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Supplementary Materials for

Ecosystem services lost to oil and gas in North America

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Published 24 April 2015, *Science* **348**, 401 (2015)
DOI: 10.1126/science.aaa4785

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Other Supplementary Material for this manuscript includes the following:
(available at www.sciencemag.org/content/348/6233/401/suppl/DC1)

Code for analyses as zipped archive

Supplementary Materials

Materials and Methods

Well data

We utilized proprietary (purchased from state oil and gas commissions, IHS Inc.) and publicly available well data to examine trade-offs in ecosystem services (see Table S1). Data were aggregated by state/province and consisted of: spatial geometry (latitude, longitude), drill date, license date, and fluid type. We identified the drilling of wells based on unique combinations of spatial geometry and drill date. License date was substituted for drill date when the latter was unavailable. Wells with no dates (the majority of which occurred within the states of Kansas and Texas, approximately 86,000 and 194,000 wells, respectively) were excluded from analyses. We filtered wells by fluid type and included only oil, gas, coalbed methane, and 'not available' fluid types in analyses.

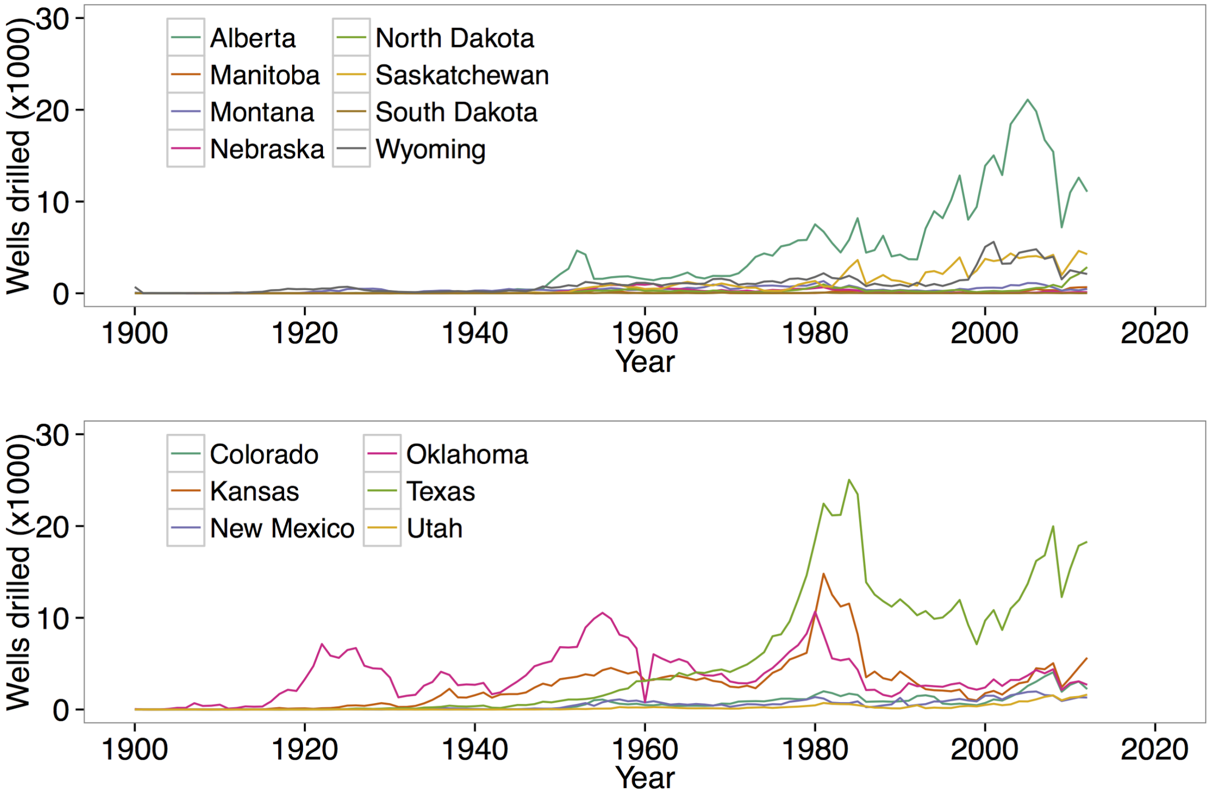


Figure S1. The number of oil and gas wells from 1900 to 2012, separated by state and province.

Table S1. Well data location sources.

Province/State	Source	URL	Data availability
Alberta	IHS, Inc.	https://www.ihs.com/	restricted[1]
Saskatchewan	IHS, Inc.	https://www.ihs.com/	restricted[1]
Manitoba	IHS, Inc.	https://www.ihs.com/	restricted[1]
Montana	IHS, Inc.	https://www.ihs.com/	restricted[1]
North Dakota	IHS, Inc.	https://www.ihs.com/	restricted[1]
Wyoming	IHS, Inc.	https://www.ihs.com/	restricted[1]
South Dakota	South Dakota Geological Survey Program	http://www.sdgs.usd.edu/	online
Nebraska	Nebraska Oil and Gas Conservation Commission	http://www.nogcc.ne.gov/	online
Utah	Utah Oil and Gas	http://oilgas.ogm.utah.gov/	online
Colorado	Colorado Oil and Gas Conservation Commission	http://cogcc.state.co.us/	online
Kansas	Kansas Geological Survey	http://www.kgs.ku.edu/	online
New Mexico	New Mexico GO-TECH	http://octane.nmt.edu/gotech/	online
Oklahoma	Oklahoma Corporation Commission	http://www.occeweb.com/	restricted[2]
Texas	Railroad Commission of Texas	http://www.rrc.state.tx.us/	restricted[3]

[1] Redistribution of data restricted. Contact IHS Sales: +1-844-301-7334

[2] Redistribution of data restricted. Contact OCC: +1-405-521-2211

[3] Redistribution of data restricted. Contact RRC: +1-877-228-5740

Code

Code for analyses can be found in the accompanying file “scienceCode.zip”. Examine the README file first.

Years 2000 to 2012 analysis

We performed analyses for the 2000 to 2012 time period annually with cumulative effects (i.e., 2005 analysis included wells drilled 2000 to 2005).

