



An Improved Approach for Forecasting Ecological Impacts from Future Drilling in Unconventional Shale Oil and Gas Plays

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Received: 2 October 2017 / Accepted: 2 April 2018 / Published online: 13 April 2018
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Abstract

Directional well drilling and hydraulic fracturing has enabled energy production from previously inaccessible resources, but caused vegetation conversion and landscape fragmentation, often in relatively undisturbed habitats. We improve forecasts of future ecological impacts from unconventional oil and gas play developments using a new, more spatially-explicit approach. We applied an energy production outlook model, which used geologic and economic data from thousands of wells and three oil price scenarios, to map future drilling patterns and evaluate the spatial distribution of vegetation conversion and habitat impacts. We forecast where future well pad construction may be most intense, illustrating with an example from the Eagle Ford Shale Play of Texas. We also illustrate the ecological utility of this approach using the Spot-tailed Earless Lizard (*Holbrookia lacerata*) as the focal species, which historically occupied much of the Eagle Ford and awaits a federal decision for possible Endangered Species Act protection. We found that ~17,000–45,500 wells would be drilled 2017–2045 resulting in vegetation conversion of ~26,485–70,623 ha (0.73–1.96% of pre-development vegetation), depending on price scenario (\$40–\$80/barrel). Grasslands and row crop habitats were most affected (2.30 and 2.82% areal vegetation reduction). Our approach improves forecasts of where and to what extent future energy development in unconventional plays may change land-use and ecosystem services, enabling natural resource managers to anticipate and direct on-the-ground conservation actions to places where they will most effectively mitigate ecological impacts of well pads and associated infrastructure.

Keywords Hydraulic fracturing · Directional drilling · Eagle Ford Shale Play · Ecosystem services · *Holbrookia lacerata* · Spot-tailed Earless Lizard

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s00267-018-1042-5>) contains supplementary material, which is available to authorized users.

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Introduction

To support both domestic and international energy demands, total energy production in the United States (US) is predicted to rise 20% by 2040 (EIA 2017a). Meeting these energy demands will almost certainly increase the land-use footprint of energy development (Trainor et al. 2016) with implications for biodiversity and ecosystem services (e.g., McDonald et al. 2009).

In particular, while energy markets are subject to uncertainty (i.e., technological improvements, demographic and economic trends, and resource availability are difficult to forecast), energy production from unconventional shale oil and gas plays may double by 2040 due to recent technological advances (i.e., directional drilling and hydraulic fracturing; EIA 2017a). While unconventional resource production forecasts have discrepancies in ultimate output, this study uses an approach considered to be relatively conservative by a review of publicly available resource

assessments (Inman 2014). In light of potential expansions in drilling activity, this highlights the importance of mapping and quantifying changes in vegetation and habitat fragmentation that resulted from new well pads, pipelines, and other oil and gas production infrastructure (Wolaver et al. 2018; Allred et al. 2015; Drohan et al. 2012; Entrekin et al. 2015; Jones et al. 2015; Moran et al. 2015, 2017; Pierre et al. 2015, 2017; Slonecker et al. 2014). Equally important as retrospective studies assessing how energy development affected the landscape is the development of techniques to forecast the extent of land use change and ecological impacts which may result from future drilling.

Recent improvements have been made in oil and gas production outlook models, which use rich geological and hydrocarbon production databases with economic modeling to predict future drilling patterns in terms of location and number of wells. Such approaches have been applied in the Barnett, Fayetteville, Haynesville, and Eagle Ford plays (Browning et al. 2013; Gülen et al. 2014, 2015; Ikonnikova et al. 2014). However, these drilling forecasts have not considered how forecasted energy development may alter the landscape and potentially impact ecosystems. To this end, we made advances in predicting ecological impacts which may result from future drilling and well pad construction. For example, forecasts of cumulative ecosystem service losses were estimated for development of several major US unconventional plays through 2040 (Moran et al. 2017).

We recognize that all parts of a play do not develop similarly (Pierre et al. 2017) and that the distribution of drilling across the landscape is fundamentally controlled by the underlying geology and well economics. Thus, we present an approach to forecast ecological impacts that may be expected from future drilling in unconventional oil and gas plays by (1) incorporating geologic and economic data which control expected drilling and (2) adding a spatial component to drilling forecasts and associated vegetation and habitat effects. We illustrate this approach with the rapidly expanding Eagle Ford Shale Play of Texas; however, the improved methods we present can be used to forecast ecological effects of future drilling in unconventional plays globally. The number of drilling permits in the Eagle Ford peaked in 2014 (5613), reached a low in 2015 (1119), and increased through November 2017 (the most recent data available) to nearly 2000 as oil price recovered from a low in 2016 (Fig. 1a; RRC 2018); thus, the play continues to be an important hydrocarbon source. We also illustrate the ecological utility of this approach using the Spot-tailed Earless Lizard (*Holbrookia lacerata*) as the focal species, which historically occupied much of the Eagle Ford (Axtell 1998) and awaits a federal decision for possible Endangered Species Act protection because of a historic decline in the past 70 years. The decline is not



Fig. 1 Eagle Ford drilling and oil price history (a) and resulting landscape alteration from December 2008 (b) through December 2016 (c) for a representative portion of the play northeast of Cotulla, TX (southwest corner of images). Infrastructure construction includes roads, well pads, surface impoundments, storage facilities and railway transport terminal. Asterisks indicates well permitted by Texas Railroad Commission for Q1 and Q2 of 2017 (RRC 2018). Imagery: Landsat/Google Earth Pro. Oil price from EIA (2017c)

necessarily tied to energy expansion, but is potentially exacerbated by anthropogenic habitat alterations such as invasive vegetation and fauna and urbanization, which may follow land-use changes associated with drilling. To our knowledge, this is one of the first spatially-explicit forecasts of unconventional play development to integrate geologic and economic insights to more realistically assess where drilling may occur and estimate the ecological impacts from energy infrastructure development.

