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Does Unconventional Energy Extraction Generate More Wastewater? A Lifetime Perspective

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ABSTRACT

Unconventional energy extraction has been accompanied by a faster increase in aggregate wastewater generation compared with conventional practice. Understanding the extent to which it is due to technologies, energy production, or geological characteristics has implications for reducing the associated environmental risks. We analyze how wastewater generation patterns differ between unconventional wells and conventional wells, accounting for differences in well configurations and local geology. Using the 2008–2016 monthly production data from 50,039 wells, we show that unconventional wells generated more wastewater in the first 12 months of production but less cumulative discharge than conventional wells. Unconventional oil wells had a lower wastewater-to-energy ratio throughout their lifetime than their conventional counterparts, whereas no efficiency gap existed among gas wells. We find both an increasing initial discharge gap and growing efficiency gains between unconventional wells and conventional wells starting production in more recent years, likely due to increased penetration and persistent improvements of unconventional technologies over time. Our findings call for targeted strategies to balance the short-term disposal burden and the long-term efficiency gains of unconventional energy extraction.

1. Introduction

Wastewater discharge in oil and gas production has increased significantly in recent years with the rapid growth in unconventional energy extraction using hydraulic fracturing combined with horizontal drilling. The annual total wastewater released by horizontal wells in shale regions ("unconventional oil and gas (UOG) wells" hereafter) increased by 14.5 times from 2003 to 2016 in 17 drilling states of the U.S.,[1] whereas the amount of wastewater discharged by vertical wells ("conventional oil and gas (COG) wells" hereafter) remained relatively unchanged over this period (Panel A of Fig. 1). Although UOG and COG wastewater contain similar chemicals in many regions (Haluszczak et al., 2013), the former has triggered more public concerns because of its rapidly growing volume. The surge in UOG wastewater generation has led to increased storage violations and accidents due to high short-term pressure on existing infrastructure (Kuwayama et al., 2017). Many energy-producing states have reported a growing number of spills due to leaks, overflows, and insufficient capacity of pits and tanks since the shale energy boom,[2] potentially causing significant human health costs and ecological impacts (Vengosh et al., 2014; Currie et al., 2017; Loomis and Haefele, 2017). Moreover, large volumes of UOG wastewater needs to be trucked away to be injected into disposal wells rather than injected underground onsite like COG wells (Veil, 2015; Scanlon et al., 2017), which has caused additional traffic fatality and injury costs (Xu and Xu, 2020; Muehlenbachs et al., 2021) and injection-induced seismic risks (Ellsworth, 2013; Weingarten et al., 2015).

To seek more effective ways to manage the growing environmental risks associated with UOG wastewater discharge, it is critical to determine the extent to which it is caused by extraction technologies, increased energy production, geological characteristics, or regulatory

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[1] The 17 states include Alabama, Arkansas, California, Colorado, Florida, Michigan, Mississippi, Montana, Nebraska, Nevada, New Mexico, New York, North Dakota, South Dakota, Texas, Utah, and Wyoming, which provide wastewater generation information in the Enverus data.

[2] From 2005 to 2014, a total of 6648 spills were reported in Colorado, New Mexico, Pennsylvania, and North Dakota, most of which were related to storage and transportation (Patterson et al., 2017). Evidence from multiple shale regions shows a significant association between new hydraulic fracturing wells and elevated salt concentrations in watersheds, which was most likely to result from undetected on-site leaks and spills (Bonetti et al., 2021).

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differences across regions. Data from our 17-state sample of wells show that UOG wells have been growing in terms of both the well count (Panel B of Fig. 1) and the average per-well generation since 2010 (Panel C of Fig. 1). By 2014, UOG wells have exceeded COG wells in the average per-well wastewater generation. However, comparing the average discharge of the two types of wells does not account for differences in their production ages. While wastewater generation by a UOG well is concentrated in the early stage of production and declines with a well's production age, wastewater discharge from a COG well tends to be modest initially and may increase as wells age (Bai et al., 2013; Nicot et al., 2014; Veil, 2015). Thus, a mean comparison would be confounded by a higher share of new wells among UOG wells that are at their lifetime peak of wastewater release (Panel D, Fig. 1). Moreover, Kondash et al. (2018) found that the average first-year wastewater generation of a UOG well grew by up to 550% from 2011 to 2016 in major shale plays. These findings suggest that discharge volume may vary across the groups of wells starting production in different years, i.e., cohorts, due to improvements in drilling and supporting technologies over time. Meanwhile, persistent technological innovations boost a well's energy productivity while reducing its water footprint, which may also improve the production efficiency of UOG wells in more recent cohorts. We thus need an age- and cohort-specific comparison between UOG wells and COG wells to identify the associated benefits and challenges to wastewater management of the industry.

This study compares wastewater generation patterns of UOG wells and those of COG wells throughout their lifetime by production cohorts using a difference-in-difference-in-differences model. We control for well-level heterogeneities in well configurations and local geology using the 2008–2016 monthly production data from 50,039 wells in 17 drilling states. The sample spanning nine years of production allows us to examine both the monthly and cumulative wastewater generation of a well. Moreover, by comparing the two types of wells across cohorts, we investigate how technological improvements over time have led to changing patterns in discharge volume and efficiency. Our econometric method improves upon the bootstrapped mean comparison approach (e.g., Kondash et al., 2017; Kondash et al., 2018) that compares wastewater generation across multiple shale regions regardless of substantial differences in geological conditions and regulatory standards.

Our study shows that starting from the 2010 cohort UOG wells generated more wastewater than COG wells in each of the first 12 months of production. Their monthly gap in the initial production stage became larger among wells in more recent cohorts, implying that UOG wells became increasingly more front-loaded in wastewater generation over time. However, the gap always decreased with a well's age and tended to reverse eventually in every cohort. Our findings are consistent with Kondash et al. (2017) who found that 20–50% of the first ten years' wastewater of UOG wells was generated in the initial six months. Moreover, our analyses provide additional insights by examining wastewater generation over the lifetime of a well, which shows that by the end of their lifetime UOG wells had lower monthly discharge than COG wells.

We then examine the cumulative wastewater generation by each month of a well's lifetime. In the pre-2010 cohorts, we find that UOG wells had less cumulative discharge than COG wells throughout the entire lifetime. In the post-2010 cohorts, UOG wells exceeded COG wells in cumulative discharge in the initial production stage, which is consistent with the upfront-loaded pattern in monthly discharge. The gap in cumulative discharge between the two types of wells declined with their production age until the cumulative discharge by UOG wells fell below that by COG wells. The "breakeven" time at which their

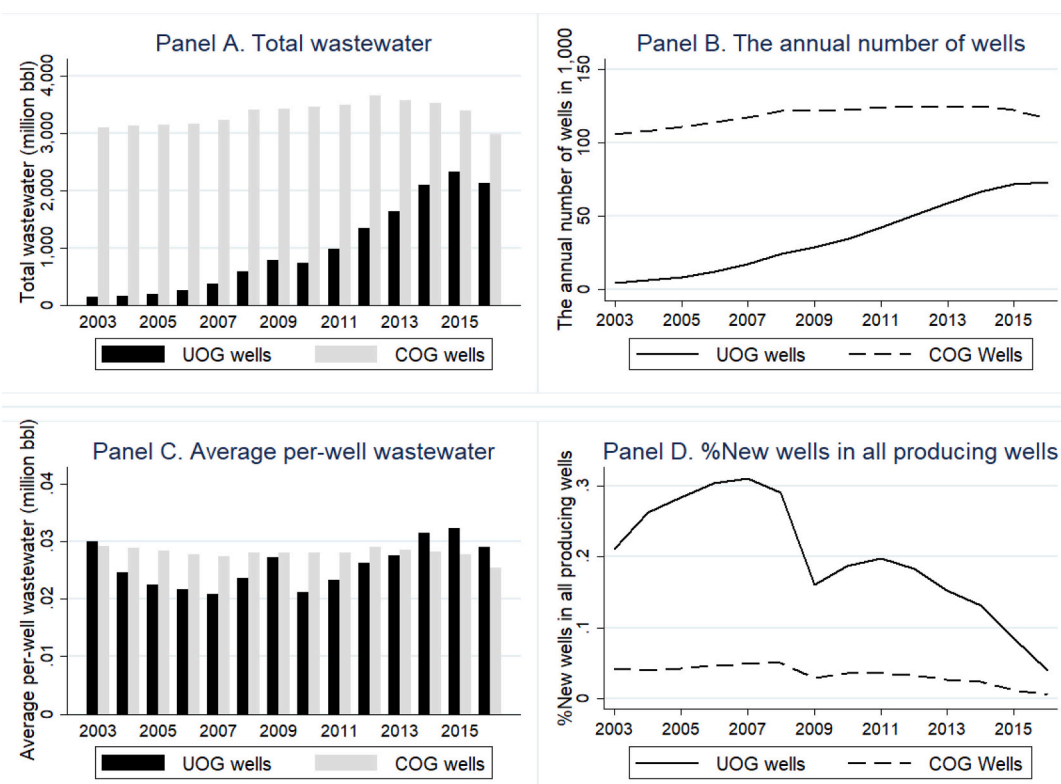

Fig. 1. Wastewater generation by UOG wells and COG wells.
Notes: The figure is based on oil and gas wells in 17 drilling states, including Alabama, Arkansas, California, Colorado, Florida, Michigan, Mississippi, Montana, Nebraska, Nevada, New Mexico, New York, North Dakota, South Dakota, Texas, Utah, and Wyoming, which provide wastewater generation information in the Enverus data. UOG wells are defined as horizontal wells in shale regions, whereas COG wells are defined as vertical wells regardless of the resource type. Panels A-C plot the annual total wastewater generation, the annual number of wells, and the annual average per-well wastewater generation by UOG wells and COG wells, respectively. Panel D plots the share of wells newly starting production in a year among all producing wells for each type of wells, which is in the range of 0 to 1.
Source: Summarized by authors using the Enverus data at https://www.enverus.com/

cumulative discharge was equal occurred in the 7th month of production in the 2010 cohort. The point was delayed to the 15th month in the 2011 cohort and has not yet been achieved during the observable lifespan of wells in more recent cohorts. Our study extends the timespan of Lutz et al. (2013), which found that in the initial four years of production the cumulative wastewater generated by a UOG well was almost three times that of a COG well. Our findings show that, compared with conventional methods, the state-of-the-art unconventional extraction technologies have lower cumulative discharge in the long run despite higher initial discharge.

We further show that unconventional *oil* wells had a lower wastewater-to-energy ratio over the entire lifetime compared with conventional *oil* wells, whereas such energy efficiency gains did not exist for unconventional *gas* wells in any cohort. Moreover, this persistent gap in the wastewater-to-energy ratio increased across cohorts, from 0.19 barrels per million British thermal units (bbl/mmBtu) for wells in the 2011 cohort to 0.26 bbl/mmBtu for wells in the 2015 cohort. Lutz et al. (2013) found that unconventional wells in the Marcellus Shale, where gas is the dominant type of energy produced, discharged 35% less wastewater per unit of natural gas than their conventional counterparts despite a larger discharge volume in the initial production year. We extend their study by characterizing general wastewater discharge patterns using a representative sample of 17 states while controlling for regional differences. Our cohort-specific analyses show that the efficiency advantage of unconventional oil wells relative to conventional oil wells increased in younger cohorts, which could be attributable to the increased penetration of unconventional extraction technologies and persistent technological improvements over time.

2. Conceptual Framework

Hydraulic fracturing is a stimulation technology to enhance the productivity of oil and gas wells. Before the advent of horizontal drilling, hydraulic fracturing was mainly applied to conventional geological formations and mature reservoirs of low productivity (Wang and Krupnick, 2015). Horizontal drilling expands the range of hydraulic fracturing sideways by drilling a well along a horizontal path after reaching a target depth vertically, which greatly increases the area of reservoirs where hydrocarbons can be extracted. The innovative combination of the two technologies makes it technically and economically feasible to extract oil and gas trapped in shale regions that feature extremely low permeability and limited natural transmissivity (Fitzgerald, 2014).

Due to the lack of data on the extraction technology used and the reservoir geology targeted by a national sample of wells, we exploit a well's drill direction information (horizontal or vertical) provided by the Enverus data and the geographic location information (shale or non-shale) from the U.S. Geological Survey (USGS) to infer the adoption of hydraulic fracturing (Feyrer et al., 2017). Assuming that hydraulic fracturing is most likely to be applied with horizontal drilling to extract shale resources, we define UOG wells as horizontal or directional wells producing oil and gas in shale regions and COG wells as vertical wells in both shale and non-shale regions.[3] It is worth noting that, although modern vertical wells may also be fracked, unconventional vertical wells were drilled mostly during the early exploratory phase of shale energy development. In the Permian basin, for example, the number of unconventional vertical wells peaked in 2012 and has declined by 70% since then (Scanlon et al., 2017).

The unconventional drilling and stimulation technologies changes the distribution of discharge volume during the lifetime of a well. In conventional formations, oil and gas wells go through drilling, well completion, and production. Oil and gas are pumped to flow out without a stimulation process (Triepke, 2014). Because COG extraction only has modest water needs for drilling and production with occasional water demand to enhance the productivity of mature wells (Veil, 2015), COG wells release a moderate amount of wastewater in the initial stage of production with increasing wastewater discharge over time. UOG extraction differs from conventional practice in that hydraulic fracturing is necessary to release the trapped oil and gas before production begins. Hydraulic fracturing, as a stimulation process in well completion, occurs within a few days near the end of this phase, during which up to 16 million gallons of water is injected into a well (U.S. Geological Survey, 2022). The upfront water use requirement for hydraulic fracturing leads to an extremely high rate of initial flowback with up to 70% of injected fluids discharging back out of the well shortly after the process (U.S. Environmental Protection Agency, 2015). After the first few weeks, the volume of wastewater returning to the surface diminishes to a considerably low level as energy production continues over the rest of the lifetime (Veil, 2015). Given different wastewater release curves, we expect UOG wells to have higher monthly discharge than COG wells during the initial phase of the lifetime. In addition, whether the former can exceed the latter in cumulative wastewater generation depends on how fast their respective monthly discharge declines with the production age.

We further explore how technological improvements over time have influenced wells' wastewater generation patterns across different production cohorts. In the past few decades, the oil and gas industry has experienced persistent advancements in drilling, completion, and other supporting technologies. For example, the length of laterals, i.e., the horizontal portion of a well, has been extended continuously over time, which allows for more energy to be extracted per well (Nicot and Scanlon, 2012; Nicot et al., 2014; Edelstein, 2019). Besides the per-well productivity improvement, another important objective of technological innovations is to minimize water use and limit wastewater generation. These technological achievements may enhance the production efficiency for wells in younger cohorts, as measured by a lower amount of wastewater per unit of energy produced. We thus expect that, while UOG wastewater generation increases as a byproduct of growing energy production over time, the wastewater-to-energy ratio of UOG wells might decrease if the improved energy production efficiency compensated for the growing wastewater volume in more recent cohorts

3. Empirical Method

3.1. Data and Descriptive

We conduct the analysis using proprietary well-level data through an academic use agreement with the Enverus company. Across 31 oil and gas producing states in the U.S., 17 states provide wastewater generation information either from disclosures by operators or from calculations by the Enverus company. The wastewater discharge data do not distinguish flowback, i.e., injected water that returns to the surface immediately following hydraulic fracturing, from produced water, i.e., water trapped in underground formations and brought to the surface along with oil and gas (Veil, 2015). Our analyses thus may capture the former in the early stage of a well's lifetime and the latter as oil and gas production continues over the rest of the lifetime. We refer to both types of water as wastewater.

