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FOREST ROAD EROSION CONTROL USING MULTIOBJECTIVE OPTIMIZATION[1]

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ABSTRACT: Forest roads are associated with accelerated erosion and can be a major source of sediment delivery to streams, which can degrade aquatic habitat. Controlling road-related erosion therefore remains an important issue for forest stewardship. Managers are faced with the task to develop efficient road management strategies to achieve conflicting environmental and economic goals. This manuscript uses mathematical programming techniques to identify the efficient frontier between sediment reduction and treatment costs. Information on the nature of the tradeoffs between conflicting objectives can give the decision maker more insight into the problem, and help in reaching a suitable compromise solution. This approach avoids difficulties associated with *a priori* establishment of targets for sediment reduction, preferences between competing objectives, and mechanisms to scale noncommensurate objectives. Computational results demonstrate the utility of this multiobjective optimization approach, which should facilitate tradeoff analysis and ideally promote efficient erosion control on forest roads.

(KEY TERMS: sediment; water policy; optimization; nonpoint source pollution; point source pollution.)

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INTRODUCTION

Forest roads are associated with accelerated erosion and can be a major source of sediment delivery to streams, which can degrade aquatic habitat (Forman and Alexander, 1998; Jones *et al.*, 2000; Lugo and Gucinski, 2000). Although landslides and other mass movements are responsible for the majority of road-related erosion in areas with steep slopes, surface erosion can be a significant source of road-related sediment input to streams (Gucinski *et al.*, 2001). Timber hauling during the wet season can be the most significant source of fine sediment associated with forest practices (Oregon Department of Forestry, 2003). Fine sediment can originate from the road surface itself due to the breakdown of the aggregate over time from crushing under heavy tire loading, weathering, and the introduction of finer material from the road subgrade as surface aggregate are forced downward by heavy traffic. Sediment production is related to many road design elements, including segment length and gradient (Luce and Black, 1999), aggregate quality (Foltz and Truebe,

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2003), and aggregate depth (Bilby *et al.*, 1989). Management activities such as maintenance and especially log truck traffic also influence sediment production (Reid and Dunne, 1984; Bilby *et al.*, 1989; Luce and Black, 2001).

The presence of a forest road can substantially alter natural hillslope hydrologic and geomorphic processes. Forest roads intercept rainfall and subsurface flow, concentrate flow on the surface or adjacent ditches, and divert or reroute water from natural flow paths (Gucinski *et al.*, 2001). They also accelerate chronic and episodic erosion processes, alter channel structure and geometry, alter surface flow paths, and cause interactions of water, sediment, and woody debris at engineered stream crossings (Gucinski *et al.*, 2001). Road surface shapes are therefore designed to "encourage shedding of water from the surface before it gains enough concentration and velocity to cause unacceptable surface erosion" (Moll *et al.*, 1997, p. 1). Likewise, road drainage systems are designed to move water away from the road surface as quickly as possible, ideally to the forest floor where the water can disperse and infiltrate into the soil. Unfortunately, in some circumstances, poorly designed and/or maintained drainage systems deposit sediment directly into streams at road-stream crossings. Road removal is generally thought the most effective way to reduce long-term environmental impact (Switalski *et al.*, 2004), but comes with the potential opportunity cost of lost access for fire management, commodity production, or other activities (Anderson *et al.*, 2006).

In the United States (U.S.), roads in the national forest system are chronically under-maintained, with a backlog of necessary improvement and removal needs (USDA Forest Service, 2002; Sample *et al.*, 2007). The Aquatic Conservation Strategy of the Northwest Forest Plan cites prevention of road-related runoff and sediment production as one of the most important components of a watershed restoration program (USDA Forest Service and USDOI Bureau of Land Management, 1994; Reeves *et al.*, 2006). Watersheds that have seen the most improvement to date had relatively extensive road removal programs (Gallo *et al.*, 2005), and a majority of the funding to date has been allocated for road-related treatments (Heller, 2002). Roni *et al.* (2002) recommended managers focus on road decommissioning and maintenance, among other treatments, to restore hydrologic and geologic processes. Thus, erosion control on forest roads is crucial to an effective watershed restoration strategy.

Beyond efforts to improve aquatic habitat on federally owned land, the Clean Water Act (CWA) provides a strong motivation to pursue effective erosion control methodologies. Road-related sediment is recognized as a contributing source of pollution for many rivers and streams listed as water quality limited under the CWA (e.g., Environmental Protection Agency, Impaired Waters and Total Maximum Daily Loads: Examples of Approved Sediment TMDLs, http://www.epa.gov/owow/tmdl/examples/sediment.html). Further, contemporary court precedent relating to the CWA suggests that forest road management may be subject to additional regulations under the National Pollutant Discharge Elimination System (NPDES) permitting requirements (Boston and Thompson, 2009). NPDES standards would effectively require landowners to reduce pollution (sediment delivery) to the point where the marginal benefits per dollar spent begin to markedly decline (Thompson, 2009). That is, the NPDES presents a statutory requirement to perform a cost/benefit tradeoff analysis in order to establish pollution control standards.