The Eagle Ford is an unconventional play where drilling and associated land-use changes expanded rapidly. Drilling took off in 2010 and continued until a precipitous oil price decline in 2014 (Fig. 1; Figure S1). Prices remained under \$50 per barrel and drilling since 2015 has been modest. However, the play remains economically important and produced ~15% of U.S. oil in March 2017 (EIA 2017b). While technological innovations enabled development in the Eagle Ford, energy price now limits drilling. We used a recent study, which modeled the probability of drilling and resulting drilling density for new Eagle Ford wells drilled through 2045 for three oil price scenarios (Ikonnikova et al. 2017). This approach used a unique geologic dataset of ~11,000 existing wells to evaluate the play's productivity and a spatially-explicit economic model to map the geography of expected drilling. Using this forecast of likely drilling patterns, we distributed future well pads throughout the play and assessed vegetation conversion and habitat impacts resulting from well pad construction. Impacts to major ecoregions in the Eagle Ford were assessed by classifying vegetation types of affected habitats (Figure S1). We illustrate this approach for a single species in a specific unconventional play (i.e., *H. lacerata* in the Eagle Ford Shale Play); however, this novel method can be applied to analyze future drilling and resulting vegetation and habitat alteration in unconventional oil and gas plays occupying other environments globally with implications for a variety of taxa and communities.

Methods and materials

Future drilling patterns

We used for our study a mapping of projected drilling patterns in the Eagle Ford through 2045 generated by a comprehensive production outlook model (Ikonnikova et al. 2017). This model assigned for the entire play a probability of drilling and resulting drilling density based on (1) productivity expectations using comprehensive geologic and petrophysical analyses from existing wells and (2) economic assumptions, including oil and natural gas prices and cost projections. Profitability and corresponding probability of drilling were mapped for the entire play using an estimate

of the total number of wells already drilled per unit area (1 mi², ~259 ha), distance to existing infrastructure, historical oil and natural gas decline data, projected well spacing, and expected energy prices (after Gherabati et al. 2016; Gülen et al. 2014; Ikonnikova et al. 2014; Male et al. 2016). As energy price is the primary factor affecting well drilling (Weijermars 2014), drilling development uncertainty was captured by assessing three energy price scenarios: \$40, \$50, and \$80/barrel, which represent the lowest observed price (on an annual basis), current price, and the most likely future high price from the U.S. Energy Administration's energy outlook (Ikonnikova et al. 2017). Natural gas prices also affect well economics and therefore drilling dynamics; however, the amount of natural gas produced even in more natural gas rich parts of the Eagle Ford is insufficient to affect drilling dynamics appreciably. For example, modeling by Ikonnikova et al. (2017) revealed that a change in natural gas price of \$1/MMBtu would change a wells' net cash flow by less than 7%. Thus, it is acceptable to forecast projected regional-scale drilling patterns in the Eagle Ford using potential future oil prices.

The production outlook model used a geologic input dataset compiled from 335 well logs, of which 120 had associated petrophysical analyses. These data were used to create maps of Eagle Ford net and gross thickness, porosity, water saturation, and pressure (Hammes et al. 2016). Based on historical oil and natural gas production, hydrocarbon quality (i.e., specific gravity), and directional surveys from ~11,000 wells drilled 2009–2016, a map was developed for areas of similar well productivity (Gherabati et al. 2016; Male et al. 2016) and divided into "tiers" of similar well productivity (following the approach of Gülen et al. 2013). Wells were analyzed for drilling depth and well lateral length. Future well production and profitability was predicted using a cash flow model incorporating each well's production, drilling and operating costs, taxes and royalties, and other factors for the three energy price scenarios (following Gülen et al. 2013; Ikonnikova et al. 2014). We assumed a static price over time, but recognize energy prices and resulting drilling fluctuates and moves around geographically to where drilling is profitable. Operators economically drill wells over the widest geographic area when energy prices are high. When energy prices decline, drilling moves to high-Btu parts of unconventional plays, which produce oil instead of lower-price natural gas (Gülen et al. 2013).

Vegetation conversion from new well pads

We forecasted the extent and type of vegetation conversion from new well pads. Based on historical prices and observed drilling, estimates were made by Ikonnikova et al. (2017) of the total number of wells that would be drilled for

each oil price scenario. Potential drilling locations were identified by mapping wells drilled by the end of 2015 and the outlook model was calibrated using observed 2016 drilling. We excluded horizontal laterals buffered by 250 m, urban areas, roads, rivers and water bodies, state protected areas, cemeteries, and airports from potential drilling locations. The number of wells to fill undrilled space for each price scenario was calculated under the assumption that future wells are similar to those drilled 2014–2016 from Information Handling Services (IHS) U.S. Well Database (i.e., well laterals length: ~1675 m, average lateral spacing: ~150 m). We then assigned likely future drilling locations—and associated well pads—using spatially-balanced random points in ArcGIS. New wells within 90 m of 2014 well pads were assigned to existing well pads. Operator practices vary throughout the play. Thus, we mapped 2014 pads following Pierre et al. (2017) and calculated the mean pad size and mean number of wells drilled per pad for each productivity tier. Vegetation conversion resulting from new pad construction was estimated for each price scenario for major vegetation types (e.g., grassland, row crops, and shrubs) using a field-verified database of modeled vegetation (TPWD 2017). We assumed operators would construct future well pads using 2014 well pad attributes and that pre-existing vegetation in a pad's footprint would be completely converted to drilling infrastructure. Because Texas does not require operators to restore drilling sites to pre-existing conditions and considering the play's semi-arid climate, we assumed nominal revegetation of well pads.

Habitat impacts

The Texas Conservation Action Plan (TCAP; TPWD 2012) describes conservation challenges affecting habitats for dozens of species of state and federal interest and guides local and regional natural resource management, conservation, and mitigation strategies. For the three ecoregions overlapping the Eagle Ford (South Texas Plains, East Central Texas Plains, Texas Blackland Prairies; Figure S1), the plan identified energy production and transmission as a priority anthropogenic impact. We quantified total vegetation conversion, identified which vegetation types would be most affected by construction of new well pads for each ecoregion, and assessed potential ecological implications of this forecasted landscape alteration.

Results

We estimated ~32,000–83,000 wells would be drilled from 2017 to 2045 (\$40–\$80 per barrel; Table S1). Our assessment of existing well pads found a mean of 1.3–2.9 wells per pad, depending on expected well productivity (Figure

S2). The number of potential well pads was reduced to ~17,000–45,500 by assuming operators continue using multi-well pads and by placing wells within 90 m of an existing pad onto that pad. The mean size of well pads constructed through 2014 was 1.5–1.9 ha (Table S1), which we assumed would continue.