We first retain onshore wells of the 17 states with available wastewater discharge information. Because some operators reported zero wastewater generation for certain states and years, we drop these operator-state-year observations to avoid systematic data reporting

[3] We categorize both horizontal and directional wells as UOG wells by treating the former as a particular type of the latter. To address the concern that some directional wells used conventional extraction technologies, we exclude directional wells from UOG wells as a robustness check. We obtain findings consistent with the baseline estimates. The results are available upon request.

errors.[4] Next, we exploit the production type information to keep wells producing oil, gas, or both while dropping wells of other types, e.g., wells producing coal-bed methane and wells applying the enhanced oil recovery technology to depleted conventional reservoirs. We then keep wells with a drill direction of horizontal, directional, or vertical by dropping wells of an unknown drill type.[5]

We focus on wells of eight cohorts that started oil and gas production over the shale energy boom period of 2008–2015. We calculate a well's production age from the first month when its energy production and wastewater discharge can be observed for a full month. For wells of the cohort year t, we track their monthly wastewater discharge and energy production up to 12 * (2016 − t) months so that all wells of the cohort can be observed over the same number of months. Otherwise, wells going into production at the beginning of a year would be observed over a longer lifespan compared with those starting production near the end of the year. We exclude wells that did not report any wastewater discharge during their lifetime to avoid systematic data reporting errors. We also drop wells switching between active energy production and shutdown. We thus obtain a sample of wells with continuous energy production over their lifetime.

To calculate the monthly energy production of a well, we convert oil and gas production to their energy equivalents in mmBtu.[6] We then normalize energy production in mmBtu and wastewater generation in bbl by the number of days in each month to account for the calendar month effects on production. We exclude wells whose wastewater discharge or wastewater-to-energy ratio was once greater than the 99th percentile or whose energy production was once less than the 1st percentile among wells of the same technology type, production age, and cohort, as our results are sensitive to the inclusion of these outlier wells with substantial wastewater discharge or negligible energy production.

The baseline sample contains the monthly wastewater generation and energy production information of 50,039 wells from 2008 to 2016. Table 1 reports the summary statistics by UOG wells and COG wells. Compared with a COG well, a UOG well generated more wastewater and energy with a lower wastewater-to-water ratio. On average, UOG wells were younger than COG wells (30 months versus 35 months). All UOG wells were in shale regions by definition, whereas 54% of COG wells were in shale areas. Gas wells accounted for 64.1% among UOG wells, whereas their share was 39.7% of COG wells. The share of wells of different cohorts was more evenly distributed among UOG wells, whereas wells in more recent cohorts accounted for a smaller share among COG wells, indicating a declining number of new COG wells drilled in recent years.

Table 1
Summary statistics.

	UOG wells		COG wells	
	Mean	Std. Dev.	Mean	Std. Dev.
Log (1 + wastewater) (bbl)	6.206	1.980	5.858	2.260
log (energy) (mmBtu)	9.442	1.111	8.199	1.231
Wastewater-to-energy ratio (bbl/mmBtu)	0.122	0.291	0.417	0.960
Age	29.835	22.143	34.668	24.024
Shale region	1.000	0.000	0.540	0.498
Gas well	0.641	0.480	0.397	0.489
Oil well	0.359	0.480	0.603	0.489
2008 Cohort	0.155	0.362	0.276	0.447
2009 Cohort	0.108	0.311	0.155	0.362
2010 Cohort	0.141	0.348	0.164	0.371
2011 Cohort	0.152	0.359	0.146	0.354
2012 Cohort	0.164	0.370	0.120	0.325
2013 Cohort	0.138	0.344	0.074	0.262
2014 Cohort	0.103	0.304	0.050	0.218
2015 Cohort	0.039	0.193	0.014	0.119
Observations		1,489,324		887,682

Notes: The table describes the summary statistics of the baseline sample, which contains the 2008–2016 monthly production data from 50,039 oil and gas wells. *Log(1 + wastewater)* is the log form of the monthly wastewater generation in bbl. *Log(energy)* is the log form of the monthly energy production, which is constructed as the total energy equivalents of oil and gas production in mmBtu. *Wastewater-to-energy ratio* is the ratio between the monthly wastewater generation and energy equivalents in bbl/mmBtu. *Age* is the number of months since a well started producing energy. *Shale region* is a dummy indicating a well's geographic overlap with shale regions. Gas (*Oil*) *well* is a dummy indicating that the dominant hydrocarbon type produced by the well is gas (oil). *2008–2015 Cohort* are dummies indicating the groups of wells starting production in 2008–2015, respectively.

3.2. Difference-in-Difference-in-Differences Model

We estimate the following difference-in-difference-in-differences model to examine how wastewater generation of UOG wells varies with the production age and cohort relative to that of COG wells controlling for differences in well configurations and local geology. We examine three dependent variables, including the monthly and the cumulative wastewater generation and the monthly wastewater-to-energy ratio.

$$\begin{aligned} y_{it} = {} & \beta_0 + \mu uog_i + \sum_{j=2}^{J_k} \gamma_j A_{ij} + \sum_{k=2009}^{2015} \rho_k C_{ik} \\ & + \sum_{k=2009}^{2015} \sum_{j=2}^{J_k} \tau_{jk} A_{ij} {}^* C_{ik} + \sum_{j=2}^{J_k} \pi_j uog_i {}^* A_{ij} \\ & + \sum_{k=2009}^{2015} \vartheta_k uog_i {}^* C_{ik} + \sum_{k=2009}^{2015} \sum_{j=2}^{J_k} \sigma_{jk} uog_i {}^* A_{ij} {}^* C_{ik} \\ & + \beta_1 shale_i + \beta_2 gas_i + \beta_3 log(energy_{it}) + reservoir_i + county_i + state_i {}^* year_t + state_i {}^* operator_i + \varepsilon_{it} \end{aligned} \tag{1}$$

where i indexes well and t indexes month-year. The dependent variable y_{it} represents one of the three variables: the log form of the monthly wastewater discharge, the log form of the cumulative wastewater

[4] See Table A1 in Appendix for a detailed record of sample restriction.

[5] In particular, we drop horizontal and directional wells starting production before 1990 when large-scale commercial horizontal drilling was unsuccessful (King and Morehouse, 1993). We also exclude horizontal and directional wells in non-shale regions due to the substantial uncertainty of the target reservoir and the technology choice in these areas.

[6] We source the annual data of the crude oil production heat content and the natural gas production dry heat content from the U.S. Energy Information Administration at https://www.eia.gov/totalenergy/data/monthly/index.php#appendices

Table 2
Baseline results.

	(1)	(2)	(3)
	Monthly wastewater	Cumulative wastewater	Wastewater-to-energy ratio
Shale region	-0.064	-0.063	-0.148***
	(0.060)	(0.063)	(0.030)
Gas well	-0.368***	-0.427***	-0.030*
	(0.050)	(0.062)	(0.016)
Log(energy)	0.699***	0.605***	
	(0.006)	(0.009)	
UOG dummy (μ)	Yes	Yes	Yes
Age dummy (γ_j)	Yes	Yes	Yes
Cohort dummy (ρ_k)	Yes	Yes	Yes
Age*Cohort (τ_{jk})	Yes	Yes	Yes
UOG*Age (π_j)	Yes	Yes	Yes
UOG*Cohort (υ_k)	Yes	Yes	Yes
UOG*Age*Cohort (σ_{jk})	Yes	Yes	Yes
Reservoir FE	Yes	Yes	Yes
County FE	Yes	Yes	Yes
State by year FE	Yes	Yes	Yes
State by operator FE	Yes	Yes	Yes
Observations	2,376,972	2,376,972	2,376,972
R-squared	0.633	0.683	0.434

Notes: The table reports the baseline estimation results based on Eq. (1). The dependent variables are listed as the column title. *Shale region* is a dummy indicating a well's geographic overlap with shale regions. *Gas well* is a dummy indicating that the dominant hydrocarbon type produced by the well is gas. *Log(energy)* in Column 1 (2) is the log form of the monthly (cumulative) energy production, which is constructed as the total energy equivalents of oil and gas production in mmBtu. Figs. 2–4 plot the estimates of $\mu + \pi_j$ as differences between UOG wells and COG wells at age j for wells in the 2008 cohort and the estimates of $\mu + \pi_j + \vartheta_k + \sigma_{jk}$ as differences between the two types of wells at age j in cohort k for wells in the 2009–2015 cohorts. Standard errors clustered at the well level are reported in parentheses *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

discharge,[7] and the amount of wastewater per unit of energy produced every month. The dummy variable uog_i indicates whether a well is a UOG well, i.e., a horizontally drilled well in shale regions. The variable A_{ij} is an age dummy indicating whether well i had an age of j months, whereas C_{ik} is a cohort dummy indicating whether well i started production in year k. The reference group is COG wells in the 2008 cohort with an age of 1 month. For wells in the 2008 cohort, $\mu + \pi_j$ represent differences between UOG wells and COG wells at age j. For wells in the 2009–2015 cohorts, $\mu + \pi_j + \vartheta_k + \sigma_{jk}$ represent differences between the two types of wells at age j in cohort k.

We control for a series of well configurations, geological features, and regulatory differences. First, our model includes a dummy indicating a well's resource type, $shale_i$, which is defined by a well's geographic overlap with shale regions, and a dummy indicating the dominant hydrocarbon type produced by a well, gas_i. Next, we control for a well's monthly (cumulative) energy production, $\log(energy_{it})$ when examining the monthly (cumulative) wastewater release. Moreover, we exploit a series of fixed effects to account for unobservable regional heterogeneities. We first control for the reservoir fixed effects, $reservoir_i$, to capture confounders such as the accessibility of formations and the primary recovery mechanisms of reservoirs in local areas (Satter and Iqbal, 2016). We then control for the county fixed effects, $county_i$, to allow for county-level time-invariant differences such as energy extraction history. We also include the state-by-year fixed effects, $state_i * year_t$, to control for the state-specific time trends in oil price and state laws and legislations. We further include the state-by-operator fixed effects, $state_i * operator_i$, to account for the state- and operator-specific business model that could lead to differences in the grade of oil and gas produced. We cluster standard errors at the well level.

4. Empirical Results

4.1. Baseline Results

4.1.1. Monthly Wastewater Generation

Based on the estimation results of Eq. (1), Fig. 2 plots the age-specific differences in the log form of the monthly wastewater generation between UOG wells and COG wells over their lifetime by cohort. The coefficients are interpreted as differences in percentage terms.[8] Two patterns emerge from the figure. First, within each cohort, the monthly gap between the two types of wells always decreased with a well's production age. Among wells starting production before 2010, UOG wells discharged a statistically similar or lower monthly amount of wastewater than COG wells over their lifetime. In the 2010 cohort, UOG wells exceeded COG wells in monthly wastewater release most of the time in the first 12 months, after which the two types of wells discharged a similar monthly volume. The former began to fall below the latter (p-value$<$0.05) starting from the 26th month, showing an age-decreasing trend in the monthly discharge gap. Starting from the 2011 cohort, UOG wells released more monthly wastewater than COG wells over a more extended initial period of the lifetime, while their gap always decreased over the production age and tended to close by the end of the observable lifespan. The pattern indicates that UOG wells discharged more than COG wells in the early stage of the production life whereas the former eventually released less than the latter as they both aged.

Second, across cohorts, UOG wells released an increasingly higher amount of wastewater than COG wells in the initial production stage. The pattern was particularly pronounced in the post-2011 cohorts. For instance, UOG wells generated 11.3% (p-value$<$0.05) more wastewater than COG wells in the first production month in the 2011 cohort, whereas the first-month discharge gap increased to 64.9% (p-value$<$0.01) in the 2015 cohort. Moreover, the early-stage monthly gap tended to close sooner for wells in younger cohorts, which occurred in the 38th month, the 37th month, and the 27th month for the 2011–2013 cohorts, respectively. The trajectories imply that the monthly gap would

[7] Because of the existence of wells with zero wastewater generation (about 3.6% of the sample), we take the log transformation of discharge volume as log (1 + wastewater). We obtain similar estimates when taking the Inverse Hyperbolic Sine transformation alternatively.

[8] We report the coefficients of the key control variables in Table 2.

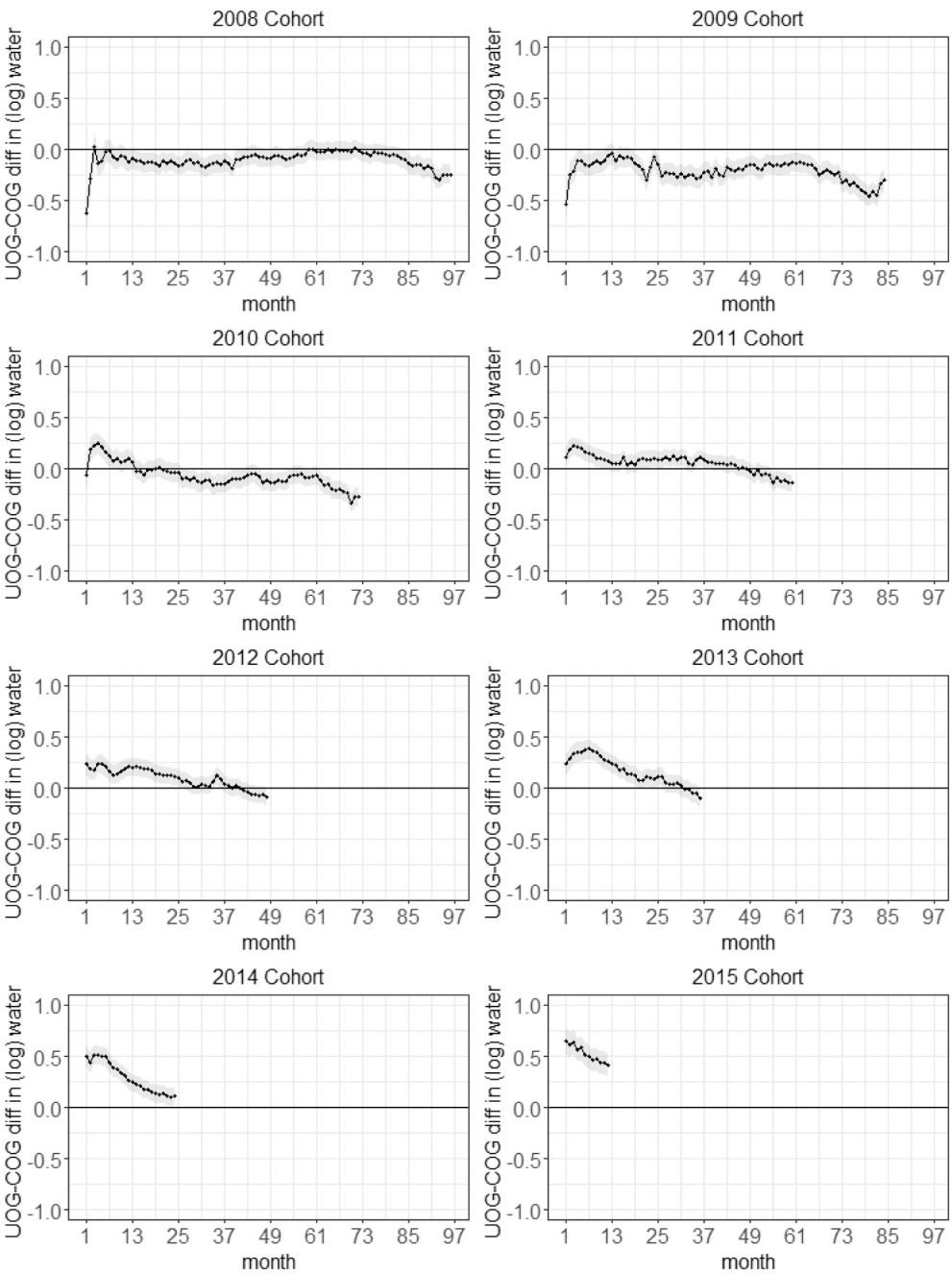

Fig. 2. Baseline sample: differences in the monthly wastewater generation.
Notes: The figure plots the baseline-sample estimates and the 95% confidence intervals for the cohort- and age-varying differences in the log form of the monthly wastewater generation (bbl) between UOG wells and COG wells. The model controls for a well's resource type, dominant hydrocarbon type, and monthly energy production in the log form, the reservoir fixed effects, the county fixed effects, the state-by-year fixed effects, and the state-by-operator fixed effects. The coefficients are interpreted as differences in percentage terms.

