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Research Paper

Assessing highway's impacts on landscape patterns and ecosystem services: A case study in Puli Township, Taiwan

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HIGHLIGHTS

- Highway construction results in isolation and fragmentation of land uses.
- The road-effect zone is highly asymmetric along either side of the highway. Spatial policies result in land-use changes along major roads.
- Maintaining forest lands improves habitat quality.
- An integrated approach is needed to assess highway-induced changes.

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ABSTRACT

Highway construction facilitates urban growth in Taiwan. However, the long-term effects of transportation infrastructure are not well understood; these include land-use changes, changes in landscape patterns, and the alteration of ecosystem services. To assess the effects of different land-use scenarios under various agricultural and environmental conservation policy regimes, this study applies an integrated approach to analyze the effects of Highway 6 construction on Puli Township. Interviews with neighborhood leaders of Puli Township, along with remote sensing analysis, reveal that both biophysical and socioeconomic factors are the major forces driving land-use change. The effects of these land-use changes are varied. An example is the road-effect zone, which for Puli Township extends 400 m perpendicular to the length of the highway; however, due to differing spatial patterns it is highly asymmetric; indirect effects include the spatial restructuring of certain landscapes, which can drastically influence habitat dynamics. Land-use simulation results indicate that agricultural and environmental conservation policies have significant effects on projected land-use patterns in the southern part of Puli's downtown area and in areas along major roads. Specifically, highway construction and subsequent urbanization under various land-use policies result in varying degrees of isolation and fragmentation in the overall landscape pattern. A habitat quality assessment using the InVEST model indicates that the conservation of agricultural and forested lands improves habitat quality and preserves rare habitats. In summary, appropriate environmental policies will mediate both the direct and indirect impacts of Highway 6 on landscape patterns and ecosystem services in Puli Township.

1. Introduction

Highway construction often leads to land-use changes such as urbanization. However, urban growth resulting from highway construction may adversely impact an area when growth is not in line with local planning policies (Bartholomew & Ewing, 2009; Gessaman & Sisler, 1976). As such, the relationship between highway construction and urban development patterns is an important research topic in modern regional planning (Funderburg, Nixon, Boarnet, & Ferguson, 2010). The ecological effects of highway construction have been assessed in many ecological studies (Boarman & Sazaki, 2006; Cai, Wu, & Cheng, 2013; Eigenbrod, Hecnar, & Fahrig, 2009; Forman, 2000; Forman & Deblinger, 2000; Forman et al., 2003; Godar, Tizado, & Pokorny, 2012; Riitters

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& Wickham, 2003; Saunders, Mislivets, Chen, & Cleland, 2002; Semlitsch et al., 2007; Theobald, Crooks, & Norman, 2011; Torres, Palacín, Seoane, & Alonso, 2011). Forman (2000) applied the concept of a "road-effect zone" to assess the impacts of road construction and use. The road-effect zone is the area on either side of a road that experiences the direct effects of road construction and use (Forman & Deblinger, 2000). Moreover, land-use patterns, human activities, and their combination strongly influence road patterns, that is, the placement of highways in a landscape (Forman et al., 2003). Forman et al. (2003) demonstrated that road mortality, habitat loss, reduced habitat quality, and reduced connectivity in a landscape are the dominant effects of road construction. Therefore, identifying and assessing land-use changes and their impacts on habitat quality, particularly within road-effect zones, are tasks that must precede highway construction.

The ecological road-effect zone is central to road system evaluations (Forman & Deblinger, 2000) and impact assessments. Road-effect zones are typically asymmetric due to intrinsic directional flows found in biophysical systems along with varying spatial patterns on either side of a road (Forman & Deblinger, 2000). A road system typically has both positive and negative ecological effects, and their identification is essential to transportation policy and planning (Forman, 2000). For example, for some species, road infrastructure such as fencing can create high-quality habitats and markedly enhance existing habitats (Forman et al., 2003). Conversely, road construction can cause habitat loss by transforming habitats into pavement and roadsides (Forman et al., 2003). The overall effects of roads on animal populations can comprise (1) a barrier effect blocking movement and thereby subdividing species into subpopulations; (2) animal avoidance of a nearby habitat due to traffic noise; and (3) road kill (Forman & Alexander, 1998; Forman & Deblinger, 2000). For instance, bird mating may be adversely affected by highway noise (Forman & Deblinger, 2000). Most forest bird species are particularly sensitive. In fact, for some species, the adverse effects can even extend hundreds of meters from a busy road (Forman & Deblinger, 2000). Traffic-related disturbances, particularly noise, can interfere with bird courtship (Forman et al., 2003). Finally, distant areas, including expansive patches of natural vegetation, which often support large mammal and bird populations, need to be considered carefully, as they are oftentimes sources of and destinations for animals approaching or crossing highways (Forman & Deblinger, 2000).

