Equivalent Roaded Area as a Measure of Cumulative Effect of Logging

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ABSTRACT / A watershed disturbance index developed by the USDA Forest Service called equivalent roaded area (ERA) was used to assess the cumulative effect from forest management in California's Sierra Nevada and Klamath mountain ranges. The basins' ERA index increased as logging and road-building occurred and then decreased over time as management ceased and vegetation recovered. A refinement of the standard index emphasized disturbances in sensitive, near-channel areas, and evaluated recovery periods of 20, 30, and 50 years. Shorter recovery periods yielded better correlations between recovering forest systems and aquatic response than the longer recovery period, as represented by ERA and diversity or dominance, respectively. The refined ERA index correlated more closely with macroinvertebrate dominance and diversity information that was available for part of the study period. A minimum ERA threshold of 5% was detected, below which no effect to the macroinvertebrate community was observed. Above this threshold, elevated ERA values were associated with a decline in macroinvertebrate diversity and an increase in dominance of the top five taxa. Use of an ERA technique that emphasizes near-channel areas and biological thresholds would contribute to the Forest Service's implementation of ecosystem management.

In forested watersheds, excessive management may lead to disturbance adjacent to the stream channel and may raise water temperature, decrease slope stability, and increase the potential for erosion. As a result, prediction of land-use impacts on fisheries is important because fisheries are a major beneficial use of many stream systems in the western United States (Geppert and others 1984).

The need to evaluate and predict the effects of forest management activities has increased as competition for use of the limited resource base has increased. Most cumulative effects techniques evaluate disturbed area, potential for sediment yield, water quality, or changes in probable peak flow (Harr 1982, Dickert and Olshansky 1986, Haskins 1987, Weaver and others 1987, Johnston and others 1988). Although these methods are excellent approaches for assessing the physical and chemical impacts of cumulative land-use activities in watersheds, less work has been done to implement biotic assessments of management practices. Salo and Cederholm (1981) examined the cumulative effects of two different anthropogenic stresses superimposed on the natural mortality of a hypothetical coho population that might result in extinction. Furthermore, Geppert and others (1984) identified several aquatic habitat modifications caused by forest practices that could change rates of fish growth, survival, abundance, and species composition.

Aquatic insects are important indicators of aquatic ecosystem health (Rosenberg and others 1986). Because invertebrates are also a primary food source for fish, insect abundance is generally linked to productive fisheries (Plafkin and others 1989). Although fish and invertebrate populations vary dramatically due to climate, fires, and other factors unrelated to management, benthic macroinvertebrate communities better reflect management impacts on the aquatic system than most other biological measures considered for routine monitoring (Plafkin and others 1989). Their sedentary life-styles and relatively fast rate of reproduction make them useful indicators of local environmental changes. The effect of disturbances on macroinvertebrates is dependent on the magnitude and scale of the disturbance, and disturbance scales range from areas less than a few hectares (logging, mass wasting) up to whole basins (wildfire) (Richards and Minshall 1992). Macroinvertebrate indices such as

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abundance, dominance, and diversity vary from minor, short-term changes in response to small-basin logging, to decade-long shifts and extinctions because of wildfire or chemical spills. Diversity has been shown to decline after logging that caused disturbance in the near-stream area, and then approach predisturbance levels over times ranging from 7 to 11 years (Newbold and others 1980; Erman and Mahoney 1983; Roby and Azuma 1995).

Biotic assessments are useful indicators of current conditions, but unlike land-disturbance methods, they cannot be done in retrospect. Disturbance measures can be based on historical land-use changes, but the significance and veracity of the results are difficult to assess in most cases.

This paper reports on a study that uses the results of a long-term biotic assessment in California to evaluate a land disturbance methodology and suggest improvements to that methodology.

