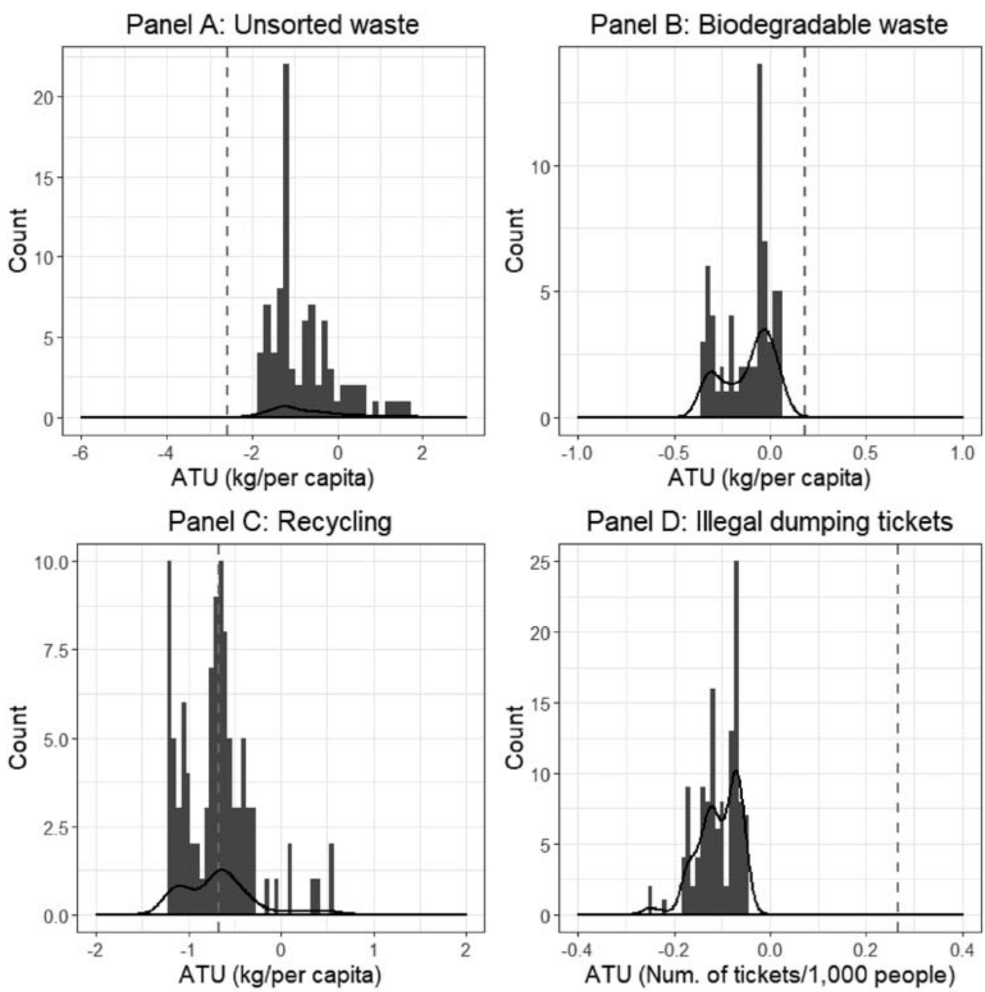

Figure 3. Placebo test for the difference-in-differences model. Note: The vertical dashed lines in the graphs indicate the average treatment effect on the untreated (ATU) estimated by using the same specification of Model (1), (4), (7), and (10) in Table 2.

Table 3. Robustness check for the difference-in-differences model.