Disturbance index

We utilized a modified disturbance index (*23*) to detect immediate impacts and loss of vegetation for each individual well to provide independent evidence of vegetation degradation due to well establishment. The algorithm utilizes land surface temperature (LST) and normalized difference vegetation index (NDVI) to detect disturbances and changes in vegetation at the land surface. The disturbance index is defined as:

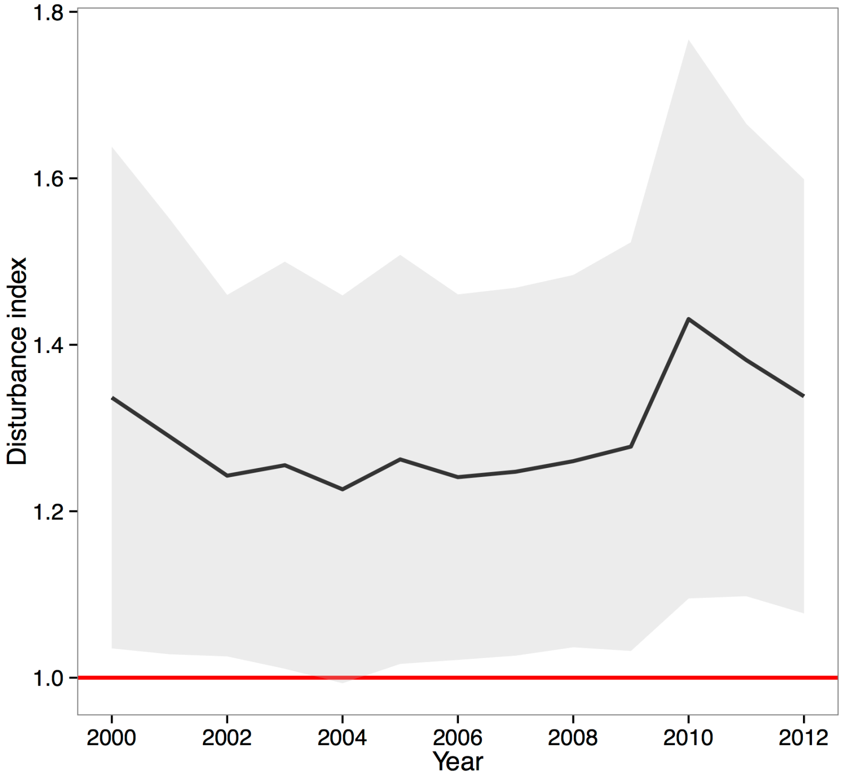


Figure S2. Mean disturbance index (black line) and standard deviation (gray shading) for wells drilled 2000 to 2012. Red line represents 1.0 or the multiyear mean prior to drilling. Values greater than the multiyear mean represent disturbance and loss of vegetation. Though variable, areas surrounding wells yielded disturbance indices indicative of change and loss of vegetation immediately following drilling.

Satellite vegetation indices

The normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI) are satellite-derived measures of live green vegetation that have been well documented to strongly correlate with NPP, especially for seasonal grassland and rangeland ecosystems (*27*). Thus, assessing trends in NDVI and EVI data in areas of high well density can provide independent evidence of vegetation degradation due to well establishment at the large scale.

We quantified the impact of well development on 30 m^2 Landsat annual maximum NDVI data for the period 1984–2011 for a small region in Wheeler County, TX, USA. The full annual maximum NDVI time series (1984–2011) was retrieved for all pixels that experienced new well development within a given year from 2000 to 2011 using Google Earth Engine (*26*). We then plotted the mean and standard deviation of these time-series data for all years from 2000 to 2011, which revealed a significant, temporally persistent reduction in annual maximum NDVI following well establishment. These results indicate that NDVI is reduced by roughly 50% following well establishment and does not recover over the timeframe of the analysis.

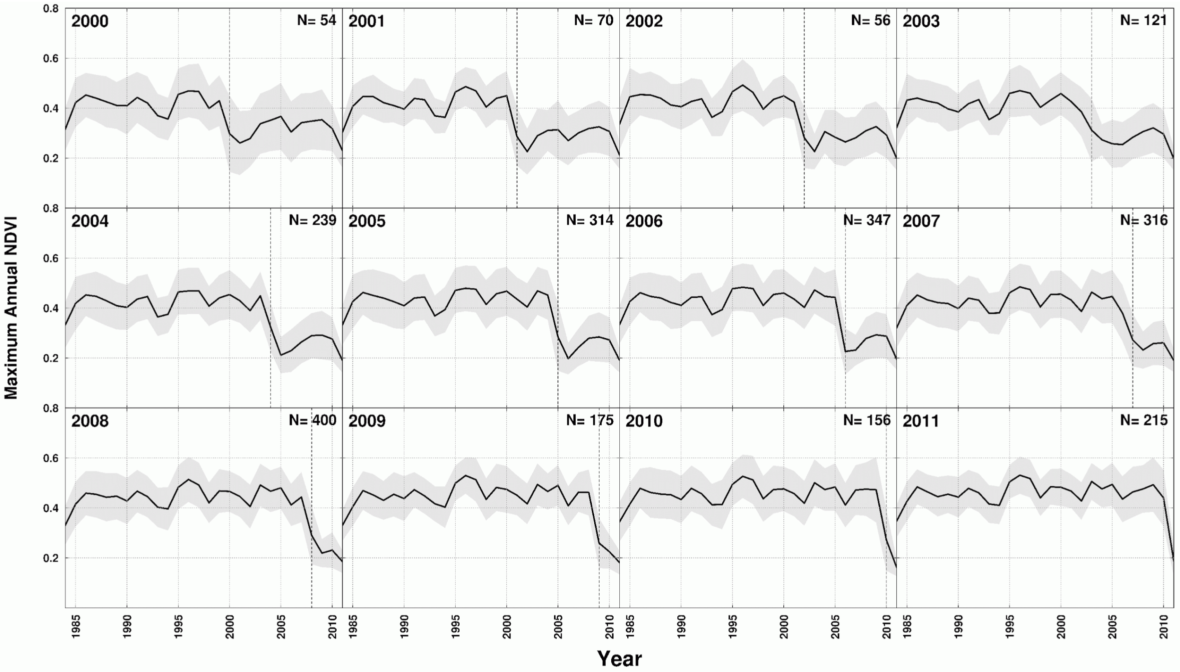


Figure S3. The pixel-level mean change in 30 m^2 Landsat 5 annual maximum NDVI data due to well development for all wells established from 2000 to 2011 for a small region in Wheeler County, TX, USA. Mean (black lines) and standard deviation (gray shading) across the total number of wells established (N) in a given year (2000–2011) are shown. Vertical dashed lines indicate the year of well establishment. A roughly 50% reduction in NDVI data is observable following well establishment for all years considered, and the reduction is shown to persist through time.