Equivalent Roaded Area: A Cumulative Effects Methodology

The USDA Forest Service (FS) has played an active role in developing and implementing a cumulative effects assessment methodology for public forest lands in California. Public concern, the National Environmental Policy Act of 1969, and the National Forest Management Act of 1976 demand that FS land managers assess current conditions and predict the effects of management alternatives on the terrestrial and aquatic ecosystems. Additionally, implementation of Section 208 of the Clean Water Act (as amended) caused the FS in California, in conjunction with other agencies, to develop best management practices for water quality management planning (USDA Forest Service 1988). Numerous lawsuits have alleged the FS's failure to consider various aspects of cumulative watershed effects (CWE), underscoring the need to fully incorporate an analysis of CWE in all resource planning.

Although controversy continues regarding the nature and definition of CWE, most authors agree that a basin's harvest history should be documented, and that effects are cumulative if they occur within a certain time period (Klock 1985). In addition to logging, forest fires, grazing, mining, recreation, and other activities affect watersheds and associated streams. The combined effects of the full range of land-use activities should be considered when any individual activity's effects are evaluated.

The Pacific Southwest Region of the FS developed a generalized framework to examine CWE in a small- or moderate-sized basin by: (1) identifying the beneficial uses of the stream and the water, (2) examining the factors influencing the beneficial uses, and (3) assessing the effects of multiple management actions on beneficial uses (Seidelman 1981; USDA Forest Service 1988). This disturbance index method was designed to satisfy the National Environmental Policy Act of 1969 through its consideration of past, present, and anticipated management activities. A land-use history is developed that details the date, area, type of logging and yarding, and miles of various types of roads for both public and private lands in the basin. The method standardizes past and planned disturbance activities (clear-cuts, selective cuts, prescribed burns, wildfires, etc.) in terms of equivalent roaded area or equivalent road acres (ERA) through the use of disturbance coefficients (Haskins 1987). For example, the coefficient for a light selective cut with tractor yarding counts half as much per acre as a clear-cut with tractor yarding. Clear-cuts that have had several decades to recover are discounted compared to recent cuts, and the disturbance areas in the basin are summed and divided by the total basin area to yield the basin ERA. By converting all typical activities to an ERA index, disturbances throughout the basin are incorporated. Although the ERA methodology was developed in California, the technique could be applied to other regions or disturbance regimes by modifying the coefficients to reflect local practices.

Basin disturbance indices such as the ERA method can be used to achieve dispersion of practices over space and time. Based on indices, logging would be spread across the forest rather than concentrated within a basin, or a clear-cut might be delayed until recently cut areas recover. Thresholds can be selected that correspond with the onset of detectable change, with the onset of undesirable change, or with the onset of damage levels thought to be irreversible. In watershed management, for example, 15–20% of the timber in a watershed must be cut within a decade before a measurable change in runoff volume will occur (Bosch and Hewlett 1982). Conversely, extreme disruption from logging, fire, or other disturbances may reduce the species diversity and carrying capacity of the aquatic ecosystem (Geppert and others 1984). To avoid undesirable change, a threshold of concern is selected based on an historical analysis of similar watersheds. If the ERA exceeds the threshold, the district ranger may call for on-site investigations and may then either delay the planned harvest or specify extra mitigation to avoid creating off-site effects.

The current ERA methodology is far from perfect. To reflect watershed disturbance accurately, disturbance coefficients need to be determined for land management activities such as grazing, mining, and recreational developments. Distinct thresholds of concern also are needed for diverse geographic regions and beneficial uses. Validation is difficult because of the multiresource, long-term data that are required. Climatic variability, particularly in the arid West, may mask the linkage between upland activities and stream ecosystem response. For example, periods of drought (such as occurred in California between 1987 and 1992) delay the transport of sediment through the system. Conversely, infrequent high flows from heavy rains on the snowpack can cause major changes in the fluvial and biotic systems that may or may not be affected by past management. The ERA methodology has been implemented by the FS in California, but further evaluation is needed.

