Do Agronomic Prescription Mandates Reduce Pesticide Use?*

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Abstract

Mandatory agronomic prescriptions are an increasingly common regulatory instrument that inserts a licensed intermediary into pesticide purchase decisions, yet their causal effects on pesticide use remain largely unknown. We exploit Québec's 2018 prescription requirement for neonicotinoids and atrazine as a natural experiment to estimate how mandatory prescriptions affect pesticide use. Using annual compound-level sales data and combining difference-in-differences, slope-break, and synthetic control methods, we identify three main findings. First, the regulation reduced atrazine sales by approximately 92 percent on average over 2018–2022, relative to the counterfactual trajectory. Second, despite being a primary target of the reform, we find no evidence that it reduced neonicotinoid sales, once we account for their pre-existing downward trend. Third, the response across neonicotinoid substitutes was heterogeneous: diamide sales nearly tripled following the reform, while the adoption of sulfoximines and butenolides slowed markedly relative to their pre-reform trajectories. These findings demonstrate that agronomic prescription mandates can be effective in reducing the use of targeted pesticides. However, they can also generate substantial shifts in pesticide use across chemical classes, highlighting the importance of accounting for cross-compound substitution when evaluating prescription-based pesticide policies.

JEL Codes: Q53, Q58, L51, C21.

Keywords: Pesticide regulation, Environmental policy, Regulatory substitution, Natural experiment, Causal inference

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1 Introduction

Does requiring farmers to obtain a professional pesticide prescription reduce pesticide use? Governments increasingly rely on mandatory agronomic prescriptions as an alternative to taxes, bans, and use restrictions for regulating high-risk pesticides.[1] Under this approach, farmers must obtain authorization from a licensed agronomist before purchasing designated compounds. The objective is to optimize pesticide use by combining technical expertise with professional accountability, thereby reducing unnecessary applications while preserving access when treatment is agronomically justified. Despite the growing adoption of this regulatory instrument, there is little causal evidence on whether it actually reduces pesticide use or how producers adjust their input choices. This paper addresses these questions by exploiting Québec's 2018 agronomic prescription reform as a natural experiment.

The economic effects of prescription requirements are theoretically ambiguous. Agricultural pesticide markets are characterized by two well-known distortions. First, pesticides provide insurance against uncertain yield losses, leading farmers to apply treatments even when the expected marginal return is low or negative (Lichtenberg and Zilberman, 1986; Schreinemachers and Tipraqsa, 2012). Second, decisions regarding pesticide choice, dosage, and timing are technically complex, while product recommendations are frequently provided by agents with commercial incentives that may not coincide with socially efficient pesticide use (Möhring et al., 2020).[2] Mandatory prescriptions seek to address these distortions by inserting a professional intermediary into the purchase decision. If excessive pesticide use primarily reflects informational frictions or weak agronomic oversight, the policy should reduce demand for targeted compounds. However, if farmers can readily substitute toward unregulated pesticides that provide similar agronomic services, the policy may simply reallocate demand across active ingredients rather than reduce overall pesticide use. Evaluating such policies solely through changes in the sales of targeted compounds can therefore be misleading, and understanding how producers substitute across pesticide classes becomes essential for judging whether prescription mandates achieve their stated objectives.

Québec's 2018 agronomic prescription reform provides a natural setting to examine how prescription-based regulation affects pesticide use. Beginning with the 2018 growing season, farmers were required to obtain a written prescription from a licensed agronomist before purchasing high-risk pesticides, including atrazine herbicide and three widely used neonicotinoid insecticides. The prescription had to specify the active ingredient, the crop, and the quantity of pesticide or pesticide-treated seed required, with the prescribing agronomist assuming professional responsibility for the recommendation. Unlike pesticide taxes, the reform did not alter product prices, and unlike product bans, it did not prohibit pesticide use. Instead, it changed the institutional process through which regulated pesticides could be accessed by increasing the administrative cost of adoption while introducing an information and accountability mechanism into pesticide-use decisions.

Existing research has focused primarily on pesticide taxes (Böcker and Finger, 2016; Nielsen et al.,

[1] Brazil has required agronomic prescriptions for pesticide purchases since 1989 (Soares and Porto, 2012), while the European Union has required Member States to establish frameworks for professional pesticide advice and integrated pest management since Directive 2009/128/EC (European Parliament and Council, 2009). Québec followed with a mandatory prescription system for specified pesticides in 2018.

[2] The distortion is not hypothetical: global pesticide use grew by more than 80 percent over the past three decades (Carvalho, 2017), environmental and public-health costs in the United States alone exceed several billion dollars annually (Pimentel, 2005), and documented harms range from neonicotinoid disruption of pollinator communities (Woodcock et al., 2017; European Food Safety Authority, 2018) to atrazine's endocrine-disrupting effects on aquatic wildlife (Hayes et al., 2010).

2023), product bans (Schneider et al., 2018), and voluntary advisory programs (Lohr et al., 1999; Deperrois et al., 2025), leaving the effects of mandatory prescription requirements largely unexplored. By providing the first causal evaluation of this regulatory instrument, our paper fills this gap and advances our understanding of how environmental regulations that restrict access to pesticides, rather than changing their prices or prohibiting their use, affect producer behavior.

Implementing this causal evaluation is challenging because prescription requirements can affect pesticide demand through several distinct channels. The most direct channel is a reduction in the use of regulated compounds if professional oversight discourages unnecessary applications. A second possibility is that prescriptions have little effect: because farmers were already following agronomic recommendations before the reform, or because a compound's primary channel of use—such as insecticide-treated seed—sits outside what the requirement can practically reach. A third possibility is that restricting access to selected pesticides induces reallocation toward unregulated substitutes, and that this reallocation need not favor the closest available alternative: producers may instead diversify away from an entire chemical family once its flagship compounds are regulated, anticipating that regulation will eventually reach the rest of it. Distinguishing among these mechanisms is essential for understanding the effectiveness of prescription-based regulation.

To identify these mechanisms, we exploit Québec's prescription reform as a natural experiment using annual compound-level pesticide sales. Our empirical strategy combines three complementary approaches. First, we estimate two-way fixed-effects (TWFE) difference-in-differences models comparing regulated compounds with counterfactual compounds selected to share similar cropping systems and market conditions, while remaining sufficiently distinct in their agronomic function and substitution potential.[3] Second, we estimate slope-break specifications that separately identify an immediate level effect and a change in the post-reform trajectory. Third, we employ synthetic control methods to construct data-driven counterfactuals for the principal treated compounds. Unlike the TWFE and slope-break specifications, which rely on a specified set of control compounds, the synthetic control approach constructs the counterfactual from a weighted combination of untreated compounds, providing a complementary assessment of the estimated effects. Using three approaches with distinct identifying assumptions provides a complementary assessment of the reform and the robustness of the estimated effects.

Our analysis highlights three key findings. First, the prescription requirement generated a pronounced structural break in atrazine sales, placing them well below the counterfactual trajectory. Second, despite being a primary target of the reform, we find no evidence that the reform reduced neonicotinoid sales, once we account for their pre-existing downward trend.[4] Third, the response among neonicotinoid substitutes was heterogeneous, and in the opposite direction from what simple substitution would predict. Sales of diamide insecticides increased substantially following the reform, whereas the adoption of sulfoximines and butenolides, chemically closer to neonicotinoids, slowed relative to their pre-reform trajectories, even though neither was itself regulated. A plausible explanation is that farmers reallo-

[3] Potential pesticide substitutes are agronomically interchangeable compounds that target the same pests or provide similar crop protection functions.

[4] One possible explanation is that neonicotinoids are commonly applied through treated seeds rather than purchased and applied separately by farmers. The reform primarily affected the justification required for using treated seed, rather than the quantity of neonicotinoid contained in each treated seed unit. As a result, the link between the prescription requirement and measured neonicotinoid sales may have been less direct than for pesticides purchased and applied separately.

cated away from the entire nicotinic-receptor-active family in anticipation of its regulatory trajectory, rather than toward the nearest chemical substitute—an account that does not require neonicotinoid sales themselves to have fallen.

Related Literature. This paper contributes to three strands of the literature. First, it contributes to the literature on pesticide regulation and the effectiveness of environmental policy instruments (Freshwater and Short, 2005; Vercammen, 2011; Boxall, 2018; Rude and Weersink, 2018). Most existing studies examine price-based interventions, particularly pesticide taxes calibrated to environmental hazard. A substantial body of European evidence points to the limitations of these instruments. Fémenia and Letort (2016) show that pesticide demand is relatively price inelastic in the short run, implying that even large tax increases generate only modest reductions in use (Fadhuile et al., 2016). Similarly, Böcker and Finger (2016) document a trade-off between effectiveness and political feasibility: tax schemes capable of substantially reducing pesticide use impose welfare costs that are often difficult to sustain, whereas politically feasible policies induce only limited behavioral responses. Finger et al. (2017) and Jacquet et al. (2011) further argue that meaningful reductions in pesticide use generally require broader changes in production practices rather than price incentives alone. We contribute to this literature by providing the first causal evidence on a non-price regulatory instrument that conditions access to pesticides through mandatory agronomic prescriptions.

