

Supplementary Materials for

The intensification of the water footprint of hydraulic fracturing

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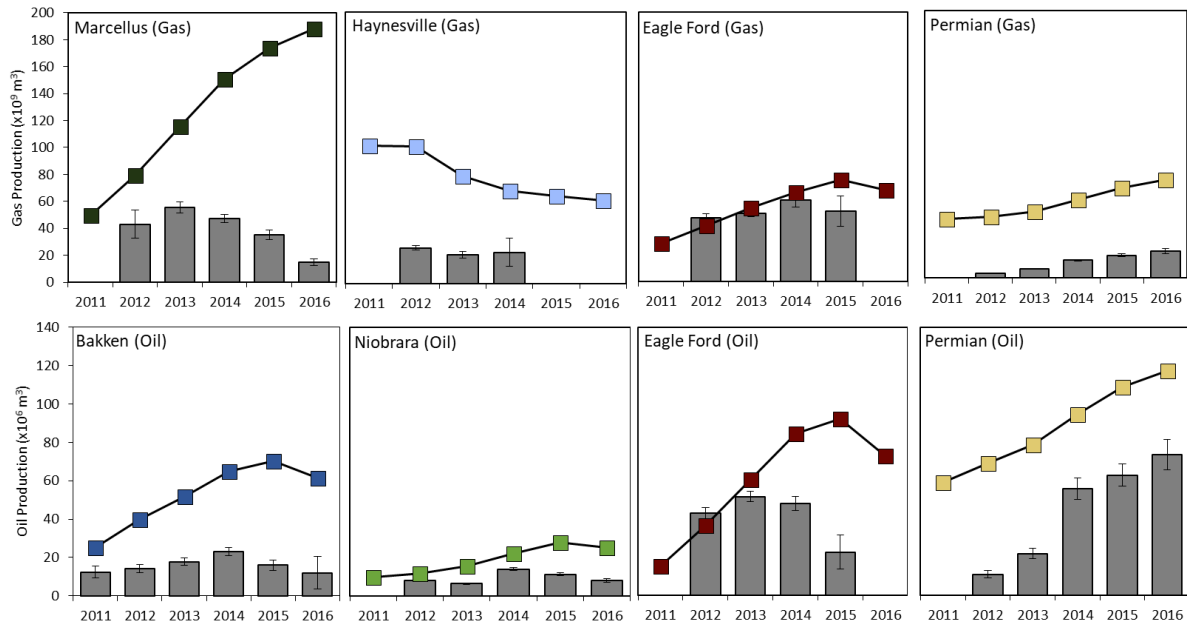


Fig. S1. Cumulative production comparison. Total hydrocarbon production (connected squares) and year-one cumulative production (bars) for each unconventional shale gas producing region (top row) and unconventional tight oil producing region (bottom). Total annual hydrocarbon production volumes were calculated by multiplying daily production values for each month from the EIA’s drilling productivity report by the number of days in that month, then adding up monthly production for each year (31). Year one cumulative hydrocarbon production was calculated by multiplying the well count estimate by the production per well volumes for each year (table S1). Whiskers represent 95% bootstrap confidence intervals.

