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IDEAS & INNOVATIONS

Disentangling road network impacts: The need for a holistic approach

Michael C. Duniway and Jeffrey E. Herrick

The scale and rate of development of linear disturbances has increased dramatically in the past decade. Traditional and alternative energy development, logging and mining activities, together with off-highway vehicles and exurban development, have increased the density of linear disturbances on public and private lands throughout the world. In developing countries, the replacement of livestock with motor vehicles as the dominant form of transportation has had unforeseen consequences (figure 1) (Okayasu et al. 2007). In the western United States, some of the greatest increases are associated with energy development (Brooks and Lair 2005; Watts et al. 2007). In the Powder River Basin of northeastern Wyoming, an additional 28,572 km (17,754 mi) of roads and 42,095 km (26,157 mi) of pipelines and overhead electric lines are planned to support energy development activities between 2003 and 2013 (BLM 2003). Road construction generally leads to increased off-road vehicle use as land becomes more accessible to a growing global population (Cordell et al. 2005; Okayasu et al. 2007; Chomitz and Gray 1996).

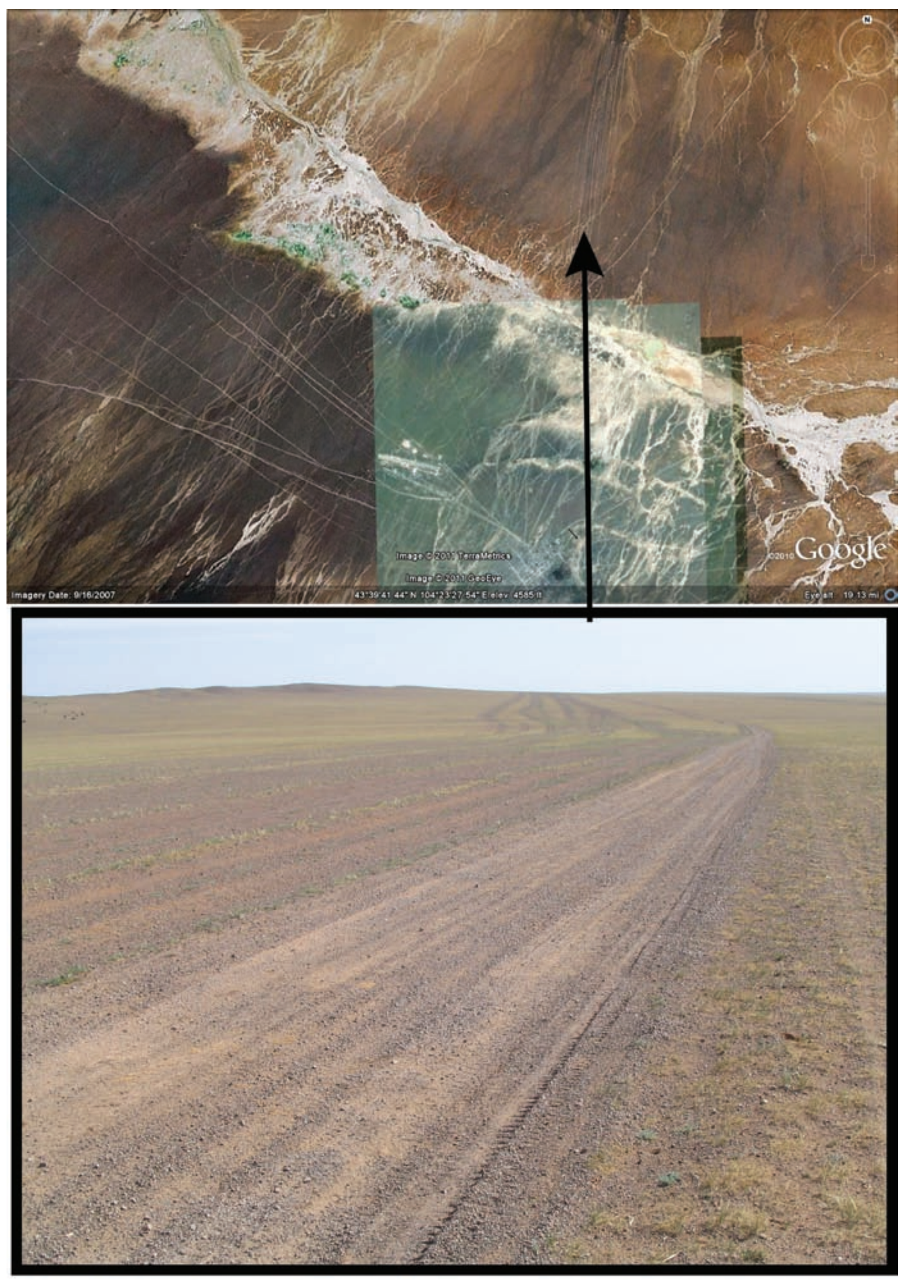
We argue that the dramatic increase in linear disturbances occurring globally has the potential to drastically alter landscape ecosystem processes, including soil and water conservation, and thus presents one of the greater challenges faced by natural resource scientists today—a challenge we are poorly prepared to meet. We also argue that the information gap is greatest in arid and semiarid ecosystems. Analytical tools and data are needed to systematically predict, assess, and minimize the impacts of these linear disturbances.