Second, the paper contributes to the literature on information frictions and intermediary incentives in agricultural input markets. Excess pesticide use can reflect imperfect information among farmers and commercial incentives that distort pesticide recommendations. Schreinemachers and Tipraqsa (2012) document that pesticide use intensifies with agricultural commercialization, consistent with suppliers influencing demand beyond agronomic necessity. The identity of the adviser also matters. Among Swiss fruit growers facing an invasive pest, Wuepper et al. (2021) find that advice from pesticide-company-affiliated extension services is associated with greater use of synthetic insecticides, whereas advice from public extension services is associated with greater adoption of preventive measures. Advice can also reduce pesticide use directly: Deperrois et al. (2025) show that a French pesticide-reduction programme based on demonstration days lowered pesticide use among farmer cohorts linked to participating farms. Together, these studies highlight the role of advisory arrangements in shaping pesticide decisions, consistent with Möhring et al. (2020), who argue that durable reductions in pesticide use require changes in the advisory chain itself. Our setting provides a distinct test of professional advice through mandatory prescriptions. However, the effectiveness of such a mandate depends on whether the prescription requirement reaches the decision margin through which pesticides enter production. Neonicotinoids are widely delivered through treated seeds, with adoption decisions shaped by seed suppliers and established production practices. This limits the scope for a requirement governing pesticide purchases to affect the principal channel through which these compounds enter production, consistent with our finding that the reform did not produce a robust, sustained reduction in neonicotinoid sales.

Third, the paper contributes to the literature on behavioral responses to environmental regulation. A central insight from this literature is that regulations targeting one dimension of behavior often induce adjustment along other margins. For example, Greenstone (2002) documents the relocation of economic activity in response to environmental regulation, while Ryan (2012) shows that stricter environmental standards can impose substantial sunk adjustment costs that reshape industry structure. In agricultural

markets, Sharma and Villoria (2026) use a gravity model to show that the EU Deforestation Regulation, which restricts market access rather than production itself, could divert soy exports toward unregulated destinations, thereby diluting the regulation's intended effect. In the context of pesticide regulation, this logic suggests that restricting access to one group of compounds may increase demand for close substitutes. The closest evidence is provided by Perry and Moschini (2020), who show that the adoption of neonicotinoid seed treatments in U.S. maize displaced foliar pyrethroid and organophosphate applications. We extend this literature by showing that a prescription requirement can generate anticipatory reallocation across a whole chemical family, rather than narrow substitution toward the nearest available alternative. Diamides, which differ in their mode of action from the regulated compounds, saw sales rise substantially, whereas sulfoximines and butenolides, which are more closely related to neonicotinoids, experienced a slowdown in adoption.

Outline. The remainder of the paper is organized as follows. Section 2 describes the institutional setting of Québec's 2018 agronomic prescription reform. Section 3 presents the data, the construction of the treatment and control groups, and the empirical strategy. Section 4 reports the main empirical findings and presents a series of robustness analyses. Section 5 concludes.

2 Institutional Background

In 2018, Québec introduced a province-wide mandatory agronomic-prescription requirement for the highest risk agricultural pesticides, making it the only North American jurisdiction with such a regime. This institutional change provides the basis for the empirical analysis that follows.

Agricultural pesticide use in the province expanded substantially after the mid-1990s, alongside the intensification of corn and soybean production (Carvalho, 2017; Pimentel, 2005). At the same time, Québec had established a regulatory framework to mitigate pesticide risks.[5] Despite these measures, concerns about the use of particular high-risk pesticides, notably atrazine and neonicotinoids, persisted. In response, Québec introduced a mandatory prescription requirement for selected high-risk pesticides in 2018.

Two compound classes concentrated regulatory concern: atrazine, a persistent groundwater contaminant with endocrine-disrupting effects on aquatic organisms (Hayes et al., 2010; Pest Management Regulatory Agency, 2010), and neonicotinoid insecticides, whose use became nearly universal in corn and soybean seed treatments after 2005 despite accumulating evidence of adverse effects on pollinators and insect biomass more broadly (Woodcock et al., 2017; European Food Safety Authority, 2018). The compound *chlorpyrifos* was also targeted by the regulation in April 2019. However, due to its harmful health effects, the Government of Canada announced in 2019 its intention to ban its sale nationwide. This ban came into effect in December 2021 (Health Canada Pest Management Regulatory Agency, 2020). Consequently, we excluded this ingredient from our treated group.

In Québec, pesticides are regulated under the Pesticides Act (CQLR, c. P-9.3) and its two implementing regulations, namely the *Code de gestion des pesticides (CGP)* and the *Règlement sur les permis*

[5] Before 2018, Québec had adopted several pesticide-mitigation measures, including the Pesticides Act (1987) and the Pesticides Management Code (2003), as well as restrictions introduced in 2006 on certain products used for residential lawn maintenance and on pesticide applications near sensitive sites and waterways.

et certificats pour la vente et l'utilisation des pesticides (RPCVUP). The RPCVUP establishes, among other things, the classification of pesticides, the permit and certification regime, and restrictions on their sale, while the CGP regulates the storage, sale, use, and possession of pesticides. In this context, the application, for agricultural purposes, by land or by aircraft, of a Class 1, 2, or 3 pesticide containing atrazine, chlorpyrifos, or any of the three targeted neonicotinoids (clothianidin, imidacloprid, or thiamethoxam) is prohibited, as is the planting of seeds treated with a Class 3A insecticide, unless an agronomic prescription has first been obtained from an agronomist who is a member of the *Ordre des agronomes du Québec* (OAQ) (CGP, arts. 74.1 and 86.1). The prescription also authorizes the purchase of the pesticide (RPCVUP, art. 44).[6]

The regulatory amendments introduced in March 2018 progressively brought the highest-risk pesticides within the prescription requirement, with the measure fully phased in by April 2019. These pesticides included atrazine, chlorpyrifos, clothianidin, imidacloprid, and thiamethoxam, making their use conditional on justification by an agronomist. Starting in 2025, Class 3A, which since 2018 had covered seed treatments with the three targeted neonicotinoids for the eight specified crops, was expanded to include seeds of these eight crops treated with any insecticide other than a biopesticide. Their use is therefore conditional on obtaining an agronomic prescription.

The prescription mechanism operates as a sequential, multi-actor process. A farmer wishing to purchase a regulated compound must first obtain a document provided by a licensed agronomist. This document is then presented at the point of retail sale as the legal condition for purchase. The MELCCFP staff carry out verification of agronomic prescriptions among farmers and, when necessary, report deficiencies in prescription quality to the agronomists' professional association.

3 Empirical Strategy

This section describes our empirical strategy for estimating the effect of Québec's mandatory prescription policy on agricultural pesticide use. The main identification challenge is that pesticide use may have evolved differently across treated and untreated units even in the absence of the reform. We address these identification concerns using three estimators that rely on progressively weaker assumptions about pre-treatment trends. The two-way fixed effects (TWFE) specification serves as a baseline and relies on the assumption that treated and control units would have followed parallel trends in the absence of the reform. The slope-break specification relaxes this assumption by allowing for differential linear trends prior to 2018 and identifies the treatment effect from deviations relative to these trends. The synthetic control approach imposes no functional-form restriction on pre-treatment dynamics, requiring only that a weighted combination of control units reproduces the treated unit's pre-reform trajectory. Before outlining the specific estimators, we first describe the data employed in our analysis.

[6]The prescription is a legal document specifying the document number, the farmer's information, the agronomist's information (including the OAQ member number), a description of the intervention required (parcel, crop/plant species, name of active ingredient, names of pesticides, quantity required) the expiry date, the agronomist's signature and date (CGP, art. 74.1). Non-compliance is subject to monetary penalties. A penalty of $1,500 applies to individuals and $7,500 in other cases when a pesticide is applied in contravention of section 74.1 (CGP art. 86.9).

3.1 Data

Data source. The primary data come from Ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs (MELCCFP) of Québec, which compiles annual records of pesticide sales at the compound level for the entire province. The dataset covers the period 2000–2022 and reports the total quantity sold (in kilograms of active ingredient) for each registered commercial product.[7] Annual pesticide sales closely track annual use. Using comprehensive records of active-substance purchases in France, Bareille et al. (2024) find that farmers store relatively little pesticide from one year to the next. The outcome variable in all specifications is the logarithm of annual quantity sold.[8]

Treated groups. The treated compounds comprise the herbicide atrazine, the three neonicotinoid insecticides (clothianidin, imidacloprid, and thiamethoxam), and potential substitutes. The potential substitutes for the regulated compounds consist of agrochemically related insecticides that target the same pest spectrum but were not subject to the prescription requirement, thereby providing a natural setting to examine substitution effects. Although atrazine has numerous agronomic alternatives, they are dispersed across several herbicide classes rather than concentrated in a single close substitute.[9] Consequently, producers responding to the prescription requirement are unlikely to substitute toward a single active ingredient. Instead, they are more likely to re-optimize weed-management strategies by combining herbicides from different chemical classes or adjusting application practices. For this reason, we do not identify a potential substitute for atrazine. Our analysis focuses on the reduction in its sales rather than attempting to identify substitution toward a specific herbicide.

We identify diamides, sulfoximines, and butenolides as potential substitutes for neonicotinoids based on agronomic evidence that they provide effective control of many of the same economically important insect pests while relying on distinct active ingredients. Anthranilic diamides have been shown to achieve pest control comparable to neonicotinoid seed treatments in vegetable crops (Lahm et al., 2009; Larson et al., 2012; Schmidt-Jeffris and Nault, 2016). Sulfoximines and butenolides were subsequently developed as novel insecticide classes that provide alternatives to neonicotinoids in the control of economically important pests, including pests targeted through the nicotinic acetylcholine receptor pathway (Sparks et al., 2013; Nauen et al., 2015; Sparks et al., 2019). We treat sulfoximines and butenolides as a single group in the analysis because both represent newer chemical alternatives to neonicotinoids and

[7] For three herbicides used as atrazine controls—2,4-D, MCPA, and dicamba—we aggregate sales to the active-ingredient level because multiple commercial formulations may contain the same active ingredient under different trade names; for 2,4-D, all registered products whose names begin with "2,4-D" (excluding 2,4-DB) are grouped into a single series, and MCPA and dicamba are treated analogously (Table A.1).

