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Function, effects, and management of forest roads

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Abstract

We propose a unified approach to the management and analysis of the function and effects of roads on forested rural landscapes. The approach is based on considering roads as ecosystems (techno-ecosystems) and conducting analyses of road ecology prior to making policy or management decisions. An ecosystem approach to road issues has four advantages: (1) allows for the analysis of all types of roads irrespective of geographic location; (2) provides a holistic framework for analyzing all aspects of roads from their alignment to their operation and decommissioning as well as all road functions irrespective of value judgment; (3) provides a holistic focus to their management; and (4) supplements landscape management approaches based on spatial concepts. We present five precautions to be considered when evaluating road ecosystems: (1) identify the type of road under consideration; (2) differentiate the effects and conditions of individual road segments from those of road networks; (3) be explicit about what phase of road development the argument applies because different phases of development have different effects on the landscape; (4) ascertain the age of the road and evaluate the degree of landscape adjustment to the road and vice versa; and (5) not to prejudge human-induced changes in landscapes as automatically good or bad for the ecology or economy of a region. This ecosystem focus and guiding principles are applied to several issues that road policy and management activities must address. Published by Elsevier Science B.V.

Keywords: Roads; Ecotone; Alien species; Ecosystem; Technoecosystem

1. Introduction

Roads are a critical component of civilization. Developing and maintaining the economic activity that is vital for the quality of modern life would be difficult without roads. Roads provide access for people to study, enjoy, or contemplate natural ecosystems. In fact, the development of human civilization has benefited from transportation systems that evolved from foot trails to complex highway systems (Chisholm, 1990; Grübler, 1994). Building and maintaining roads have become controversial, however, because of public concerns about their short- and long-term effects on the environment and the value that society now places on roadless wilderness (Cole and Landres, 1996; Williams, 1998). Opposition to road building and pressure to decommission roads in rural landscapes will continue to increase as roadless areas decrease in relation to roaded ones.

Decisions about road alignment, building, maintenance, or decommissioning are complex because of the many tradeoffs involved. One example is the quote below expressed for rural roads through tropical forests. Another example might be the tradeoff between access to roads for recreation and research with the potential effects of that access on biodiversity. Roads have been evaluated from physical, biological, and

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socioeconomic points of view, often under only one set of criteria in isolation from others. Such an approach is useful for identifying issues, but it can lead to conflict and flawed policy because it may play one set of values against another. For example, a road that is justified only by economic criteria at the expense of ecological ones – or vice versa – is likely to be questioned by advocates of the missing criteria. A unified approach to alignment, constructing, maintaining, and decommissioning roads is needed to optimize resource use.

The focus of much of the ecological literature on roads is on their deleterious effects (Scheidt, 1967; Forman, 1995a; Forman et al., 1997). Typically, the effects of roads on a wide variety of parameters are compiled to demonstrate their harmful consequences. The listings are usually collected from various parts of the world e.g., the Arctic (Bliss, 1990; Auerbach et al., 1997), Belize (Chomitz and Gray, 1996)[1], United States (Furniss et al., 1991; Miller et al., 1996; Forman et al., 1997), Bolivia (Gullison and Hardner, 1993), the Amazon (Turner and Meyer, 1994), the Philippines (Liu et al., 1993), Thailand (Ziegler and Giambelluca, 1997), Puerto Rico (Patterson Zucca, 1978; Olander et al., 1998), St. John, US Virgin Islands (MacDonald et al., 1997; Anderson and MacDonald, 1998), or Europe (Reck and Kaule, 1993), and then combined, as if all of the effects will happen regardless of environmental conditions, use, or engineering and design considerations. Are road effects universal or are there patterns or differences that can be used to improve road policy and management? Are any desired ecological effects associated with roads or are all effects negative?

Part of the problem with evaluating ecological effects of roads is that their ecological benefits are hard to confirm (Lyon, 1984) and all ecological changes tend to be interpreted as negative. For example, the positive effects of road runoff on plant growth in low rainfall areas is deemed negative to slow growing, drought-adapted plants, or due to alien species that take advantage of the increased moisture (Huey, 1941). Moreover, though road effects change over time, they start with a 'negative balance' because of the high impact of construction activities (Lyon, 1984). Few studies explore the long-term aspects of road ecology or consider available management opportunities (Lyon, 1984; Furniss et al., 1991; LaFayette et al., 1996; Olander et al., 1998). Evaluating the ecological effects of roads requires rigorous analysis and an understanding of the ecology of roads, that is, the interplay between all of the living components, the function of roads, and the environmental factors that regulate processes along the road corridor (Forman et al., 1997).

