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ARTICLE



Urban growth and landscape connectivity threats assessment at Saguaro National Park, Arizona, USA

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ABSTRACT

Urban and exurban expansion results in habitat and biodiversity loss globally. We hypothesize that a coupled-model approach could connect urban planning for future cities with landscape ecology to consider wildland habitat connectivity. Our work combines urban growth simulations with models of wildlife corridors to examine how species will be impacted by development to test this hypothesis. We leverage a land use change model (SLEUTH) with structural and functional landscape-connectivity modeling techniques to ascertain the spatial extent and locations of connectivity related threats to a national park in southern Arizona, USA, and describe how protected areas might be impacted by urban expansion. Results of projected growth significantly altered structural connectivity (80%) when compared to current (baseline) corridor conditions. Moreover, projected growth impacted functional connectivity differently amongst species, indicating resilience of some species and near-complete displacement of others. We propose that implementing a geospatial-design-based model will allow for a better understanding of the impacts management decisions have on wildlife populations. The application provides the potential to understand both human and environmental impacts of land-system dynamics, critical for long-term sustainability.

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Landscape connectivity modeling; wildlife corridors; SLEUTH; conservation planning; Saguaro National Park

1. Introduction

Anthropogenic landscape alterations are both far reaching and increasing in rapidity. Within the conterminous U.S. alone, roughly one-third of the country's land area was classified as human-dominated in 1992 and continues to trend upward (Theobald, 2010). According to the U.S. Census Bureau (2010), Arizona is the second fastest growing state exhibiting a population increase of approximately 24.6% over the last 10 years, making the state's natural landscapes among the most threatened in the nation. Growth models indicate that these trends are likely to continue resulting in a doubling of the State's population by the year 2050. Most of this projected growth is expected to occur along Arizona's 'Sun Corridor', spanning from Tucson along 1–19 to the south and north west along 1–10 towards Phoenix (Yang, Dominguez, Gupta, Zeng, & Norman, 2015). Development associated with this growth is anticipated to be widely dispersed and sprawling; taking the form of less-dense exurban development. This development, and its corresponding infrastructure, will

destroy, degrade and fragment natural systems, impeding the movement of species across the landscape (Theobald, Crooks, & Norman, 2011; Theobald, Reed, Fields, & Soulé, 2012).

Landscape fragmentation is the process of land-use change that divides natural areas into smaller pieces, reducing its productivity and efficacy for supporting wildlife and the natural systems they depend on (Didham, 2010). This fragmentation is among the leading causes of species loss and biodiversity decline (Crooks & Sanjayan, 2006). Conservation planners are responding by shifting their focus from protecting isolated reserves to identifying and protecting critical habitat linkages which together, comprise reserve networks (Soulé & Terborgh, 1999; Theobald, 2006). A tactic central to this conservation strategy is to link landscapes and protected areas through the implementation of landscape corridors. Establishing corridors in fragmented landscapes – either through rehabilitating known historical connections or implementing newly modeled corridors – has been shown to have numerous positive effects on biodiversity (reviewed in Hilty, Lidenicker, & Merenlender, 2006; Rudnick et al., 2012). In addition to serving as habitat (Hess, 1994; Machtans, Villard, & Hannon, 1996; Perault & Lomolino, 2000), corridors have been shown to facilitate movement within and among meta-populations (Beier & Loe, 1992; Beier, Majka, & Spencer, 2008; Brosset, Charles Dominique, Cockle, Cosson, & Masson, 1996; Laurance, 1991) and promote species resiliency to environmental change (Banks, Lindenmayer, Ward, & Taylor, 2005; Beier & Loe, 1992; Bennett, 2003; Rosenberg, Noon, & Meslow, 1997). Functional corridors may also assist dispersing individuals to circumvent predation (Noss, 1987) and avoid human-caused wildlife mortality such as roadkill and harvest (Haddad, 1999; Noss, 1987).

Pressey, Cabeza, Watts, Cowling, and Wilson (2007) promote conservation planning that spatially considers both biodiversity and human alterations; furthermore, they suggest that decision support modelling incorporate these two facets. Peterson, Cumming, and Carpenter (2003) advise using scenarios to lead to better decisions. The primary goal of this research was to develop a utility to examine scenarios of landscape connectivity threats (existing and projected) based on urban growth predictions. Additionally, we aim to provide resulting natural and anthropogenic dynamics in a clear manner to stakeholders.

1.1. Case study

Our case study is the Saguaro National Park (SNP) and wild areas around Tucson, Arizona, USA (Figure 1). Tucson is a desert city, population over ½ MIL (2016) that is surrounded by mountain ranges in the Madrean Archipelago Ecoregion. This globally unique region, commonly referred to as the Sky Islands, has unparalleled diversity with native inhabitants dangerously close to extinction (Skroch, 2008). SNP is comprised of two separate districts including the Tucson Mountain District (TMD) located to the west of Tucson and the Rincon Mountain District (RMD) located to the east. These districts are separated by substantial urban development, exurban land alteration, and infrastructural barriers; all of which have increased pressures on natural resources and wildlife populations. Recently, the TMD portion of the park has become nearly entirely encircled by a variety of development, likely contributing to a recent decline in the biological diversity and ecological connectivity with surrounding natural areas (National Park Service, 1995). Local conservationists have identified a need to preserve landscape connectivity for wildlife (Skroch, 2008). National Park resource managers strive to consider development pressures on open space and habitats, and address future potential threats, such as landscape fragmentation, before losses in biodiversity occur. We developed an urban growth model to predict spatial impacts of development and consider a linkage design around the Park to evaluate how connectivity, and by extension wildlife populations, might be impacted by growth scenarios.

2. Methods

Parameterizing a landscape's permeability, or its inverse resistance, to species movement represents the foundation upon which virtually all connectivity modeling takes place (Compton, Mc

