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ORIGINAL PAPER

# Estimating the Tobacco Kuznets relationship in Spain (1957–2023): income curvature, projected turning points, and policy implications

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## Abstract

This paper estimates a Tobacco Kuznets Curve (TKC) for Spain on the full national series, 1957–2023, to estimate the income–consumption curvature underlying the Tobacco Kuznets hypothesis and derive the associated model-implied turning points. Understanding these model-implied turning points may contribute to discussions of tobacco control, taxation, and regulation, and to translating long-run demand patterns into operational policy benchmarks. Using annual adult cigarette consumption, real GDP per capita, and real pack prices, we estimate three nested models: (i) a simple bivariate benchmark specification included for illustrative comparison purposes only; (ii) an augmented model adding ln(real price) and post-2005/2010 indicators; and (iii) a segmented-trend specification interacting each indicator with time. Baseline estimation relies on OLS with Newey–West HAC inference, while robustness checks, such as GLS(AR1), Huber RLM, DOLS with leads/lags where available, and ARDL long-run coefficients, ensure that the identified turning points are not artifacts of persistence, outliers and dynamic adjustment. Across specifications, ln(GDP pc) is positive and $[\ln(\text{GDP pc})]^2$ is negative, confirming an inverted-U conditional on price and policy timing. The estimated curvature parameters imply turning points between approximately €39,000 and €58,000 and the implied peak consumption (≈ 118–158 packs per adult/year). Short-run price elasticities are negative (about −0.17), and post-reform dynamics are consistent with a persistent decline. These thresholds should be interpreted as model-implied projections rather than empirically observed policy thresholds. While they help characterize the long-run relationship between economic development and cigarette consumption, they do not by themselves imply specific excise-tax recommendations.

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**Keywords** Tobacco Kuznets Curve (TKC) · Cigarette demand · Price elasticity · Smoke-free laws · Excise taxation · Time-series econometrics

## 1 Introduction

Extensive empirical and theoretical research examines the nexus between tobacco, the economy, and health—most notably in middle- and high-income countries (Papanicolas et al. 2018). The policy salience is clear: tobacco use contributes to multiple cancers, cardiovascular and respiratory diseases, reproductive disorders, and other adverse outcomes, while dependence complicates quitting. In high-income settings, daily smoking prevalence remains sizable, and health expenditure absorbs a large share of GDP, so understanding demand responses to prices, income, and regulation is central to cost-effective control (Papanicolas et al. 2018). A consistent result is an inverse price–consumption relationship: higher prices (largely via excise taxation) depress cigarette demand (Contreary et al. 2015); accordingly, taxes are a first-order lever for reducing consumption (Pinilla and Abásolo 2017; Escario and Molina 2004; Chaloupka et al. 2012). This underpins a vast literature estimating price and income elasticities across countries and time (Pesko et al. 2014; Hanewinkel et al. 2008; Mushtaq et al. 2011; Cornelsen and Normand 2014; Martínez et al. 2015; Stoklosa et al. 2019; Gallus et al. 2006; Kostova et al. 2014), alongside welfare-based tax models that internalize health and external costs (Saffer and Chaloupka 1994).

Recent evidence further suggests that the structure of tobacco taxation is itself relevant for cigarette affordability and consumption incentives. Using a panel of 28 EU member states between 2010 and 2020, Primorac et al. (2025) show that specific and ad valorem excise taxes exhibit different pass-through effects on cigarette prices, with implications for down-trading behaviour and smoking prevalence. Their findings reinforce the importance of price mechanisms as a central channel through which tobacco-control policies influence long-run cigarette demand.

From an economic perspective, however, a key open question remains unresolved: how does the long-run relationship between income and cigarette consumption evolve once affordability and regulation are explicitly accounted for? In standard demand models, rising income relaxes budget constraints and may increase consumption at early stages of development, but preferences for health, information, and regulatory pressure can eventually dominate. Whether this transition exists, and at which income level it occurs, is critical for excise calibration, the welfare consequences of taxation, and the long-run dynamics of harmful consumption. Moreover, the effectiveness of tobacco taxation may depend on cross-border purchasing incentives and tax harmonisation across jurisdictions, as highlighted by Ranđelović and Bisić (2021). Identifying such nonlinearities goes beyond estimating elasticities: it quantifies structural thresholds at which economic development ceases to sustain cigarette demand.

From an empirical perspective, long-run cigarette demand studies typically recover price and income elasticities. Early cross-sectional evidence for Europe reported a price elasticity near −0.4 and an income elasticity around 0.5 (Townsend 1988), while more recent work often finds that a 1% income increase raises cigarette consumption by roughly 0.39–0.43% (Gallet and List 2003; Fernández et al. 2004).

Beyond averages, the macro cycle matters unemployment, and recessions are linked to sizable changes in smoking behavior (Montgomery et al. 1998; Hammarström and Janlert 2003; De Vogli and Santinello 2005), and several contributions emphasize asymmetries—booms and busts do not affect all products or margins in the same way (Rothwell et al. 2015). In Spain, much of the price-elasticity evidence predates key policy shifts (e.g., analyses of 1965–2000) (Fernández et al. 2004; Escario and Molina 2004; Martín-Álvarez et al. 2020a), motivating an updated long-run assessment that incorporates later reforms.

Complementing elasticity studies, policy evaluation shows that smoke-free environments reduce exposure and can lower consumption (Fichtenberg and Glantz 2002; Pinilla et al. 2019; Del Arco-Osuna et al. 2023), and that non-price measures—advertising restrictions, information, and education—shape demand (Almeida et al. 2021; Golpe et al. 2022). Socioeconomic gradients are pervasive: lower-income groups tend to be more price sensitive and face higher smoking prevalence (Hiscock et al. 2012), echoing broader evidence linking income, inequality, and health (Deaton 2003; Marmot 1999; Case et al. 2002; Preston 1975). Notably, the health–cycle relationship can be non-monotonic: recessions may temporarily improve some health indicators (Ruhm 2000; Martín-Álvarez et al. 2020b), though effects vary across periods and outcomes (Ruhm 2015).

Existing studies estimate elasticities or evaluate reforms, but none provides a long-run assessment of whether the relationship between economic development and cigarette consumption exhibits the curvature predicted by the Tobacco Kuznets hypothesis. Nor do existing studies derive the model-implied income level at which the estimated relationship would be expected to reverse. This distinction is important because the turning point may lie beyond the observed support of the data and therefore represents a projection implied by the estimated functional form rather than an empirically observed threshold.

These insights intersect with the Kuznets-curve tradition. Originally proposed for income inequality, the inverted-U has been extended to environmental outcomes (World Bank 1992; Grossman and Krueger 1995) and health-related behaviors—e.g., obesity (Grecu and Rotthoff 2015) and tobacco/alcohol (Cantarero-Prieto et al. 2019, 2023; Del Arco-Osuna et al. 2025)—with the common intuition that development initially relaxes budget constraints but, beyond some turning point, stronger regulation, information, and preferences for health (a normal good) bend harmful consumption downward. Systematic reviews also stress that the growth–health link is multivariate and time-scale dependent (Costa-Font et al. 2018; Patterson 2023), reinforcing the case for models that combine income curvature with explicit price and policy controls.

Methodologically, recent research has emphasized the challenges of identifying non-linear long-run relationships among highly persistent variables. Kivedal (2023), for example, applies an I(2) cointegration framework to estimate an Environmental Kuznets Curve and demonstrates how non-linear long-run dynamics can be recovered despite strong trending behaviour in the underlying series. Although focused on $CO_2$ emissions rather than tobacco consumption, the econometric issues addressed are closely related to those examined in the present study.