Establishing a new road segment or road network on a landscape is equivalent to adding a new ecosystem to the existing one. Although road ecosystems are human creations like railroad or powerline rights of way, they have natural analogs in riverine and riparian corridors. Treating roads and other human-created corridors as ecosystems might be used in developing methods for analyzing and evaluating them in the context of their surrounding landscapes. Naiman and Décamps (1997) proposed terminology and formalized an ecological approach for studying ecosystem interfaces using riparian corridors as examples. Much of what they discuss applies to road corridors, but differences exist between roads and riparian corridors. For example, the nature, frequency, and intensity of material exchanges across the interfaces differ in roads and riparian zones. Nevertheless, a unified ecological approach to roads and road networks is useful in making decisions about road management issues and can provide a mechanism in developing consensus among stakeholders.

In this paper we treat roads as ecosystems and propose a unified ecosystem approach to road management. We focus attention on roads in forested landscapes but the principles discussed can also be applied to nonforested lands.

2. Roads as ecosystems

Roads can be defined as ecosystems because they occupy ecological space (sensu Hall et al., 1992), have structure, support a specialized biota, exchange matter and energy with other ecosystems, and experience temporal change. Road ecosystems are built and maintained by people (techno-ecosystems sensu Haber, 1990). Road ecosystems are characterized by open fluxes of energy and matter and a predominance

[1] "Rural roads promote economic development, but they also facilitate deforestation". Chomitz and Gray, 1996, p 487.

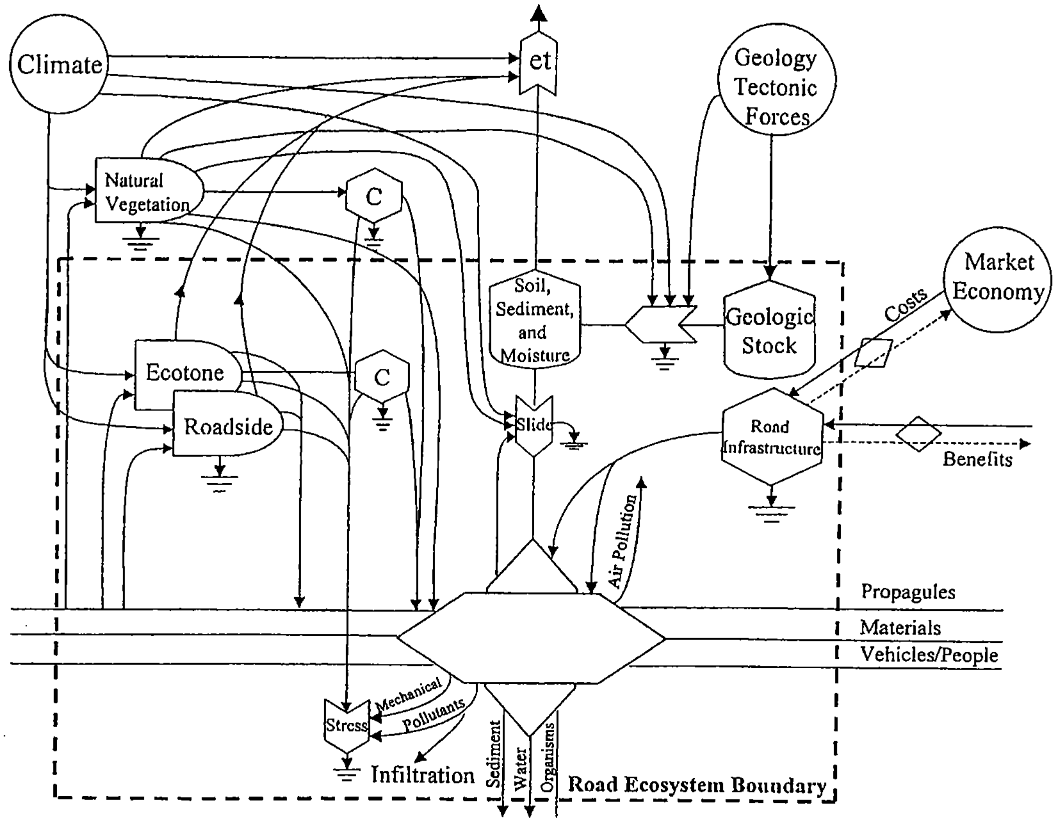

Fig. 1. Model of a road ecosystem using the energy symbols of Odum (1996). The heavy dotted line outlines the boundary of the road ecosystem. Consumers are "C".

of respiration over photosynthesis, i.e., they are subsidized heterotrophic systems. The road ecosystem includes both the paved and unpaved rights of way and adjacent structures, including other infrastructure, ditches, drainage features, and other components that provide the means for vegetation to establish and provide habitat for associated plants and animals (Fig. 1).

The model in Fig. 1 highlights the six-way flow of materials, energy, and organisms along the road corridor; vegetation zonation; the interaction with the human economy and human activity; and the external forces that converge on the road corridor. This is a heuristic model that facilitates the identification of the main components, fluxes, and interactions that characterize the road ecosystem. The model is consistent with Forman's (1995a) five functions of corridors: habitat, conduit, filter or barrier, source, and sink. The details of the model will obviously change with the type of road, its use, and the environment through which it transverses. For example, on agricultural landscapes, a forested road corridor contain the most developed vegetation when compared to adjacent fields of crops. In this example, the road corridor may be negatively impacted by runoff from the fields, and interactions at the ecotone are different to those in forested rural landscapes.

