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Optimization strategies for sediment reduction practices on roads in steep, forested terrain

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Abstract

Many forested steeplands in the western United States display a legacy of disturbances due to timber harvest, mining or wildfires, for example. Such disturbances have caused accelerated hillslope erosion, leading to increased sedimentation in fish-bearing streams. Several restoration techniques have been implemented to address these problems in mountain catchments, many of which involve the removal of abandoned roads and re-establishing drainage networks across road prisms. With limited restoration funds to be applied across large catchments, land managers are faced with deciding which areas and problems should be treated first, and by which technique, in order to design the most effective and cost-effective sediment reduction strategy. Currently most restoration is conducted on a site-specific scale according to uniform treatment policies. To create catchment-scale policies for restoration, we developed two optimization models – dynamic programming and genetic algorithms – to determine the most cost-effective treatment level for roads and stream crossings in a pilot study basin with approximately 700 road segments and crossings. These models considered the trade-offs between the cost and effectiveness of different restoration strategies to minimize the predicted erosion from all forest roads within a catchment, while meeting a specified budget constraint. The optimal sediment reduction strategies developed by these models performed much better than two strategies of uniform erosion control which are commonly applied to road erosion problems by land managers, with sediment savings increased by an additional 48 to 80 per cent. These optimization models can be used to formulate the most cost-effective restoration policy for sediment reduction on a catchment scale. Thus, cost savings can be applied to further restoration work within the catchment. Nevertheless, the models are based on erosion rates measured on past restoration sites, and need to be updated as additional monitoring studies evaluate long-term basin response to erosion control treatments. Copyright © 2006 John Wiley & Sons, Ltd.

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Introduction

Stream restoration is of growing interest to both public agencies and individual landowners. ‘Restoration’ can address a wide range of problems, including urbanization, channelization, streambank erosion, changes in flow regime or water temperatures, degradation of water quality, sediment augmentation or sediment reduction. According to the US National Water Quality Inventory of 10^6 km of rivers and streams, about 45 per cent were impaired or threatened, with siltation being the leading stressor (USEPA, 2000). Consequently, much of the stream restoration work in the United States has concentrated on reduction of sediment and in-stream habitat improvement. To date, restoration work has been implemented primarily on a trial-and-error basis, with the principal focus on establishing an appropriate channel form rather than understanding geomorphic processes and linkages across several scales. In addition, the spatial scales of restoration efforts commonly are relatively small, from restoring a single hydraulic unit (i.e. pool enhancement) or controlling point sources of pollution, to a reach scale (i.e. levee manipulation or riparian planting). Scant attention has been paid to the trade-offs implicit in choosing a site-scale rather than basin-scale perspective of river restoration strategies.

Many anadromous fisheries streams in the Pacific Northwest have been damaged by various land-use activities, including timber harvest and road construction. Roads can have adverse hydrologic and geomorphic effects (Luce and Wemple, 2001), and unpaved forest roads can cause erosion and downstream sedimentation damage in anadromous fish-bearing streams. Roads commonly increase the rate of landslides (Swanson and Dryness, 1975), surface erosion (Megahan *et al*., 2001) and delivery of fine sediment to channels (Furniss *et al*., 1991), and extend channel networks by the construction of roadside ditches (Wemple *et al*., 1996). In addition, roads can alter hydrology by concentrating water through road drainage structures and converting subsurface flow to surface flow (Luce, 2002). Road drainage structures can also impede the routing of wood to downstream reaches (Roni *et al*., 2002).

Roads are a significant source of sediment in many areas of the world. Road erosion threatens coral reefs in the Virgin Islands of the Caribbean (MacDonald *et al*., 1997), and roads cause gully initiation in Australia (Croke and Mockler, 2001), long-term gully erosion in the tropics (Douglas, 2003) and increase landslide susceptibility (Fransen *et al*., 2001) and surface erosion (Fahey and Coker, 1989) in New Zealand. Environmental and ecological problems related to roads have been formally recognized by many European governments through the establishment of road ecology units (Forman *et al*., 2003). The road network on public and private lands in North America is extensive, at nearly 8×10^6 km (Forman *et al*., 2003). More than 850 000 km of roads have been built on federal lands in the USA (Havlick, 2002), yet the length of river channels impacted by roads is unmeasured.

During the last two decades, thousands of kilometres of roads in the United States have been removed to ameliorate erosion problems. Road removal restores the hydrological and geomorphological processes in a basin by reconstructing natural drainage patterns through the removal of drainage structures (culverts), filling in roadside ditches or disconnecting them from stream channels, and reshaping and revegetating stream banks, but little research has been done on the effectiveness of road removal (Switalski *et al*., 2004).

Although road removal and road upgrading activities have been conducted on many roads, these activities have usually been implemented and evaluated on a site-specific basis without the benefit of a basin-wide perspective of sediment reduction. Land managers still struggle with designing the most effective road treatment plan to minimize erosion, while keeping costs reasonable across a large land base. To broaden the perspective to a catchment scale, we examine the suite of erosional problems and possible treatments in an entire basin, not just in a limited area perceived to be critical by land managers. Trade-offs between costs of different levels of treatment and the net effect on reducing sediment risks to streams need to be quantified for effective sediment management. If sediment reduction to anadromous fish-bearing streams is the desired outcome of restoration activities, a more rigorous evaluation of risks and treatments across entire catchments is needed. In this study, we combine field-based investigations and modelling of sediment savings to evaluate the effectiveness of various restoration strategies in steep, forested terrain in reducing sediment loads to streams. We hypothesize that the use of optimization techniques can prescribe greater sediment savings for equivalent costs than two erosion control strategies commonly used by land managers.