Spain is a compelling setting: real prices rose with tax policy and industry responses; extensive smoke-free laws arrived in 2005 and 2010; and long expansions and recessions generated rich income variation. Spanish evidence reports negative price elasticities consistent with international benchmarks and cycle asymmetries—expansions modestly raise cigarette consumption, recessions reduce it more strongly, and downturns trigger substitution toward cheaper products (RYO, pipe tobacco, cigars) (Cantarero-Prieto et al. 2023; Martín-Álvarez et al. 2020a, b). These patterns motivate non-linear income specifications that hold prices and policy timing constant. The Kuznets-curve framework provides a natural synthesis: it captures the non-linear link between development and harmful consumption while accommodating the roles of price and regulation. Applying this perspective to Spain, with its long income cycle and two major smoke-free reforms, allows us to identify model-implied turning points that are useful for interpreting the interaction between development and tobacco-control policies.

However, despite abundant evidence on elasticities and policy effects, no study has quantified a Tobacco Kuznets Curve (TKC) for Spain using the complete national series from the 1950s onward. Addressing this gap allows us to shift from partial elasticities or short-period analyses toward income-based thresholds where cigarette consumption turns downward, offering reference points for understanding the interaction between economic development, cigarette consumption, and tobacco-control policies. By translating the Tobacco Kuznets Curve into income and consumption thresholds, our analysis provides not only an account of Spain's long-run smoking trajectory but also a framework for interpreting how economic development, prices, and regulation jointly shape cigarette demand. Rather than treating the TKC as a mere empirical regularity, we use it as a device for characterizing long-run consumption dynamics across stages of economic development.

Our empirical approach follows a standard reduced-form demand framework widely used in applied economics. The Kuznets specification can be interpreted as a flexible representation of a class of demand models in which income influences both consumption and health preferences, while prices and institutional changes shift affordability and constraints. By nesting price effects, policy reforms, and segmented post-reform trends within the same structure, the empirical model provides a transparent way to identify how development, affordability and regulation jointly determine long-run consumption patterns. This approach is fully consistent with economic modelling of non-durable demand and avoids black-box or machine-learning methods.

To address this gap, this paper makes two contributions. First, we provide, to our knowledge, the first Spain-specific Tobacco Kuznets Curve (TKC) estimated on the complete national historical series—1957 through 2023—integrating six-plus decades of income growth, pricing, and regulation. Second, we estimate the curvature parameters of the Tobacco Kuznets relationship and derive the corresponding model-implied turning point in economically interpretable units: (i) real GDP per capita and (ii) predicted cigarette consumption per adult. Because the estimated turning point lies beyond the observed income range, it should be interpreted as a projection implied by the estimated specification rather than as a threshold directly observed in the historical data. Substantively, identifying these thresholds shows that, beyond that level, income growth no longer sustains cigarette demand—prices and regulation act against a backdrop where development itself is neutral or countervailing. Knowing the mean adult consumption associated with the model-implied turning point helps characterize the scale of cigarette demand at different stages of economic development, complementing well-documented elasticity magnitudes and socioeconomic gradients (Hiscock et al. 2012; Martín-Álvarez et al. 2022). Because cycles and substitution can blur aggregate trends, explicitly modeling income curvature while controlling for prices and policy timing provides a clearer account of how development, affordability, and regulation jointly shape long-run cigarette demand.

Our central hypothesis is that cigarette consumption in Spain follows a Tobacco Kuznets Curve: it rises with income at lower levels of development, reaches a turning point, and then declines as higher incomes interact with affordability constraints and stronger regulation. Estimating this curve allows us to move beyond average elasticities and characterize the income–consumption curvature implied by the Tobacco Kuznets hypothesis.

To test this hypothesis, we estimate three nested specifications that progressively incorporate economic and institutional structure. We start with a simple bivariate benchmark specification, included for illustrative comparison purposes only. Because it omits affordability and policy controls, it is not intended for substantive interpretation. We then augment the model with the log real retail price of a 20-cigarette pack and post-2005/2010 indicators, comparing like-for-like consumption across regimes at given income and price levels. Finally, we allow segmented post-reform trends by interacting a linear time index with each policy dummy (an ITS-type refinement common in public-health evaluation). Estimation relies on OLS with HAC (Newey–West) inference; we report GLS(AR1), Huber M-estimation, DOLS with leads/lags, and ARDL long-run coefficients as robustness to persistence, outliers, and dynamic adjustment. For clarity, only Bivariate, M1, and M2 appear in the figure (curves and turning points); robustness estimators are summarized in tables.

The rest of the paper is structured as follows. Section 2 describes data (cigarette consumption per adult, real GDP per capita, real prices) and the institutional timeline (2006, 2011). Section 2 presents the empirical framework and the computation of the income turning point and the implied consumption at that point. Section 3 reports baseline TKC estimates and turning-point results. Section 4 discusses policy implications and concludes.

## 2 Data and methods

To estimate a long-run Tobacco Kuznets Curve for Spain, we construct a consistent annual series covering 1957–2023. This long horizon is essential for capturing both the expansionary phases that lifted cigarette demand and the later periods when affordability pressures and comprehensive regulation reshaped smoking behavior. Our dataset combines three core variables: (i) per-adult cigarette consumption (population aged $\geq 16$), derived from official tax-paid sales reported by Tabacalera S.A. and, for later years, by the Comisionado para el Mercado de Tabacos; (ii) the real GDP per capita expressed in thousands of 2010 euros, which anchors the development trajectory; (iii) the real retail price of a 20-cigarette pack, which reflects affordability after deflating nominal prices using the GDP deflator. Annual population (≥16) and macro aggregates come from Prados de la Escosura (2017, 2024).

From an economic modelling perspective, this empirical framework can be viewed as a reduced-form representation of a class of demand systems in which income affects consumption both directly—by relaxing budget constraints—and indirectly through evolving preferences for health, information acquisition, and regulatory intensity. The Kuznets polynomial offers a transparent way to capture this nonlinear income channel, while real prices account for affordability and policy dummies capture institutional discontinuities. As in standard empirical demand analysis, the aim is not to identify a structural causal model but to recover long-run patterns and thresholds that summarise how development and regulation jointly shape consumption. This ensures that the empirical strategy remains firmly grounded in economic theory rather than in purely epidemiological modelling.

The modelling choices are deliberately simple and transparent, avoiding black-box or machine-learning approaches. All specifications rely on linear regression in logs, augmented with polynomial income terms and institutional dummies, which is standard practice in applied microeconometrics (Angrist and Pischke 2009; Wooldridge 2010; Box-Steffensmeier et al. 2014) and empirical macro-demography. The segmented-trend specification can be interpreted as an econometric approximation to structural changes in the slope of demand following regulatory shocks. This keeps the analysis interpretable, comparable with the elasticity literature.

All models use natural logarithms: $lnC_t$ (per-adult consumption), $lnY_t$ (real GDP per capita, in thousand 2010 euros), $lnP_t$ (real pack price), and $lnY_t^2$ for the Kuznets polynomial. To capture institutional effects, we include two post-reform indicators equal to 1 from the year of enactment onward (2006 and 2011) and, for the segmented-trend specification, a linear time index t interacted with each post-reform dummy. "Consumption" denotes tax-paid domestic sales; unrecorded/illicit sales are not observed.

