Network and accessibility methods to estimate the human use of ecosystems

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SUMMARY

Scientists who develop estimates of the effect of humans on global and regional ecosystems are increasingly using geo-information science methods with massive global and national spatial datasets. Although conservation scientists increasingly stress the distinction between existence of a road and the use (or traffic level) of a road, nearly all existing methods are simple estimates of the existence of the transportation infrastructure such as road density, distance from roads, or roadedness. Here I provide a novel application of accessibility and use decay to model a more direct, fine-grain estimate of the "human footprint", called Human Use of Ecosystems. A case study example of the state of Colorado, USA is provided.

INTRODUCTION

Scientists who develop estimates of the effect of humans on global and regional ecosystems are increasingly using geo-information science methods with massive global and national spatial datasets. Although some of these approaches employ just population or housing density, most use some metric based on the transportation infrastructure. For example, Sanderson et al. (2002) estimate that 83% of the global land surface bears some form of the "human footprint" as measured by population >1 person/km^2 population or less than 15 km of a road or river.

Conservation scientists increasingly stress the distinction between existence of a road and the use (or traffic level) of a road (Forman et al. 2003; Crooks and Sanjayan 2006; Riley et al. 2006). However, most GIS-based approaches to examine the effect of roads are based simply on estimates of the *existence* of the transportation infrastructure (Theobald 2006). Typically, four main approaches have been used to incorporate roads into an overall measure of effects: (i) road density; (ii) distance from road; (iii) road buffers or "roadedness"; and (iv) network structure (Haggett and Chorley 1969; Forman et al. 2003). It is typically assumed that all road types are roughly the same, particularly in distance-based metrics (e.g., Riitters and Wade 2003; Watts et al. 2007). Occasionally, some nominal classification of roads is used to differentiate interstate highways from a secondary road (Lesslie et al. 1988; Theobald 2003), for example Forman (2000) estimates 100 m secondary, 305-365 primary roads, 810 m near urban areas. Yet, all locations along a road type are treated the same, which does not differentiate the traffic volume (though admittedly there is some correlation of type with use). Road effects onto adjacent lands are computed either by density computations (e.g., km/km^2) that assume a (typically circular) neighborhood of an arbitrary size (e.g., 1 km; Mladenoff et al. 1995) or by measuring distance from the road. Both of these ignore any differences in topography, vegetation, or other natural features that might restrict or enhance the diffusion of noise, air pollution, or human accessibility.

My goal in this paper is to describe a new method called *human use of ecosystems (HUE)* to more directly estimate the effect of road use that incorporates accessibility. The specific objectives are to: (1) describe the data and specific techniques used to estimate HUE; (2) provide illustrations of computing HUE on a case study example in the state of Colorado, USA. This work draws heavily on work regarding network-based accessibility that has been developed largely in the transportation IGS field (GIS-T; Kansky 1963; Geertman and Ritsema van Eck 1995; Miller and Shaw 2001). In addition, I combine the GIS-T work with concepts from the ecological literature (especially road ecology) to better understand the direct and indirect on and off road ecological effects.

METHODS

Here I describe a novel application of a transportation measure of road use using an accessibility framework implemented within a geographical information system (GIS) (ESRI, Redlands, CA, USA). Three steps are needed to compute the HUE measure: compiling estimates of traffic volume, modeling how traffic diffuses across the transportation and the adjacent landscape, and modeling the functional relationship of how use declines with distance (measured by travel time).

Traffic volume

The fundamental basis for the HUE index is an estimate of traffic volume, and we employ a standard transportation measure of traffic: Annual Average Daily Traffic (AADT; Figure 1). AADT is the total volume of vehicle traffic in both directions of a highway or road for a year divided by 365 days. It is a simple but useful measurement of how busy a road is. In the US, the Federal Highway Administration provides national-scale estimates of AADT for thousands of road segments along their National Highway Planning Network, while state and county transportation departments typically have their own, more detailed monitoring stations. AADT is a powerful, direct estimate of the likely effect on ecosystems because it directly measures human activity and captures relatively fine-scale spatial patterns as well. Compared to typical indicators of human activity, AADT varies considerably – e.g., urban areas are characterized by relatively high AADT levels (e.g., ~10^4-10^6 AADT), but can have high or low (commercial/industrial district) population and housing density.