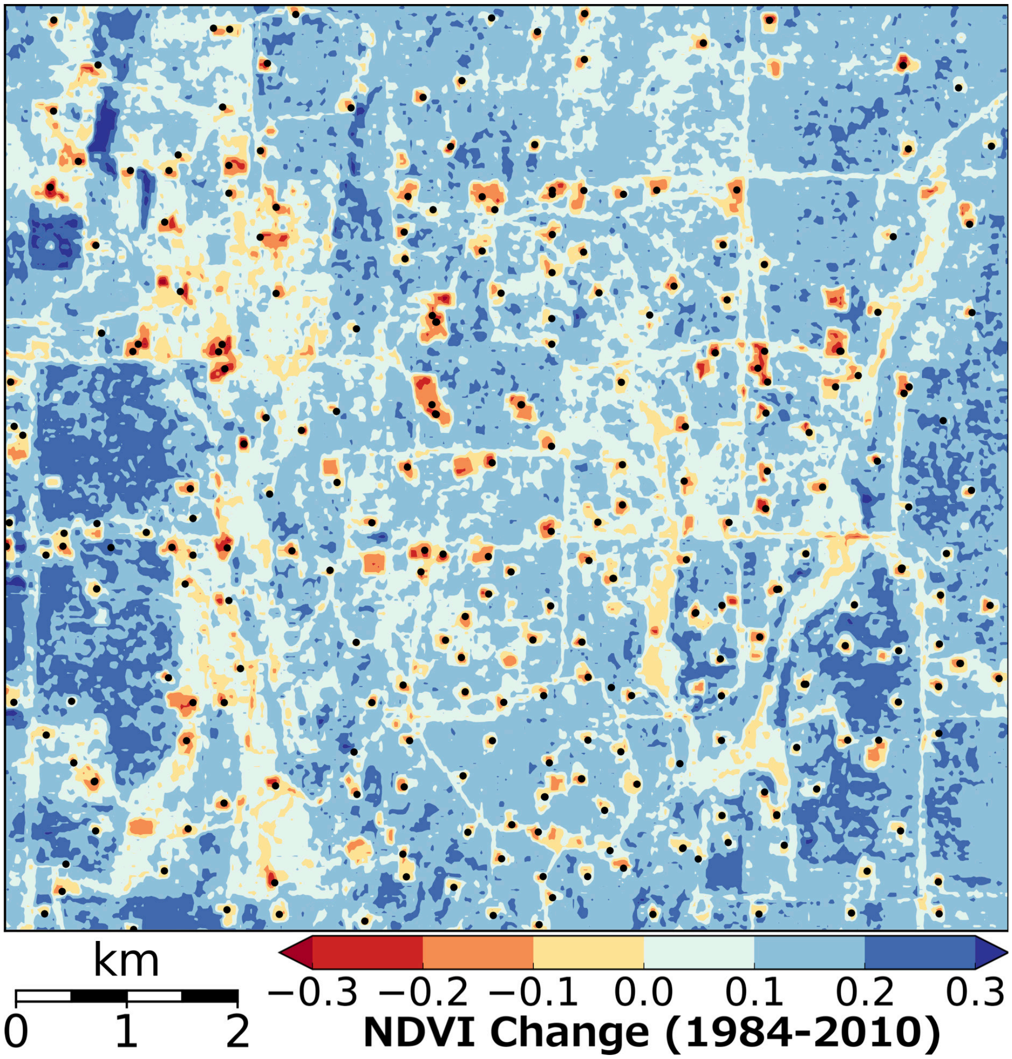


Figure S4. Change in normalized difference vegetation index (NDVI) of an area in Wheeler County, TX, USA from 1984 to 2010 at 30 m^2 spatial resolution. The change in NDVI shows the reduction in landscape productivity and connectivity due to increased oil and gas drilling. Black dots represent wells drilled from 1984 to 2010.

We further quantified the impact of well development on 250 m^2 MODIS EVI data, available at https://lpdaac.usgs.gov/products/modis_products_table (*28*). We aggregated 16-day EVI data to annual maximum EVI for the full study period 2000–2012. All cloud and ice contaminated pixels were removed prior to the data aggregation. Next, the pixel-level correlation coefficient between annual well density (determined at the same spatial resolution of 250 m^2) and detrended annual maximum EVI was calculated. We then grouped the resulting pixel-level correlation coefficients according to the number of wells established over the time period and plotted the distributions. The results of the analysis indicate a strong negative correlation between annual maximum EVI and well establishment that becomes more negative as the number of wells increases. These results provide additional independent support for a large scale degradation of vegetation productivity due to well establishment. However, we also find large noise exists in the distributions which may be due to the high spatial heterogeneity of well establishment.