Vegetation conversion totaled ~26,485–70,623 ha, or 0.73–1.96% of pre-development vegetation, depending on price scenario (Tables 1, S2). Heat maps revealed the spatial extent of well pad construction with energy price (Fig. 2; GIS files available at: <https://doi.org/10.18738/T8/ILLQCM>). At \$40 per barrel, drilling was constrained to the most productive parts of the play, including wet gas in the northeast. As price increased to \$50 per barrel, drilling expanded in wet gas and oil. At \$80 per barrel, operators could profitably drill wells throughout the oil and wet gas parts of the play; however, dry gas was generally too deep to be profitable.

Habitats most likely affected by future drilling included cold deciduous shrubs, grasslands, and cold deciduous forests (up to 28,407, 26,209, and 8752 ha, respectively; Table 1), which included native brushland/brush, native grassland/savannah, non-native pasture, forests/timberlands, bottomland/riparian, and wetlands (Supporting Documents of Elliott et al. 2014). Grasslands and row crops were the two most affected habitats in terms of percent reduction (up to 2.30 and 2.82%, respectively, depending on ecoregion; Table S2). Habitats of the South Texas Plains ecoregion were most affected in terms of total area, followed by East Central Texas Plains and Texas Blackland Prairies (Fig. 3; Table 1). The Texas Blackland Prairies has the highest percent vegetation reduction (1.3–2.2%), while East Central Texas Plains has the highest rate of change in percent vegetation conversion as energy price increased (0.8–2.2%).

Discussion

Estimating current and future impacts of energy infrastructure on land-use is a critical component of future conservation and natural resource management strategies. Forecasting where future development is likely to occur is a poorly understood, but essential question to answer for successful conservation of species' habitats in unconventional plays. Natural resource managers on public and private lands need more accurate maps of expected drilling patterns to effectively plan for and mitigate effects of associated vegetation conversion on biodiversity. To this end—illustrating for the Eagle Ford—our study revealed that up to ~83,000 wells would be drilled through 2045 on as many as ~45,500 well pads, causing vegetation conversion of ~26,485–70,623 ha (Table 1; Table S1). While we

Table 1 Estimated vegetation conversion (as reduction of current hectares) from well pad construction through 2045 by ecoregion. Price scenarios are low (\$40/barrel), medium (\$50/barrel), and high (\$80/barrel)

Ecoregion Vegetation type	South Texas Plains			East Central Texas Plains			Texas Blackland Prairies					
	2006 Estimate (ha)	2045 Estimate (ha reduction)			2006 Estimate (ha)	2045 Estimate (ha reduction)			2006 Estimate (Ha)	2045 Estimate (ha reduction)		
		Low	Med.	High		Low	Med.	High		Low	Med.	High
CD shrub	1,396,532	8126	12,269	24,125	167,693	1494	2329	3771	24,203	346	429	510
Grassland	473,479	3587	5572	10,536	483,737	4245	6256	11,116	198,107	2642	3472	4557
CD forest	239,511	1709	2744	4716	148,071	1160	1808	3265	35,255	534	568	771
EG shrub	190,758	1008	1453	2787	9,469	93	110	203	2600	14	21	23
Row crops	59,031	369	574	1318	21,796	211	314	475	3894	73	90	110
BLEG forest	18,538	102	172	388	20,749	105	159	302	12,202	143	182	269
Urban low	17,849	90	123	217	10,696	61	85	125	3291	12	21	31
Barren	9724	75	108	214	4723	25	71	102	121	0	0	1
Urban high	8654	26	40	86	2077	11	11	22	456	1	1	3
NLEG forest	3493	22	34	63	495	3	4	9	1185	10	16	18
Open water	12,776	16	24	56	1014	8	13	19	61	1	0	1
CD mixed forest	2908	14	16	24	13,567	68	118	232	6773	61	84	104
Marsh	1822	8	10	22	1206	13	13	27	363	3	5	6
Total	2,435,077	15,152	23,139	44,551	885,291	7496	11,291	19,669	288,511	3837	4889	6402

Swamp and Grass Farm vegetation types had <50 ha for 2006 estimate and were omitted
BLEG broadleaf evergreen, *CD* cold-deciduous, *EG* evergreen, *NLEG* needle-leaf evergreen

forecasted probable well pad locations, we did not map potential future locations of associated infrastructure (e.g., surface water impoundments, compressor stations, etc.) or access roads and pipelines that would connect to drilling pads. Also, this study also did not calculate habitat fragmentation because population surveys to assess the current distribution of *H. lacerata* are ongoing. However, similar land-change analyses studies in unconventional oil and gas play have revealed that effects of land-use change extend beyond well pads (Johnson et al. 2010; Drohan and Brittingham 2012; Pierre et al. 2015; Pierre et al. 2018). For example, Drohan and Brittingham (2012) found that for the Marcellus Shale Play, the median area of land-change (which accounted for ancillary infrastructure, access roads, and pipelines) to be approximately twice the size of the well pad alone. Thus, doubling land-change results of this study (Table 1) would result in a reasonable estimate of overall footprint of all hydrocarbon extractive infrastructure (following the approach of Pierre et al. 2018). In addition, while this study did not formally evaluate fragmentation, the spatial representation of the anthropogenic activity causing changes in land-use would affect fragmentation. For example, well pad construction would cause many point changes in land-use. Conversely, the installation of hydrocarbon pipelines and well pad access roads (which were not directly assessed by this study) would cause long, linear

changes in vegetation. Thus, both point and linear changes in land-use would be associated with edge effects which would act to increase the overall impact of land-change.