Figure 1 plots the evolution of the three variables (normalized to each series' maximum for comparability). Real GDP per capita (in thousand 2010 euros) rises steadily, with faster convergence through the 1990s–2000s and cyclical pauses around the Great Recession and the pandemic. Real pack prices trend upward—especially since the early 2000s—consistent with tax and industry changes; vertical dashed lines mark the 2006 and 2011 smoke-free laws. Per-adult cigarette consumption increases from the late 1950s to the late 1980s/early 1990s, stabilizes, and then falls sharply after the mid-2000s.

Table 1 reports descriptive statistics for 1957–2023 (N = 67). On average, Spaniards consume 104.0 packs per adult per year (SD 28.0), with an IQR of 78.9–128.1 packs and a maximum of 140.9 packs. Real GDP per capita averages €19.9 thousand (2010 euros; SD €7.6 thousand), ranging from €5.9 thousand to €30.4 thousand (IQR €14.9–€26.9 thousand). The real price averages €1.97 per pack (SD €1.24), ranging €0.79–€4.34 (IQR €0.98–€2.51). In logs, $lnC_t$ has mean 4.601 (SD 0.312), $lnY_t$ mean 2.896 (SD 0.476), and $lnP_t$ mean 0.499 (SD 0.591). These moments—rising income (in thousand euros), higher real prices, and the post-mid-2000s drop in con-

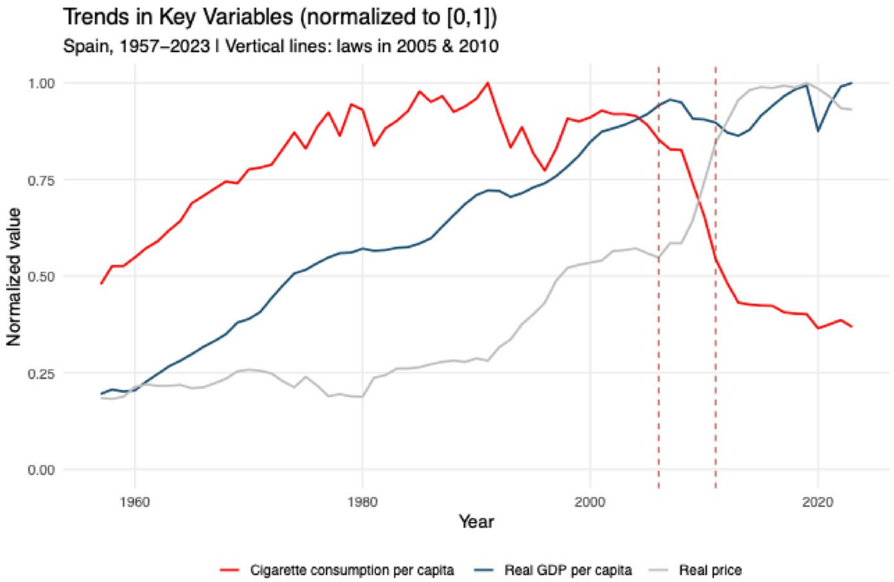


**Fig. 1** Annual per capita consumption of cigarettes, real price of cigarettes and annual per capita GDP

**Table 1** Descriptive statistics of the variables used

| Variable | N | Mean | SD | Min | Q1 | Q2 | Q3 | Max |
|---|---|---|---|---|---|---|---|---|
| Cigarettes_pc | 67 | 104.035 | 28.042 | 51.378 | 78.947 | 116.410 | 128.061 | 140.872 |
| GDP_pc | 67 | 19.918 | 7.610 | 5.924 | 14.924 | 21.410 | 26.932 | 30.372 |
| Real price | 67 | 1.971 | 1.238 | 0.790 | 0.977 | 1.222 | 2.511 | 4.342 |
| Ln(cigarettes) | 67 | 4.601 | 0.312 | 3.939 | 4.369 | 4.757 | 4.853 | 4.948 |
| Ln(GDP) | 67 | 2.896 | 0.476 | 1.779 | 2.702 | 3.064 | 3.293 | 3.414 |
| Ln(Real price) | 67 | 0.499 | 0.591 | − 0.236 | − 0.024 | 0.201 | 0.921 | 1.468 |

sumption—motivate our non-linear income specification and the inclusion of price and policy-timing controls.

While Fig. 1 and Table 1 highlight broad patterns of rising income, higher real prices, and a post-2000s decline in consumption, testing the TKC hypothesis requires formal models that can disentangle income curvature from affordability and institutional effects. To that end, we study the income–tobacco Kuznets relationship for Spain using annual data from 1957 to 2023. The dependent variable is the logarithm of cigarette consumption per-adult aged sixteen or more, denoted $lnC_t$. Income is measured as real GDP per capita, and we work with its logarithm $lnY_t$; the curvature of the relationship is captured by the square $(lnY_t)^2$. The logarithm of the real retail price of a 20-cigarette pack (ln $P_t$) accounts for affordability, while two policy dummies, $D_{2005,t} = 1\{t \geq 2006\}$ and $D_{2010,t} = 1\{t \geq 2011\}$, capture the smoke-free reforms of 2006 and 2011. In the segmented-trend specification, we further interact each dummy with a linear time index $t$ to allow slope changes. All logarithms are natural logs, and all models include an intercept. Disturbances are denoted $\varepsilon_t$.

The objective of the empirical strategy is to estimate how income, cigarette prices, and regulatory timing shape long-run cigarette consumption. The nested specifications below progressively incorporate this information structure. The baseline Kuznets regression captures the nonlinear income channel. The augmented model conditions on real prices and institutional reforms to recover "like-for-like" income effects. The segmented-trend model allows post-reform trajectories to differ from the pre-reform trend; an approach commonly used in empirical economics to model structural breaks in policy environments. Together, these models provide a coherent framework for identifying the income turning point relevant for excise policy and long-run tobacco control. Earlier tobacco-control regulations enacted during the late 1970s and early 1980s were examined in additional robustness analyses. Their inclusion, either as level-shift indicators or as level-and-slope interventions, does not materially affect the qualitative shape of the Tobacco Kuznets relationship. Consequently, the preferred specifications focus on the major nationwide reforms of 2005 and 2010, which represent the most comprehensive structural changes in Spain's tobacco-control framework.

We estimate three nested specifications that progressively incorporate this structure. The baseline bivariate model relates consumption to income and its square. This specification is included solely as an illustrative benchmark. Given the omission of affordability and policy controls, it is not treated as a preferred model for inference, turning-point estimation, or policy interpretation.

$$lnC_t = \alpha + \beta_1 lnY_t + \beta_2 lnY_t^2 + \varepsilon_t \tag{1}$$

The augmented model adds ln $P_t$ and the policy indicators, thereby comparing like-for-like consumption at given income and price levels across regimes:

$$lnC_t = \alpha + \beta_1 lnY_t + \beta_2 lnY_t^2 + \gamma lnP_t + \delta_1 D_{2005,t} + \delta_2 D_{2010,t} + \varepsilon_t \tag{2}$$

The third specification retains price and policy dummies and introduces segmented post-reform trends by interacting the time index with each policy indicator, so that the post-policy slope can differ from the pre-policy trajectory. This refinement follows the interrupted time-series approach commonly used in public-health evaluation (Bernal et al. 2017):

$$lnC_t = \alpha + \beta_1 lnY_t + \beta_2 lnY_t^2 + \gamma lnP_t + \delta_1 D_{2005,t} + \delta_2 D_{2010,t} + \theta_1 \left(tD_{2005,t}\right) + \theta_2 \left(tD_{2010,t}\right) + \varepsilon_t \tag{3}$$

All baseline columns are estimated by ordinary least squares. Inference uses heteroskedasticity- and autocorrelation-consistent covariance matrices of the Newey–West type with automatic bandwidth selection and prewhitening (Newey and West 2014). If we collect regressors in $X_t$ and stack them as $X$, the estimator is $\hat{\beta} = \left(X'X\right)^{-1} X'lnC$ and the HAC covariance is

$$\widehat{Var}\left(\hat{\beta}\right) = \left(X'X\right)^{-1} X'\hat{\Omega}X \left(X'X\right)^{-1} \tag{4}$$

where $\hat{\Omega}$ is the Newey–West estimate of the long-run variance of the score $X_t\hat{\varepsilon}_t$. Throughout we report coefficient estimates with HAC standard errors in parentheses and conventional significance markers.