Models have been applied in many land-use change studies to simulate the resulting patterns and consequences of land-use changes driven by various forces, including highway construction and ecology conservation policies. Stochastic models, optimization models, dynamic process-based simulation models, and empirical models are common (Castella, Pheng Kam, Dinh Quang, Verburg, & Thai Hoanh, 2007; Lin, Hong, Wu, Wu, & Verburg, 2007; Lin, Verburg, Chang, Chen, & Cheng, 2009; Verburg et al., 2002; Wu, Lin, & Lin, 2011). The Conversion of Land Use and its Effects (CLUE-s) model is also a typical approach. This scheme uses dynamic modeling to simulate land-use changes by considering empirically quantified relationships between a land use and its causes (Verburg et al., 2002; Verburg & Veldkamp, 2004). Logistic regression is generally applied prior to empirical land-use modeling to approximate the relationships between land uses and their drivers (Lin, Wu, Chu, & Verburg, 2011; Lin, Wu, & Hong, 2008). Logistic regression estimates the probability of land-use distributions. A number of recent studies utilized logistic regression and the CLUE-s model to simulate land-use changes in urban and suburban contexts under various land-use scenarios (Lin et al., 2007, 2008, 2009, 2011; Trisurat, Alkemade, & Verburg, 2010; Wu et al., 2011). Notably, researchers have recently begun to pay close attention to the applications of "grounded theory" (Strauss & Corbin, 1998). This theory focuses on the subjective experiences and insights of people as they are influenced by their broad historical, geographical, and social context, making grounded theory a useful tool for analysis of human related topics such as social structures, small- to large-scale social phenomena, and the ever illusive relationship that specific instances have with broad social trends (Knigge & Cope, 2006). Thus, grounded theory has strong potential for use in much of the current work in critical geography (Knigge & Cope, 2006) such as in studies assessing land-use change. Furthermore, qualitative methods can identify questions which were formerly overlooked.

An ecological approach to landscape analysis is helpful because it identifies ecological threats and thus mitigation priorities intrinsic to an existing road network (Forman & Deblinger, 2000). For instance, Fahrig and Rytwinski (2009) and Theobald et al. (2011) demonstrated that many of the species considered for conservation in connectivity assessments in forests in the western United States are sensitive forest specialists, *i.e.*, species that are very sensitive to fragmentation effects, including those generated by roads. Land-use change caused by road construction also changes landscape patterns. Landscape composition, configuration, and connectivity are the primary characteristics of landscape patterns that are associated with land-use changes (Turner, Gardner, & O'Neill, 2001). Landscape configuration is defined as the spatial characteristics of an area, including the arrangement, shape, size, position, and orientation of distinct patches within a landscape (Lin et al., 2007; McGarigal & Marks, 1995). Landscape indices or metrics, such as mean patch size (MPS), total edge (TE), mean shape index (MSI), and the isolation index, are typically utilized to characterize landscape configurations and quantify landscape patterns. To identify changes in landscape configurations caused by road construction and use, many studies have applied landscape metrics (Cai et al., 2013; Fahrig & Rytwinski, 2009; Geneletti, 2004; Riitters & Wickham, 2003; Saunders et al., 2002; Theobald et al., 2011).

Land-use changes markedly affect ecosystems worldwide (Polasky, Nelson, Pennington, & Johnson, 2011). Alterations to ecosystem services due to land-use changes can be quantified by assigning unit values to each ecosystem service in each land-use category (Li, Wang, Hu, & Wei, 2010; Liu, Li, & Zhang, 2012) or by applying models that can determine the extent of changes to ecosystem services (Ooba, Wang, Murakami, & Kohata, 2010; Tallis et al., 2011). The Integrated Valuation of Environmental Services and Tradeoffs (InVEST) model generates spatially explicit predictions of biophysical supply and ecosystem services, displaying natural capital in map and tabular formats environmental data which is essential for competent land management decisions. This model combines information on land use/land cover and threats to biodiversity to create habitat quality and rarity maps (Tallis et al., 2011). The model also generates two key sets of data that are applicable to an initial investigation of conservation needs: the relative extent of specific habitat types within a region and the degradation of these habitats (Tallis et al., 2011). Therefore, in the context of biodiversity and conservation biology (Tallis et al., 2011), one can apply the InVEST model to simulate habitat quality and rarity as biodiversity proxies, where habitat quality is defined as the ability of an environment to provide conditions that sustain an individual or population, while habitat rarity is defined as the extent to which natural land cover types and patterns in a landscape compare to the extent of the same natural land cover in reference to a baseline period (Tallis et al., 2011). As mentioned, changes in landscape patterns resulting from human activities can cause habitat fragmentation, adversely affecting habitat integrity. A recent example of the InVEST model in action was its recent application in identifying the health of ecological services and/or biodiversity in river basins under different land-use management scenarios (Goldstein et al., 2012; Nelson, Mendoza, & Regetz, 2009; Polasky et al., 2011).