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The Potential Effects of Forest Roads on the Environment and Mitigating their Impacts

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Abstract Forest roads are a necessary element for accessing forestry resources, but their impact on the environment can be significant. Forest roads can cause a variety of impacts on local wildlife that may lead to extirpation: facilitating the spread of invasive organisms, causing death or harm by vehicle strikes, and changing the behavior of animals to their detriment. Roads create improved access to forests, which can increase predation rates from hunters. Animals may move to avoid traffic noise, increasing their vulnerability to predation by other animals. One of the most significant impacts of forest roads is on water quality, through both catastrophic and chronic sources of water pollution, primarily from sediment. While it is not the case that every road will cause any or all of these impacts, for those that do, mitigation measures can be used to lessen these negative effects. These mitigation measures must begin during the location phase of the road and should continue through construction, use, and maintenance of the roads. Application of these mitigation measures allows forest managers to minimize the impacts from their forest roads when necessary.

Keywords Forest roads · Environmental impacts · Mitigation measures

Introduction

The existence, development, and maintenance of forest roads have both positive and negative effects. Many of the benefits are generated from improved access to both extractive and non-consumptive resources that are produced from our forests. Non-consumptive resources include access to hunting, camping, wildlife viewing, and general site seeing—all of which use forest roads.

Improperly designed, constructed, or maintained forest roads can have a significant impact on the environment. Roads can be vectors for the spread of diseases or noxious weeds. They can both directly and indirectly harm terrestrial wildlife. Perhaps the largest impact from forests roads is on water quality, through both chronic and acute deposition of sediment that can limit the beneficial uses of water and harm aquatic organisms in waters that originate from forests. Many of these impacts can be minimized through the adoption of mitigation measures that change the manner in which roads are designed, built, maintained, and used. These mitigation measures might result in additional costs but can lessen the environmental impacts from forest roads.

This paper will describe both the benefits and impacts that can occur from forest roads and will describe mitigation measures to lessen the damage forest roads cause. The goal is to provide a review of mitigation opportunities to forest road managers, in order to assist them in lessening the impacts from their forest roads when they occur as well as promoting sustainable management of forests. The paper will primarily focus on examples from North America, as that has been the source of much of the research cited, but will occasionally use international examples where possible and applicable. The intention is not to suggest that all roads produce all of the outlined impacts, but to provide a description of some common impacts that occur from forest roads,

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and to suggest some mitigation measures that can reduce these impacts.

The Costs and Benefits of Forest Roads

A well planned, designed, constructed, and maintained forest road can be a valuable asset to a landowner. Access to extractive resources is the first step in the forestry supply chain, eventually allowing forest products to be transported around the world. These supply chains can be entirely owned by the same firm (vertically integrated) or owned by a combination of multiple independent organizations such as the landowner, logging and hauling contractors, and various manufacturing facilities (mixed-ownership supply chains) [1]. A mixed-ownership supply chain creates additional difficulties with managing forest roads, because the cost and benefits of road management are usually spread among multiple parties, often unequally. For example, a road could be built to a lower standard, creating a savings in construction costs that are offset by higher hauling costs, due to the resulting longer travel times. In a mixed-ownership supply chain, however, this road construction benefits the forest landowner, who typically pays for road construction, while the added cost for hauling is placed on the trucker. The trucker may not be aware or able to distinguish between the different road standards and thus might plan for a road of average quality, thereby underestimating their costs. Subsequently, their bid will not accurately reflect road conditions, and the landowner will not have an incentive to improve those conditions. A vertically integrated firm does not need to be concerned about the transference of cost and benefits among the parties in the supply chain, as they are all contained within the same firm. Forestry supply chains that are composed of multiple firms must balance costs and benefits among the actors in the supply chain. If the actors in these supply chains are unable or unwilling to share data, then the ability to apply alternative and potentially mitigating road practices can be compromised. Troncoso [2••] showed that decoupling the forest from the manufacturing facility resulted in a 5 % reduction in net present value over a 25-year planning period. The ability to share product demand information in the vertically integrated firm was the key to the improvement. Thus, when describing investment in forest roads, it is important to consider what parties are responsible for the cost of the mitigation measures and what parties will benefit from those measures. Since these are often different parties, all parties will need to understand the magnitude of the potential savings and costs before they can distribute them equitably. Data collection and sharing may be needed to capture the benefits from the alternative practices.