The structure and functioning of a road varies according to its design, use, type of surface, and location. The diversity of roads complicates the ecological analysis because both the effects and functioning of the road system vary with the type of road being considered. The first precaution in evaluating a road, generalizing about roads, or studying roads is to identify the type of road.

The width of the surface of a road differs from the width of its ecological influence (Reck and Kaule, 1993; Forman, 1995a; Auerbach et al., 1997; Forman et al., 1997; Larsen and Parks, 1997; Olander et al., 1998). A road may be x m wide, but it may influence an additional y m of adjacent land because of disturbance during construction and operation plus the buffer zone for the road surface, which would make the road effectively $x + y$ m wide. That same road has an ecological influence that can extend an additional z m in terms of water runoff, its influence over the home range of wildlife, geomorphic alterations both upstream and downstream, the distance its noise and dust carries, and the view it provides. The vertical distribution of pollutants emitted when the road is used or the infiltration of substances running off the road surface influence the space above and below the road by v m. Thus, depending on the criteria used, a road can influence space anywhere between x and $x + y + z$ m wide plus v m on the vertical plane.

Forman (1995a) and Forman et al. (1997), summarized data on the width of roads by using a variety of hydrologic, geomorphic, and biotic criteria. They reported values that range to as high as thousands of meters from the road, and discussed upslope and downslope differences as well as downwind and upwind ones. With these data, Forman et al. (1997) and Forman (1998), estimated the area of the United States influenced by roads as equivalent to 1% of the area of the country, a value that changes as better information on the ecological width of roads becomes available.

We set the interface boundary for the road ecosystem at the limits of its measurable ecological effects. We recognize that this boundary changes over time due to succession and human activity. Therefore, like that of any other ecosystem, the boundary of the road ecosystem is arbitrary and dynamic. A road ecosystem can be defined by the dynamics within and through a 'cylinder' with changing dimensions that meanders across the landscape. Along its path, the road ecosystem interacts with many other systems and environmental conditions, with the result that the cross sectional area of the cylinder is not constant. It expands when the road traverses sites vulnerable to its presence, and contracts when conditions are more resistant to change. The cylinder also changes with the passage of time or with changes in the level of use and maintenance. For this reason, not all segments of a road are equivalent in terms of their effects on the environment. Moreover, the volume of a road through particular landscapes can be used as an indicator to direct resources to mitigation measures.

Roads are also corridors that can connect contrasting ecosystem types. Since roads provide a fairly homogeneous condition through the length of the corridor, they provide opportunity for organisms and materials to move along the corridor, thus increasing the connectivity (sensu Merriam, 1984) among those ecosystems that interface with the road. The length to width ratio of road ecosystems is much greater than 1, which maximizes the interface surface between roads and the ecosystems of the landscape that it traverses. Naiman and Décamps (1997, p. 622) recognized that the strength of the interactions at these interfaces vary with time and space and are controlled by the contrast between adjacent resource patches or ecological units. They compared these interfaces to semipermeable membranes regulating the flow of energy and materials between adjacent systems (Fig. 1). They further noted that interfaces "have resources, control energy and material flux, are potentially sensitive sites for interactions between biological populations and their controlling variables, have relatively high biodiversity, maintain critical habitat for rare and endangered species, and are refuge and source area for pests and predators."

In describing ecological processes at the interface along corridors, Naiman and Décamps (1997) used the terms ecotone, transition zone, and boundary interchangeably. We split the road interface (Fig. 1) into two zones (roadside and ecotone) to highlight the difference between vegetation along the roadside and vegetation in the zone at the interface of the road with the natural vegetation. That interface can be sharp or gradual, forming an ecotone that differs from both the roadside and the adjacent natural ecosystem. Auerbach et al. (1997) reported cross-sectional data for arctic roads to illustrate environmental and biotic gradients from the road surface to undisturbed tundra. Many indicators of road disturbance changed exponentially from the road surface to native vegetation, and different types of tundra responded differently to roads.

Road segments can be part of road networks crisscrossing the landscape. A road network has environmental effects and ecosystem properties that appear to transcend those of its individual segments. For example, some wildlife species, such as bear, wolf, or mountain lion, respond more to road density than to individual road segments (Forman et al., 1997). Similarly, road networks are more relevant to issues of forest fragmentation or to hydrological effects than are isolated road segments (Jones, 1998). For this reason, a second precaution is to differentiate the effects and conditions of individual road segments from those of road networks.

Like all ecosystems, roads are constantly changing as do the relations between the road ecosystem and adjacent ecosystems. The major phases of road development are building, operating, maintaining, and abandonment. Road building is often the most environmentally traumatic to adjacent ecosystems because earth movement and other activities can disturb whole watersheds. Changes – mechanical, geochemical, hydrologic, biotic, and so on – to the immediate land area and any adjacent upstream and downstream ecosystems affected by building activities can be predicted. During this phase, the road is primarily a disturbance and an agent of change.