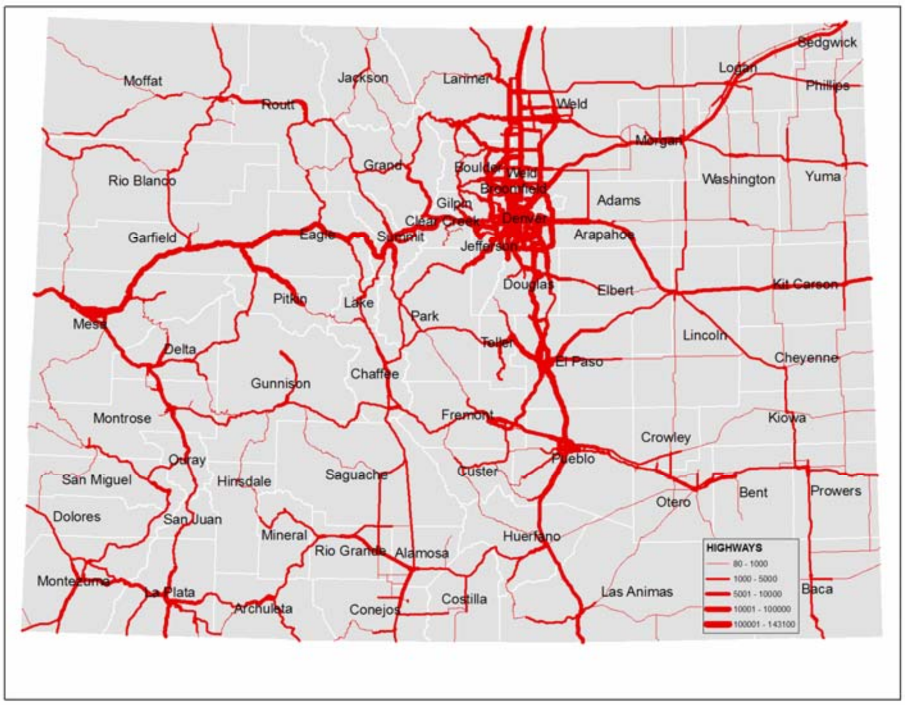

Figure 1: The average annual daily traffic (AADT) volume for Colorado highways in 2005.

Accessibility

The second step in computing HUE is to estimate how use (as measured by AADT) diffuses both along the transportation network and off the road network into adjacent lands. That is, for those portions of a road for which AADT is not directly measured for, an estimate is needed. Accessibility is commonly measured in GIS using cost-distance methods that employ Dijkstra's algorithm (Douglas 1994; Geertman and Ritsema van Eck 1995), which account for the time it takes to travel across a given unit of space (e.g., a 30 m x 30 m cell in a raster map) given different characteristics at each location. Note that there occasionally are "gaps" in the estimates of AADT on roads, and ideally AADT should be interpolated between road segments with known values to estimate it for the "gaps", though here I made the simpler assumption that use would decline as a function of travel time.

I used the COSTDISTANCE tool in ArcGIS to compute the travel time. The "seed" or starting values are defined by the locations (raster cells) that correspond to a segment of the transportation network for which AADT is estimated. For all other locations I estimated cost weights that correspond to the travel speed. For locations along the road network (based on ESRI's StreetMap), we used the posted speed limit (e.g., 70 mph for US interstates; 55 mph highways; 40 mph secondary; 25 mph local). For off-road locations travel time is estimated using walking/hiking speeds adjusted by slope computed from 0.2 ha resolution US Geological Survey's National Elevation Dataset (Table 1). Output rasters of both the cost distance (travel time in minutes) and allocation (the closest AADT value) were computed.

Table 1: Average walking travel speed on off-road locations provided by Tobler (1991).

Slope (degrees)	Speed (km/h)
0	6.0
5	5.1
10	4.0
20	2.0
30	1.0

Distance decay

The final step was to estimate the pattern and likelihood that humans will be able to access or visit a given location that is not directly on the transportation network, or how human use would spread throughout the transportation network and off-road by spilling out onto the adjacent landscape. I assumed that human use declines rapidly with distance (measured in travel time) away from road segments with estimated AADT, which builds distance-decay models of spatial interaction from human geography (Haggett and Chorley 1969) and emerging literature on recreation accessibility (Ode and Fry 2006). I computed the rate of decline as a function of the travel time to halving the traffic volume. That is, I estimate that every ½ hour AADT variable would drop by 50% (Figure 2). Although much work is needed to better quantify the specific shape of this decay curve, it closely mirrors recent empirical findings (Ode and Fry 2006).