There are many variables to consider when constructing efficient forest operations. Determining the appropriate road density and total length of road to area to optimize forest operations requires knowing the extraction costs of these operations. Extraction costs include components such as the skidding or yarding, road, and landing constructions costs. To lower extraction costs, the interaction between roading and skidding costs must be accounted for in the analysis. The lower the skidding costs, the farther apart the roads can be constructed, as logging itself can consume a greater portion of the total extraction costs.

There are optimization models to determine how to lower extraction costs, which include logging, hauling, landing construction, and road construction costs [3–6]. These models compute optimal spacing and road standards to support commercial operations at the lowest extraction cost. The methods currently developed are designed for gentle ground where there are a multitude of possible road locations. Figure 1 is an aerial photograph from New Zealand's plantation forest in the country's North Island. The small dots are landings for collection and processing of tree boles. This area has gentle terrain and demonstrates the use of road and landing spacing solutions to assist in determining the optimal road density in large commercial operations. In many parts of the world where the ground is steep, however, there are limited options for roads. Nevertheless, one can consider roading and logging costs simultaneously in steep terrain to develop extraction models that minimize the combined costs.

Forest roads may be one of the most used recreational features in a forest. They can facilitate many functions, including providing driving challenges, allowing site seeing, and facilitating an opportunity to observe wildlife or other esthetically pleasing vistas. Roads can also provide access to favorite hunting or camping sites [7]. However, forest roads may need additional care in their design to safely allow for recreational passenger vehicles, which might not be well suited for a forest road designed exclusively for trucks. There can be a

Fig. 1 An example of road and landing spacing for plantation forests on New Zealand's North Island [used with permission via Google's guidelines]

need to alter the design standards of many roads to better accommodate smaller vehicles that might not be as visible as the traffic associated with logging trucks, whose drivers often use radios to warn one another of their location. Additionally, there may be a need to educate all forest road designers on how to minimize accidents when the traffic on these narrow roads contains both commercial and recreation traffic. This can include items such as increased sight distance along curves or a wider or more frequent construction of turnouts on narrow roads to allow vehicles to safely pass.

The Environmental Impacts of Forest Roads and the Methods to Mitigate these Impacts

There are many negative environmental impacts from forest roads. These impacts can decrease or negate many of the benefits derived from forests. Roads can facilitate the introduction of noxious pests and often have both direct and indirect impacts on wildlife. Roads can impact water quality though both chronic and acute sources of pollution, as well as through altering floodwater patterns. Roads are commonly seen as the pathways to environmental degradation, but a commitment to implementation of mitigation measures can reduce many of the impacts associated with forest roads, allowing management and use of our forests while protecting forest ecosystems. There are a variety of possible mitigating measures that can be deployed during design, construction, hauling, and maintenance of roads.

Noxious Pests

Noxious pests include pathogens and plants (weeds). These introduced, non-native organisms can spread rapidly through their introduced landscapes, as they often lack any environmental control to limit their expansion. Noxious pests can have a tremendous impact on native plants and wildlife. An example is the spread of the root pathogen, *Phytophora latoralis*, a fungus that infects yellow cedars such as the Port Orford cedar (*Chamaecyparis lawsoniana*). The spores from the fungus travel in water and attack these trees by girdling the roots, causing mortality. The spores are commonly dispersed along the roads. The access provided by the road allows contaminated soil attached to vehicles and heavy equipment from infected areas to become dislodged and deposited on the road surface. The spores are then carried into streams with storm water that runs across the road, creating new infection sites [8].

Noxious weeds can result in significant financial and environmental damage. Olson [9] has estimated the annual cost of invasive plants in various countries: \$4 billion in Australia, \$100 million in New Zealand, €103 million in Germany, and \$34.5 billion in the USA. Noxious weeds contribute to this damage in a variety of ways; their spread can reduce foraging opportunities for livestock and wildlife species or limit the opportunities for native plants to thrive, harming the ecological resiliency of the environment. Noxious weeds are commonly spread along roads. Seeds of noxious weeds are often attached to the fur of animals, the clothing of people, or in various ways to vehicles. Often, these seeds are contained in vegetation, such as straw mulches, that are often spread along roads to control erosion. The exposed soil following road construction is often the ideal site for these aggressive colonizing species.