Most of the research on impacts of roads and other linear disturbances has focused either on direct effects on soils and vegetation (Iverson 1980; Gellis 1996; Webb 2002) or on direct and indirect impacts on wildlife due to habitat fragmentation, traffic fatalities, and noise (Ingelfinger and Anderson 2004; Talley et al. 2006). A notable exception to this trend is the research in forest systems on how roads alter landscape-scale hydrologic connectivity (Jones et al. 2000; Eastaugh et al. 2008). There are relatively few studies in arid and semiarid ecosystems on indirect effects due to

Michael C. Duniway and Jeffrey E. Herrick are research soil scientists at the USDA Agricultural Research Service Jornada Experimental Range, Las Cruces, New Mexico.

Figure 1

Example of the proliferation of unimproved roads in the Gobi Desert near Dalandzadgad, Mongolia (Photo courtesy of Brandon Bestelmeyer, Research Ecologist, USDA Agricultural Research Service Jornada Experimental Range, Las Cruces, New Mexico).



changes in hydrologic and eolian processes, and even fewer on cross-scale interactions. A recent analysis of the extent of the human footprint in the western United States was limited by a lack of data even on the directly affected areas of many linear features and was forced to make an even larger number of assumptions to estimate the spatial extent of indirect effects (Leu et al. 2008).

In summary, while there have been some comprehensive reviews of direct and indirect impacts of roads and road networks on hydrology, vegetation, and wildlife (Yorks et al. 1997; Forman and Alexander 1998; Forman et al., 2003; Angermeier et al. 2004; Coffin 2007), systematic approaches for predicting, assessing, minimizing, monitoring, and mitigating linear disturbance impacts on soil and water conservation are rarely applied, particularly in arid and semiarid ecosystems where some of the highest rates of increase are occurring.

