Understanding productivity effects of hydraulic fracturing in unconventional natural gas deposits and implications for adoption in the developing world

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ONLINE APPENDIX

Table A1. Characterization of fluid additives by purpose

Category	Additive	Purpose	Examples
Gels	Gels & Foamers	To create a high viscosity fluid, firms mix various gelling or foaming agents to help transport proppant.	Guar gum, ethanol, methanol
Slicks	To reduce friction and ease the burden on pumping equipment, friction reducers and surfactants are added to the fluid.	Reduce Viscosity	Polyacrimide
	Surfactants	Maintain Viscosity	Sodium lauryl sulfate
Linker & Breaker	Crosslinker	Crosslinkers increase viscosity of fluid to increase the amount of proppant that can be transported by fixed pumping capacity.	Borate salts, ammonium chloride, ethylene glycol
	Breaker	Crosslinking must be reversed to recover fluid and leave proppant in place, so chemical reactions triggered by breakers, often after some delay, are used to reverse the process.	Calcium chloride, sodium chloride, ammonium sulfate
	Crosslinker	Crosslinkers increase viscosity of fluid to increase the amount of proppant that can be transported by fixed pumping capacity.	Borate salts, ammonium chloride, ethylene glycol
Biocide	Biocide	Biocides are used to kill bacteria that might clog the wellbore and impede flow. Because their purpose is to kill microorganisms, the compounds that are used can be harmful to humans.	Quartenary ammonium compounds, glutaraldehyde
Additives	pH Adjuster	Chemical Performance	Acetic acid, potassium hydroxide, sodium hydroxide
	Corrosion Inhibitor	Prevent Corrosion	Acetaldehyde, acetone
	Scale Inhibitor	Protect Piping, Maintain Flow	Phosphonic acid salts, sodium polycarbonate
	Iron Control	Maintain Flow	Citric acid, acetic acid, sodium erythorbate
	Clay Control	Maintain Flow	Choline chloride, potassium chloride, sodium chloride
Unspecified	Non-Specific	Various	

Notes: Categories provided by Stringfellow *et al.* (2014). Classification of additives was made from cross-references within FracFocus records, Stringfellow *et al.* (2014), and EPA (2015).

Table A2. Variable definitions

Variable	Units	Source	Description
H_2O volume	MM gal	WOGCC	Base fluid injected into each individual well during frac. Log is used as explanatory variable in table 4.
Sand/Water ratio	ratio	FracFocus	Ratio of mass of proppant and water injected into each individual well during frac.
Ingredients	count	FracFocus	Count of total additives to frac for each individual well. Further details of different types of additives is included in table A.1.
Stages	count	WOGCC	Count of frac stages for each individual well.
Treated interval	M ft	WOGCC	Length of perforated interval in wellbore of each individual well.
Total well depth	M ft	WOGCC	Total well depth for each individual well.
Gas produced	Mcf	Enverus	Volume of natural gas produced in specified time period (1, 6, 12 month period) by each individual well. The logarithm is used as dependent variable in table reftab:panelresults.
Aggregate oil equivalent	BOE	Enverus	Energy content of production in specified time period (6, 12 month period) by each individual well. This includes liquids, but also

Table A3. Summary statistics for frac jobs

	Mean	Std. Dev.	Min	Max
H_2O Volume (MM gal)	1.614	1.039	0.364	5.614
Sand/Water Ratio	0.149	0.070	0.023	0.370
Ingredients (count)	84.273	11.753	28.000	90.000
Stages	15.458	4.777	3.000	27.000
Treated Interval (M ft)	4.266	1.439	1.113	6.324
Total Well Depth (M ft)	13.334	0.869	10.491	14.914

Notes: Data compiled from FracFocus records and WOGCC completion reports. *N*=297.

Table A4. Summary of production measures

Measure	Mean	Std. Dev.	Min	Max
Aggregate Natural Gas (Mcf)				
First 6 Months	350,068	169,848	10,591	1,060,576
First 12 Months	569,017	250,554	11,554	1,693,901
Aggregate Oil Equivalent (BOE)				
First 6 Months	61,590	29,232	1,921	177,155
First 12 Months	100,268	43,333	2,082	287,199

Notes: Data provided by Enverus. *N*=297.