Thus, one control mechanism for noxious pests is to require sanitation permits on logging equipment and trucks from other areas. Permitting must be followed by inspections to ensure that vehicles have no vegetation or remaining soil attached to their equipment when they enter a new area. These restrictions can extend to trails; Valachovic et al. [10] have found the spores that transmit sudden oak death are transported in the mud attached to soles of hiking boots. Thus, places to clean boots at trailheads may be necessary to control these invasive organisms.

Exposed sites such as cut and fill slopes still need protection from erosion; therefore, it may be necessary to use alternative mulches to protect road fills from erosion while mitigating the harm from noxious pests. Even the use of certified weed-free straw has been documented to increase the abundance of non-native species occurring on these construction sites following treatment [11]. Foltz [12••] tested three types of wood mulches for their effectiveness in reducing erosion from the unprotected fills following construction. One was straw, while the other two were derived from wood products, wood shreds, and wood strands. Wood shreds are made locally from logging residue that is processed in a tub grinder and can be produced in the same forest where the mulch will be spread. Wood strands are a by-product of veneer manufacturing and are made by shredding wood to a common thickness and length. The first-year results showed no statistical differences in tree growth, sedimentation, or ground cover from the two wood-based mulches when compared to straw, and the wood-based mulches reduced the opportunities for invasive plants to spread through the road prism [12••].

Impacts to Wildlife

Forest roads can impact wildlife in both direct and indirect ways. Some of these impacts can occur on low volume roads, while others may be more common on higher-standard roads that allow increased traffic speed. The direct impacts are primarily through vehicle strikes that kill or maim animals, while the indirect effects are a result of habitat modification or changes to the use of existing habitat. Mitigation methods can include alternative road locations, regulation of vehicle speed through wildlife high-use areas, seasonal restrictions that limit noise during breeding or rearing seasons, and design modifications to reduce road impacts perceived by animals. In some cases, it may be necessary to construct specialized features to allow wildlife to cross the road.

Direct Impact to Wildlife

Vehicle strikes can result in a significant impact on wildlife populations, especially on higher-standard roads through forested areas where vehicles travel at a higher speed. Traffic on these larger forest roads can be one of the leading causes of mortality to large animals. One example is the endangered Florida panther (*Felis concolor coryir*): vehicle strikes account for 10 % of population mortality [13]. Vehicles strikes have also had a significant impact on river otters (*Lutra lutra*) in Germany and badgers (*Meles meles*) in the United Kingdom. Marsh and Jaeger [14] list the mortality rates for small vertebrates; the range in the data is large but can reach 37 % of the mortality rate for some animals, such as spotted salamanders (*Ambystoma maculatum*).

Vehicle strikes are not limited to larger animals crossing the road on the ground. Hundreds of millions of birds are struck by vehicles annually [15]. DeVault [15] used brown-headed cowbirds (*Molothrus ater*) in an experiment to test the birds' responses to vehicles traveling at different speeds and with different sight distance between the birds and the vehicles. This study used simulated vehicles similar to those used in human-vehicle interaction studies in order to not harm the birds. As expected, DeVault found as the vehicle's speed increased, the birds were increasingly unable to escape being harmed [15].

Analysis of vehicle strike data shows evidence of spatial or temporal patterns to these incidences. They most often occur in areas of high animal density or on common migration routes. For example, amphibians' mortality due to vehicle strikes is high where roads are appurtenant to wetlands [14], thus avoiding these locations when locating roads is one available mitigation measure.

Case [16] has stated that speed and traffic volumes are two of the more important variables in predicting vehicle strikes. It is often road segments with moderate traffic and high speed that produce the highest mortality rates. High traffic volume keeps many animals from attempting to cross roads, as these roads can be perceived as a barrier to the animals. These vehicle strikes also can pose a safety hazard for the vehicle occupants.

There are several mitigation measures that can reduce the impacts of vehicle strikes on wildlife. One is to work with wildlife professionals to identify migration routes and, if possible, locate roads to minimize intersections with these commonly used routes. Vehicle speed can be reduced through these migration areas if the road cannot be located elsewhere. Seasonal restrictions might be considered to limit traffic during critical times, such as mating or migrating seasons, when animals may be most vulnerable. Finally, managing roadside vegetation can make road right-of-ways less attractive places for wildlife to congregate.

Indirect Impact to Wildlife

Indirect effects of roads on wildlife do not necessarily directly harm an individual animal but prevent or limit the animal from its natural movement or activities. Roads can be a physical barrier to some animals. Burrowing invertebrates are especially vulnerable, as they are unable to navigate across the road due to the dry surface or the compacted subsoil. There are a variety of causes for why animals avoid roads; these behaviors can be grouped into two categories: avoidance of vehicles in general and merely the avoidance of road-based emissions, such as fumes or noises [17••].