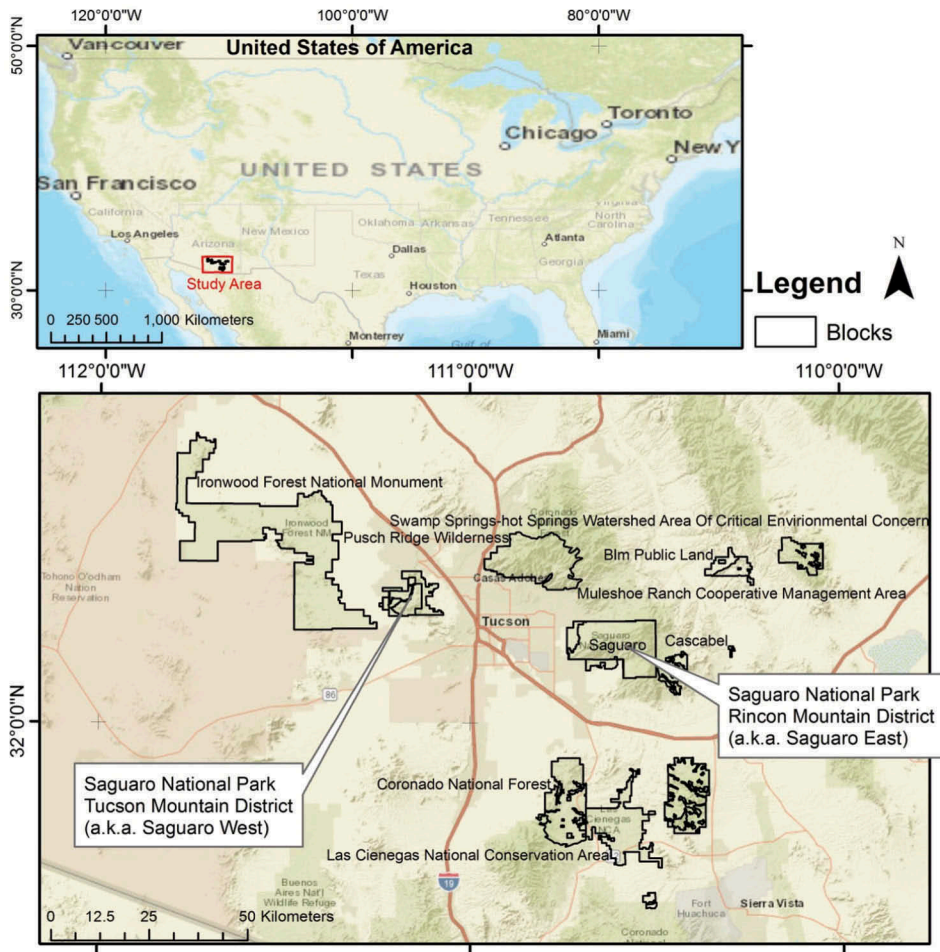


Figure 1. Map portraying the study area and wildland blocks surrounding the Tucson metro region and adjacent to Saguaro National Park in southern Arizona, USA.

Garigal, Cushman, & Gamble, 2007; McRae & Beier, 2007). In either case, the landscape's surface is parameterized to reflect how its characteristics are thought to influence an organism's movement. Such data is then utilized to simulate the expected pathways of species movement throughout the landscape. The most common and widely understood representation of these pathways is the delineation of spatially-explicit landscape corridors which link user defined locations (Rudnick et al., 2012). Such outputs result in linearly arranged landscape elements which either represent structural connections between locations and/or functional pathways through which wildlife are expected to move.

First we developed a 'baseline connectivity scenario' to depict current conditions of the region's *structural* (using landscape integrity data) and *functional* (using focal species habitat data) connectivity. We then developed a projected development scenario using an urban-growth simulation model to estimate expected alterations to existing development. A 'projected connectivity scenario' was modeled utilizing a growth-modified landscape-integrity surface and growth-modified focal-species habitat surfaces. Finally, landscape corridors were modelled between areas targeted as biodiversity centers to reflect both current and projected-future landscape conditions pertaining to both *structural* and *functional* connectivity of the region; The baseline and projected corridor

models were compared to discern the potential impacts and locations of conflict stemming from projected urban growth.

2.1. Structural connectivity using landscape integrity data

Landscape integrity is defined as a measure of the landscape's naturalness, or its inverse, the level of human modification. As such, a wide array of spatial data were incorporated in the landscape integrity model utilized here, including: airports, camping/recreation areas, canals, housing density, impaired waters, impervious surface, land cover, landfills, military operations, mines, oil/gas extraction, pipelines, point source pollution generators, population density, railroads, renewable energy, roads, and utility lines. Individually, each factor can serve as a measure of human impacts. Taken together, the cumulative impacts of these factors reduce the naturalness of the landscape and can be utilized to infer landscape integrity (Perkl, 2013, 2017).

We adapted our approach to merge components of human footprint mapping with landscape-naturalness indices as an alternative method, intended to substitute habitat suitability in large-scale connectivity modeling (Alagador et al., 2012; Baldwin, Perkl, Trombulak, & Burwell, 2010; Cook, 2002; Panitsa, Koutsias, Tsiripidis, Zotos, & Dimopoulos, 2011; Perkl, 2013, 2016; Perkl, Baldwin, Trombulak, & Smith, 2016; Spencer et al., 2010; Theobald et al., 2011; WHCWG 2010). We modeled baseline landscape corridors using an existing peer-reviewed statewide landscape integrity dataset, originally developed for the Arizona Game and Fish Department (Perkl, 2013, 2017; Figure 2).

2.2. Functional connectivity using focal species habitat data

Functional connectivity uses species specific data to model corridors between target species locations. We developed focal-species habitat-suitability surfaces to provide an assessment of the regions' functional connectivity. To the extent possible, focal species selection and the subsequent habitat suitability modeling for each species followed the methods developed in the Tucson-Tortolita-Santa Catalina Linkage Design Report (Beier et al., 2008) created as part of the Arizona Missing Linkages Project. This consisted of: 1) research pertaining to individual species requirements whereas each species was investigated to catalog their particular habitat preferences and 2) suitability modeling whereas a geospatial model was built for each focal species reflecting important habitat characteristics.

Focal species selection included consideration of a wide array of potential candidates with particular consideration given to selecting species with varying mobility/agility, trophic stature, habitat requirements, and sensitivities to anthropogenic landscape change. By virtue of the broad spectrum of variation, it is assumed that the focal species selected here are likely to serve as umbrella species for other species also found throughout this landscape. Focal species included: the North American badger (*Taxidea taxus*), American black bear (*Ursus americanus*), Sonoran Desert tortoise (*Gopherus morafkai*), gila monster (*Heloderma suspectum*), mountain lion (*Puma concolor*), and mule deer (*Odocoileus hemionus*). A final analysis was conducted in order to determine the impacts of growth having aggregated all focal species corridors amongst all connections.

2.2.1. Corridor modeling

Least-cost corridors were modeled using the Corridor Designer Toolset developed by Majka, Jenness, and Beier (2007). The Corridor Designer is an Arc Toolbox for creating habitat and corridor models with ArcGIS and an ArcMap extension for evaluating corridors, free for download (<http://corridordesign.org/downloads>). Within the state of Arizona, USA, parameterized models, justification and conceptual basis for 25 species are available for download (Beier et al., 2008; Majka et al., 2007). Corridors were modeled using the default moving window size of 3×3 cells in order to maintain data specificity and reduce surface averaging. Wildland blocks are defined as the large