[8] For compound-year cells with zero recorded sales, we assign $\ln(0.01)$, imposing a lower bound of 0.01 kg. Across all estimation panels, 108 compound-year cells (17.4% of observations) are imputed; these are concentrated in the substitute panels (sulfoximines/butenolides and diamides) before 2010, when these classes were pre-diffusion in Québec.

[9] These include (i) photosystem II inhibitors, such as simazine and metribuzin; (ii) HPPD inhibitors, including mesotrione, tembotrione, and isoxaflutole; (iii) ALS inhibitors, such as nicosulfuron and rimsulfuron; (iv) synthetic auxins, including 2,4-D and dicamba; (v) PPO inhibitors, such as flumioxazin and sulfentrazone; and (vi) non-selective herbicides, notably glyphosate and glufosinate. Among these alternatives, simazine is the closest chemical substitute because it belongs to the same triazine family. Simazine shares the HRAC Group 5 mode of action (photosystem II inhibition), and has overlapping applications in corn production. However, simazine accounts for only a small share of the Québec herbicide market (0.1 percent of provincial herbicide sales, 2012–2017) compared to 5.5 percent for atrazine.

occupy a similar role as substitute chemistries following the reform. Because these compounds offer agronomically viable alternatives without being subject to the prescription requirement, they represent the most plausible candidates for substitution for neonicotinoids following the 2018 reform.

Control groups. For each treatment panel (atrazine, neonicotinoids, diamides, and sulfoximine and butenolide), we construct a control group of compounds that were not subject to the prescription requirement and can therefore be used to estimate the counterfactual evolution of treated compounds. Control compounds are selected according to three criteria. First, they are used in similar cropping systems and therefore face comparable weather conditions and market demand. Second, they are not intended to control the same pests as the treated compounds, reducing the scope for reform-induced substitution and potential contamination of the control group. Third, they exhibit sufficiently continuous sales throughout the sample period to permit reliable estimation.

According to these criteria, the control group for atrazine consists of herbicides used to control weeds in the same cereal and broadleaf cropping systems. For the neonicotinoid analysis, the control group includes synthetic pyrethroids and organophosphate insecticides that target similar economically important insect pests in the same crops. For the diamide analysis, the control group comprises ecdysone agonists and broad-spectrum pyrethroids used against similar insect pests in the same crops. For the sulfoximine and butenolide analysis, the control group consists of selective aphicides and broad-spectrum pyrethroids targeting similar insect pests. The complete list of control compounds for each treatment panel is reported in Tables A.1–A.4.

3.2 Baseline Estimation: Two-Way Fixed Effects

The outcome variable, y_{ct}, is the natural logarithm of the annual quantity of compound c sold in year t, in kilograms of active ingredient. The baseline specification is

$$y_{ct} = \alpha_c + \gamma_t + \beta\, T_c \times \mathbf{1}_{\{t \geq 2018\}} + \varepsilon_{ct}, \tag{3.1}$$

where α_c are compound fixed effects, γ_t are year fixed effects, T_c indicates the treated compounds, and $\mathbf{1}_{\{t \geq 2018\}}$ marks the years from the reform onward. The compound fixed effects absorb time-invariant differences in scale across active ingredients; the year fixed effects absorb shocks common to all compounds, such as weather and market-wide price movements. The coefficient of interest, β, is the average change in the log sales of the treated compounds, relative to the controls, from 2018 onward.

We estimate Equation (3.1) separately for each treated class: atrazine, neonicotinoids, sulfoximines and butenolides, and diamides. Each estimation uses the compounds in the treated class together with a matched set of control compounds.[10] Because the treatment indicator T_c is defined at the class level, the coefficient β identifies the average treatment effect for the corresponding compound class rather than for individual active ingredients.

The coefficient β admits a causal interpretation under the parallel trends assumption. Specifically, in the absence of the prescription requirement, the average evolution of pesticide sales for treated compounds would have been the same as that of the control compounds. In other words, any pre-existing differences between treated and control compounds are assumed to be time-invariant, while common

[10] Tables A.1–A.4 report the complete list of control compounds for each treatment panel.

shocks affect both groups similarly over time. Under this condition, the year fixed effects γ_t capture the common counterfactual time path, and the within-compound change in y_{ct} after 2017 identifies the treatment effect.

To assess the validity of the parallel trends assumption and to characterize the dynamic effects of the reform, we estimate the following event-study specification:

$$y_{ct} \;=\; \alpha_c + \gamma_t + \sum_{\substack{k=\underline{k} \\ k\neq -1}}^{\bar{k}} \theta_k \, T_c \cdot \mathbf{1}_{\{t-2018=k\}} \;+\; \varepsilon_{ct}, \tag{3.2}$$

where k indexes event time relative to the reform year, and $k = -1$ (corresponding to 2017) is omitted as the reference period. The coefficients θ_k trace the dynamic evolution of treated compounds relative to the control group before and after the reform.

The pre-treatment coefficients, $\{\theta_k\}_{k<0}$, provide a direct assessment of the parallel-trends assumption. Under this assumption, coefficients $\{\theta_k\}_{k<0}$ should be jointly indistinguishable from zero, indicating the absence of differential pre-treatment trends between treated and control compounds.

3.3 Slope-Break Specification

The baseline two-way fixed-effects (TWFE) specification in Equation (3.1) estimates the average post-2017 effect of the reform under the parallel trends assumption. However, for compounds exhibiting pre-existing secular trends, this specification may attribute part of the underlying trend to the policy. To distinguish an immediate level shift from a change in the post-reform trajectory, we estimate a slope-break specification that allows the reform to affect both the level and the slope of pesticide sales, following the trend-adjusted difference-in-differences framework discussed by Angrist and Pischke (2009):

$$y_{ct} = \alpha_c + \gamma_t + \delta_1 T_c \times \mathbf{1}_{\{t\geq 2018\}} + \delta_2 T_c \times \mathbf{1}_{\{t\geq 2018\}} \cdot (t - 2018) + \varepsilon_{ct}, \tag{3.3}$$

where compound fixed effects α_c absorb time-invariant heterogeneity across compounds, and year fixed effects γ_t capture aggregate shocks common to all compounds. The coefficient δ_1 measures the discrete level shift at the reform date; δ_2 captures the post-2017 change in slope relative to the common time path. Identification rests on the parallel-trends assumption applied to the pre-2018 window.

In the sulfoximine and butenolide panel, treated compounds were still entering the Québec market during the pre-reform years, producing a substantial differential pre-trend relative to the control group. Imposing common year effects would conflate this entry dynamic with the reform's causal effect. Following Pischke (2005), we augment Equation (3.3) with a treated-group-specific linear pre-treatment trend for sulfoximine and butenolide panel:

$$y_{ct} = \alpha_c + \gamma_t + \rho \, T_c \cdot (t - t_0) + \delta_1 T_c \times \mathbf{1}_{\{t\geq 2018\}} + \delta_2 T_c \times \mathbf{1}_{\{t\geq 2018\}} \cdot (t - 2018) + \varepsilon_{ct}, \tag{3.4}$$

where $t_0 = 2014$ denotes the first year of positive treated-group sales, and ρ captures the differential pre-2018 growth trend. Under Equation (3.4), the coefficient δ_2 measures the post-reform change in slope relative to the pre-existing trend.

3.4 Synthetic Control Method

The difference-in-differences estimators described above identify treatment effects under assumptions on the evolution of untreated outcomes. As a complementary approach, we estimate treatment effects using the synthetic control method (SCM), which constructs a data-driven counterfactual for the treated group without imposing a parametric specification on pre-treatment dynamics. SCM, developed by Abadie et al. (2010) , is particularly useful when treated and control units exhibit heterogeneous trends prior to the intervention, provided that the treated trajectory can be closely reproduced by a weighted combination of untreated compounds.

The synthetic control method assigns non-negative weights to donor compounds so that a weighted combination of control units closely matches the treated group's pre-2018 trajectory. The weights are chosen to minimize the pre-treatment distance between the treated unit and its synthetic counterpart over a set of lagged outcomes, subject to the weights summing to one. The estimated treatment effect is the post-2017 difference between the observed outcome and the synthetic control. To improve comparability across compounds, all series are normalized to their base-year value.

Statistical inference follows the permutation procedure proposed by Abadie et al. (2015). The treatment is iteratively reassigned to each donor compound, and the synthetic control is re-estimated to generate the distribution of placebo effects under the null hypothesis of no treatment effect. We measure pre- and post-treatment fit using the root mean squared prediction error (RMSPE), defined as the square root of the mean squared difference between the observed outcome and its synthetic-control counterpart over the corresponding period. The one-sided p-value is then computed as the proportion of placebo units whose post-to-pre RMSPE ratio is at least as large as that of the treated unit. Synthetic controls are implemented using the algorithm of Abadie et al. (2011).

3.5 Inference With Few Clusters

The number of clusters ranges from five to thirteen across estimation panels. With so few clusters, conventional cluster-robust standard errors may be downward biased and over-reject the null hypothesis (Cameron et al., 2008). We therefore report wild cluster bootstrap p-values following Roodman et al. (2019), based on 999 bootstrap replications with Rademacher weights, alongside conventional cluster-robust standard errors. When the two inference procedures differ, we base our conclusions on the bootstrap results.