Shepard et al. [18] provided a literature review of the impact of roads on a variety of species from large mammals (such as wolves and grizzly bears) to small invertebrates (such as beetles) to document the impact of roads on wildlife movement through their preferred habitat. In a capture-mark and recapture study, for example, Keller and Largiadèr [19] were able to show that only one of the 742 large, flightless beetles that were recaptured had crossed a six-meter wide road. They were able to show that these types of forest roads contributed to a significant difference in the genetic makeup among the local invertebrate population in a Swiss forest, and that this genetic difference was caused by forest roads [19]. Thus, the isolation caused by roads can contribute to a reduction in species diversity within the forest. Langton [20] modified small culverts to allow amphibians to cross below roads, which may be a mitigation for road-caused isolation.

Indirect impacts are not limited to small animals or invertebrates. In North America, Roosevelt elk *(Cervus elaphus roosevelti*) have been found to be impacted by road use. The traffic noise associated with roads was sufficient to cause elk to alter their behavior. The noise disrupts their feeding patterns and makes them move, which increases their vulnerability to predation from a variety of animals, such as mountain lion. When gates were installed on the road, they eliminated all but managerial traffic. The reduction in noise reduced the need for elk to move and their survival rates increased [21]. Additionally, the gates reduced elk losses to illegal hunting by limiting vehicle access to the area [22]. For those animals that avoid roads due to traffic noise, gates or other road closure techniques can reduce some of the disturbances that stress the animals.

Impacts on Aquatic Resources

Forests are often the originating sources of water for urban areas, and high-quality water is becoming a scarce and valuable resource in many parts of the world. Many forests are habitats for species that contribute to large commercial and sport fisheries, including Pacific or Atlantic salmon (*Oncorhynchus spp*. or *Salmo spp*.). Often, the highest value good produced by a forest may not be its timber resources but its clean, cold water that supports valuable fisheries or domestic water supplies.

The impact of forest roads on water quality can be grouped into acute and chronic sources. Acute sources of water pollution are associated with road failures that reach water primarily through debris slides. Chronic sources of pollution can be from the cut or fill slopes, the ditch, or the surface of the road. This sediment is usually delivered through the road's own drainage system.

In the USA, forest roads have been subject of recent litigation that reached the highest court in the USA. The controversy surrounded the methods used to regulate sources of pollution under the US Clean Water Act, 33 U.S.C. 1251–1387. This case involved determining whether the pollution from ditch system associated with forest roads was a point source of pollution as defined by the act. One that has pollutant (sediment) transferred using a discrete conveyance (ditches) and deposit in the waters of USA and in non-exempt cases would require a National Pollution Discharge Elimination Permit, (NPDES) [23•], [24]. The case was resolved by allowing the Environmental Protection Agency (EPA) the discretion to categorize the pollution from forest roads as stormwater from an exempt source. However, this case highlighted the increased public concern about the quality of water originating from forests and the contribution of forest roads to impairing water quality.

Forest roads in the Pacific Northwest region of the USA have been shown to increase the peak flow of storm events. The greater connectivity of roads to streams allows stormwater to be more efficiently delivered to streams, causing higher peak flows [25]. This is often combined with poor stream crossing designs from improperly installed culverts in streams. These poor designs can cause scour in the stream channel below the pipes, resulting in a barrier to movement upward from the culvert. This has been shown to eliminate access to kilometers of suitable fishery habitat in streams.

Many forests exist in steep rugged terrain, examples include: The Rocky Mountains, the Cascades, and the Coast range of North America, and the mountains of New Zealand. These areas have the peculiar combination of steep slopes, significant rainfall events, and weak geological material that make landslides a common problem. Roads, especially those constructed using side-casting techniques (where excavated material is simply pushed over the edge of the roadway), are especially vulnerable to landslides. This fill material is not compacted or stabilized in any way and often rests in unconsolidated piles on steep slopes. When this material becomes saturated, its strength is reduced until the material fails; often this occurs during large precipitation events (Fig. 2).