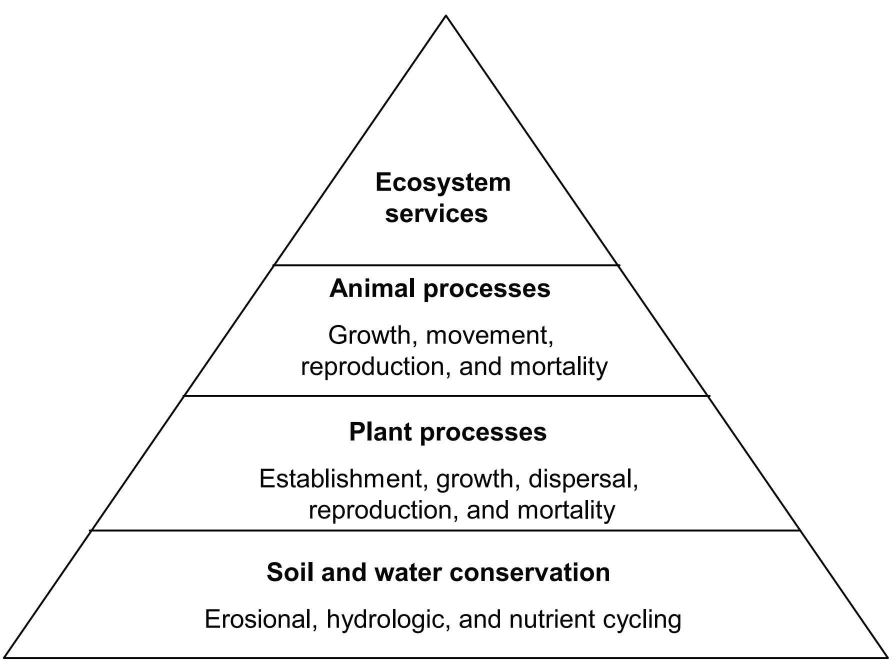
The objective of this paper is to define the elements of analysis that can be used to systematically predict, assess, and minimize road impacts on ecosystem services across multiple spatial scales (figure 2). These elements also serve as the foundation for focusing monitoring efforts on those areas most likely to experience the greatest change in ecosystem processes and, similarly, target mitigation to areas with the greatest potential for recovery. The focus of this paper is on unimproved, unpaved roads in arid and semiarid ecosystems; however, the general approach is relevant for most ecosystems and to all linear disturbances, from interstate highways, to above- and below-ground utilities (pipelines, power lines, communication lines, etc.) and nonstructured off-highway vehicle disturbances.

BUILDING UNDERSTANDING FROM THE GROUND UP: SIX NECESSARY ELEMENTS OF A HOLISTIC ANALYSIS

The most basic element of analysis is identifying direct effects on plant and animal communities and soils. In addition, there are three elements of analysis that together define the extent and importance of interactions among the direct effects: describing spatial interactions, defining feedbacks among processes, and defining interacting effects of other stressors, such as grazing. Finally, there are two elements related to spatial patterns: considering the extent to which these effects vary spatially (e.g., among units) and considering thresholds and other nonlinear dynamics that can occur with increasing road length and density (cumulative effects). These elements are interrelated and are therefore designed to be applied iteratively.

Figure 2

Soil and water conservation provide the foundation on which nearly all ecosystem services depend, including biodiversity conservation, food and fiber production, air and water quality, recreation, and aesthetic and spiritual values. By increasing runoff and erosion, road networks affect these services both directly and indirectly through their effects on plant and animal processes.



Element 1: Identify Direct Effects. The first step is to identify the direct effects of roads on soils, plants, and animals. Direct effects are associated with the physical area of disturbance (figures 3 and 4). Many of these direct effects have been well documented in previous reviews; although, their extent is poorly documented in most arid and semiarid regions, including the western United States (Leu et al. 2008). Earth moving equipment used to establish and maintain roads scrapes away surface horizons, alters topography, and compacts soils. Vehicle traffic also compacts, churns, and ruts soil surfaces. All of these activities can alter soil properties in roadways. These changes can result in altered hydrologic processes, including slower infiltration, increased runoff, and diversion and concentration of overland flow (figure 4) (Webb 2002; Thurow et al. 1993), as well as increased erosion due to higher wind and water erodibility and erosivity (Gellis 1996; Belnap & Gillette 1997). Similarly, road establishment, maintenance, and use often drastically alter plant community processes by removing or crushing existing vegetation and facilitating dispersal and establishment of nonnative species. The effect of disturbance on these processes will be species specific, governed by the species' tolerance of road-related disturbance and method of dispersal (Yorks et al. 1997). Direct effects on animals have been extensively documented (Coffin 2007). At smaller scales, roads are primarily a barrier to movement of some species. Noise and visual disturbance can cause stress that alters growth and reproduction processes. At larger scales, roads and road networks can serve both as obstructions that fragment habitat and as conduits that concentrate and increase animal movement (Theobald et al. 1997).

