



An approach for evaluating changes in land-use from energy sprawl and other anthropogenic activities with implications for biotic resource management

Brad D. Wolaver¹ · Jon Paul Pierre¹ · Benjamin J. Labay^{2,6} · Travis J. LaDuc² · Charles M. Duran³ · Wade A. Ryberg⁴ · Toby J. Hibbitts^{4,5}

Received: 27 September 2017 / Accepted: 5 February 2018
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Abstract

This study presents a novel approach for evaluating land-use changes caused by energy development and other anthropogenic activities. We illustrate this technique by assessing the landscape footprint of energy development in the Eagle Ford Shale Play and Permian Basin of Texas, which saw rapid expansion in drilling during 2008–2012. We compare changes in land-use from oil and gas infrastructure construction during this time period with that of wind energy development in West Texas, urbanization in Central Texas, and extensive agricultural areas. Previous studies often use land-use proxies when comparing the footprint of energy infrastructure (e.g., 1 km² gridded well density or proposed wind project footprints) with other anthropogenic land-change. This study presents an improved technique because it compares high-resolution datasets of agricultural activity and urbanization with mapped—not surrogate—land-change from oil and gas and wind power infrastructure using high-resolution (1 m) aerial imagery. We found that changes in land-use caused by anthropogenic factors affected 1.06% (3456 km²) of the ~ 324,000 km² study area. Oil and gas development (well pads and pipelines) was ~ 48% of total changes in land-use (but did not account for access roads), changes in agriculture caused ~ 26%, and urbanization was ~ 24%. Construction of wind turbine pads and high voltage power transmission lines was less important (~ 1%). We illustrate this approach for a single species (i.e., Spot-tailed Earless Lizard, *Holbrookia lacerata*) in Texas. This study is part of an ongoing, multi-year research program generating science to inform the federal Endangered Species Act listing decision for *H. lacerata*. Additionally, this technique can facilitate effective management of a variety of biotic resources in other rapidly developing environments globally by identifying what anthropogenic activities are most important and where land-change is most intense so that on-the-ground conservation strategies can be implemented where they are needed most.

Keywords Unconventional shale oil and gas plays · Eagle Ford Shale Play · Permian Basin · Landscape alteration · Species Status Assessment (SSA) · Spot-tailed Earless Lizard (*Holbrookia lacerata*)

Introduction

Improvements in directional well drilling and hydraulic fracturing contributed to a rapid increase in oil and gas production from unconventional shale plays since 2008 in Texas

and other hydrocarbon-producing states (Fig. 1; Allred et al. 2015). As a result, construction of oil and gas well pads, access roads, pipelines, and other surface infrastructure has increased and caused important changes in land-use (Abrahams et al. 2015; Brand et al. 2014; Drohan et al. 2012;

✉ Brad D. Wolaver
brad.wolaver@beg.utexas.edu

¹ Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin, Austin, TX 78758, USA

² Department of Integrative Biology, College of Natural Sciences, The University of Texas at Austin, Austin, TX 78712, USA

³ The Nature Conservancy, San Antonio, TX 78215, USA

⁴ Texas A&M Natural Resources Institute, College Station, TX 77843, USA

⁵ Department of Wildlife and Fisheries Sciences, Biodiversity Research and Teaching Collections, Texas A&M University, College Station, TX 77843, USA

⁶ Present Address: Siglo Group, Austin, TX 78702, USA

Kiviat 2013). For example, oil and gas infrastructure constructed 2000–2012 in North America is estimated to have removed ~ 30,000 km² of vegetation from the continent's ecosystems (Allred et al. 2015). Texas led US hydrocarbon production, accounting for ~ 44% of total US crude oil output in November, 2016 (U.S. Energy Information Administration, EIA 2017a). In addition to oil and gas development, the expansion of wind power generation across the USA has converted land for turbines, access roads, and high voltage power transmission lines (Kuvlesky et al. 2007; McDonald et al. 2009). For example, Texas now produces more wind energy than any other state in the USA (Shrimali et al. 2015). Texas also has five of the eleven fastest-growing cities in the USA and forecasts of population growth from 2020 to 2070 estimate a 70% increase in future residents (Census 2016). Thus, it is important to understand the relative contribution to changes in land-use from these various anthropogenic activities.

Recent research has investigated how surface infrastructure associated with urbanization, roads, agriculture, wind power, and oil and gas development has altered the landscape across North America—and has identified Texas as a critical area for continued research (Alig et al. 2004; Allred et al. 2015; Drohan et al. 2012; Entekin et al. 2015; Jones et al. 2015; Liu et al. 2013; McGuire et al. 2016; Milt et al. 2016; Moran et al. 2017; Pierre et al. 2015, 2017; Theobald et al. 2012; Wiggering 2014). “Energy sprawl”—the rapid expansion of the footprint of oil, gas, wind, and other industries—has been identified as an important anthropogenic process with implications for biotic resource management (Copeland et al. 2011; McDonald et al. 2009; Trainor et al. 2016). However, how land-use change caused by energy sprawl compared to that resulting from urbanization and agriculture is an important, but poorly understood question that is the focus of this study.

We demonstrate a novel approach to map and evaluate anthropogenic changes in land-use using the Spot-tailed Earless Lizard (*Holbrookia lacerata*) as an example of how results of this technique can be used to inform biotic resource management. This land-change mapping approach improves upon previous studies because it directly maps changes in land-use from oil and gas and wind power development, whereas many previous studies use lower-resolution proxies for land-change from energy sprawl (e.g., well density or proposed project footprints; Trainor et al. 2016; Copeland et al. 2009).

Historically, *H. lacerata* occupied much of Central and South Texas (Fig. 1), in open native grasslands with gentle slopes and soils with low sand content (Axtell 1956, Duran et al. 2011). Anthropogenic activities in the lizard's historic range include the Eagle Ford and the Permian Basin hydrocarbon provinces, in addition to areas that were converted to agriculture or experienced extensive urbanization. After

1970, however, the species' populations appear to have declined sharply (Axtell 1968, 1998; Duran and Axtell 2010; Duran et al. 2011). Hypotheses for this decline in *H. lacerata* reflect trends affecting reptiles globally (Gibbons et al. 2000), including: (1) agricultural practices and pesticide use (Axtell 1998; Chapin et al. 2000; Duran et al. 2011; Flanders et al. 2006; Fulbright et al. 2013; Sparling et al. 2010), (2) introduced invasive species, (3) road construction (direct vehicle contact and habitat fragmentation; Andrews et al. 2008), (4) urbanization (McKinney 2008; Wolf et al. 2013), and (5) energy development. The decline is not necessarily tied to energy expansion, but is potentially exacerbated by urbanization and invasive vegetation and fauna, which may follow land-use changes associated with drilling. Thus, in light of the species' historic decline in population, *H. lacerata* awaits a decision by U.S. Fish and Wildlife Service (FWS) for possible protections under the Endangered Species Act.