Research History and Site Description

The macroinvertebrate and recovery results in this study are derived from long-term work directed by Erman (Erman and others 1977, Erman and Mahoney 1983, Fong 1991). He and students from the University of California at Berkeley (UCB) showed that macroinvertebrate communities in several geographically distinct, northern California streams responded to localized logging-related disturbances (Erman and others 1977; Newbold and others 1980). Later studies directed by Erman followed the recovery of these communities after the initial disturbance (Erman and Mahoney 1983; O'Connor 1986; Fong 1991). These studies partitioned watersheds into blocks, and a subset of three blocks from the UCB studies was used in our analysis of the ERA index (Figure 1). The New York, Taylor, and Bit blocks have treatment watersheds with different amounts of logging-related disturbances and control drainages with minimal logging activities and roads. The treatment watersheds experienced timber removal within the streamside riparian zone during the early 1970s. Most controls had no logging activities next to the stream channel. If some harvest did occur, it was not close to the macroinvertebrate sampling sites.

Located primarily on national forest lands, the UCB study sites were first- and second-order streams draining midelevation watersheds ranging from 61 to 828 ha (Table 1). The New York block drains into the North Yuba River, the Taylor block drains into the North Fork Feather River, and the Bit block drains into the Klamath River. The predominant vegetation in the watersheds included Douglas fir (*Pseudotsuga menziesii*), true fir (*Abies* spp.), and mixed conifers

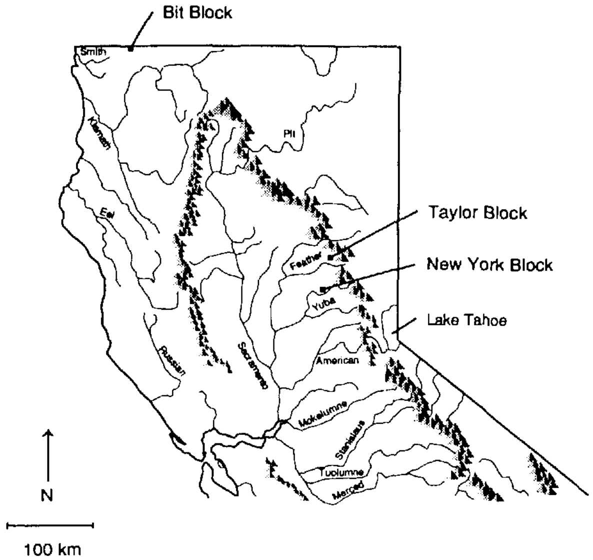

Figure 1. Study site locations in northern California, USA.

(*Calocedrus decurrens*, *Pinus* spp., and *Abies* spp.). Hardwood trees and deciduous shrubs (*Acer* spp., *Alnus* spp., *Quercus* spp., and *Salix* spp.) occur frequently within the riparian corridors.

Methods

Equivalent Roaded Area

The methodology for calculating ERA has been described in detail by Seidelman (1981), Haskins (1987), and the USDA Forest Service (1988). Aerial photography has been the primary source of historical disturbance and condition information in cumulative impact studies (Dickert and Tuttle 1985; Grant 1988; Johnston and others 1988). Since the 1940s, most national forests have aerial photography of their lands at 5- to 15-year intervals. This photographic record remains the best (and often only) source of information over time concerning land use, soil disturbance, mass wasting, and vegetation cover (Dickert and Tuttle 1985).