Maintaining roads, particularly if improperly done, acts as a periodic disturbances to both the road biota and the landscape as a whole. Maintenance activities can approximate building activities in the amount and extent of disturbance, and they can prolong environmental effects to adjacent ecosystems. Not maintaining roads, however, can hinder the primary function of the road and also significantly affect the environment. For example, poorly maintained drainage systems in wet montane roads can induce mass-wasting events large enough to destroy the road and affect adjacent forests and aquatic systems. Such events sometimes exceed those observed during road building (Larsen and Parks, 1997).

Road use itself affects the landscape, for example through spills of toxic substances, pollution, dust, or effects on plants and animals by the presence of people. Roads as part of long-range transportation networks are likely to introduce alien species. The type and intensity of use are associated with particular environmental effects. For example, logging truck traffic is known to facilitate the transport of fungal root diseases such as *Phytopthora lateralis* (Zobel et al., 1985), and heavy vehicular traffic increases the risk of dispersing roadside weeds and different types and intensities of pollution (air, soil, or water) or chemical spills.

Road abandonment allows successional processes to recapture the road corridor. The speed and direction of succession after a road is abandoned depends on the type of road, landscape, and environment. Some road segments may be overgrown with vegetation quickly, but the pavement can arrest succession in others. Rehabilitation techniques are usually needed to accelerate succession to reach management goals after abandonment (Luce, 1997). A third precaution in generalizing about road development is to be explicit about what phase is meant because different phases of development affect the landscape differently.

With time, the road ecosystem ages and matures. As it does, and regardless of disturbances, segments of the road can adjust to conditions, blend with the landscape, and reach a new ecological and hydrological state (Olander et al., 1998). A critical issue in decisions about road decommissioning is whether disrupting the new environmental balance created by the presence and aging of the road is desirable. Sometimes, decommissioning a road can have significant environmental effects because the road has become part of the evolving landscape. On the other hand, the road is an artificial barrier in the environment and a manager may decide to decommission the road and restore original vegetation to the site. A fourth precaution in generalizing about the environmental effects of roads is to determine the age of the road and evaluate the degree of landscape adjustment to the road and vice versa.

Finally, like other ecosystems, roads produce long-term legacies on the landscape. For example, many roads built by the Roman Empire centuries ago have disappeared from the landscape, but their legacies remain in the sediment layers of Italian lakes (Hutchinson, 1973) and in strips of unique vegetation growing on limestone soils (derived from the limestone slabs used to build the road) in landscapes of acid podzolic soils (Detwyler, 1971). In Lago di Montesori, Italy, the building and use of Via Cassia resulted in a pulse of eutrophication that lasted 2,000 years before it abated when the road was abandoned (Hutchinson, 1973). Strips of fern populations in the Caribbean National and Luquillo Experimental Forest in Puerto Rico, serve as indicators of the location of skid trails abandoned more than six decades ago in these wet forests (García Montiel and Scatena, 1994). These legacies are useful in historical reconstruction of landscapes because they help explain the relevance of yesterday's activities to today's landscapes. In the process, we learn more about ecosystem resilience and how ecosystems continuously adjust to change.

The presence of techno-ecosystems and their legacies can enrich human-dominated landscapes, making them more ecologically diverse and productive. Two notable examples are the European hedgerows and railroad rights of way in the United States. Hedgerows in France, England, and elsewhere in Europe contain high biodiversity compared to the agricultural landscape in which these corridors are found (Burel and Baudry, 1990; Barrow, 1991). They are techno-ecosystems with a few millennia of development and continuity on the landscape (Forman, 1995a). As a result, the distribution of organisms, ecosystem functions, and biotic richness have developed unique and sustainable ecological patterns (Burel and Baudry, 1990). The destruction of hedgerows to increase agricultural productivity was objected to successfully on conservation grounds and hedgerows are now valued in Europe.

Railroads appeared about a century and a half ago and initially passed through natural prairie landscapes in the United States but the prairies were converted to agriculture. Today, some of the best examples of the original prairie vegetation are along railroad right of ways along with cosmopolitan alien weeds (Reed and Schwarzmeier, 1978; Borowske and Heitlinger, 1981). In South Africa, road corridors are important to conservation and road reserves have been established (Dawson, 1991). In parts of Australia, roadside natural strips have been established where the landscape has been cleared for intensive uses (Forman, 1995a). These strips form a "giant green network in the landscape... with few disadvantages and many ecological and human advantages (Forman, 1995a, p 171)." These and other examples in Forman (1995a) highlight a fifth precaution, which is not to automatically prejudge human-induced changes in landscapes as good or bad for the environment or economy of a region.