This study presents a novel approach for comparing 2008–2012 land-use changes caused by a suite of anthropogenic activities within the historic range of *H. lacerata* in Texas. We selected this time period because it corresponds with the initial rapid expansion of oil and gas well drilling associated with directional drilling and hydraulic fracturing (Fig. 1) and enables the comparison of high-resolution mapping of “energy sprawl” with other major anthropogenic land uses. Specifically, this study addressed the following questions:

1. What changes in land-use occurred within the study area?
2. What are the implications of such land-use change for management of biotic resources?

This study is part of a larger research program developing science to inform management actions for *H. lacerata*. Thus, we illustrate this land-mapping approach for one widely distributed species in Texas; however, the technique can be used to assess a variety of anthropogenic activities in other environments globally to inform biotic resource management for a variety of species.

Materials and methods

Study area

We mapped changes in land-use within the historic range of *H. lacerata* (Fig. 1; Axtell 1998), a study area which included ~ 47% of the land area of Texas (324,300 km²). Annual precipitation ranged from 260 to 1250 mm (west to east, respectively; PRISM 2016). Primary land cover included shrub/scrub (53%), herbaceous (13%), cultivated

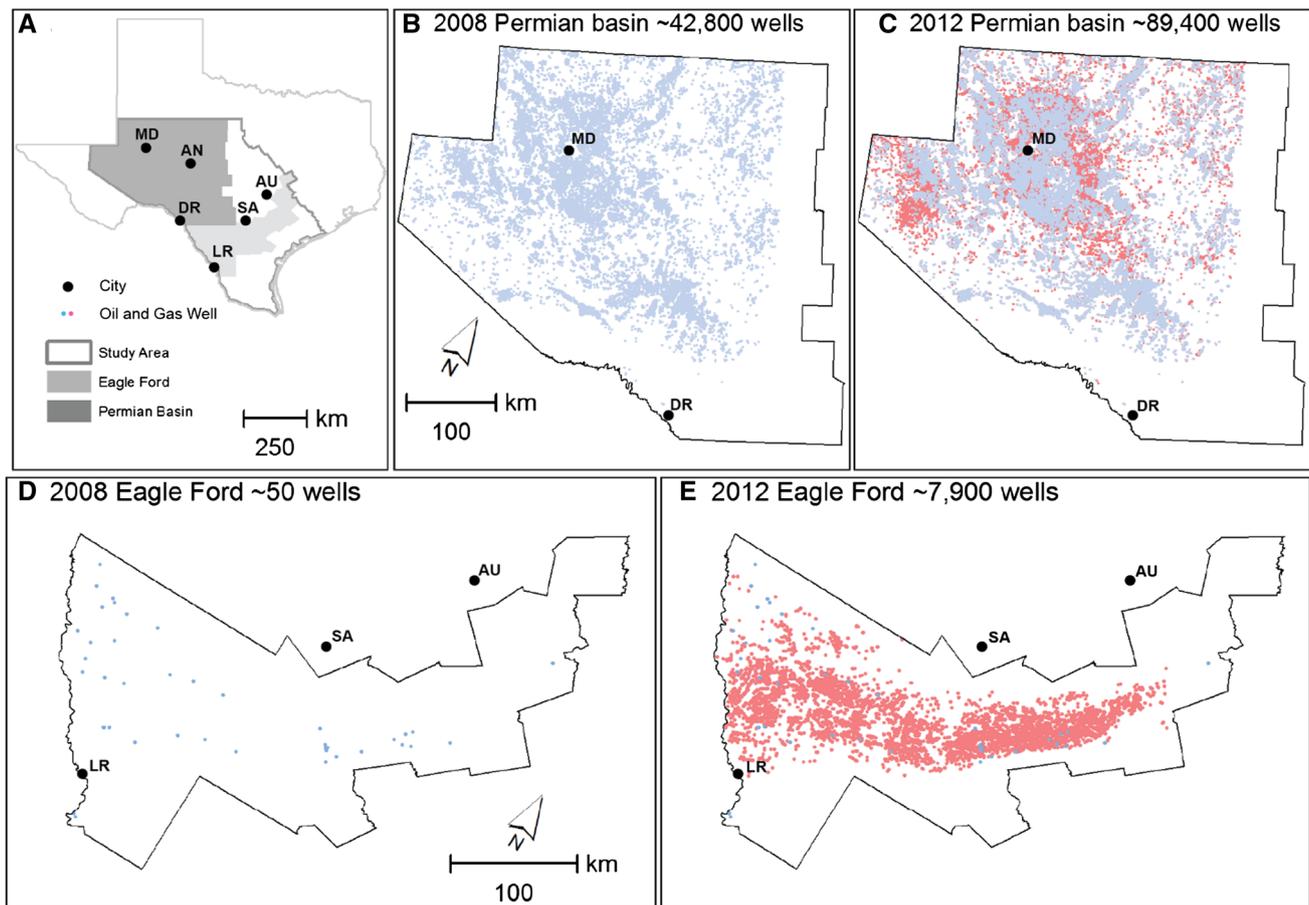


Fig. 1 Study area (a) and Oil and gas wells permitted in 2008 (blue) and 2009–2012 (red) in the Permian Basin (b, c) and Eagle Ford Shale Play (d, e); well locations from IHS (2014). The historic dis-

tribution of *H. lacerata* (Axtell 1998) is included within the spatial extent of the study area (a). Cities: AN = San Angelo; AU = Austin; DR = Del Rio; LR = Laredo; MD = Midland; SA = San Antonio