close even faster for the most recent two cohorts, although we cannot observe the closure given the limited lifespan in our sample. The findings indicate that UOG wastewater generation became increasingly front-loaded over time. One reason may lie in the increased penetration of hydraulic fracturing technologies among UOG wells drilled in recent years. Meanwhile, improvements in drilling technologies such as the extended length of laterals significantly boosted the well-level energy productivity (Nicot and Scanlon, 2012; Nicot et al., 2014; Edelstein, 2019), which might also contribute to the ever-growing early-stage discharge of UOG wells in younger cohorts.

4.1.2. Cumulative Wastewater Generation

While UOG wells exceeded COG wells in the monthly wastewater volume in the initial stage of the lifetime, it remains unclear whether the former surpassed the latter in the cumulative wastewater generation given the fast closure of their monthly discharge gap. We answer this question by plotting the cohort- and the age-specific differences in the log form of the cumulative wastewater release between UOG wells and COG wells in Fig. 3. The coefficients are interpreted as differences in percentage terms. The figure shows different patterns before and after the 2010 cohort. In the pre-2010 cohorts, the cumulative wastewater released by UOG wells was significantly lower than that by COG wells throughout the observable lifespan. Specifically, in the 2008 and 2009 cohorts, UOG wells discharged 21.2% (p-value<0.01) and 28.2% (p-value<0.01) less cumulative wastewater than COG wells by the end of the observable lifespan, respectively.

By contrast, UOG wells of the post-2010 cohorts started to release less cumulative wastewater than COG wells after the early stage of production. In the 2010 cohort, UOG wells had discharged 8.4% (p-value<0.1) more cumulative wastewater than COG wells by the 6th month. The two types of wells then released a statistically similar amount of cumulative wastewater until the 23rd month when the

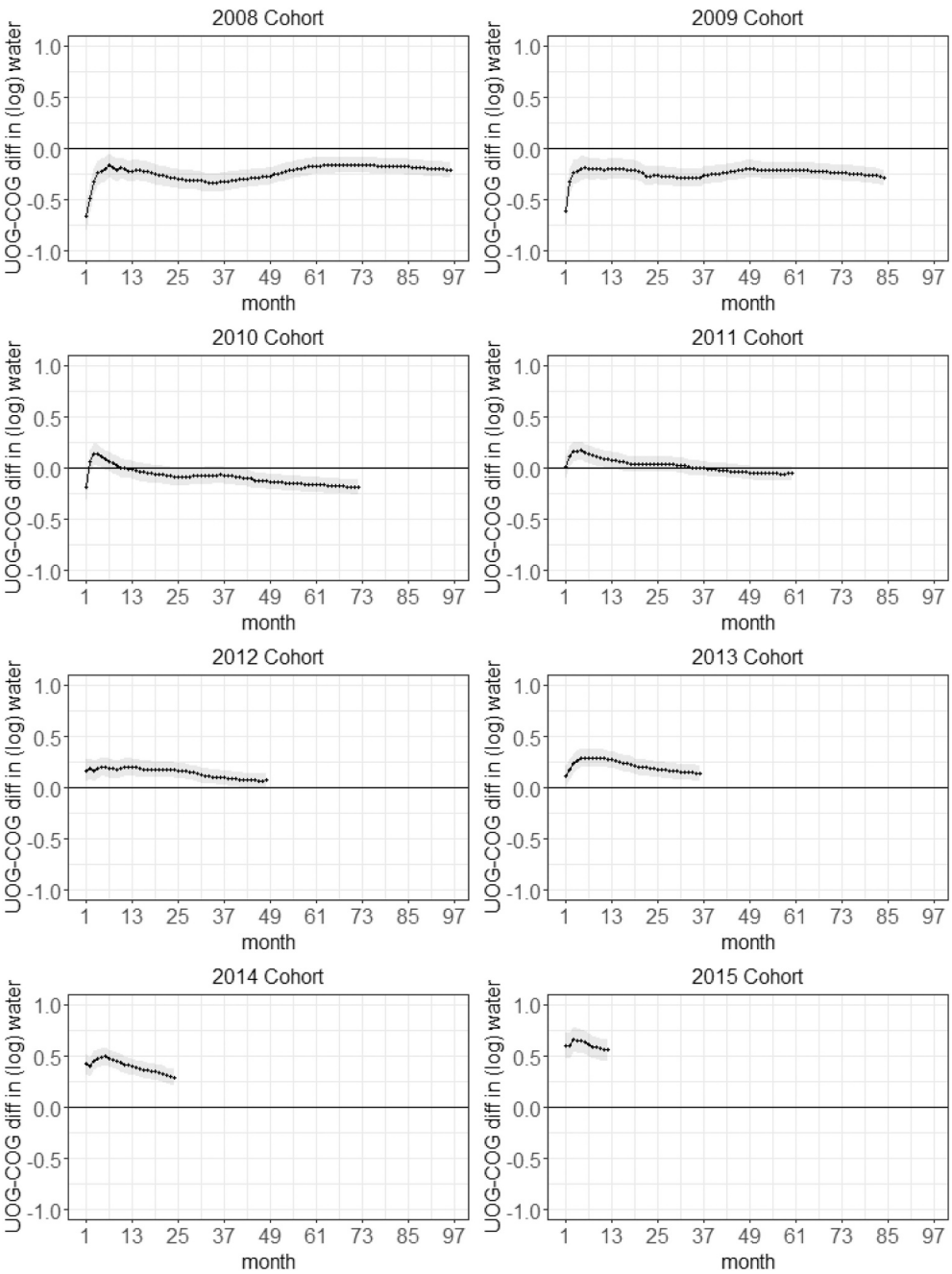

Fig. 3. Baseline sample: differences in the cumulative wastewater generation.
Notes: The figure plots the baseline-sample estimates and the 95% confidence intervals for the cohort- and age-varying difference in the log form of the cumulative wastewater generation (bbl) between UOG wells and COG wells. The model controls for a well's resource type, dominant hydrocarbon type, and cumulative energy production in the log form, the reservoir fixed effects, the county fixed effects, the state-by-year fixed effects, and the state-by-operator fixed effects. The coefficients are interpreted as differences in percentage terms.

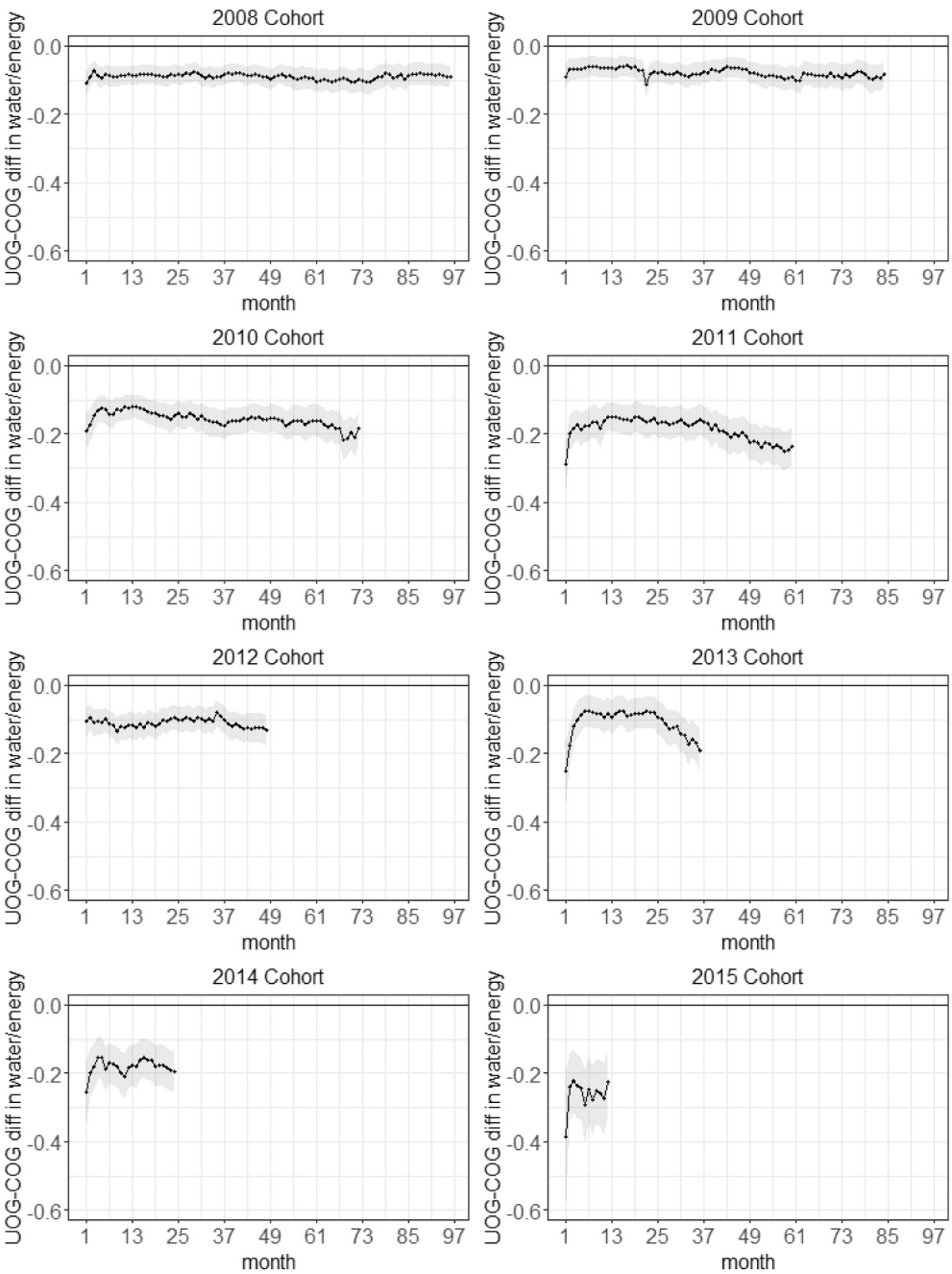

Fig. 4. Baseline sample: differences in the wastewater-to-energy ratio.
Notes: The figure plots the baseline-sample estimates and the 95% confidence intervals for the cohort- and age-varying difference in the wastewater-to-energy ratio (bbl/mmBtu) between UOG wells and COG wells. The model controls for a well's resource type and dominant hydrocarbon type, the reservoir fixed effects, the county fixed effects, the state-by-year fixed effects, and the state-by-operator fixed effects.

cumulative discharge of UOG wells was 7.5% (p-value<0.1) less than that of COG wells. By the end of the observable lifespan, i.e., the 72nd month, UOG wells discharged 18.8% (p-value<0.01) less than COG wells, or 23,692 bbl equivalently. The findings indicate that, despite higher cumulative wastewater generation in the initial stage of production, the lifetime total discharge by UOG wells was lower than that by COG wells.

The breakeven point at which UOG cumulative discharge equals that of COG wells was gradually delayed in more recent cohorts. For instance, the cumulative wastewater discharge of the two types of wells equaled each other in the 15th month of production in the 2011 cohort, which was 9 months later compared with the point achieved in the 2010 cohort. In the post-2011 cohorts, we do not observe the gap closure within the observable timeframe despite age-decreasing differences between the two types of wells. This pattern is consistent with our findings that UOG wells in younger cohorts released increasingly more wastewater in the initial stage of the lifetime.

4.1.3. Wastewater-to-Energy Ratio

While UOG wells discharged more than COG wells in the initial stage of the lifetime, the former also featured higher energy production than the latter. The additional UOG wastewater release might be compensated by improved energy production efficiency, i.e., a lower amount of wastewater per unit of energy produced. Fig. 4 plots the cohort- and age-varying differences in the wastewater-to-energy ratio between UOG wells and COG wells. Within each cohort, UOG wells were more efficient than COG wells with a constant energy efficiency gap throughout their lifetime. Across cohorts, UOG wells became more efficient than COG wells with increased efficiency gains in younger cohorts. In the 2008 cohort, the wastewater-to-energy ratio of UOG wells was about 0.09 bbl/mmBtu lower than that of COG wells throughout their lifetime. By comparison, the relative efficiency gains of UOG wells increased to 0.19 bbl/mmBtu in the 2011 cohort and 0.26 bbl/mmBtu in the 2015 cohort. Our findings indicate that within a cohort wastewater volume varied proportionally with energy production over a well's production age whereas across cohorts UOG energy production increased faster than wastewater byproduct.

4.2. Robustness Checks

4.2.1. Cohort Effects Versus Shale Effects

In our sample, the share of wells in shale regions decreased over cohorts among COG wells. As we identify cohort-increasing differences in discharge volume and efficiency between UOG wells and COG wells, the cohort effect might be confounded by geological differences between shale and non-shale regions given that all UOG wells were in shale regions. To rule out this possibility, we re-run the baseline model using a shale-region sample by excluding COG wells in non-shale regions. The subsample estimates show the same qualitative patterns as our baseline findings (Figs. A1–A3), indicating that the baseline estimates were unlikely to be confounded by the cohort-varying share of wells in shale regions among COG wells.