Panel A: Statistic summary of counterfactual treatment effect				
	Unsorted waste	Biodegradable waste	Recycling	Illegal dumping
Mean	-0.783	-0.118	-0.689	-0.1078
95% CI	(-0.9500, -0.6157)	(-0.15056, -0.0855)	(-0.7651, -0.6128)	(-0.1154, -0.1002)
P-value	0.000	0.000	0.7075	0.000
Estimated ATE of UBP	-2.5900	0.1779	-0.6745	0.2689
Panel B: *T*-test for growth rate of variables of interest across municipalities				
	Unsorted waste	**Biodegradable waste**	**Recycling**	**Illegal dumping**
NTC = TPC	**0.337**	**0.936**	**0.769**	**0.9878**
NTC = KLC	**0.425**	**0.666**	**0.398**	**-**
NTC = YLC	**0.536**	**0.623**	**0.695**	**-**
NTC = TYC	**0.572**	**0.125**	**0.731**	**0.8473**
NTC = TCC	**0.496**	**0.101**	**0.152**	**0.9244**
NTC = TNC	**0.516**	**0.525**	**0.602**	**0.9836**
NTC = KSC	**0.451**	**0.918**	**0.560**	**0.8977**

Note: NTC represents as New Taipei City; KLC represents as Keelung City; YLC represents Yilan County; TYC represents Taoyuan City; TCC represents Taichung City; TNC represents Tainan City; KSC represents Kaohsiung City. Panel A shows the distribution of counterfactual treatment effects (τ_C) using the same model specification with Model (1), (4), (7), and (10) of Table 2. The values in Panel B are *p*-values obtained from *t*-test.

in recycling, the treatment effect estimated by the DID model is larger than would be expected by chance, indicating that our estimated ATEs of Table 2 capture the actual policy impact.

In addition to the Placebo test we construct a *t*-test to examine whether the quantity of unsorted waste, biodegradable waste, recycling, and illegal dumping have common trends for the treatment and control municipalities in the pre-treatment period. The growth rate is calculated by $(Y_{t+1} - Y_t)/Y_t$, where Y_t is the quantity of unsorted, biodegradable waste, recycling, or illegal dumping in month t. The p-values of the t-tests are presented in Panel B of Table 3. The null hypotheses, which assumes the average growth rates in the treated and control municipalities are identical in the pre-treatment period, cannot be rejected in a 90% confidence level. That is, the identifying assumption of parallel trends can be rejected using a difference-of-means test.

5.2. Dynamic effects of UBP

The dynamic treatment effects of the UBP policy in New Taipei City are reported in Figure 4. The UBP policy effect on unsorted waste began with an insignificantly small reduction during the pilot program (i.e. 2008-2010, or lagging years 0-2), and the effect size increased and remained significant after the policy went into effect for all of New Taipei City (i.e. 2011-2016 or lagging years 3-8). On the other hand, the effect of UBP on biodegradable waste was not measurable during the pilot program, but a significantly positive effect is estimated at the beginning of the city-wide policy rollout (i.e. 2011-2012 or 3rd - 4th lagged year) and slightly diminishes as time passes. Unlike the significant results for unsorted and biodegradable waste, the UBP policy had an unclear effect on recycling in New Taipei City but had significant effects on increasing recycling in Taipei City. This result suggests that the growth in recycling in New Taipei City shown in Figure 2 could be mainly explained by the MR policy, which is consistent with the estimated result for recycling in Table 2.

Illegal dumping also changes over time. The dynamic DID model for illegal dumping shows that the incremental amount of illegal dumping in New Taipei City spiked after the UBP policy was introduced and diminished with the passage of time. Also note that the increase in illegal dumping was not evident during the pilot program (i.e. 2008-2010, or with years lagged at 0-2) and only became evident after the full implementation of the UBP policy (i.e. 2012 and 2014, or lagged years 4 and 6). However, the UBP policy in Taipei City did not increase illegal dumping.