In this manuscript, we advocate adoption of tradeoff analysis for facilitating forest road erosion control planning. Irrespective of whether forest roads are subject to CWA NPDES requirements, tradeoff analysis is attractive because it can help decision makers achieve desired environmental and economic results in the most efficient manner. Specifically, we propose multiobjective optimization techniques based on the concept of technical efficiency. This paradigm is suitable for environmental decision-making contexts, facilitates tradeoff analysis, and can lead to informed compromise (Kennedy *et al.*, 2008). In the following sections, we will review existing planning techniques for road erosion control and the more general case of water pollution control, present the multiobjective erosion control model formulation, briefly discuss available solution techniques, then demonstrate the utility of approaching erosion control through the lens of technical efficiency with results from an example, and lastly offer concluding thoughts.

DECISION SUPPORT FOR FOREST ROAD EROSION CONTROL

Controlling road-related erosion to minimize sediment delivery and degradation of aquatic habitat remains an important issue for forest stewardship. Managers are faced with the task to develop efficient road management strategies to achieve conflicting ecological and economic goals. Identification of an appropriate suite of road management treatments can be difficult. Blanket prescription of best management practices can prove ineffective and economically infeasible (Barrett and Conroy, 2002); in general, it is not an efficient approach to apply treatments to problem areas independently of their impact on overall cost-effectiveness (Weaver and Hagans, 1999). At the watershed scale the pool of possible road treatment combinations is frequently too large for explicit consideration, necessitating some mechanism to facilitate generation and evaluation of alternatives. Appropriate decision support tools can and have been used to help managers plan cost-effective erosion control treatments.

Weaver and Hagans (1999, p. 236) present a five-step process for forest road erosion prevention and control: (1) problem identification (through inventory and assessment); (2) problem quantification (determination of future yield in the absence of treatment); (3) prescription development (both heavy equipment and labor-intensive); (4) cost-effectiveness evaluation and prioritization of treatment sites; and (5) implementation. In this manuscript, we target Step 4, cost-effectiveness evaluation and prioritization of treatment sites. The aim is to develop computer-based decision support methods that better integrate environmental objectives into forest transportation planning.

To prioritize treatments, and to assess how well environmental objectives are met as a result of treatment, environmental performance measures for forest roads are required (Mills, 2006). The next step is the generation of a predictive or "forward looking" sediment inventory in terms of the chosen environmental performance measure, in order to be able to prioritize alternate road treatments on the basis of cost/benefit. The California North Coast Regional Water Quality Board has codified this best management practice into their General Waste Discharge Requirement program, requiring forestland owners to develop and implement Erosion Control Plans to "prevent and minimize the discharge of sediment" prior to initiating timber harvest (Robert Klamt, North Coast Regional Water Quality Control Board, 2007, personal communication). Erosion Control Plans must contain an inventory identifying potential discharge sources, their locations, and estimated sediment volume, as well as a description and timeline of prevention and minimization measures that will be used.

Having then defined the problem and developed estimates for the cost/benefit of various treatment alternatives, the transportation manager can begin to prioritize treatments. Prioritization requires the balancing of multiple, conflicting objectives. As stated earlier, in such planning environments decision support tools have proven helpful.

Despite the presence of conflicting objectives, however, most applications of decision support for erosion control have considered a decision-making environment with a single objective. A common approach assumes the decision maker manages to minimize treatment costs (e.g., Thompson and Tomberlin, 2005; Rackley and Chung, 2008). In some applications, additional environmental objectives are modeled as side constraints under an economic objective (e.g., Bettinger *et al.*, 1998; Akay and Sessions, 2005; Contreras and Chung, 2006; Aruga *et al.*, 2007). Alternatively, the decision maker can seek to optimize an environmental objective, subject to budgetary constraints and other resource limitations (e.g., Eschenbach *et al.*, 2005; Madej *et al.*, 2006; Thompson and Sessions, 2008).

As an alternative to modeling objectives as constraints, multiple objectives can be condensed into a single objective function (e.g., Srivastava *et al.*, 2002; Veith *et al.*, 2003; Coulter *et al.*, 2006). Goal programming and weighting objectives are two common methods of creating single objective functions. Goal programming requires identification of target environmental performance levels. Both techniques require an appropriate mechanism to scale noncommensurate objectives (e.g., $ and kg sediment), as well as *a priori* elicitation of preferences between objectives.