4.2.2. Gas Wells Versus Oil Wells

Gas wells and oil wells differ in the dominant hydrocarbon type produced and well configurations such as depth and surface pressures (Kaiser, 2019; U.S. Energy Information Administration (US EIA), 2022). The two types of wells thus have different technical requirements that may lead to distinct wastewater generation patterns. Additionally, the share of gas wells in both UOG wells and COG wells decreased over cohorts due to declining natural gas prices during the sample period. The cohort-increasing differences between the two types of wells may reflect the unique production patterns of oil wells. In this subsection, we split the sample by oil wells and gas wells to re-run the baseline analyses respectively.

We find that, regardless of the hydrocarbon type, the subsample estimation results align with the baseline patterns regarding wastewater volume (Figs. A4–A7), especially for gas wells. Among gas wells of the pre-2010 cohorts, UG wells generated a similar or lower amount of wastewater every month during the lifetime than CG wells (Fig. A4). Since the 2010 cohort, UG wells have exceeded CG wells in the monthly wastewater generation in the initial stage of the lifetime. Their first-month discharge gap was up to 97.4% (p-value<0.01) in the 2015 cohort. By comparison, among oil wells (Fig. A5), UO wells generated similar or less wastewater than CO wells throughout the entire lifetime in the pre-2012 cohorts. It was not until the 2012 cohort that UO wells started to surpass CO wells in the early-stage wastewater generation. In the 2015 cohort, UO wells discharged 46% (p-value<0.01) more than CO wells in the first production month. Consistently, UG wells released an additionally higher cumulative discharge than CG wells in the early production stage relative to the gap between UO wells and CO wells (Figs. A6–A7). In the 2012 cohort, UG wells discharged 55.2% more than CG wells whereas UO wells exceeded CO wells by 11.6% in the first-twelve-month cumulative discharge (p-value<0.01). In the 2015 cohort, the contrast became 77.5% versus 40.2%. The larger differences in cumulative discharge between UG wells and CG wells than those among oil wells reflect the fact that the U.S. shale gas production preceded large-scale shale oil development (US EIA, 2021).

Moreover, UO wells became increasingly more efficient than CO wells across cohorts, whereas no such pattern existed among gas wells. Among gas wells (Fig. A8), UG wells were slightly more efficient than CG wells during a certain stage of the lifetime in the 2009 and 2010 cohorts. In the post-2010 cohorts, however, UG wells became statistically similar to CG wells in production efficiency most of the time during the lifetime. Among oil wells (Fig. A9), within each cohort, UO wells always had a lower wastewater-to-energy ratio than CO wells. Across cohorts, UO wells were increasingly more efficient than CO wells. In the 2008 cohort, UO wells had a 0.10 bbl/mmBtu (p-value<0.01) lower wastewater-to-energy ratio than CO wells at the end of the first year. The efficiency gains of UO wells at the same age reached 0.32 bbl/mmBtu (p-value<0.01) in the 2015 cohort. The subsample analyses indicate that the increased efficiency gains of unconventional energy extraction were mainly achieved among oil wells.

4.2.3. Unconventional Vertical Wells

In this paper, we identify shale regions using the USGS shale play boundaries without the information about the reservoir geology targeted by each well in reality. By our definitions of UOG wells and COG wells, we exclude horizontal wells in non-shale regions for which the target reservoir is more ambiguous. Our study assumes that, compared with vertical wells, horizontal wells in shale regions are more likely to adopt unconventional extraction technologies due to higher economic returns. To alleviate the concern that some vertical wells in shale regions might apply unconventional technologies in practice, we compared the performance across UOG wells, vertical wells in non-shale regions ("VNS wells"), and vertical wells in shale regions ("VS wells") simultaneously using subsamples by cohort. Figs. A10-A12 plot the UOG-VS differences (left column) and the VNS-VS differences (right column) for the most recent four cohorts of 2012–2015. In each cohort, we find significant differences in both the initial-stage discharge and the lifetime efficiency

between UOG wells and VS wells, in contrast to statistically insignificant differences between VNS wells and VS wells most of the time during the lifetime. The results support that VS wells behaved more like conventional wells by applying conventional technologies to non-shale resources coexisting in shale regions, especially in recent cohorts as implied by Scanlon et al. (2017).

5. Conclusions

In this study, we identify the systematic differences in wastewater generation patterns between UOG wells (horizontal wells in shale regions) and COG wells (vertical wells in both shale and non-shale regions). We compare their discharge volume and efficiency over the production age by the year when a well started production, controlling for heterogeneities in wells' resource type, dominant hydrocarbon type, energy production, local geology, and regulations. Our analyses show that, in every cohort, UOG wells had a higher near-term wastewater volume but lower lifetime cumulative discharge compared with COG wells. Unconventional oil wells also had a lower wastewater-to-energy ratio over the entire lifetime than their conventional counterparts, whereas such efficiency advantage did not exist for unconventional gas wells. Across cohorts, both the short-term discharge load and the lifetime efficiency advantage of UOG wells became increasingly larger among wells in younger cohorts. Our findings reveal the tradeoff between the short-term disposal burden and the long-term efficiency gains of unconventional energy production.

In our analyses, COG wells provide an appropriate reference point for UOG wells given that the discharge patterns of the former remain relatively stable over time and across regions. We acknowledge that part of the identified differences between the two types of wells may be attributed to the district geology and unique extraction requirement of different energy resources, as rarely can both conventional and unconventional techniques be applied to the same formations. However, our econometric method accounts for geological heterogeneities to the best of our knowledge, we thus interpret the findings as average differences between the two types of wells. More importantly, our study reflects the ever-growing disposal burden and efficiency gains brought about by continuously improving unconventional technologies while conventional extraction is on the decline. Although we cannot observe the performance of wells in cohorts younger than 2015, we expect the identified patterns to apply to wells drilled in more recent years given persistent advancements in drilling technologies that continued to improve wells' productivity and efficiency over the past few years.

The patterns identified in our study have implications for addressing the current oil and gas wastewater disposal burden. In the short run, the main wastewater management challenge results from the concentrated production of large numbers of new UOG wells at their peak production stage, which can impose substantial pressure on regional storage and disposal infrastructure (Shih et al., 2016). As the early-stage disposal burden continues to grow among wells in more recent cohorts, we expect even greater infrastructure pressure in future unconventional energy development. To reconcile large volumes of wastewater discharge with existing infrastructure capacity, regulating the time distribution of hydraulic fracturing across wells could be more efficient than simply banning the technology. Local governments may restrict the number of new wells that can be permitted at the same time to reduce the total volume of wastewater to be stored, transported, and disposed of. Permitting of new drilling activities should also consider the age distribution of existing wells.

In the long run, although UOG wells have less cumulative discharge and increasingly higher efficiency than COG wells, the rapid expansion in production scale may still result in a large overall wastewater disposal burden. By the end of 2018, the number of horizontal wells nationwide has been increasing to almost 110,000, whereas that of vertical wells has declined to 88,000 (US EIA, 2019). The growth was interrupted by the COVID-19 pandemic, yet new drilling of UOG wells is expected to grow when energy demand rebounds and economic conditions improve. Our study points out an imperative for sustainable infrastructure investment to match the expanding scale of unconventional energy production and the ever-growing wastewater disposal challenge.

Declaration of Competing Interest

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

Acknowledgments

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Appendix A

Table A1
Baseline sample restriction.

Conditions	Obs.
Keep wells in 17 states with available wastewater generation data	34,336,840
Drop offshore wells	34,225,506
Drop operator-state-year observations if operators did not report any wastewater discharge for certain states in some years	32,951,738
Keep wells with the production type as “GAS”, “OIL”, or “O&G"	26,790,946
Keep wells with identifiable drill type	20,968,716
Drop horizontal or directional wells starting production before 1990	20,524,265
Drop non-vertical wells in non-shale regions	19,177,008
Keep wells of eight cohorts starting production over 2008–2015	5,313,957
Track the production history of 12*(2016-t) months for each well of cohort t	4,765,851
Drop wells that never reported wastewater discharge over the lifetime	4,506,346
Drop wells switching between active production and shutdown over the lifetime	2,902,860
Drop wells whose wastewater discharge or wastewater-to-energy ratio was once greater than the 99th percentile or whose energy production was once less than the 1st percentile among wells of the same type of technology use, production age, and cohort	2,377,006

Notes: The table documents the baseline sample restriction.

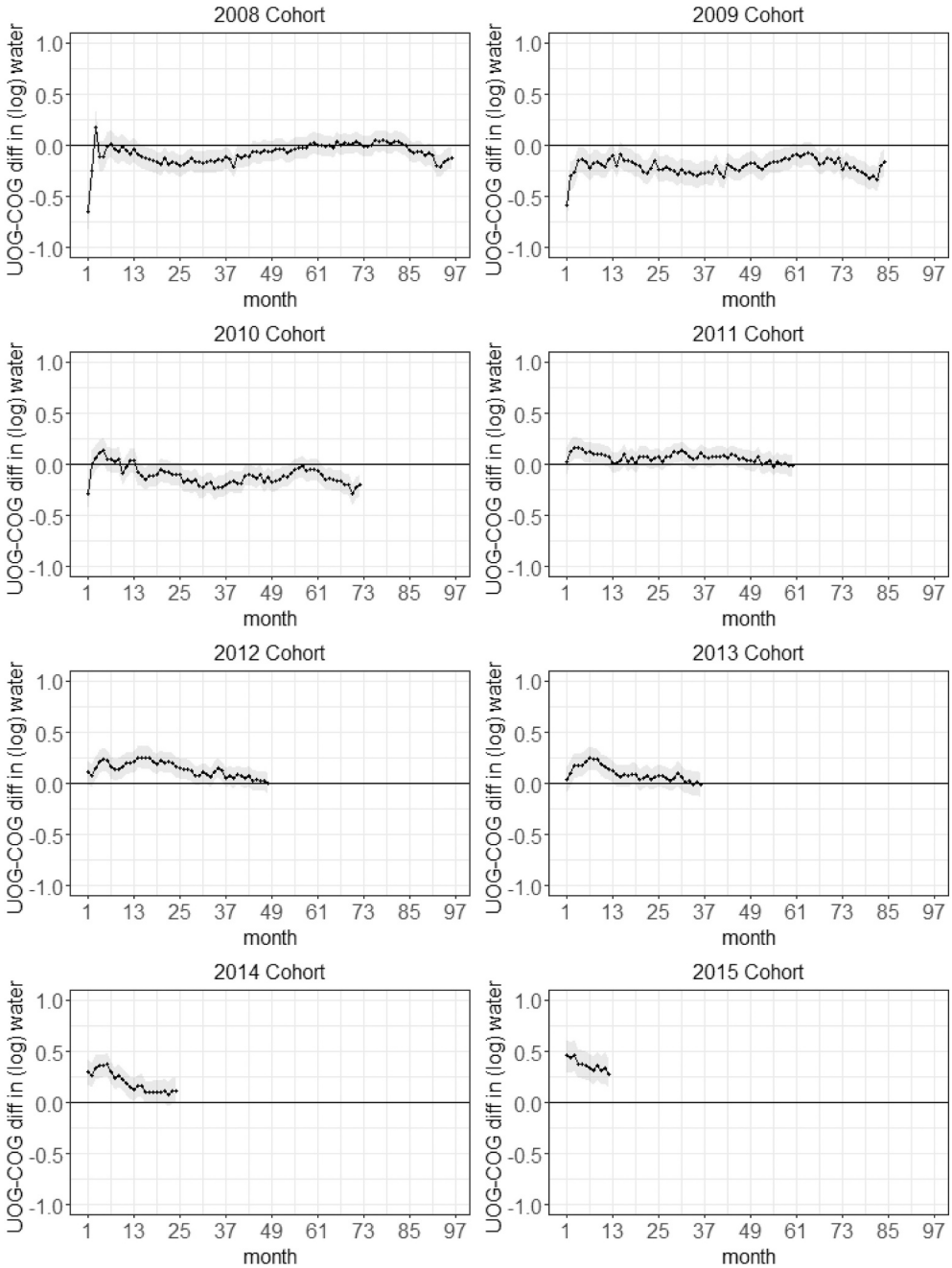

Fig. A1. Shale-well sample: differences in the monthly wastewater generation.
Notes: The figure plots the shale-well-sample estimates and the 95% confidence intervals for the cohort- and age-varying differences in the log form of the monthly wastewater generation (bbl) between UOG wells and COG wells. The model controls for a well's dominant hydrocarbon type and monthly energy production in the log form, the reservoir fixed effects, the county fixed effects, the state-by-year fixed effects, and the state-by-operator fixed effects. The coefficients are interpreted as differences in percentage terms.

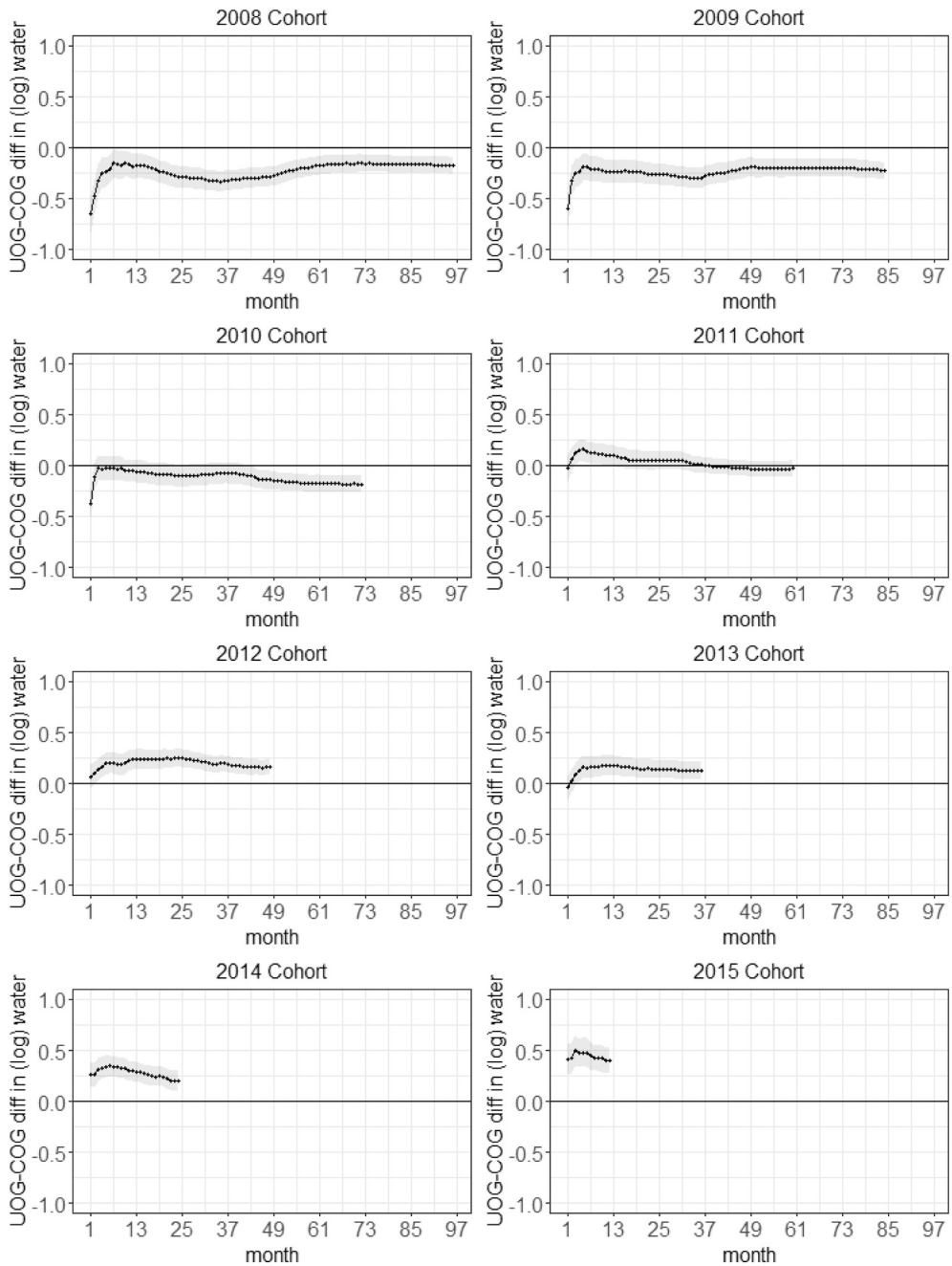

Fig. A2. Shale-well sample: differences in the cumulative wastewater generation.
Notes: The figure plots the shale-well-sample estimates and the 95% confidence intervals for the cohort- and age-varying differences in the log form of the cumulative wastewater generation (bbl) between UOG wells and COG wells. The model controls for a well's dominant hydrocarbon type and cumulative energy production in the log form, the reservoir fixed effects, the county fixed effects, the state-by-year fixed effects, and the state-by-operator fixed effects. The coefficients are interpreted as differences in percentage terms.