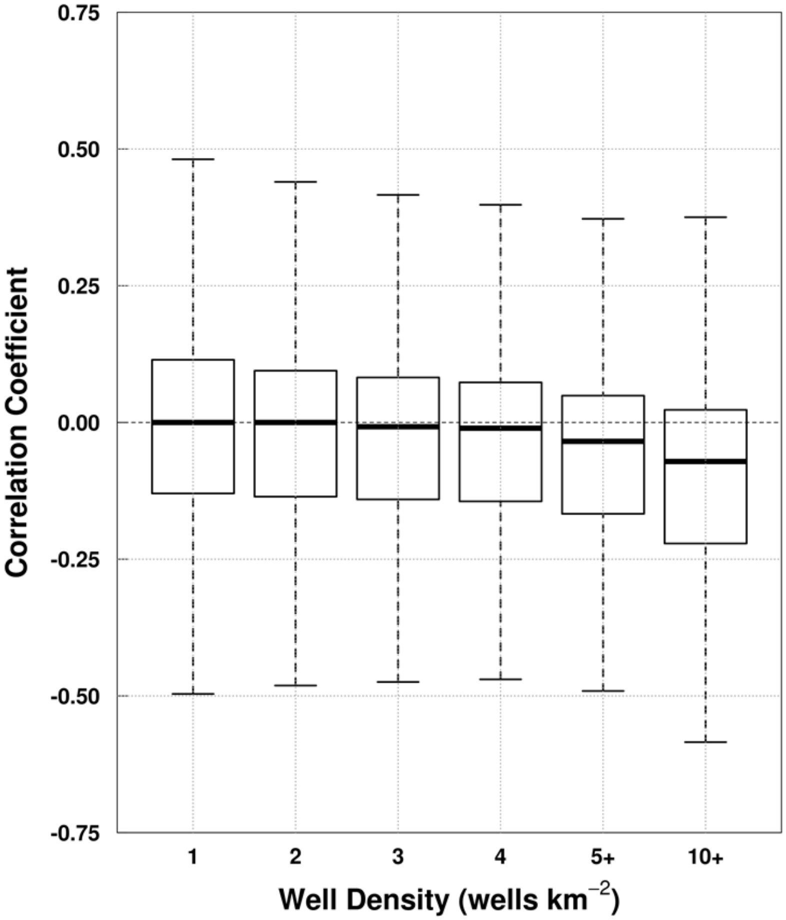


Figure S5. The pixel-level distribution of well density and detrended 250 m^2 MODIS annual maximum EVI correlation coefficients for the full study region from 2000 to 2012. The results of the analysis indicate a strong negative correlation between annual maximum EVI and well establishment that becomes more negative as well density increases. Noise in the data is likely attributable to the spatially heterogeneous impact of well establishment on vegetation productivity.

Net primary production

At the broader spatial resolution of available net primary production data (NPP; ~1 km^2), individual oil and gas disturbance events are difficult to resolve, resulting in a general lack of accounting. However, by integrating high-resolution (30 m^2 to 250 m^2) estimates of vegetation displacement due to oil and gas disturbance with estimates of the density of oil and gas wells at 1 km^2 spatial resolution, we provide a first estimate of the large-scale impact of oil and gas well expansion on NPP. We used 30 arc sec (~1 km^2) MODIS NPP data averaged over the 2000–2012 period to estimate mean annual NPP (*9*). We calculated well density on the same grid as MODIS NPP data. We estimated NPP reductions annually using a linear ramp function from 0 to 10 wells km^{-2}, such that densities of zero wells related to a 0% reduction in NPP, whereas densities of 10 wells related to a 33% reduction in NPP. We capped the reduction in NPP at 33%, although some areas had well densities much greater than 10 wells km^{-2}. Our previous high-resolution analyses showed vegetation displacement roughly equivalent to 5.67 ha well^{-1} or 0.0567 km^2 well^{-1}, a value supported by previous research (*29*). Although 10 wells within a 1 km^2 area would have an estimated impact of 10 x 0.0567 km^2 or ~ 0.5 km^2 (an approximate 50% reduction in NPP), we chose a more conservative estimate of 0.33 km^2 (an approximate 33% reduction) due to multi-well pads, etc. Reductions in NPP were categorized relative to land cover, determined by the 2005 North American Land Cover Monitoring System. MODIS NPP data can be downloaded from http://www.ntsg.umt.edu/project/mod17.

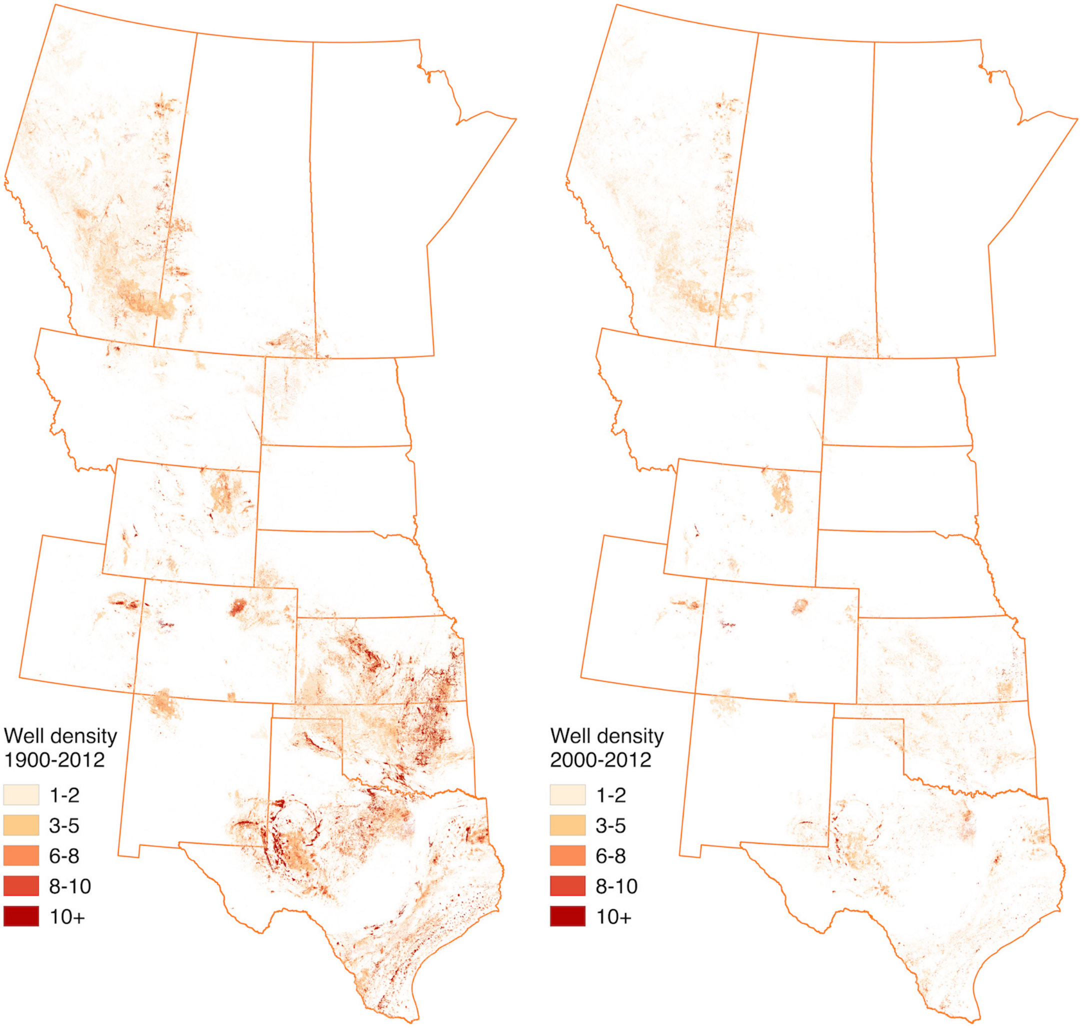


Figure S6. Oil and gas well density (wells km^{-2}) for years 1900 to 2012 and 2000 to 2012.