Field Area

The restoration strategies modelled in this paper are based on restoration work conducted since 1978 in the Redwood Creek catchment, located in the northern Coast Ranges of California, USA. Redwood Creek drains an area of 720 km^2 and the basin receives an average of 2000 mm of precipitation annually, most of which falls as rain between October and March. Total basin relief is 1615 m and the average hillslope gradient is 26 per cent. The catchment has about 3200 km of first- and second-order stream channels, which are generally 10 per cent in grade or steeper. The catchment has more than 7000 road-stream crossings on a network of 2000 km of forest roads which affect these small channels. Since 1978, about 300 km of forest roads on federal lands have been removed. In this study we focus on Lost Man Creek, a 25 km^2 tributary basin of Redwood Creek, which still has an extensive network of unmaintained and unpaved roads that are being considered for treatment. The logging history, geology, terrain, road density and road-related erosion problems in this sub-basin are typical of the region and are well documented. Consequently Lost Man Creek represents a good test case to evaluate sediment reduction schemes applied to roads in steep, forested terrain.

Road Removal Techniques

Roads have two major components: (1) a *stream crossing* is the location where a road crosses a stream and some type of drainage structure conveys runoff under the road prism; and (2) *road segments* are intervening stretches of road that

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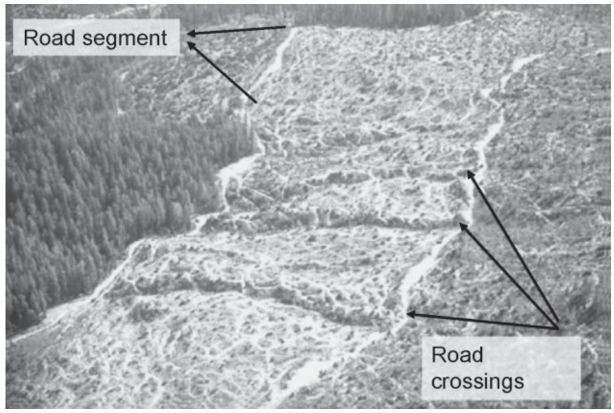

Figure 1. Recently deforested hillslope in the Redwood Creek catchment showing a network of road segments and road-stream crossings on major forest roads. At stream crossings, culverts convey runoff under the road prism.

consist of the roadbed, cutbank and fillslope (Figure 1). A road can be removed by a variety of techniques. In this study, we evaluate three treatments for road crossings and four treatments for road segments. For road crossings (Figure 2), 'no treatment' leaves the drainage structure intact. 'Basic excavation' removes the drainage structure (commonly culverts), and excavates the road fill down to the original channel bed elevation. 'Total excavation' removes the drainage structure and sediment that may have accumulated upstream of the road prism, as well as reshaping the streambanks to a greater extent than under 'basic excavation.' For road segments, under 'No treatment' the road remains on the landscape, but is allowed to revegetate naturally. 'Rip and drain' (minimal treatment) decompacts the road surface, increases infiltration, and directs runoff into drains or ditches to carry it across the road. 'Partial outslope' excavates some sidecast fill, places it at the base of a cutbank, and obliterates roadside ditches. 'Total outslope' completely recontours the road bench to mimic the natural hillslope (Figure 3). At completion, roads that have been treated no longer convey vehicle traffic and require no maintenance.

The volume of road material moved increases with the level of treatment. As the extent of excavation increases, the effectiveness of the treatment in reducing sediment input increases, but the costs of the treatment also increase. Consequently, land managers must weigh the relative benefits of treating more sites less intensively against treating fewer sites more intensively. Most road-related erosion occurs during large storms, when high runoff can overwhelm culvert capacity or long-duration rainfall can saturate road fills, causing landslides in the fill material. Land management agencies attempt to reduce the risk from road-related erosion during the next large storm through various strategies. One common treatment policy in the western United States is to treat all roads at a minimum level (that is, rip and drain for road segments and basic excavation for crossings). In fact, some government performance goals use the metric of 'length of road treated' to measure success, a practice which encourages land managers to treat roads lightly. With this approach, the goal is to treat the greatest length of road for a given budget, assuming that even limited treatment across a large road network before the next large flood is the best risk-reduction strategy. A contrasting strategy that is used by some agencies is to treat only those roads near critical fish habitat, but at the maximum level. In this case the goal is to reduce sediment risks as much as possible in a limited area, with the assumption that sediment risks decrease with increasing distance from the stream. In this paper we compare the results of treating roads under these two policies with those developed with two optimization models.

Optimization models to reduce impacts to streams and lakes have been used previously in agricultural settings. A genetic algorithm found a set of pollution reduction schemes for a 725 ha catchment that reduced sediment, nitrogen, phosphorus and organic carbon loads by about half as compared to original cropping practices (Srivastava *et al*., 2002). Veith *et al*. (2003) then adapted this genetic algorithm approach to model successive runs of reductions in sediment yield from croplands and pastures until acceptable pollutant loads and costs were met. A Dynamic Programming approach evaluated a range of agricultural management alternatives for reducing the sediment input into reservoirs (Bouzaher *et al*., 1990). Until recently, however, optimization strategies have not been applied to erosion control efforts in mountainous terrain. Tomberlin *et al*. (2002) used Stochastic Dynamic Programming to determine whether a single forest road in northern California should be left untreated, upgraded or removed, based on its erosion potential and maintenance costs. They weighed the relative costs of maintaining a road for many years against the costs of removing the road. Pilot studies using Dynamic Programming (Teasley, 2002) and Genetic Algorithms to evaluate road removal strategies (Eschenbach *et al*., 2005) provided the basis for the present analysis.