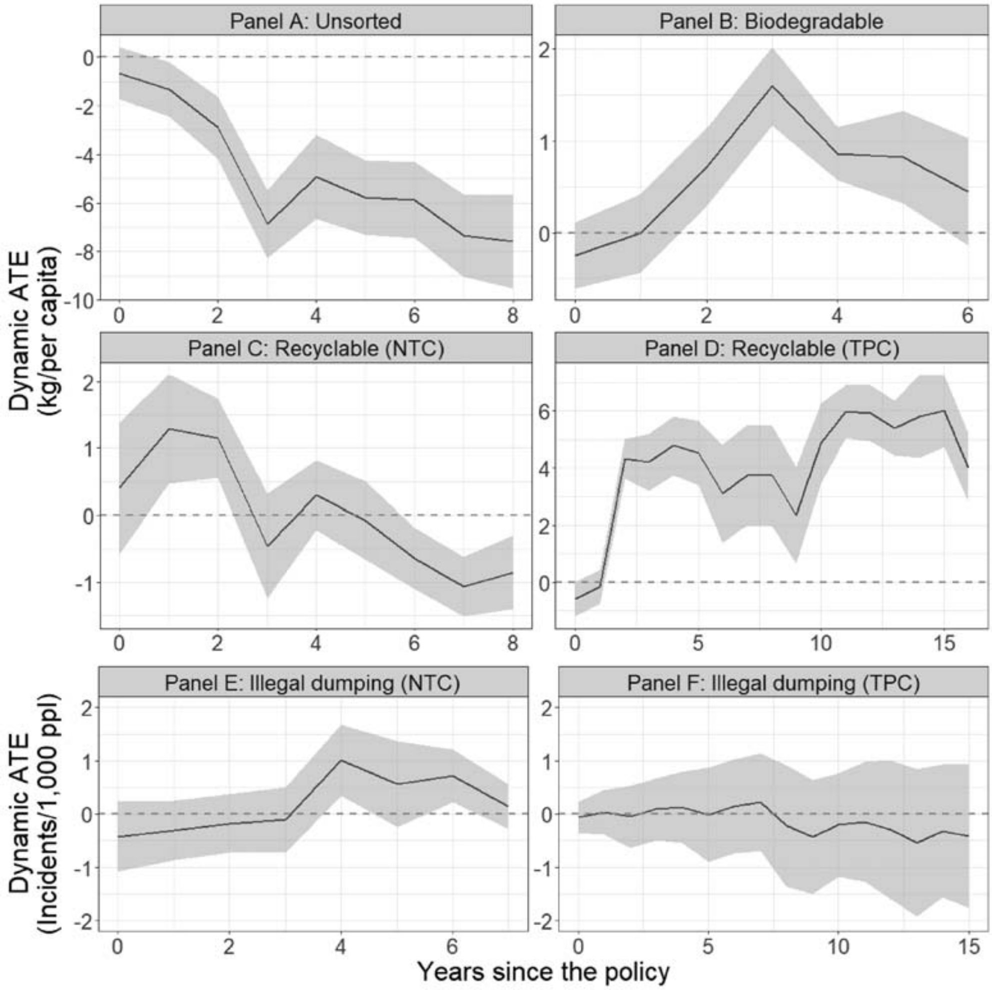

Figure 4. Dynamic average treatment effects (ATE). Note: Gray shades indicate a 95% confidence interval. All estimates control city and monthly fixed effects. All standard errors are clustered by cities.

5.3. Analysis of spatial spillover effects of UBP

The examination of potential spatial waste spillovers using the municipality-specific time-series model in Section 4.3 is presented in Table 4. The insignificant coefficients of the UBP policy in New Taipei City suggest that there are no waste spillovers from New Taipei City to neighboring municipalities except for Yilan County. The marginally significant coefficient indicates that the UBP of New Taipei City may marginally increase unsorted waste in Yilan County, implying that there may be spatial waste spillover from New Taipei City to Yilan County. Besides that, the MR policy increased the amount of unsorted waste in Yilan County. Note that Yilan County is a rural area where the enforcement of inspecting non-recycling behaviors may not be as strict as urban areas are. The population density of Yilan county is much lower than in other urban municipalities, so it would be more difficult to observe neighbors' non-recycling behaviors.