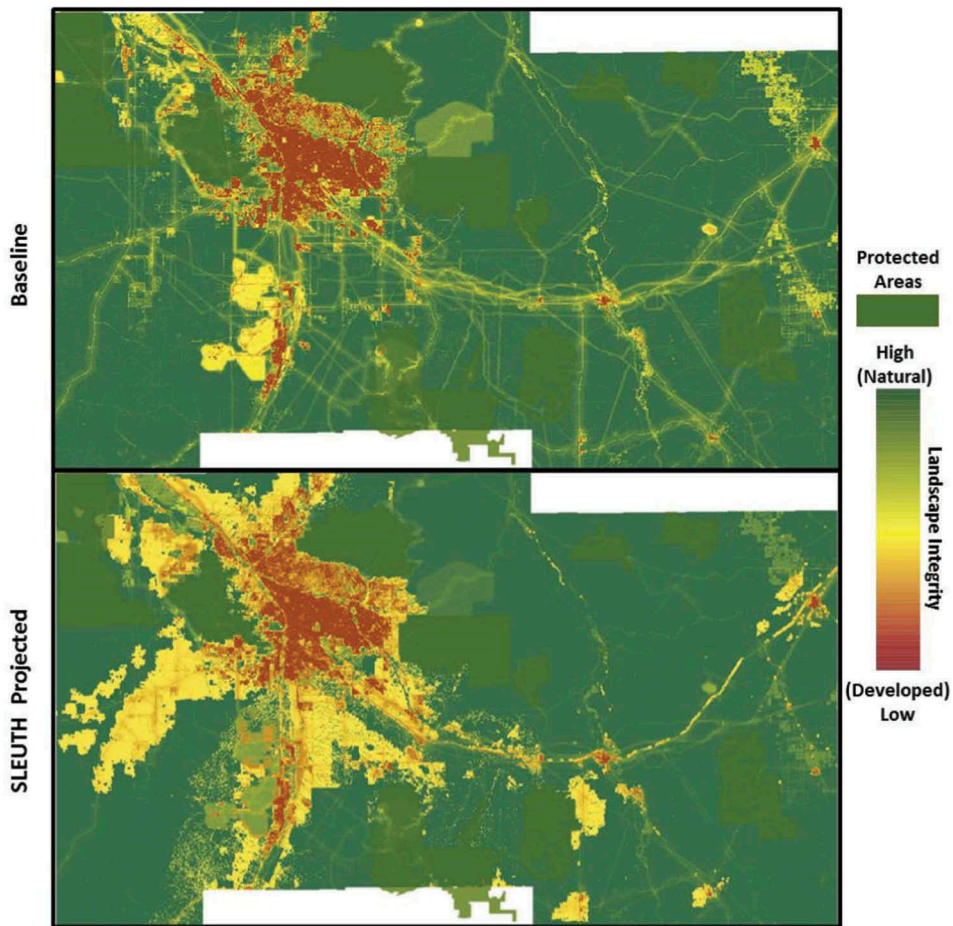


Figure 2. Maps portraying Baseline and Projected Landscape Integrity, where green depicts highly natural and undeveloped and red is highly developed.

areas of publicly-owned or other land expected to remain in a relatively natural condition for at least 50 years and have a long-term prospect of serving as wildlife habitat (Majka et al., 2007). No minimum habitat quality value or block size was parameterized into the model as connections were being modeled between landscape blocks reflecting jurisdictional ‘protected status’ rather than the biological needs of any focal species. Corridors were modeled between the landscape block pairs throughout the region. The resulting modeled corridors exhibit areas of the highest landscape integrity and reflect the most natural and permeable structural and functional connections amongst each landscape block pair. These landscape corridors can be thought of as multi-directional pathways through which species are expected to move.

2.3. Urban growth simulation (SLEUTH)

SLEUTH is a cellular-automaton model that predicts the spatial extent of urban growth based on the pattern of existing urban cells, a series of growth rules, and the interaction of urban cells with their surroundings (Clarke, 2003; Clarke & Gaydos, 1998; Norman, Feller, & Guertin, 2009; Norman, Feller, & Villarreal, 2012; U.S. Geological Survey, 2002). The SLEUTH model is implemented by first calibrating the model using historical development trends and patterns extracted from a time

series of satellite images and coupled with data inputs including slope, excluded areas, transportation and hillshade data. These data, and the subsequent calibration, are used to predict the spatial location and extent of future urban growth, represented as a binary surface whereas cells are classified as 'developed' or 'not developed'. SLEUTH operates under sets of predefined growth rules, applied in a set of nested loops, including: (i) spontaneous neighborhood growth; (ii) diffusive growth and new growth centers; (iii) organic growth, expanding cities into surroundings, plus infill; and (iv) road influenced growth (Silva & Clarke, 2002). Norman et al. (2012) applied the SLEUTH-3r-rev.1.1 version of the model for the Santa Cruz Watershed, located in parts of Pima, Cochise, and Santa Cruz Counties in Arizona and in Sonora, Mexico, to evaluate plausible future scenarios of land use change into the year 2050, as a first iteration for the landuse deltatron portion of the SLEUTH model. The historical urban area was documented from 1979 to 2009 (30 years) to grow by approximately 60%; the SLEUTH model mimics this pattern of exponential growth when predicting urban development to the year 2050 ($y = 6E-17e^{0.0232x}$; Norman et al., 2012). Model outputs from this work were used to assess the impacts of growth scenarios on biodiversity (Villarreal, Norman, Boykin, & Wallace, 2013) and in an ecosystem portfolio model (Norman et al., 2013). Because of the co-location of the city of Tucson and the study area extent of this work, and time constraints, we calibrated an extension of the SLEUTH model to this aforementioned peer-reviewed and published work (Norman et al., 2012, 2013). The extended SLEUTH model was then utilized to project growth, at annual intervals, to the year 2050 for the study area extent. SLEUTH-derived projected growth was then added to the existing landscape-integrity surface (Perkl, 2013, 2017) and focal-species habitat surfaces to reflect anticipated landscape integrity (naturalness) and habitat quality for the year 2050.

2.3.1. Inputs

We developed input in ArcGIS 10.1 by combining readily available data products, resampling, and Graphics Interchange Format (GIF) file conversion for the following raster datasets:

- **Slope/Hillshade:** The slope input requires 1-arc second Digital Elevation Model (DEM) Data, obtained from the USGS National Map Viewer, and processed to derive required rasters.
- **Urban Areas:** A minimum of 4 historic urban area datasets are required for model calibration and subsequent projections. The USGS National Map Viewer was utilized to obtain The National Land Cover Dataset (NLCD) for 2001, 2006, and 2011. Urban areas were extracted from these surfaces based on using the 'developed' land cover classification category. Landscape integrity data (Perkl, 2013, 2017) was used to derive the 4th urban area time step. This was accomplished by snapping and projecting the data to match existing project data, reclassifying landscape integrity values where $0 - 75 = 1$ (urban) and $76 - 100 = 0$ (not urban), and merging this product with the last urban dataset (2011) from the NLCD resulting in a 2-bit raster. Data were then converted to the required 8-bit format for the model.
- **Excluded Areas:** SLEUTH utilizes 'excluded areas' to denote cells where future growth is not allowed. Excluded areas included all mining, landfills, golf courses, airports, protected areas, preserves, federal lands, state parks, county parks, and municipal parks found throughout the study area extent. Exclusions for Pima County were developed based on available Pima County vector data and exclusions for Cochise County were developed based on property use tax codes for parcels. The ALRIS streams were used in both Pima and Cochise counties and buffered 50ft; these were merged with Pima County major washes which broadened some of the streams for more accurate representation of their footprints. Stream data was included as exclusion data to reflect current land use regulations found throughout portions of the study's extent.
- **Roads:** A minimum of two historic roads datasets are required for SLEUTH model calibration and subsequent projections. Roads data were obtained from Pima and Cochise Counties and merged to produce a single roads dataset spanning the study area extent for 2006 and 2014.