3. Factors that influence the function of roads

The environmental gradients believed to be most important in describing the ecological space in which roads function as ecosystems are shown in Fig. 2. The gradients are arrayed hierarchically from the most general to the most detailed. An advantage of this approach is that it does not compare roads on the basis of geographic space (eastern roads with western, tropical with temperate) and avoids lumping roads as if they all behaved in the same way. Instead, this approach allows analysis or comparison of different types of roads from any part of the world, by using gradients of ecological space as the discriminating functions.

The first level axes are the climatic, geologic, and use gradients (Fig. 2a). We hypothesize that road effects on surrounding environments and road function as ecosystems are mainly influenced by climate, geologic conditions, and uses or functions of the road. Climatic conditions are mainly the precipitation and temperature regime, and the frequency and intensity of climatic disturbance events (Fig. 2b). The geologic axis is the type of substrate such as volcanic, limestone, or alluvial and the topography (Fig. 2c). These two axes are intimately related and could be summarized as a geoclimatic gradient. The use or function axis includes traffic, maintenance intensity, and road size or type (Fig. 2d).

The importance of geoclimatic and maintenance conditions was demonstrated in the Caribbean National and Luquillo Experimental Forest by Larsen and Parks (1997) who found that all roads in these mountains were associated with increased slope failure and mass-wasting, but those along a particular geological region of the forest were more likely to cause these events then those elsewhere. The determinants of slope failure was a combination of rainfall intensity and duration, geologic type, steep slopes, and poor road maintenance (Larsen and Simon, 1993; Larsen and Parks, 1997).

Temperature is a factor with wide amplitude across latitudinal and altitudinal gradients. Temperature gradients influence rates of metabolism in organisms and watershed-scale water budgets, which in turn affect runoff, mass wasting, and plant growth along road corridors. The type of precipitation, that is, rain or snow, is also temperature-dependent. Climate in general regulates the kinds of organisms that grow on roadsides and road ecotones, and the complexity of vegetation throughout the road corridor (Holdridge, 1967). The complexity of vegetation in turn buffers the

Water balance concept prob. a better function for plants.

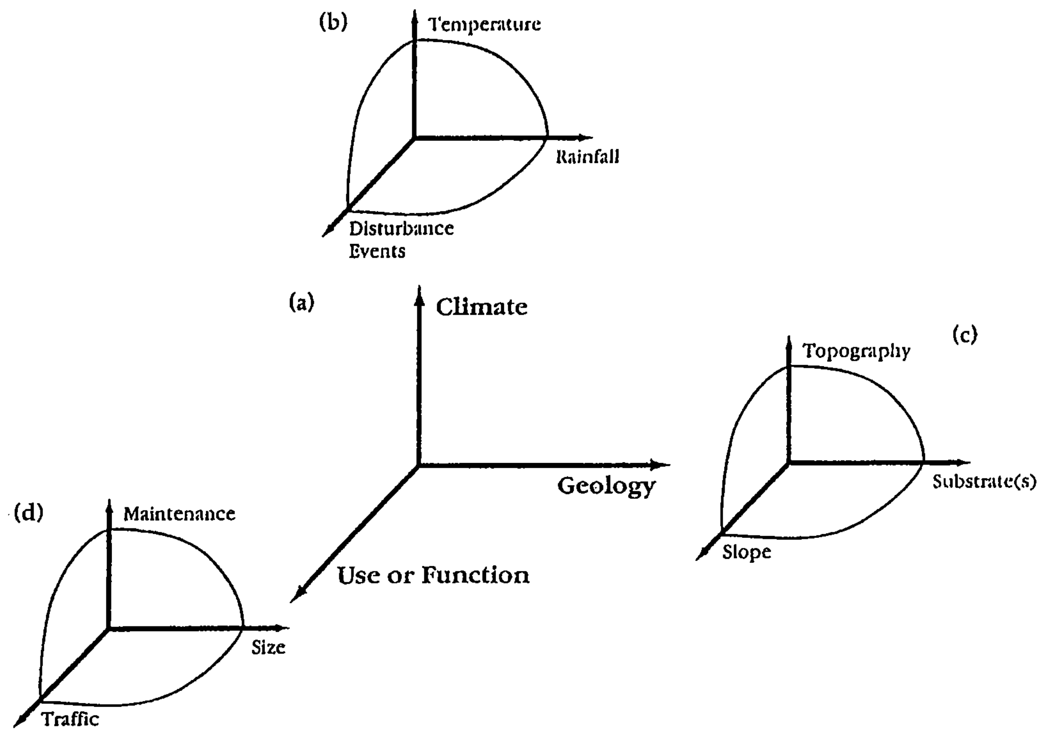

Fig. 2. Axes of the parameters that define the ecological space or the environmental gradients within which roads function. The main gradients are shown in (a) and each (climate, geology, and use/function) are further subdivided into component factors in (b), (c), and (d), respectively.

road from surrounding conditions and influences the effects of roads on the landscape.