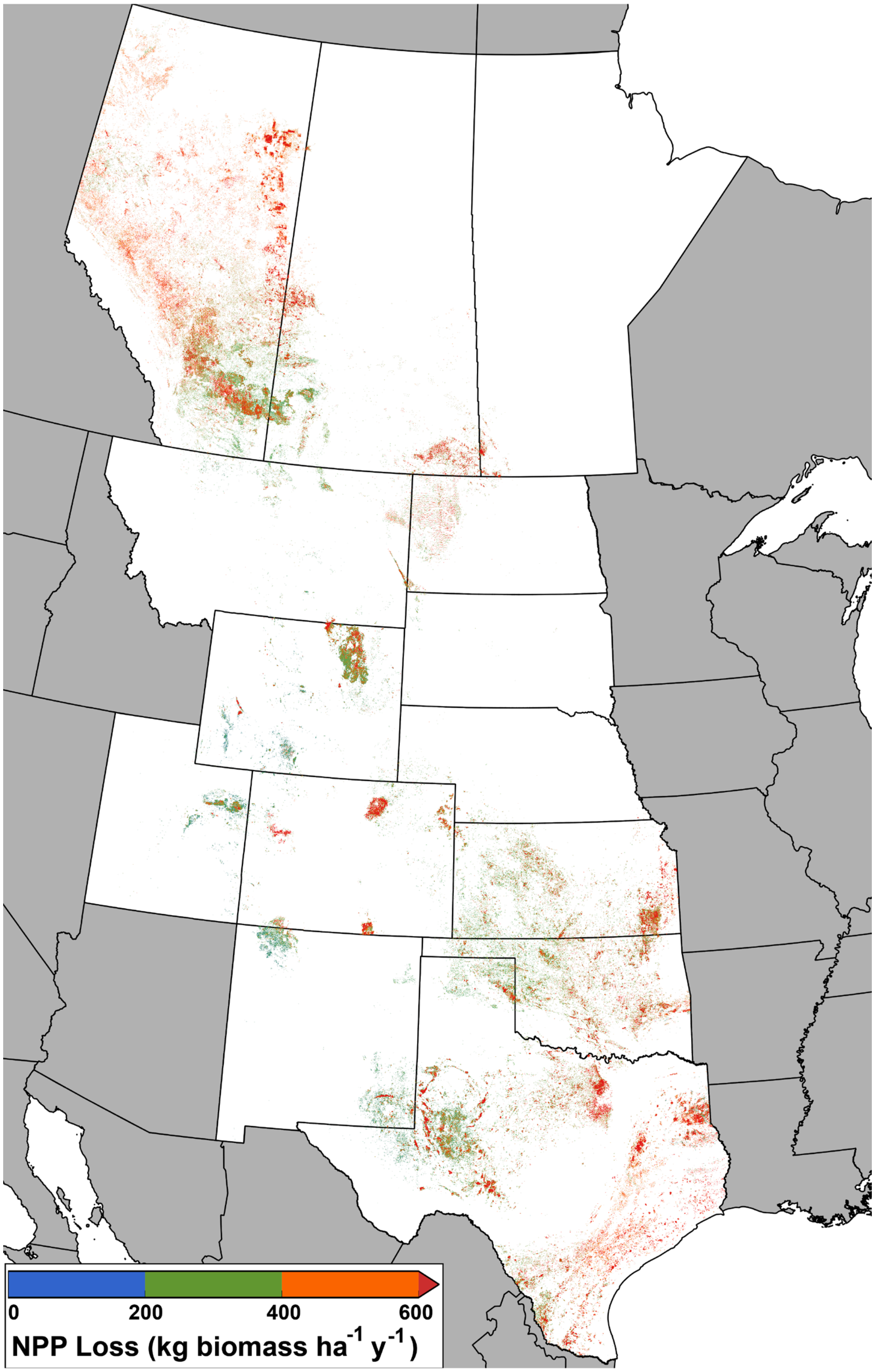


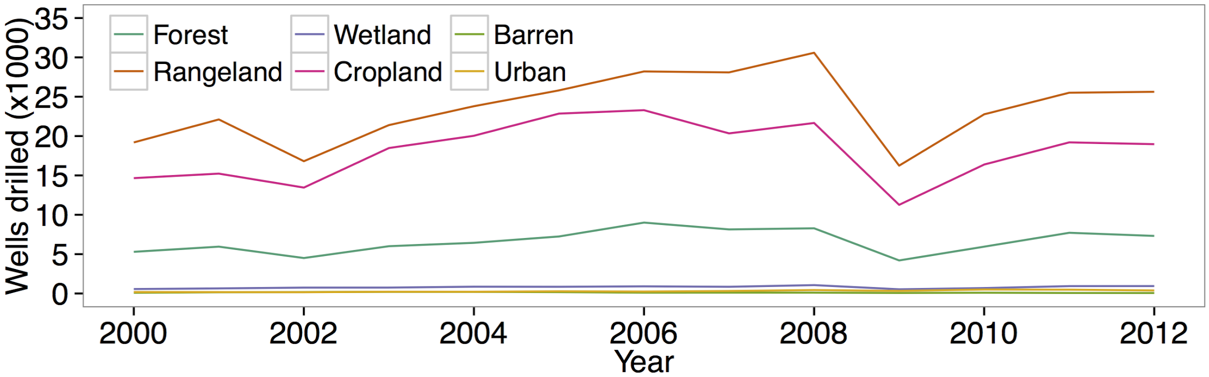
Figure S7. Net primary production (NPP) loss due to oil and gas activity across the central provinces and states of North America. NPP loss represents the cumulative effect of annual losses from 2000 to 2012.