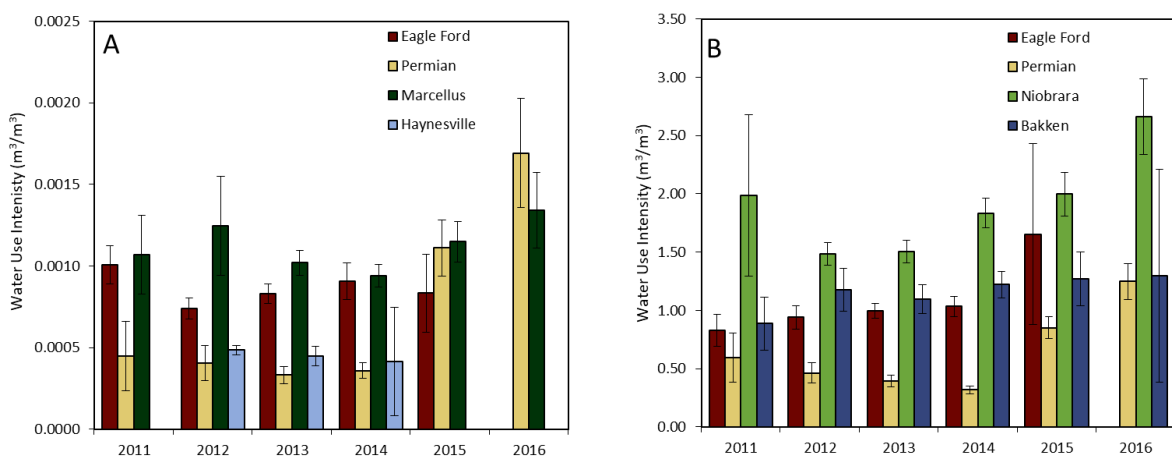


Fig. S2. Volumetric water-use intensity. Volumetric water use intensities for shale gas (A) and tight oil (B) basins. Ratios are reported as the ratio between volume injected water (m³) and volume of produced hydrocarbon (m³). Whiskers represent 95% bootstrap confidence intervals.

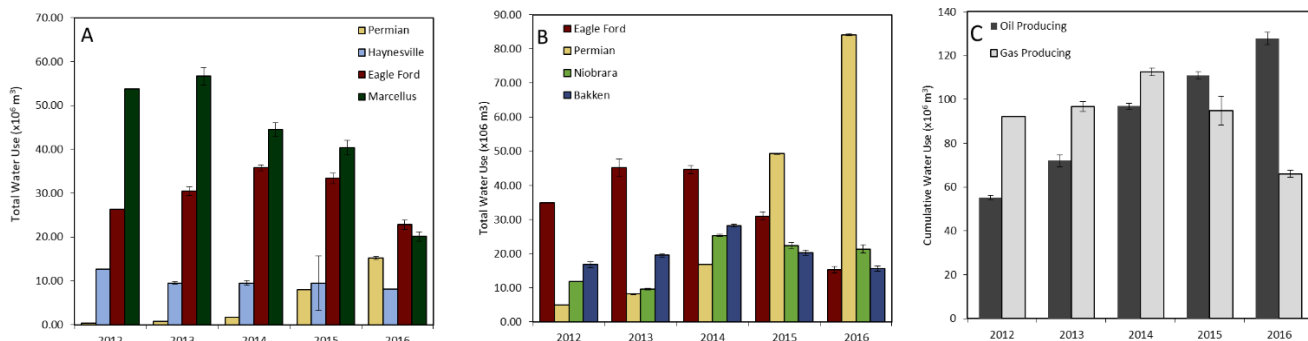


Fig. S3. Total water use for hydraulic fracturing. Total water use for hydraulic fracturing in shale gas (A) and tight oil (B) producing formations. Total water use was calculated by multiplying the number of wells in each year by the median production volume within a given year (table S1). Cumulative water use volume (C) for shale gas (grey) and tight oil (black) producing regions in this study from 2012 to 2016 was calculated by adding up values in panel A and B. Whiskers represent 95% bootstrap confidence intervals.