The mitigation efforts for these types of roads can occur in the location stage of the road planning, as overly steep slopes may be avoided. The problems can also be mitigated during initial construction with the use of end-haul techniques that load excess material and haul it to stable disposal sites. As one might expect, end-haul techniques can result in a significant expense through the costs of hauling large amounts of surplus material on steep roads to distant disposal sites [26]. However, a study in coastal Oregon (USA) showed a significant reduction in landslide frequency and size when end-haul techniques were used [26]. For roads that have already been constructed using side-casting techniques, much of this material can often be retrieved using hydraulic excavators, which is then loaded into dump trucks and hauled to disposal sites. If a road is being decommissioned, then the side-cast material can be placed on the road surface. Often, these piles are planted with trees to encourage rapid colonization and promote stabilization of this material. The cost for this work can be high; examples from western Washington (USA) required 135 h to pull side-cast material from 2.6 km of road [27].

The chronic sources of sediment impacting the environment are produced from all parts of the road prism; these impact water quality and ultimately impact fisheries. Juvenile Coho salmon (*Oncorhychus kisutch*) have been documented to avoid turbid water once it reached a level of 70 Nephelometric Turbidity Units (NTU) [28]. This turbidity can be caused by sediment from the road surface, the cut and fill slopes, and the ditch surface [29••]. The amount of sediment generated depends on several factors: the condition of the road; the maintenance practices for the ditch; the amount of exposed surfaces on the cut and fill slopes; the soil texture, with finer soils being more erosive than coarse soils; and the climate as it influences the amount, type, and intensity of precipitation events.

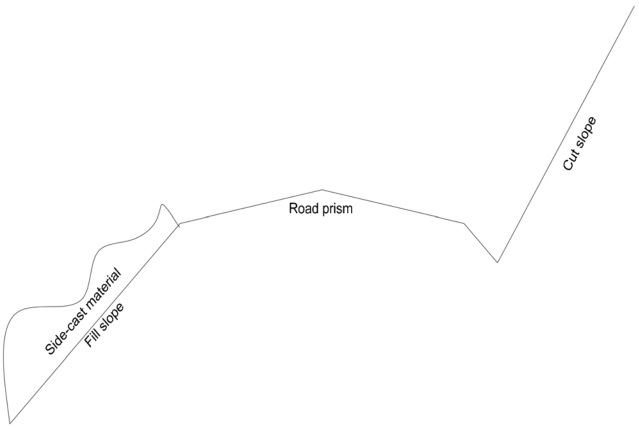

Fig. 2 A road prism with a crowned cross section with side-cast material on the edge of the road

Fahey and Coker [30] categorized the amount of sediment produced from forest roads in the Marlborough Sounds in the northern part of New Zealand's South Island. Their results indicated that little material was produced from the cut bank. The major contributions of sediment were from the side-cast fill and the road surfaces. These areas produced a mix of material sizes, including a significant volume of fine-grained materials less than 2 mm in diameter. This fine-grained material is the type of material most detrimental to the survival of aquatic organisms [31], and it is an example of the chronic sediment that can be continually produced by forest roads. Luce and Black [29••] had similar results, finding that bare soil from the road prism resulted in a 7.4 factor increase in sediment yield from a forest road.

There are a number of factors that influence the amount of sediment produced from the surface of the road. Aggregate quality is one; in forestry, heavy loads on the road can both fracture and abrade the rock and create smaller particles. Figure 3 shows an example of weak aggregate that is being rapidly degraded during hauling and then washed from the road during wet-weather hauling.

Precipitation transports smaller particles from the road surface though the drainage system and ultimately to streams. Foltz and Truebe [32, 33] found that aggregates rated as "moderate" produced 4 to 17 times the sediment compared to "good" (strong) aggregate. Thus, testing aggregate and eliminating the weaker rock can limit the generation of these sources of chronic sediment. This is especially important on road segments where it is impossible to hydrologically disconnect the road from the stream. This mitigation measure can increase road construction complexity and cost, but it is possible to reduce environmental impacts by being selective about what rock is selected and where it is placed.

Brown et al. [34•] showed the placement of an aggregate surface on a stream crossing resulted in a large reduction in sediment delivered to streams when compared to native soils crossings in the Piedmont region in Virginia (USA). Extending their example further, high quality rock could be used on sections of roads that remain hydrologically connected to streams while lower quality rock can be used in places where the road is hydrologically disconnected to streams. Thus, the highest quality and likely most valuable rock can be saved for use in the most critical places, decreasing costs.