Grasslands and row crops had the two highest percent reductions from pre-development vegetation (>2% in all ecoregions) for the \$80 per barrel scenario, which resulted in essentially all undrilled parts of the play being developed. Most affected, in terms of area, were habitats of cold deciduous shrubs, grasslands, and cold deciduous forests. Percent vegetation reduction was similar for the three ecoregions (~1.8–2.2% for \$80 per barrel scenario). Our results are consistent with findings from other studies. Allred et al. (2015) assessed ecosystem services lost to North American oil and gas infrastructure construction and found that ~70% of total “land degradation” from 2000 to 2012 affected rangelands and croplands. Moran et al. (2017) found disproportionately high ecosystem service losses from unconventional plays to grassland and deciduous forest habitats—and also to agricultural lands (i.e., high-intensity agricultural development, such as row crops), which occupy a relatively small area overall but are economically important. It is important to note, however, that grasslands, which could contain agricultural activity (i.e., potentially grazing pasture for cattle and hunting ranches), were not included in the Moran et al. (2017) classification of agricultural lands, which identified that 7.9% of the area of

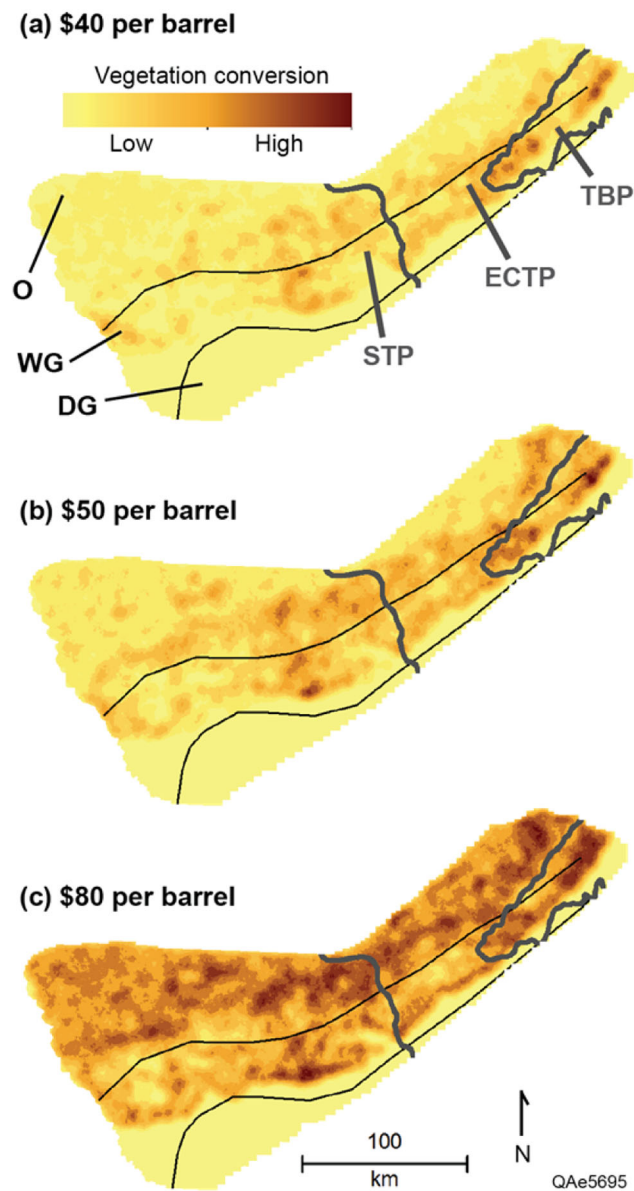


Fig. 2 Heat map of vegetation conversion from estimated drilling through 2045 for three scenario: low, \$40/barrel (a) medium, \$50/barrel (b), and high, \$80/barrel (c). Hydrocarbon type: O oil, WG wet gas, DG dry gas (thin black line; U.S. Energy Information Administration 2014 Updates to the Eagle Ford Play Maps). Ecoregions: *STP* South Texas Plains, *ECTP* East Central Texas Plains, *TBP* Texas Blackland Prairies (thick dark gray line; TPWD 2012)

the eight major U.S. shale plays are “agricultural lands”. In the Eagle Ford, we classified agricultural lands more broadly (i.e., grassland and row crops) to reflect working rangelands within the play and found these to comprise a much higher percent of land cover: 32.0% of pre-development vegetation is classified as grasslands and 2.3% as row crops. Thus, understanding potential impacts to the economically important agricultural and ranching sectors and to species utilizing farms and rangelands for

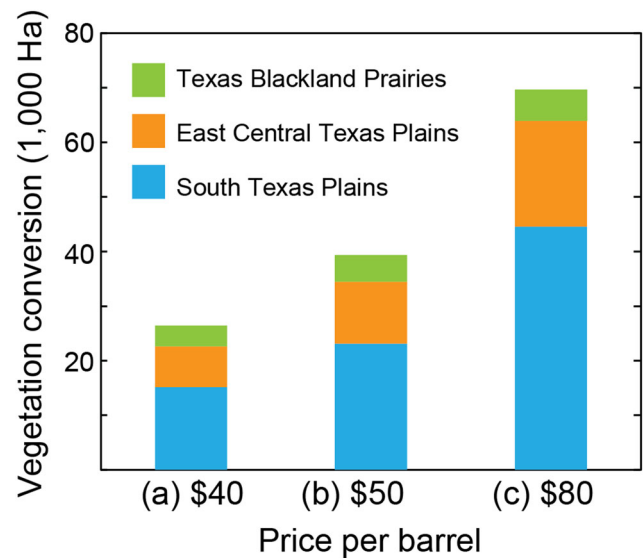


Fig. 3 Estimated vegetation conversion by ecoregion from well pad construction through 2045 for each energy price scenario

habitats remains an important research topic in the Eagle Ford and unconventional plays.

We illustrated our approach for the first play-specific evaluation of vegetation and habitat impacts from future well pads in a semi-arid unconventional play—and the only one we are aware of to generate spatially-explicit forecasts of the ecological impacts of drilling in the Eagle Ford. While we recognize that any model forecasting future drilling patterns is uncertain, we found that the spatial extent of drilling that would occur under \$80 per barrel would essentially fill all remaining undrilled portions of the play. Thus, this value makes sense as the highest price to model, and, because we assessed a range of reasonable future energy prices, we are confident that we accurately estimated how future Eagle Ford drilling could be expected to impact vegetation and habitats.