MULTIOBJECTIVE OPTIMIZATION AND TRADEOFF ANALYSIS: A NEW PARADIGM FOR FOREST ROAD EROSION CONTROL

Arguably, the aforementioned decision support approaches are unsuitable for road erosion control under conflicting economic and environmental objectives. Kennedy *et al.* (2008) referred to the notion of identifying a singularly "optimal" solution to such problems as a "fallacy of the weighted sum approach," because preferences can change, and because no single answer simultaneously optimizes all objectives. Further, identification of appropriate sediment reduction goals is not a trivial task. As with other environmental management contexts, such as managing for wildlife habitat objectives, *a priori* establishment of target values is a difficult, uncertain exercise. Contreras and Chung (2006) set as an upper bound the estimated sediment delivery associated with the minimal cost solution found absent sediment constraints, then arbitrarily reduced that amount by 17%. Bettinger *et al.* (1998), to the contrary, established sediment production goals from estimates of impacts from the previous 10 years of harvest activity within the study watershed. Notably, the authors acknowledged the inherent difficulty and ambiguity in establishing such a goal. Rackley and Chung (2008) avoided the difficulties associated with identifying target sediment production levels by instead assigning a dollar value to sediment, but noted the challenge of selecting an appropriate environmental cost factor.

Here we assume instead the decision maker explicitly wants to understand the tradeoffs prior to rendering an opinion on how to allocate weights between objectives, on how to scale noncommensurate objectives, or on what environmental targets/goals should be. More specifically, we want to understand the relationship between increasing road treatment costs and decreasing sediment delivery to streams, and in so doing identify a tradeoff curve comprised of technically efficient solutions. A solution is considered efficient when it is not possible to improve one objective (e.g., reduce cost) without degrading another objective (e.g., increase sediment delivery). Efficient solutions are also referred to as "nondominated" or "noninferior." The set of all efficient solutions is called the efficient frontier.

Figure 1 displays an example of an efficient frontier for a two objective cost-minimization, environmental benefit-maximization planning problem, such as that the transportation manager faces. The ideal solution incurs maximal benefit at minimal cost, but is infeasible. Efficient solutions lie along the boundary of the infeasible region; feasible solutions below this tradeoff curve are inefficient (or inferior, or dominated). Where along the efficient frontier the "best" solution lies is dependent upon the relative preferences of the decision maker(s). For an industrial ownership, keeping costs low might be relatively more important, in which case the preferred alternative may lie in the lower left region of Figure 1. An ownership more focused on improving watershed health may prefer instead a solution in the upper right

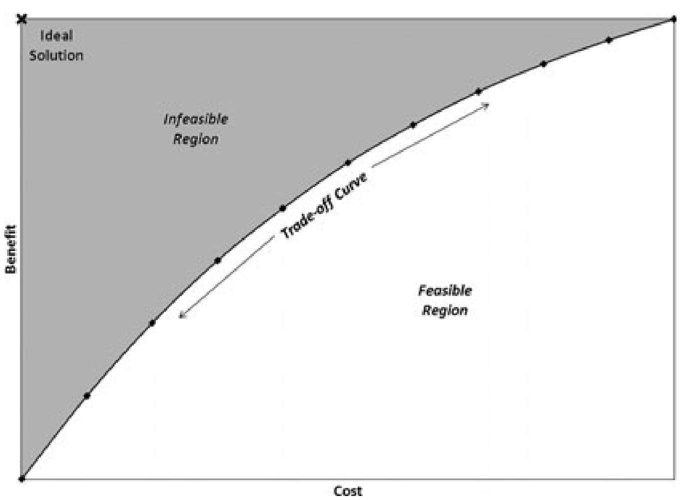

FIGURE 1. Stylized Example of a Minimize-Cost, Maximize-Benefit Efficient Frontier. The ideal (min cost, max benefit) solution is located in the upper left-hand corner of the infeasible region. Feasible solutions below the tradeoff curve are referred to as inefficient, dominated, or inferior. In the context of our application, the transportation manager aims to minimize treatment cost and maximize environmental benefit (as measured by reduction in sediment delivery). Identifying this curve will help the decision maker to examine the tradeoffs in objective space between alternative courses of action.

region, with higher cost but higher associated environmental benefit as well. If the landowner is subject to regulations, such as the NPDES permitting system referenced above, the question might be less about satisfying preferences and more about satisfying the intent and language of the CWA.

Information on the nature of the tradeoffs between conflicting objectives can give the decision maker more insight into the problem, and help in reaching a suitable compromise solution (Toth *et al.*, 2006). This process represents *a posteriori* preference articulation, where the decision maker selects from a set of nondominated solutions (Hwang and Masud, 1979). Ultimately the final solution results from both optimization, used to identify the efficient frontier, and some decision process, used to select a preferred alternative (Van Veldhuizen and Lamont, 2000). If the decision maker has difficulty in articulating preferences and identifying a superior alternative, multicriteria decision analysis (MCDA) can help by providing systematic methodologies for the elicitation of preferences (de Steigeur *et al.*, 2003). Readers wishing for more information regarding the use of MCDA in forest planning are referred to excellent reviews: Mendoza and Martins (2006) and Kangas and Kangas (2005). Our focus in this manuscript is on the optimization component and generation of the efficient frontier.