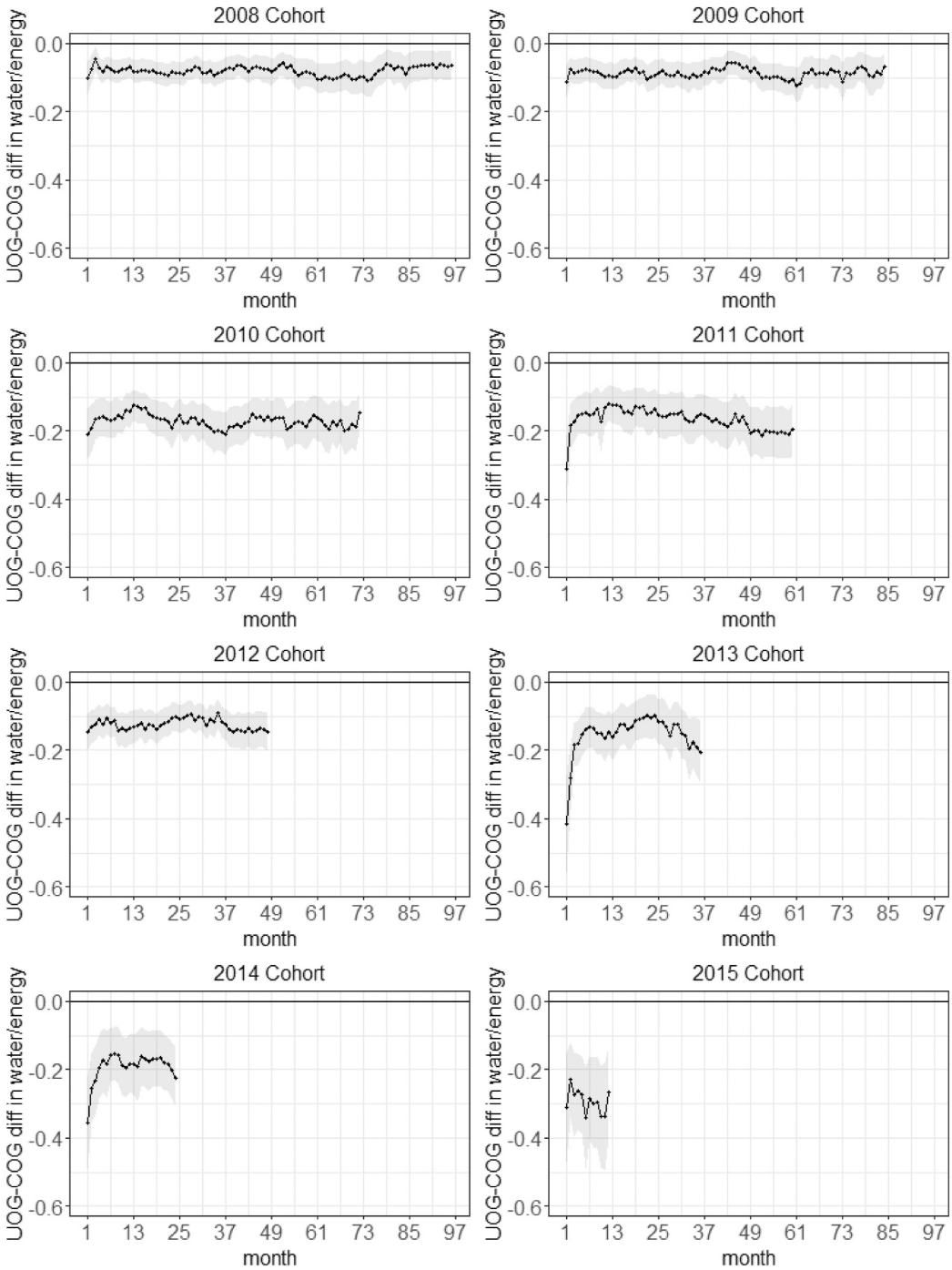

Fig. A3. Shale-well sample: differences in the wastewater-to-energy ratio.
Notes: The figure plots the shale-well-sample estimates and the 95% confidence intervals for the cohort- and age-varying difference in the wastewater-to-energy ratio (bbl/mmBtu) between UOG wells and COG wells. The model controls for a well's dominant hydrocarbon type, the reservoir fixed effects, the county fixed effects, the state-by-year fixed effects, and the state-by-operator fixed effects.

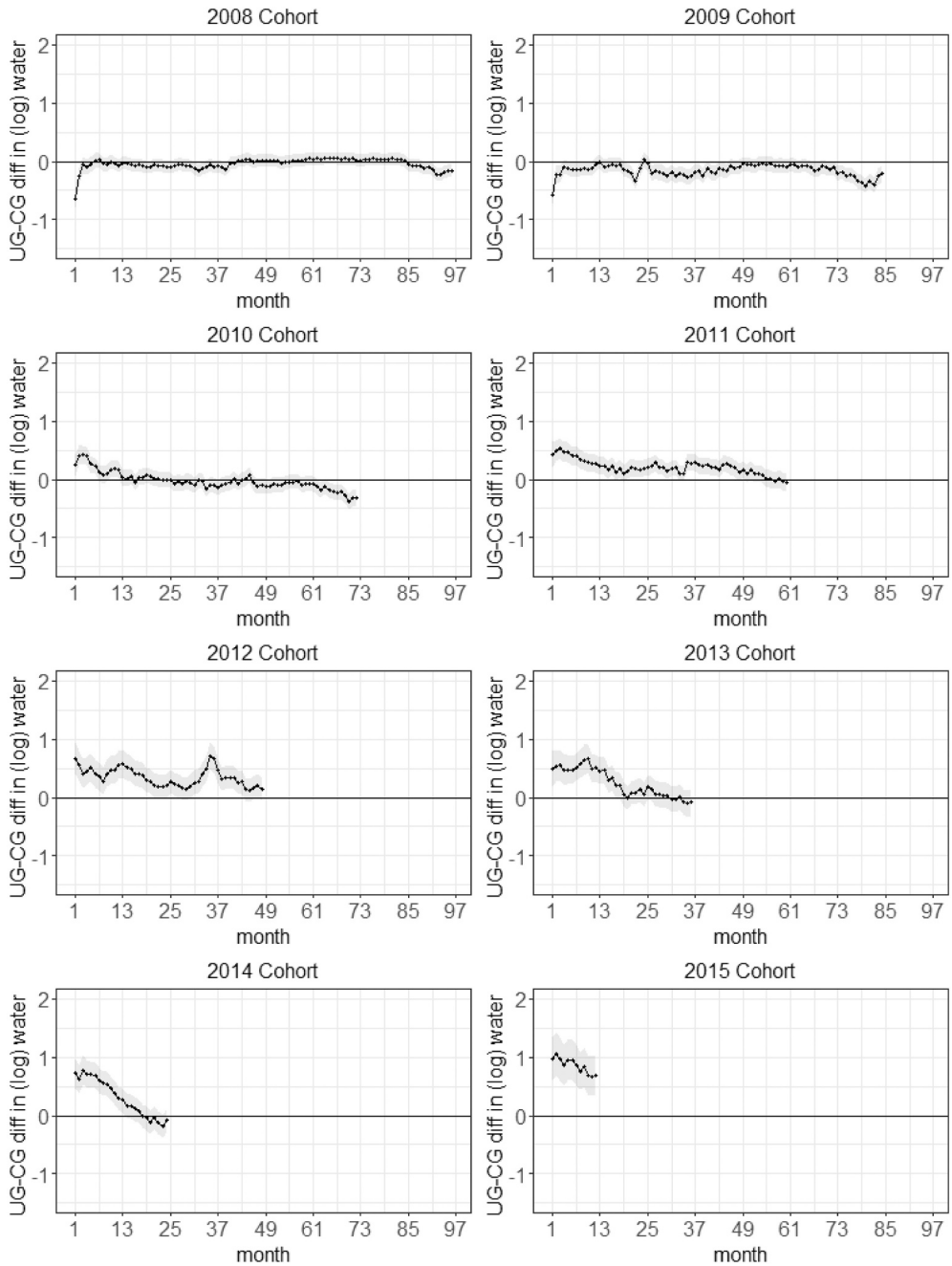

Fig. A4. Gas-well sample: differences in the monthly wastewater generation.

Notes: The figure plots the gas-well-sample estimates and the 95% confidence intervals for the cohort- and age-varying differences in the log form of the monthly wastewater generation (bbl) between UG wells and CG wells. The model controls for a well's resource type and monthly energy production in the log form, the reservoir fixed effects, the county fixed effects, the state-by-year fixed effects, and the state-by-operator fixed effects. The coefficients are interpreted as differences in percentage terms.

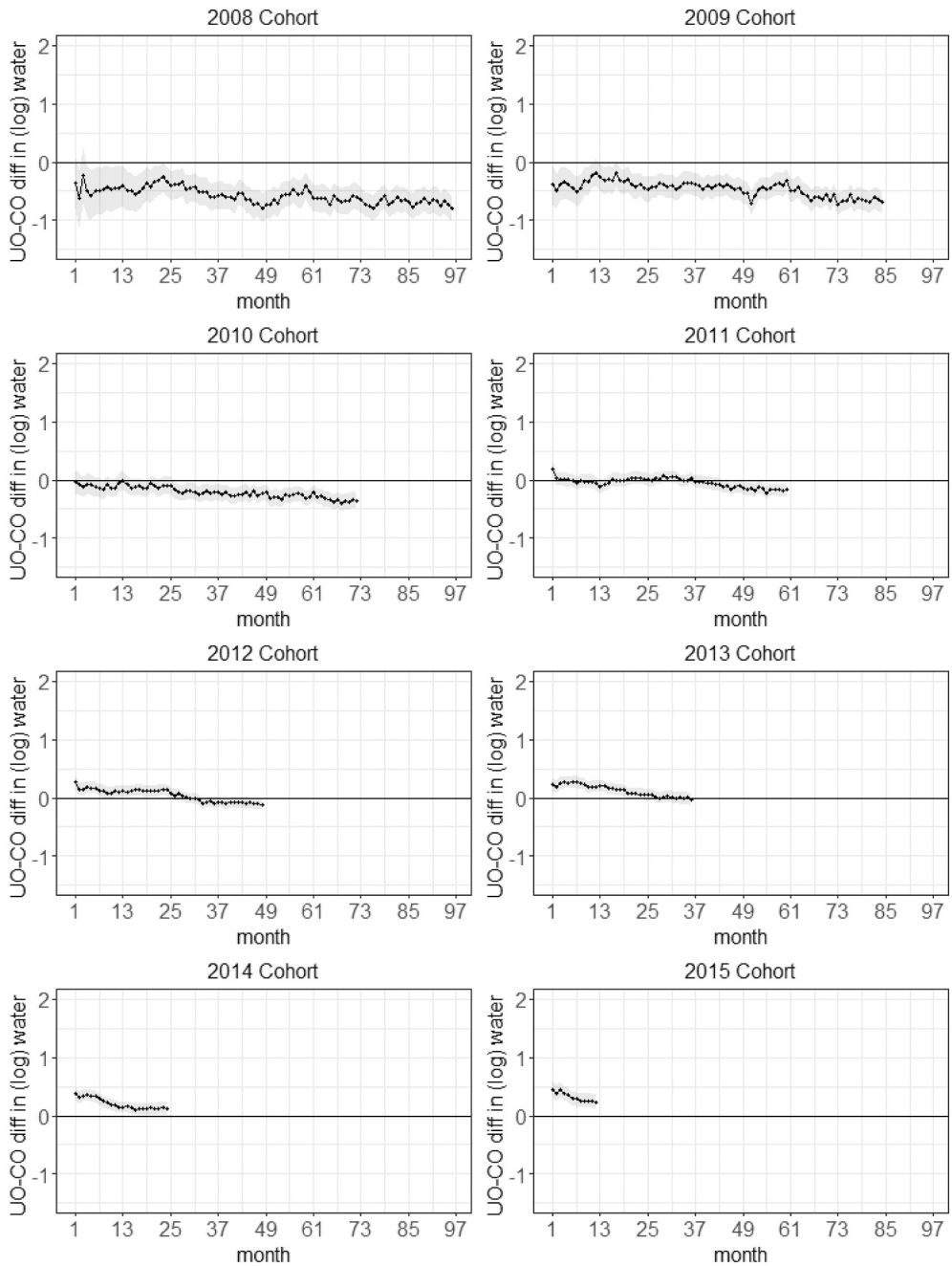

Fig. A5. Oil-well sample: differences in the monthly wastewater generation.
Notes: The figure plots the oil-well-sample estimates and the 95% confidence intervals for the cohort- and age-varying differences in the log form of the monthly wastewater generation (bbl) between UO wells and CO wells. The model controls for a well's resource type and monthly energy production in the log form, the reservoir fixed effects, the county fixed effects, the state-by-year fixed effects, and the state-by-operator fixed effects. The coefficients are interpreted as differences in percentage terms.