Taken together, the results in Table 4 suggests that the implementation of the UBP policy in New Taipei City did not induce garbage tourism in its adjacent urban municipalities but likely in its neighbor rural municipality.

Table 4. Examination of spatial waste spillovers from New Taipei City to neighbor municipalities.

	Unsorted waste (kg per capita)			
	Taipei City	Taoyuan City	Keelung City	Yilan County
	(1)	(2)	(3)	(4)
Income (NTD 1,000)	0.017	0.004	0.003	-0.006**
	(0.011)	(0.005)	(0.004)	(0.003)
Percentage of babies	51.470	781.951***	468.891***	966.927***
	(83.636)	(118.284)	(157.717)	(176.111)
Household size	42.210**	-43.733**	-38.316	-0.848
	(19.764)	(19.332)	(25.507)	(24.180)
I(UBP in NTC)	0.647	-0.625	-2.107***	1.214*
	(0.838)	(0.815)	(0.753)	(0.682)
MR	-0.634	-0.362	-2.131**	2.074**
	(0.941)	(0.755)	(0.968)	(0.815)
Time trend	-0.022	-0.143***	-0.092	0.007
	(0.039)	(0.054)	(0.062)	(0.083)
Constant	-130.513**	115.172**	105.927*	-13.055
	(59.828)	(57.766)	(61.402)	(70.265)
Observations	190	190	190	190
Monthly dummies	Yes	Yes	Yes	Yes
Log Likelihood	-343.210	-346.390	-350.374	-289.835
Akaike Inf. Crit.	726.420	732.780	740.747	619.669
Bayesian Inf. Crit.	789.370	795.730	803.697	682.619

Note: *p<0.1; **p<0.05; ***p<0.01. The unit of income is NT$ thousands (US$ 1 = NT$ 30). The treatment effects of UBP and MR policies are in terms of kg per capita. All standard errors are with correction for autocorrelation of first order.

6. Discussion

6.1. Comparison between the UBP policy and the MR policy

Which waste management instrument is more effective between the UBP and MR policy? To answer this question, we first compare which policy instrument is more effective to achieve the basic policy goal of more greatly reducing unsorted waste, increasing biodegradable waste and recycling. The comparison is based on the estimates from our DID models presented in Section 5.

The results of the DID model in Table 2 demonstrate that the UBP policy alone significantly reduced the quantity of unsorted waste in New Taipei City by 2.59 kg per capita/month, the combination of the UBP and MR policy decreased in unsorted waste by 3.48 kg per capita/month, and increased recycling by 0.99 kg per capita/month. Model 7 of Table 2 shows that the UBP policy did not increase recycling in New Taipei City but in Taipei City. A possible reason is that Taipei City implemented the UBP policy earlier than the MR policy and had a relatively lower benchmark level of recycling, so the UBP policy in Taipei City had much more room to stimulate recycling. The growth of recycling in New Taipei City was affected more by the MR policy than the UBP policy because the latter was implemented later in the period. On the other hand, the MR policy did not lead to reducing unsorted waste but inducing an increase in the quantity of biodegradable waste and recycling by 0.62 and 1.6 kg per capita/month, respectively. Importantly, the MR policy did not cause illegal dumping. However, the UBP policy in New Taipei City increased illegal dumping (Panel E of Figure 4) but did not significantly increase illegal dumping (Panel F of Figure 4) in Taipei City. Note that there is no garbage tourism caused by both UBP and MR policy in neighbor urban municipalities but likely in adjacent rural municipalities (Table 4).

Overall, according to the estimation results in Section 5, the UBP policy in New Taipei City was more effective than the MR policy in curbing unsorted waste but could also lead to increasing illegal dumping. On the other hand, the MR policy leads to increased biodegradable waste and recycling without causing illegal dumping. With these tradeoffs the optimal policy thus depends on policy-maker's specific goals, as well as their available waste management resources. The cities need to have corresponding administrative resources ready to prevent the illegal dumping (Ichinose and Yamamoto 2011).