Equivalency calculations

Estimates of NPP reduction were calculated in grams carbon year^{-1}. We converted these estimates to dry biomass and provide equivalent numbers in bushels of wheat, feed for cattle, and animal unit months (AUMs). These equivalency estimates are solely to put carbon and biomass estimates into a format more readily recognized and understood by the general public and policymakers, and do not represent an actual amount of wheat, livestock forage, or AUMs lost to oil and gas development.

Bushels of wheat in 2012

Contemporary usage of bushel is a unit of mass or weight. One bushel of wheat equals 27.21 kg (60 lbs) (*30*). Plant carbon was determined as 45% of dry biomass (*31*). The value used for aboveground biomass for wheat was 81% (*32*). In 2012, we estimate a loss of 1.81 Tg carbon yr^{-1} for areas categorized as croplands.


Forest
Rangeland
Wetland
Cropland
Barren
Urban
Wells drilled (x1000)
35
30
25
20
15
10
5
0
2000
2002
2004
2006
2008
2010
2012
Year

Private and public land—USA only

The number of wells drilled on U.S. private, federal, state, and Native American lands were quantified using the Protected Areas Database of the United States (PAD-US) version 1.3. We spatially intersected wells with PAD-US and categorized wells by the domain description. Due to difficulty in obtaining ownership history, ownership is as published by PAD-US in 2012 (i.e., a well drilled in 1950 is categorized relative to ownership circa 2012).

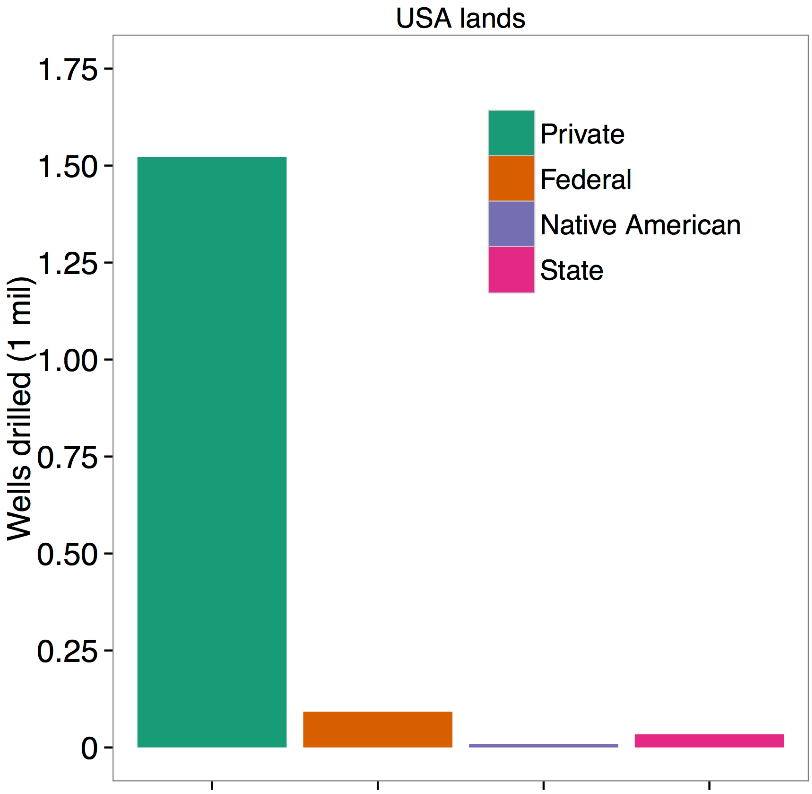


Figure S9. The number of oil and gas wells drilled within the central states of the USA from 1900 to 2012 relative to surface land ownership. Land ownership determined using the Protected Areas Database of the United States version 1.3. Due to difficulty in obtaining ownership history, ownership is as is in 2012 (i.e., a well drilled in 1950 is categorized relative to ownership in 2012).

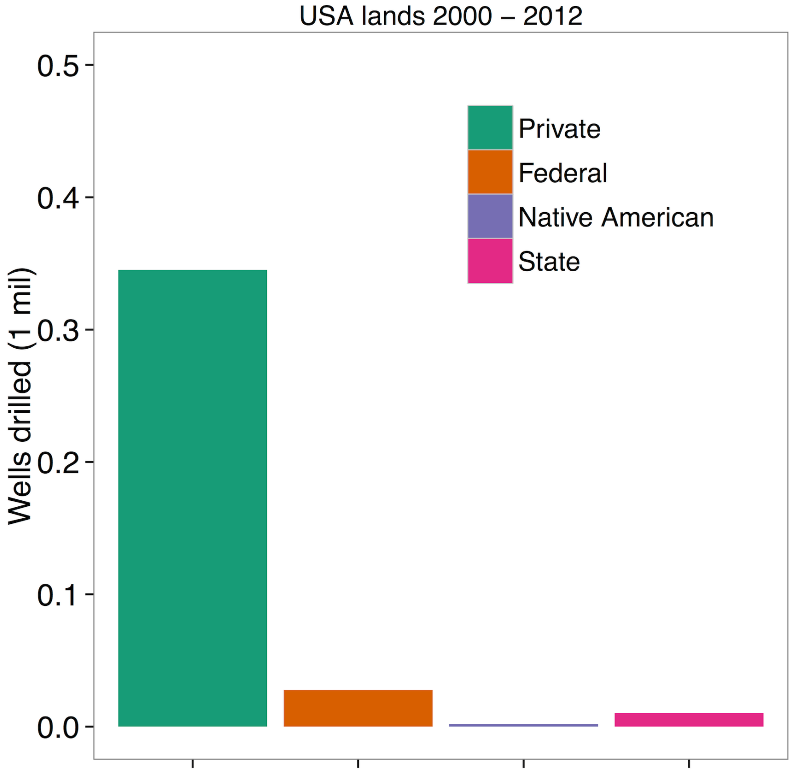


Figure S10. The number of oil and gas wells drilled within the central states of the USA from 2000 to 2012 relative to surface land ownership. The vast majority of wells have been drilled on private lands. Land ownership determined using the Protected Areas Database of the United States version 1.3.