Fig. 3 Erosion from surface material during hauling

It is not just the aggregate that influences the impact from the forest roads but the interaction between the road surfacing and the subgrade. Both contribute to supporting large vehicle loads [35]. Many forest road subgrades are not built using traditional civil engineering techniques that control compaction by applying water or drying techniques to reach the optimal water content to promote efficient compaction of the subgrade. In fact, many in the forest industry believe that heavy, tracked forestry equipment will suffice for compaction; however, this equipment is designed for low ground pressure and does little to improve the bearing strength of the soil. The result from these uncontrolled construction practices is subgrade soil densities that are significantly below typical target values. For example, 90 % of standard Proctor levels could be achieved if construction practices were better controlled [36]. Weak subgrades have insufficient strength to fully support the heavy wheel loads of fully laden logging trucks. Ruts are quickly formed when the road's surface fails either due to its subgrade or due to the entire road structure. These ruts produce higher amounts of sediment, as water is more likely to flow down the rut rather than to the ditch. Studies have shown that rutted roads produce double the sediment of roads without a rutted surface when subjected to heavy truck traffic [36].

The mitigation efforts for these types of impacts can include alternative construction, use, and maintenance practices. One of the simplest methods to reduce the impact of sediment from forest roads is to hydrologically disconnect ditches from streams and allow water from the ditch, road surface, and cut slope (with its sediment) to be diverted into an armored outlet in the forest and not into a stream. There will always be some portion of a road that cannot be hydrologically disconnected, but the goal is to remove as much of the sediment-containing water as possible from a ditch and avoid interacting with a stream system.

Improved construction practices such as controlled compaction can reduce rut formation on forest roads. Construction activities that apply aggregate testing practices can identify rock sources that might not be suitable for hydrologically connected sections of roads and use proper aggregate instead. This method may be able to reduce the amount of sediment being produced during hauling. However, road segments using these construction techniques can require a greater level of engineering skill in their design and construction, which might not currently be available in all forestry operations.

Another mitigation measure to reduce sediment from forest roads is to use low-pressure tires when hauling wood. Low-pressure tires have a larger contact area with a road, lowering the stress transferred from the vehicle to the road surface. Lower stress reduces the wear rate of the aggregate material. Foltz and Burroughs [37] showed a significant reduction in sediment yield with use of low-pressure tires, with 1.6–1.71 times more sediment produced when hauling with conventional highway tire pressure on aggregate roads as compared to low-pressure tires. Similarly, Moore et al. [38] showed that hauling with low-pressure tires could reduce sediment by up to 84 %. One problem with using lower tire pressure systems on wood-hauling trucks is that its cost is born by the truck owner, as the increased rolling resistance can increase fuel consumption and tire wear, while its benefit accrues to the forestland owner through less road wear. Thus, finding an equitable compensation arrangement for both the trucker and landowner is necessary to balance these costs and benefits, but this can be difficult due to difficulties in quantifying the value of reduced sediment production and in identifying the change in rock wear rate.

Conclusion

Active forest management relies on its transportation systems. Roads provide access to the various resources generated from forests. Forest roads are generally developed for extractive resources, but forest roads enhance many of the non-consumptive uses of the forest. However, forest roads impact many aspects of the environment and can have the greatest environmental effect through facilitation of the spread of noxious weeds, through impacts to wildlife and through contamination of water resources. In essence, roads can facilitate the spread of harmful agents, prevent the movement of species, or be a source of pollution. While the application of various mitigation measures may increase the hauling, construction, or maintenance costs of roads, these measures can lessen the road's environmental impacts. This work will often require working with a variety of professionals such as forest pest experts, hydrologists, geologists, or wildlife biologists to help develop the appropriate mitigating measures to reach a balance for these impacts. Ultimately, however, applying appropriate mitigation measures will allow access to forestry resources with the least amount of environmental degradation possible.

Compliance with Ethical Standards

Conflict of Interest Dr. Boston has no conflicts of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by the author.