The wild cluster bootstrap provides valid inference with a limited number of clusters, provided that at least two treated clusters are available (MacKinnon and Webb, 2017). This condition is satisfied for all estimation classes except atrazine. For atrazine, we therefore place greater weight on the joint F-test from the slope-break specification and the synthetic control permutation test for statistical inference.

3.6 Estimation Windows

The difference-in-differences and slope-break specifications are estimated over a common 2012–2022 window for all four classes. We do not extend these regressions to an earlier pre-reform period because sulfoximines and butenolides entered the Québec market only around 2012. Applying a common window across all classes also keeps the estimates comparable across pesticide classes. The synthetic-control analysis instead uses the longest pre-treatment history available for each class, conditional on

positive sales, because a longer pre-treatment period provides more information for constructing the synthetic counterfactual and assessing its pre-treatment fit. For atrazine and neonicotinoids, this period is 2000–2017; for diamides, 2008–2017; and for sulfoximines and butenolides, 2012–2017.

The two approaches therefore use different calendar windows by design. The difference-in-differences and slope-break specifications prioritize comparability by using a common estimation window across pesticide classes, whereas the synthetic-control analysis prioritizes counterfactual fit by using the longest credible pre-treatment history available for each class, beginning with its observed entry into the market.

4 Results

This section presents the main empirical results on the effects of the 2018 prescription requirement on pesticide sales. We first report the baseline difference-in-differences and slope-break estimates for the four treated classes: atrazine, neonicotinoids, diamides, and sulfoximines/butenolides. We then examine each class separately, assessing the identifying assumptions and complementing the regression estimates with event-study and synthetic-control analyses.

4.1 Main Results

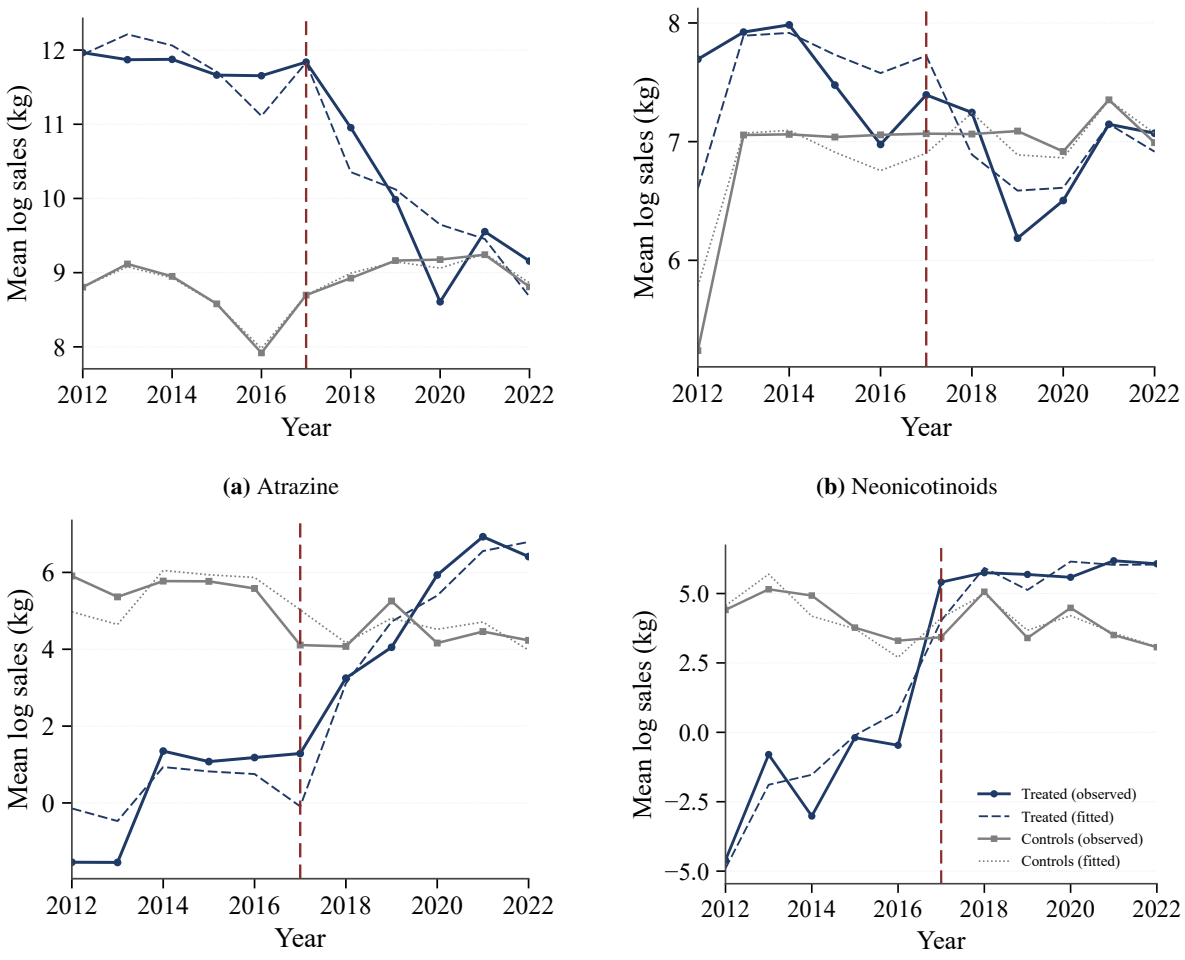
This section provides an overview of the main findings. The subsequent class-by-class discussions examine each estimate in detail, assess the corresponding identifying assumptions, and evaluate the evidence from alternative estimators.

Table 1 presents the class-specific estimates. Columns (1), (3), and (6) report the average post-2017 effects, $\hat{\beta}$, from the two-way fixed-effects specification in Equation (3.1) for atrazine, neonicotinoids, and diamides, respectively. Columns (2), (4), and (5) report the corresponding slope-break estimates for atrazine, neonicotinoids, and sulfoximines/butenolides, respectively. These specifications distinguish between an immediate level shift following the reform, $\hat{\delta}_1$, and a change in the post-reform trajectory, $\hat{\delta}_2$. For sulfoximines and butenolides, the specification additionally accounts for the treated group's differential pre-reform trend using Equation (3.4).

The estimates reveal substantial heterogeneity in the response to the prescription requirement. Three findings stand out. First, the reform accelerated the decline in atrazine sales, generating both an immediate reduction and a steeper post-reform decline in sales. Second, for neonicotinoids, we find no evidence of a reform-induced decline once pre-existing trends are taken into account. Third, diamide sales increased substantially following the reform, consistent with a reallocation of demand toward this class of insecticides.

Figure I provides a visual summary of these results by plotting observed and fitted mean log sales for each treated class alongside its corresponding control group.[11] For neonicotinoids, diamides, and atrazine, the short-dashed lines show the fitted trajectories implied by the slope-break specification. For

[11] The choice between the TWFE and slope-break specifications reflects the pre-reform dynamics of each treatment panel. When treated and control compounds exhibit differential trends before the reform, the TWFE estimator may confound these underlying dynamics with the policy effect. In such cases, the slope-break specification provides a more appropriate characterization of the reform's impact. For sulfoximines and butenolides, which were still in the early stages of market adoption, the parallel-trends assumption underlying the TWFE specification is clearly violated (see Figure Id); we therefore report only the pre-trend-adjusted slope-break estimates from Equation (3.4).



(a) Atrazine

(b) Neonicotinoids

(c) Diamides

(d) Sulfoximines and butenolides

FIGURE I: Mean log quantity sold by compound group: treated and control trajectories.

Notes: This figure plots, by year, the mean log quantity sold (in kilograms of active ingredient) for each treated compound group and its control group. Solid lines show the treated group as observed; long-dashed lines show the controls as observed. Short-dashed lines (with markers) overlay the fitted trajectories from the slope-break specification in Equation (3.3) for panels (a)–(c), and from the pre-trend-adjusted variant in Equation (3.4) for panel (d). Fitted lines include the absorbed compound and year fixed effects, so the post-2017 gap between observed and fitted visualises the estimated reform effect $\hat{\delta}_1 + \hat{\delta}_2(t - 2018)$. The vertical dashed line marks the prescription boundary (2017, the year before the requirement took effect). Treated- and control-group compositions are listed in Table 1 and Section 4.

sulfoximines and butenolides, the fitted trajectory is based on the pre-trend-adjusted specification in Equation (3.4), which controls for the differential pre-2018 growth path before estimating $\hat{\delta}_1$ and $\hat{\delta}_2$.

The figure reveals clear heterogeneity across compound classes. In the atrazine panel (Figure Ia), the treated series remains close to a stable plateau of approximately 12 log points over 2012–2017, compared with about 9 log points for the control group. Following the reform, treated sales fall sharply and continue to decline, nearly converging toward the control level by 2020; the fitted trajectory captures this steep and sustained post-reform decline.

In the neonicotinoid class (Figure Ib), treated sales had already been declining from their 2014 peak before the reform, while sales of the control compounds remained comparatively stable. The treated series declined further in 2018 and 2019, immediately following the introduction of the prescription requirement, whereas the control series showed little corresponding movement. This initial post-reform

decline was partly offset by an increase in treated sales after 2019, leaving the later trajectory closer to the pre-reform decline than the immediate post-reform movements would suggest. The figure therefore shows a short-run decline in neonicotinoid sales following the reform, superimposed on an ongoing pre-reform downward trend, rather than a clear and persistent break in the trajectory.