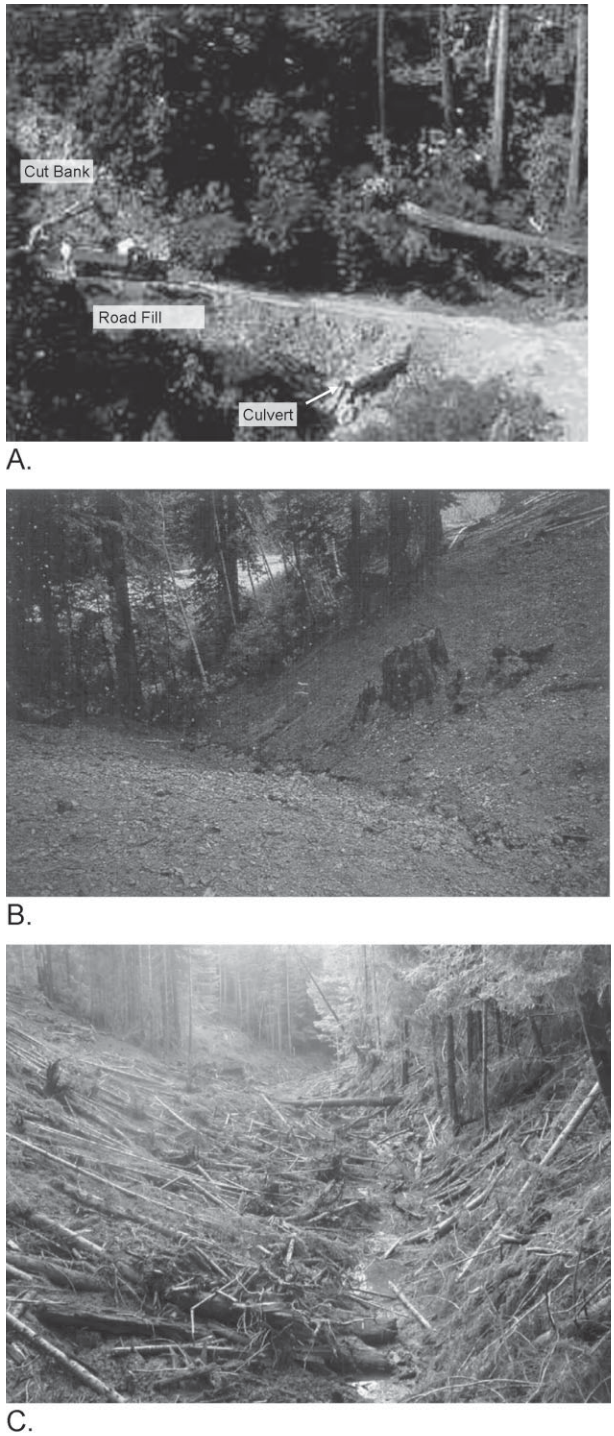

Figure 2. Three treatment options for road crossings. (A) No treatment: drainage structure and road fill remain in stream channel. (B) Basic excavation: culvert and road fill are excavated from stream channel. (C) Total excavation: culvert, road fill and excess sediment are excavated from stream channel and stream banks are reshaped extensively. In this example a mulch of wood and branches was applied on the newly excavated stream banks.

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Figure 3. Four treatment options for road segments. (A) No treatment: cutbank and fillslope remain intact and road surface is allowed to revegetate. (B) Rip and drain: road surface is decompacted and drains are constructed to convey flow across the road prism. (C) Partial outslope: some road fill is moved to the cutbank to form a gentle slope across the former road prism. (D) Total outslope: the road prism is reshaped to mimic the natural contours of the hillslope.

Methods

In order to assess various restoration strategies, certain data requirements must be fulfilled. First, existing threats to aquatic resources were inventoried through field inventories of untreated roads, in which the volume of road fill in crossings was surveyed and unstable fillslopes were identified (Redwood National and State Parks (RNSP), unpublished surveys). Road inventories are a common assessment tool used by land management agencies in the western United States (Weaver *et al*., 2005). Figure 4 shows the network of abandoned roads scheduled to be treated in the Lost Man Creek catchment which was used in this modelling effort. Secondly, an estimate of sediment savings from the various restoration techniques was needed. Erosion and sediment delivery from both untreated and treated roads in the Redwood Creek basin were assessed following a 12-year storm in 1997 by measuring the voids created by cutbank and road fill failures, gullies, channel incision and streambank erosion (Madej, 2001). We used that assessment to evaluate the effectiveness of various restoration techniques in terms of decreasing sediment loads. Effectiveness was a function of the geomorphic setting of the road. For example, higher sediment savings resulted from more intensive treatments on roads on steep lower hillslopes adjacent to perennial streams, but the more intensive treatments did not result in increased sediment savings from roads on gentler, upper hillslopes (Madej, 2001). Finally, it was necessary to know the costs to implement different restoration strategies. Costs of past restoration activities were available from RNSP records.

Based on these data sets, we developed two optimization models – dynamic programming (DP) and genetic algorithm (GA) – to determine a strategy that maximizes the sediment prevented from entering stream channels while maintaining a specified budget. Each model accepted road survey data from the RNSP's GIS layers for the pilot basin, Lost Man Creek, which had approximately 700 road segments and stream crossings. The output from the model was the treatment level for each road segment and crossing, and the total cost of the road removal management plan. The output was then imported to the GIS.