References

Papers of particular interest, published recently, have been highlighted as:

- Of importance

•• Of importance

1. Borges JG, Diaz-Balteiro L, McDill ME, Rodriguez LC (Eds.). The management of industrial forest plantations: theoretical foundations and applications. Vol. 33. Springer; 2014.
2. •• Troncoso J, D'Amours S, Flisberg P, Rönnqvist M, Weintraub A. A mixed integer programming model to evaluate integrating strategies in the forest value chain—a case study in the Chilean forest industry. Can J For Res. 2011;45(7):937–49. **The authors describe the benefits of an integrated supply chain when compared to a decoupled supply chain**.
3. Matthews DM. Cost control in the logging industry. McGraw-Hill Book Company; 1942.
4. Larsson G. Studies on forest road planning. Transactions of the Royal Institute of Technology 147. Stockholm, Sweden; 1959.
5. Sessions J, Boston K. Optimization of road spacing for log length shovel logging on gentle terrain. Int J For Eng. 2006;17(1):67–75.
6. Sessions J, Boston K, Murphy G, Kellogg L, Pilkerton S, Zweede J, Heinrich R. Harvesting operations in the tropics. Berlin: Springer-Verlag; 2007.
7. Queen LP, Vlaming JC, Arthaud GJ, Lime DW. Modeling impacts of forest roads on recreation opportunities. North J Appl For. 1997;14(4):194–201.
8. Jules ES, Kauffman MJ, Ritts WD, Carroll AL. Spread of an invasive pathogen over a variable landscape: a nonnative root rot on Port Orford cedar. Ecology. 2002;83(11):3167–81.
9. Olson LJ. The economics of terrestrial invasive species: a review of the literature. Agric Resour Econ Rev. 2006;35(1):178–94.
10. Valachovic Y, Lee C, Marshall J, Scanlon H. Wildland management of *Phytophthora ramorum* in Northern California forests. In: Frankel, S.J., Kliejunas, J.T., and Palmieri, K.M. Technical editors. Proceedings of the Sudden Oak Death Third Science Symposium. United States Department of Agriculture, Pacific Southwest Research Station, Albany, CA. General Technical Report PSW-GTR-214. 2008; pp. 305–312.
11. Kruse R, Bend E, Bierzychudek P. Native plant regeneration and introduction of non-natives following post-fire rehabilitation with straw mulch and barley seeding. For Ecol Manag. 2004;196(2): 299–310.
12. •• Foltz RB. A comparison of three erosion control mulches on decommissioned forest road corridors in the northern Rocky Mountains, United States. J Soil Water Conserv. 2012;67(6):536–44. **Two woody-based mulches were compared with agriculture straw that showed no statistical difference in ground cover after use for three years. There was no difference in sediment produced from treatment sites with any of the three cover types**.
13. Coffin AW. From roadkill to road ecology: a review of the ecological effects of roads. J Transp Geogr. 2007;15(5):396–406.
14. Marsh, D. M. Jaeger, J.A.C. Direct effect of roads on small animal population. In: Andrews, K. M., Nanjappa, P., and Riley, S.P.D. editors. Roads and ecological infrastructure: concepts and applications for small animals. John Hopkins University Press. 2015; pp. 42–56.
15. DeVault TL, Blackwell BF, Seamans TW, Lima SL, Fernández-Juricic E. Speed kills: ineffective avian escape responses to oncoming vehicles. Proc R Soc Lond B Biol Sci. 2015;282(1801) 10 p.
16. Case RM. Interstate highway road-killed animals: a data source for biologists. Wildl Soc Bull. 1978;6(1):8–13.

17.•• McGregor RL, Bender DJ, Fahrig L. Do small mammals avoid roads because of the traffic? J Appl Ecol. 2008;45(1):117–23. **Roads can act as barriers to animal movement, which may reduce population persistence by reducing recolonization of empty habitats. Our results suggest that small mammals avoid the road itself, and not emissions such as noise from the traffic on the roads. Our results imply that the barrier effect of roads on these species cannot be mitigated by measures aimed at reducing traffic amount**.

18. Shepard DB, Kuhns AR, Dreslik MJ, Phillips CA. Roads as barriers to animal movement in fragmented landscapes. Anim Conserv. 2008;11(4):288–96.

19. Keller I, Largiader CR. Recent habitat fragmentation caused by major roads leads to reduction of gene flow and loss of genetic variability in ground beetles. Proc R Soc Lond B Biol Sci. 2003;270(1513):417–23.

20. Langton, T.E. A History of small animal road ecology. In: Andrews, K. M., Nanjappa, P., & Riley, S.P.D. editors. Roads and ecological infrastructure: concepts and applications for small animals. John Hopkins University Press. 2015; pp. 7–20.

21. Cole EK, Pope MD, Anthony RG. Effects of road management on movement and survival of Roosevelt elk. J Wildl Manag. 1997;61(4):1115–26.