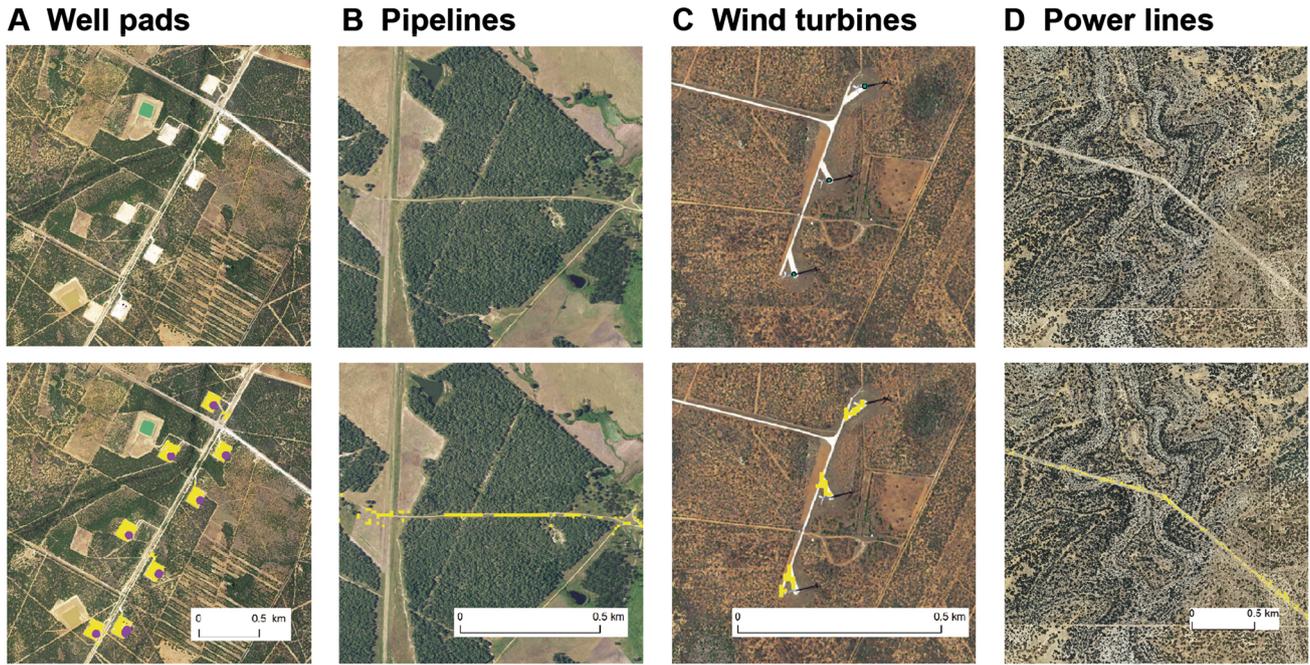
crops (9%), hay/pasture (7%), and evergreen forest (5%; Homer et al. 2015). The study area included Austin and San Antonio—two of the ten most rapidly urbanizing areas in the country (2010–2015; U.S. Census 2016)—in addition to the cities of Del Rio, Laredo, Midland, and San Angelo. Extensive wind power generation (~ 4700 wind turbines; FAA 2016) occurs between Midland and San Angelo and east of Laredo (see Fig. 5 of Fischlein et al. 2013). Two important and rapidly expanding oil and gas producing regions, the Permian Basin and Eagle Ford Shale Play, are also included in the study area (Fig. 1).

Mapping anthropogenic changes in land-use

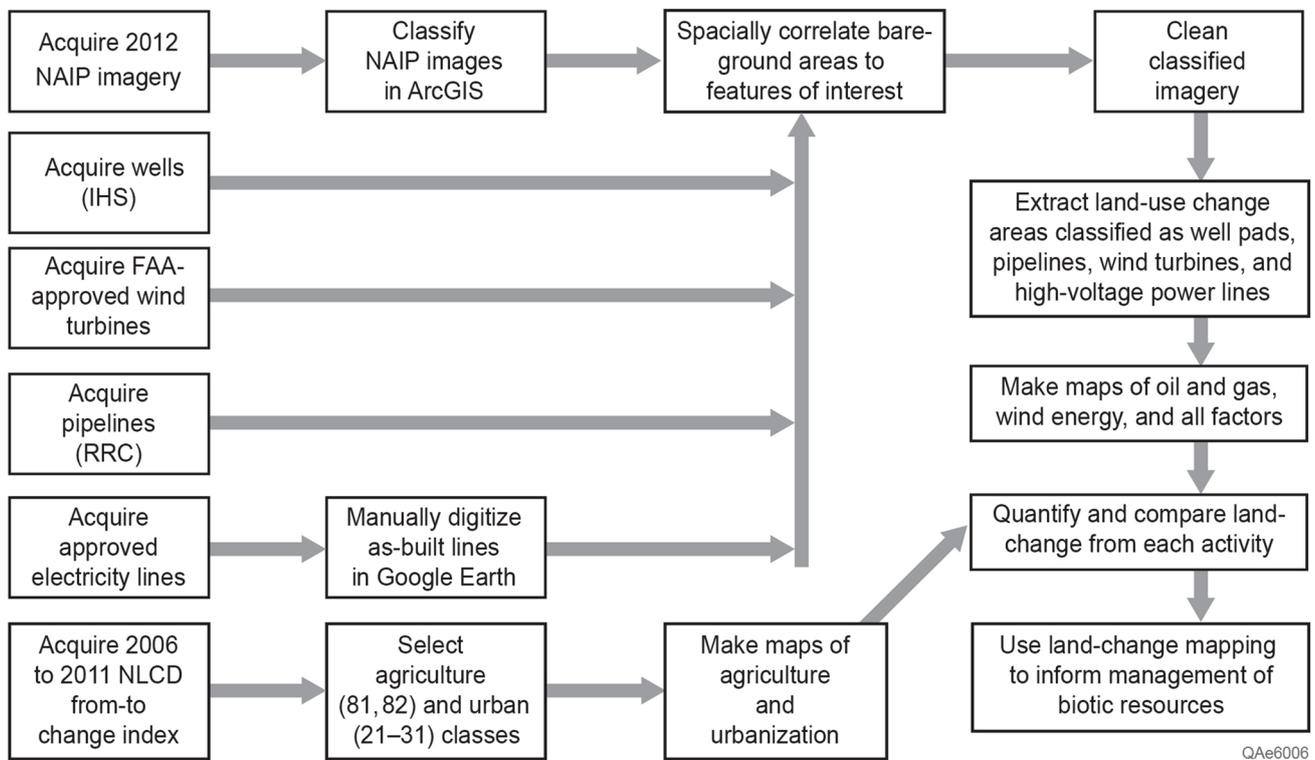
Changes in land-use from unconventional shale oil and gas well pad development, hydrocarbon pipeline construction, wind power turbine, and electrical transmission line installation were mapped using aerial imagery interpretation. Importantly, publicly available land-use databases, such as the National Land Cover Dataset (NLCD; Homer et al. 2015;

USGS 2014), which were used to map agricultural activity and urbanization do not expressly map oil and gas pads and pipelines, wind generation turbine pads, and high voltage power transmission lines. Thus, we created these datasets following the workflow of Pierre et al. (2015, 2017), which is summarized in Fig. 2. The objective of our study is similar to that of Pierre et al. (2017); however, we evaluated a larger geographic area and also included wind energy, urbanization, and agriculture in our land-use change analysis.

We compiled datasets of anthropogenic activities within the study area during the 2008–2012 time period, which corresponded with the initial period of rapid development of unconventional oil and gas drilling in the Permian Basin and Eagle Ford Shale Play (Fig. 1). However, if a dataset did not fall exactly within this range, we used the closest year available. We defined “land-use change” as landscape converted from preexisting vegetation to another use. While these changes in land-use may not necessarily have occurred simultaneously over time, we assume that cumulative effects were considered during the study period.



E Land-use change evaluation approach



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Fig. 2 Land-use change evaluation approach for energy sprawl and other anthropogenic activities. **a–d** Representative energy-related oil and gas and wind power activities (top) resulting in changes in land-

use mapped in this study (bottom) using the work flow of **(e)** which can be used to inform on-the-ground biotic resource management strategies. Refer to Methods section for complete data source citations

We used a semiautomatic approach to identify and quantify land cover changes attributed to high voltage power transmission lines, oil and gas development, and wind turbine pads, incorporating unsupervised image classification (ISO unsupervised classification in ArcGIS 10.2) and supervised image classification (maximum likelihood classification in ArcGIS 10.2; Crews-Meyer et al. 2004). We compared our mapping of energy-related changes in land-use to existing databases of agricultural activity and urbanization (i.e., NLCD).