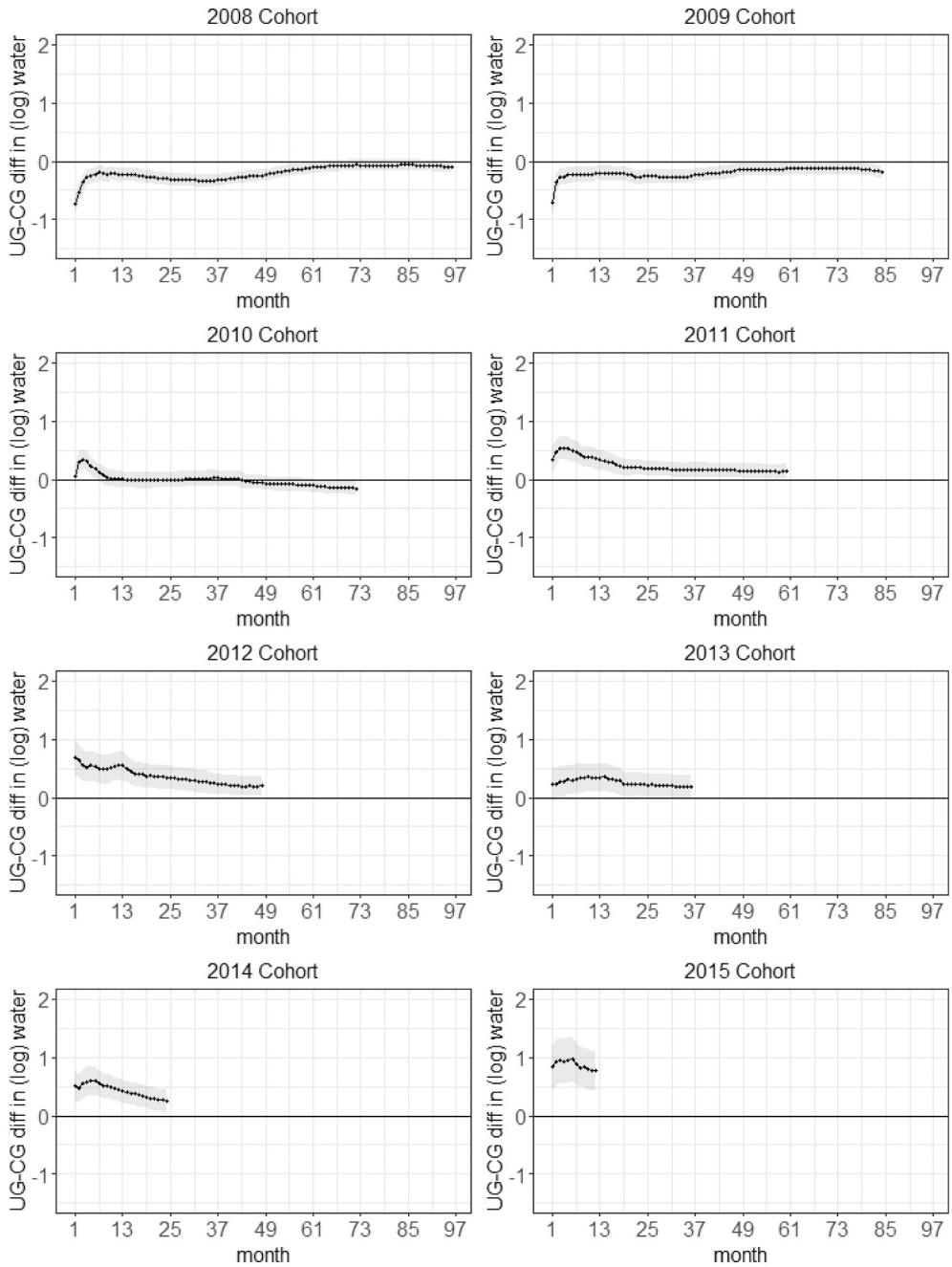

Fig. A6. Gas-well sample: differences in the cumulative wastewater generation.
Notes: The figure plots the gas-well-sample estimates and the 95% confidence intervals for the cohort- and age-varying differences in the log form of the cumulative wastewater generation (bbl) between UG wells and CG wells. The model controls for a well's resource type and cumulative energy production in the log form, the reservoir fixed effects, the county fixed effects, the state-by-year fixed effects, and the state-by-operator fixed effects. The coefficients are interpreted as differences in percentage terms.

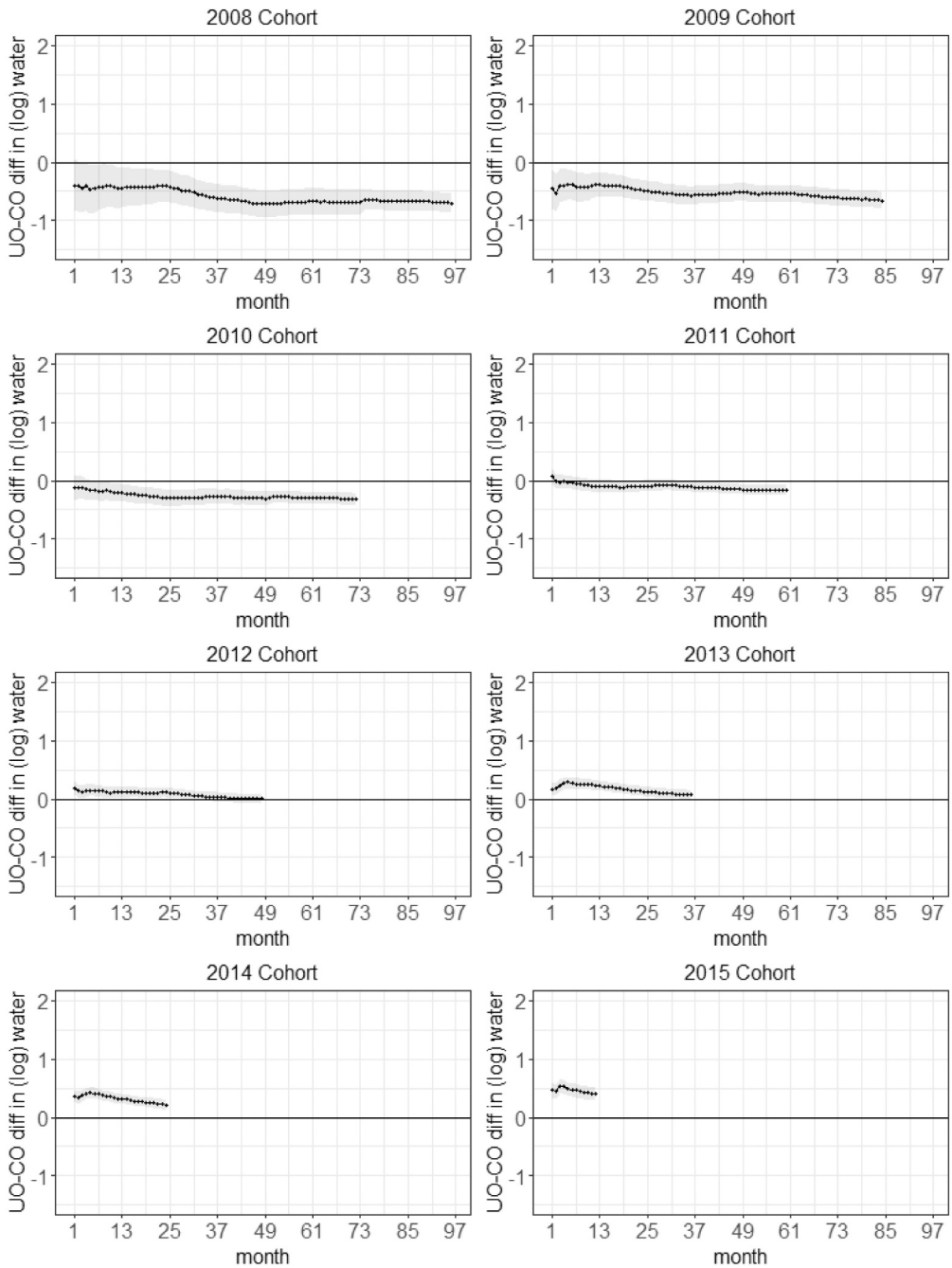

Fig. A7. Oil-well sample: differences in the cumulative wastewater generation.

Notes: The figure plots the oil-well-sample estimates and the 95% confidence intervals for the cohort- and age-varying difference in the log form of the cumulative wastewater generation (bbl) between UO wells and CO wells. The model controls for a well's resource type and cumulative energy production in the log form, the reservoir fixed effects, the county fixed effects, the state-by-year fixed effects, and the state-by-operator fixed effects. The coefficients are interpreted as differences in percentage terms.

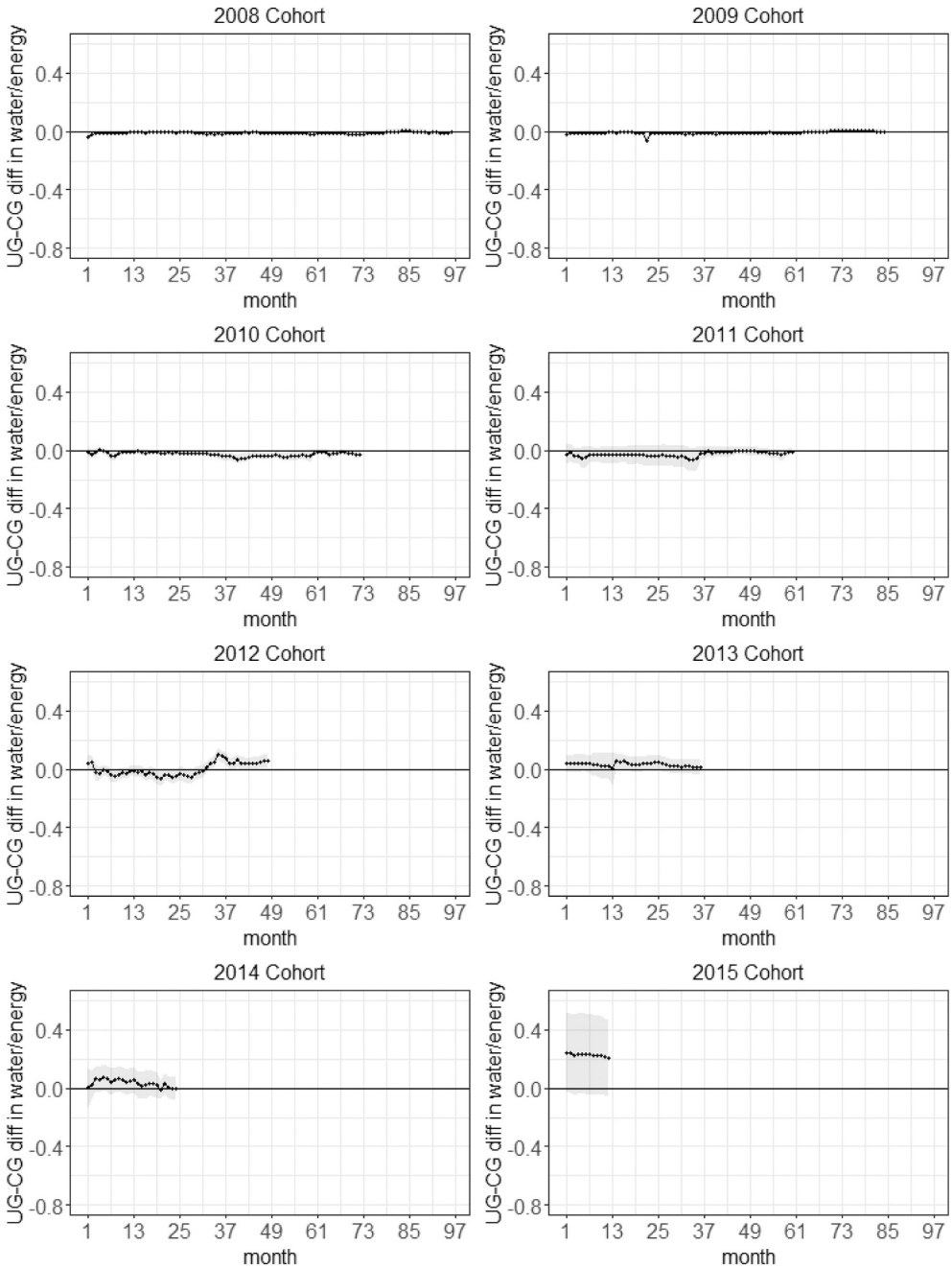

Fig. A8. Gas-well sample: differences in the wastewater-to-energy ratio.
Notes: The figure plots the gas-well-sample estimates and the 95% confidence intervals for the cohort- and age-varying difference in the wastewater-to-energy ratio (bbl/mmBtu) between UG wells and CG wells. The model controls for a well's resource type, the reservoir fixed effects, the county fixed effects, the state-by-year fixed effects, and the state-by-operator fixed effects.

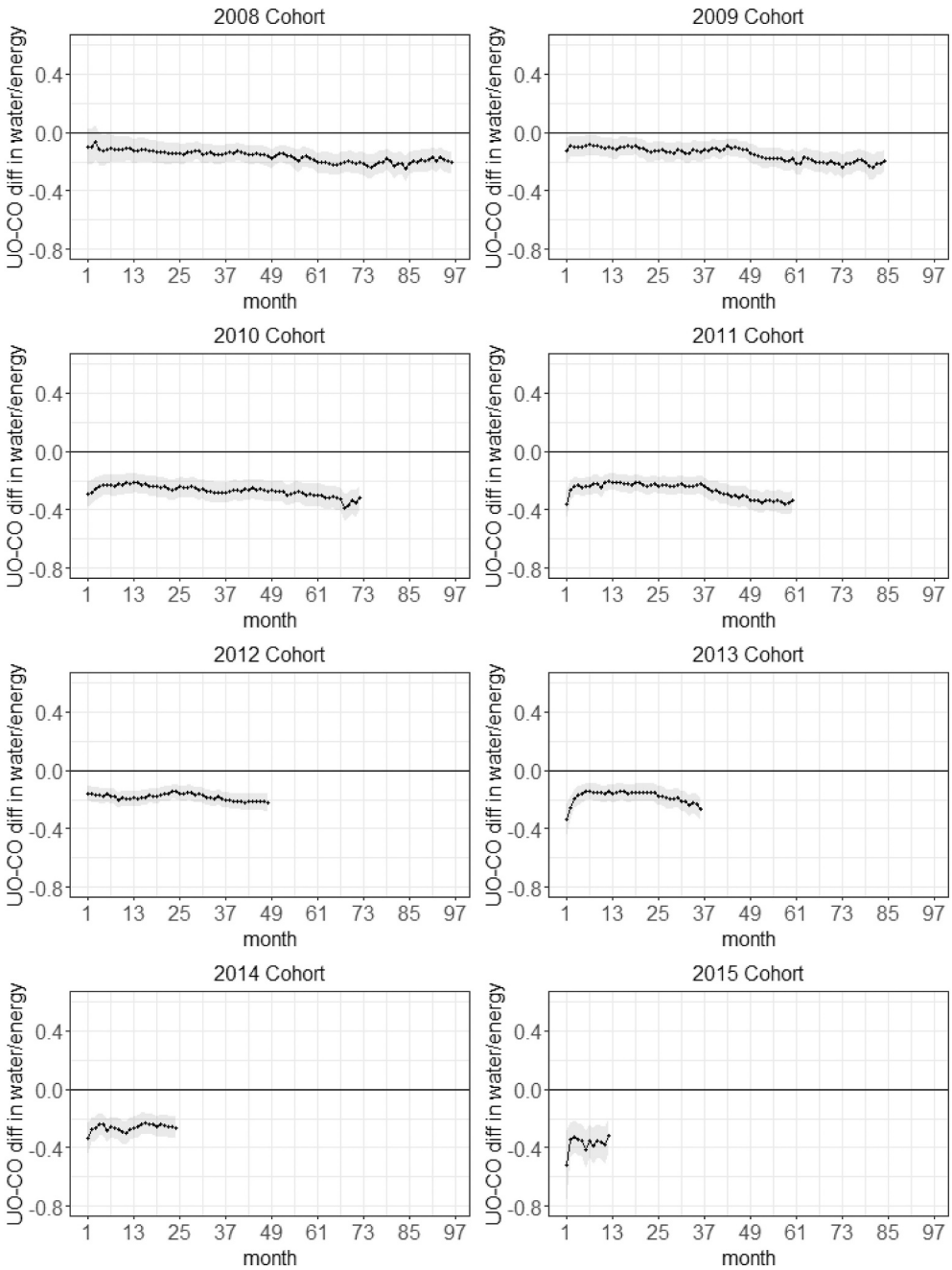

Fig. A9. Oil-well sample: differences in the wastewater-to-energy ratio.
Notes: The figure plots the oil-well-sample estimates and the 95% confidence intervals for the cohort- and age-varying difference in wastewater-to-energy ratio (bbl/mmBtu) between UO wells and CO wells. The model controls for a well's resource type, the reservoir fixed effects, the county fixed effects, the state-by-year fixed effects, and the state-by-operator fixed effects.