We now expand from the stylized example in Figure 1 in order to demonstrate multiobjective optimization in the context of forest road erosion control. Consider a forest landowner with three roads requiring treatment. Four treatments are available per road, amounting to 43 = 64 total treatment combinations. The landowner has a predictive inventory for road-related sediment production with and without treatment. Benefit is calculated as the sediment saved from entering the stream compared to the baseline, no-treatment scenario. Cost and efficacy of treatment vary by road segment, as can be seen in Table 1.

Figure 2 displays the efficient frontier for this example scenario. In total 12 efficient solutions were identified, with the other 52 solutions in some way dominated. There are three noteworthy aspects to Figure 2. First, the efficient frontier curve is not convex. Second, beyond a certain point additional expenditures on erosion control clearly have decreasing marginal sediment reduction benefit. Third, in a single objective, cost-minimization framework, the selection of a target constraint level for sediment production could bias the ultimate decision, possibly resulting in an undesirable allocation of resources. For instance, it may be that bolstering sediment reduction from 100 to 500 kg is worth the marginal expenditure, a possibility that would not have been explored absent a tradeoff analysis.

TABLE 1. Example Inventory of Sediment Reduction and Treatment Cost.

Treatment	Sediment Reduction (kg)/Cost of Treatment (US$)		
	Road 1	Road 2	Road 3
A (no treatment)	0/0	0/0	0/0
B	161/600	127/600	497/600
C	60/638	84/425	308/552
D	157/940	151/898	526/855

Notes: This table constitutes a predictive sediment inventory used as an input for the multiobjective optimization process. In the absence of such estimates, prioritizing alternative treatments on the basis of cost/benefit is not possible. Examination of these values indicates, for instance, that Treatment B is clearly preferable to Treatment C for Road 1.

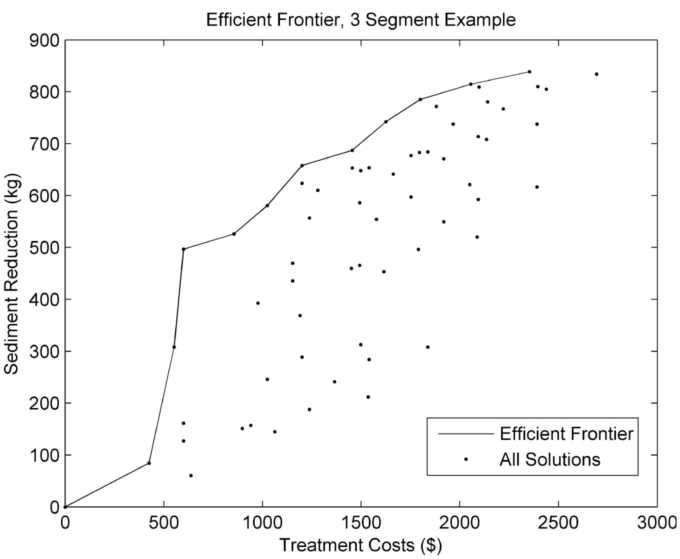

FIGURE 2. Efficient Frontier, 3-Segment Example. A total of 64 solutions are displayed, 52 of which are inferior with respect to the 12 efficient solutions. There are three illustrative points to be made from this figure: (1) the efficient frontier is not convex; (2) declining marginal benefit associated with increased expenditures; and (3) establishing a sediment constraint in a cost-minimization framework without first examining this tradeoff curve could lead to an undesirable, although efficient, allocation of resources (consider for instance the environmental benefit to be gained from a marginal increase in treatment cost from just below US$500 to just above US$500).

PROBLEM FORMULATION

In this section, we present the mathematical formulation of our multiobjective erosion control planning problem. First we define the problem parameters:

I set of road segments, indexed by i;

J_i set of road treatments available to road segment i, indexed by j, including "no treatment";

$C(i, j)$ cost of implementing treatment j on road segment i ($);

$S(i, j)$ sediment reduction achievable by implementing treatment j on road segment i (kg);

The decision variables of this problem are defined as:

$X(i, j)$ binary variable indicating whether road segment i receives treatment j.

The objective function and constraints can now be defined as:

$$\min \quad Z_c = \sum_{i \in I} \sum_{j \in J_i} C(i,j) \times X(i,j) \tag{1}$$

$$\max \quad Z_s = \sum_{i \in I} \sum_{j \in J_i} S(i,j) \times X(i,j) \tag{2}$$

Subject to:

$$\sum_{j \in J_i} X(i,j) = 1 \qquad \text{for all } i \in I \tag{3}$$

$$X(i,j) \in \{0,1\} \qquad \text{for all } i \in I,\ j \in J_i \tag{4}$$

Equation (1) presents the cost minimization objective, Z_c, as the summation, over all road segments and associated available treatments, of the cost of selected treatments. Equation (2) similarly presents the sediment reduction maximization objective, Z_s, as the summation of the sediment reduction benefits of selected treatments. Equation (3) ensures that each road segment is assigned exactly one treatment, and Equation (4) requires that each decision variable remain binary.