Oil and gas drilling pad infrastructure was mapped by first downloading all oil and gas wells permitted in the study area March 2001–December 2012 (i.e., production, injection, horizontal, vertical, abandoned, wildcat, etc.; IHS 2016). We chose 2001 as our starting point to be sure that changes in land-use caused by the 50 wells permitted before 2008 that were classified as producing from the Eagle Ford Shale Play were mapped. We used the permit date, not the date drilling began (i.e., spud date) because changes in land-use occur before a well is drilled when the well pad is constructed (e.g., Pierre et al. 2015). It is permissible to include permitted but undrilled wells because changes in land-use would not be mapped.

The footprint of oil and gas well pads was mapped using 1-m resolution National Agriculture Imagery Program (USDA 2012) aerial images acquired in 2012. This imagery was the most recent available at start of the study. Iso cluster unsupervised image classification was executed in ArcGIS (version 10.2) to create 10 landscape classes (following the methods of Pierre et al. 2015). Classified imagery was resampled to 10-m resolution and converted to “bare-earth” polygons. We “cleaned” our mapped changes in land-use by removing areas less than 300 m², which we found—based on visual inspection of aerial imagery in active oil and gas areas—were generally too small to be associated with anthropogenic processes of interest. We assigned wells to mapped changes in land-use that occurred within 90 m of a bare earth polygon to represent land-use change from drilling pads. A 90 m distance was selected through an iterative manual process which optimized the area of resulting well pads based on visual inspection of aerial imagery. We visually inspected areas of land-use change that were greater than three standard deviations of the mean and accepted only changes in land-use clearly associated with drilling activity.

Efforts have been made to map land-change resulting from well pad access road construction in unconventional oil and gas plays and wind power generation regions (e.g., Allred et al. 2015; Moran et al. 2015; Jordaan et al. 2017 manuscript and Supplementary Table 2). However, we did not include access roads in our analysis because a database containing private oilfield road locations—which is necessary to constrain the spatial extent of our alteration mapping—was not available. While the

land-change mapping of Johnson et al. (2010) specifically reported alteration from (1) well pad construction and (2) other infrastructure (e.g., access roads, pipelines, water impoundments), we are not aware of a study that specifically presents land-use change resulting only from the construction of access roads. Reasons for this may be because semi-automated mapping approaches (e.g., Allred et al. 2015; Jordaan et al. 2017; Pierre et al. 2017) have difficulty separating access roads and well pads from one contiguous bare earth polygon. Also, because access roads are constructed by the field operator and are not generally publicly funded, they are not typically included in publicly available road databases (e.g., state highway databases or TIGER; Census 2017). Without mapped access road right-of-ways, the semi-automated mapping approaches we used could over-attribute land-use changes from access roads. Second, manually digitizing landscape alteration from aerial imagery by a GIS analyst (e.g., Johnson et al. 2010; Drohan et al. 2012) is not feasible for large regional studies such as this (324,300 km²). Thus, this study does not map land-change from well pad access roads, which remains an important topic for future research.

We extracted the footprint of oil and gas pipelines, wind power turbine pads, and high-voltage electrical lines using the well pad mapping approach. We acquired hydrocarbon pipeline locations from the Railroad Commission of Texas (RRC 2014) and identified changes in land-use along pipelines using our imagery classification approach. Jordaan et al. (2009) estimated pipeline construction edge effects using a 100-m buffer; however, we found that a buffer of this width overestimated changes in land-use. Thus, we visually inspected aerial imagery and applied a 30-m buffer to RRC pipelines using an iterative manual approach so that mapped bare earth was only associated with pipeline construction (following the approach of Pierre et al. 2017).

We downloaded a database of wind turbine locations, which was based upon a Federal Aviation Administration (FAA) dataset (FWS 2015). Wind turbine pads were mapped in the same way as oil and gas well pads, except we used locations permitted by the FAA. Based on visual inspection of aerial imagery, we found 90 m to be a suitable distance to optimize classification of bare earth polygons resulting from wind turbine pad construction. For wind power transmission lines, we acquired mapping of the 2011 approved Competitive Renewable Energy Zone (CREZ) high voltage (345 kV) routes from Texas Parks and Wildlife Department (Wicker 2014). Because as-built plans are not publicly available, we manually digitized final line locations in Google Earth using the 2011 approved routes as a guide, resulting in ~ 4800 km of lines. We applied a 30-m buffer to the edited high voltage transmission routes and extracted land-use change resulting from the construction of power lines, after the methods of Pierre et al. (2017).

Changes in agricultural activity and urbanization were assessed using the NLCD 2006–2011 from-to change index, which was the closest temporally available to our 2008–2012 study period. Classes 81 and 82 (pasture/hay and cultivated crops, respectively) were used to map changes in agriculture. Urban expansion was mapped using classes 21–31 (Developed, Open Space–High Intensity and Barren Land; Jin et al. 2013; USGS 2014). Finally, we compared changes in land-use caused by each anthropogenic activity during 2008–2012 (i.e., oil and gas, agriculture, urbanization, wind power).

Implications for biotic resource management

This study generated a dataset to support conservation efforts in Texas and is also part of an ongoing, multi-year research program filling data gaps to improve our understanding of *H. lacerata*. We guided the development of this research program by organizing our hypotheses regarding what factors *H. lacerata* need for its survival in a structured framework. We constructed an influence diagram for *H. lacerata* using expert elicitation of knowledge pertaining to this and other phrynosomatine lizards of LaDuc, Ryberg, and Hibbitts (e.g., Failing et al. 2007; Uusitalo 2007; Kuhnert et al. 2010). An influence diagram is a form of a Bayesian belief network, which presents causal relationships of factors affecting a species (e.g., Marcot et al. 2001; O’Laughlin 2005) in terms of a suite of landscape-scale factors, called “sources.” These affect habitat quality and can be mapped and classified with a quantifiable metric, such as the land-change mapping of this study. We used the influence diagram to identify data gaps in the current understanding of *H. lacerata* to inform the development of additional scientific studies to elucidate how each source may ultimately affect the species. The proposed research program was then presented to FWS and interested stakeholders (i.e., state agencies, private industry, etc.) for feedback as part of a public, transparent stakeholder-driven process (e.g., Gulley 2015), facilitated by the Texas Comptroller of Public Accounts to assure that the right science was being developed to guide efforts to conserve the species and inform the federal Endangered Species Act listing decision.

Results

What anthropogenic activities were most important contributors to land-use change?