6.2. Quantifying illegal dumping

To quantify the amount of illegal dumping caused by the UBP policy, Fullerton and Kinnaman (1996) estimate the effect of UBP on illegal dumping by using indirect survey questions. Carattini, Baranzini, and Lalive (2018) evaluate illegal dumping by using the number of illegal dumping citations. Due to our identification strategy and data availability, this study not only can assess the effect of the UBP policy on illegal dumping citations but also can quantify the amount of illegal dumping in terms of weight. The illegal dumping data are based on the frequency of incidences rather than actual weight, so we provide a possible frequency range based on the results of the DID model in Table 2.

To estimate the approximate amount of illegal dumping caused by the UBP policy alone, we use the estimated results with the post-2006 model of Table 2. The post-2006 model shows that the UBP policy not only significantly reduced the quantity of unsorted waste in New Taipei City by 4.58 kg per capita/month but also increased the quantity of biodegradable waste and recycling by 0.88 and 0.67 kg per capita/month. Part of the 4.58 kg reduction per capita/month of unsorted waste can be accounted for by an increase of 1.55 kg per capita/month biodegradable and recyclable waste that would have otherwise been included in unsorted waste. After accounting for this, and because there is no significantly adverse evidence of garbage tourism in municipalities nearby New Taipei City (Table 4), the UBP leads to a net unsorted waste reduction of 3.03 kg per capita/month. This missing unsorted waste could be explained by illegal dumping, lifestyle changes, or other unobserved factors which can reduce residents' waste disposal and which were not controlled for by time trend, time and municipal fixed effects. If all of the missing trash is considered to be illegal dumping, then the amount is 3.03 kg per capita/month or 143,160 tons per year (31% of average annual total collected waste from 2009 to 2016). One can scale this back by making assumptions on the proportion of missing trash that is illegal dumping. A detailed range analysis on illegal dumping is shown in the upper part of Table 5.

6.3. Welfare analysis

The results of Section 5 only address the effectiveness of the UBP policy. To be comprehensive, a cost-effective policy might be of interest to policymakers. To analyze the change in welfare due to the implementation of UBP, a similar analytical framework to that undertaken in previous studies is pursued here and is illustrated in Figure 5 (Fullerton and Kinnaman 1996; Kinnaman 2006; Allers and Hoeben 2010).

First, the annual per household demand and supply for garbage collection service were constructed as follows. The demand for garbage collection service is defined by the marginal benefit (MB) to residents. The supply for garbage collection service is determined by the social marginal cost (SMC) of garbage collection service which has two components: private (PMC) and external marginal costs (EMC). PMC is estimated using the average cost of purchasing garbage bags per household. To compare our welfare results with other literature, the unit price per bag is converted from \$/liter to \$/kg by using the maximum load per bag shown in Table 1. In case households do not fully load bags, we offer estimates assuming 100%, 75%, 50%, and 25% of the maximum load per bag. Based on the distinct scenarios, PMC ranges from US\$ 19.53/kg to US\$ 84.3/kg. EMC refers to the administrative costs of waste collection (US\$ 0.42/kg), operating costs incineration plants (US\$ 0.07/kg), and management costs for landfills (US\$ 5.66/kg). Note that the administrative cost of waste collection here also includes costs associated with the implementation of the UBP policy, such as establishing additional recycling stations, enhancements to better deal with illegal dumping. According to the annual financial statement from Environmental Protection Bureau of New Taipei City, the average EMC in New Taipei City during the post-UBP-policy period (from 2009 to 2016) is US\$ 6.16/kg. Thus, our estimated SMC varies from US\$ 25.69/kg to US\$ 84.3/kg based on the different load assumptions.

Table 5. Quantified illegal dumping, efficiency measure, welfare analysis.