When the estimated quadratic coefficient is negative the Kuznets curve exhibits an interior turning point. Denote the income at the turning point by $Y^*$ and its logarithm by $lnY^*$ From Eqs. (1)–(3) the turning point in log income is

$$lnY^* = -\frac{\hat{\beta}_1}{2\hat{\beta}_2}, \quad Y^* = exp\left(-\frac{\hat{\beta}_1}{2\hat{\beta}_2}\right), \quad defined\ only\ if\ \hat{\beta}_2 < 0 \tag{5}$$

Confidence intervals for $lnY^*$ and $Y^*$ are obtained via the delta method using the HAC covariance of $(\hat{\beta}_1, \hat{\beta}_2)$. Let $V$ denote the $2 \times 2$ submatrix of $\widehat{Var}\left(\hat{\beta}\right)$ corresponding to $(\hat{\beta}_1, \hat{\beta}_2)$. The gradient for $g(\beta_1, \beta_2) = -\frac{\beta_1}{2\beta_2}$ is

$$\nabla g(\beta_1, \beta_2) = \left(-1\frac{1}{2\beta_2}, \frac{\beta_1}{2\beta_2^2}\right)^T \tag{6}$$

so that

$$\widehat{Var}\left(lnY^*\right) = \nabla g(\hat{\beta}_1, \hat{\beta}_2)^T V \nabla g(\hat{\beta}_1, \hat{\beta}_2), \widehat{Var}\left(Y^*\right) \approx exp(\widehat{2lnY^*})\widehat{Var}\left(lnY^*\right). \tag{7}$$

To compare magnitudes across specifications we also evaluate the predicted consumption at the turning point while holding the remaining regressors fixed at their sample means. Write the regressor vector at a generic point as $x\left(lnY\right)$. For the bivariate model $x\left(lnY\right) = \left(1, lnY, \left(lnY\right)^2\right)$. For model M1 the vector expands to $\left(1, lnY, \left(lnY\right)^2, \overline{lnP}, \overline{D_{2005}}, \overline{D_{2010}}\right)$. For model M2 it further includes $t\overline{D_{2005}}$ and $t\overline{D_{2010}}$. Let $\widehat{lnY^*}$ be the turning point from (5). The fitted value at the turning point is

$$\widehat{lnC}\left(lnY^*\right) = x\left(\widehat{lnY^*}\right)^T\hat{\beta} \tag{8}$$

with delta-method variance

$$\widehat{Var}(\widehat{lnC}\left(lnY^*\right) \approx X^*\widehat{Var\left(\hat{\beta}\right)}X^* + \left(\left.\frac{\partial x(lnY)}{\partial lnY}\right|_{lnY=\widehat{lnY^*}}\hat{\beta}\right)^2\widehat{Var}\left(\widehat{lnY^*}\right) \tag{9}$$

where $X^* = x(\widehat{lnY^*})$ and $\frac{\partial x(lnY)}{\partial lnY}$ accounts for the propagation of uncertainty in $(\widehat{lnY^*})$ through the quadratic terms. For presentation and to preserve legibility we omit confidence bands around the plotted curves in the main figure; the corresponding intervals for $Y^*$ and for $\widehat{lnC}\left(lnY^*\right)$ are reported in the tables.

Robustness estimators address alternative concerns without changing the core interpretation. A feasible GLS with AR(1) errors assumes $u_t = \rho u_{t-1} + \eta_t$ with

$|\rho| < 1$ and estimates $\beta$ by GLS to improve efficiency in the presence of serial correlation; we implement this under REML. A robust regression with Huber loss solves

$$\min_{\beta} \sum_{t} \rho \left( \frac{lnC_t - x_t^T \beta}{\hat{\sigma}} \right), \tag{10}$$

with $\rho(\cdot)$ equal to the Huber function and $\hat{\sigma}$ an M-scale, thereby reducing the influence of outliers on the estimated curvature.

Dynamic OLS augments the static cointegrating regression with leads and lags of first differences of the right-hand-side variables (Stock and Watson 1993):

$$lnC_t = x_t^T \beta + \sum_{k=-K}^{K} \Gamma_k \Delta x_{t-k} + e_t \tag{11}$$

which yields consistency under cointegration but can widen finite-sample intervals for the turning point. An ARDL(1,1) in levels (Pesaran et al. 2001)

$$lnC_t = \emptyset lnC_{t-1} + \kappa_0^T w_t + \kappa_1^T w_{t-1} + \nu_t \tag{12}$$

with $w_t = (1, lnY_t, (lnY_t)^2, lnP_t, D_{2005,t}, D_{2010,t})$, implies long-run coefficients

$$\beta^{LR} = \frac{\kappa_0 + \kappa_1}{1 - \emptyset} \tag{13}$$

which we report via the delta method using the estimated covariance of $(\emptyset, \kappa_0, \kappa_1)$. These long-run coefficients are informative about steady-state elasticities but are not directly comparable to the static turning-point plot, therefore we keep ARDL long-run results in the robustness table and do not include them in the figure.

For identification we rely on smoothness of the income–consumption relationship in logs and on the policy and price controls to absorb confounding variation. HAC inference addresses generic heteroskedasticity and serial correlation. The cointegration-robust DOLS and the dynamic ARDL specifications act as sensitivity checks (Staiger and Stock 1994). In the main figure we plot only the three baseline specifications in Eqs. (1)–(3) and we mark a turning point only when $\hat{\beta}_2 < 0$. All other estimators are reported in the parameter table as robustness evidence and are not plotted, since highly dynamic specifications tend to produce wide bands and GLS targets efficiency rather than structural interpretation of the peak. This modeling strategy allows us to quantify the income turning point and the implied consumption at that threshold, which we report in Sect. 3.

For this reason, turning points are computed only for the three nested baseline specifications. These models share the same static quadratic income structure and therefore yield directly comparable fitted Kuznets curves. The remaining estimators are included as robustness checks with distinct diagnostic purposes: GLS addresses serial correlation, RLM reduces the influence of outliers, DOLS controls for dynamic adjustment through leads and lags of first differences, and ARDL reports long-run coefficients from a dynamic specification. Although these estimators are informative about coefficient stability, their implied turning points are not directly comparable with those obtained from the baseline static specifications.

## 3 Results

In this section we present the results of the estimations. The bivariate specification is reported only as an illustrative benchmark. Because it excludes both affordability and policy controls, the substantive discussion focuses on Models M1 and M2, which provide the preferred basis for inference. We first discuss the baseline Kuznets specifications (Bivariate, M1 and M2), then summarize the robustness estimators (GLS with AR(1), Huber RLM, DOLS with leads/lags of first differences, and ARDL(1,1) long-run coefficients). Throughout, the dependent variable is ln(C), income is ln(Y) where Y is real GDP per capita in thousand 2010 euros, the price regressor is ln(P) (real pack price), and standard errors for OLS columns are Newey–West HAC (Table 2).