We understand that changes in land-use from anthropogenic activities threaten biodiversity globally (Fahrig 2003); however, species-specific responses span a broad range. For example, wildlife-vehicle collisions—such as from increased oilfield traffic—are a primary cause of some species’ mortality but may have nominal effects for other species (Forman et al. 2003). In the case of our focal species, *Holbrookia lacerata*, we suspect the lizard to be an early successional species that may favor certain types of vegetation conversion. However, invasive vegetation and fauna following changes in land-use may adversely affect the species (Axtell 1998). To understand potential threats to the species, we found that drilling would occur in much of the species’ historic range within the Eagle Ford at high oil prices. However, the species’ habitat does not include forests/timberlands, bottomland/riparian, or wetlands and the

effects of drilling in these areas could be nominal. In contrast, future drilling at \$80 per barrel in native brushland/brush, native grassland/savannah, and non-native pasture of grasslands and row crops has direct relevance to the species because recent surveys indicate continued persistence at sites with these vegetation types. Conversely, at \$40 per barrel, drilling is concentrated in the northeast of the play and potentially affects the species much less. Importantly, if currently low prices were to continue, resource managers would have more time to plan conservation actions before price recovery and drilling expansion to a larger portion of the species' historic range.

Identifying potential threats to species' habitat and developing mitigation strategies is essential to biodiversity conservation in expanding unconventional oil and gas plays globally. Our illustration of the approach for *H. lacerata* is relevant to other species in the Eagle Ford. For example, these may include those species identified in the Texas Conservation Action Plan (TPWD 2012), which outlines species of conservation interest, threats to habitats, and proposes conservation strategies. The plan identified effects of oil and gas development in the three ecoregions overlapping the Eagle Ford as potentially causing habitat loss and fragmentation, particularly in drier areas that may not revegetate quickly. In addition, the results of this study may inform recovery efforts of species currently listed as federally endangered or threatened under the Endangered Species Act (Fig. 4; Table 2). Our results reveal where Eagle Ford well pad construction and associated vegetation conversion may be most intense. These future vegetation conversion estimates will inform the extent of habitat loss and effects thereof on distribution, abundance, and diversity of the focal species.

Towards the goal of elucidating the connection between forecasts of ecological stressors, improving understanding of how stressors may affect focal species, and identifying suitable conservation strategies, Wolaver et al. (2018) presents an approach to generate science to inform the federal Endangered Species Act listing decision for *H. lacerata* as part of an ongoing, multi-year research program, of which this Eagle Ford study is a component. Specifically, the research program is currently filling data gaps to improve our understanding of *H. lacerata*. The U.S. Fish and Wildlife Service (FWS) will use these data to develop a Species Status Assessment (SSA) for the species and inform their decision whether the species warrants protection under the Endangered Species Act (see FWS 2016 and Smith et al. 2018 for a description of the current U.S. Fish and Wildlife Service species assessment process). Specifically, the SSA framework—and our research program objectives—contributes towards improving our understanding of: (1) what the species needs, (2) what is the current condition of the species, and (3) what is the species' likely future condition

(see Wolaver et al. 2018 Fig. 5 and Table 2). Thus, an SSA organizes all the biological information needed for all Endangered Species Act decisions for a particular species, which may include the listing decision, grant allocation, permitting, and recovery planning by supporting resource managers to design effective conservation strategies. Thus, our forecasts of vegetation conversion caused by possible Eagle Ford development scenarios fit directly into the SSA framework by assessing the species' likely future condition. See Wolaver et al. (2018) for a detailed discussion of the larger research program and implications the program's results for species conservation.

While we illustrate the approach presented in this study and Wolaver et al. (2018) for a single focal species (i.e., *Holbrookia lacerata*) in Texas, these novel approaches for landscape and habitat assessment can be used to compare changes in land-use for a suite of anthropogenic activities in other environments globally, with implications for management for a variety of biotic resources. For species not currently protected by under the Endangered Species Act (such as *H. lacerata*), our future vegetation conversion estimates could inform pre-listing conservation strategies (e.g., Donlan 2014) for these candidate species (Fig. 4; Table 2). These could include development of a Candidate Conservation Agreement with Assurances (CCAA), which would outline voluntary strategies to remove or reduce threats to the species. If a species found in the Eagle Ford were federally listed, our study results could also inform a Habitat Conservation Plan (HCP), which would show how impacts to a species would be minimized and mitigated. In the Eagle Ford, mitigation strategies for a CCAA or HCP may include (1) concentrating wells and along pre-existing development corridors, (2) using multi-well pads (Fig. S3), (3) focusing development in the play to the least sensitive habitats, and (4) revegetating well pads to native vegetation once operations cease (Jones et al. 2015; Thompson et al. 2015; TPWD 2012). Thus, our forecasts of spatial trends in Eagle Ford drilling could minimize risks to biodiversity and potentially save operators money by enabling them to apply mitigation strategies only to where they are needed most.

Conclusions

We present a novel approach to forecast ecological impacts of expected drilling patterns in unconventional shale oil and gas plays. Using an energy production outlook model, which incorporated geologic and economic data from thousands of wells and three oil price scenarios to forecast drilling patterns, we mapped the location of future well pads. This technique improved estimates of future vegetation conversion and habitat impacts by adding a spatial