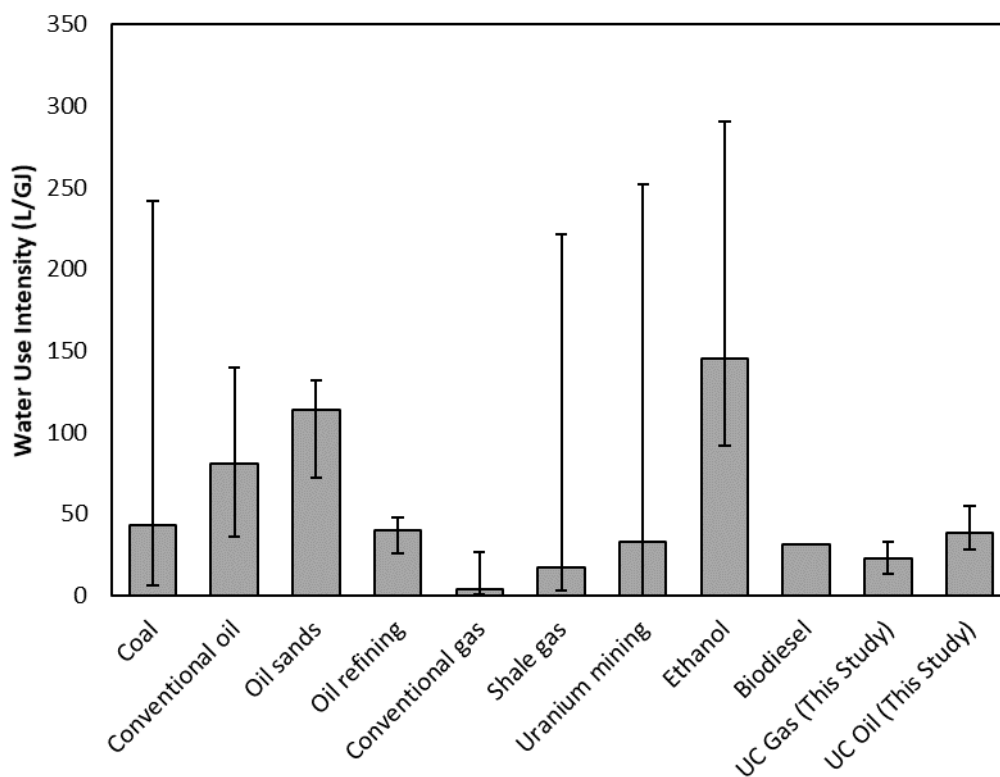


Fig. S4. Water-use intensity for other energy-producing materials. Water use intensity (L/GJ) for a number of energy sources compared to the results for this study (33). Shaded columns indicate average water use intensity, while the whiskers show minimum and maximum observed values.