The 2014 roads data was used as the closest available proxy for 2011 roads data, as the model requires consistency in timestamps among the urban areas and roads datasets.

2.3.2. *Extended calibration*

We calibrated the SLEUTH model to the exact specifications of existing peer-reviewed and published work (Norman et al., 2012, 2013). Norman et al. (2012) used a land-use dataset at decadal intervals (1979, 1989, 1999, 2009; Villarreal, Norman, Wallace, & van Riper, 2011). These data were reclassified for purposes of urban area delineation used in model calibration: one for initialization and three additional for a least-squares calculation. The urban extent for the seed year, was used to initialize the model (which is the basis for the Cost-automaton driven urban growth), and subsequent urban layers, or control years, to measure several statistical best fit values.

We used a Brute Force Monte Carlo method, where given a range of values, the model iterates using every possible combination of parameters. The individual metrics (compare, population, shape index, and goodness of fit metric) and the modified metrics (population, edges, cluster, and size) from the Santa Cruz calibration runs (Norman et al., 2012, 2013) were found to be within the statistical limits of those generated from the calibration module (Silva & Clarke, 2002). Calibration coefficients representing the best statistical fit between the historic control and predicted future data were then evaluated to determine the best model parameterization. The coefficient of determination (R^2), or proportion of variability in a data set that is accounted for by the model, equaled 0.9832, meaning that predicted values statistically demonstrate a high 'goodness of fit' (Norman et al., 2012). Our Monte Carlo analysis indicated that the models predictive runs best matched the historic data when the model was parameterized using the coefficients portrayed in Table 1. These calibration derived coefficients were used to predict future patterns of urbanization, allowing the model to parallel known historical conditions when projecting future growth.

2.4. *Projected connectivity development*

The SLEUTH urban growth model was utilized to model projected growth based on the existing landscape integrity and other historical data. SLEUTH derived projected growth was then added to the original landscape-integrity surface to reflect future landscape conditions. This altered landscape-integrity surface was used to model projected structural connectivity and future landscape corridors. The growth modified landscape integrity surface was used as input to the focal species habitat models (described in section 2.2) in order to reflect variations in habitat quality as it relates to future human development and least-cost corridors were modeled using the Corridor Designer Toolset developed by Majka et al. (2007). The SLEUTH model results were used to derive new connectivity layers and corridors around projected growth scenarios. Model parameterization mirrored that of the baseline scenario corridor modeling in that corridors were modeled using

Table 1. Growth coefficients, their descriptions, and calibrated values for this study (Clarke 2000; Crosier and Golstein 2001; Norman et al., 2012).

Growth Coefficient	Description	Value
Dispersion/ Diffusion	Controls the number of times a cell will be randomly selected for urbanization based on spontaneity and the influence of roads.	85
Breed	Determines the probability of spontaneous growth cells becoming a new spreading center and the influence of roads.	15
Spread	Determines the probability that a spreading center cell will generate an additional urban cell in its neighborhood.	25
Slope	Establishes the relationship between slope values and ease of development through the use of slope influenced development probabilities.	35
-Road Gravity:	Determines maximum neighborhood search distances from road cells for urbanization.	60

the default moving window size of 3×3 cells and no minimum habitat quality threshold or block sizes. Corridors were modeled among the same user defined natural landscape blocks. The baseline and projected connectivity scenarios were overlaid and analyzed to determine network congruency.

3. Results

3.1. Structural corridor comparison

The results of the projected urban growth model were overlaid with the baseline landscape-integrity surface for refinement (Figure 2). Cells from the urban growth model that had a greater probability of becoming developed (>50%) were selected for addition to the baseline landscape-integrity surface and otherwise neglected from further analyses. To determine the level of score refinement for the cells with projected development, an analysis was conducted to determine the mean landscape integrity score for municipalities located within the study area extent (Perkl, Mitchell, Norman, & Feller, 2015). These scores were then adjusted to remove large undeveloped land, normalized by area across each jurisdiction, and compiled to determine the mean landscape integrity score amongst developed jurisdictions within the study area. The mean landscape integrity score for existing developed cells was then applied to cells where development was projected to occur given the growth simulation. This resulted in the derivation of a growth adjusted landscape-integrity surface for use in the projected connectivity scenario (Figure 2).

Corridors were developed to represent the least-costly pathways of movement among the modeled protected areas for both the baseline and projected (SLEUTH-modified landscape) integrity surfaces. The structural corridors represent the future least-costly pathways of movement given anticipated landscape modifications due to growth. Figure 3 presents the results of the baseline scenario reflecting the landscape's structural corridors (bottom left), results of the projected growth scenario (bottom right) and a comparison of the two to identify which are at the most risk of alteration or loss due to urban growth. We define our comparison of corridor results (larger top panels) using the following descriptions:

- (I) Baseline (RED): represents the proportion of the corridor area that is included in the baseline scenario only, this area is expected to 'go away' or be lost to development.
- (II) Projected (ORANGE): represents the proportion of the corridor area that is included in the projected scenario only, this area is expected to replace what is lost from the baseline scenario.
- (III) Agreement (GREEN): represents the proportion of the corridor area that is in agreement between the baseline and projected scenarios, this area is not expected to be impacted by development trends.

3.2. Functional corridor analysis

Using the functional corridors for each focal species and each scenario (described in section 2.2), we compared the impacts of growth on the focal species in a change analysis (Figure 4). For each focal species (described in Section 2.2.1), we repeated the analysis to document (i.) the baseline functional habitat suitability and corridor analysis whereas the underlying surface represents current habitat suitability and the corridors represent the least-costly pathways of movement among the modeled protected areas (Figure 4, bottom left panels); (ii.) the projected functional habitat suitability and corridor analysis whereas the underlying surface is the SLEUTH modified habitat suitability surface (Figure 4, bottom right panels); and (iii.) compared them to identify corridors that are in agreement and therefore least threatened by urban developments (Figure 4, larger top panels).