Across the baseline models, the coefficient on ln(Y) is positive while the coefficient on $[\ln(Y)]^2$ is negative, indicating an inverted-U relationship between income and cigarette consumption. In the bivariate specification, signs are consistent with the Kuznets hypothesis but precision is poor (ln(Y) = 5.117 with s.e. 31.666; $[\ln(Y)]^2 = -0.960$ with s.e. 6.427) and fit is modest (Adj. $R^2 = 0.419$), which is consistent with omitted variables and serial dependence in a long annual series. Conditioning on affordability and institutional timing sharpens inference markedly. In M1, ln(Y) = 1.535*** (0.318) and $[\ln(Y)]^2 = -0.209$** (0.066), with Adj. $R^2 = 0.954$. Extending to segmented post-reform trends in M2 preserves the curvature and further improves fit: ln(Y) = 1.296*** (0.210) and $[\ln(Y)]^2 = -0.160$*** (0.043), Adj. $R^2 = 0.980$. These patterns indicate that the Kuznets curvature is not an artifact of ignoring price or policy; it remains after explicitly controlling for both.

Price effects are negative and statistically significant in the OLS baselines. The estimated elasticity is −0.157** (0.058) in M1 and −0.173*** (0.048) in M2, consistent with inelastic but policy-relevant responses. In M1, the post-2005 and post-2010 level indicators are both negative (−0.120* and −0.556***), pointing to lower consumption levels after each reform at given income and price. In M2, the segmented-trend terms show that the trajectory changes after each reform: the post-2005 slope becomes more negative ($t \times$ Post-2005 law = −0.049*** (0.008)), while the post-2010 slope change is small and positive (0.022** (0.007)). In an interrupted time-series setting, level and slope effects must be interpreted jointly; the combination of a negative post-2010 level effect (−1.423***) and the estimated slopes implies a persistent downward path in the later period.

Figure 2 plots the illustrative bivariate benchmark together with the two preferred conditional specifications (M1 and M2). Because the bivariate model omits affordability and policy controls, its estimates are substantially less precise and are shown for comparison purposes only. Once price and policy are held at sample means (M1 and M2), the curve shifts to the right and down. Vertical dashed lines identify each

**Table 2** Estimation results of the models for the cigarette consumption in Spain

| Coefficient | Bivariate | M1 | M2 | GLS (AR(1)) | RLM (Huber) | DOLS (Δ leads/lags) | ARDL(1,1) LR |
|---|---|---|---|---|---|---|---|
| Constant | −1.949 (37.522) | 2.172*** (0.373) | 2.452*** (0.246) | 2.985 (1076.528) | 2.174*** (0.370) | 2.436** (0.795) | – |
| ln(Y) | 5.117 (31.666) | 1.535*** (0.318) | 1.296*** (0.210) | 0.524 (0.622) | 1.544*** (0.300) | 0.921 (0.570) | 1.103* (0.451) |
| $\ln(Y)^2$ | −0.960 (6.427) | −0.209** (0.066) | −0.160*** (0.043) | 0.007 (0.115) | −0.212*** (0.060) | −0.029 (0.111) | −0.161* (0.092) |
| ln(P) | – | −0.157** (0.058) | −0.173*** (0.048) | −0.369*** (0.086) | −0.127** (0.045) | −0.388** (0.123) | −0.068 (0.067) |
| Post-2005 law (level) | – | −0.120* (0.061) | 2.393*** (0.420) | −0.065 (0.044) | −0.111 (0.072) | −0.094 (0.070) | – |
| Post-2010 law (level) | – | −0.556*** (0.151) | −1.423*** (0.396) | −0.133** (0.045) | −0.609* (0.347) | −0.461*** (0.078) | – |
| t × Post-2005 law (slope change) | – | – | −0.049*** (0.008) | – | – | – | – |
| t × Post-2010 law (slope change) | – | – | 0.022** (0.007) | – | – | – | – |
| L1 Δln(Y) | – | – | – | – | – | −0.776 (0.993) | – |
| F1 Δln(Y) | – | – | – | – | – | 2.704 (1.913) | – |
| L2 Δln(Y) | – | – | – | – | – | 3.772* (1.779) | – |
| F2 Δln(Y) | – | – | – | – | – | 4.282* (2.541) | – |
| L1 $\Delta[\ln(Y)^2]$ | – | – | – | – | – | 0.255 (0.177) | – |
| F1 $\Delta[\ln(Y)^2]$ | – | – | – | – | – | −0.408 (0.298) | – |
| L2 $\Delta[\ln(Y)^2]$ | – | – | – | – | – | −0.751* (0.355) | – |
| F2 $\Delta[\ln(Y)^2]$ | – | – | – | – | – | −0.639* (0.374) | – |
| L1 Δln(P) | – | – | – | – | – | 0.312* (0.148) | – |
| F1 Δln(P) | – | – | – | – | – | −0.111 (0.152) | – |
| L2 Δln(P) | – | – | – | – | – | 0.307* (0.136) | – |
| F2 Δln(P) | – | – | – | – | – | −0.026 (0.137) | – |
| LR Constant | – | – | – | – | – | – | 3.009*** (0.547) |
| LR Post-2005 law (level) | – | – | – | – | – | – | −0.234*** (0.049) |
| LR Post-2010 law (level) | – | – | – | – | – | – | −0.616*** (0.060) |

**Table 2** (continued)

| Coefficient | Bivariate | M1 | M2 | GLS (AR(1)) | RLM (Huber) | DOLS (Δ leads/lags) | ARDL(1,1) LR |
|---|---|---|---|---|---|---|---|
| N | 67 | 67 | 67 | 67 | 67 | 62 | – |
| Adj. $R^2$ | 0.419 | 0.954 | 0.980 | – | – | 0.960 | – |

DV ln(C) = ln(cigarette consumption per adult, 16+). ln(Y) = real GDP per capita; ln(P) = nominal pack price deflated by the GDP deflator. D2006/D2011 = 1 from 2006/2011. M1 = Kuznets + ln(P) + policy dummies; M2 = M1 + segmented trends t × D2006 and t × D2011. OLS columns use Newey–West HAC s.e.; GLS assumes AR(1); RLM = Huber; DOLS uses leads/lags of first differences; ARDL(1,1) reports long-run coefficients (delta method). Only Bivariate, M1 and M2 are plotted

Standard errors in parentheses; asterisks indicate statistical significance

*Significance at the 10% level

**Significance at the 5% level

***Significance at the 1% level

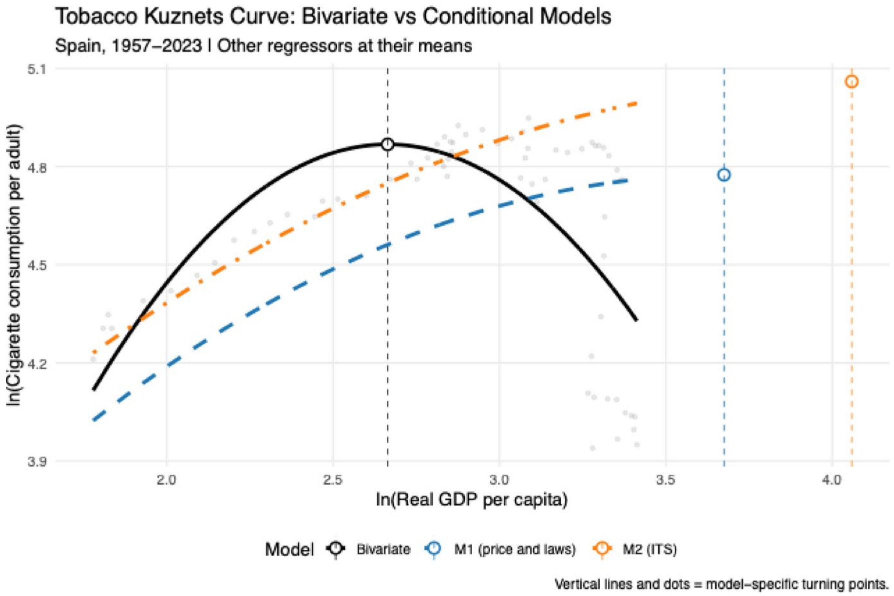


**Fig. 2** Tobacco Kuznets Curve and turning points by model

model's turning point, making clear that conditioning on affordability and policy timing relocates the peak to a later stage of development and lowers the fitted path of consumption.