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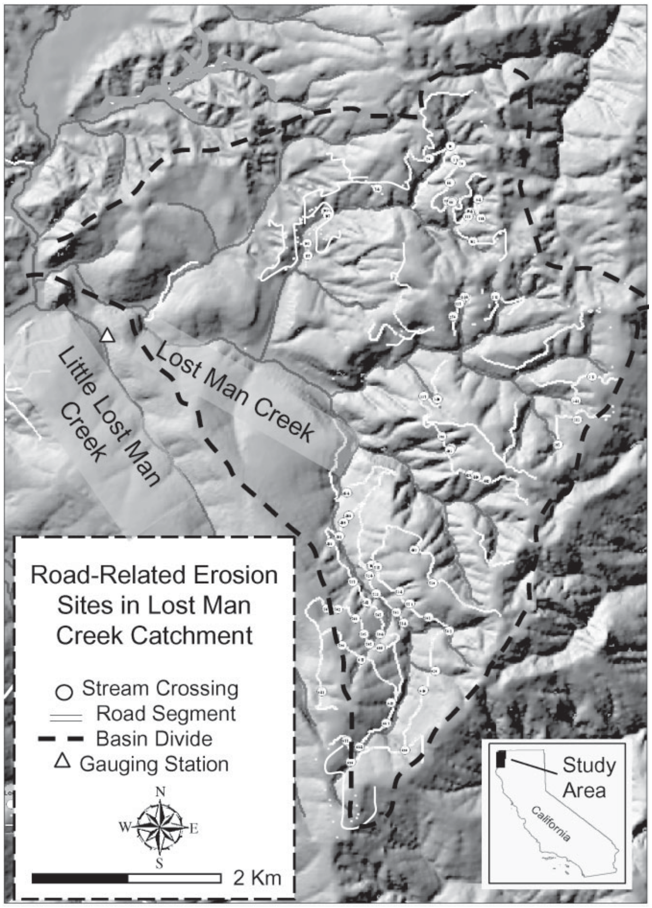

Figure 4. Shaded relief map of Lost Man Creek basin, a tributary of Redwood Creek, showing the network of untreated forest roads. (Long-term access roads not scheduled for treatment are not shown.) Circles represent road-stream crossing sites where culverts or other drainage structures convey runoff under the road prism. The volumes of road fill required to be excavated to remove the culvert and the road segments are included in the optimization models.

The problem is formulated with the objective: 'maximize the sediment saved from entering a stream channel as a function of the level of treatment selected for various road segments and stream crossings located in various hillslope positions'. The optimization problem is constrained by the budget and by the existing treatment methods. The problem is stated mathematically as:

$$\max_{\forall x_r, x_c} z = \left\{ \sum_{\forall r} W_r L_r S_r(x_r) + \sum_{\forall c} W_c V_c S_c(x_c) \right\}$$

subject to

$$TC = \sum_{\forall r} L_r C_r(x_r) + \sum_{\forall c} V_c C_c(x_c) \le B$$

where S_r = sediment saved/km on road segment r, S_c = sediment saved/m^3 on crossing c, x_r = treatment level for road segment r, x_c = treatment level for crossing c, L_r = length of road segment r (in km), V_c = volume of crossing c (in m^3), W_r = critical habitat weighting factor for road r, W_c = critical habitat weighting factor for crossing c, TC = total cost of all road segments and crossing treatments (in US\$), C_r = cost (in \$ km^{-1}) to treat road segment r, C_r = cost (in \$ m^{-3}) to treat crossing c, and B = budget (in \$).

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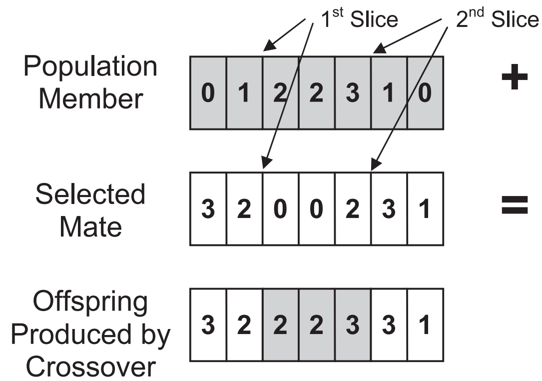

Figure 5. Example of crossover methodology used in genetic algorithms. In this example, each box represents a 'gene' which corresponds to a specific erosion control treatment for a road segment or a crossing. The string of genes, or 'chromosome', is the set of erosion control treatments for the pilot catchment. Through 'mating' the chromosomes can produce 'offspring' representing new sets of treatments, which can then be rated by the amount of sediment saved. The offspring are then evaluated in terms of 'fitness' (amount of sediment saved).

The formulation above allows for the weighting of sediment depending on its location or importance to habitat within the catchment via the weighting factors for roads and crossings: W_r and W_c.

Genetic Algorithms (Holland, 1992) are based on the mechanics of natural selection and genetics, where the most 'fit' of randomly generated solutions are allowed to 'mate' with the hope of creating more 'fit' solutions. Each solution is a 'chromosome' that is made up of a string of 'genes' where each gene carries an integer value that represents the level of treatment applied to a road or crossing. The 'fitness' of each chromosome (solution) is measured by the objective function. In this case, solutions that produce the most sediment savings are considered the most fit. Mating occurs via Selection, Crossover and Mutation to combine the more fit solutions into a new generation of solutions. In Selection, chromosomes with higher fitness have a higher probability of mating. In Crossover, each member's chromosome is sliced in two locations, and the centre pieces are swapped with each other (Figure 5). Mutation is the random alteration of genes in randomly selected chromosomes to diversify the population. Generations of chromosome populations are generated iteratively until a near-global optimum is achieved. In our problem we used the software program Generator to build and run the GA for about 20 000 generations. This software is easy to use and runs through an Excel interface.