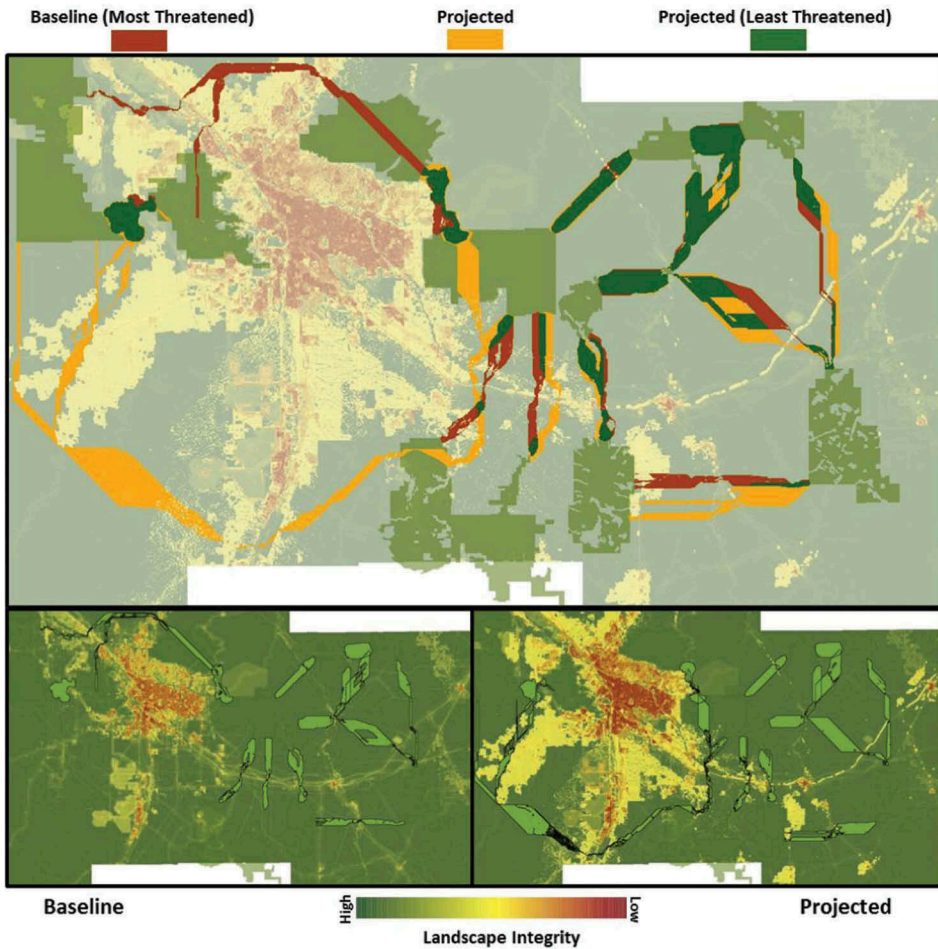


Figure 3. Maps represent the results of the change analysis between the baseline and projected structural corridors overlain on landscape integrity.

3.3. Network change analysis

The baseline and projected connectivity scenarios were overlaid and analyzed to determine network congruency. Individual corridors are examined and described in higher detail in a report sent to the Saguaro National Park (Perkl et al., 2015). Corridor agreement represents an indicator of potential threats to the modeled corridor. Greater agreement indicates that the corridor is less impacted by projected urban growth. Less corridor agreement indicates that the corridor is more adversely impacted by projected urban growth. The results of the structural landscape connectivity analysis using landscape integrity data indicate that 7 of the 16 corridors lost over 50% of their current footprints to projected development and growth. We were able to identify three baseline corridors that were completely altered and vanish due to the regions projected growth (Perkl et al., 2015).

Each block pair connection was scrutinized by aggregating the corridors of all focal species into a single corridor assemblage. This illustrated the relative threat to each modeled connection, taking into account all focal species, given projected urban growth. These results identify connections most adversely effected for all species, one as much as ~76% loss and one as little as ~5% loss (Perkl et al., 2015).

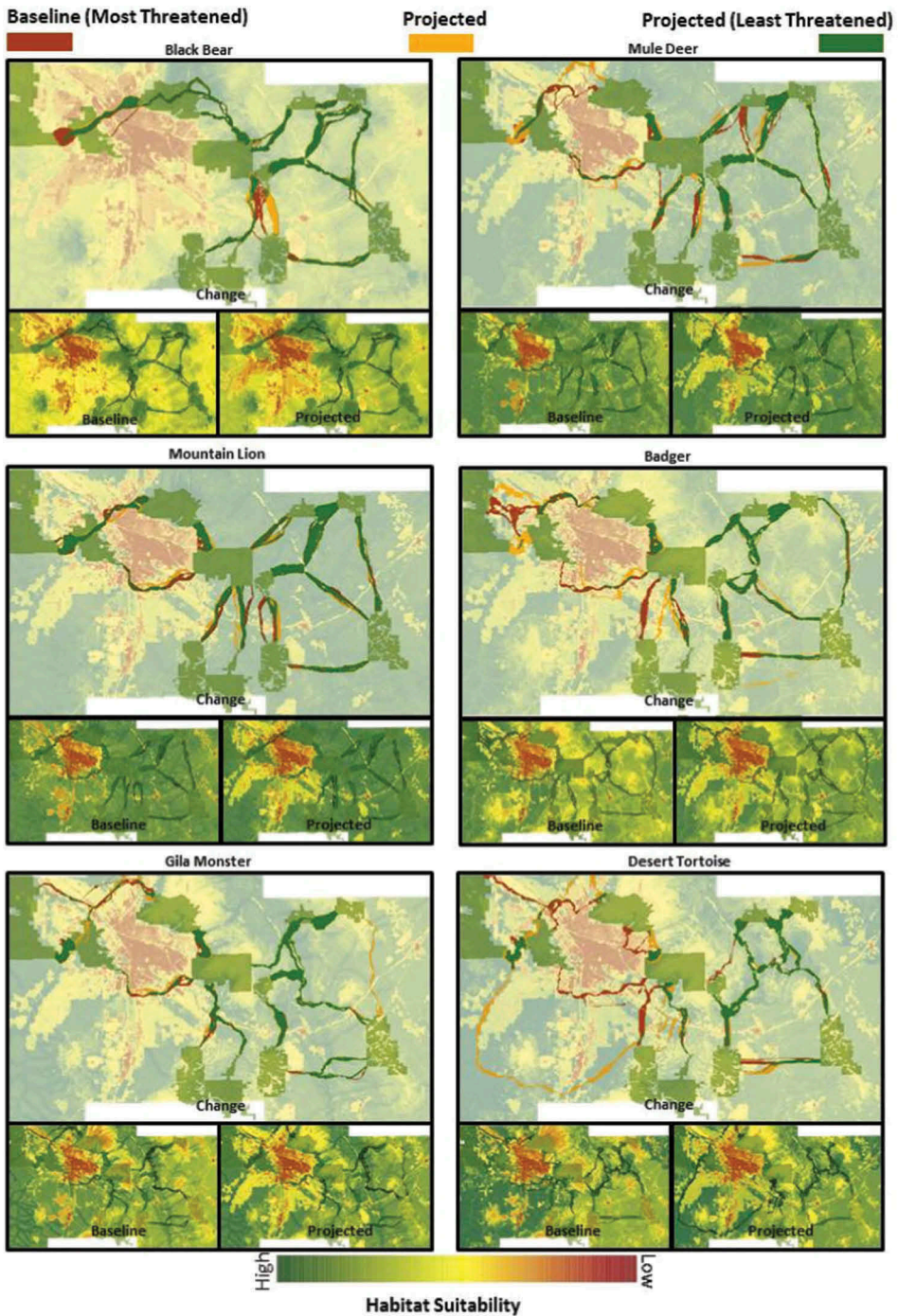


Figure 4. Maps depict the baseline (lower left), projected (lower right) and change analysis (larger/top panel) between the baseline and projected functional corridors.