Table A5. Pairings of operators and service companies

	Service Company				
Operator	No Report	A	B	C	Total
I	21	15	0	142	178
II	0	0	52	0	52
III	0	64	0	0	64
IV	0	0	3	0	3
Total	21	79	55	142	297

Notes: Compiled from WOGCC reports, FracFocus records, and Enverus.

Table A6. Various fixed effect results, first six months' gas

	(1)	(2)	(3)	(4)	(5)	(6)
Log Water Volume	0.076	0.055	0.24***	0.074	0.077	0.074
	(0.089)	(0.087)	(0.089)	(0.14)	(0.11)	(0.13)
Sand/Water Ratio	-1.27*	-0.84	0.69	-1.33	-0.81	-1.56**
	(0.71)	(0.74)	(0.93)	(0.83)	(0.75)	(0.75)
Stages		0.050***	-0.010	-0.0050	0.0015	-0.016
		(0.0067)	(0.0065)	(0.015)	(0.011)	(0.015)
2011			0.49**			
			(0.21)			
2012			0.75***			
			(0.22)			
2013			0.70***			
			(0.24)			
Operator II				0.022		
				(0.15)		
Operator III				0.0010		
				(0.18)		
Operator IV				0.36**		
				(0.18)		
Service Company A					-0.33**	
					(0.16)	
Service Company B					-0.22	
					(0.15)	
Service Company C					-0.24*	
					(0.13)	
Constant	10.4***	11.2***	7.36***	10.5***	10.5***	11.1***
	(1.35)	(1.30)	(1.43)	(1.91)	(1.55)	(1.88)
Spatial FE	N	N	N	N	N	Y
Observations	298	297	297	297	297	297
R^2	0.049	0.17	0.14	0.054	0.066	0.18

Notes: Dependent variable is the log of gas production per treated foot during the first 6 months of production. Robust standard errors in parentheses. 2010 is the excluded year in column (3). Operator I is the excluded group in column (4). Missing service company is the excluded group in column (5). Column (6) includes spatial fixed effects, which are jointly significant.

Table A7. Various fixed effect results, first twelve months' gas

	(1)	(2)	(3)	(4)	(5)	(6)
Log Water Volume	0.18**	0.17**	0.27***	0.14	0.15	0.12
	(0.084)	(0.082)	(0.090)	(0.13)	(0.10)	(0.12)
Sand/Water Ratio	-0.41	-0.31	0.89	-0.41	0.11	-0.79
	(0.72)	(0.73)	(0.87)	(0.87)	(0.74)	(0.75)
Stages		-0.013**	-0.017**	-0.0076	-0.0051	-0.020
		(0.0061)	(0.0064)	(0.015)	(0.010)	(0.014)
2011			0.17			
			(0.13)			
2012			0.40***			
			(0.14)			
2013			0.36**			
			(0.16)			
Operator II				-0.060		
				(0.15)		
Operator III				-0.092		
				(0.17)		
Operator IV				0.13		
				(0.14)		
Service Company A					-0.36**	
					(0.15)	
Service Company B					-0.27*	
					(0.14)	
Service Company C					-0.22*	
					(0.13)	
Constant	9.31***	9.59***	7.74***	10.0***	9.90***	10.9***
	(1.29)	(1.24)	(1.43)	(1.90)	(1.50)	(1.71)
Observations	298	297	297	297	297	297
R^2	0.053	0.068	0.12	0.071	0.088	0.23

Notes: Dependent variable is the log of gas production per treated foot during the first 12 months of production. Robust standard errors in parentheses. 2010 is the excluded year in column (3). Operator I is the excluded group in column (4). Missing service company is the excluded group in column (5). Column (6) includes spatial fixed effects, which are jointly significant.