We found that construction of oil and gas infrastructure (i.e., well pads and pipelines) was the most important process during 2008–2012, which corresponds with the initial rapid development of the Eagle Ford Shale Play

and drilling in the Permian Basin (Figs. 3, 4; Table 1; GIS files available at: <http://dx.doi.org/10.18738/T8/K6GPPD>). Land-use change from all anthropogenic factors affected 3456 km², or 1.06% of the study area. Changes in land-use from oil and gas infrastructure caused 48% of total land-use change at 1664 km², or 0.51% of the study area. As expected, changes in land-use for oil and gas activities were focused in the Permian Basin and throughout the Eagle Ford Shale Play toward the Gulf of Mexico. Between these two broad zones of energy alteration, the installation of hydrocarbon pipelines caused long, linear changes in land-use compared to the many point changes in land-use caused by well pads (Fig. 4b). Changes in agricultural land-use (907 km²) and urbanization (837 km²) were each responsible for around a quarter of the total changes in land-use each. Agricultural changes in land-use were focused along an approximately 400 km long and 100 km wide swath to the south of San Antonio and east of Austin. Interestingly, this zone of changes in agricultural land-use is adjacent to major areas of urbanization in and around the San Antonio and metropolitan areas. Changes in land-use from wind turbine pads and high voltage power transmission lines were relatively minor at 48 km², or 1% of total changes in land-use. The spatial distribution of the wind power land-use change footprint was limited to a few areas near the Permian Basin and in along three major transmission lines leading from generating zones in the west to San Antonio, Austin, and Dallas in the east. We also identified, for all anthropogenic activities, relatively unchanged areas of the landscape between the cities San Angelo, Austin, San Antonio, and Del Rio (Fig. 4a). Contiguous parcels of relatively unchanged landscape also remained east of Laredo, San Antonio, and Austin (Fig. 4b).

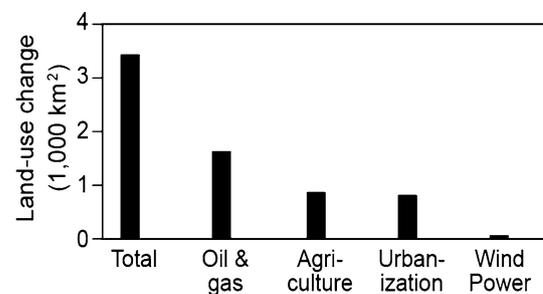


Fig. 3 Changes in land-use from 2008 to 2012 anthropogenic activities. Oil and gas includes changes in land-use from construction well pads and pipelines (but not access roads), while wind power includes land-use changes from installation of wind turbine pads and power transmission lines (Table 1). Total is the sum of all changes in land-use resulting from anthropogenic activities

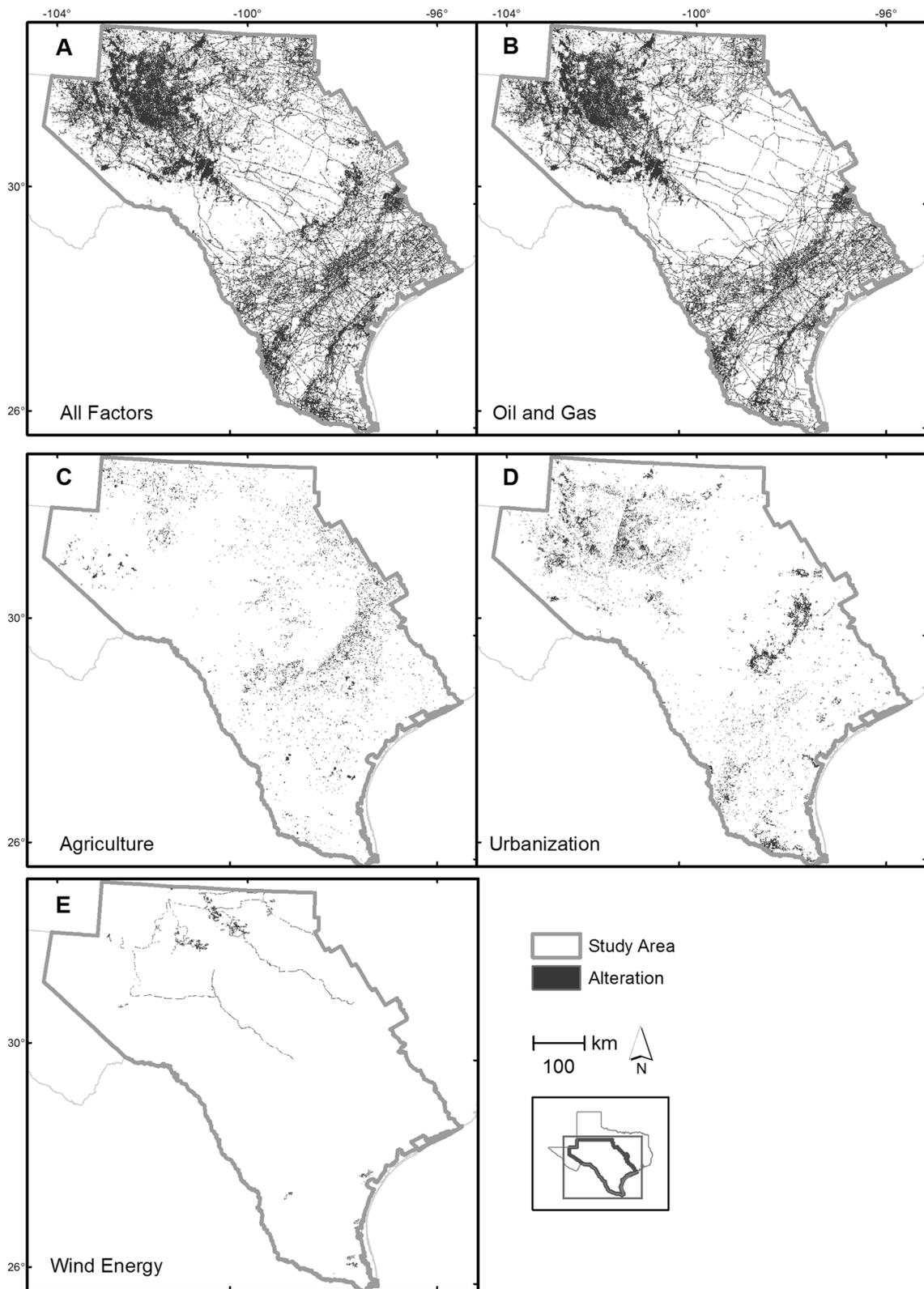


Fig. 4 Changes in land-use from a suite of anthropogenic activities (**a**), including: oil and gas infrastructure (**b**), agriculture (**c**), urbanization (**d**), and wind turbines and high-voltage–power lines (**e**). Note: Black shading is used to make changes in land-use apparent in regional maps