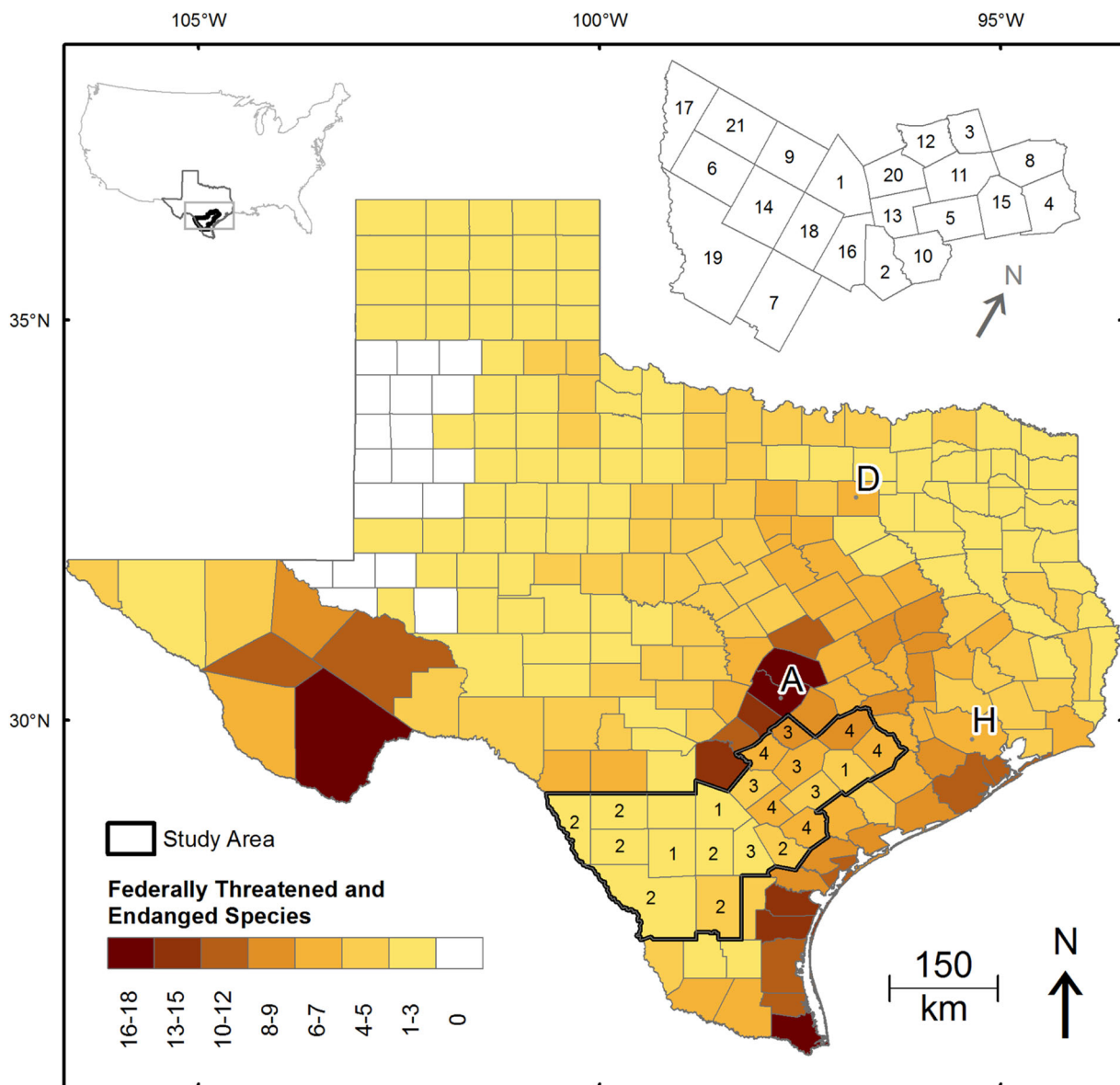


Fig. 4 Species listed as federally threatened or endangered under the Endangered Species Act (Table 2). A county is considered to potentially include a listed species where it contains an elemental occurrence for a species based on records from the Texas Natural Diversity Database (TNDD; TPWD 2018). The number of candidate species awaiting federal listing determination as threatened or endangered is labeled on counties within the study area (where present). As *Holbrookia lacerata subcaudalis* is not formerly included as a candidate species in TNDD, the historic range is from Axtell (1998). Note that TNDD may not include the results of all population surveys for all

species of potential interest and that some federally listed or candidate species may currently be extirpated in some portions (or all) of their historic ranges. The names of counties in study area, which correspond to those in Table 2, are indicated as numbers on the inset map at the top left of this figure and are: 1. Atascosa, 2. Bee, 3. Caldwell, 4. Colorado, 5. DeWitt, 6. Dimmit, 7. Duval, 8. Fayette, 9. Frio, 10. Goliad, 11. Gonzales, 12. Guadalupe, 13. Karnes, 14. La Salle, 15. Lavaca, 16. Live Oak, 17. Maverick, 18. McMullen, 19. Webb, 20. Wilson, 21. Zavala. A Austin, D Dallas, H Houston

component to forecasts of ecological impacts in developing unconventional oil and gas plays. Illustrating this approach in the Eagle Ford for *H. lacerata*, we found that future drilling and associated well pad construction may cause important reductions in grasslands, row crops, and cold deciduous forests and shrubs. The potential effects of development increased in spatial extent and magnitude as

oil price increased from \$40 to \$80 per barrel. Natural resource managers can use these results to proactively identify where future vegetation conversion and habitat impacts may be greatest so that on-the-ground conservation actions may be optimized to mitigate potential effects of drilling. We illustrated this approach in the Eagle Ford Shale Play of Texas for the Spot-tailed Earless Lizard;

Table 2 Species of conservation interest within Eagle Ford footprint listed as federally threatened or endangered under the Endangered Species Act or candidates for federal listing. *T* Threatened, *E* Endangered, *C* Candidate for federal listing. Names of counties in study area correspond to those in Fig. 4 inset map are: 1. Atascosa, 2. Bee, 3. Caldwell, 4. Colorado, 5. DeWitt, 6. Dimmit, 7. Duval, 8. Fayette, 9. Frio, 10. Goliad, 11. Gonzales, 12. Guadalupe, 13. Karnes, 14. La Salle, 15. Lavaca, 16. Live Oak, 17. Maverick, 18. McMullen, 19. Webb, 20. Wilson, 21. Zavala