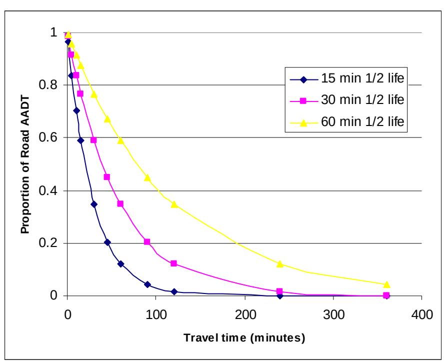

Figure 2: The travel-time decay curve for human use reflects an estimated halving of AADT for 15, 30, and 60 minutes.

RESULTS/DISCUSSION

The distribution of HUE values is shown for Colorado (Figure 3) and the US (Figure 4).

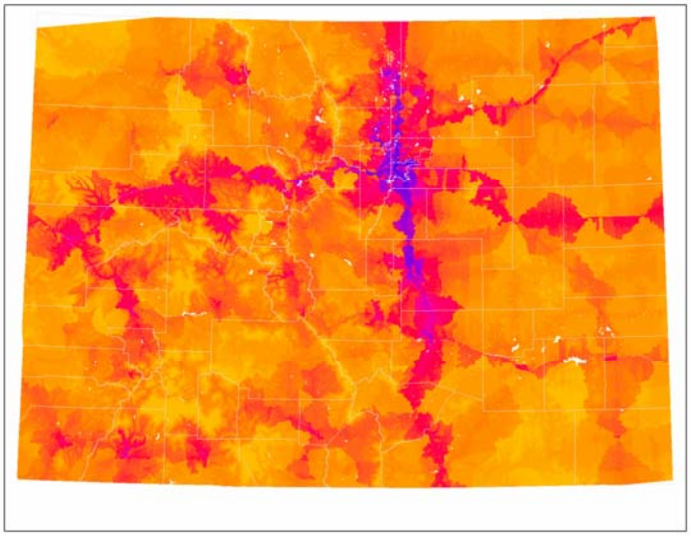

Figure 3: The Human Use of Ecosystems values for Colorado in 2005 assuming a 30 minute 50% decay, using interstate and state highways recorded by the Colorado Department of Transportation. Areas of high AADT (purple) lie along the Front Range corridor (home to Denver) while areas of low AADT (light orange/yellow) occur in wilderness areas in the mountain (left side), but also in many places in the plains (right side). Small white patches are reservoirs.

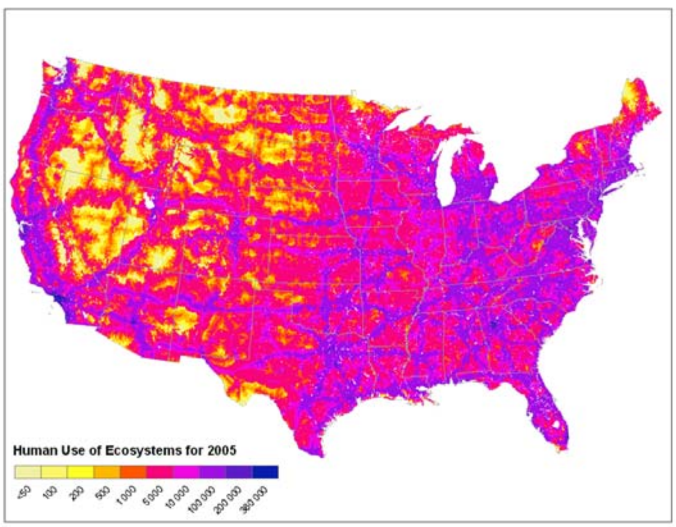

Figure 4: The Human Use of Ecosystems values for the United State in 2005 assuming a 30 minute 50% decay. Areas of high AADT (purple) lie along the urban corridors.

I believe that HUE is a good, robust metric of human use that may provide, for many situations, a more detailed estimate of human use than measures of population density. For example, in many exurban and rural areas (Theobald 2005), particularly "high-amenity" vacation and second-home destinations can have low population density (as measured by Census) and relatively high housing density, yet large traffic volumes that are disproportionate to "resident" population can occur, particularly in tourist destinations such as national parks can have neither high population or housing density (e.g., Yosemite Valley in Yosemite National Park, California, USA). Another advantage of HUE is that AADT is a commonly measured by Department of Transportation units, typically on an annual basis. For example, the US Department of Transportation's High Performance Monitoring System provides estimates of AADT for the major transportation routes. This means that change through time can be evaluated.

Although it is difficult to directly validate the HUE estimates, and future research should be directed towards this effort, I believe that the results from this approach are more refined and logically more consistent that any existing approach (particularly simple distance from road). Moreover, it will remain important to incorporate other direct measures of human use, such as population, housing density or visitation rates, yet improvements to broader, integrated indices such as the Human Footprint can be improved by replacing simple distance-based measures with HUE.

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