Table 3 reports the turning-point estimates for all specifications. The bivariate results are shown only for illustrative comparison and should not be interpreted substantively because the associated confidence intervals are extremely wide. This table quantifies the income turning point Y* (thousand 2010 euros) and the implied mean consumption per adult at that income, C*. As expected for an illustrative benchmark that omits affordability and policy controls, the bivariate model yields Y* ≈ €14.35 k with an extremely wide confidence interval for C* (11.80–1433.01 packs). These

**Table 3** Turning point (Y*) and consumption at Y* (C*) (95% CI), Spain, 1957–2023

| Model | Y* | C* | N | Adj. $R^2$ |
|---|---|---|---|---|
| Bivariate | 14.35 [1.03, 199.62] | 130.03 [11.80, 1,433.01] | 67 | 0.419 |
| M1 (price and laws) | 39.46 [17.94, 86.77] | 118.47 [98.48, 142.53] | 67 | 0.954 |
| M2 (ITS) | 57.93 [24.02, 139.72] | 157.57 [127.37, 194.94] | 67 | 0.980 |

Y* denotes the income turning point (real GDP per capita, thousand 2010 euros). Brackets report 95% confidence intervals. Cigarette consumption per adult refers to packs per person aged 16+. Bivariate is a log-income polynomial; M1 adds ln(Real price) and post-2006/2011 indicators; M2 adds segmented post-reform trends. Robustness estimators are reported in the parameter table

estimates are therefore not suitable for substantive interpretation and are reported only to highlight the gain in precision obtained once prices and policy interventions are incorporated. Conditioning reduces uncertainty and shifts the threshold to higher development levels: in M1, Y* ≈ €39.46 k and C* ≈ 118.47 packs/adult and year (95% CI 98.48–142.53); in M2, Y* ≈ €57.93 k and C* ≈ 157.57 packs/adult and year (95% CI 127.37–194.94). The increase in Y* from M1 to M2 reflects that the segmented-trend specification attributes part of the late-period decline to policy-timed changes in slopes; once those trend breaks are accounted for, the income level at which consumption starts to fall is located at a more advanced stage of development. Reporting both thresholds—income Y* and peak consumption C*—facilitates interpretation of the estimated income curvature. Because the turning points are model-implied projections beyond the observed income range, they should not be interpreted as policy targets.

An important qualification is that the estimated turning points lie beyond the maximum observed real GDP per capita in the sample (approximately €30.4 thousand in 2010 prices). Consequently, the descending portion of the Tobacco Kuznets Curve is not directly observed in the historical data. The estimated turning points should therefore be interpreted as model-implied projections derived from the estimated income curvature rather than as empirically observed thresholds. While the sign and significance of the curvature parameters provide evidence consistent with the Tobacco Kuznets hypothesis, uncertainty necessarily increases when predictions are extrapolated beyond the observed support of the explanatory variable.

Robustness estimators are broadly consistent with the baseline interpretation while illuminating the role of persistence and dynamics. GLS with AR(1) errors implies a larger price elasticity (−0.369***; SE = 0.086), although the income-curvature terms are estimated imprecisely. Huber RLM produces coefficients very similar to the baseline OLS estimates, including a negative and statistically significant price elasticity (−0.127**; SE = 0.045), indicating that the main results are not driven by outliers. DOLS, which augments the cointegrating regression with leads and lags of first differences, yields a negative and statistically significant price coefficient (−0.388**; SE = 0.123) and several significant dynamic terms. The estimated income-curvature coefficients retain the expected signs but are less precisely estimated, partly because the usable sample falls to N = 62.

The ARDL(1,1) long-run estimates also support the Tobacco Kuznets hypothesis. The long-run coefficient on ln(Y) is positive (1.103*; SE = 0.451), whereas the coefficient on $[\ln(Y)]^2$ is negative (−0.161*; SE = 0.092), consistent with an inverted-U relationship between income and cigarette consumption. The model also indicates sizable long-run reductions associated with the 2005 and 2010 tobacco-control reforms (−0.234***; SE = 0.049 and −0.616***; SE = 0.060, respectively). By contrast, the estimated long-run price elasticity is smaller in magnitude and statistically insignificant (−0.068; SE = 0.067).

The variation in estimated price elasticities across robustness specifications reflects differences in how persistence and long-run dynamics are modelled rather than a reversal of the underlying price–consumption relationship. The preferred OLS specifications estimate a contemporaneous conditional elasticity of approximately −0.16 to −0.17. GLS produces larger elasticities in absolute value because serial dependence is modelled explicitly rather than absorbed through HAC inference. DOLS also yields larger elasticities because it estimates the cointegrating relationship while conditioning on leads and lags of first differences, although this comes at the cost of a reduced effective sample and a substantially richer dynamic specification. By contrast, the ARDL coefficient is a derived long-run elasticity from a dynamic adjustment model in which lagged consumption absorbs a substantial part of the persistence in cigarette demand, resulting in a smaller and statistically imprecise long-run price coefficient.

In addition, real income, real prices, policy reforms, and time trends evolve jointly over the sample period, so some variation in coefficient magnitudes is expected across alternative estimators. Importantly, however, all specifications recover a negative price coefficient, indicating that the direction of the price effect is robust even though its precise magnitude depends on the treatment of dynamics and persistence.

Because GLS and DOLS do not yield turning-point estimates that are directly comparable with those obtained from the static baseline specifications, they are not shown in Fig. 2 nor included in the turning-point table. These estimators are reported in Table 2 as complementary robustness checks on coefficient stability rather than as alternative characterizations of the Tobacco Kuznets Curve.

Taken together, model fit improves substantially as additional economic and institutional structure is included (Adj. $R^2$ rises from 0.419 in the bivariate model to 0.954 in M1 and 0.980 in M2). The Kuznets curvature is a stable feature of the data once price and regulation are accounted for. The conditional short-run price elasticity around −0.17 implies that a 10 percent real price increase is associated with roughly a 1.7 percent reduction in per-adult consumption, holding income and policy constant. The estimated model-implied turning points indicate that beyond approximately €40–€58 thousand (2010 euros) further economic development is not associated with higher cigarette consumption; instead, rising health preferences, real price growth, and post-reform trajectories are consistent with decline. These results are consistent with the view that taxation and comprehensive smoke-free regulation remain important components of tobacco-control policy, although the present analysis does not identify optimal policy levels or welfare-maximizing interventions. Short-run price elasticities are negative and economically meaningful, indicating that higher prices are associated with lower cigarette consumption.

The robustness exercises reinforce these conclusions. Estimates that account for persistence (GLS), outliers (Huber RLM) or dynamics (DOLS, ARDL) all confirm the same qualitative pattern: curvature is inverted-U, price effects are negative, and post-reform periods are associated with lower consumption. Differences in magnitudes across estimators are expected given their distinct assumptions, but the core message that Spain exhibits a stable TKC is unchanged.