Consider again our three-segment example road network (Table 1). For Road Segment 2 the costs for treatments A, B, C, and D are US$0, US$600, US$425, and US$898, respectively. Likewise expected sediment reduction benefits for Treatments A-D are 0, 127, 84, and 151 kg, respectively. Assume for the moment that Treatment B is selected [i.e., X(2,A) = 0, X(2,B) = 1, X(2,C) = 0, X(2,D) = 0; note the vector sums to 1], the cost would be US$600 and the sediment reduction benefit 127 kg. Given this information, the solution technique seeks to generate a set of alternate treatment combinations that are efficient with respect to the competing objectives.

Approaches to identify the efficient frontier vary. One common approach is to assign a weight to each objective in order to create a singular objective function, as described above, and then iterate over all possible combinations of weights (e.g., Stückelberger *et al.*, 2006; Qi *et al.*, 2008). Unfortunately iterating over objective weight combinations is only guaranteed to find all efficient solutions if the frontier is convex. In this planning context the frontier is not convex due to the presence of binary decision variables, as we demonstrated in the example above.

Another common approach is the epsilon-constraint method, wherein an algorithm iteratively optimizes for a single objective while updating constraint levels representing other objectives (e.g., Connaughton and Fight, 1984; Richards and Gunn, 2000; Calkin *et al.*, 2002; Nalle *et al.*, 2004). Initially two boundary solutions are obtained, corresponding to solutions optimizing each objective (treatment cost and sediment reduction) without constraints on the other objective. The algorithm then progressively proceeds from one end of the frontier to the other. For our implementation we adopted a modified version of the epsilon-constraint method, described in Toth *et al.* (2006).

Whether the specific algorithm iterates over objective weights or constraint levels, a solution technique is required to generate solutions to the single-objective problems. Depending upon problem size and complexity, exact methods can be used (e.g., Toth *et al.*, 2006; Toth and McDill, 2008), but use of heuristics is probably more common (e.g., Calkin *et al.*, 2002; Nalle *et al.*, 2004; Stückelberger *et al.*, 2006; Qi *et al.*, 2008). In fact, with some heuristic implementations it is unnecessary to iteratively solve for a single objective. Population-based methods, by generating a suite of possible solutions, allow for the approximation of the efficient frontier in a single run of the algorithm. In particular, multiobjective evolutionary algorithms (MOEA) have become a popular tool for solving multiobjective forest planning problems (e.g., Ducheyne *et al.*, 2004, 2006; Kennedy *et al.*, 2008).

EXAMPLE APPLICATION

We now present a hypothetical example of moderate complexity to demonstrate identification of the efficient frontier. We use road data collected from road segments in the Caspar Creek watershed of the Jackson State Demonstration Forest (Figure 3) in northern California (Ish and Tomberlin, 2007). Specifically we use data on road segment length, width, and gradient from 47 hydrologically connected road segments, and from this dataset we abstract to a hypothetical road network, overlaying additional information such as surfacing and expected traffic. Of

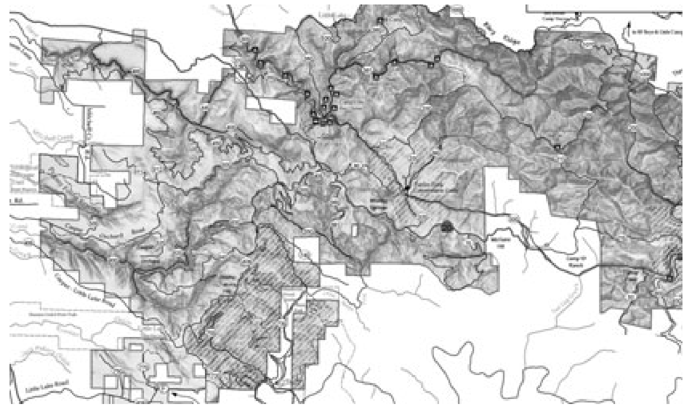

FIGURE 3. Road Network of Jackson Demonstration State Forest. Ish and Tomberlin (2007) collected data on road segments in the Caspar Creek watershed, located in the lower left-hand corner of this image. Image obtained from http://www.fire.ca.gov/resource_mgt/downloads/jd_brochure_detail2.pdf (last *accessed* April 6, 2010).

the 47 road segments, 21 are modeled as having a sandy loam surface and 26 as having an aggregate (marginal quality) surface; all segments have a vegetated ditch. Table 2 summarizes the road segment information by gradient, length, surfacing, traffic, and available treatments (described in more detail below).

For the purposes of this illustration, we opted to use the Watershed Erosion Prediction Project (WEPP) model. Previous applications of WEPP to predict erosion from forest roads include Rackley and Chung (2008), Ish and Tomberlin (2007), Brooks *et al.* (2006), Contreras and Chung (2006), Thompson and Tomberlin (2005), and Elliot and Tysdal (1999). Specifically, we used the WEPP:Road (USDA Forest Service WEPP Interfaces; http://forest.moscowfsl.wsu.edu/fswepp/) web interface to estimate sediment delivery. WEPP:Road is an extension of the WEPP model developed to predict erosion for forest road settings.