When all corridors are considered, ~30% of the entire network belonged to the baseline network only, the projected network was comprised of ~50% of the networks total area, and only ~20% of the total network was in agreement amongst the two scenarios. This means that the

majority of the total network (~80%) was altered from the original baseline corridors and impacted by projected urban growth, indicating substantial displacement and alternation of existing landscape connectivity

Moreover, altering the physical footprints of the corridors location also has impacts on the land area comprising the network. The total area of all corridors within the baseline scenario encompasses approximately 1014 km². The total area of all corridors within the projected scenario encompasses approximately 1428 km² acres. This represents an increase of approximately 414 km² (~41%) across the entire network. Pragmatically, the projected corridor network is far less efficient as it utilizes more circuitous and longer corridors to facilitate the same connections as the baseline scenario.

The results of the focal species analysis also indicate widely varying impact across focal species and individual corridors. When evaluating each focal species separately across all connections within the network, desert tortoise corridors were the most negatively impacted with ~47% loss, followed by badger (~45% loss), mule deer (~44% loss), gila monster (~30% loss), mountain lion (~28% loss), and black bear (~25% loss).

These results of the aggregate focal species analysis (described in [Section 2.2](#)) indicate that if all corridors and connections are considered, ~19% of the entire network belonged to the benchmark network only, ~19% belonged to the projected network only, and that ~62% of the total network was in agreement amongst the two scenarios. This indicates that ~38% of the entire focal species network was negatively impacted by projected urban growth.

4. Discussion

A major challenge in urban planning and landscape ecology is to extend conservation science in such a way as to inform land-use decision making (Pressey et al., 2007; Theobald et al., 2000). The primary goal of this research was to implement complimentary modelling techniques that could be used to assess future threats to landscape connectivity due to urbanization, necessary to prevent unnecessary habitat loss while allowing for growth. Our case study considered Saguaro National Park, the larger complex of protected lands surrounding the Tucson metro region, and portions of the landscape located to the east of the park such as the San Pedro River Valley, in southeastern Arizona, United States.

We applied a series of well-documented routines in landscape planning to model corridors that reflect both current and projected-future landscape conditions throughout the region using both a structural assessment of the landscapes connectivity as well as functional assessments using focal species. The 'least-cost' derived corridors presented may serve as critical connections between target natural areas in the future, given projected landscape alterations due to development. Additionally, we evaluated network congruency to identify the level of threat in high-priority areas for conservation action by comparing the spatial extents of the baseline and projected corridor networks.

Applying a geospatial design-based approach to evaluating these differences, whereby comparisons are made amongst impact models (corridors), can provide guidance as to where alterations to future development patterns may be mitigated by present-day land use planning decisions. Left unchecked, future development trends will displace and alter existing pathways of connectivity (red, baseline). By identifying these areas, local planners and land managers are better equipped to understand the scope, scale, and extent of potential conflicts, thereby allowing for pre-emptive mitigation in the form of zoning alterations, land acquisition, or other means to be implemented before these lands are lost. Similarly, by identifying those areas that may serve as future surrogates for existing connectivity pathways (orange, projected), these same practitioners can better plan for next-best alternatives. Moreover, should existing connectivity be maintained, these areas may serve as a form of insurance for enhancing network resiliency. The identification of congruent corridors (green, agreement), can help to illustrate areas that are critical to connectivity, but are relatively

unthreatened, thus allowing for resources to flow to the more threatened aforementioned areas of potential conflict (Peterson et al., 2003; Pressey et al., 2007).

Computational modelling allows for some possible outcomes to be examined, but there are various ways to improve upon. Analysis may be enhanced with additional data, such as movement information, which can accuracy of connectivity assessments (Ziolkowska et al., 2016). Additionally, our urban growth scenario could be improved upon. Silva and Clarke (2002) suggest detailed and exhaustive calibration to improve the performance of the SLEUTH model. Instead of performing a new analysis, we used the SLEUTH predictions from a previously calibrated study (Norman et al., 2012; Yang et al., 2015) to compare. Other urban growth models might also allow for different growth patterns to be considered. Dorning, Koch, Shoemaker, and Meentemeyer (2015) use the Future Urban-Regional Environment Simulation (FUTURES) model to investigate how patterns of future development influence landscape patterns and connectivity. However, our initial combination of urban growth modeling and connectivity assessment are not meant to reflect 100% accuracy but rather to allow for consideration of how habitats might be impacted, based on model application and their associated assumptions and uncertainty analyses. Our results are completely dependent on the particular urban growth and corridors models we chose.

In our study, all of the 16 modeled structural connections are predicted to exhibit corridor alternations from anticipated development and, given the nature of our analysis, we were also able to identify the exact locations where these perturbations are likely to occur. Alterations to the structural corridors varied markedly, ranging from 100% (complete alteration) to ~5% (minimal alternation), however, the majority of the landscape network (~80%) was predicted to be negatively altered. The projected landscape network size was increased by ~41%, indicating a less-efficient corridor network than when compared to the baseline scenario. This less-efficient network may have negative effects on individual species and regional biodiversity as the routes of movement are less direct and span larger areas. It is thereby expected that implementation and managerial costs associated with the projected network will also exceed the baseline given the additional associated land area.

Alterations to the functional focal species corridors were also predicted in all instances, varying from one corridor that the desert tortoise relied on, which experienced complete alternation (100%), to minimal impact to a corridor the gila monster would travel (~9% alteration). In evaluating each focal species separately across all connections within the network, again, the sum of the desert tortoise corridors were the most negatively impacted with ~47% alteration through to the sum of the black bear (~25% alteration). Through examining differences between changes in focal species functional corridors, a pattern of vulnerability emerge. Of our focal species, desert tortoise functional corridors are constrained to very narrow range of gentle slopes while black bear function corridors can include a wide range of slopes. Additionally, the narrow range slopes used by the desert tortoise coincide with slopes that are ideal for development which increases the tortoise's corridors vulnerability to urban growth. In comparison, gila monster functional corridors have similar slope constraints but are not affected by low intensity development land cover; correspondingly gila monster corridors were less affected by urban growth. When the functional corridors of a species are based on landscape characteristics that are narrowly constrained due to species traits (e.g. desert tortoises can't navigate moderate or steep slopes) and those constrained landscape characteristics are also characteristics preferred for development, then functional corridors are highly vulnerable to development. Furthermore, if species are particularly sensitive to development then functional corridors affected by development, even low intensity development, may be lost. To use resources most effectively, Beier et al. (2008) recommend designing corridor linkages to serve multiple focal species. When all species were aggregated and evaluated amongst each connection, alteration ranged from ~76% to ~5%, again indicating that some connections are more threatened than others. We combined all of the aggregated species and all block connections to identify the total impacts across the entire corridor network, finding that ~38% of the functional corridors in the network would be negatively altered by projected growth and development.

When evaluating alteration amongst the aggregated structural network to that of the aggregated focal species network, the structural network is more negatively impacted. The structural network experienced ~80% alteration whereas the focal species network experienced ~38% alteration. While both are potentially alarming alterations to the regions connectivity given projected growth, it appears that the focal species modeled here may be slightly less impacted than the landscape as a whole. In our aggregate analysis, all focal species were equally weighted but it might be relevant to consider the listing status of these species when performing multi-species analysis. Our analysis considered species with secure populations as well as listed species, developing additional species specific corridor analysis based on listing status or other conservation concern would further assist in prioritizing land use management and corridor design. Coupling such work with population viability models and landscape genetic analysis however is a necessary next step if the differences of these impacts are to be fully quantified and understood (Mateo-Sánchez et al., 2015).