	Quantified illegal dumping					Note
(1)	Percentage in missing trash is illegal dumping	0	0.1	0.5	1	Assume different scenario assumptions
(2)	Missing trash (kg per capita/month)		0.30	1.52	3.03	= the reduction in unsorted waste - increases in biodegradable - recycling (from the Post-2006 model of Table 2)
(3)	Estimated illegal dumping (ton/year)		14,316	71,580	143,160	=(1) × (2) × (3)x(annual average population in NTC during 2009-2016)×12
(4)	Percentage in total collected waste (2009-2016 annual average)		0.03	0.16	0.31	=(3)/(annual average total collected waste in NTC during 2009-2016)
	Efficiency measure					
(5)	Actual reduction in unsorted waste (kg per capita/month)	4.58	4.28	3.07	1.55	=4.58 (Reduction in unsorted waste by UBP from the post-2006 model) - (2)
(6)	kg of waste reduction per household per month	12.37	11.55	8.28	4.19	=(5)×2.7 (Average household size in NTC during 2009-2016)
(7)	kg of waste reduction per household per year	148.39	138.57	99.31	50.22	=(6)×12
(8)	Ponuds of waste reduction per $1 per household per year	630.70	588.97	422.07	213.45	=(7)×2.2 (kg to pounds) /0.52 (Annual average cost of waste collection per household in NTC during 2009-2016, USD)
(9)	Ponuds of waste reduction per $1 per household per week	12.13	11.33	8.12	4.10	=(8)/52
	Welfare gains					
(10)	EMC (USD/kg-yr)	6.16	6.16	6.16	6.16	= Cost of waste collection + Cost of landfill + Cost of incineration
		100% of maximum load per bag				
(11)	PMC (USD/kg-yr)	19.53	19.53	19.53	19.53	= 0.05 (Cost per bag per kg conditional on fully using the maximum load per bag) × 365 (Assume every household uses one trash bag everyday of a year)
(12)	SMC (USD/kg-yr)	25.69	25.69	25.69	25.69	=(10)+(11)
(13)	Welfare gains per household per year (USD)	2363.40	2207.05	1581.62	799.84	=[(10)+(12)] × (7)/2
		75% of maximum load per bag				
(14)	PMC (USD/kg-yr)	26.05	26.05	26.05	26.05	= 0.07 (Cost per bag per kg conditional on using 75% of the maximum load per bag) × 365 (Assume every household uses one trash bag everyday of a year)
(15)	SMC (USD/kg-yr)	32.21	32.21	32.21	32.21	=(10)+(14)
(16)	Welfare gains per household per year (USD)	2846.53	2658.21	1904.94	963.34	=[(10)+(15)] × (7)/2
		50% of maximum load per bag				
(17)	PMC (USD/kg-yr)	39.07	39.07	39.07	39.07	= 0.11 (Cost per bag per kg conditional on using 50% of the maximum load per bag) × 365 (Assume every household uses one trash bag everyday of a year)
(18)	SMC (USD/kg-yr)	45.23	45.23	45.23	45.23	=(10)+(17)
(19)	Welfare gains per household per year (USD)	3812.77	3560.53	2551.56	1290.35	=[(10)+(18)] × (7)/2
		25% of maximum load per bag				
(20)	PMC (USD/kg-yr)	78.14	78.14	78.14	78.14	= 0.21 (Cost per bag per kg conditional on using 25% of the maximum load per bag) × 365 (Assume every household uses one trash bag everyday of a year)
(21)	SMC (USD/kg-yr)	84.30	84.30	84.30	84.30	=(10)+(20)
(22)	Welfare gains per household per year (USD)	6711.51	6267.49	4491.44	2271.36	=[(10)+(21)] × (7)/2