The advantages of genetic algorithms are: (1) GAs are robust and can solve complex, non-linear problems that are not solvable by classic non-linear approaches; and (2) the method provides a diverse group of near-optimal solutions (Goldberg, 1989). This diverse set of solution can provide a land manager with a choice of near-optimal treatment schemes, to compare and contrast. In our own experience, we have found that this heuristic approach is intuitive to non–optimizaton experts, and thus more credible to land managers. Drawbacks of GAs are: (1) it is a heuristic method and one cannot prove the global optimal solution has been obtained; (2) convergence slows as the GA approaches the optimal solution; and (3) GAs require tuning and adjustment of parameters to reach a solution (Goldberg, 1989).

The dynamic programming (DP) approach (Bellman, 1957) separates the problem into a series of sub-problems using stages and states. Each stage has a number of states. The stages are each of the road segments and crossings. The states are the amount of remaining budget available to spend to treat that road segment or crossing. Once each sub-problem is solved, one can forward-simulate through all the solutions to determine the optimal treatment for each road segment and crossing that meets the specified budget.

Dynamic programming has the following formulation which is a resource allocation DP. Given the end condition, where $N = N_c + N_r$:

$$f_N(R_N) = \max_{x_N} \{W_N V_N S_N(x_N)\}$$

The recursive equation is solved for $n = N_c + N_r - 1, \ldots, 1$

For $n = N_c + N_r, \ldots, N_r + 1$, the recursive equation for crossings is:

$$f_n(R_n) = \max_{x_{lc}} \{W_n V_n S_n(x_n) + f_{n+1}(R_n - V_n C_n(x_n))\}$$

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For $n = N_r, \ldots, 1$, the recursive equation for roads is:

$$f_n(R_n) = \max_{x_{lc}} \{W_n L_n S_n(x_n) + f_{n+1}(R_n - L_n C_n(x_n))\}$$

Where $N = N_c + N_r$ = the total number of road segments and total number of crossings, R_n = the amount of remaining budget for treatment of road segment or crossing n, $C_n(x_n)$ = the cost to treat road segment or crossing n at treatment level x_n, $f_{n+1}(R_n - L_n C_n(x_n))$ = the maximum amount of sediment saved using the budget remaining after treating road segment or crossing n at treatment level x_n at cost C_n. Other variables are as previously defined.

$$TC = \sum_{n=N_r+1}^{N_r+N_c} V_n C_n(x_n) + \sum_{n=1}^{N_r} L_n C_n(x_n) \leq B$$

A strength of the DP approach is that a global optimum is guaranteed. A drawback of DP is the 'curse of dimensionality' where the computation requirements grow exponentially as the size of the problem increases. However, using a resource allocation formulation, the computational requirements grow linearly in the number of road segments and crossings considered.

The optimization algorithms were applied to a sample network of 50 km of roads in the Lost Man Creek catchment (Figure 4). We used a field-based road inventory to generate a GIS data base with 618 different road segments and 73 stream crossings. Given four possible road treatments and three possible crossing treatments, the total possible policies for this basin is $(4^{618}) \times (3^{73})$. This number of policies is much too large to examine individually. Optimization algorithms provide a rational method to consider such a large number of policies.

Results

Comparison of two optimization strategies at two budget levels

The two optimization strategies (DP and GA) were applied to the road network in the Lost Man Creek basin at budget levels that were not adequate to treat every existing problem. For perspective, if each site in this catchment were treated by the most intensive restoration techniques (using total excavation for all crossings and total outslope for all road segments) the cost would be about US$1 000 000 for a total sediment saving of 68 000 m^3. Because most land managers do not have unlimited budgets at their disposal, we instead tested the sediment savings strategies that were developed for budgets of US$250 000 and US$500 000. Table I summarizes the policies by reporting costs, sediment saved and an overall cost–benefit ratio. As described earlier, no global optimum is guaranteed with GAs while DP results reflect a global optimum. Nevertheless, Table I results demonstrate that the GA is obtaining a result that is close to optimal. Table I also shows that as the budget increases, the cost–benefit ratio also increases. In the case of the US$250 000 budget, the models chose to treat the highest erosion risks first. As the budget increased to US$500 000, sites that had lower erosion risks were also treated, which increased the cost–benefit ratio. Within a small area, treatments could be chosen based on only their cost–benefit ratio, but on a catchment scale, with thousands of treatment choices, the use of cost–benefit ratios becomes cumbersome.

Although the summaries of the DP and GA polices are similar, they reached their goal of maximizing sediment savings through slightly different strategies (Figure 6A and B). A comparison of the prescribed treatments for individual sites shows that both algorithms treated roads and crossings at higher levels as the budget increased, and both

Table I. Comparison of dynamic programming (DP) and genetic algorithm (GA) policies for US$250 000 and US$500 000 restoration budgets

Budget (US$)	Optimization method	Cost (US$)			Sediment Saved (m^3)			Cost/benefit ratio (US$ m^{-3})
		Roads	Crossings	Total	Roads	Crossings	Total	
250 000	DP	152 450	97 250	249 700	18 900	11 500	30 400	8·2
0	GA	153 800	96 200	250 000	18 000	11 100	29 100	8·6
500 000	DP	347 000	153 000	500 000	24 700	13 300	38 000	13·2
0	GA	346 800	153 200	500 000	24 600	13 000	37 600	13·3