Photographic coverage of the Bit and Taylor blocks was acquired for the period from the mid-1940s to the mid-1980s. Coverage of the New York block was unavailable before the mid-1960s. Photo scale ranged from 1:12,000 to 1:24,000. The earliest photos were used to approximate the ages of roads and timber harvests. The last 20 years of the photo record were combined with available timber sales records from FS district offices to develop a sequential land-use history. A zoom transfer scope was used to

Table 1. Range of characteristics for stream reaches in Taylor, New York, and Bit blocks of northern California[a]

Blocks	Subwatershed area (ha)	Reach elevation (m)	Mean annual precip. (cm)[b]	Geologic type[c]
Taylor	113-828	1700–1930	100	gr
New York	92-531	1030–1330	159	lp, gr
Bit	61-218	1145–1380	141	m, g

[a]Sources: Erman and others (1977), Erman and Mahoney (1983), and Fong (1991).
[b]NOAA (1989).
[c]lp = Paleozoic marine, m = pre-Cenozoic metamorphic, g = granitics, gr = Mesozoic granitics.

correct for geographic displacement and tilt as the photo information was transferred onto Mylar at a common scale. The information was entered into a geographic information system to analyze the temporal and spatial trends. A map of the Taylor block is included as an example (Figure 2).

Land-use information was transformed into percent ERA values following a procedure developed by Haskins (1987). The terms used in the procedure are defined as:

- Harvest unit ERA (area) = recovery factor × disturbance factor × area
- Road ERA (area) = road length × average width
- Total ERA (area) = sum of harvest unit and road ERAs
- Percent ERA = (total ERA/watershed area) × 100

Harvest units. Each harvest unit was classified according to harvest and timber removal methods. Harvest methods included clear-cut, light selection, and heavy selection. Removal methods included tractor, cable, and skyline techniques. The severity of selective harvests was classified by using an estimate of percent of the area covered by skid trails (5%–40%) and an estimate of percentage of trees removed. The area of each harvest unit was determined by the geographic information system or a planimeter.

Recovery factor. Barring additional disturbances, bare lands revegetate with grasses, shrubs, herbs, and trees. Rooting by herbaceous and woody plants stabilizes streambanks, retards erosion, and shapes bank morphology (Swanson and others 1982). As revegetation progresses, flow peaks and volumes have been shown to return to preharvest conditions in about 30 years (Swanson and Hillman 1977). Except for roads, ERAs for disturbed areas are therefore discounted based on an assumed 30-year linear recovery rate (USDA Forest Service 1988). In addition, 20- and 50-year recovery periods were tested. The recovery factor for any time after a harvest is:

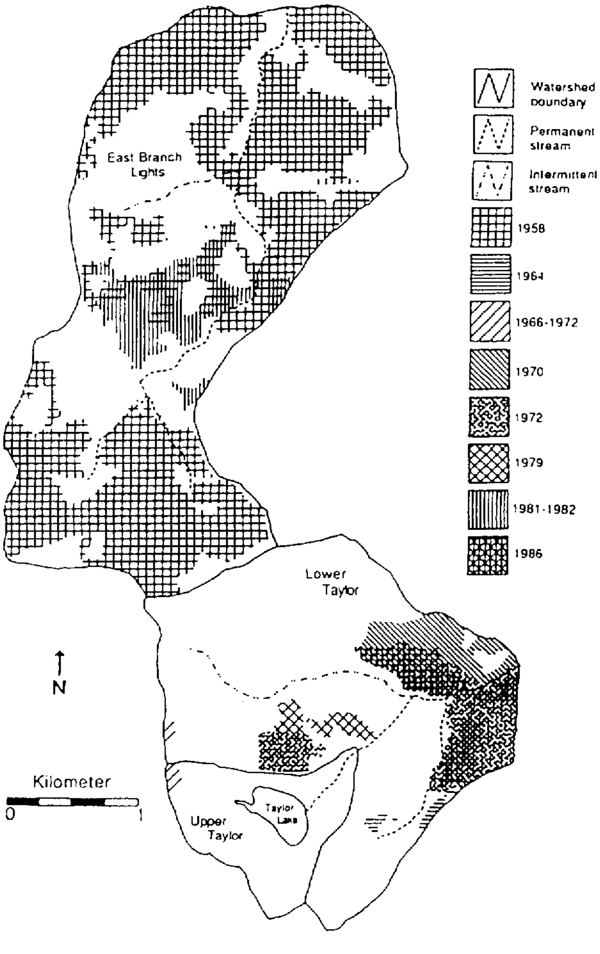

Figure 2. The extent and date of historic logging activities since the 1940s in watersheds of the Taylor block.