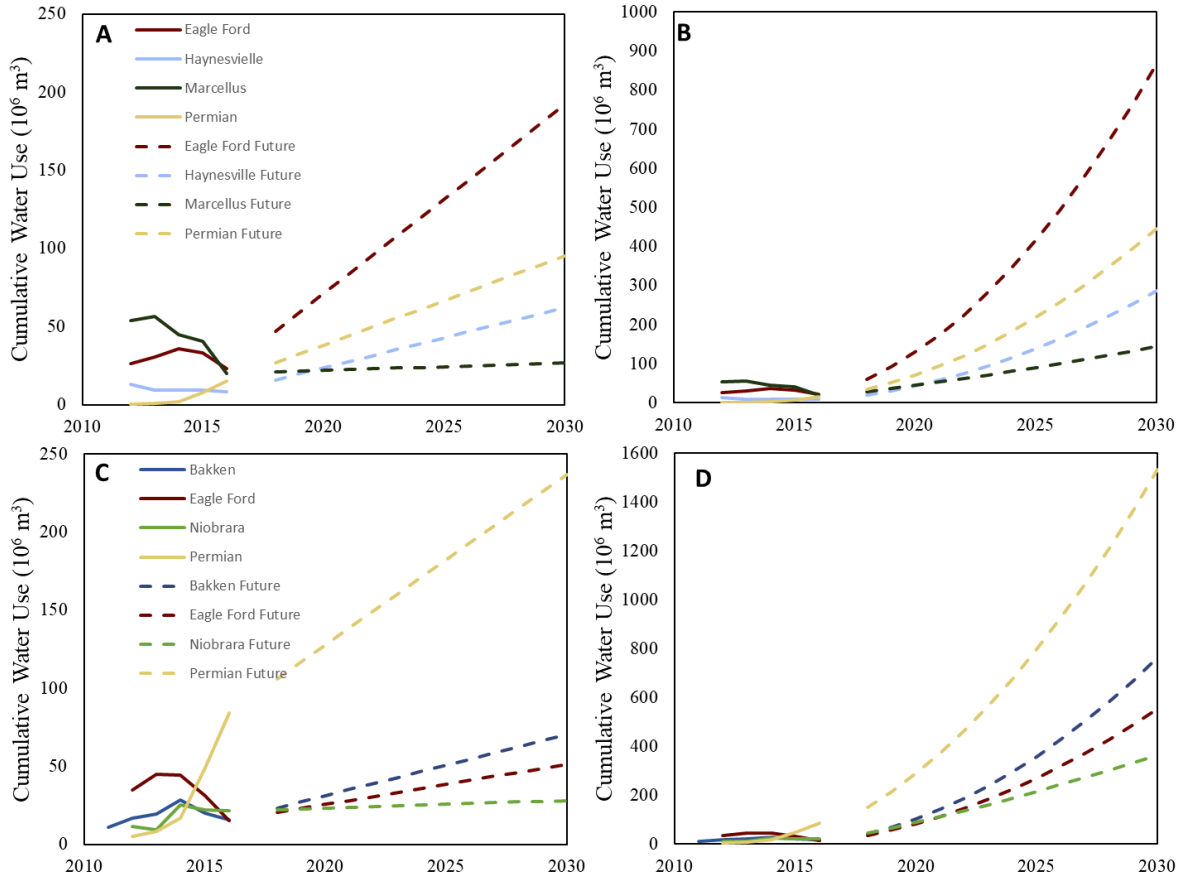


Fig. S5. Projected water use for future hydraulic fracturing operations in the United States. Water use (in million m^3) predictions for unconventional gas (**A** and **B**) and unconventional oil (**C** and **D**) producing regions. Predictions for the business as usual scenario (**A** and **C**) show total water use predictions assuming drilling rates will stay at 2016 levels, while the future increase scenario (**B** and **D**) show total water use predictions by assuming drilling rates will match the previously high rates seen in each shale basin.