Table 1 Changes in land-use between 2008 and 2012

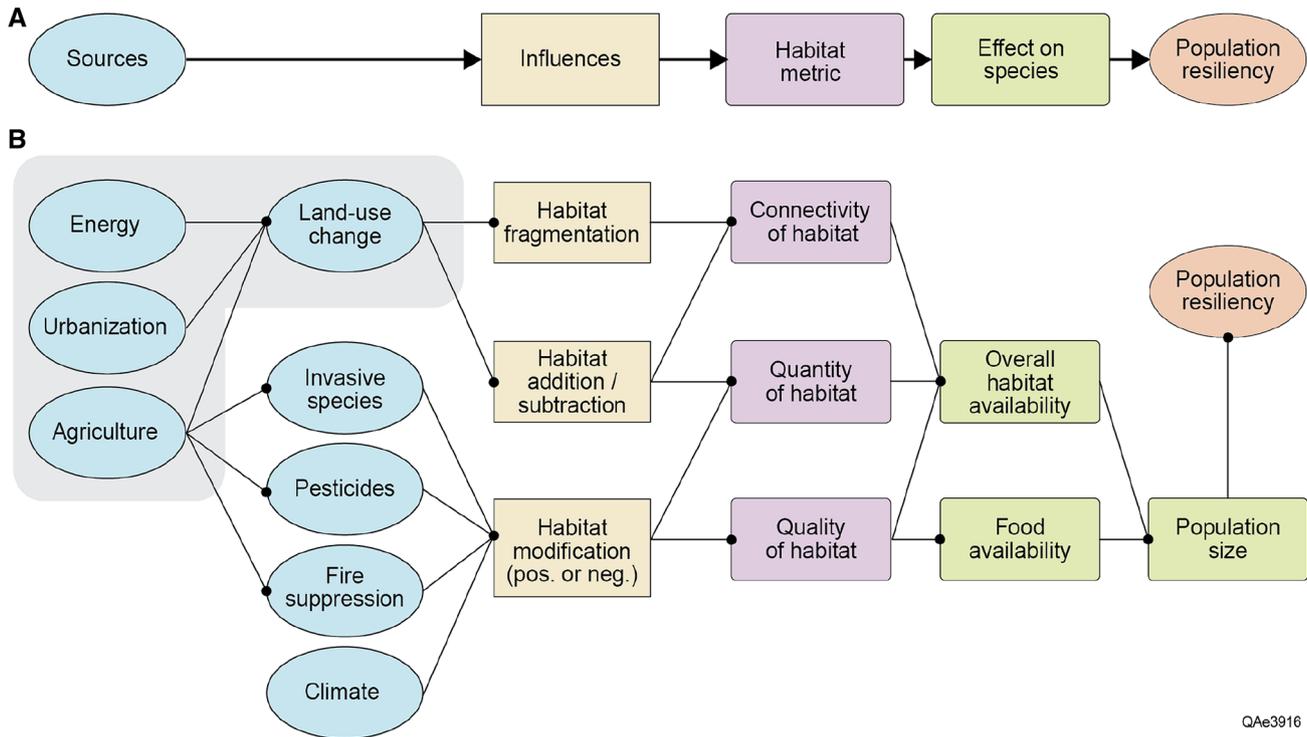
	Total	Oil and gas pads and pipelines	Agriculture	Urbanization	Wind power pads and power lines
Study area (km ²)	324,000				
Total land-use change (km ²)	3456	1664	907	837	48
Total land-use change as percent of study area	1.06	0.51	0.28	0.26	0.01
Percent of total land-use change ^a		48	26	24	1

^aSum does not equal 100 due to rounding

Implications for biotic resource management

The influence diagram for the *H. lacerata* (Fig. 5) revealed gaps in our understanding of the species’ biological needs and how sources may affect habitat quality, habitat quantity, and food availability. Using this information, along with stakeholders, we designed additional ongoing research

studies (Table 2), which included: (1) guiding the locations of ongoing surveys by biologists to assess the species’ current range and how different land-use types may affect habitat quality and population size, (2) improving the understanding of ecological needs of species, such as evaluating gut contents to determine what food sources are most important, (3) describing current habitat conditions and



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Fig. 5 Influence diagram showing how changes in land-use and other factors may affect the focal species. An influence diagram is a form of a Bayesian belief network which outlines causal relationships, called “sources” which could act on the focal species in a positive, negative, or null manner. For *H. lacerata*, we used expert elicitation to identify sources, which included a suite of land-use factors affecting the species’ needs, current habitat, and future viability. The influence diagram shows generic relationships of this Bayesian belief network (a). These linkages represent hypothesized pathways through which land-use (and other factors) may influence the species by causing increase or decrease in population size. The gray shaded box indicates factors considered by this study (b). Other components

of this ongoing, multi-year research program for this species are generating the data needed to understand how sources actually affect the species (Table 2). The results of this research program will inform a Species Status Assessment (SSA; FWS 2016; Earl et al. 2017; Smith et al. 2018) to be prepared by FWS, which will be used to guide the Endangered Species Act listing decision for *H. lacerata*. The SSA could also be used by biologists to design on-the-ground conservation efforts, which may be included in a Candidate Conservation Agreement with Assurances (CCAA) prior to a possible federal listing, or a Habitat Conservation Plan (HCP) if the species were to receive federal protections under the Endangered Species Act

Table 2 Implications for biotic management of focal species within Species Status Assessment framework

	1. Species' needs	2. Current condition	3. Future condition
Components of Species Status Assessment (SSA; FWS 2016)	Improve understanding of ecological needs of species	Describe current conditions of habitat and demographics and explain past and ongoing changes in abundance and distribution	Forecast species' response to probable future scenarios of environmental conditions and conservation efforts
Summary of how this research program is developing science to inform SSA	Assessing species' response to changes in land-use Evaluating habitat needs Analyzing diet Conducting distribution-wide surveys of species (i.e., mark-recapture, yielding estimates of density, vital rates)	Evaluating current land-use changes (and possible threats to species)† Mapping current potential habitat Assessing genetic structure of populations and using morphology to understand taxonomic boundaries Conducting conservation assessment and evaluating population connectivity	Forecasting future land-use changes (and possible threats to species) Mapping future potential habitat Quantifying range of potential climate effects on species Using models to forecast species' extinction probability

We illustrate this approach for *H. lacerata* in Texas. The objectives of the larger, multi-year research program include developing science to inform the U.S. Fish and Wildlife Service listing decision for possible protections under the Endangered Species Act. The research topic covered by the present study (indicated by gray shaded area in Fig. 5 and † in this table) developed a novel mapping approach to assess 2008–2012 changes in land-use with the species' historic range. Other research program components are evaluating the species' needs, current conditions, and future viability (also shown on influence diagram in Fig. 5)

demographics and also explaining past and ongoing changes in abundance and distribution, (4) assessing morphology and genetic structure of populations to understand taxonomic boundaries, and (5) forecasting the species' response to probable future scenarios of environmental conditions—such as climate change—and conservation efforts. These include estimating future changes in land-use from forecasted urbanization and Eagle Ford Shale Play and Permian Basin drilling patterns. When complete in 1–2 years, the results of this research program will be used by the U.S. Fish and Wildlife Service to inform their federal listing decision and by biologists to guide successful conservation strategies for the species.