Watershed Erosion Prediction Project simulates the daily climactic conditions using a stochastic climate simulator, and ultimately calculates erosion and deposition rates for a representative hillslope. Annual sediment yields are calculated from these daily estimates (Elliot *et al.*, 1999). We selected the Fort Bragg, California climate data for the WEPP weather simulator. Erosion processes are modeled to occur along a hillslope that is defined by a series of overland flow elements (OFE). An OFE is a unique combination of soil, slope, and vegetation. In WEPP:Road, three OFEs are used: the road, fillslope, and forest buffer. Four soil textures are available: clay loam, silt loam, sandy loam, and loam. Four road designs are available: in-sloped rocked or vegetated ditch, in-sloped bare ditch, out-sloped un-rutted, and

TABLE 2. Road Segment Information, 47-Segment Example.

Segment	Gradient (%)	Length (m)	Effective Length (m)
Native Surface, Low Traffic, Available Treatments: All			
1	2	100	65
2	2	44	15
3	4	72	35
4	8	138	84
5	0	23	9
Native Surface, High Traffic, Available Treatments: N, C, MA, HA, CMA, CHA			
6	6	115	52
7	2	28	13
8	4	65	34
9	3	69	29
10	3	79	42
11	2	171	66
12	2	147	49
13	4	70	47
14	1	50	17
15	7	145	83
16	6	96	64
17	0	16	6
18	7	214	148
19	4	187	121
20	4	75	36
21	2	91	46
Aggregate Surface, High Traffic, Available Treatments: N, C			
22	3	169	104
23	5	119	77
24	1	58	26
25	2	47	18
26	5	140	61
27	4	145	68
28	2	112	41
29	4	105	58
30	3	112	38
31	4	146	56
32	1	147	86
33	0	79	40
34	3	89	33
35	3	90	63
36	4	220	109
37	2	120	36
38	1	39	19
39	4	147	62
40	2	159	97
41	1	70	47
42	2	68	43
43	3	84	31
44	6	68	23
45	6	105	32
46	2	32	12
47	7	109	50

Notes: Segment gradient, length, and effective length are provided, arranged by road surfacing, expected traffic levels, and the corresponding available treatments. Possible treatments displayed include: no treatment (N), install cross drain (C), apply marginal quality aggregate (MA), apply high-quality aggregate (HA), install drain and apply marginal aggregate (CMA), and install drain and apply high-quality aggregate (CHA).

out-sloped rutted. The user is responsible for specifying road segment length, road width, and steepness of road and buffer.

We consider three treatments that reflect a directed effort to control primary factors thought to influence sediment generation and delivery. Treatment 1 is to install additional cross-drain culverts in order to reduce effective road segment length. Effective lengths after culvert installation vary by segment, with length reductions ranging from 30 to 70% of the initial segment length. Treatment 2 upgrades the road surface from native soil to aggregate. We assume the manager has access to sources of both marginal and high-quality aggregate for use in improving native-surfaced roads. Higher-quality aggregate, although significantly more expensive, can also significantly reduce sediment production. Foltz and Truebe (2003) reported that marginal aggregate produced ~3 times the sediment produced by high-quality aggregate. Here, we conservatively estimate that higher-quality aggregate produces 50% less sediment. Simulations from WEPP:Road with gravel (aggregate) were assumed to represent the marginal quality scenario. Lastly, the third treatment is decommissioning. Only those segments servicing low levels of traffic may be decommissioned, and the expectation is that all chronic sedimentation and delivery will cease. Native-surfaced roads servicing high levels of timber haul traffic in the next planning period are not eligible for decommissioning, but can have cross-drains installed and rock applied, as well as combinations thereof. For the aggregate-surfaced segments the only available improvement is to install cross-drain culverts.

Cost estimates for the treatments were obtained from Weaver and Hagans (2010). Installing ditch relief culverts cost US$600 each. Purchase and application of marginal quality aggregate was estimated to be US$9.84 per linear meter (US$3/ft), with costs rising to US$13.94 per linear meter (US$4.25/ft) for higher-quality aggregate. Decommissioning costs were estimated as US$13.12 per linear meter (US$4/ft).

Unlike the earlier simple example, here the cardinality of the solution space is far too large for enumeration. However, with only 136 binary decision variables, the problem is not too large as to be prohibitive for mixed integer programming. We therefore opted to employ the modified epsilon-constraining method, with δ set to 0.05 kg of sediment. Arguably this value could have been set much higher to a more reasonable unit of management for sediment control, but since our problem was sufficiently small we opted to pursue an accurate approximation of the frontier. The algorithm was coded using GAMS v22.7 (GAMS Development Corporation, Washington, D.C.), and used the CPLEX solver.