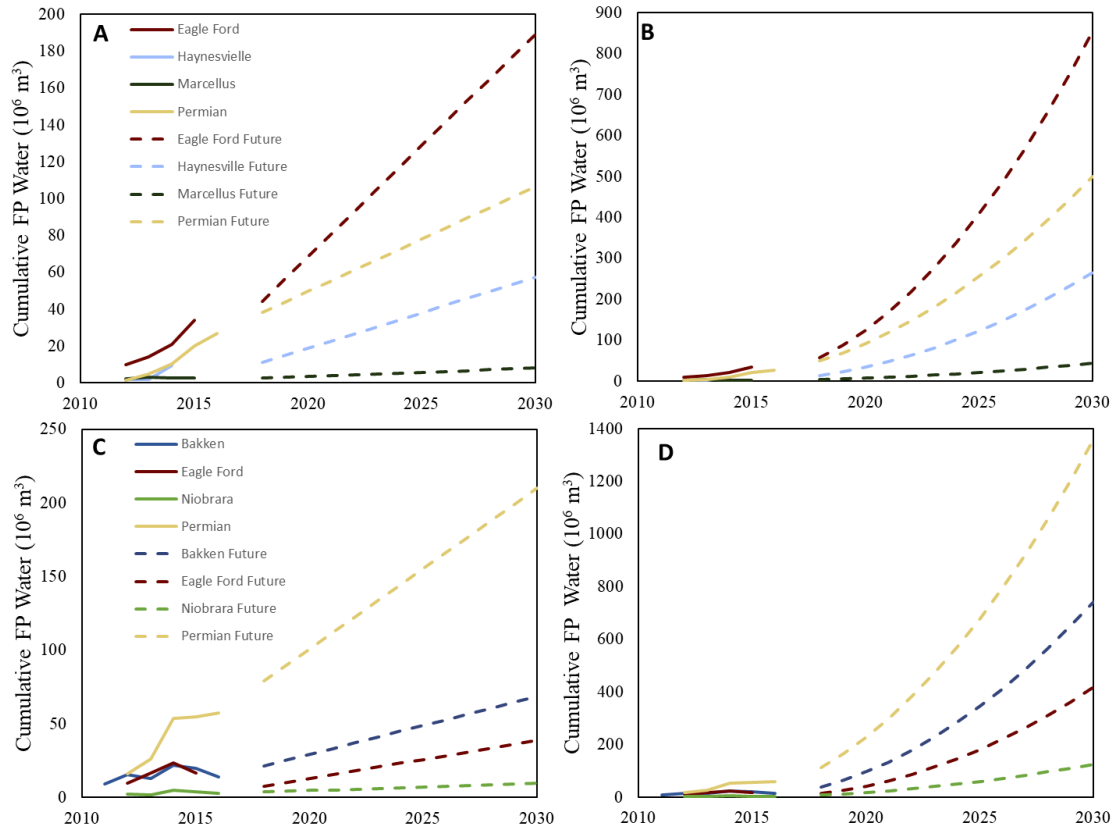


Fig. S6. Projected first year FP water derived from future hydraulic fracturing operations in the United States. Cumulative FP water from the first 12 months of production (in million m³) predicted for unconventional gas (**A** and **B**) and unconventional oil (**C** and **D**) producing regions. Predictions for the business as usual scenario (**A** and **C**) show FP water predictions assuming that drilling rates will stay at 2016 levels, while the future increase scenario (**B** and **D**) show FP water predictions assuming that drilling rates will match previously high drilling rates seen in each shale basin.

Table S1. Production volumes in unconventional gas-producing formations. Estimates of well count, median values for water use, gas, oil, and FP production per well from each of the gas producing regions. Data for 2017 is shown but not used in the report because there were not a reasonable number of observations available to draw relevant conclusions. Marcellus data was available on a year by year basis from 2011-2015, and thus all Marcellus FP water data is reported as 12 month cumulative production. EUR estimate was calculated by assuming that the first 12 months of production represent approximately 35% of total well production. Note: this calculation is simple model of estimating ultimate recovery; performing decline curve analysis can give a much more realistic estimate for ultimate recovery. * marks years when less than 5% of the well count within a region have DrillingInfo (35) reports. ** marks years when Marcellus formation data from DrillingInfo were replaced with data from PADEP (36). Water use intensity, waste water intensity, and water use/gas and water use/FP water ratios for shale gas producing regions. The