A potential limitation of tax-paid cigarette sales is that they may differ from actual cigarette consumption because of illicit trade, tourism-related purchases, and cross-border transactions. This issue is particularly relevant in Spain, where tobacco purchases have historically been affected by price differentials with neighbouring jurisdictions.

To assess the sensitivity of our results to this measurement issue, we construct an adjusted consumption series using the annual Lower Anomaly Ratios (LAR) and Upper Anomaly Ratios (UAR) reported by Cadahia et al. (2021), a previously published peer-reviewed study that shares one co-author with the present article. The anomaly measures are taken directly from that publication and are not re-estimated here. These anomaly measures capture both potential under-recording of domestic consumption and potential over-recording associated with tourism and cross-border purchases. The adjusted series is defined as:

$$C^{adj} = C \times (1 + LAR - UAR)$$

and is available for the period 2002–2017. Outside this interval, the original tax-paid sales series is retained.

Appendix Table 4 reports the results obtained using the adjusted series. Reassuringly, the main findings remain unchanged. Across the preferred specifications, the coefficient on ln(Y) remains positive and statistically significant, whereas the coefficient on $\ln(Y)^2$ remains negative and statistically significant. Appendix Fig. 3 further shows that the estimated Kuznets curvature is highly similar before and after the anomaly adjustment. If anything, the estimated curvature becomes stronger after adjustment.

These results suggest that the Tobacco Kuznets relationship identified in the baseline analysis is unlikely to be driven solely by distortions in recorded cigarette sales arising from illicit trade, tourism, or cross-border tobacco purchases. More generally, this issue is not unique to Spain. As noted by Ranđelović and Bisić (2021), cross-border purchasing and other forms of unrecorded tobacco trade may partially offset the effects of domestic tobacco taxation and complicate the interpretation of observed cigarette sales. Although the anomaly-adjustment exercise reported above provides reassurance regarding the robustness of our results, comparable long-run information on cross-border purchases and illicit trade is not available for the full 1957–2023 period. Consequently, tax-paid cigarette sales remain the closest consistent proxy for long-run cigarette consumption available for Spain.

Substantively, these findings imply that if income levels eventually approach the model-implied turning points identified here, further development would no longer be expected to sustain cigarette demand under the estimated specification. Instead, rising health preferences, higher real prices, and comprehensive regulation reinforced the decline. These findings suggest that the estimated income curvature is robust to potential distortions arising from illicit trade, tourism, and cross-border purchases. Together with the price and policy estimates, they contribute to understanding the long-run relationship between economic development and cigarette consumption.

However, the estimated turning points should be interpreted as model-implied projections rather than policy targets, and the present analysis does not identify optimal tax rates or welfare-maximizing interventions.

Several qualifications should accompany the policy interpretation of these results. First, the estimated turning points lie beyond the observed income range and therefore represent model-implied projections rather than empirically verified thresholds. Second, the analysis is based on aggregate national data and does not capture heterogeneity across income groups, regions, or demographic subpopulations. Third, the study does not conduct a welfare analysis and therefore cannot be used to derive optimal excise-tax rates or assess the distributional consequences of tobacco taxation. Accordingly, the estimated thresholds should be interpreted as analytical reference points rather than direct policy prescriptions.

## 4 Conclusion

This paper set out to reconcile the long-run economics of cigarette demand with the policy and development narratives highlighted in the introduction. Using Spain's complete historical series (1957–2023), we estimated a Tobacco Kuznets Curve (TKC) and estimated its model-implied turning points: the income level at which cigarette consumption begins to fall and the implied mean consumption at that point. The baseline evidence is clear. Once affordability and institutional timing are held constant, cigarette consumption follows an inverted-U in income: the coefficient on ln(GDP per capita) is positive and that on $[\ln(\text{GDP per capita})]^2$ is negative in all baseline specifications. Relative to the bivariate polynomial—which is imprecise and prone to omitted-variable bias—the conditional models (M1 and M2) deliver tight estimates and very high fit, showing that the Kuznets curvature is not an artifact of ignoring prices or the timing of smoke-free legislation.

Beyond their empirical precision, these results also contribute to economic modelling by providing a reduced-form summary of how income, affordability, and regulatory timing jointly shape the demand for a harmful addictive good. The TKC estimated here can be interpreted as a non-linear demand schedule in which income affects both consumption and the valuation of health, while prices and institutions shift constraints over time. This interpretation links the empirical findings to broader economic discussions of demand, regulation, and health-related externalities, and clarifies that the turning point is not merely a descriptive artifact but an economically meaningful threshold summarising long-run preferences and constraints. By framing the TKC in this way, the analysis complements the elasticity literature and provides a modelling tool that can be embedded in broader economic debates around taxation, regulation, and health-related externalities.

Two quantitative results are particularly relevant for interpreting the long-run dynamics identified in the analysis. First, conditional short-run price elasticities are negative and economically meaningful (about $-0.17$ in OLS baselines), so real price increases—primarily through excise taxation—continue to reduce cigarette demand in a predictable way, consistent with the broad literature summarized in the introduction. Second, the estimated TKC turning point occurs at income levels around

€39–€58 thousand (2010 euros) depending on specification, with an associated peak consumption of roughly 118–158 packs per adult (16+). Interpreting these thresholds together, income growth initially relaxes budget constraints and can lift consumption, but beyond the turning point the combination of rising health preferences, stronger regulation, and higher real prices bends demand downward. In other words, development becomes neutral or countervailing rather than supportive of cigarette use.

The institutional timeline matters for how this transition unfolds. In the interrupted-time-series refinement (M2), the 2006 law is associated with a steeper post-reform decline, while the 2010 law adds a sizable negative level shift; the joint effect is a persistent downward trajectory in the late period. This aligns with the policy evaluations cited in the introduction, which emphasize that comprehensive smoke-free environments and complementary non-price measures (information, advertising controls, education) shift behavior in tandem with affordability. By quantifying the TKC in income and consumption units, our results provide a quantitative characterization of the long-run relationship between economic development and cigarette consumption.

The robustness checks reinforce the baseline interpretation. Estimators that address persistence (GLS), outliers (Huber M-estimation), cointegration dynamics (DOLS), and adjustment with long-run decomposition (ARDL) deliver the same qualitative message: curvature is inverted-U, price effects are negative, and the post-reform regime is associated with lower consumption. Differences across methods—e.g., a larger price elasticity under GLS or a smaller long-run price effect in ARDL—are expected given their distinct treatments of serial correlation and dynamics, and they underscore that precise elasticities depend on how persistence is modeled. We therefore treat GLS, DOLS, RLM, and ARDL as complementary evidence that the core TKC pattern is not fragile.

These findings align with and extend the literature reviewed in the introduction. They corroborate the inverse price–consumption link and the importance of comprehensive regulation, and they add a long-horizon, country-specific TKC for Spain based on the full national series. Most importantly, they derive projected development turning points at which income would cease to sustain cigarette demand under the estimated specification and indicate the scale of consumption at the peak. These estimated thresholds provide reference points for discussing how economic development may interact with tobacco-control policies over the long run. First, taxation remains an important component of tobacco-control policy, although the estimates do not identify optimal tax rates or welfare-maximizing interventions. Second, the location of the turning point provides an analytical reference point for discussing how economic development may interact with non-price tobacco-control measures over the long run.