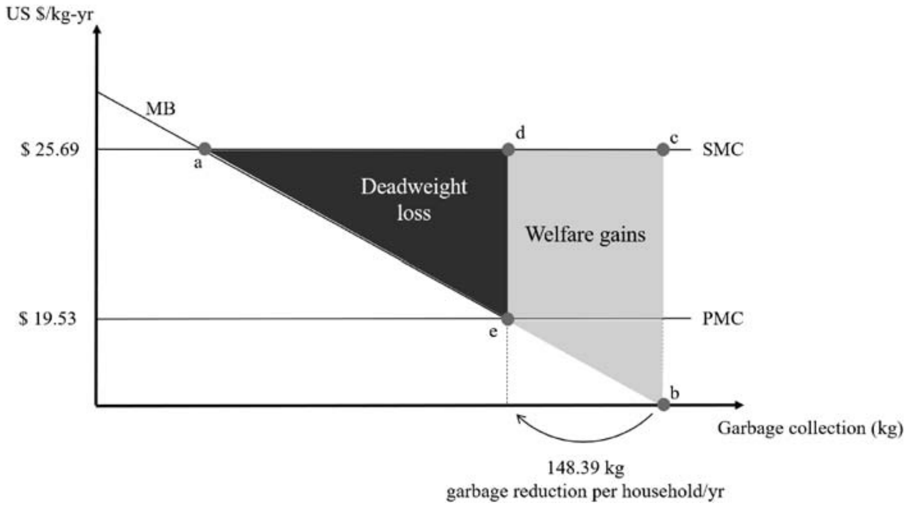

Figure 5. Welfare analysis of implementing the UBP policy.

Based on results from the post-2006 model in Table 2, the effect of the UBP policy on reducing unsorted waste in New Taipei City is 4.58 kg per capita/month. Thus, welfare gains of implementing the UBP policy range from US$ 799.84 to US$ 6,711.51 per household per year varying by different assumptions of the maximum load per bag and the frequency of illegal dumping. The welfare analytic framework of evaluating the UBP policy (Fullerton and Kinnaman 1996; Kinnaman 2006; Allers and Hoeben 2010) is illustrated and explained in Figure 5, and the corresponding range analysis is shown in Table 5. Note that the estimations do not include non-monetary costs, such as the residents' time or any other additional personal cost for devoting effort to recycling.

To compare the efficiency, or cost-effectiveness, of UBP policy with that found by Kinnaman (2006) and Allers and Hoeben (2010), the efficiency of the UBP policy was measured by how much of the reduction in unsorted waste in terms of pounds per household per week resulted from a $1 garbage fee. The weekly household reduction of unsorted waste per $1 garbage fee is from 4.1 to 12.13 pounds in New Taipei City, which varied by the different assumptions for illegal dumping. Garbage reduction associated with $1 garbage fee in the U.S. is from 0.15 to 14.28 pounds per household per week, which varied by pricing programs and regions. In the Netherlands, the UBP effect ranged from 1.35 to 2.89 pounds per household per week, which varied by UBP systems. This result shows that the efficiency of the UBP policy in New Taipei City is higher than UBP policies in the Netherlands and is in the similar range of the U.S.

7. Summary and concluding remarks

The analysis in this paper demonstrates that results of a UBP policy can be specific to the locale, which may help explain mixed conclusions about its effectiveness. Our results show that the UBP policy reduced the quantity (by weight) of unsorted waste and caused an increase in recycling in Taipei City, but not in New Taipei City. There is no garbage tourism caused by New Taipei City's UBP in its adjacent urban municipalities, but there is an mild increase in unsorted waste in its adjacent rural municipality after the implementation of the UBP policy (Model 4 of Table 4). Besides, there is a short-term increase in illegal dumping that appears to diminish in the long term. In contrast, the MR policy boosted biodegradable waste and recycling without detecting illegal dumping.