Formation	Year	Well Counts	Water Use	Laterals (meters/well)	Water Use/Lateral Length	Gas Production (m ³ /well)	Oil Production (m ³ /well)	FP Water (m ³ /well)	Water Use Intensity for All Products	Water Use Intensity for All Products	Waste Water Intensity for	Water Use/Gas	Water Use/FP Water
		New Wells/Year	(m ³ /well)	Lateral Length	(m ³ /m)	First 12 Months	First 12 Months	First 12 Months	(L/GJ) EUR Estimate	(L/GJ) First 12 months	(L/GJ) First 12 months	m ³ /m ³	m ³ /m ³
EF (gas)	2011		17870	1480	12.08	17771454	6461	1343	5.03	14.37	1.44	0.0010	0.08
EF (gas)	2012	1966	13360	1507	8.87	16056108	6040	4910	5.15	14.72	5.29	0.0007	0.37
EF (gas)	2013	2230	13652	1560	8.75	16456747	6274	6408	5.74	16.40	7.35	0.0008	0.47
EF (gas)	2014	2503	14297	1512	9.46	15766239	8249	8294	7.81	22.31	9.09	0.0009	0.58
EF (gas)	2015	1639	20363	1572	12.96	24401224	7425	20705	6.57	18.78	16.57	0.0008	1.02
EF (gas)	2016*	973	23457										
Haynesville	2011			1352		49392272	13	4663					
Haynesville	2012	461	27585	1347	20.48	56903034	8	3853	2.72	7.76	1.38	0.0005	0.14
Haynesville	2013	397	23943	1347	17.78	53306447	9	4911	4.02	11.50	1.87	0.0004	0.21
Haynesville	2014	467	20359	1324	15.38	49152202	22	20238	4.70	13.43	8.37	0.0004	0.99
Haynesville	2015*	340	27804										
Haynesville	2016*	251	32328										
Marcellus	2011		23401	1124	20.82	21865936	1000	567	7.39	21.12	0.51	0.0011	0.02
Marcellus	2012	1938	27703	1101	25.16	22246358	40	1054	8.85	25.28	0.96	0.0012	0.04
Marcellus	2013	2182	25955	1244	20.86	25463090	4252	1342	6.53	18.67	0.96	0.0010	0.05
Marcellus	2014	1649	26395	1342	20.12	28665521	694	1564	6.59	18.84	1.09	0.0009	0.06
Marcellus	2015**	1210	33357			29025671		2204	8.18	23.36	1.54	0.0011	0.07
Marcellus	2016**	720	27958			20836518			9.55	27.28		0.0013	
Permian (gas)	2011		4897	1138	4.30	10915036	3642	14233	3.93	11.22	32.62	0.0004	2.91
Permian (gas)	2012	82	4868	1186	4.10	11983033	4243	15680	3.52	10.06	32.40	0.0004	3.22
Permian (gas)	2013	150	5531	1294	4.27	16705199	6306	30372	2.75	7.84	43.07	0.0003	5.49
Permian (gas)	2014	232	7277	1358	5.36	20331972	11643	44084	2.53	7.24	43.83	0.0004	6.06
Permian (gas)	2015	334	23812	1421	16.75	21443548	14256	60031	7.51	21.47	54.12	0.0011	2.52
Permian (gas)	2016	358	42560	1428	29.80	25151817	16734	74471	11.48	32.79	57.37	0.0017	1.75

Table S2. Production volumes in unconventional oil-producing formations. Estimates of well count, median values for water use, gas, oil, and FP production per well from each oil producing region. Data for 2017 is shown but not used in the report because there were not a reasonable number of observations available to draw relevant conclusions. Water use intensity, waste water intensity, and water use/gas and water use/FP water ratios for oil producing regions. The EUR estimate was calculated by assuming that the first 12 months of production represent approximately 35% of total well production. Note: this calculation is simple model of estimating ultimate recovery; performing decline curve analysis can give a much more realistic estimate for ultimate recovery. * Years when less than 5% of the well count within a region have DrillingInfo (35) reports.