Road maintenance affects the state of road ecosystems. Roadside plants and animals and those adjacent in ecotones can come to depend on the maintenance regime. For example, use of fire to control roadside weeds can result in increased fire frequency in adjacent lands; the ecotone between the road and adjacent ecosystems expands as it becomes fire dependent. Mowing selects for particular plant species and also affects how other organisms (birds, for example) interact with vegetation (Harper, 1977). Road maintenance activities tend to favor the establishment and survival of alien, oftentimes weedy species because maintenance activities expose organisms to selective and repetitive forces, such as periodic fire, mowing, fertilization, or salinization that favor some alien and non-alien species. Alternatively, absence of road maintenance allows plant succession to proceed to unpredictable states that could influence road function and safety.

The intensity and type of road use also influences the road ecosystem. Rates of use select for certain types of organisms that can respond to road use. For example, with increased road traffic, elk move away from roads, but deer move closer (Lyon, 1984). Some birds respond negatively to increased road noise (van der Zande et al., 1980). And the amount and type of road use has implications to the function of roads as corridors for alien species, agents of fragmentation, accidental spills of pollutants, levels of pollution, amount of dust produced, production of sediments, and so on.

Not shown in Fig. 2 are the temporal aspects of road development. The age of the road ecosystem is relevant to the rate of biotic processes both on the roadside and at the ecotone with the natural landscape (Olander et al., 1998). Designing maintenance schemes that allow components of the road ecosystem to adjust to the environment and stabilize in locations where slope and other conditions allow stabilization should be possible. For example, the soil compartment, riparian zones along drainages, and the vegetation of the ecotone could be allowed to develop, adjust to prevailing conditions, and mature as part of a strategy to stabilize hydrological and geomorphic processes along the road network or individual road segments. The alternative strategy is not to consider the state of the road ecosystem as part of the road management plan and allow maintenance activities to haphazardly disrupt the succession of all road components, maintaining the system in a state of continuous change.

The successional state and diversity of roadside biota influences the ecological function of roads because it can influence the rate of further species invasions; mitigate some of the effects of road construction, operation, and use; and provide habitat for generalist wildlife species or for human activities, including commerce and recreation . Although many roadside weeds and alien species tend to be cosmopolitan, the species composition of the biota of roads changes along gradients of geoclimate and road use. Less weedy species and fewer alien plants grow on road segments exposed to extreme conditions of moisture and temperature, such as deserts, high elevation, and very wet areas. Weeds and alien species should also diminished where roadside vegetation is allowed to develop to mature stages.

4. Management implications

An ecosystem approach to road issues has four advantages. First, it allows for analysis of all types of roads irrespective of geographic location, i.e., either latitudinal or elevational position. Roads are compared by their location in ecological space. Second, it provides a holistic framework for analyzing all aspects of roads from their alignment to their operation and decommissioning as well as all road functions irrespective of value judgment. Third, it provides a holistic focus to road management. Concepts of ecosystem management apply as much to road ecosystems as they do to forest or grassland ecosystems. Fourth, it supplements landscape management approaches based on spatial concepts (Forman, 1995b; Forman and Collinge, 1996; Forman and Hersperger, 1996). The ecosystem approach focuses on functional attributes that explain and underpin the spatial concepts of landscape ecology. In this section we briefly explore ecological, socioeconomic, and physical road management issues using an ecosystem framework.

5. Ecological issues

5.1. Fragmentation

Roads fragment the landscape and affect populations and communities. However, the evaluation of the effects of roads on fragmentation is difficult for three reasons: (1) different types of roads as well as different levels of road use and maintenance pose different barriers to organisms, (2) different species or groups of organisms have different thresholds of tolerance to dispersal barriers, and (3) the size threshold for normally functioning community fragments is not known, but expected to vary with the type of community. Moreover, landscape fragmentation is a phenomena that is best analyzed over large spatial scales at the level of road networks because the effects of fragmentation is not necessarily the sum of effects due to individual road segments. Scale issues are discussed later.

In some instances, roads and road density have a neutral effect on forest fragmentation (Miller et al., 1996). In the montane landscapes of Colorado, topographic variation had a greater effect on the average size of stands and the distribution of vegetation types than the location and density of the road network. However, roads influenced the age of stands along the road alignment. Younger seral stages were closer to the road than older ones. Miller et al. (1996) concluded that the effects of roads on landscape patterns were localized along the road themselves and that roads should be considered inherent components of landscape structure.

Forest fragmentation due to roads could be mitigated by appropriate road location (Forman, 1995a, Forman et al., 1997), and managing the connectivity of roads. Connectivity of wildlife across roads can be improved with wildlife crossing structures (Forman and Hersperger, 1996; Forman et al., 1997), strategically closing roads, or by actively managing roadsides and road ecotones. Use of native species on roadsides while minimizing the establishment of alien species, promote the function of roads as corridors for both flora and fauna between forest fragments. Ries and

Debinski (1998), for example, found greater abundance and diversity of butterflies along road corridors dominated by native plant species that in corridors dominated by alien species.