Two caveats suggest directions for future research. Our national-aggregate series cannot fully identify product substitution and heterogeneous responses across regions or socioeconomic groups; panel evidence at finer geographic or demographic levels would help quantify these margins. In addition, while we mitigate endogeneity using alternative estimators, instrumental-variable strategies exploiting tax design or cross-border pricing could sharpen causal interpretation of price effects. Extending the TKC framework to incorporate illicit trade, pass-through heterogeneity, or richer measures of health information would also be valuable.

In sum, the Spanish data provide evidence of statistically significant income curvature consistent with the Tobacco Kuznets hypothesis. The associated turning points are model-implied projections rather than empirically observed thresholds and should therefore be interpreted with appropriate caution. Coupled with a stable, negative price elasticity, this provides a coherent economic account of Spain's long-run smoking trajectory and of the role played by income, prices, and regulation in shaping cigarette demand. The estimated turning points should be interpreted as model-implied projections rather than observed thresholds, but they nevertheless help characterize the long-run curvature underlying the Tobacco Kuznets hypothesis.

## Appendix: robustness to tobacco-sales anomaly adjustments

See Table 4, Fig. 3.

**Table 4** Robustness of the Tobacco Kuznets relationship to tobacco-sales anomaly adjustments

| Coefficient | Bivariate | M1 | M2 | GLS (AR(1)) | RLM (Huber) | DOLS (Δ leads/lags) | ARDL(1,1) LR |
|---|---|---|---|---|---|---|---|
| Constant | −2.838 (3.183) | 1.843*** (0.304) | 1.750*** (0.410) | 2.686 (2474.135) | 2.087*** (0.311) | 1.461 (1.237) | – |
| ln(Y) | 5.887* (2.680) | 1.801*** (0.246) | 1.892*** (0.342) | 0.705 (0.814) | 1.606*** (0.256) | 1.771* (0.809) | 2.547 (2.809) |
| $\ln(Y)^2$ | −1.121* (0.543) | −0.261*** (0.049) | −0.282*** (0.070) | −0.036 (0.151) | −0.223*** (0.052) | −0.209 (0.139) | −0.507 (0.691) |
| ln(P) | – | −0.222** (0.074) | −0.191*** (0.055) | −0.340** (0.113) | −0.177** (0.062) | −0.381** (0.119) | −0.292 (0.497) |
| Post-2005 law (level) | – | −0.337*** (0.081) | 3.530*** (0.237) | 0.077 (0.058) | −0.371* (0.163) | −0.297* (0.112) | – |
| Post-2010 law (level) | – | −0.287*** (0.075) | −3.638*** (0.273) | −0.020 (0.059) | −0.337· (0.176) | −0.215* (0.090) | – |
| t × Post-2005 law (slope change) | – | – | −0.074*** (0.005) | – | – | – | – |
| t × Post-2010 law (slope change) | – | – | 0.066*** (0.005) | – | – | – | – |
| L1 Δln(Y) | – | – | – | – | – | −1.131 (1.101) | – |
| F1 Δln(Y) | – | – | – | – | – | 3.025 (3.074) | – |
| L2 Δln(Y) | – | – | – | – | – | 0.073 (1.730) | – |
| F2 Δln(Y) | – | – | – | – | – | 4.861 (3.521) | – |
| L1 $\Delta[\ln(Y)^2]$ | – | – | – | – | – | 0.267 (0.218) | – |
| F1 $\Delta[\ln(Y)^2]$ | – | – | – | – | – | −0.461 (0.472) | – |

**Table 4** (continued)

| Coefficient | Bivariate | M1 | M2 | GLS (AR(1)) | RLM (Huber) | DOLS (Δ leads/lags) | ARDL(1,1) LR |
|---|---|---|---|---|---|---|---|
| L2 $\Delta[\ln(Y)^2]$ | – | – | – | – | – | 0.098 (0.400) | – |
| F2 $\Delta[\ln(Y)^2]$ | – | – | – | – | – | −0.754 (0.520) | – |
| L1 Δln(P) | – | – | – | – | – | 0.324* (0.135) | – |
| F1 Δln(P) | – | – | – | – | – | −0.014 (0.131) | – |
| L2 Δln(P) | – | – | – | – | – | 0.406** (0.128) | – |
| F2 Δln(P) | – | – | – | – | – | −0.020 (0.130) | – |
| LR Constant | – | – | – | – | – | – | 1.709 (2.526) |
| LR Post-2005 law (level) | – | – | – | – | – | – | −0.109 (0.943) |
| LR Post-2010 law (level) | – | – | – | – | – | – | −0.197 (0.383) |
| N | 67 | 67 | 67 | 67 | 67 | 62 | – |
| Adj. $R^2$ | 0.542 | 0.950 | 0.959 | – | – | 0.944 | – |

DV = ln(adjusted cigarette consumption per adult, 16+). The adjusted consumption series corrects tax-paid cigarette sales using annual Lower Anomaly Ratios (LAR) and Upper Anomaly Ratios (UAR) reported in Cadahia et al. (2021): $C^{adj} = C \times (1 + LAR - UAR)$

Lower anomalies proxy potential under-recording of domestic consumption associated with illicit or unrecorded inflows, whereas upper anomalies proxy potential over-recording associated with tourism and cross-border purchases. For years outside 2002–2017, the original tax-paid sales series is retained. All other model specifications are identical to those reported in the main text. The positive coefficient on ln(Y) and the negative coefficient on $\ln(Y)^2$ remain robust across the preferred specifications, indicating that the estimated Tobacco Kuznets curvature is not driven by distortions in recorded cigarette sales.

Standard errors in parentheses; asterisks indicate statistical significance.

*Significance at the 10% level

**Significance at the 5% level

***Significance at the 1% level

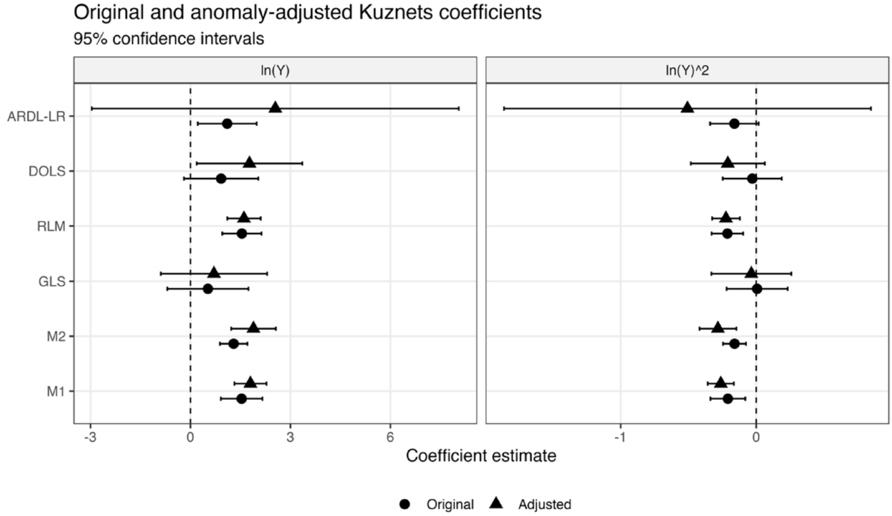


**Fig. 3** Robustness of the Tobacco Kuznets curvature to tobacco-sales anomaly adjustments

**Author contributions** J.M.M.-Á., M.Á.D.A.-O., A.G., and B.V.-L.H. contributed equally to the conception and design of the study, data collection, econometric analysis, and interpretation of results. J.M.M.-Á., M.Á.D.A.-O., A.G., and B.V.-L.H. jointly drafted the manuscript and prepared the tables and figures. All authors reviewed, revised, and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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## Declarations

**Competing interests** The authors declare no competing interests.



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