Formation	Year	Well Counts	Water Use	Laterals (meters/well)	Water Use/Lateral Length	Gas Production (m ³ /well)	Oil Production (m ³ /well)	FP Water (m ³ /well)	Water Use Intensity for All Products	Water Use Intensity for All Products	Waste Water Intensity for	Water Use/Oil	FP Water/ Water Use
		New Wells/Year	(m ³ /well)	Lateral Length	(m ³ /m)	First 12 Months	First 12 Months	First 12 Months	(L/GJ) EUR Estimate	(L/GJ) First 12 months	(L/GJ) First 12 months	m ³ /m ³	m ³ /m ³
Bakken	2011	1528	7166	2904	2.47	997884	8083	5965	7.28	20.80	17.31	0.89	0.83
Bakken	2012	2086	8047	2919	2.76	814589	6842	7437	9.69	27.68	25.58	1.18	0.92
Bakken	2013	2254	8655	2896	2.99	887576	7878	5842	9.10	25.99	17.54	1.10	0.68
Bakken	2014	2480	11381	2911	3.91	1247044	9320	8878	9.94	28.41	22.16	1.22	0.78
Bakken	2015*	1483	13661	2957	4.62	1486009	10751	13390	10.31	29.46	28.88	1.27	0.98
Bakken	2016*	738	21128	2940	7.19	3545985	16275	18688	9.92	28.35	25.07	1.30	0.88
EF (oil)	2011		16028	1631	9.83	3132235	19334	2385	9.34	26.69	3.37	0.83	0.15
EF (oil)	2012	1822	19110	1647	11.60	3183799	20326	5395	10.19	29.10	8.22	0.94	0.28
EF (oil)	2013	2165	20856	1691	12.34	2872626	20949	7722	11.04	31.54	11.68	1.00	0.37
EF (oil)	2014	1778	25112	1809	13.88	2850382	24303	13350	12.44	35.53	18.89	1.03	0.53
EF (oil)	2015*	999	31071	1791	17.35	3902027	18790	16328	19.14	54.67	29.79	1.65	0.54
EF (oil)	2016*	457	33492								202.68		
Niobrara (oil)	2011		8997	1481	6.07	1613647	4529	1823	13.78	39.38	7.98	1.99	0.20
Niobrara (oil)	2012	1217	9682	1292	7.49	3577360	6511	2104	9.14	26.13	5.68	1.49	0.22
Niobrara (oil)	2013	933	10324	1177	8.77	3738809	6861	2163	9.28	26.51	5.55	1.50	0.21
Niobrara (oil)	2014	1814	13971	1277	10.94	4512622	7616	2667	11.00	31.43	6.00	1.83	0.19
Niobrara (oil)	2015	1347	16570	1433	11.56	4561893	8295	2859	12.28	35.08	6.05	2.00	0.17
Niobrara (oil)	2016	959	22296	2141	10.42	5770553	8378	2959	15.12	43.21	5.74	2.66	0.13
Permian (oil)	2011		4897	1254	3.91	2083055	8252	10070	4.42	12.64	25.99	0.59	2.06
Permian (oil)	2012	1009	4868	1276	3.81	2421554	10507	15841	3.51	10.02	32.62	0.46	3.25
Permian (oil)	2013	1487	5531	1316	4.20	2916234	14064	17612	3.03	8.65	27.55	0.39	3.18
Permian (oil)	2014	2319	7277	1363	5.34	3706457	22836	23123	2.54	7.25	23.05	0.32	3.18
Permian (oil)	2015	2070	23812	1364	17.46	4728552	28023	26578	6.74	19.25	21.48	0.85	1.12
Permian (oil)	2016	1977	42560	2243	18.97	5649697	34128	29021	9.91	28.32	19.31	1.25	0.68

Table S3. Example calculation for future production estimate, business-as-usual scenario. This data set was used to generate fig. S5, A and C. Water use slope is the maximum difference between two consecutive years of production. In the case of the Bakken, water use in 2016 was 21,128 m³/well and water use in 2015 was 13,661 m³/well (fig. S2). The difference between those two, 7,467 m³/well is the slope, or maximum amount of change seen in water use over a one-year period.