Federal status	Taxon	Common name	Scientific name	Counties which may have species ^a
T	Amphibian	San Marcos Salamander	<i>Eurycea nana</i>	3
T	Bird	Piping Plover	<i>Charadrius melodus</i>	1, 2, 3, 4, 5, 7, 8, 10, 11, 12, 13, 15, 16, 18, 20
T	Bird	Red Knot	<i>Calidris canutus rufa</i>	2, 3, 4, 5, 8, 10, 11, 13, 15
T	Fish	Devils River minnow	<i>Dionda diaboli</i>	6, 17
E	Amphibian	Houston Toad	<i>Anaxyrus houstonensis</i>	3, 4, 8, 15
E	Amphibian	Texas Blind Salamander	<i>Eurycea rathbuni</i>	3, 12
E	Bird	Attwater's Greater Prairie-chicken	<i>Tympanuchus cupido attwateri</i>	4, 10
E	Bird	Golden-cheeked Warbler	<i>Setophaga chrysoparia</i>	8, 13
E	Bird	Northern Aplomado Falcon	<i>Falco femoralis septentrionalis</i>	7
E	Bird	Whooping Crane	<i>Grus americana</i>	1, 2, 3, 4, 5, 8, 10, 11, 12, 13, 15, 16, 20
E	Fish	Fountain darter	<i>Etheostoma fonticola</i>	3, 11, 12
E	Fish	Sharpnose Shiner	<i>Notropis oxyrhynchus</i>	3, 4, 5, 8, 10, 11, 12, 13, 15, 20
E	Fish	Smalleye Shiner	<i>Notropis buccula</i>	3, 4, 5, 8, 10, 11, 12, 13, 20
E	Mammal	Ocelot	<i>Leopardus pardalis</i>	1, 2, 6, 7, 9, 13, 14, 16, 17, 18, 19, 21
E	Plants	Ashy dogweed	<i>Thymophylla tephroleuca</i>	19
E	Plants	Black lace cactus	<i>Echinocereus reichenbachii</i> var. <i>albertii</i>	7
E	Plants	Navasota ladies'-tresses	<i>Spiranthes parksii</i>	8
E	Plants	Texas prairie dawn	<i>Hymenoxys texana</i>	14
E	Plants	Walker's manioc	<i>Manihot walkerae</i>	7
C	Bird	Black Rail	<i>Laterallus jamaicensis</i>	2, 3, 4, 5, 8, 10, 11, 12, 13, 15, 20
C	Mollusks	Golden Orb	<i>Quadrula aurea</i>	1, 3, 5, 10, 11, 12, 13, 16, 18, 20
C	Mollusks	Smooth Pimpleback	<i>Quadrula houstonensis</i>	4, 8
C	Mollusks	Texas Fawnsfoot	<i>Truncilla macrodon</i>	4, 8
C	Mollusks	Texas Hornshell	<i>Popenaias popeii</i>	17, 19
C	Mollusks	Texas Pimpleback	<i>Quadrula petrina</i>	3, 4, 5, 8, 10, 11, 12, 13, 20
C	Plants	Bracted twistflower	<i>Streptanthus bracteatus</i>	12
C ^b	Reptile	Spot-tailed Earless Lizard	<i>Holbrookia lacerata</i>	2, 6, 7, 10, 13, 14, 16, 17, 18, 19, 21

^aThe Texas Natural Diversity Database (TNDD; TPWD 2018) may not necessarily include the results of all population surveys for all species of potential interest and some federally listed or candidate species may currently be extirpated in some portions (or all) of their historic ranges

^bAs *Holbrookia lacerata* is not formerly included as a candidate species in TNDD, the historic range of this species is from Axtell (1998)

however, this novel method can be applied to improve conservation outcomes for a wide range of taxa and communities in other rapidly developing unconventional plays in the U.S. and globally.

Acknowledgements This study was funded by Texas Comptroller of Public Accounts Endangered Species Research Fund (grant number 14-000769 to LaDuc and Wolaver) and The University of Texas at Austin Jackson School of Geosciences and College of Natural Sciences. The authors declare that they have no conflicts of interest. We thank the Texas Comptroller of Public Accounts Interagency Task Force on Economic Growth and Endangered Species Spot-tailed Earless Lizard Working Group, R Gulley, M Hope, A Zerrenner, and

M Young for helpful discussions and Bob Gottfried and Laura Dugan for TNNd assistance.

References

- Allred BW, Smith WK, Twidwell D, Haggerty JH, Running SW, Naugle DE, Fuhlendorf SD (2015) Ecosystem services lost to oil and gas in North America. *Science* 348:401–402. <https://doi.org/10.1126/science.aaa4785>
- Axtell RW (1998) Interpretive atlas of Texas Lizards. No. 20. *Holbrookia lacerata*. Self-Published, p 11
- Browning J, Ikonnikova S, Gülen G, Tinker S (2013) Barnett shale production outlook SPE Econ Manage 5:89–104