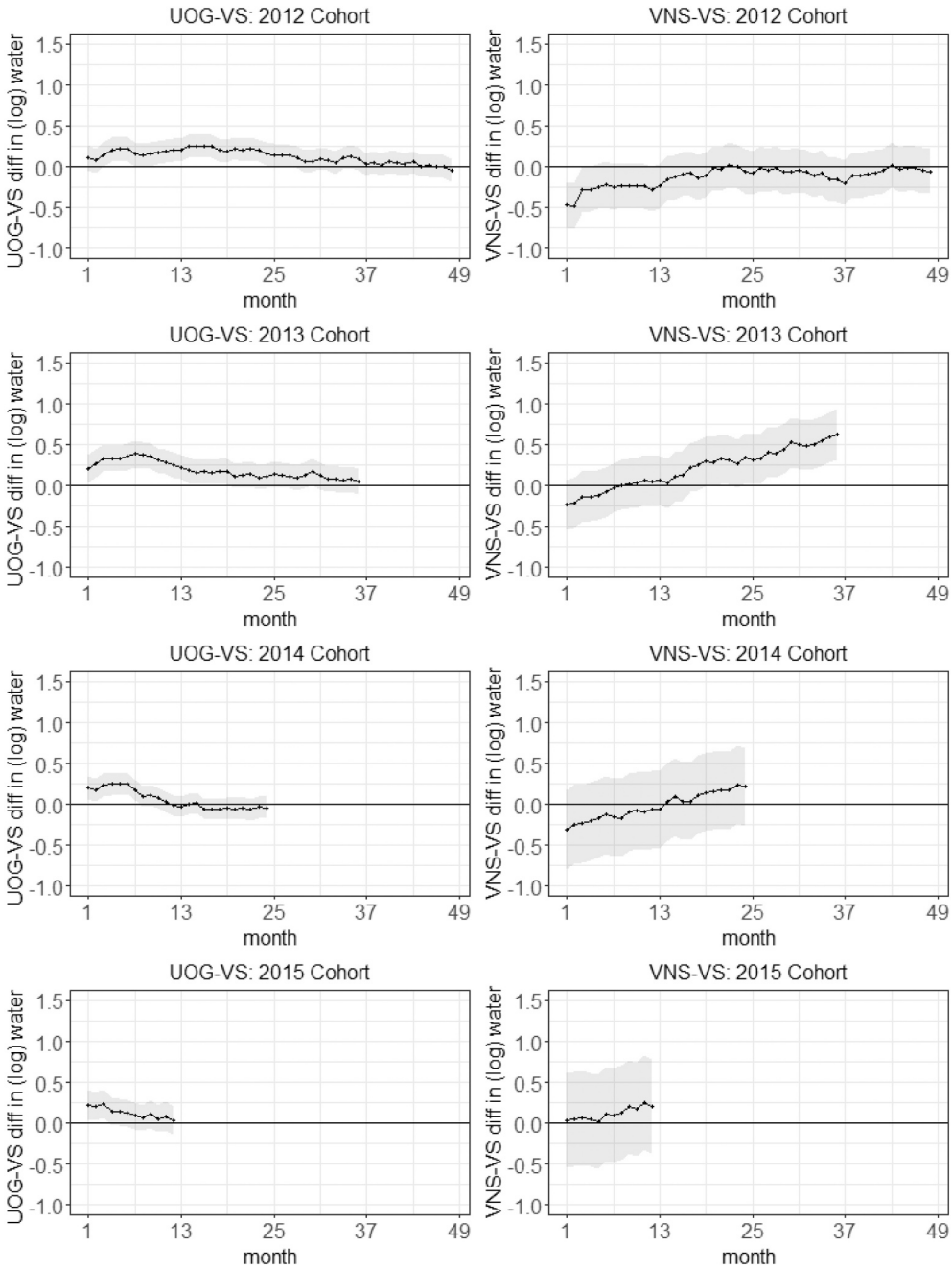

Fig. A10. UOG-VS versus VNS-VS: differences in the monthly wastewater generation.

Notes: Based on subsamples by cohort, the figure plots the estimates and the 95% confidence intervals for the cohort- and age-varying differences in the log form of the monthly wastewater generation (bbl) between UOG wells and vertical wells in shale regions ("VS wells") (left column), and those between vertical wells in non-shale regions ("VNS wells") and VS wells (right column). The model controls for a well's dominant hydrocarbon type and monthly energy production in the log form, the reservoir fixed effects, the county fixed effects, the state-by-year fixed effects, and the state-by-operator fixed effects. The coefficients are interpreted as differences in percentage terms.

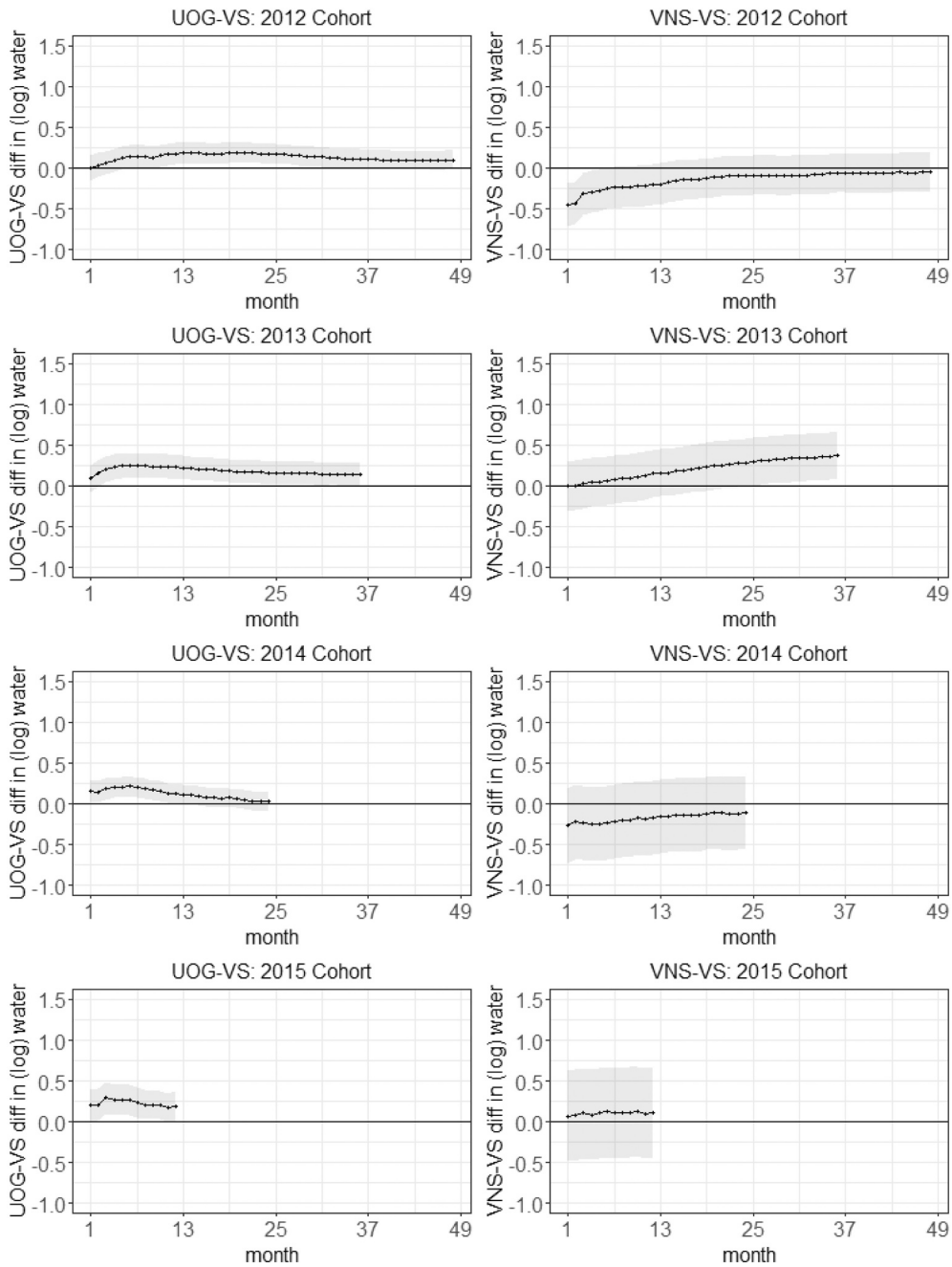

Fig. A11. UOG-VS versus VNS-VS: differences in the cumulative wastewater generation.
Notes: Based on subsamples by cohort, the figure plots the estimates and the 95% confidence intervals for the cohort- and age-varying differences in the log form of the cumulative wastewater generation (bbl) between UOG wells and vertical wells in shale regions ("VS wells") (left column), and those between vertical wells in non-shale regions ("VNS wells") and VS wells (right column). The model controls for a well's dominant hydrocarbon type and cumulative energy production in the log form, the reservoir fixed effects, the county fixed effects, the state-by-year fixed effects, and the state-by-operator fixed effects. The coefficients are interpreted as differences in percentage terms.

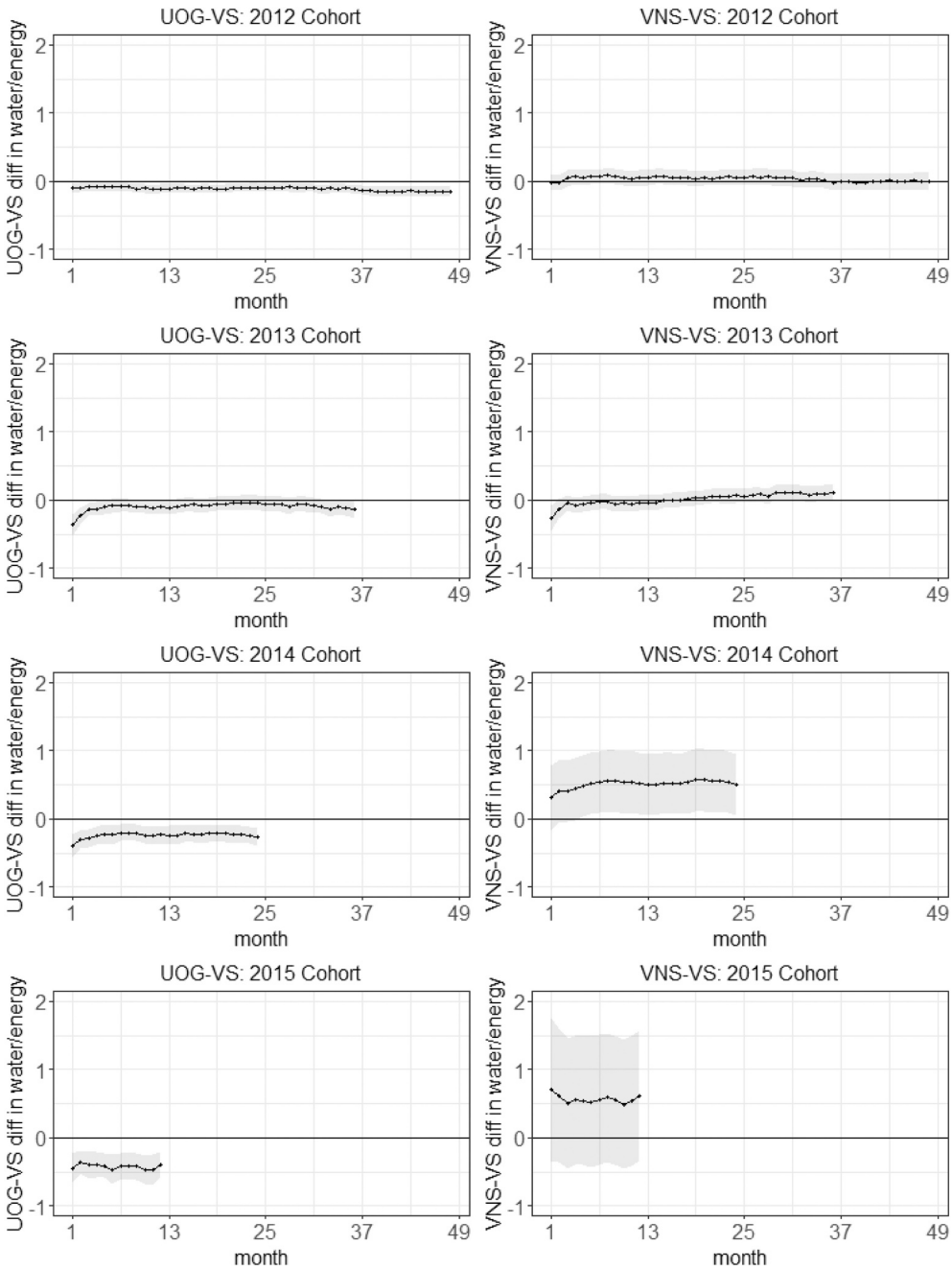

Fig. A12. UOG-VS versus VNS-VS: differences in the wastewater-to-energy ratio.
Notes: Based on subsamples by cohort, the figure plots the estimates and the 95% confidence intervals for the cohort- and age-varying differences in the wastewater-to-energy ratio (bbl/mmBtu) between UOG wells and vertical wells in shale regions ("VS wells") (left column), and those between vertical wells in non-shale regions ("VNS wells") and VS wells (right column). The model controls for a well's dominant hydrocarbon type, the reservoir fixed effects, the county fixed effects, the state-by-year fixed effects, and the state-by-operator fixed effects.