Water

We estimate the water used for hydraulic fracturing by multiplying the total number of wells drilled from 2000 to 2012 by a low (10,600 m^3) and high (50,000 m^3) estimate of water use per well (*14*). We then divided by 13 years to obtain an annual average. This assumes that hydraulic fracturing occurred with every well, which may not occur. We reduced the estimate stepwise to 0% (i.e., hydraulic fracturing occurred with 50% of wells, 25%, etc.) to provide additional estimates.

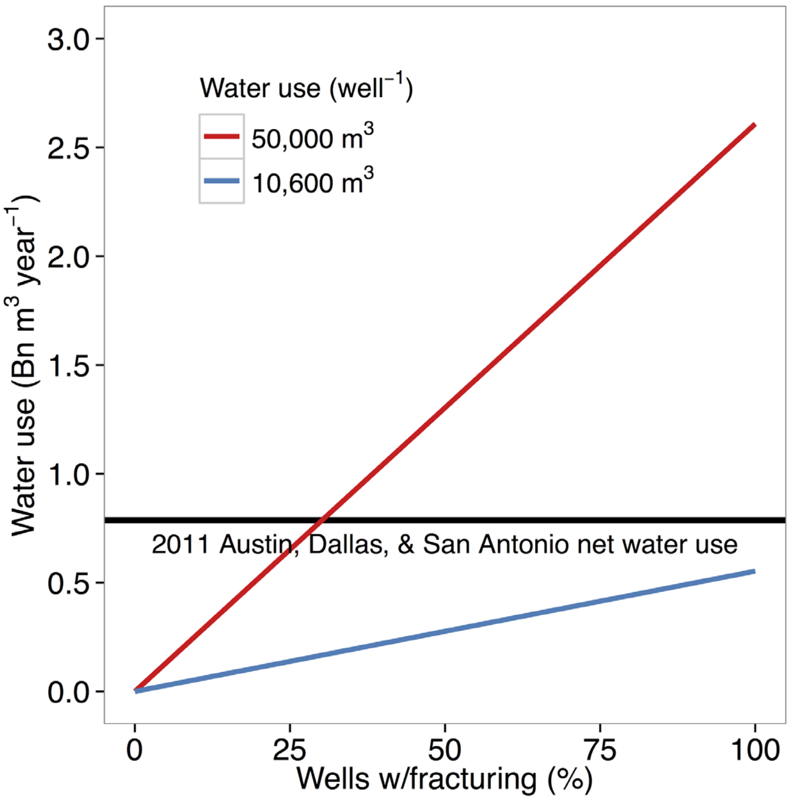


Figure S11. Estimated annual water (billion m^3) used for hydraulic fracturing as a function of the percentage of wells with hydraulic fracturing. A low and high estimate of water used per well is provided (*14*). Horizontal line represents the 2011 net water use of Texas cities Austin, Dallas, and San Antonio combined (*38*).

We calculated the number of wells drilled in water stressed areas using Aqueduct Global Maps 2.0 (*22*). We spatially intersected wells with Aqueduct and summed the number of wells by low, medium low, medium high, high, and extreme (combination of extreme and arid) water stress.

References and Notes

1. International Energy Agency, "World energy outlook 2013" (IEA, Paris, 2013).

2. U.S. Energy Information Administration, "International energy outlook" (EIA, Department of Energy, Washington, DC, 2013).

3. J. G. Weber, The effects of a natural gas boom on employment and income in Colorado, Texas, and Wyoming. *Energy Econ.* **34**, 1580–1588 (2012). doi:10.1016/j.eneco.2011.11.013

4. N. Butt, H. L. Beyer, J. R. Bennett, D. Biggs, R. Maggini, M. Mills, A. R. Renwick, L. M. Seabrook, H. P. Possingham, Biodiversity risks from fossil fuel extraction. *Science* **342**, 425–426 (2013). Medline doi:10.1126/science.1237261

5. D. P. C. Peters, P. M. Groffman, K. J. Nadelhoffer, N. B. Grimm, S. L. Collins, W. K. Michener, M. A. Huston, Living in an increasingly connected world: A framework for continental-scale environmental science. *Front. Ecol. Environ* **6**, 229–237 (2008). doi:10.1890/070098

6. D. Sontag, R. Gebeloff, *New York Times*, 22 November 2014; www.nytimes.com/interactive/2014/11/23/us/north-dakota-oil-boom-downside.html.

7. N. F. Jones, L. Pejchar, Comparing the ecological impacts of wind and oil & gas development: A landscape scale assessment. *PLOS ONE* **8**, e81391 (2013). Medline doi:10.1371/journal.pone.0081391

8. Millennium Ecosystem Assessment, *Ecosystems and Human Well-Being* (Island Press, Washington, DC, 2005).

9. M. Zhao, S. W. Running, Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. *Science* **329**, 940–943 (2010). Medline doi:10.1126/science.1192666

10. A. L. Mitchell, E. A. Casman, Economic incentives and regulatory framework for shale gas well site reclamation in Pennsylvania. *Environ. Sci. Technol.* **45**, 9506–9514 (2011). Medline doi:10.1021/es2021796

11. M. A. Drummond, R. Auch, "Land cover trends in the United States Great Plains" (U.S. Geological Survey, 2012); http://landcovertrends.usgs.gov/gp/regionalSummary.html.