Table A8. Baseline results

	(1) Log 6 Mo. Gas	(2) Log 6 Mo. Gas	(3) Log 12 Mo. Gas	(4) Log 12 Mo. Gas	(5) Log 6 Mo. BOE	(6) Log 6 Mo. BOE	(7) Log 12 Mo. BOE	(8) Log 12 Mo. BOE
Log Water Volume	0.076	0.24*	0.18**	0.31**	0.065	0.23	0.17*	0.30**
	(0.089)	(0.14)	(0.084)	(0.14)	(0.091)	(0.14)	(0.085)	(0.14)
Sand/Water Ratio	-1.27*	-1.40*	-0.41	-0.82	-1.40*	-1.56*	-0.53	-0.98
	(0.71)	(0.82)	(0.72)	(0.81)	(0.72)	(0.82)	(0.74)	(0.82)
Additives		0.022		0.032		0.026		0.036
		(0.038)		(0.037)		(0.039)		(0.037)
Biocides		0.0055		0.00016		0.0052		-0.00037
		(0.010)		(0.0092)		(0.010)		(0.0093)
Breakers		0.028**		0.019**		0.028**		0.019**
		(0.013)		(0.0091)		(0.013)		(0.0092)
Gels		0.041		0.069		0.043		0.071
		(0.10)		(0.096)		(0.10)		(0.098)
Slicks		-0.023		-0.022		-0.023		-0.022
		(0.018)		(0.014)		(0.018)		(0.014)
Unspecified		0.029		0.0033		0.024		-0.00064
		(0.027)		(0.023)		(0.026)		(0.023)
Constant	10.4***	8.29***	9.31***	7.72***	8.81***	6.77***	7.75***	6.18***
	(1.35)	(1.89)	(1.29)	(1.87)	(1.37)	(1.91)	(1.31)	(1.90)
Observations	298	298	298	298	298	298	298	298
R^2	0.049	0.085	0.053	0.088	0.051	0.086	0.052	0.090

Notes: Robust standard errors in parentheses.

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Table A9. Trade secret results

	(1) Log 6 Month Gas	(2) Log 6 Month Gas	(3) Log 12 Month Gas	(4) Log 12 Month Gas	(5) Log 6 Month BOE	(6) Log 6 Month BOE	(7) Log 12 Month BOE	(8) Log 12 Month BOE
Log Water Volume	0.24*	0.13	0.31**	0.20**	0.23	0.11	0.30**	0.18*
	(0.14)	(0.097)	(0.14)	(0.097)	(0.14)	(0.099)	(0.14)	(0.100)
Sand/Water Ratio	-1.40*	-1.08	-0.82	-0.50	-1.56*	-1.24	-0.98	-0.65
	(0.82)	(0.81)	(0.81)	(0.84)	(0.82)	(0.82)	(0.82)	(0.85)
Additives	0.022		0.032		0.026		0.036	
	(0.038)		(0.037)		(0.039)		(0.037)	
Biocides	0.0055		0.00016		0.0052		-0.00037	
	(0.010)		(0.0092)		(0.010)		(0.0093)	
Breakers	0.028**		0.019**		0.028**		0.019**	
	(0.013)		(0.0091)		(0.013)		(0.0092)	
Gels	0.041		0.069		0.043		0.071	
	(0.10)		(0.096)		(0.10)		(0.098)	
Slicks	-0.023		-0.022		-0.023		-0.022	
	(0.018)		(0.014)		(0.018)		(0.014)	
Unspecified	0.029		0.0033		0.024		-0.00064	
	(0.027)		(0.023)		(0.026)		(0.023)	
Secret × Additives		0.025*		0.025*		0.026*		0.026*
		(0.013)		(0.014)		(0.014)		(0.015)
Secret × Biocides		-0.020**		-0.016*		-0.019**		-0.015
		(0.0090)		(0.0092)		(0.0094)		(0.0096)
Secret × Breakers		-0.014		-0.027		-0.015		-0.028
		(0.031)		(0.022)		(0.032)		(0.022)
Secret × Gels		-0.0019		-0.022		-0.0032		-0.021
		(0.057)		(0.048)		(0.057)		(0.048)
Secret × Slicks		-0.0040		0.0050		-0.0011		0.0074
		(0.012)		(0.013)		(0.013)		(0.015)
Secret × Unspecified		0.023		0.013		0.023		0.013
		(0.014)		(0.0095)		(0.015)		(0.0096)
Constant	8.29***	9.63***	7.72***	8.99***	6.77***	8.20***	6.18***	7.55***
	(1.89)	(1.49)	(1.87)	(1.50)	(1.91)	(1.52)	(1.90)	(1.54)
Observations	298	298	298	298	298	298	298	298
R^2	0.085	0.069	0.088	0.065	0.086	0.067	0.090	0.063