Element 2: Describe Important Spatial Interactions (Among Units and Groups of Units). Spatial interactions between roads and both contiguous and spatially connected landscape units are important for a wide variety of ecosystem processes. Roads can simultaneously increase and reduce connectivity at multiple spatial scales. For example, roads cutting across slopes can capture overland sheet flow, reducing plant water availability downslope, increasing plant water availability upslope, and increasing water erosivity by concentrating flow through culverts (figures 3 and 4) (Jones et al. 2000). Similarly, spatial interactions can be important for determining how roads affect animal processes. For example, utilization of otherwise suitable winter breeding grounds by female greater sage grouse (*Centrocercus urophasiunus*) has been shown to dramatically decrease with increasing density of natural gas wells and associated roads, even at fairly large scales (Doherty et al. 2008).

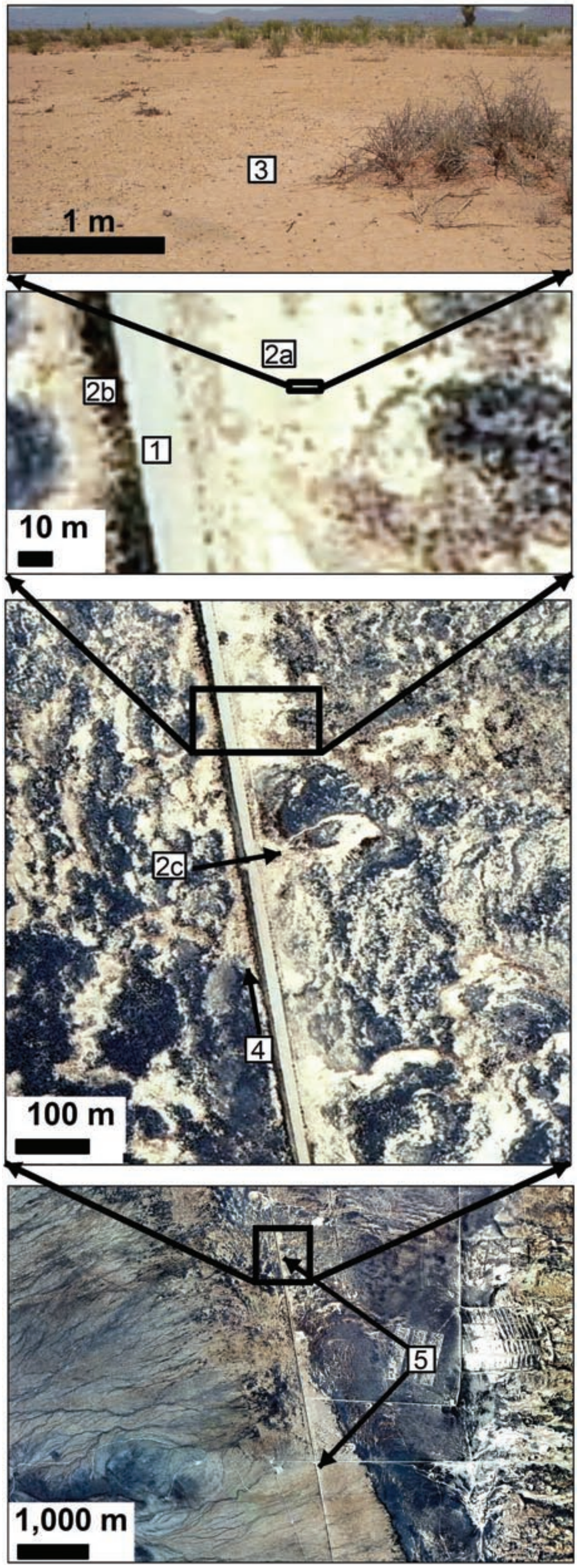


Figure 3

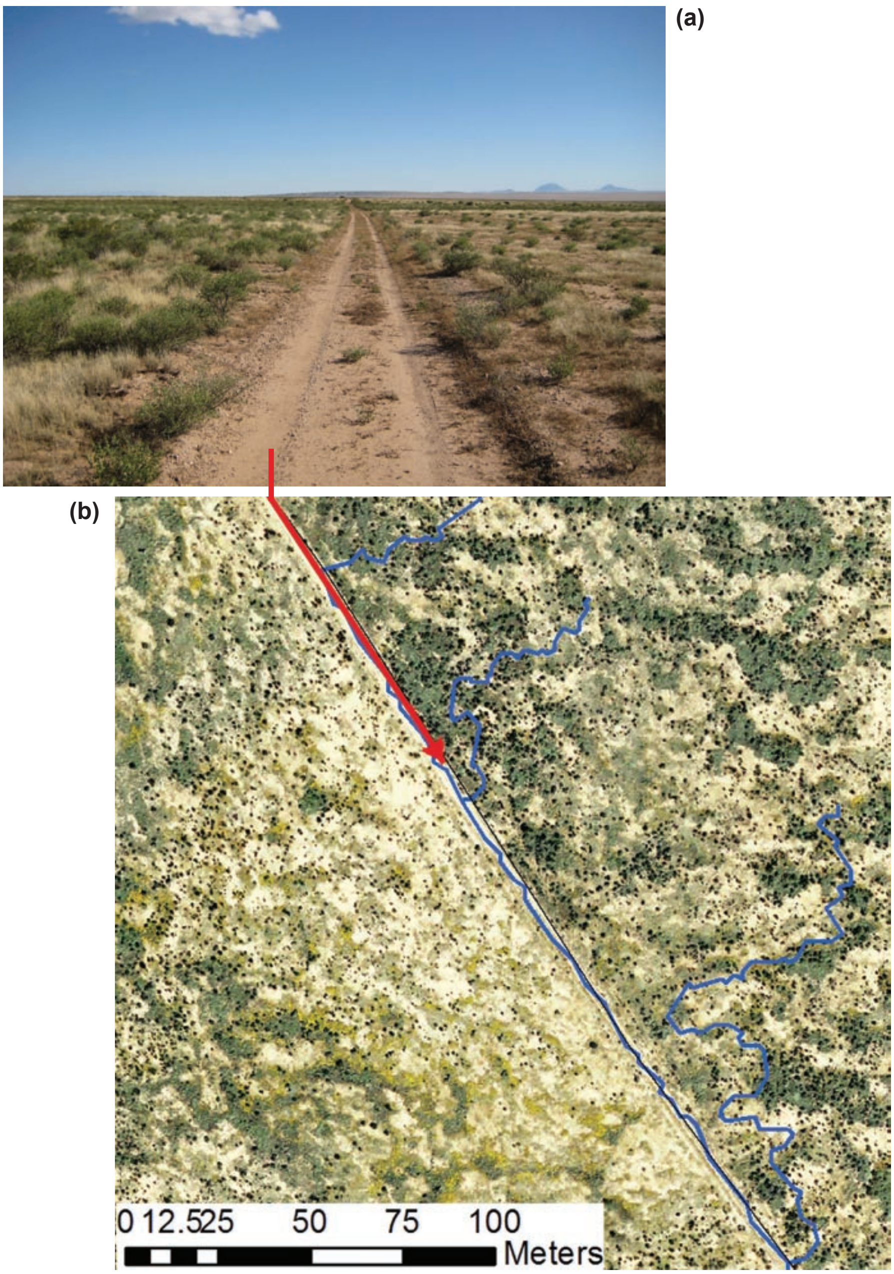
Illustration of five of the six elements of analysis for part of a road network located on an alluvial fan in the northern Chihuahuan Desert, United States: (1—direct effects) loss of all vegetation in roadway; (2—spatial interactions) retention of overland flow by a road causes loss of plant available water downslope (2a), increased plant available water upslope (2b), and increased erosion and loss of plants far downslope via concentration of flow through culverts (2c); (3—feedbacks among processes) loss of soil quality in water-deprived downslope areas (reduced infiltration capacity and increased evaporation) further reduces plant available water; (4—interactions with other stressors) increased trailing and grazing by livestock along roadway; and (5—spatial variability of responses) the same road impacts ecological processes on these two landscape units differently, particularly interactions driven by altered hydrology. Spatial interactions due to altered hydrology are less severe in the coarse soil (southern arrow) than in the fine soil (northern arrow).