The diamide class (Figure Ic) shows the opposite pattern. Treated sales start well below the control level in 2012 and increase in 2013 and 2014, after which they remain relatively stable through the pre-reform period. Following the 2018 reform, treated sales increase sharply, while the control series remains comparatively stable, with treated sales rising above the control group by 2019. The widening gap is closely tracked by the fitted trajectory and is consistent with increased diamide sales following the reform. Finally, in the sulfoximine and butenolide class (Figure Id), the treated compounds exhibit a steep pre-reform diffusion trend. Although sales continue to increase after 2017, they flatten relative to the pre-trend-adjusted projection, indicating a deceleration in adoption rather than an outright decline.

Table 1: Effects of the 2018 Prescription Requirement on Pesticide Sales

	Atrazine		Neonicotinoids		Sulfoximines	Diamides
	(1) TWFE	(2) Slope-break	(3) TWFE	(4) Slope-break	(5) Slope-break	(6) TWFE
$\hat{\beta}$ (TWFE level)	-2.545^{***}		-1.073^{*}			5.995^{**}
	(0.513)		(0.511)			(2.041)
$\hat{\delta}_1$ (slope-break level)		-1.771^{***}		-1.172^{**}	-0.830	
		(0.432)		(0.457)	(3.047)	
$\hat{\delta}_2$ (slope, per year)		-0.387^{***}		0.049	-1.370^{***}	
		(0.110)		(0.085)	(0.199)	
$F(\delta_1, \delta_2)$		12.553		3.825	63.608	
p-value $[F]$		0.002		0.068	0.000	
Bootstrap p-value	—[a]	—[a]	0.082	0.062	0.000	0.033
N (compound × year)	110	110	99	99	66	110

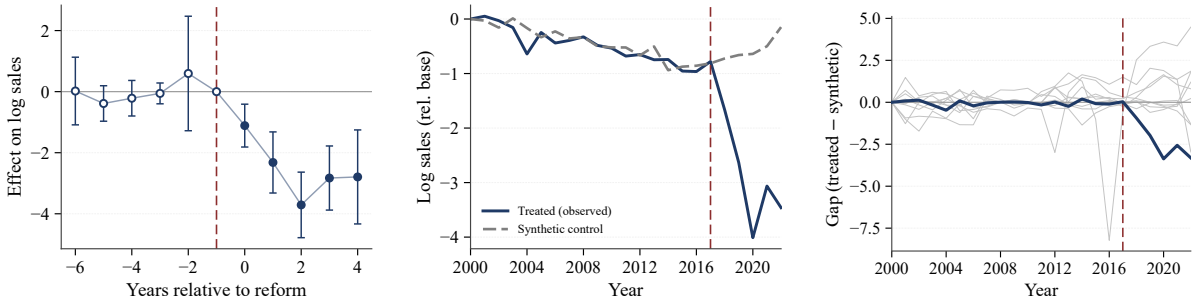
Notes: This table presents difference-in-differences estimates of the effect of the 2018 prescription requirement on log annual sales (kg of active ingredient) for the four treated compound classes. Columns (1), (3), and (6) report the two-way fixed-effects level effect $\hat{\beta}$ from Equation (3.1); columns (2), (4), and (5) report the slope-break decomposition ($\hat{\delta}_1$ = discrete level shift at 2018; $\hat{\delta}_2$ = post-reform slope change) from Equation (3.3). Standard errors clustered at the compound level are in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$. Bootstrap p-values are from wild cluster bootstrap with 999 replications and Rademacher weights. Significance stars reflect conventional cluster-robust standard errors; given the small number of clusters (Section 3.5), the bootstrap p-value row is the primary basis for inference where the two diverge, and is what Section 4.2.2's discussion of the neonicotinoid results relies on. [a] Bootstrap p-value not reported for atrazine: the panel contains a single treated cluster (atrazine enters as one aggregated compound), a case in which the wild cluster bootstrap is unreliable. Inference rests on the joint F-test ($F = 12.55$, $p = 0.003$) and the synthetic-control permutation ($p_{\text{perm}} = 0.100$) shown in Table B.1.

4.2 Results by Compound Class and Robustness Checks

We now examine each compound class. Each subsection follows a common structure. We first discuss the corresponding estimates reported in Table 1, then assess identification using the event-study and synthetic-control evidence, and finally interpret the magnitude and pattern of the estimated response.

4.2.1 Atrazine

The prescription requirement produced a large and persistent reduction in atrazine sales, with evidence of both an immediate level shift and a subsequent change in the sales trajectory. As shown in Table 1, the slope-break DiD estimate implies an immediate decline of $\hat{\delta}_1 = -1.771$ log points relative to the control group, corresponding to a reduction of approximately 83 percent relative to the pre-2018 level.[12] The initial decline was followed by an additional reduction of $\hat{\delta}_2 = -0.387$ log points per year relative to the pre-reform trajectory. Thus, the reform did not simply produce a one-time contraction in atrazine sales; the gap continued to widen after 2018. The joint null hypothesis $\hat{\delta}_1 = \hat{\delta}_2 = 0$ is rejected at the 1 percent level ($p = 0.002$), providing evidence of both a discrete break at the time of the reform and a sustained departure from the pre-reform trajectory. Averaged over the post-reform period, the estimated gap corresponds to a reduction of approximately 92 percent relative to the counterfactual path.



(a) Event study **(b)** Actual vs. synthetic atrazine **(c)** Placebo gaps

FIGURE II: Atrazine: three independent pieces of evidence.

Notes: This figure presents three independent pieces of evidence for the atrazine result. Panel (a) plots the event-study coefficients from Equation (3.2); the reference year is 2017, and the vertical dashed line marks that boundary so that 2018 onward is post-reform. Panel (b) plots observed atrazine log sales against its synthetic counterpart (normalised to 2000); the synthetic series is constructed as described in Section 3.4. Panel (c) plots the treated minus synthetic gap (navy) against the placebo-donor gaps (grey); the treated gap leaves the placebo cloud only after the reform. Vertical dashed lines mark the prescription boundary (2017).

The event-study estimates provide a direct assessment of the timing of this break. Figure IIa shows that the estimated pre-treatment coefficients are small and jointly insignificant, indicating no detectable differential trend between atrazine and the control group before the reform.[13] This pattern is important because the identifying variation in the slope-break specification comes from the change in the trajectory at the time of the policy. Following the reform, the estimated treatment effect becomes sharply negative in 2018 and grows increasingly negative in subsequent years. The post-reform coefficients therefore trace a pattern that is difficult to reconcile with a continuation of the pre-2018 decline alone: the policy is associated with an immediate downward shift followed by a persistent widening of the gap.

The synthetic-control results provide a second assessment of the counterfactual trajectory without relying on the common-trend structure of the DiD specification. As shown in Figure IIb, observed atrazine sales closely track the synthetic control throughout the pre-reform period, indicating a strong

[12] Log-point coefficients are converted to proportional changes as $\exp(\hat{\delta}) - 1$. The immediate decline is $\exp(-1.771) - 1 \approx -0.83$. The total post-reform effect in year t is $\hat{\delta}_1 + \hat{\delta}_2(t - 2018)$. Averaged over 2018–2022, this effect is -2.545 log points, implying a reduction of $1 - \exp(-2.545) \approx 0.92$, or approximately 92 percent relative to the counterfactual path.

[13] Table B.3 tests whether the control compounds themselves shifted post-2017, which would violate the exclusion restriction.

pre-treatment fit. From 2018, however, the two series diverge sharply, with observed atrazine sales falling substantially below the synthetic trajectory. The timing of this divergence closely coincides with the introduction of the prescription requirement, while the pre-treatment correspondence provides little indication of a comparable gap emerging in the absence of the reform.

The permutation analysis further indicates that this divergence is unusually large relative to the distribution of placebo effects. Figure IIc compares the treated-minus-synthetic gap for atrazine with the corresponding gaps obtained by assigning the treatment to each donor compound. Before the reform, the atrazine gap lies within the placebo distribution; after 2018, it falls well below the placebo gaps and remains separated from them throughout the post-treatment period. The post-to-pre RMSPE ratio of 16.0 is by far the largest in the placebo distribution—atrazine is the single most extreme of the ten herbicide units—though with so few donors the permutation p-value attains only its floor of 10% (Table B.1). The synthetic-control results therefore provide evidence that the post-2017 divergence is unlikely to reflect the type of idiosyncratic movement observed among untreated compounds.

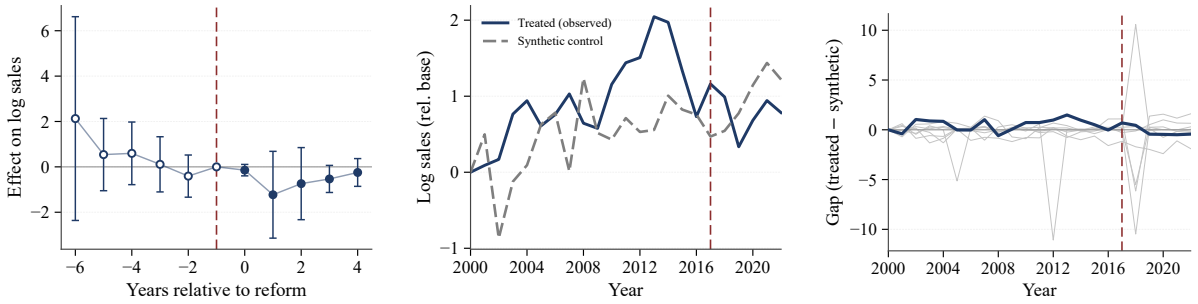
Taken together, the slope-break DiD, event-study, and synthetic-control estimates point to the same conclusion: the 2018 prescription requirement generated a large immediate reduction in atrazine sales that persisted and intensified over the subsequent years.