Discussion

We developed an approach to map and quantify the relative contributions of different anthropogenic activities to changes in land-use, illustrating this technique for *H. lacerata* as a focal species in Texas. We found that 2008–2012 oil and gas infrastructure construction during this time period caused approximately the same area of land-use change (1664 km²) as both agriculture and urbanization combined (1744 km²; Fig. 3; Table 1) and that effects of wind power generation and transmission infrastructure construction were relatively minor (48 km² total land-use change). The high-resolution land-use dataset generated by this is important because oil and gas and wind power are not directly included in current land cover databases such as the NLCD.

While drilling of unconventional shale oil and gas plays has slowed in recent years, energy resource development in Texas—as with many shale plays in North America—is expected to continue when oil prices rebound (West Texas Intermediate Crude was ~ \$53/barrel in March 2017, falling from > \$100/barrel 2 years before; EIA 2015, 2017b). For example, only 10% of expected wells have been drilled in the Eagle Ford Shale Play (Gong et al. 2013; Scanlon et al. 2014), and a detailed economic outlook model supports an expected future up-tick in Eagle Ford drilling under higher oil price scenarios (Ikonnikova et al. 2017; Table 2). However, future drilling trends will also be influenced by a suite of socioeconomic factors (e.g., future energy type demands, environmental protections, etc.), and actual drilling in the Eagle Ford and other plays may ultimately differ from forecasts of Ikonnikova et al. (2017).

Urbanization was also an important anthropogenic process, amounting to approximately one quarter of total changes in land-use. The urbanization trend is expected to continue in Texas, particularly between Dallas, Austin, San Antonio, and Houston (Census 2016). Our results also reveal different spatiotemporal trends in land-use change depending on the cause. For example, urbanization is focused around

existing metropolitan areas (Fig. 4d), while the spatial pattern of oil and gas well pads and wind turbine pads is much more widely distributed in many smaller areas (Fig. 4b, e). We also found that spatial patterns of oil and gas pipelines and electricity transmission lines were linear, resulting in the bisection of preexisting land-cover (Fig. 4b, e).

Comparison of this approach with other land-use change mapping techniques

We applied a novel anthropogenic land-change mapping technique, which facilitates a high-resolution comparison of energy sprawl with other land uses. This approach mapped land-change resulting from well pads, pipelines, wind turbine pads, and transmission lines so that as-built footprints, instead of proxy datasets (e.g., well density per unit area or planned infrastructure), can be compared to other non-energy-related anthropogenic changes in land-use, such as croplands and growing cities. In contrast to our approach, Trainor et al. (2016) assessed the amount of land required to produce a unit energy (km^2/TWhr ; termed “land use efficiency”) from drilled energy resources (oil and gas), mined energy resources (coal, uranium), biofuel biomass, and renewable electricity (wind, solar, hydropower, geothermal, bioelectricity). Changes in land-use from drilled energy resources using were estimated EIA 2012–2040 cumulative production forecasts, which were based on state well spacing requirements—not actual mapping of land-use. Land-use for wind power projects was evaluated using project plans presented in environmental impact statements (EIS), environmental assessments (EA), and other publicly available sources (similar to the approach of Denholm et al. 2009)—not more correctly using as-built project maps. Of the $\sim 55,000 \text{ km}^2$ they identified as recent energy sprawl, 7% was from oil and natural gas and 3% from renewables (including wind power and other sources, such as biofuels). For estimating continental-scale changes in land-use from energy sprawl, the approach of Trainor et al. is satisfactory; however, the higher-resolution approach presented by this study may be better suited for land-change mapping of individual unconventional resource plays.

Proxy datasets for land-change mapping were also used by Kiesecker et al. (2011) and Fargione et al. (2012). These studies used an “oil and gas fields” dataset compiled by Copeland et al. (2009) based on the same oil and gas wells dataset of the present study (i.e., IHS). However, resolution was degraded by creating a binary 1-km^2 grid classified as (1) “producing” if any oil and gas well was present in a particular grid cell or (2) “non-producing” if a cell lacked wells. As a result, this technique could potentially overestimate land-change if few wells are present in a given cell. In contrast, we assessed changes in land-use on a well-by-well basis, which was more spatially explicit. If desired, the

land-change dataset we present here could easily be converted to a 1-km^2 well presence/non-presence grid. But, in many cases, it may be more desirable to assess potential overlap of activities with a species’ habitats using the actual well or turbine pad footprints. In this aspect, the approach we present markedly improves upon that of Copeland et al. (2009), Kiesecker et al. (2011), and Fargione et al. (2012).

Another study that evaluated the footprint of energy sprawl is Copeland et al. (2011), who forecasted the spatial distribution of a suite of energy sources (i.e., hydrocarbons, uranium, wind, solar, geothermal) in Western North America. The hydrocarbon footprint was mapped using oil and gas lease boundaries from the Bureau of Land Management National Integrated Lands System database. However, using lease boundaries would aggregate actual well pad and infrastructure locations. While this approach may be satisfactory for regional-scale studies in the Western USA where drilling primarily occurs on public lands, most development in Texas and other states in the Eastern USA occurs on private land, where mapping the footprint of drilling activity requires using locations of individual wells (typically IHS or state sources). Copeland et al. (2011) also mapped potential wind power areas using US and Canadian industry trade association data and U.S. Department of Energy footprint estimates per megawatt, instead of the actual FAA-permitted turbine locations we used in this study. Copeland et al. (2011) found that wind power had highest “land use intensity” of energy types assessed. In contrast, using area of land-change, we found the wind power footprint in Texas to be quite small compared to that of oil and gas development.

Implications for biotic resource management

An important product of this study is a foundation dataset for conservation efforts in Texas. We developed these maps as part of larger research program for *H. lacerata* with the long-term goal of improving our understanding of what the species needs for its survival, what may threaten its long-term viability, and what management actions may result in its conservation (Table 2). Our research program results will be used by FWS to inform its listing decision whether the species warrants protection under the Endangered Species Act by developing a Species Status Assessment (SSA) for *H. lacerata* (SSA; FWS 2016, Earl et al. 2017; Smith et al. 2018). Specifically, the SSA framework—and our research program objectives—contributes toward 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 (Fig. 5; 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. To this end, our results may also inform pre-listing conservation efforts as part of a Candidate Conservation Agreement with Assurances (CCAA)—or a Habitat Conservation Plan (HCP), should the species ultimately receive federal protection under the Endangered Species Act.