The mixed-integer algorithm identified a total of 635 nondominated efficient solutions. The last nondominated solution was identified after just under 5 min of computing time. For larger or more constrained problems, however, solution times may be much greater. Compared to the time and effort spent inventorying roads and modeling sediment delivery, the time spent identifying the efficient frontier may actually be quite small. If the decision maker wishes to perform a great deal of sensitivity analysis, however, having a technique capable of generating solutions more quickly might be preferred. Thus, for much larger planning problems heuristics may be more suitable. At a minimum, the exact approaches used here could be used to validate a combinatorial heuristic approach.

Figure 4 displays the calculated efficient frontier for erosion control on the 47 segment example road network. Note the decreasing marginal benefit (in terms of sediment reduction) associated with increased treatment costs. To illustrate the cost/benefit tradeoffs, we consider Efficient Solutions (EFS) 176 and 635, with objective function values of (Z_c = US\$14,560, Z_s = 26,086 kg) and (Z_c = US\$45,000, Z_s = 32,591 kg), respectively. By opting for EFS 176 a landowner could achieve 80% of the estimated total sediment reduction of EFS 635 at only 32% of the cost of EFS 635. The former solution appears to be a preferable outcome to a blanket prescription of treatments resulting in significantly greater costs with only marginal benefits.

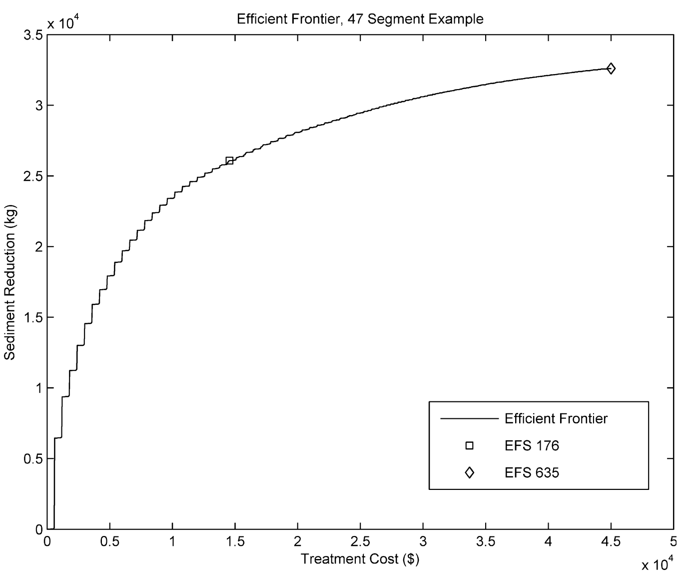

FIGURE 4. Efficient Frontier, 47-Segment Example. This figure again demonstrates the decreasing marginal benefit (in terms of sediment reduction) associated with increased treatment costs. Efficient Solution (EFS) 176 achieves 80% of the estimated total sediment reduction at only 32% of the cost of EFS 635, the latter corresponding effectively to a blanket assignment of the most costly treatments.

DISCUSSION

Our results demonstrate that identification of the efficient frontier is an important tool for selecting appropriate environmental performance measures for forest road management. This type of tradeoff analysis facilitates cost-effective erosion control, helping decision makers identify a reasonable relationship between treatment cost and sediment reduction. We propose an *a posteriori* approach, wherein optimization techniques are used to demonstrate to decision makers the realm of possible efficient solutions. Decision makers then, based upon their preferences, select from this set of noninferior solutions. This approach avoids difficulties associated with requiring decision makers to assign weights to various, noncommensurate objectives prior to examining the tradeoff surface. Further, it lessens the likelihood that weights could be manipulated in order to achieve a desired outcome without justification relative to possible superior alternatives.

It is important to emphasize that the techniques introduced in this manuscript are intended to be used as decision support tools, not decision-making tools. The onus lies with the transportation manager to arrive at defensible road erosion control strategies. As Allison *et al.* (2004, p. 184) states, "the systematic consideration of each road section together with its alternative restoration treatments reflects an appropriate diligence in generating a ranking of restoration choices." By carefully examining the results of multiobjective optimization and exploring the inherent tradeoffs between reducing costs and improving environmental performance, the transportation manager can better arrive at a compromise solution that best satisfies conflicting objectives.

The intent of this manuscript is to demonstrate the utility of multiobjective programming and tradeoff analysis for erosion control planning, and so we did not describe in great detail the relative treatment breakdown of any particular solution or set of solutions. We could have employed MCDA techniques to identify a nominally preferred efficient solution, but our scope of inference would be limited. Firstly because of the specifics of the case study as we implemented it (road network characteristics, etc.), and secondly due to other limitations described below. We anticipate that our proposed methods will be useful if practitioners adopt tradeoff analysis for forest road erosion control.