4.2.2 Neonicotinoids

Neonicotinoids were among the principal targets of public concern surrounding the 2018 reform. The baseline two-way fixed-effects specification suggests that the reform reduced neonicotinoid sales, with an estimated effect of -1.073 log points (Table 1, column 3). This estimate would imply a sizable reduction in sales following the introduction of mandatory agronomic prescriptions. However, the TWFE estimate collapses the entire sample into a single before-after comparison, and Figure Ib shows that treated sales had already been declining from their 2014 peak while sales of the control compounds remained comparatively stable. If this pre-existing divergence simply continued after 2018, TWFE would register it as a statistically significant effect. We therefore turn to specifications that do not force the post-reform trajectory into a single level shift, and to event-study and synthetic-control evidence that impose no particular functional form on the pre-reform period.

The slope-break specification separates an immediate level shift ($\hat{\delta}_1$) from a change in the post-reform slope ($\hat{\delta}_2$). The level shift is statistically significant ($\hat{\delta}_1 = -1.172$, $p < 0.05$), essentially mirroring the TWFE estimate, while the slope change is not ($\hat{\delta}_2 = 0.049$, not significant); the joint test of $\hat{\delta}_1 = \hat{\delta}_2 = 0$ is only marginal ($F = 3.825$, $p = 0.068$; bootstrap $p = 0.062$). Because this specification does not separately model the pre-2018 trend, the significant level shift alone does not establish that it is attributable to the reform rather than to the pre-existing decline documented above. The event study in Figure IIIa, which imposes no functional form at all, speaks more directly to this question. None of the individual post-reform coefficients is statistically distinguishable from zero, and the pre-treatment coefficients, while tracing a pattern consistent with the pre-existing decline, are not jointly significant either ($F = 1.67$, $p = 0.246$)—a reflection of the limited power available with only nine compounds in this panel. Taken together, the evidence does not establish that anything specific to 2018 interrupted or accelerated a trajectory that was already underway.

The synthetic-control analysis provides a further check on this interpretation. Because the donor weights are chosen to match the treated series' own pre-2018 trajectory, the synthetic control implicitly



(a) Event study **(b)** Actual vs. synthetic **(c)** Placebo gaps

FIGURE III: Neonicotinoids: event-study and synthetic-control evidence.

Notes: Event-study and synthetic-control evidence for the neonicotinoid aggregate. Panel (a) plots the event-study coefficients from Equation (3.2); Panel (b) plots the observed neonicotinoid aggregate against its synthetic counterpart (normalised to 2000). Panel (c) plots the treated minus synthetic gap (navy) against the placebo-donor gaps (grey); the treated gap stays within the placebo cloud throughout, consistent with a null.

absorbs the pre-existing decline rather than assuming it away. The synthetic series tracks observed neonicotinoid sales closely before the reform and continues to follow the treated series from 2018, with no pronounced post-reform divergence. In contrast to atrazine, therefore, the reform does not generate a gap that is large relative to the variation observed among the donor compounds. Taken together, the event-study and synthetic-control estimates—neither of which assumes parallel pre-trends—do not corroborate a reform-induced reduction in neonicotinoid sales, even though the TWFE and slope-break level estimates are individually significant. The contrast is informative: once the analysis stops forcing the full sample period into a single before-after comparison, the apparent effect no longer holds up, indicating that the negative TWFE coefficient most plausibly reflects the continuation of a pre-existing decline rather than a causal policy effect.

One possible interpretation of this result is that the reform did not substantially alter an input decision that was already well established in Québec crop production. By 2018, neonicotinoid use was widespread in major field crops (Pest Management Regulatory Agency, 2016; Labrie et al., 2020), and the prescription requirement may therefore have added an administrative step without materially changing established production practices. The absence of a statistically detectable and sustained decline is consistent with this interpretation, although the aggregate sales data do not allow us to directly test the underlying behavioral mechanism.[14]

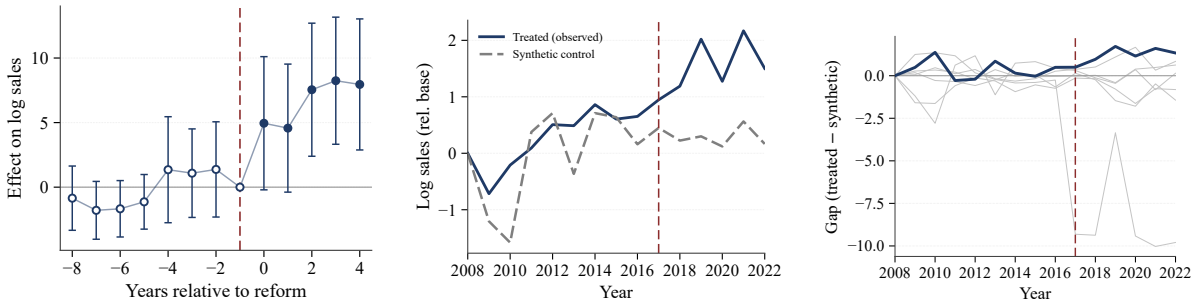
The way neonicotinoids are used in Québec agriculture provides a further possible explanation for the absence of a detectable decline in measured sales. Unlike products such as atrazine, which are typically purchased and applied directly by producers, neonicotinoids are widely delivered through commercially treated seed. When neonicotinoids are incorporated into treated seed, producers acquire the insecticide indirectly through seed purchases rather than as a standalone pesticide product. The 2018 Québec reform did not directly regulate the quantity of neonicotinoid contained in treated seed; rather, it required agronomic justification for the purchase and use of treated seed. Thus, the policy affected

[14] A direct test of this mechanism would require farm- or field-level data linking pesticide use to crop choices, pest conditions, and other production decisions, ideally together with information on prescription applications and substitution across insecticide classes. Our aggregate sales data do not contain these dimensions and therefore cannot distinguish whether the limited response reflects the persistence of established production practices, substitution across products, or other behavioral responses to the reform.

the authorization to use treated seed without changing the amount of active ingredient embodied in each seed. Consequently, observed sales of neonicotinoid active ingredients may respond less directly to the regulation than sales of pesticides purchased and applied separately by producers, such as atrazine. The distinction is therefore between regulating access to treated seed and regulating the pesticide dose applied conditional on seed use.

4.2.3 Diamides

The TWFE estimate in column 6 of Table 1 indicates a statistically significant increase in diamide sales of approximately 6.0 log points relative to the control group. The result is robust to wild cluster bootstrap inference.[15]



(a) Event study **(b)** Actual vs. synthetic **(c)** Placebo gaps

FIGURE IV: Diamides: evidence of post-2017 substitution.

Notes: Event-study and synthetic-control evidence for the diamide aggregate. Panel (a) plots the event-study coefficients from Equation (3.2); the reference is 2017, marked by the vertical dashed line so that 2018 onward is post-reform. Panel (b) plots the observed diamide aggregate against its synthetic counterpart (normalised to 2008). Panel (c) plots the treated minus synthetic gap (navy) against the placebo-donor gaps (grey); the treated gap rises above the cloud after the reform.

The event-study estimates in Figure IVa provide further support for this pattern. Moreover, the synthetic-control analysis offers a complementary perspective (Figure IVb). The synthetic series tracks observed diamide sales reasonably well during the pre-reform period, although the pre-treatment fit is less close than for atrazine. The pre-period RMSPE is 0.59, compared with 0.16 for atrazine, reflecting the smaller and noisier donor pool available for diamides. Beginning in 2018, observed sales rise above the synthetic counterpart. The permutation exercise provides less precise evidence of this divergence (Figure IVc): the post-to-pre RMSPE ratio is 2.34, below three of the six placebo ratios, yielding a permutation p-value of 0.571 (Table B.1). The limited number of close biological comparators also constrains the available donor pool.[16]

In sum, diamide sales increased following the reform rather than continuing their relatively stable pre-reform trajectory. Before the reform (2012–2017), annual diamide sales averaged approximately

[15] A potential concern is that pyrethroids, which are included among the control compounds for diamides, may themselves have been affected by the reform through substitution toward diamides. Pyrethroids and diamides target different biological pathways but are both widely used against insect pests, making substitution between the two classes plausible. Such reallocation could overstate the estimated diamide effect. We therefore test whether pyrethroid sales changed relative to organophosphates using the same difference-in-differences framework. Table B.4 in Appendix B shows a small and statistically insignificant post-reform effect, while Figure B.1 shows event-study coefficients close to zero before and after 2018. These results provide no evidence that pyrethroids were materially affected by the reform, supporting their use as controls.

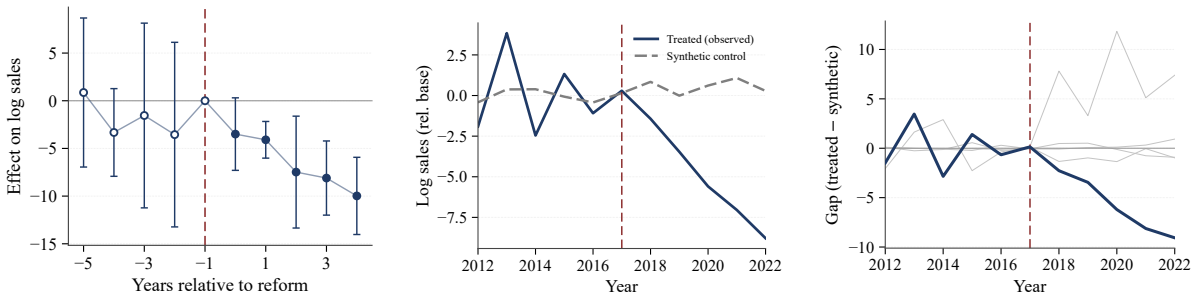
[16] Only two ecdysone-agonist compounds and one chitin-synthesis inhibitor are available as close biological comparators.