22. Stussy RJ, Edge WD, O'Neil TA. Survival of resident and translocated female elk in the Cascade Mountains of Oregon. Wildl Soc Bull. 1994;22(2):242–7.

23.• Boston K, Thompson M. Argument for placing logging roads under the NPDES Program. Ecology L Currents. 2009;36:169–76. **Authors make an argument of the use of NPDES permits for regulating road-based pollution carried to streams through ditches**.

24. Boston K. Impact of the ninth Circuit court ruling (Northwest Environmental defense center v. Brown) regarding forest roads and the clean water act. J For. 2012;110(6):344–6.

25. Jones JA, Swanson FJ, Wemple BC, Snyder KU. Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. Conserv Biol. 2000;14(1):76–85.

26. Sessions J, Balcom JC, Boston K. Road location and construction practices: effects on landslide frequency and size in the Oregon coast range. West J Appl For. 1987;2(4):119–24.

27. Harr RD, Nichols RA. Stabilizing forest roads to help restore fish habitats: a Northwest Washington example. Fisheries. 1993;18(4): 18–22.

28. Bisson PA, Bilby RE. Avoidance of suspended sediment by juvenile Coho salmon. N Am J Fish Manag. 1982;2(4):371–4.

29.•• Luce CH, Black TA. Sediment production from forest roads in western Oregon. Water Resour Res. 1999;35(8):2561–70. **Prevention and estimation of soil erosion from forest roads requires an understanding of how road design and maintenance affect sediment production. Sediment production was not correlated to the cutslope height. Road segments where vegetation was cleared from the cutslope and ditch produced about 7 times as much sediment as road segments where vegetation was retained, showing the potential reduction in erosion by revegetation following construction and the potential impact of ditch cleaning during maintenance**.

30. Fahey BD, Coker RJ. Sediment production from forest roads in queen Charlotte Forest and potential impact on marine water quality, Marlborough sounds, New Zealand. N Z J Mar Freshw Res. 1992;26(2):187–95.

31. Cederholm CJ, Reid LM, Salo EO Cumulative effects of logging road sediment on salmonoid populations in the Clearwater River, Jefferson County, Washington, in Salmon-Spawning Gravel: A Renewable Resource in the Pacific Northwest? Contribution 543. College of Fisheries, University of Washington, Seattle; 1980.

32. Foltz RB, Truebe M. Effect of aggregate quality on sediment production from a forest road. Sixth international Conference on Low-Volume Roads. Transportation Research Board, National Research Council, Washington, DC. 1995; 1: 49–57.

33. Foltz, R. B., Truebe, M. Locally available aggregate and sediment production. Transportation Research Record: National Research Council, Transportation Research Board (2): 185–193.

34.• Brown KR, McGuire KJ, Aust WM, Hession WC, Dolloff CA. The effect of increasing gravel cover on forest roads for reduced sediment delivery to stream crossings. Hydrol Process. 2015;29(6): 1129–40. **These three were applied to forest road crossing treatments: no gravel (10–19% cover), low gravel (34–60% cover), and high gravel (50–99% cover). Results showed that total suspended solid concentration of surface run-off for the no gravel treatment (2.84 g l^{-1}) was greater than low gravel (1.10 g l^{-1}) and high gravel (0.82 g l^{-1}) by factors of 2.6 and 3.5 respectively**.

35. Boston K, Pyles M, Bord A. Compaction of forest roads in northwestern Oregon–room for improvement. Int J For Eng. 2008;19(1): 24–8.

36. Foltz RB, Burroughs Jr ER. Sediment production from forest roads with wheel ruts. In: Riggins RE, Jones EB, Singh R, Rechard PA, editors. Watershed planning and analysis in action. New York: American Society of Civil Engineers; 1990. p. 266–75.

37. Foltz RB, Burroughs Jr ER. A test of normal tire pressure and reduced tire pressure on forest roads: sedimentation effects. In: Stokes BJ, Rawlins CL, editors. Proceedings of conference of forestry and the environment: engineering solutions. St. Joseph, MI: American Society of Agricultural Engineers; 1991. p. 103–12.

38. Moore T, Foltz RB. Cronenwett, L. Central tire inflation (CTI) reduces sediment up to 84 %: a method to help meet new water quality standards and guidelines. 1; engineering tech tips. Forest Service, San Dimas Technology and Development Center, San Dimas, CA: U.S. Department of Agriculture; 1995. p. 1.