We made several simplifying assumptions for illustrative purposes. In particular we limited our choice of management treatments and used an off-the-shelf erosion model with little site-specific information. Generation of predictive inventories that estimate erosion levels under alternate treatments, necessary for the type of analysis promoted here, has many challenges. Various approaches include, like ours, the use of existing predictive models (e.g., Brooks *et al.*, 2006; Rackley and Chung, 2008), or proprietary erosion models (e.g., Bolstad and Peterson, 2005), field-based estimates (e.g., Madej *et al.*, 2006), risk assessments (e.g., Rice and Lewis, 1991), and environmental rating scores used as a proxy (e.g., Dai *et al.*, 2004).

One problem with existing erosion prediction models such as WEPP is that much of the variation is explained by contributing drainage area and road gradient, and not the hillslope hydrology. That is, models based largely upon road geometry may not fully account for other processes known to influence erosion, such as interception of subsurface flow. Surfleet (2008) demonstrated, however, that pairing field data with road erosion models improved watershed scale estimates of road sediment delivery. Further, he demonstrated that road runoff observations could be used to accurately estimate road sediment production at the catchment and road scale.

To prioritize spending, having information on the sedimentation potential and likely efficacy of treatment at the segment scale is therefore very important. Chronic sediment often comes from a minority of road segments, which cannot be identified *a priori* (Skaugset *et al.*, 2007). Inspection and monitoring can therefore be useful by allowing managers to "buy" information today in order to cost-effectively avoid sediment in the future. Here, forest engineers can play an important role through careful design of monitoring programs to link data collection, analysis and reporting to management objectives, and to incorporate new knowledge into future design (Pyles, 2005). Monitoring and evaluation allow for improvements in understanding and planning, and learning should therefore be an active component of resource management (Olson and Orr, 1999).

The transportation manager therefore faces the challenges of how to allocate scarce resources between erosion monitoring and control efforts and how to amend management strategies given new information. With new information on expected erosion from segments before and after treatment(s), a new efficient frontier can be generated and a new suite of road management actions identified. Innovative decision support tools may be necessary to help managers evaluate these difficult decisions. Partially observable Markov decision processes are one proposed tool for identifying conditions under which immediate expenditures on erosion control are less costly than the cost of monitoring and follow-up (Tomberlin and Ish, 2007). Bayesian inference and decision theory may be another promising approach for updating our beliefs as monitoring generates new information (e.g., Dorazio and Johnson, 2003).

Future research could seek to apply the methods presented here across a larger ownership, or to include a broader scope of possible treatments. For instance, researchers could include as decision variables maintenance regimes, traffic levels, seasonal road closure, and reduced tire inflation. Many of these practices are designed to limit rut formation, which can be a primary driver of road surface erosion (Burroughs and King, 1989). Excessive rut depth jeopardizes the road structure and can interfere with normal function of the road's designed drainage system. Concentration of water in the wheel rut increases runoff length and water velocity, with the potential to detach and transport additional particles. It may be possible to leverage previous decision support relating to rut formation with the techniques described in this paper. Thompson *et al.* (2007), for instance, developed a combinatorial heuristic to route a maintenance vehicle across a network to smooth road surfaces, and this work was furthered in Thompson (2009) with the application of multiobjective optimization to simultaneously minimize rut depth and maintenance and vehicle operations costs.

Also important to include in the tradeoff analysis are the opportunity costs of such management actions. Toman *et al.* (2007) for example demonstrated that the opportunity costs associated with restricting wet weather timber haul and harvest could be up to 18% of total net revenue. Work pairing tradeoff analysis with adaptive management paradigms would also be a promising direction. For instance, it may be possible to incorporate model uncertainty into our multiobjective programming approach, perhaps through robust optimization or other techniques. Alternatively, it may be possible to develop approaches that identify not only optimal allocations of resources between monitoring and treatment, but what types of monitoring and treatment to apply.

CONCLUDING REMARKS

Controlling road-related erosion to protect water quality is a widely occurring problem, and forest managers across the globe could benefit from more efficient and effective erosion control measures. The authors are most familiar with the legal and regulatory situation in the U.S., and therefore used this context to motivate additional research into efficient erosion control planning.

We presented an application of decision support applied to forest road management, wherein we used the principles of forest and industrial engineering to identify efficient road management alternatives. Specifically we proposed the use of multiobjective programming techniques to identify the efficient frontier between sediment reduction and management costs. In natural resources management, road management in particular, incorporation of competing objectives is common and therefore having a tool to facilitate tradeoff analysis should prove useful. Ultimately, the tradeoff-analysis techniques promoted here should facilitate improved and efficient forest road management, and contribute to enhanced watershed health.

Advancements in computing capacity and in algorithmic development increasingly make solving more complex problems, such as those with multiple objectives, possible. We therefore expect that techniques to identify efficient frontiers will become preferable to traditional methods that seek to condense multiple objectives into a single objective function. It is our hope that this manuscript demonstrating the utility of technical efficiency for erosion control will spur future research into efficient multiobjective road management.

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