This research describes how innovative urban growth simulations can extend the capabilities of linking landscapes and protected areas through the implementation of landscape corridors into future planning. By identifying the specific areas of projected threats, managers are poised to prioritize, guide, and coordinate conservation and local development decisions where they are most needed. Such work could serve as a catalyst for synchronizing land use decisions and helping to guide development to ensure connectivity in the larger region is conserved into the future. This is an important first step in a larger regional planning effort for which interjurisdictional cooperation and additional partnerships amongst a diverse set of stakeholders will be necessary.

5. Conclusions

A better understanding of the ecological impacts of urbanization is critical to help guide the construction of cities as well as to inform policy and practices that can mitigate harm to surrounding natural lands. Land-use planning professionals may benefit from an increased focus on conserving wildlife when engaged in planning and development activities, and likewise, ecologists may benefit from a better understanding of the impacts of urbanization and land-use decision making when observing wildlife populations. Research to consider both human populations and wildlife habitat requirements together is ongoing and necessary to better understand their dynamics. Our work combines previously documented models from land-use planning with those from wildlife ecology to illustrate how a geospatial-design approach, whereby inventories of current landscape conditions are evaluated within the context of impacts resulting from future projections. In our analysis, not one species is predicted to be completely immune to habitat connectivity threats of projected urban growth, but there are scenarios in which those might be less severe. We aim to encourage a dialog around how to consider and accommodate the ecological impacts of urbanization. Results can be used to help better guide current land-decision making processes for future populations. We introduce this as a novel example of how land planners may integrate the natural sciences into their processes and vice versa for landscape ecologists.

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References

- Alagador, D., Trivino, M., Cabeza, M., Araujo, M.B., Cerdeira, J.O., & Bras, R. (2012). Linking like with like: Optimizing connectivity between environmentally-similar habitats. *Landscape Ecology*, 27, 291–301.
- Baldwin, R.F., Perkl, R.M., Trombulak, S.C., & Burwell, W.B., III. (2010). Modeling ecoregional connectivity. In S. C. Trombulak & R. F. Baldwin (Eds.), *Landscape-scale conservation planning*. New York, NY: Springer-Verlag.
- Banks, S.C., Lindenmayer, D.B., Ward, S.J., & Taylor, A.C. (2005). The effects of habitat fragmentation via forestry plantation establishment on spatial genotypic structure in the small marsupial carnivore, *Antechinus agilis*. *Molecular Ecology*, 14, 1667–1680.
- Beier, P., & Loe, S. (1992). A checklist for evaluating impacts to wildlife movement corridors. *Wildlife Society Bulletin*, 20, 434–440.
- Beier, P., Majka, D.R., & Spencer, W.D. (2008). Forks in the road: Choices in procedures for designing wildland linkages. *Conservation Biology: The Journal of the Society for Conservation Biology*, 22(4), 836–851. Retrieved from <https://doi.org/10.1111/j.1523-1739.2008.00942.x>
- Bennett, A. F. (2003). *Linkages in the landscape: The role of corridors and connectivity in wildlife conservation*. Gland, Switzerland: IUCN-the World Conservation Union.
- Brosset, A., Charles Dominique, P., Cockle, A., Cosson, J.-F., & Masson, D. (1996). Bat communities and deforestation in French Guiana. *Canadian Journal of Zoology-Revue Canadienne De Zoologie*, 74, 1974–1982.
- Clarke, K., (2000) SLEUTH: Land Cover transition Model, version 3.0. Retrieved from http://www.ncgia.ucsb.edu/projects/gig/project_gig.htm
- Clarke, K. C. (2003). The limits of simplicity: Toward geocomputational honesty in urban modeling. *Proceedings of the 7th international conference on geocomputation* (p. 15).
- Clarke, K. C., & Gaydos, L. J. (1998). Loose-coupling a cellular automaton model and GIS: Long-term urban growth prediction for San Francisco and Washington/Baltimore. *International Journal of Geographical Information Science*, 12(7), 699–714.
- Compton, B. W., Mc Garigal, K., Cushman, S. A., & Gamble, L. R. (2007). A resistant-kernel model of connectivity for amphibians that breed in vernal pools. *Conservation Biology*, 21, 788–799.
- Cook, E. A. (2002). Landscape structure indices for assessing urban ecological networks. *Journal of Planning Literature*, 17, 85–168.
- Crooks, K. R., & Sanjayan, M. A. (2006). *Connectivity conservation*. Cambridge: Cambridge University Press.
- Crosier, S., & Goldstein, N. (2001, August 17). Sleuth: land transformation model. Retrieved from <http://www.ncgia.ucsb.edu/projects/metadata/standard/uses/sleuth.html>
- Didham, R. K. (2010). Ecological consequences of habitat fragmentation. In John Wiley & Sons, Ltd (Ed.), *Encyclopedia of life sciences*. Chichester, UK: John Wiley & Sons, Ltd. Retrieved from doi:10.1002/9780470015902.a0021904
- Dorning, M. A., Koch, J., Shoemaker, D. A., & Meentemeyer, R. K. (2015). Simulating urbanization scenarios reveals tradeoffs between conservation planning strategies. *Landscape and Urban Planning*, 136, 28–39.