Element 3: Define Indirect Effects, Including Process Feedbacks. Direct impacts and spatial interactions can result in feedbacks among ecosystem processes that lead to further alteration of ecological processes. For example, loss of soil quality (compaction and loss of surface horizons) at local scales, either due to direct effects or through spatial interactions, can result in further vegetation loss due to a reduction in plant water availability (increased runoff), nutrients, and recruitment and growth (figures 3 and 4). These feedbacks among altered soil processes and vegetation, coupled with initial vegetation loss, can further alter animal process through changes to available forage, nesting habitat, and protective cover. At larger scales, an example of an important feedback among processes might include changes to soil surface processes (decreased infiltration) and plant processes (decreased establishment and growth) interacting synergistically with concentration of water to produce larger and higher energy water flows (Gellis 1996; Jones et al. 2000).

Element 4: Define Interactions with Other Stressors. There are often interactions between roads and road effects and other stressors such as grazing, development, recreation, and climate. Just as roads can be conduits of wildlife movement, they also tend to concentrate livestock movement, resulting in further impacts on soil and plant processes (figure 1) (Okayasu et al. 2007). In addition, roads are conduits for movement of people, increasing devel-

Figure 4

An example of spatial interactions (element 2) due to subtle changes in topography (element 1) by a lightly bladed road on a gently sloping (~1%), loamy soil in southern New Mexico. Diversion of water by the slightly incised road has resulted in decreased productivity and increased bare ground on the downslope side of the road (right side of photo [a] and left side of photo [b]). Blue lines in (b) are water flow paths derived from a high-resolution digital elevation model.



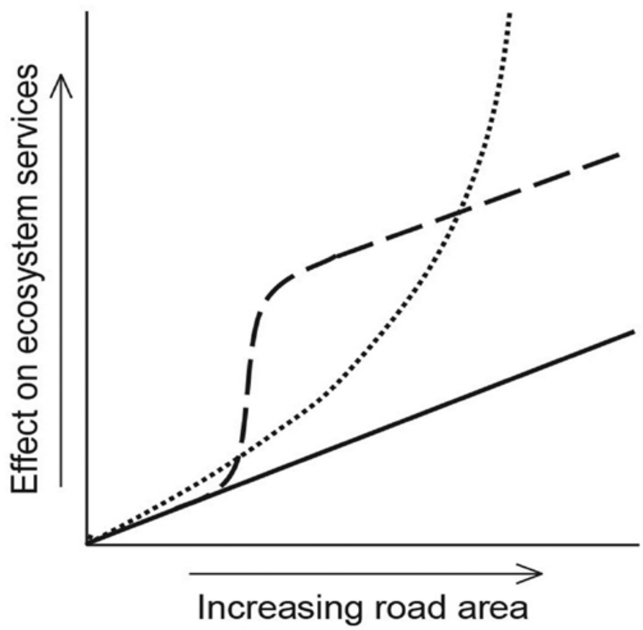
opment and recreational activities along road corridors (Chomitz and Gray 1996). The impacts of roads can be mediated by climate as well. Drought can intensify negative impacts on plant growth, whereas increased frequency of intense rain storms can increase negative effects due to hydrologic concentration.