Notes: Robust standard errors in parentheses.

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Table A10. Toxicity results

	(1) Log 6 Month Gas	(2) Log 6 Month Gas	(3) Log 12 Month Gas	(4) Log 12 Month Gas	(5) Log 6 Month BOE	(6) Log 6 Month BOE	(7) Log 12 Month BOE	(8) Log 12 Month BOE
Log Water Volume	0.24*	0.042	0.31**	0.17	0.23	0.035	0.30**	0.16
	(0.14)	(0.11)	(0.14)	(0.10)	(0.14)	(0.11)	(0.14)	(0.10)
Sand/Water Ratio	-1.40*	-0.51	-0.82	-0.21	-1.56*	-0.67	-0.98	-0.36
	(0.82)	(0.90)	(0.81)	(0.90)	(0.82)	(0.91)	(0.82)	(0.91)
Additives	0.022		0.032		0.026		0.036	
	(0.038)		(0.037)		(0.039)		(0.037)	
Biocides	0.0055		0.00016		0.0052		-0.00037	
	(0.010)		(0.0092)		(0.010)		(0.0093)	
Breakers	0.028**		0.019**		0.028**		0.019**	
	(0.013)		(0.0091)		(0.013)		(0.0092)	
Gels	0.041		0.069		0.043		0.071	
	(0.10)		(0.096)		(0.10)		(0.098)	
Slicks	-0.023		-0.022		-0.023		-0.022	
	(0.018)		(0.014)		(0.018)		(0.014)	
Unspecified	0.029		0.0033		0.024		-0.00064	
	(0.027)		(0.023)		(0.026)		(0.023)	
Toxic × Additives		-0.023		-0.011		-0.022		-0.0100
		(0.019)		(0.018)		(0.019)		(0.017)
Toxic × Breakers		0.0034		-0.014		0.00079		-0.016
		(0.012)		(0.011)		(0.012)		(0.011)
lToxic × Gels		-0.0090		-0.026		-0.0082		-0.025
		(0.026)		(0.022)		(0.026)		(0.022)
Toxic × Slicks		-0.048		-0.038		-0.051		-0.041
		(0.035)		(0.032)		(0.035)		(0.032)
Toxic × Unspecified		0.030		0.015		0.023		0.0087
		(0.053)		(0.050)		(0.053)		(0.051)
Constant	8.29***	10.6***	7.72***	9.21***	6.77***	8.94***	6.18***	7.60***
	(1.89)	(1.59)	(1.87)	(1.57)	(1.91)	(1.60)	(1.90)	(1.58)
Observations	298	298	298	298	298	298	298	298
R^2	0.085	0.086	0.088	0.085	0.086	0.088	0.090	0.088

Notes: Robust standard errors in parentheses.
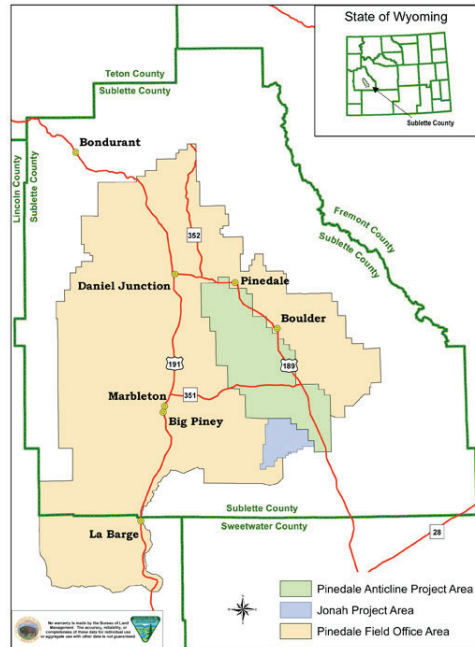
Table A11. Count model full results: secrecy