Appendix B

B.1. Texas Wells

As Texas leads the nation in oil and gas extraction history and energy production level, unconventional extraction technologies could have been more prevalent and mature in the state. In this subsection, we report the estimation results using the subsample of Texas wells as a case study, which accounts for 37% of the full sample. Figs. B1–B3 show that the baseline patterns were robust and more striking in Texas. Within each cohort, the early-stage gap between UOG wells and COG wells in Texas was larger than the full sample estimates in both the monthly and cumulative wastewater generation. In the 2012 cohort, for example, in the first production month, UOG wells released 58.4% more wastewater than COG wells in Texas whereas the gap was 23.3% in the full sample; by the end of the first production year, UOG wells discharged 61% more cumulative wastewater than COG wells based on the Texas estimates compared with the baseline estimate of 20.4%. Consistently, the breakeven point in cumulative discharge occurred at a later age for wells in Texas than comparable wells in other states. For example, in the 2010 cohort, UOG wells and COG wells released the

same cumulative amount of wastewater by the 25th month in the Texas sample, whereas the point occurred at the 7th month in the full sample. The differences might be caused by the distinct permeability of shale resources in Texas. Another reason could be that unconventional extraction technologies have been introduced earlier and thus are applied more extensively in this state compared with other regions of the country.

Across cohorts, UOG wells also showed a growingly higher early-stage wastewater discharge consistent with the baseline findings. However, the energy efficiency gains of UOG wells relative to COG wells only appeared in the pre-2011 cohorts with smaller gap compared with the full-sample estimates. For instance, the lifetime efficiency gap between the two types of wells increased from 0.04 to 0.19 bbl/mmBtu over the 2008-2011 cohorts in Texas, whereas the change was from 0.09 to 0.19 bbl/mmBtu in the full sample. One possible explanation for the smaller efficiency gap is that shale extraction has been at a more mature stage in Texas, which lowered the per-well energy productivity and efficiency of UOG wells relative to the national average level. In the post-2011 cohorts, the relative efficiency gains of UOG wells turned insignificant, indicating that the growth in the per-well energy productivity did not match the increase in wastewater generation of UOG wells across cohorts.

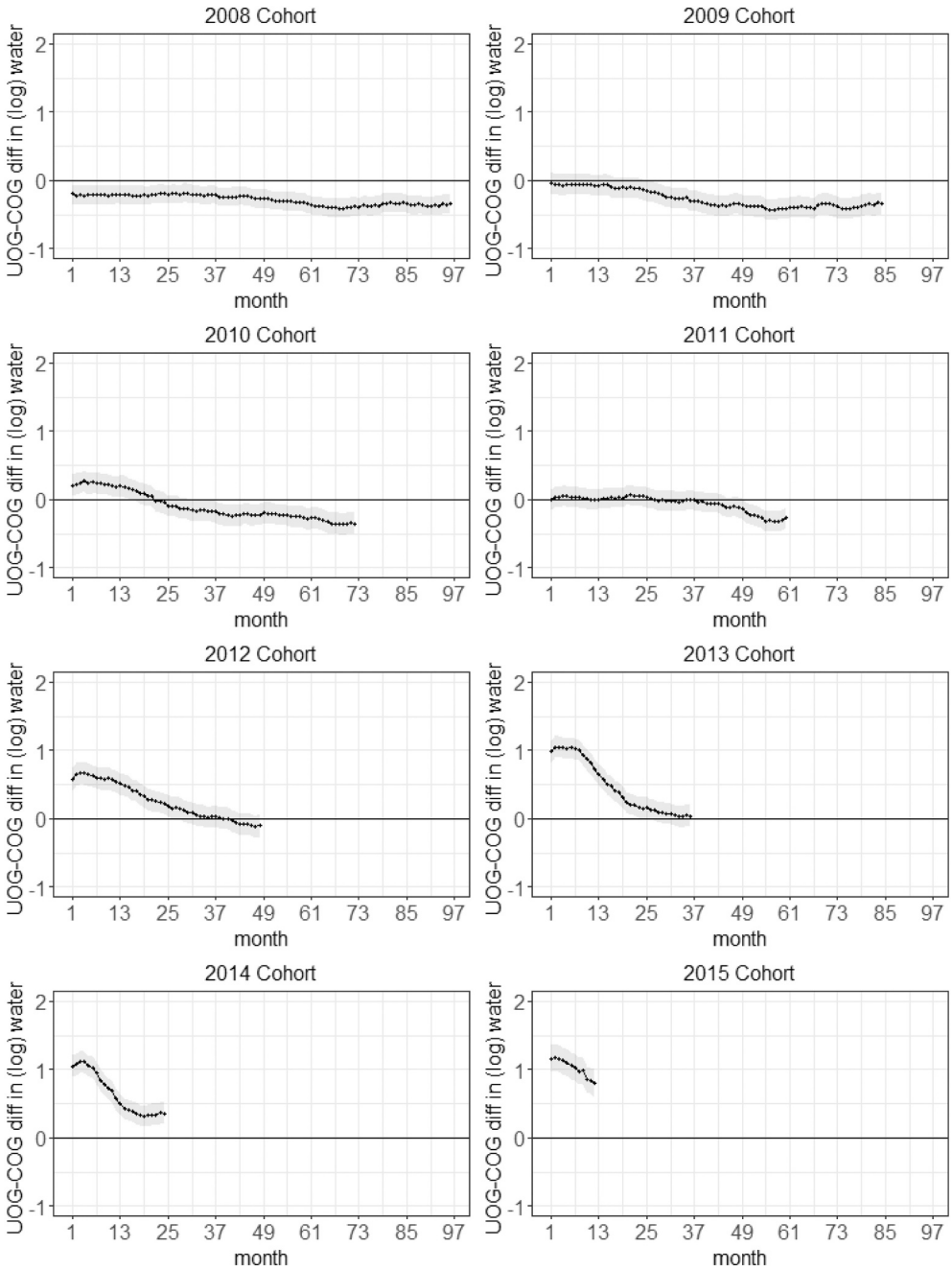

Fig. B1. Texas sample: differences in the monthly wastewater generation.

Notes: The figure plots the Texas-sample estimates and the 95% confidence intervals for the cohort- and age-varying differences in the log form of the monthly wastewater generation (bbl) between UOG wells and COG wells. The model controls for a well's resource type, dominant hydrocarbon type, and monthly energy production in the log form, the reservoir fixed effects, the county fixed effects, the state-by-year fixed effects, and the state-by-operator fixed effects. The coefficients are interpreted as differences in percentage terms.

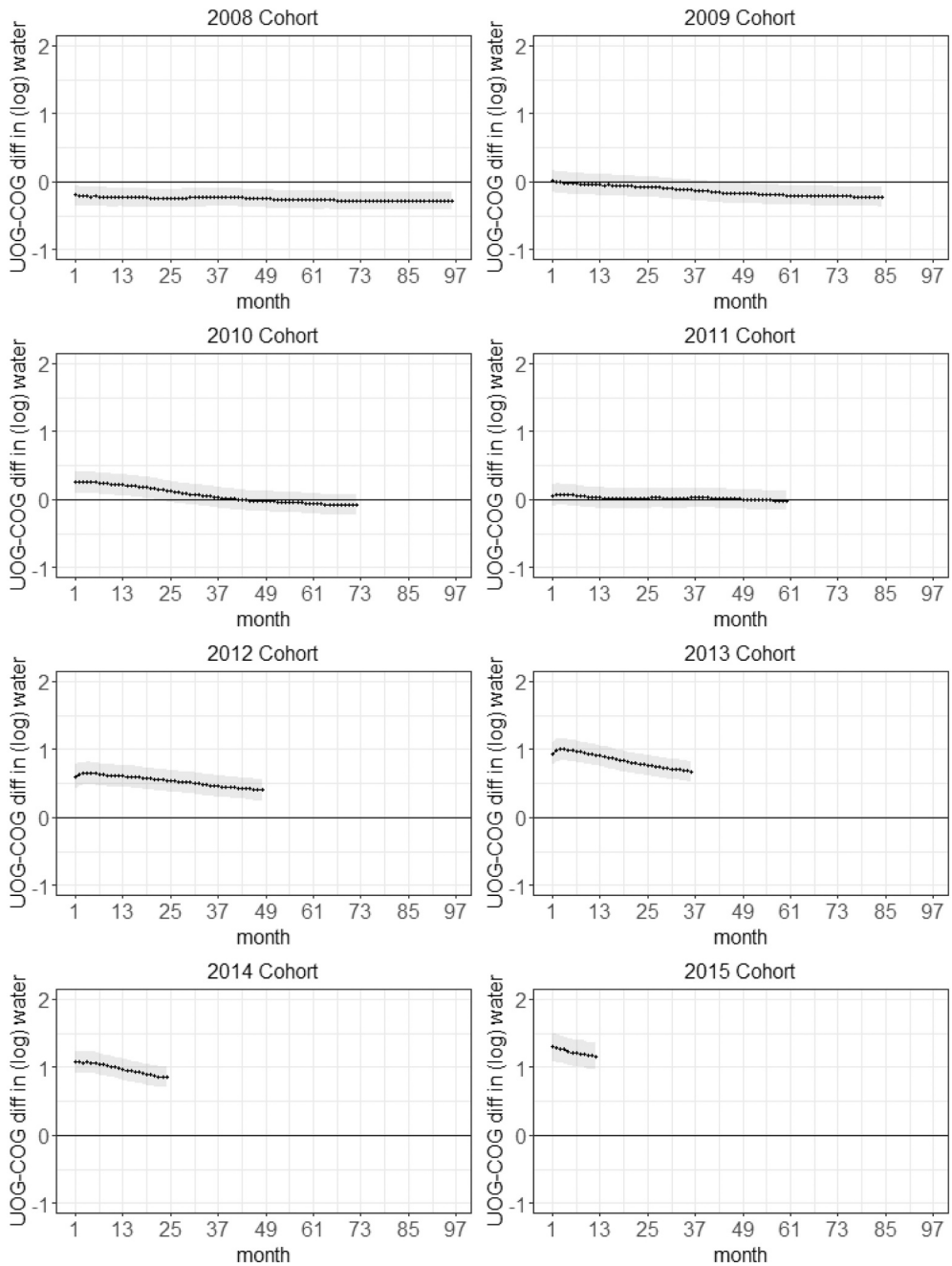

Fig. B2. Texas sample: differences in the cumulative wastewater generation.
Notes: The figure plots the Texas-sample estimates and the 95% confidence intervals for the cohort- and age-varying differences in the log form of the cumulative wastewater generation in bbl between UOG wells and COG wells. The model controls for a well's resource type, dominant hydrocarbon type, and cumulative energy production in the log form, the reservoir fixed effects, the county fixed effects, the state-by-year fixed effects, and the state-by-operator fixed effects. The coefficients are interpreted as differences in percentage terms.

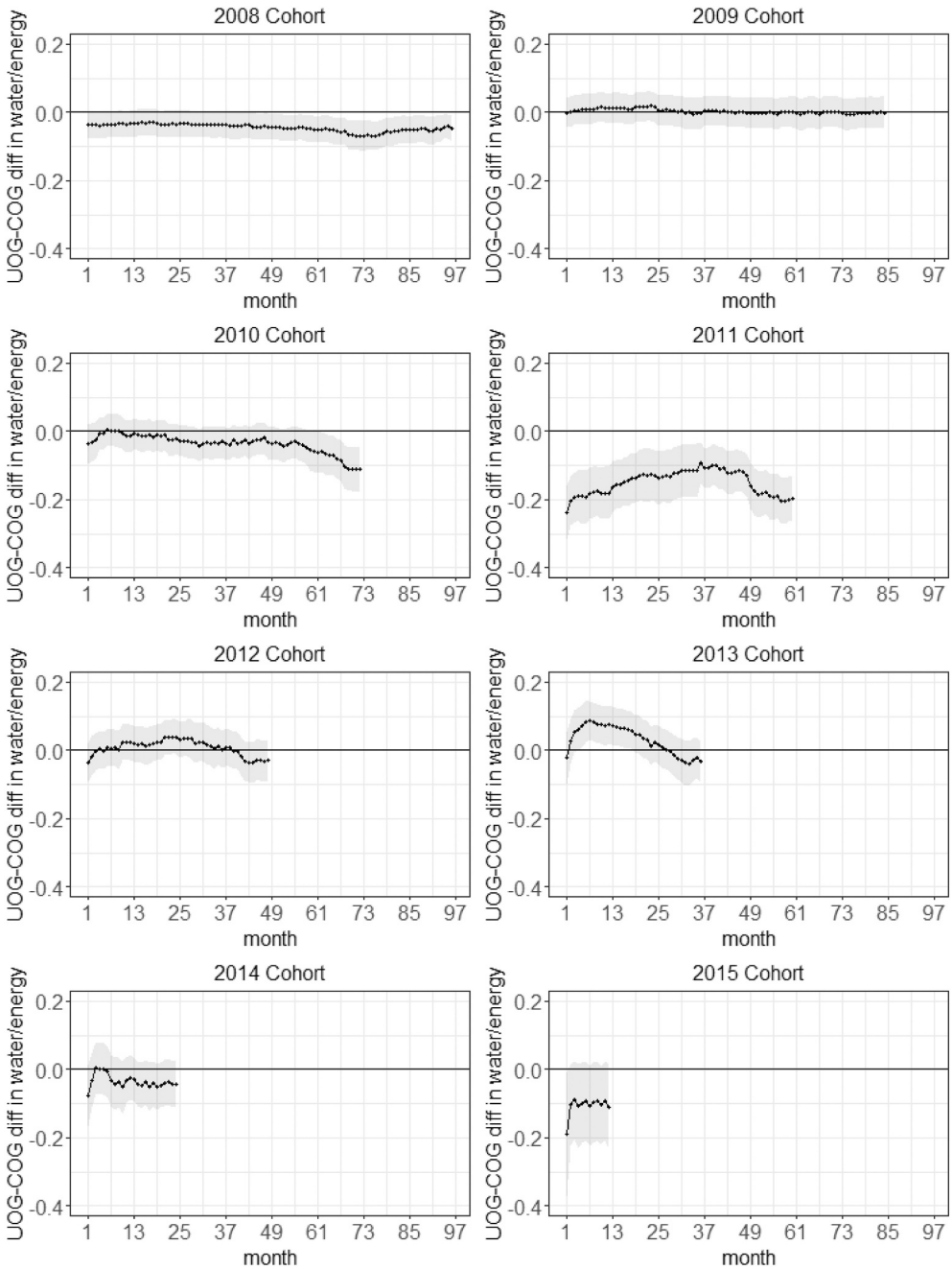

Fig. B3. Texas sample: differences in the wastewater-to-energy ratio.
Notes: The figure plots the Texas-sample estimates and the 95% confidence intervals for the cohort- and age-varying difference in the wastewater-to-energy ratio in bbl/mmBtu between UOG wells and COG wells. The model controls for a well's resource type and dominant hydrocarbon type, the reservoir fixed effects, the county fixed effects, the state-by-year fixed effects, and the state-by-operator fixed effects.

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