Element 5: Consider Spatial Variability of Responses to Roads Associated with Differences in Soils, Ecological State (Including Plant Community and Soil Quality), and Landscape Position. Spatial variability is important for both direct and indirect impacts and spatial interactions. The magnitudes of road effects are often highly variable due to differences in topography, soils, and plant community composition and spatial patterns, all of which affect resilience (figures 3 and 5). For example, the same amount of force applied to a soil surface (direct effect) will cause less compaction in a sandy soil (where there is a narrow distribution of particle sizes) than in a loamy soil (where there is a wide distribution of particle sizes), resulting in less change in infiltration rate in the sand than in the loam (Webb 2002). Similarly, contribution of overland flow to plant water availability might be a less important process in a sandy than in a loamy soil, making changes to hydrologic connectivity (spatial interaction and indirect effects) have less of an impact on plant growth in the sand than in the loam (figure 4). Resilience of ecosystem processes to road effects can also vary with ecological state. Some degraded ecological states can be very resilient to change. For example, establishing a two-track road through a pasture that had previously been severely compacted and denuded by overgrazing might not further significantly alter ecosystem processes. For landscape position, the effects of roads on drainage networks are smaller for roads located on ridge tops where there is a little upslope contributing area than for roads located on toe slopes with a high contributing area (Eastaugh et al. 2008).

Element 6: Consider Thresholds and Other Nonlinear Dynamics that Occur with Increasing Road Density or Length (Cumulative Effects). For each process affected, there is frequently a critical scale where the effects of disturbances, including road networks, are greatest (Reynolds et al. 2007). For example, in many instances the effect of road development on infiltration should scale linearly with increasing length and area of disturbances (figure 5). However, processes related to altered hydrologic connectivity, including concentration and disruption of drainage networks, can often be nonlinear and become an important emergent altered process at larger scales (Croke et al. 2005) (figures 3 and 4). Similarly, the effects of roads on animal growth via forage availability might scale linearly with increasing amounts of roads, whereas the effects on

Figure 5

Conceptual figure of the impacts on soil and water conservation due to the development of a road network through time. The Y-axis represents increasing amounts of soil and/or water lost from the system through time. The X-axis represents increasing area directly impacted by roads within a landscape. The three lines represent scenarios of road development. The simplest scenario (____) might represent a diffused network of two-track roads in a resilient ecosystem where increasing amount of roads has a linear impact on soil and water conservation with no spatial variability among landscape units (element 5) and no threshold dynamics (element 6). The next example (_ _ _) is similar to the first scenario except that a few road segments were established with a decidedly nonlinear effect on losses of soil and/or water due to either development of roads on a more sensitive portion of the landscape (element 5), a critical scale reached (element 6), or some combination of the two. The third example (.......) represents development in a low-resilience ecosystem, where increasing amount of roads results in an exponential loss of soil and/or water due to nonlinear dynamics (element 6).



habitat fragmentation might become nonlinear after a critical road density is surpassed (Doherty et al. 2008) (figure 5). Understanding when effects on processes will scale linearly and when it is necessary to incorporate nonlinear dynamics and cross-scale interactions into analysis is crucial for evaluating cumulative impacts (Peters et al. 2004).

CONCLUSION

For effective local to landscape-scale management of transportation networks, a holistic approach is needed that accounts for how roads, trails, and other development activities directly and indirectly alter ecosystem services (figure 2). The approach advocated here begins with a comprehensive understanding of how roads impact ecosystem processes in the management area (elements 1 through 6 above). This understanding allows for prediction of road impacts at various spatial scales across the landscape. Prediction of road impacts is important for both planning new developments and designing assessment and monitoring programs. Predictions could be used to design road networks that avoid critical areas that lead to strong nonlinear impacts on ecosystem processes (figure 5). Similarly, predictions could be used for designing cost-effective assessment and monitoring programs that capture road impacts at the relevant scale (figure 3).

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