	(1) Poisson	(2) Negative Binomial	(3) OLS
Log Water Volume	-0.21***	-0.21***	-0.22**
	(0.048)	(0.048)	(0.095)
Sand/Water Ratio	1.21***	1.21***	2.99***
	(0.26)	(0.26)	(0.87)
Stages	0.027***	0.027***	0.035*
	(0.0071)	(0.0071)	(0.019)
Secret × Gels	0.14***	0.14***	0.80***
	(0.034)	(0.034)	(0.11)
Secret × Slicks	-0.46	-0.46	2.06***
	(0.58)	(0.58)	(0.29)
Secret × Unspecified	0.61***	0.61***	1.88***
	(0.045)	(0.045)	(0.066)
Operator I	-1.66	-1.66	2.16***
	(1.14)	(1.14)	(0.50)
Operator II	0.92	0.92	3.95***
	(1.66)	(1.66)	(1.14)
Service Company A	14.6***	13.7***	0.39*
	(0.46)	(0.52)	(0.23)
Service Company B	13.6***	12.7***	0.94
	(2.24)	(2.26)	(1.21)
Service Company C	14.6***	13.8***	0.43***
	(0.52)	(0.55)	(0.13)
2011	-0.080**	-0.080**	-0.052
	(0.039)	(0.039)	(0.15)
2012	-1.53***	-1.53***	0.46**
	(0.48)	(0.48)	(0.21)
2013	-0.90*	-0.90*	1.54***
	(0.46)	(0.46)	(0.28)
Constant	-10.7***	-9.79***	-0.58
	(1.74)	(1.76)	(1.55)
Indiv. Hetero.		-17.5***	
		(0.16)	
Observations	297	297	297
R^2			0.98

Notes: Dependent variable is count of all injected additives that are withheld as trade secrets. Point estimates with robust standard errors reported in parentheses.

Table A12. Count model full results: toxicity

	(1) Poisson	(2) Negative Binomial	(3) OLS
Log Water Volume	-0.24***	-0.24***	-1.44***
	(0.058)	(0.058)	(0.48)
Sand/Water Ratio	3.24***	3.24***	23.1***
	(0.55)	(0.55)	(5.34)
Stages	0.010**	0.010**	0.073*
	(0.0051)	(0.0051)	(0.039)
Secret × Gels	0.096**	0.096**	0.28
	(0.042)	(0.042)	(0.29)
Secret × Slicks	0.073	0.073	0.80**
	(0.055)	(0.055)	(0.37)
Secret × Unspecified	-0.067***	-0.067***	-0.42***
	(0.020)	(0.020)	(0.12)
Operator I	0.64***	0.64***	4.99***
	(0.13)	(0.13)	(1.09)
Operator II	0.079	0.079	-1.16
	(0.17)	(0.17)	(1.07)
Service Company A	-0.23*	-0.23*	-1.65
	(0.12)	(0.12)	(1.06)
Service Company B	0.61***	0.61***	6.56***
	(0.20)	(0.20)	(1.59)
Service Company C	-0.088	-0.088	-0.64
	(0.061)	(0.061)	(0.55)
2011	0.0091	0.0091	0.070
	(0.080)	(0.080)	(0.67)
2012	0.45***	0.45***	2.55***
	(0.085)	(0.085)	(0.69)
2013	0.44***	0.44***	2.23***
	(0.097)	(0.097)	(0.81)
Constant	4.03***	4.03***	18.5***
	(0.83)	(0.83)	(7.00)
Indiv. Hetero.		-17.5***	
		(0.064)	
Observations	297	297	297
R^2			0.71

Notes: Dependent variable is count of all injected additives that are with-held as trade secrets. Point estimates with robust standard errors reported in parentheses.