- Haddad, N. M. (1999). Corridor and distance effects on interpatch movements: A landscape experiment with butterflies. *Ecological Applications*, 9, 612–622.
- Hess, G. R. (1994). Conservation corridors and contagious disease: A cautionary note. *Conservation Biology*, 8, 256–262.
- Hilty, J. A., Lidicker, W. Z., & Merenlender, A.M. (2006). *Corridor ecology: The science and practice of linking landscapes for biodiversity conservation*. Washington, DC: Island Press.
- Laurance, W. F. (1991). Edge effects in tropical forest fragments: Application of a model for the design of nature-reserves. *Biological Conservation*, 57, 205–219.
- Machtans, C. S., Villard, M. A., & Hannon, S. J. (1996). Use of riparian buffer strips as movement corridors by forest birds. *Conservation Biology*, 10, 1366–1379.
- Majka, D., Jenness, J., & Beier, P. (2007). CorridorDesigner: ArcGIS tools for designing and evaluating corridors. Available: *HYPERLINK". Retrieved from <http://corridordesign.org>
- Mateo-Sánchez, M. C., Balkenhol, N., Cushman, S., Pérez, T., Domínguez, A., & Saura, S. (2015). Estimating effective landscape distances and movement corridors: Comparison of habitat and genetic data. *Ecosphere*, 6(4), art59.
- McRae, B. H., & Beier, P. (2007). Circuit theory predicts gene flow in plant and animal populations. *Proceedings of the National Academy of Sciences of the United States of America* 104, 19885–19890.
- National Park Service. (1995). *Statement for management, Saguaro National Park* (pp. 33). Tucson, Arizona: Author. + appendices.
- Norman, L., Villarreal, M., Niraula, R., Meixner, T., Frisvold, G., & Labiosa, W. (2013). Framing scenarios of binational water policy with a tool to visualize, quantify and value changes in ecosystem services. *Water*, 5, 852–874.
- Norman, L. M., Feller, M., & Guertin, D. P. (2009). Forecasting urban growth across the United States-Mexico border. *Computers, Environment and Urban Systems*, 33, 150–159.
- Norman, L. M., Feller, M., & Villarreal, M. L. (2012). Developing spatially explicit footprints of plausible land-use scenarios in the Santa Cruz Watershed, Arizona and Sonora. *Landscape and Urban Planning*, 107, 225–235.
- Noss, R. F. (1987). From plant-communities to landscapes in conservation inventories: A look at the Nature Conservancy (USA). *Biological Conservation*, 41, 11–37.
- Panitsa, M., Koutsias, N., Tsiripidis, I., Zotos, A., & Dimopoulos, P. (2011). Species-based versus habitat-based evaluation for conservation status assessment of habitat types in the East Aegean islands (Greece). *Journal for Nature Conservation*, 19, 269–275.
- Perauld, D. R., & Lomolino, M. V. (2000). Corridors and mammal community structure across a fragmented, old-growth forest landscape. *Ecological Monographs*, 70, 401–422.
- Perkl, R. (2013). *Arizona landscape integrity and wildlife connectivity assessment*. Tucson, AZ: The University of Arizona and the Arizona Department of Game and Fish.
- Perkl, R. (2016). Modeling connectivity of the whole: A graph theoretic application in conservation planning prioritization. *Landscape Journal*, 35, 79–96.
- Perkl, R. (2017). Measuring landscape integrity (LI): Development of a hybrid methodology for planning applications. *Journal of Environmental Planning and Management*, 60(1), 92–114.
- Perkl, R., Baldwin, R.F., Trombulak, S. C., & Smith, G. R. (2016). Landscape network congruency at the ecoregion-scale: Can we expect corridor umbrellas? *Journal of Land Use Science*, 11(4), 429–449.
- Perkl, R. M., Mitchell, D., Norman, L. M., & Feller, M. (2015). *Saguaro National Park connectivity threats assessment* (pp. 41). Tucson, AZ: University of Arizona and Saguaro National Park Cooperative Agreement No. P13AC00690.
- Peterson, G. D., Cumming, G. S., & Carpenter, S. R. (2003). Scenario planning: A tool for conservation in an uncertain world. *Conservation Biology*, 17(2), 358–366.
- Pressey, R. L., Cabeza, M., Watts, M. E., Cowling, R. M., & Wilson, K. A. (2007). Conservation planning in a changing world. *Trends in Ecology & Evolution*, 22(11), 583–592.
- Rosenberg, D. K., Noon, B. R., & Meslow, E. C. (1997). Biological corridors: Form, function, and efficacy. *Bioscience*, 47, 677–687.
- Rudnick, D., Beier, P., Cushman, S., Dieffenbach, F., Epps, C. W., Gerber, L., ... Trombulak, S. C. (2012). *The Role of Landscape Connectivity in Planning and Implementing Conservation and Restoration Priorities. Issues in Ecology*. (Report No. 16). Washington, DC: Ecological Society of America.
- Silva, E. A., & Clarke, K. C. (2002). Calibration of the SLEUTH urban growth model for Lisbon and Porto, Portugal. *Computers, Environment and Urban Systems*, 26, 525–552.
- Skroch, M. (2008). Sky islands of North America: A globally unique and threatened inland archipelago: Articles: Terrain. org. *A Journal of the Built & Natural Environments, Islands & Archipelagos*, 21(Winter/Spring), 147–152.
- Wildlands Project; Soulé, M. E., & Terborgh, J. (1999). *Continental conservation: Scientific foundations of regional reserve networks*. Washington, DC: Island Press.
- Spencer, W. D., Beier, P., Penrod, K., Winters, K., Paulman, C., Rustigian-Romsos, H., ... Parisi, A. P. M. (2010). California Essential Habitat Connectivity Project: A Strategy for Conserving a Connected California. Prepared for California Department of Transportation, California Department of Fish and Game, and Federal Highways Administration.
- Theobald, D. M. (2010). Estimating natural landscape changes from 1992 to 2030 in the conterminous US. *Landscape Ecology*, 25, 999–1011.

- Theobald, D. M. (2006). Exploring functional connectivity of landscapes using landscape networks. In C.M. Sanjayan (Ed.), *Connectivity conservation* (pp. 416–443). Cambridge, UK: Cambridge University Press.
- Theobald, D. M., Crooks, K.R., & Norman, J. B. (2011). Assessing effects of land use on landscape connectivity: Loss and fragmentation of western U.S. forests. *Ecological Applications*, 21, 2445–2458.
- Theobald, D. M., Hobbs, N. T., Bearly, T., Zack, J. A., Shenk, T., & Riebsame, W. E. (2000). Incorporating biological information in local land-use decision making: Designing a system for conservation planning. *Landscape Ecology*, 15(1), 35–45.
- Theobald, D. M., Reed, S. E., Fields, K., & Soulé, M. (2012). Connecting natural landscapes using a landscape permeability model to prioritize conservation activities in the United States. *Conservation Letters*, 5, 123–133.
- U.S. Census Bureau. (2010). Population division interim state population projections. Retrieved March 15, 2014, from <<http://www.census.gov/population/www/cen2010/glance/>>
- U.S. Geological Survey. (2002). Project Gigalopolis: Urban and land cover modeling. Website maintained by the National Center for Geographic Information and Analysis at University of California Santa Barbara. Retrieved from <http://www.ncgia.ucsb.edu/projects/gig/project_gig.htm>
- Villarreal, M. L., Norman, L. M., Boykin, K. G., & Wallace, C. S. A. (2013). Biodiversity losses and conservation trade-offs: Assessing future urban growth scenarios for a North American trade corridor. *International Journal of Biodiversity Science, Ecosystem Services & Management*, 9(2), 90–103.
- Villarreal, M. L., Norman, L. M., Wallace, C., & van Riper, C., III. (2011). A multitemporal (1979–2009) land-use/land-cover dataset of the binational Santa Cruz watershed. *US Geological Survey Open-File Report*, 1131, 26.
- WHCWG. Washington Wildlife Habitat Connectivity Working Group. (2010). *Washington connected landscapes project: Statewide analysis*. Olympia, WA: Washington Departments of Fish and Wildlife, and Transportation. Report.
- Yang, Z., Dominguez, F., Gupta, H., Zeng, X., & Norman, L. (2015). Urban effects on regional climate: A Case study in the phoenix and tucson “Sun” Corridor. *Earth Interactions*, 151027111902006. doi:10.1175/EI-D-15-0027.1
- Ziółkowska, E., Ostapowicz, K., Radeloff, V. C., Kuemmerle, T., Sergiel, A., Zwijacz-Kozica, T., ... Selva, N. (2016). Assessing differences in connectivity based on habitat versus movement models for brown bears in the Carpathians. *Landscape Ecology*, 31(8), 1863–1882.