- Donlan CJ (2014) Proactive strategies for protecting species. Pre-listing conservation and the Endangered Species Act. University of California Press, California
- Drohan PJ, Brittingham M (2012) Topographic and soil constraints to shale-gas development in the Northcentral Appalachians. *Soil Sci Soc Am J* 76:1696. <https://doi.org/10.2136/sssaj2012.0087>
- Drohan PJ, Brittingham M, Bishop J, Yoder K (2012) Early trends in landcover change and forest fragmentation due to shale-gas development in Pennsylvania: a potential outcome for the Northcentral Appalachians. *Environ Manage* 49:1061–1075. <https://doi.org/10.1007/s00267-012-9841-6>
- EIA (2017a) U.S. Energy Information Administration (EIA). International Energy Outlook 2017. <https://www.eia.gov/outlooks/ieof/>. Accessed 12 Jan 2018
- EIA (2017b) U.S. Energy Information Administration (EIA). Rankings: crude oil production, March 2017 (thousand barrels). <https://www.eia.gov/state/rankings/?sid=TX#/series/46>. Accessed 19 June 2017
- EIA (2017c) U.S. Energy Information Administration (EIA). Petroleum & other liquids, spot prices. https://www.eia.gov/dnav/pet/pet_pri_spt_s1_d.htm. Accessed 19 Jan 2018
- Elliott LF, Diamond DD, True CD, Blodgett CF, Pursell D, German D, Treuer-Kuehn A (2014) Ecological mapping systems of Texas: summary report. Texas Parks & Wildlife Department, Austin, TX. <http://tpwd.texas.gov/gis/data/>
- Entrekin SA, Maloney KO, Kapo KE, Walters AW, Evans-White MA, Klemow KM (2015) Stream vulnerability to widespread and emergent stressors: a focus on unconventional oil and gas. *PLoS One* 10:e0137416
- Fahrig L (2003) Effects of habitat fragmentation on biodiversity. *Annu Rev Ecol Evol, Syst* 34:487–515. <https://doi.org/10.2307/30033784>
- Forman RTT et al. (2003) Road ecology: science and solutions. Island Press, Washington, DC
- FWS (2016) U.S. Fish & Wildlife Service (FWS), Species Status Assessment Framework. An Integrated Framework for Conservation. http://www.fws.gov/endangered/improving_ESA/SSA.html. Accessed 27 Mar 2018
- Gherabati SA, Browning J, Male F, Ikonnikova SA, McDaid G (2016) The impact of pressure and fluid property variation on well performance of liquid-rich Eagle Ford shale *J Nat Gas Sci Eng* 33:1056–1068. <https://doi.org/10.1016/j.jngse.2016.06.019>
- Gülen G, Browning J, Ikonnikova S, Tinker SW (2013) Well economics across ten tiers in low and high Btu (British thermal unit) areas, Barnett Shale, Texas. *Energy* 60:302–315. <https://doi.org/10.1016/j.energy.2013.07.041>
- Gülen G, Ikonnikova S, Browning J, Smye K, Tinker SW (2015) Production scenarios for the Haynesville Shale Play. SPE-176022-PA SPE Econ Manage. <https://doi.org/10.2118/176022-PA>
- Gülen G, Ikonnikova S, Browning J, Tinker S (2014) Fayetteville Shale-production outlook. SPE-173187-PA. <https://doi.org/10.2118/173187-PA>
- Hammes U et al. (2016) Regional assessment of the Eagle Ford Group of South Texas, USA: insights from lithology, pore volume, water saturation, organic richness, and productivity correlations. *Interpretation* 4:SC125–SC150. <https://doi.org/10.1190/int-2015-0099.1>
- Ikonnikova S, Browning J, Horvath SC, Tinker S (2014) Well recovery, drainage area, and future drill-well inventory: empirical study of the Barnett Shale Gas Play. *SPE Reserv Eval Eng* 17:484–496. <https://doi.org/10.1021/acs.est.7b03150>
- Ikonnikova S, Male F, Scanlon BR, Reedy RC, McDaid G (2017) Projecting the water footprint associated with shale resource production: Eagle Ford Shale Case Study. *Environ Sci Technol*. <https://doi.org/10.1021/acs.est.7b03150>
- Inman M (2014) Nat gas: the fracking fallacy *Nat News* 516:28
- Johnson N et al. (2010) Pennsylvania energy impacts assessment report 1: Marcellus shale natural gas and wind. The Nature Conservancy
- Jones NF, Pejchar L, Kiesecker JM (2015) The energy footprint: how oil, natural gas, and wind energy affect land for biodiversity and the flow of ecosystem services. *BioScience*. <https://doi.org/10.1093/biosci/biu224>
- Male F, Marder M, Browning J, Gherabati A, Ikonnikova SA (2016) Production decline analysis in the Eagle Ford. In: Unconventional Resources Technology Conference, San Antonio, TX
- McDonald RI, Fargione J, Kiesecker J, Miller WM, Powell J (2009) Energy sprawl or energy efficiency: climate policy impacts on natural habitat for the United States of America. *PLoS One* 4:e6802
- Moran MD, Cox AB, Wells RL, Benichou CC, McClung MR (2015) Habitat loss and modification due to gas development in the Fayetteville Shale. *Environ Manage* 55:1276–1284. <https://doi.org/10.1007/s00267-014-0440-6>
- Moran MD, Taylor NT, Mullins TF, Sardar SS, McClung MR (2017) Land-use and ecosystem services costs of unconventional US oil and gas development. *Front Ecol Environ* 15:237–242. <https://doi.org/10.1002/fee.1492>
- Pierre J, Abolt C, Young M (2015) Impacts from above-ground activities in the Eagle Ford shale play on landscapes and hydrologic flows, La Salle County, Texas. *Environ Manage*. <https://doi.org/10.1007/s00267-015-0492-2>
- Pierre JP, Young MH, Wolaver BD, Andrews JR, Breton CL (2017) Time series analysis of energy production and associated landscape fragmentation in the Eagle Ford Shale Play. *Environ Manage*. <https://doi.org/10.1007/s00267-017-0925-1>
- Pierre JP, Wolaver BD, Labay BJ, LaDuc TJ, Duran CM, Ryberg WA, Hibbitts TJ, Andrews JR (2018) Comparison of recent oil and gas, wind energy, and other anthropogenic landscape alteration factors in Texas through 2014. *Environ Manage*. <https://doi.org/10.1007/s12665-018-7323-8>
- RRC (2018) Railroad Commission of Texas (RRC) Texas Eagle Ford Shale drilling permits issued 2008 through November 2017. <http://www.rrc.state.tx.us/media/41506/eagle-ford-drilling-permits.pdf>. Accessed 19 Jan 2017
- Slonecker ET, Milheim LE, Roig-Silva CM, Winters SG (2014) Landscape consequences of natural gas extraction in Bedford, Blair, Cambria, Centre, Clearfield, Clinton, Columbia, Huntingdon, and Luzerne counties, Pennsylvania, 2004–2010
- Smith DR, Allan NL, McGowan CP, Szymanski JA, Oetker SR, Bell HM (2018) Development of a species status assessment process for decisions under the U.S. Endangered Species Act. *J Fish Wildl Manage* <https://doi.org/10.3996/052017-JFWM-041>
- Thompson SJ, Johnson DH, Niemuth ND, Ribic CA (2015) Avoidance of unconventional oil wells and roads exacerbates habitat loss for grassland birds in the North American great plains. *Biol Conserv* 192:82–90
- TPWD (2012) Texas Parks and Wildlife Department (TPWD). Texas conservation action plan. State/Multi-Region Handbook, Austin, TX, p 2012–2016
- TPWD (2017) Texas Parks and Wildlife Department (TPWD). Landscape Ecology Program. Ecological Mapping Systems. Data and Supporting Documents. <http://tpwd.texas.gov/landwater/land/programs/landscape-ecology/ems/>. Accessed 2 June 2017
- TPWD (2018) Texas Parks and Wildlife Department (TPWD). Texas Natural Diversity Database (TXNDD). https://tpwd.texas.gov/huntwild/wild/wildlife_diversity/txndd/. Results of data request received 19 Jan 2019
- Trainor AM, McDonald RI, Fargione J (2016) Energy Sprawl is the largest driver of land use change in United States. *PLoS One* 11:e0162269. <https://doi.org/10.1371/journal.pone.0162269>

- Weijermars R (2014) US shale gas production outlook based on well roll-out rate scenarios. *Appl Energy* 124:283–297. <https://doi.org/10.1016/j.apenergy.2014.02.058>
- Wolaver BD, Pierre JP, Labay BJ, LaDuc TJ, Duran CM, Ryberg WA, Hibbitts TJ (2018) An approach for evaluating changes in land-use from energy sprawl and other anthropogenic activities with implications for biotic resource management *Environ Earth Sci* 77:220–263. <https://doi.org/10.1007/s12665-018-7323-8>