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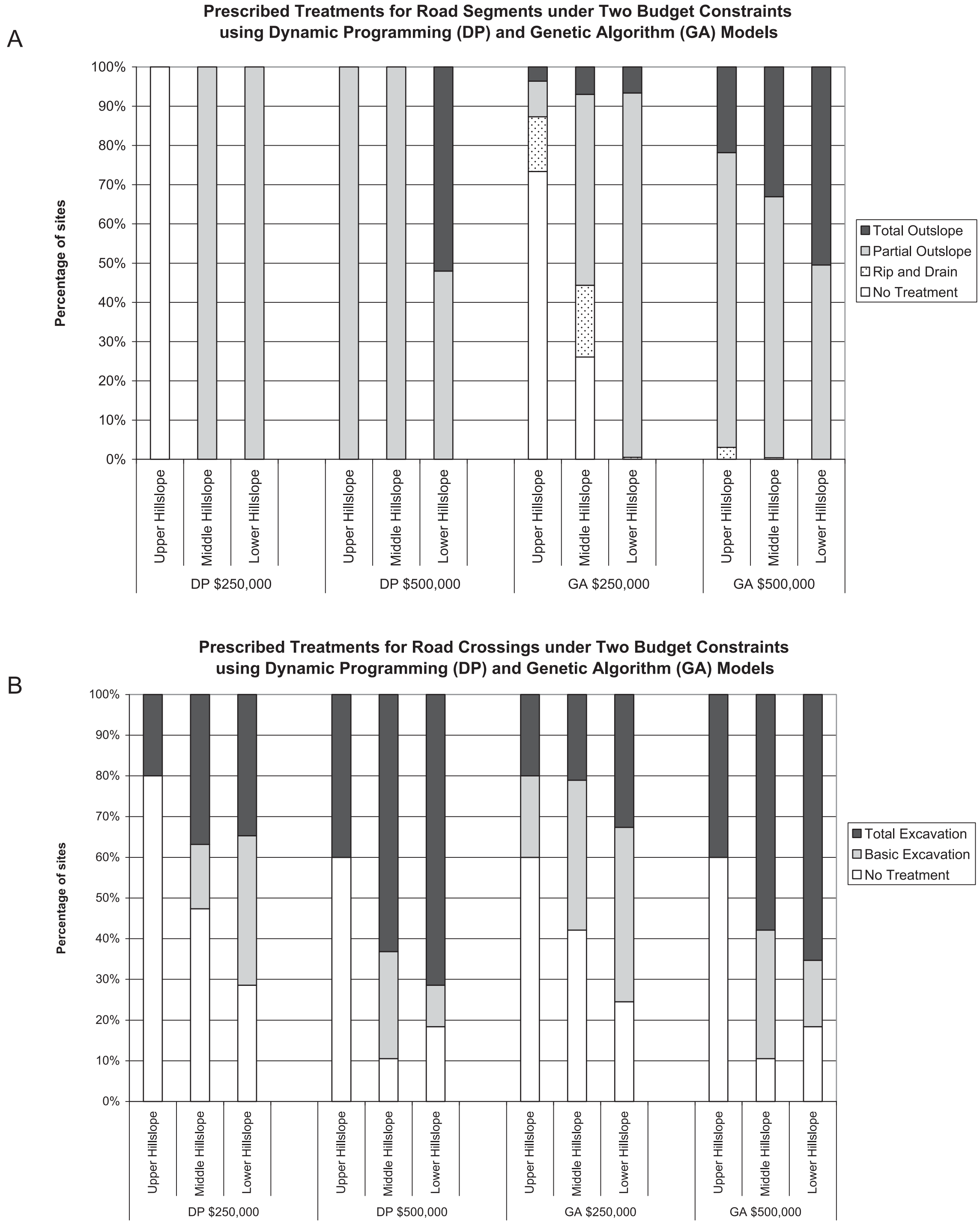

Figure 6. (A) Comparison of road segment treatments prescribed by dynamic programming and genetic algorithm policies for US$250 000 and US$500 000 restoration budgets. (B) Comparison of stream crossing treatments prescribed by dynamic programming and genetic algorithm policies for US$250 000 and US$500 000 restoration budgets. The darker the shading, the more intensive the treatment prescribed.