2,511 kg; afterward (2018–2022), they averaged approximately 6,948 kg (Table B.2). Diamides provide an alternative for controlling many of the same pests targeted by neonicotinoids, sulfoximines, and butenolides, and Kathage et al. (2018) document an expansion of alternative insecticide chemistries among European farmers facing restrictions on neonicotinoids. The increase in diamide sales, however, should not be interpreted as evidence of a direct reallocation from neonicotinoids to diamides. Neonicotinoid sales were already declining before the reform, while sulfoximine and butenolide adoption slowed following the reform, even though their sales levels never actually declined; the reform's effect on this class is better described as a drag on the rate of adoption than as a reduction in sales. The simultaneous expansion of diamides alongside this slowdown in sulfoximine and butenolide adoption is consistent with diamides replacing part of the use of multiple alternative chemistries, although the aggregate sales data do not allow us to identify the source of the additional diamide purchases.

4.2.4 Sulfoximines and Butenolides

The active ingredients in sulfoximines and butenolides were still in the diffusion phase of their product life cycle before 2018. A conventional difference-in-differences specification is therefore less suitable because the treated compounds were following a steep upward adoption path rather than a stable pre-reform trajectory. The relevant question is whether the prescription requirement changed the rate at which these compounds were entering the market relative to their pre-existing growth path. The evidence suggests that it did. Column 5 of Table 1 shows that, after controlling for the compound-specific pre-treatment trend, the estimated post-reform slope change is negative, $\hat{\delta}_2 = -1.370$ ($p = 0.001$). The estimate remains significant under wild cluster bootstrap inference, indicating a marked deceleration in market adoption following the reform.

The event-study estimates in Figure Va provide a similar picture. Because these compounds were still diffusing before 2018, the event-study coefficients measure deviations from their joint pre-reform trend rather than changes relative to a fixed pre-treatment level. Coefficients close to zero before the reform indicate that adoption remained close to this underlying trajectory, while the negative post-reform coefficients indicate a departure from it.



(a) Event study **(b)** Actual vs. synthetic **(c)** Placebo gaps

FIGURE V: Sulfoximines and butenolides: event-study and synthetic-control evidence.

Notes: Panel (a): event-study coefficients from the slope-break specification with the compound-specific pre-trend absorbed; coefficients measure deviation from the sulfoxaflor/flupyradifurone joint pre-2018 growth trajectory, not from a level baseline, and negative post-2017 values indicate adoption deceleration. Because these compounds enter the market essentially at the reform, the synthetic control in panels (b)–(c) is run on the pre-trend-adjusted outcome (each unit's deviation from its own pre-2018 linear trend, the same adjustment as panel (a)) rather than on levels.

The synthetic-control analysis provides a further check (see Figures Vb and Vc). A standard synthetic control based on raw log sales does not reproduce the steep pre-2018 adoption path of sulfoximines and butenolides. We therefore detrend each unit before matching, which yields an acceptable pre-treatment fit (RMSPE = 2.03, Table B.1). Following the reform, the treated series shows a smooth and sustained decline relative to its detrended synthetic counterpart. The corresponding gap in Figure Vc widens after 2018, while the placebo gaps display more irregular movements, providing additional descriptive evidence of a post-reform slowdown in adoption.

Taken together, the slope-break estimate, its robustness to wild cluster bootstrap inference, and the event-study pattern point to a deceleration in sulfoximine and butenolide adoption beginning in 2018.

The contrasting responses of sulfoximines and butenolides and of diamides are informative when considered together. Diamide sales increased following the reform, whereas the adoption of sulfoximines and butenolides slowed relative to their pre-reform trajectories. This contrast is notable because sulfoxaflor and flupyradifurone, the active ingredients in these two newer classes, act on nicotinic acetylcholine receptors and target pest complexes that overlap with those targeted by neonicotinoids. Diamides, in contrast, have a different mode of action and are particularly effective against chewing pests such as Lepidoptera and Coleoptera. The post-reform response therefore did not follow the expected pattern of a shift toward insecticides most similar to neonicotinoids.

One possible interpretation is that the reform affected the broader adjustment path of insecticide use rather than only the compounds directly subject to the new requirement. Neonicotinoids (IRAC 4A), sulfoximines (4C), and butenolides (4D) belong to the same nicotinic acetylcholine receptor target family, whereas diamides (IRAC 28) do not. The slowdown in sulfoximine and butenolide adoption, together with the expansion of diamides, is therefore consistent with a reallocation away from the broader nicotinic-receptor-active group and toward insecticides with a different mode of action. Such a response could arise if the reform was interpreted not only as a restriction on the use of neonicotinoids, but also as a signal of a broader regulatory trajectory for closely related compounds. Under this interpretation, diamides provided an alternative margin for diversifying insecticide use without requiring a corresponding decline in observed neonicotinoid sales.

5 Conclusion

This paper examines whether mandatory agronomic prescriptions reduce pesticide use and how producers adjust their pesticide choices when access to selected compounds becomes subject to professional authorization. Exploiting Québec's 2018 prescription reform, we combine difference-in-differences, slope-break, and synthetic control methods to identify the effects of the policy on targeted pesticides and alternative insecticide classes. The results show that prescription-based regulation can substantially alter pesticide use, but its effects vary across compounds and do not necessarily lead to substitution toward the closest chemical alternatives.

The reform had its clearest effect on atrazine, whose sales declined substantially relative to the counterfactual trajectory, suggesting that pre-reform use exceeded agronomically justified levels and that the prescription requirement reduced applications that may not have been agronomically necessary. Neonicotinoids, in contrast, show no robust reform-induced decline once we account for their pre-existing downward trend. The contrasting responses suggest that the effectiveness of prescription requirements

depends on the decision margin through which the regulation operates and on the extent to which producers can adjust their pesticide choices outside that margin.

The responses of alternative insecticides further qualify the interpretation of the reform. Diamide sales increased substantially following the policy, while the adoption of sulfoximines and butenolides—chemistries pharmacologically closer to neonicotinoids—slowed relative to their pre-reform trajectories. This is the opposite of what a simple substitution story would predict, in which producers replace a regulated compound with its closest available alternative. A more consistent account is that producers reallocated away from the entire nicotinic-receptor-active family, anticipating its regulatory trajectory—an anticipation later confirmed when sulfoximines and butenolides were themselves brought under prescription in 2025. Diamides, sharing no mode-of-action lineage with the regulated class, absorbed that reallocation.

Taken together, these findings demonstrate that the effects of pesticide regulation cannot be assessed solely from the response of the compounds directly targeted by the policy. Mandatory prescriptions can accelerate the decline of individual pesticides, but they may also induce broader changes in the composition and trajectory of pesticide use. The nature of these responses depends on the agronomic role, market position, and adoption dynamics of alternative compounds. Accounting for such cross-compound responses is therefore essential for determining whether access-based pesticide regulation reduces overall pesticide use and, ultimately, pesticide-related environmental risk.

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A Data Appendix

Tables A.1–A.4 report the treated and control compounds for each panel, along with IRAC/HRAC mode-of-action group.

Table A.1: Atrazine Panel: Treated and Control Compounds

Compound	Pesticide Mode of Action Group	Role
atrazine	HRAC 5	Treated
MCPA (aggregated)	HRAC 4	Control 1
2,4-D (aggregated)	HRAC 4	Control 1
bromoxynil	HRAC 6	Control 1
bentazone	HRAC 6	Control 2
clethodim	HRAC 1	Control 2
sethoxydim	HRAC 1	Control 2
fenoxaprop-P-ethyl	HRAC 1	Control 2
dicamba (aggregated)	HRAC 4	Control 3
pendimethalin	HRAC 3	Control 3

Notes: HRAC = Herbicide Resistance Action Committee mode-of-action classification. MCPA, 2,4-D, and dicamba are aggregated across commercial formulations (regex match on the active-ingredient name). Control definitions: Control 1 = selective broadleaf herbicides; Control 2 = graminicides; Control 3 = synthetic auxin (dicamba) and dinitroaniline (pendimethalin). *Glyphosate* is excluded because its post-2000 trajectory is dominated by the diffusion of glyphosate-tolerant GM crops, an independent shock orthogonal to the prescription requirement. *Metolachlor* and *S-metolachlor* are excluded as agronomic complements to atrazine in corn weed management, generating mechanical co-movement. *Carfentrazone-ethyl* is excluded because it has no recorded Québec sales over 2000–2022 in the MELCCFP dataset.

Table A.2: Neonicotinoid Panel: Treated and Control Compounds

Compound	Pesticide Mode of Action Group	Role
clothianidin	IRAC 4A	Treated
imidacloprid	IRAC 4A	Treated
thiamethoxam	IRAC 4A	Treated
lambda-cyhalothrin	IRAC 3A	Control 1
cypermethrin	IRAC 3A	Control 1
deltamethrin	IRAC 3A	Control 1
permethrin	IRAC 3A	Control 1
tefluthrin	IRAC 3A	Excluded
malathion	IRAC 1B	Control 2
phosmet	IRAC 1B	Control 2

Notes: IRAC = Insecticide Resistance Action Committee mode-of-action classification. Control 1 = pyrethroids (same crop and target pest spectrum); Control 2 = organophosphates (broader spectrum alternative). Treatment restricted to the three IRAC 4A compounds under the prescription requirement as of September 8, 2018 (clothianidin, imidacloprid, thiamethoxam). Acetamiprid and thiacloprid are not subject to the prescription requirement. Tefluthrin is excluded from controls: as a seed-treatment pyrethroid, it is a direct substitute for neonicotinoid seed coatings and would contaminate the control group.