The implications of our study results are as follows. First, the implementation of the UBP policy could increase illegal dumping. Still, it would drop as time passes after the policy comes into effect, as shown in Table 2 and Panel E of Figure 4. This result implies that the implementation of the UBP policy can cause unintentional environmental damage and additional administration costs to monitor illegal dumping and garbage tourism. However, these costs would diminish in the long-run because of the reduction in illegal dumping in the long-term. Second, the UBP policy could reduce waste without inducing illegal dumping if there is a proper provision of waste management resources (Ichinose and Yamamoto 2011). This argument is supported by our analysis of the UBP policy in Taipei City, where we found the UBP policy increases recycling volumes without increasing illegal dumping (see Table 2, Panel D and F of Figure 4). This result also supports work by Yang and Innes (2007), who found that illegal dumping is not a serious problem in Taipei City which has relatively more funding for environmental affairs in the city budget. Third, the MR policy can effectively encourage collecting biodegradable waste and recycling. Nevertheless, implementing the MR policy alone may not necessarily reduce unsorted waste since there is no monetary incentive for residents to do so. A combination of implementing the UBP and MR policy would be a favorable way to curb unsorted waste and to encourage sorting and recycling behaviors.

Our study has limitations and future research is needed. First, policymakers may well be interested in learning how to design a UBP policy which can reduce the possibility of causing unintentional policy effects with a relatively low policy implementation cost. Second, does the magnitude of the unit price in a UBP policy affect the magnitude of unintentional policy effects (e.g. illegal dumping and garbage tourism)? Last, how can design solid waste combustion and incineration facilities be planned for, given the impact of an implementation of UBP on waste change since those costs are known as high external costs (Muller, Mendelsohn, and Nordhaus 2011)?

This study may shed some light on differences in estimated impacts of UBP programs in the U.S. versus Europe. Many of the U.S. studies (Fullerton and Kinnaman 1995, 1996; Kinnaman and Fullerton 2000) find limited benefits of UBP due to leakage and illicit dumping. The studies conducted in European settings (Allers and Hoeben 2010; Carattini, Baranzini, and Lalive 2018; Dijkgraaf and Gradus 2009, 2004; Sterner and Bartelings 1999), provide a relatively optimistic aspect of UBP policies with lower leakage and illicit dumping conditional on enforcement. Our study shows that there were some unintended effects of illegal dumping following by the implementation of the UBP policy in the short-run. However, the benefits of the UBP occurred in both short-run and long-run. Namely, this study not only verified the concern from U.S. studies but also found appreciable benefits of the UBP policy as many European country studies find. Our Taiwan study suggests that the negative side effects appear to diminish as time passes, but the benefits brought by the UBP policy remain in the long-run.

For Taiwan, the UBP policy is a more equitable and incentive-compatible way to manage waste than a mandatory program. With a well-design mechanism and program to prevent an occurrence of side effects, the idea of 'polluter pays' is a plausible policy instrument to reflect the true social cost of managing waste.

Notes

1. The territorial area of Taiwan is 36,193 km^2, and the total population is 23,519,518 in 2016. The population density is 649/ km^2, which is second highest among the countries with at least 10,000,000 people in the world.
2. "Taiwan: The World's Geniuses of Garbage Disposal." The Wall Street Journal. May 17, 2016. Online. (Accessed December 12, 2017). "Taiwan's Recycling Boom: A Shining Example for Asia, the World." The Diplomat. December 3, 2013. Online. (Accessed December 12, 2017). "Short on Space, Taiwan Embraces a Boom in Recycling." The New York Times. November 29, 2013. Online. (Accessed December 12, 2017).
3. Despite similar names, Taipei City and New Taipei City are distinct cities, each with its own municipal government and waste disposal policies.
4. Biodegradable waste includes waste food, nut or seafood shells, fruit peels, coffee grounds, waste plants, and other decomposable waste which can use for animal feed or composting.

5. Recyclable waste also can be classified into ordinary recyclable waste and large recyclable waste. The former category includes paper, metal, plastic, glass, aluminum can, retort pouch, textile, appliance, battery, used light bulb, tire, electronics, and other recyclable items (e.g., umbrella, helmet, luggage). The latter category includes large durable goods (e.g., sofas, mattresses, air conditioners, and refrigerators).

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