5.2. Alien species

It is nearly impossible to prevent the invasion of roadsides by alien species. Alien species invasions of roadsides is an ecological process that can be managed and minimized but not avoided (Tyser et al., 1998). Aliens cannot be extirpated from road corridors as long as roads provide conditions that favor their growth and success over native species (Greenberg et al., 1997).

Alien species extend their range when the disturbance area along the road corridor expands due to improper maintenance activities, i.e., disposal of sediments over the banks of roads, escaped fire into native vegetation, killing of native vegetation by salinity or herbicides, etc. Alien plant species on road ecosystems can be managed by managing the overall conditions of the road ecosystem, by favoring the development of mature vegetation, and by promoting vegetation complexity at the ecotone between the road ecosystem and adjacent vegetation. In short, alien species require an integrated management approach (Hobbs and Humphries, 1994; Tyser et al., 1998).

Approaches to managing the alien species situation involve judgmental road design and construction techniques to reduce habitat modification, and minimize disturbances and site degradation (for example with toxic substances) while maintaining the road. Studies in the Pacific Northwest, the Arctic, and the Caribbean National and Luquillo Experimental Forest show that the dispersal distance of alien plants from roads into adjacent native vegetation falls exponentially with the distance from the road and it is limited outside the ecological width of the road ecosystem (Auerbach et al., 1997; Jones, 1998; Olander et al., 1998). Therefore, by reducing the volume of the road corridor or the total volume of the road network, alien species invasions can be minimized.

5.3. Legacies

Landscapes are constantly evolving in response to environmental change, including changes induced by humans. As they evolve, legacies from past landscapes are incorporated into the present one. It is impossible to find landscapes that are completely pristine and devoid of human legacies. Even the most extensive wilderness of the world i.e., the Amazon, Alaska, or the Boreal zones of Russia, contain human legacies (Clark, 1996) or are affected by global change phenomena such as the changes in the composition of the atmosphere (Woodwell, 1990; Meyer and Turner II, 1994). Human legacies in pristine-looking landscapes point to the resilience of natural systems and make it very difficult to segregate with certainty the purely natural from the human-affected ecosystems.

A road network is a human legacy on the landscape. The nature (type of roads), density, condition, and distribution of the road network determine the effect of the road legacy on the landscape. A dense road network for example, has a more likely effect on fragmentation than a low density network (Forman and Hersperger, 1996; Forman et al., 1997). High density road networks are more likely to affect hydrological parameters than low density ones. However, road density is less important to fragmentation of forests where topography dominates the structure and size of vegetation stands (Miller et al., 1996).

5.4. Scale: road segments versus road network

Road segments form transportation systems or networks over the landscape. The road network is likely to have effect on the landscape that exceeds the sum of the effect of road segments. For example, it is possible that individual road segments have no significant effect on fragmentation or in runoff rates. However, the network as a whole may exceed thresholds of both fragmentation and runoff whose effects are only realized at the landscape scale. Chaotic non-linear effects are probably responsible for this behavior. The way road segments are positioned on the landscape has enormous consequences to how the network behaves and interacts with that landscape. For example, road segments can form dendritic or anastomosing patterns, they can run parallel to each other and to streams or intersect perpendicularly, or they can be located either on ridges, valleys, slopes, or in any combination of topographic positions. In each instance the connectivity and source/sink function of the road changes as does their effects on water and sediment movement.

Road networks also influence large-scale ecological phenomena such as the spread of fire through the landscape.

Road networks have been defined as roadsheds, because much like hydrologists define watersheds to delimit the flow of water through a landscape, roadsheds delimit the overall distribution and influence of roads over geographic space (B. Bormann, pers. commun.). Managers need to be aware of the size, distribution, and condition of roadsheds on rural landscapes to evaluate their influence over landscape-level parameters such as the erosion cycle, biodiversity, productivity, connectivity among sectors of the landscape, and distribution of human access and effects. Roadshed size can be minimized through design, transportation planning and road closure.

Road density (km of roads/km^2 of area) was proposed as a broad index of ecological effects of roads in a landscape (Forman and Hersperger, 1996; Forman et al., 1997). This indicator was then used as a correlate of wildlife population densities and other measures of ecosystem response to the presence of the road network. Studies show strong inverse correlations between wildlife abundance and road density (Forman et al., 1997). Miller et al. (1996) found no correlation between road density and forest fragmentation in the southern Rocky Mountains. Jones (1998) found that the pattern of road distribution at the level of the landscape had significant effects on road function. Dendritic networks dispersed or collected materials while anastomosing networks facilitated exchange and migration. Similarly, clusters of road segments downslope of cleared areas could be susceptible to subsurface water flow interception and associated mass movements and transport of chemicals.

Forman et al. (1997), also suggested that an index of the variance or unevenness in the size of vegetation patches was important in the understanding of the road density effect on organisms. Large patch sizes mitigate the effect of road density in comparison with landscapes with smaller natural fragments. These studies established that an analysis of road networks facilitates the identification of troublesome road segments, and helps in the planning of development, maintenance, and decommissioning of roads. Such an analysis procedure has been developed for the Interior Columbia River Basin Ecosystem Management Project (Haynes et al., 1996; Quigley et al., 1996).