Table A.3: Sulfoximine/Butenolide Panel: Treated and Control Compounds

Compound	Pesticide Mode of Action Group	Role
sulfoxaflor	IRAC 4C	Treated
flupyradifurone	IRAC 4D	Treated
pymetrozine	IRAC 9	Control 1
flonicamid	IRAC 9	Control 1
lambda-cyhalothrin	IRAC 3A	Control 2
cypermethrin	IRAC 3A	Control 2

Notes: Control 1 = aphicides with distinct chemical scaffolds (selective insecticides targeting same pest guild); Control 2 = pyrethroids (broad-spectrum insecticides). Pirimicarb (IRAC 1A carbamate aphicide) is excluded: no recorded Québec sales over the panel window 2012–2022.

Table A.4: Diamide Panel: Treated and Control Compounds

Compound	Pesticide Mode of Action Group	Role
chlorantraniliprole	IRAC 28	Treated
cyantraniliprole	IRAC 28	Treated
tetraniliprole	IRAC 28	Treated
cyclaniliprole	IRAC 28	Treated
methoxyfenozide	IRAC 18	Control 1
tebufenozide	IRAC 18	Control 1
novaluron	IRAC 15	Control 2
deltamethrin	IRAC 3A	Control 3
cypermethrin	IRAC 3A	Control 3
lambda-cyhalothrin	IRAC 3A	Control 3

Notes: Control 1 = diacylhydrazines (IRAC 18, ecdysone agonists, same lepidopteran target as diamides); Control 2 = benzoylureas (IRAC 15, chitin synthesis inhibitors); Control 3 = pyrethroids (broad-spectrum insecticides, similar crop use).

B Output Appendix

B.1 Robustness: All Specifications

Table B.1 reports the companion synthetic-control permutation tests for all four classes.

Table B.1: Synthetic-Control Permutation Tests

	pre-2018 RMSPE	RMSPE ratio	p_{perm} (donors)
Atrazine	0.162	16.007	0.100 (1 of 10)
Neonicotinoids	0.744	0.510	1.000 (7 of 7)
Diamides	0.590	2.344	0.571 (4 of 7)
Sulfoximines/butenolides (detrended)	2.028	3.148	0.600 (3 of 5)

Notes: This Table shows the outputs from the synthetic control tests. Permutation p-values are based on the post/pre RMSPE ratio; pre-2018 RMSPE reports the pre-reform matching fit (smaller = tighter), and the count in parentheses is the number of units (treated + donors) whose ratio is at least the treated unit's. The sulfoximine synthetic control is estimated on detrended log sales.

B.2 Class-Level Aggregation

The compound-level panel in Table 1 treats each active ingredient as a separate observation. To summarise each class in a way that removes the within-class new-entry log artifact, we collapse each class to a single summed series and report the change in total class sales in levels. Table B.2 reports these total-sales changes: atrazine and neonicotinoids contract (-84.1% and -54.4%), while diamides and the sulfoximine/butenolide class expand ($+177\%$ and $+463\%$). The sulfoximine/butenolide compounds were only entering the Québec market at the start of the window, so its magnitude should be read with caution. The direction is nonetheless informative. We deliberately do not estimate a difference-in-

differences regression on the collapsed series: with a single treated unit, cluster-robust standard errors and the wild cluster bootstrap are not reliable, so such a regression cannot support credible inference.

Table B.2: Class-level total-sales changes (descriptive)

	Atrazine	Neonicotinoids	Diamides	Sulfoximines/butenolides
Total class sales (mean annual kg a.i.)				
Pre (2012–17)	135,558	7,750	2,511	190
Post (2018–22)	21,583	3,531	6,948	1,067
Change (%)	-84.1	-54.4	176.7	463.2

Notes: Each class is collapsed to a single series equal to the log of total annual sales summed over its compounds. "Total class sales" rows report mean annual volume (kg active ingredient) before (2012–2017) and after (2018–2022) the reform and the percentage change. Sales data are sourced from Ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs (MELCCFP). Because each class collapses to a single treated series, these volume changes are reported descriptively; we do not estimate a difference-in-differences regression on the aggregate, since one treated unit cannot support credible clustered inference. Inference is drawn from the compound-level panel and the synthetic control.

B.3 Control Group Falsification Tests

Table B.3 tests whether the control compounds themselves shifted post-2017, which would violate the exclusion restriction. For the atrazine panel, Control-1 herbicide controls (MCPA, 2,4-D, bromoxynil) are treated as pseudo-treated and Control-2 controls (bentazone, clethodim, sethoxydim, fenoxaprop) serve as the comparison. For the neonicotinoid and sulfoximine panels, pyrethroids are pseudo-treated against organophosphates. A null result in both rows indicates that within-control-group trajectories were parallel from 2018. The reform did not selectively displace one tier of controls relative to another, supporting the validity of the joint control pool.

Table B.3: Control Group Falsification Tests

Panel	Pseudo-treated vs. comparison	$\hat{\beta}$	(s.e.)
Atrazine	Control-1 controls vs. Control-2 controls	-1.056	(0.919)
Neonicotinoids/sulfoximines	Pyrethroids vs. organophosphates	0.309	(0.590)
Compound FE	✓		
Year FE	✓		

Notes: Each row treats one subset of the baseline control group as pseudo-treated and uses the remaining controls as the comparison group. Outcome: log annual sales (kg a.i.). Post $= \mathbf{1}_{\{t \geq 2018\}}$. A null result indicates the two control subgroups followed parallel trajectories from 2018, supporting their joint use as controls in the main DiD. *Atrazine*: Control-1 = MCPA, 2,4-D, bromoxynil; Control-2 = bentazone, clethodim, sethoxydim, fenoxaprop. *Neonicotinoids/sulfoximines*: pyrethroids (IRAC 3A) vs. organophosphates (IRAC 1B). Standard errors clustered by compound. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

B.4 Pyrethroid Falsification Test

Table B.4 and Figure B.1 present the pyrethroid falsification test. The test treats pyrethroids as a pseudo-treated group and uses organophosphates (malathion, phosmet) as the control group, estimating a TWFE DiD for the post-2017 period. If pyrethroids were themselves displaced from field applications as a result of the reform, thereby contaminating the diamide DiD, their sales should diverge from those of organophosphates after 2017.

Table B.4: Pyrethroid Falsification Test: Did Pyrethroid Sales Change Post-2018?

Pseudo-treated	Estimate	(s.e.)
Pyrethroids vs. organophosphates	0.309	(0.590)
Bootstrap p-value	0.531	
Compound FE	✓	
Year FE	✓	
N (compound × year)	138	

Notes: Pseudo-treated group is pyrethroids (IRAC 3A: lambda-cyhalothrin, cypermethrin, deltamethrin, permethrin). Control group is organophosphates (IRAC 1B: malathion, phosmet). Outcome: log annual sales (kg a.i.). A null result indicates pyrethroids followed the same post-2018 trajectory as organophosphates, supporting their use as controls in the diamide panel. Post $= \mathbf{1}\{t \geq 2018\}$. Standard errors clustered by compound. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

The estimate is $\hat{\beta} = 0.309$ (s.e. $= 0.590$, wild-bootstrap $p = 0.531$). The event-study coefficients in Figure B.1 are flat throughout both the pre- and post-reform periods: no pre-trend violation, and no post-2017 divergence. Pyrethroid sales tracked organophosphate trends before and after the reform. The contamination concern is theoretically coherent but empirically absent.

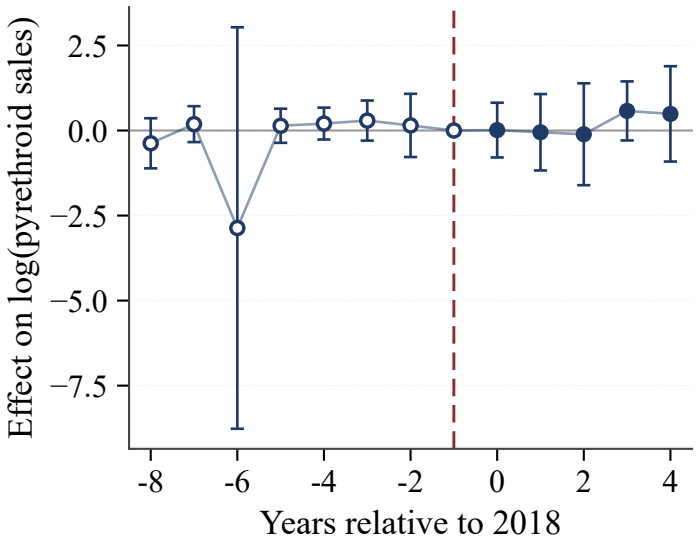


Figure B.1: Event-study: pyrethroids vs. organophosphates (falsification test), 2005–2022.

Notes: Pyrethroids are the pseudo-treated group; organophosphates (malathion, phosmet) are the control. Each coefficient is the deviation in pyrethroid log sales relative to the organophosphate trend in year t, normalized to the pre-reform mean. The vertical dashed line marks 2018. A null post-2017 path confirms pyrethroids are valid controls for diamides. Wild-cluster bootstrap p-values used throughout. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.