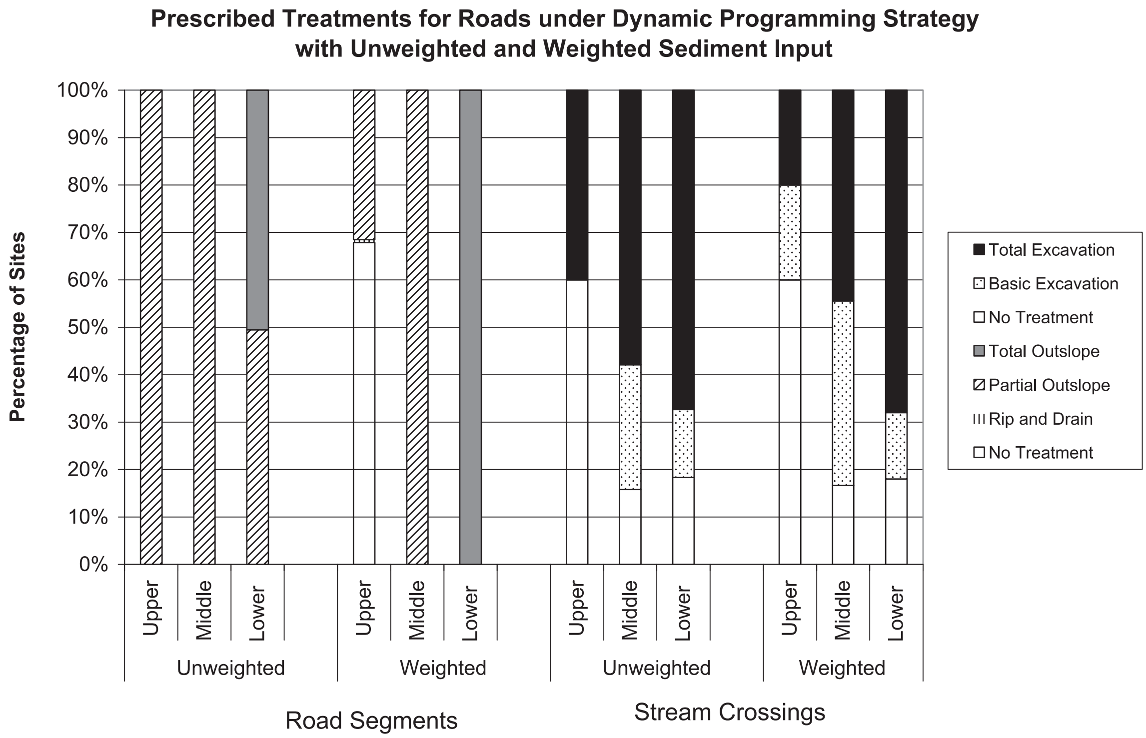

Figure 7. Comparison of road segment and crossing treatments prescribed by unweighted and weighted dynamic programming policies, given a US$500 000 restoration budget. Weights were based on distance to perennial streams. The darker the shading, the more intensive the treatment prescribed.

focused treatments on the steeper, lower hillslopes where erosion risks are usually highest. However, for crossing treatments, the DP prescribed 'total excavation' slightly more frequently as a technique for crossing removal, whereas the GA used a greater mix of crossing treatments. With a US$250 000 budget, the GA prescribed 'no treatment' or 'rip and drain' for many road segments located on gentle slopes far from the stream (upper and some middle hillslope sites), whereas the DP recommended at least partial outsloping on middle hillslope road segments. With a higher budget, both strategies prescribed partial and total outsloping on most road segments.

Incorporating a critical habitat weighting factor

The formulation of both the GA and DP strategies allows the incorporation of a weighting factor for ecological reasons. For example, erosion sites near critical fish-bearing stream reaches can be given a greater weight than potential erosion sites far from the stream. To test the effect of weights on optimization results, we applied three weights to road erosion sites, based on distance from the fish-bearing stream channel. Weights were arbitrarily assigned as '1' for lower hillslope roads near the river, '0·8' for mid-hillslope roads, and '0·5' for upper hillslope roads farthest from the river. When weights were added to the potential sediment input, the optimization results for DP with a US$500 000 budget shifted to prescribe much less treatment on upper hillslope road segments and somewhat less treatment on middle hillslope road segments (Figure 7). GA results are not plotted because they were similar to the DP, in that the focus shifted to treating lower hillslope road segments more intensely when weights were used. The cost of an increased level of treatment for lower hillslope road segments was offset by treating fewer upper hillslope stream crossings.

Comparison of optimization results with land management policies

Because the GA and DP policies resulted in about the same volume of sediment savings, the next set of comparisons uses only the DP strategy as the optimization choice. The DP results were compared with results obtained from applying two types of policies that are currently used on public lands. Table II provides a summary of the costs,

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Table II. Comparisons of strategies applying dynamic programming, uniform minimum, and maximum in-stream buffer policies

Policy	Cost (US$)			Sediment saved (m^3)			Cost/benefit ratio (US$ m^{-3})
	Roads	Crossings	Total	Roads	Crossings	Total	
Dynamic programming	236 500	106 500	343 000	22 200	11 700	33 900	10·1
Uniform minimum	178 200	165 000	343 200	11 600	11 400	23 000	14·9
Dynamic programming	152 500	81 100	233 600	18 900	10 500	29 400	7·9
Maximum in-stream buffer	163 800	69 800	233 600	10 800	5 400	16 200	14·4

sediment saved and overall cost–benefit ratio for the DP model, the uniform minimum treatment policy, and the maximum treatment in stream buffer policy. The first policy (uniform minimum treatment) treats all roads in the catchment at a minimal level. In this case all crossings in the Lost Man Creek basin would be treated by basic excavation and all road segments would be ripped and drained, for a total cost of $343 000. The DP strategy allocated the same amount of financial resources much more effectively than the minimum strategy in the Lost Man Creek Basin, in that it saved an additional 10 900 m^3 of sediment for the same expenditure, representing increased savings of almost 50 per cent (Table II). Another measure of the effectiveness of these policies is via a cost–benefit ratio, which shows that the DP approach is more cost-effective.

In general, the $343 000 DP strategy recommended full treatment of a cluster of lower hillslope crossings near high-order stream channels, and did not treat upper hillslope crossings. In terms of road segments, the DP policy recommended partial outsloping for 95 per cent of the road length, and no treatment for the remaining 5 per cent. This represents a higher level of treatment on middle and lower slope roads than the uniform minimum strategy, but no treatment on the upper slope roads. The increased cost associated with partial outsloping over a greater length of road is offset by the lack of excavation of upper hillslope stream crossings. Nevertheless, under the DP strategy, two of the crossings not recommended for treatment were located in headwater channels near settings that would be susceptible to debris torrents (steep, strongly convergent hollows). The optimization input files in the present model do not account for debris torrent risk, but could be modified to give more weight to those settings.

The second uniform policy used in the comparison (maximum treatment in stream buffers) treats roads near perennial streams at a maximum level, and leaves the remaining road network untreated. This method is commonly employed in nature reserves with critical aquatic habitat. In the test basin, applying this policy to all roads within 150 m of Lost Man Creek would cost US$233 600. In this case the US$233 600 DP strategy saved 13 400 m^3 more sediment than the maximum treatment in stream buffers strategy, which is an additional 80 per cent saving (Table II). The DP strategy accomplished the greater sediment savings by prescribing only partial outsloping of 61 per cent of the roads rather than total outsloping of all the roads, and consequently treated almost three times the length of roads (31 km versus 10·5 km) as the uniform policy. The maximum treatment in stream buffers strategy prescribed full excavations of 24 crossings, whereas the DP strategy used a combination of basic and full excavations of 43 crossings. Most of the additional crossings prescribed for treatment under DP were adjacent to the stream buffer on large tributaries. Although these additional crossing sites were not within the stream buffer zone, the sediment savings by treating these sites was substantial.