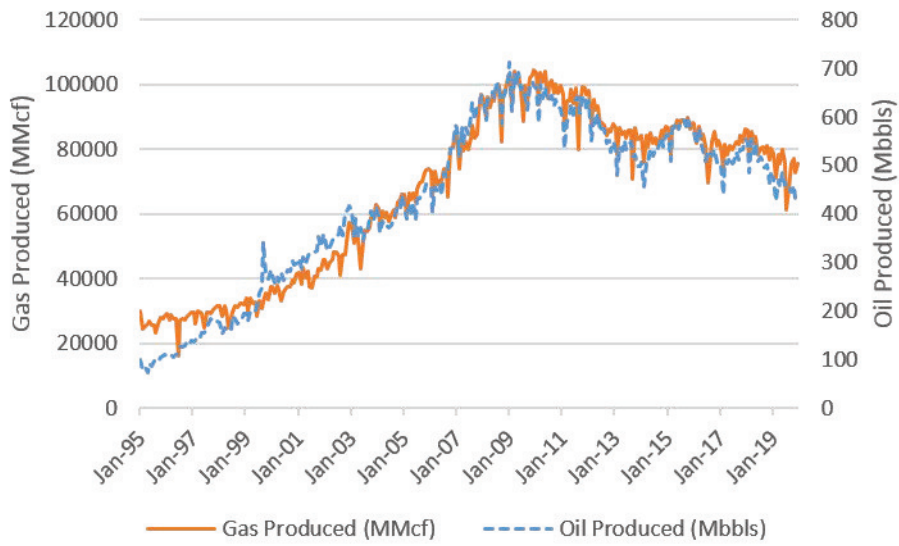Figure A1. Sublette County, Wyoming

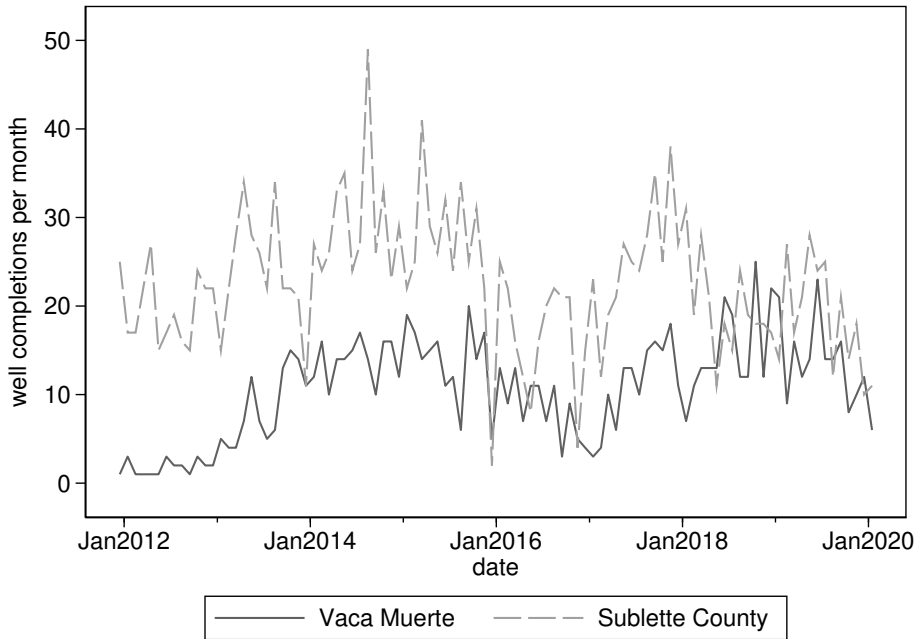Figure A2. Monthly oil and gas production in Sublette County.
Source: WOGCC.

Figure A3. Well completions: Vaca Muerta vs. Sublette County, Wyoming, 2012–2019.

Source: Enverus; Secretaria de Energia, Argentina.

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