Essential to designing and implementing effective on-the-ground conservation strategies for *H. lacerata* and other species is understanding how anthropogenic land-use may actually affect a particular species. Rapid anthropogenic infrastructure development leading to habitat loss and degradation is considered the primary driver of wildlife extinctions in terrestrial ecosystems (Forman et al. 2003; Juffe-Bignoli et al. 2014; Torres et al. 2016). To this end, assessment of changes in land-use from anthropogenic development and estimation of its effects on wildlife habitats and populations have been identified as conservation priorities of global importance (Brooks et al. 2002; Fahrig 2003; Fischer and Lindenmayer 2007; Hansen et al. 2013; Mildrexler et al. 2007). However, some reptiles favor an altered landscape, and we suspect *H. lacerata* to be an early successional species that may favor certain types of anthropogenic changes in land-use (Axtell 1968), except where urbanization has converted native vegetation. Because Texas has five of the eleven fastest-growing cities in the USA (forecasted 2020–2070 population growth of 70%; Census 2016), land-change—particularly of agricultural lands—is expected to continue around expanding urban areas within the historic range *H. lacerata* (Theobald et al. 2012; Anderson et al. 2014).

Toward improving our understanding of how anthropogenic changes in land-use actually may affect the focal species (*H. lacerata*), we used the land-change dataset generated by this study to direct biologists to specific locations affected and unaffected by different land-change processes across a variety of land-use types within the species' historic range. Biologists are currently conducting field-based surveys to improve our understanding of the causal relationships between changes in land-use and the species' behavior (i.e., Fig. 5). The surveys seek to understand how different vegetation types (e.g., grassland or crops) and activities (e.g., oil and gas operations) may affect the species. When they are available in 1–2 years, findings from ongoing biological surveys should provide insight as to (1) whether a particular anthropogenic activity has positive, negative, or neutral effects on the species, (2) estimate population density, and (3) elucidate how long-term viability may be affected by land-change processes. This information could be used to facilitate an evaluation of conservation actions similar to those of Paukert et al. (2011), who assessed how anthropogenic activities may affect aquatic biota and Fargione et al. (2012), who recommended siting wind power turbines in low-quality habitats with preexisting land-change

to minimize impacts to undisturbed temperate grasslands. While the habitat assessment and land alteration approach presented here are focused on *H. lacerata* in Texas, this methodology should be directly applicable to the conservation and management communities addressing species awaiting listing decisions by FWS or undergoing recovery actions.

Future research directions

In addition to ongoing biological surveys of *H. lacerata* elucidating how changes in land-use may affect the species, several other studies of the larger research program (Table 2) are also in progress. For example, we have assessed cumulative anthropogenic land-use changes for the same study area as the present work through 2014 (Pierre et al. 2018). That study included additional evaluations of the relative contribution of edge effects to overall land-change resulting from (1) point changes in land-use (i.e., well pads and wind turbine pads), (2) linear changes in land-use (i.e., pipelines and high voltage power transmission lines), and (3) expansion of existing large, contiguous areas of land-change (i.e., urban areas). We have also used an economic outlook model to forecast future Eagle Ford Shale Play drilling locations and vegetation conversion (Table 2). A similar study is also being completed to forecast Permian Basin drilling trends. The goal of both works is to understand where within these unconventional hydrocarbon provinces new wells are likely to be drilled to understand what habitats for *H. lacerata* and other species in the study area may be affected.

Assumptions and limitations of this approach

This study generated a valuable dataset of land-use change in Texas; however, we acknowledge several limitations of the approach. For example, agriculture caused approximately one quarter of observed changes in land-use, but the remotely sensed land cover data we used to assess agricultural activity (i.e., NLCD) may have some shortcomings. For instance, farms fallow during the early part of the study may not necessarily indicate an expansion in agricultural acreage if farming was later resumed under more favorable commodity prices. In addition, an independent assessment of Texas agricultural land-use trends using a suite of state and federal financial and crop production data (Anderson et al. 2014) revealed agricultural lands in Texas declined by ~ 400 km² through conversion to other uses—primarily urbanization—from 2007 to 2012. Thus, improving techniques to evaluate remote sensing of agricultural land conversion remains an important topic for future research. As with all anthropogenic changes in land-use mapped by this study, removal of preexisting vegetation by transmission line construction may be short term, with re-growth occurring under towers within a matter of years. However, as aridity increases toward the

western portion of the study area, it is reasonable to expect vegetation recruitment to take longer—and possibly return as early successional or invasive plant species instead of preexisting native vegetation. Despite possible changes in plant communities following anthropogenic activities, the approach mapped the type of land-use that was present at the time National Agricultural Imagery Program (NAIP) aerial imagery was acquired. Another important limitation is the time lag between NAIP aerial imagery acquisition and when it becomes available to the public. The sensors may be flown anytime between spring and early fall, to correspond with the growing season; however, acquisition for a particular state is not synoptic and it may take weeks or months to complete one state—particularly large states such as Texas. Then, inspection of imagery by NAIP analysts can last months and final aerial imagery may not be available for almost a year after the acquisition date for all states. To this end, satellite-derived imagery may in some cases be preferable to NAIP (e.g., Allred et al. 2015; Jordaan et al. 2017). Finally, reporting of infrastructure locations may vary. For example, oil and gas well location data may not be readily available, in a difficult to use format for GIS analyses, or proprietary (such as the IHS database used in this study). Furthermore, locations of infrastructure may not be accurately reported. We have noted in our visual inspection of aerial imagery that well locations may be incorrectly placed by 10 s of meters, particularly for wells drilled before global positioning system (GPS) surveying became widely used. This necessitated a “cleaning” of mapped land-change using procedures described in the Methods. Oil and gas pipelines and high-voltage–power transmission lines may be even more poorly located, with the precise location intentionally degraded due to security concerns. Despite these limitations, the land-use change dataset generated using the approach is valuable, particularly at the regional scale of this study.

Conclusions

This study presents a new method for evaluation of changes in land-use from energy development and other anthropogenic activities. We illustrate the approach in a portion of Texas that saw rapid growth of energy development in the Eagle Ford Shale Play and Permian Basin (particularly during 2008–2012), expanding wind energy development in West Texas, urbanization in Central Texas, and regionally extensive agriculture (Fig. 1). Our illustration of this approach found that oil and gas well pad and pipeline construction between 2008 and 2012 contributed approximately half of the changes in land-use in the study area. Agricultural land-use change and urbanization each contributed to around one quarter of the changes in land-use we mapped; however, fallow fields returning to production may overestimate

land-change. The construction of wind power generation turbines and associated power transmission lines contributed to around 1% of changes in land-use. Relatively continuous unchanged land parcels remained between San Angelo, Austin, San Antonio, and Del Rio, as well as parcels south of Austin and San Antonio. The results of this land-use change study are being integrated into a larger, multi-year research project developing science for *H. lacerata*, which FWS will use to develop an SSA for the species and inform their decision whether the species warrants protection under the endangered species act. While we illustrate this approach for a single focal species (i.e., *Holbrookia lacerata*) in Texas, this novel approach 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.

Acknowledgements 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, C. McDonald, A. Zerrenner, D. German, G. Pauly, and M. Young for helpful discussions. Publication is approved by the Director of the Bureau of Economic Geology.

Funding 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.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

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