Comparison of optimization results with sediment production in the catchment

Since 1975, suspended sediment yield has been measured in an adjacent, geologically similar basin, Little Lost Man Creek (Figure 4). Little Lost Man Creek is a Research Natural Area with virtually no past logging or road construction activity, and so represents a baseline of sediment production in this area. Average annual suspended sediment yield in Little Lost Man Creek is 90 Mg km^{-2} a^{-1}. Applying this rate to the 25 km^2 Lost Man Creek basin results in a background yield of 2250 Mg a^{-1}. With allocated budgets of US$250 000 and US$500 000, the optimization strategies would save about 30 000 m^3 and 38 000 m^3 of sediment, respectively. These volumes represent sediment savings of 48 000 and 60 800 Mg (based on a bulk density of 1·6 g cm^{-3}). Because not all road segments and crossings would fail in a single year, these sediment savings must be considered over a longer timescale. It is likely that over a 20-year time span a large storm would occur and most of the identified erosion problems would contribute sediment to streams. If the erosion control techniques prescribed by the optimization models were implemented, an average of 2400 to 3040 Mg a^{-1} over a 20-year time period would be saved. Even at the US$250 000 budget, this sediment saving is greater than the background annual suspended sediment yield. For perspective, all roads in the

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basin could be removed for US$1 000 000 for a sediment savings of 68 000 m^3. The results from the optimization models show that even at one-quarter of the optimal budget, significant reduction of sediment delivery to streams can be accomplished.

Discussion and Conclusions

Unpaved forest roads commonly cause erosion, which can result in downstream sedimentation and damage to aquatic habitat in streams. Rather than installing in-stream sediment traps or other structures to control sedimentation, RNSP is approaching stream restoration by ameliorating the original hillslope disturbance through the removal of roads. Although road removal activities have been conducted on many roads in the western United States, these activities have usually been implemented and evaluated on a site-specific basis without the benefit of a catchment perspective. We used optimization algorithms to develop the most cost-effective strategy for sediment reduction on a basin scale based on field inventories of past erosion and future threats from roads. This approach can be adapted as more data on erosion rates and restoration effectiveness become available.

Both dynamic programming and genetic algorithms produced rational strategies in maximizing sediment savings to streams while under budget constraints, which resulted in similar sediment savings and costs. Both models performed better than either a policy of minimal erosion control treatments applied uniformly across the landscape, or a policy of maximum treatment on roads near streams. The models can be extended to include other considerations; for example, by weighting locations that are susceptible to debris torrents or adjacent to critical habitat, by modelling changes in runoff pathways on forest road networks (Croke *et al*., 2005) or by incorporating the uncertainty of the effectiveness of road treatments through stochastic dynamic programming (Baker *et al*., 2004).

An advantage of using GA is that it provides a set of solutions that are all satisfactory and are close to optimal. Having a choice of effective solutions allows land managers to accommodate other needs besides sediment savings. For example, some high risk roads may be left untreated to retain access for transportation, forest management, recreation, fire control or monitoring. In other cases, a low risk road may still be chosen for treatment in order to restrict access to an area, to train restorationists, to test techniques or to improve the aesthetics of a high- visitor- use area. In a catchment of mixed land ownership and varied landowner response to the concept of road removal, a strategy to treat roads through a range of options is desirable. The GA provides the flexibility of still efficiently reducing sediment input on a catchment scale while having a choice of roads to treat at various levels. In addition, because the 'mating' concept underlying genetic algorithms is relatively simple to explain to land managers, many managers are more willing to apply it to their problems than more complex programmes.

Although these models were applied to a specific problem of road-related erosion in a catchment, the approach is not limited to road removal. Optimization models could be adapted to other types of restoration programmes in which managers need to choose among numerous actions. Erosion control efforts in catchments with a range of land-use practices across various terrains can be modelled. Catchment-level management of sediment can be facilitated through the use of optimization algorithms. Both dynamic programming and genetic algorithms, when used within a geographic information system framework, can characterize the performances of various erosion control policies in a spatially explicit manner, and as such represent a useful tool for catchment planning, management and implementation of best management practices. The optimization models are also valuable in testing conceptual changes to erosion control policies, and so can help focus research efforts in applied geomorphology. For example, the models could test the change in allocations across a catchment if the effectiveness of a specific treatment could be improved for a known cost. The utility of the models depends on the strength of the geomorphic input data, and illustrates the importance of involvement of geomorphologists in land-use planning.

Several questions remain. In this paper, the effectiveness of restoration work was based on past assessments of post-treatment erosion following a 12-year storm. Longer-term effectiveness is presently unquantified because the road treatments have not been subjected to a larger stressing event. The effectiveness of restoration was defined simply in terms of sediment savings, following the re-establishment of a geomorphic form (reshaping a road bench or excavating a stream channel); however, the functions of these restoration sites have not been monitored. The small, steep streams in forested terrain affected by these restoration strategies are closely linked with the hillslopes, and function as both sources of sediment and conduits of water, sediment, nutrients and large wood. Consequently, sediment production, storage and routing through these restored channels need to be assessed. The optimization algorithms can help design an effective sediment reduction strategy, but it is still unclear to what degree sediment input needs to be reduced in order to successfully restore the biological function of the streams. Certainly, long-term monitoring of the consequences of restoration actions will help address such questions, and should be incorporated into any restoration strategy.

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