5.5. Disturbances

Two aspects of road management require a consideration of disturbance. First are the effects that disturbances might have on roads. Disturbances can greatly influence road connectivity, invasion of alien species (Hobbs and Huenneke, 1992), and generally increase the volume of the road's ecological space. Earlier we discussed the management of road disturbances to minimize connectivity and alien species invasions, and below we address mitigating actions that can be taken relative to hydrological and geomorphological processes. Second, road maintenance activities introduce disturbances. We have previously discussed how maintenance operations create local disturbances and influence the structure and functioning of the road ecosystem. There is a need to recognize that road maintenance is not only an engineering activity, but it is also an ecological action that requires planning and analysis, much like other management activities do, i.e., timber harvesting, wildlife management, and so forth.

5.6. Aquatic/terrestrial interface

The interface between terrestrial and aquatic systems (identified as wetlands or riparian zones) is very productive and active in the exchange of materials and organisms. Roads can increase the connectivity of this interface usually to the detriment of the aquatic system which is vulnerable to excessive sedimentation and changes in water quality and hydroperiod. Moreover, Swanson and Wemple (1998) reported that on steep hillslopes road cuts may intercept subsurface flow and convert ditches into new stream segments, which in turn increases the network of streams in the watershed, runoff, and peak flows.

It is difficult to separate hydrological from geomorphological effects of roads because water is generally the medium for the transport of sediment in watersheds and roads influence both processes simultaneously. Travel intensity, road surface type, vegetation cover, climate, geologic substrate, road maintenance, and road-stream conductivity are primary factors in regulating sediment production in road systems. Some of these factors such as climate or geology cannot be managed directly, but need to be incorporated into the planning of road alignment. In fact, road alignment is the most critical decision made because it sets the stage for how environmentally and economically costly a road will be. Other factors are amenable to management such as road design and vegetation cover. Furniss et al. (1991), provide detailed recommendations for road construction and maintenance.

Research activity aimed at reducing the effects of roads on aquatic systems has resulted in an extensive bibliography (Moore and Furniss, 1997; Copstead et al., 1997), as well as numerous management techniques that are changing the paradigms of road design and operation (Furniss et al., 1991; LaFayette et al., 1996). These efforts involve road obliteration, road relocation, modified culvert designs, raised culvert inlets, modified bridge and ford designs, flow dispersal, stilling basins, and more frequent and effective ditch management (LaFayette et al., 1996). Furniss et al. (1991), provide detailed do's and don'ts for road construction and maintenance near streams, wetlands, and other aquatic ecosystems.

6. Socioeconomic issues

6.1. Market and non-market economics

Chomitz and Gray (1996) developed a land-use model to explore the tradeoff between economic development and deforestation in rural Belize. They observed that the conditions through which the road was passing, i.e., low human population density and nutrient-poor soils, resulted in a lose-lose situation for both the economic and the environmental aspects of the road. Soil quality, land tenure regulations, and intended uses of the road became important determinants on deciding whether placing a road on the landscape was desirable or not. This type of analysis is useful as it recognizes that different socioeconomic conditions change the results of the analysis much as different environmental ones do to the function of road ecosystems.

Kharecha (1997), evaluated all the human activities in the Caribbean National and Luquillo Experimental Forest. The road network was the most expensive human activity in the forest both in terms of economics and environmental effects. The analysis suggested road maintenance over road building as the best strategy to accomplish the goals of the transportation system without increasing environmental costs.

The analyses of Chomitz and Gray (1996) and Kharecha (1997), both provide valuable insights into methods for evaluating the tradeoffs of roads. Both assessments use market and non-market criteria in the evaluation, but the analysis by Kharecha (1997), quantified natural fluxes explicitly (Odum, 1996).

6.2. Scenery and aesthetics

The principles of landscape management for visual and aesthetic purposes were developed by the USDA Forest Service (1973), based on the characteristics of the landscape, its visual variety, and deviation from a characteristic landscape. These three basic concepts were applied to the design and alignment of roads (USDA Forest Service, 1978). This handbook contains directions and practical recommendations for minimizing the visual impact of roads and integrating them to landscapes while addressing safety, use, maintenance, and economic tradeoffs.

7. Conclusions

In summary, roads are a challenge to scientists and managers because they are complex ecosystems that traverse the landscape and affect its function at both local and regional scales. Traditionally, road analysis has been narrowly focused both geographically and ecologically. We propose that roads be analyzed as ecosystems using environmental gradient analysis to distinguish between road segments in different sectors of the landscape or across latitudes and elevation. Such an ecological approach allows the application of ecosystem management techniques to road establishment, maintenance, and decommissioning. We illustrate an ecological approach to road management by reviewing literature addressing ecological and socioeconomic aspects of roads. Because of the complexity of the road ecosystem, the analysis of each individual topic results in the identification of numerous precautions that need to be considered when intervening along a road ecosystem.

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