12. J. M. Northrup, G. Wittemyer, Characterising the impacts of emerging energy development on wildlife, with an eye towards mitigation. *Ecol. Lett.* **16**, 112–125 (2013). Medline doi:10.1111/ele.12009

13. W. K. Smith, C. C. Cleveland, S. C. Reed, N. L. Miller, S. W. Running, Bioenergy potential of the United States constrained by satellite observations of existing productivity. *Environ. Sci. Technol.* **46**, 3536–3544 (2012). Medline doi:10.1021/es203935d

14. A. Vengosh, R. B. Jackson, N. Warner, T. H. Darrah, A. Kondash, A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. *Environ. Sci. Technol.* **48**, 8334–8348 (2014). Medline doi:10.1021/es405118y

15. R. B. Jackson, A. Vengosh, J. W. Carey, R. J. Davies, T. H. Darrah, F. O'Sullivan, G. Pétron,

The environmental costs and benefits of fracking. *Annu. Rev. Environ. Resour.* **39**, 327–362 (2014). doi:10.1146/annurev-environ-031113-144051

16. B. G. Rabe, Shale play politics: The intergovernmental odyssey of American shale governance. *Environ. Sci. Technol.* **48**, 8369–8375 (2014). Medline doi:10.1021/es4051132
17. J. B. Jacquet, Review of risks to communities from shale energy development. *Environ. Sci. Technol.* **48**, 8321–8333 (2014). Medline doi:10.1021/es404647x
18. Secretary Salazar on wildlife protections in the petroleum reserve in Alaska [press release] (BLM, 2013); www.blm.gov/wo/st/en/info/newsroom/2013/february/nr_02_21_2013.html.
19. "Interior Department final rule to support safe, responsible hydraulic fracturing activities on public and tribal lands" [press release] (U.S. Department of the Interior, Washington, DC, 2015); http://www.doi.gov/news/pressreleases/interior-department-releases-final-rule-to-support-safe-responsible-hydraulic-fracturing-activities-on-public-and-tribal-lands.cfm.
20. B. Warner, J. Shapiro, Fractured, fragmented federalism: A study in fracking regulatory policy. *Publius* **43**(3), 474–496 (2013). doi:10.1093/publius/pjt014
21. Food and Agriculture Organization of the United Nations, "The water-energy-food nexus" (FAO, Rome, 2014); www.fao.org/nr/water/docs/FAO_nexus_concept.pdf.
22. F. M. Gassert, P. Reig, T. Shiao, M. Landis, M. Luck, "Aqueduct global maps 2.0," Working paper (World Resources Institute, Washington, DC, 2013); www.wri.org/publication/aqueduct-global-maps-20.
23. D. J. Mildrexler, M. Zhao, F. A. Heinsch, S. W. Running, A new satellite-based methodology for continental-scale disturbance detection. *Ecol. Appl.* **17**, 235–250 (2007). Medline doi:10.1890/1051-0761(2007)017[0235:ANSMFC]2.0.CO;2
24. J. A. Sobrino, J. C. Jiménez-Muñoz, L. Paolini, Land surface temperature retrieval from LANDSAT TM 5. *Remote Sens. Environ.* **90**, 434–440 (2004). doi:10.1016/j.rse.2004.02.003
25. Q. Weng, D. Lu, J. Schubring, Estimation of land surface temperature–vegetation abundance relationship for urban heat island studies. *Remote Sens. Environ.* **89**, 467–483 (2004). doi:10.1016/j.rse.2003.11.005
26. M. C. Hansen, P. V. Potapov, R. Moore, M. Hancher, S. A. Turubanova, A. Tyukavina, D. Thau, S. V. Stehman, S. J. Goetz, T. R. Loveland, A. Kommareddy, A. Egorov, L. Chini, C. O. Justice, J. R. Townshend, High-resolution global maps of 21st-century forest cover change. *Science* **342**, 850–853 (2013). Medline doi:10.1126/science.1244693
27. A. F. Rahman, D. A. Sims, V. D. Cordova, B. Z. El-Masri, Potential of MODIS EVI and surface temperature for directly estimating per-pixel ecosystem C fluxes. *Geophys. Res. Lett.* **32**, L19404 (2005). doi:10.1029/2005GL024127
28. A. Huete, K. Didan, T. Miura, E. P. Rodriguez, X. Gao, L. G. Ferreira, Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sens. Environ.* **83**, 195–213 (2002). doi:10.1016/S0034-4257(02)00096-2

29. R. I. McDonald, J. Fargione, J. Kiesecker, W. M. Miller, J. Powell, Energy sprawl or energy efficiency: Climate policy impacts on natural habitat for the United States of America. *PLOS ONE* **4**, e6802 (2009). Medline doi:10.1371/journal.pone.0006802

30. A. M. Johanns, "Metric conversions" (File C6–80, Iowa State University Extension, Ames, 2013); www.extension.iastate.edu/agdm/wholefarm/pdf/c6-80.pdf.

31. P. Ciais, M. Reichstein, N. Viovy, A. Granier, J. Ogée, V. Allard, M. Aubinet, N. Buchmann, C. Bernhofer, A. Carrara, F. Chevallier, N. De Noblet, A. D. Friend, P. Friedlingstein, T. Grünwald, B. Heinesch, P. Keronen, A. Knohl, G. Krinner, D. Loustau, G. Manca, G. Matteucci, F. Miglietta, J. M. Ourcival, D. Papale, K. Pilegaard, S. Rambal, G. Seufert, J. F. Soussana, M. J. Sanz, E. D. Schulze, T. Vesala, R. Valentini, Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature* **437**, 529–533 (2005). Medline doi:10.1038/nature03972

32. C. Monfreda, N. Ramankutty, J. A. Foley, Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochem. Cycles* **22**, GB1022 (2008). doi:10.1029/2007GB002947

33. Statistics Canada, CANSIM Table l001-0010, Estimated areas, yield, production and average farm price of principal field crops, in metric units (Statistics Canada, 2014).

34. National Agricultural Statistics Service, U.S. Department of Agriculture, Crop production 2013 summary (USDA, Washington, DC, 2014).

35. J. Holechek, R. D. Pieper, C. H. Herbel, *Range Management: Principles and Practices* (Prentice Hall, Upper Saddle River, NJ, 2011).

36. C. C. Cleveland, B. Z. Houlton, W. K. Smith, A. R. Marklein, S. C. Reed, W. Parton, S. J. Del Grosso, S. W. Running, Patterns of new versus recycled primary production in the terrestrial biosphere. *Proc. Natl. Acad. Sci. U.S.A.* **110**, 12733–12737 (2013). Medline doi:10.1073/pnas.1302768110

37. BLM, Fact sheet on the BLM's management of livestock grazing (BLM, Washington, DC, 2014); www.blm.gov/wo/st/en/prog/grazing.html.

38. Texas Water Development Board, Historical Water Use Estimates (Texas Water Development Board, Austin, 2014); www.twdb.texas.gov/waterplanning/waterusesurvey/estimates/index.asp.