Region		Bakken	Eagle Ford (oil)*	Niobrara	Permian (oil)	Eagle Ford (gas)*	Haynesville**	Marcellus**	Permian (gas)
Slope (additional wells per year)		0	0	0	0	0	0	0	0
2016 Well Count		738	457	959	1977	973	251	720	358
2016 Water Use (m ³)		21128	33492	22296	42560	23457	32328	27958	42560
2016 FP Water (m ³)		18688	6008	2959	29021	20705	13327	2204	74471
Water Use Slope (m ³ /well/year)		7467	5959	5726	18749	6067	7444	6362	18749
FP Water Slope (m ³ /well/year)		5298	5628	504	5511	12411	15327	640	15947
New Wells Drilled This Year	2018	738	457	959	1977	973	251	720	358
	2019	738	457	959	1977	973	251	720	358
	2020	738	457	959	1977	973	251	720	358
	2021	738	457	959	1977	973	251	720	358
	2022	738	457	959	1977	973	251	720	358
	2023	738	457	959	1977	973	251	720	358
	2024	738	457	959	1977	973	251	720	358
	2025	738	457	959	1977	973	251	720	358
	2026	738	457	959	1977	973	251	720	358
	2027	738	457	959	1977	973	251	720	358
	2028	738	457	959	1977	973	251	720	358
	2029	738	457	959	1977	973	251	720	358
2030	738	457	959	1977	973	251	720	358	
Cumulative Water Use (10 ⁶ m ³)	2018	23	20	22	106	47	16	21	27
	2019	27	23	23	117	59	20	22	32
	2020	31	26	23	128	71	24	22	38
	2021	35	28	24	139	83	27	22	44
	2022	39	31	24	150	95	31	23	49
	2023	43	33	25	160	107	35	23	55
	2024	47	36	25	171	119	39	24	61
	2025	51	38	26	182	131	43	24	67
	2026	55	41	26	193	144	47	25	72
	2027	59	44	27	204	156	50	25	78
	2028	63	46	27	215	168	54	26	84
	2029	66	49	28	226	180	58	26	89
2030	70	51	28	237	192	62	27	95	

Table S4. Example calculation for future production estimate, future growth scenario. This data set was used to generate fig. S5, B and D. Slope is the maximum difference between two consecutive years' worth of data.

Region	Bakken	Eagle Ford (oil)*	Niobrara	Permian (oil)	Eagle Ford (gas)*	Haynesville**	Marcellus**	Permian (gas)	
Slope (new wells per year)	558	343	881	832	263	70	244	102	
2016 Well Count	738	457	959	1977	973	251	720	358	
2016 Water Use (m ³)	21128	33492	22296	42560	23457	32328	27958	42560	
2016 FP Water (m ³)	18688	6008	2959	29021	20705	13327	2204	74471	
Water Use Slope (m ³ /well/year)	7467	5959	5726	18749	6067	7444	6362	18749	
FP Water Slope (m ³ /well/year)	5298	5628	504	5511	12411	15327	640	15947	
New Wells Drilled This Year	2018	1296	800	1840	2809	1236	321	964	460
	2019	1854	1143	2721	3641	1499	391	1208	561
	2020	2412	1486	3602	4473	1762	461	1452	663
	2021	2970	1829	4483	5305	2026	531	1696	765
	2022	3528	2172	5364	6137	2289	601	1940	866
	2023	4086	2514	6245	6969	2552	671	2184	968
	2024	4644	2857	7126	7800	2815	741	2428	1070
	2025	5202	3200	8006	8632	3079	811	2672	1171
	2026	5760	3543	8887	9464	3342	881	2916	1273
	2027	6318	3886	9768	10296	3605	951	3160	1374
	2028	6876	4229	10649	11128	3868	1021	3404	1476
	2029	7434	4571	11530	11960	4132	1091	3648	1578
2030	7992	4914	12411	12792	4395	1161	3892	1679	
Cumulative Water Use (10 m ³)	2018	41	36	43	151	60	20	28	34
	2019	69	58	65	215	91	31	36	51
	2020	102	83	88	289	129	43	44	71
	2021	141	113	111	372	173	58	53	94
	2022	187	146	136	464	224	75	62	120
	2023	238	183	161	565	282	94	71	149
	2024	295	224	188	676	346	115	80	182
	2025	358	269	215	796	416	138	90	218
	2026	427	318	243	924	493	164	100	257
	2027	502	371	272	1062	577	191	111	300
	2028	582	427	302	1209	667	221	121	345
	2029	669	488	333	1366	763	253	132	394
2030	762	552	364	1531	867	287	144	446	