Recovery factor = (analysis date − harvest date)/recovery period
or = 1 if harvest is over 30 years old

Table 2. Disturbance coefficients used to relate timber harvest practices to effects of road building[a]

Management activity	Disturbance coefficient
Road, cut, and fill	1.00
Tractor clearcut	0.2–0.3
Tractor light selective	0.1–0.15
Tractor heavy selective	0.2–0.3
Cable clearcut	0.15–0.2
Cable light selective	0.1

[a]Source: Haskins (1987), and USDA Forest Service (1988).

For example, a clear-cut that occurred this year has a recovery factor of zero, and the entire area is added to the basin's disturbance tally. If the clear-cut occurred 20 years ago and the recovery period is 30 years, then the cut is 67% recovered and only 33% of the original area is added to the tally. Although this procedure may be debatable in terms of movement of soil particles or nutrient releases, it is reasonable in terms of hydrologic factors such as peak flow and annual runoff volume.

In the case of the pre-1960 harvests, exact harvest dates were often unknown, so harvest dates were estimated as the midpoint year between two photographic dates. If the earliest photo showed a harvest, that photographic date became the year of harvest regardless of when it may have occurred.

We adopted a conservative approach by assuming roads would not recover. It is recognized that although roads produce sediment both immediately after they are constructed (McCashion and Rice 1983) and again after five to seven years when tree roots rot (Ziemer 1981), unused roads may not be major contributors of sediment a decade after construction. However, compacted road surfaces increase runoff and increase the risk of mass wasting. Culvert washouts also may occur at any time if they are undersized, unmaintained, or if large rain-on-snow storms occur.

Disturbance factor. The FS has established a range of disturbance factors or coefficients for various harvesting methods (USDA Forest Service 1988). The magnitude of these coefficients reflects the severity of land disturbance resulting from different practices (Table 2). Hence, tractor clear-cutting is assigned the highest coefficient after roads.

Roads. A road was defined as any constructed passage that can be used by a logging truck or passenger vehicle. This definition excluded skid trails and paths, but various sizes of roads were encountered. A width of 12 m was the dividing point in the classification of roads into narrow and wide classes. Cut and fill slopes visible on aerial photographs and in on-site inspections were included in the measurement of road width.

ERA modifications. The standard ERA method used by the FS in northern California does not include the location of roads and harvest units relative to streams and other sensitive landforms. Although the method recognizes the inherent sensitivity of active and dormant landslides, valley inner gorges, riparian areas, land slopes greater than 80%, and very highly erodible soils, these factors are not included in the determination of disturbance coefficients (USDA Forest Service 1988). In recognition of the role that sensitive lands play in CWE (Geppert and others 1984), we modified the standard FS method to focus on a 100-m streamside impact zone (SIZ) on each side of the channel. The SIZ typically includes many of the sensitive features listed above. The stream network was based on information from US Geologic Survey 7.5° topographic maps, supplemented by field observations. In essence, this modification makes the SIZ area the watershed area. Roads and harvests within each SIZ were estimated as per the FS methodology to produce an ERA for each SIZ. As with the standard ERA analysis, we computed ERA values for recovery periods of 20, 30, and 50 years.

Macroinvertebrate Analysis

Using Spearman rank correlation, diversity and dominance data for the three or four sample periods and all treated watersheds in Erman's 20-year UCB studies were compared to the time-series ERA indices for matching years and watersheds. The intent of the correlation was to determine if the pattern of the ERAs corresponded with the pattern shown by the macroinvertebrate communities over time and across all treated catchments. Erman's studies noted that Shannon diversity and taxa dominance were reflective of habitat changes that were related to management effects (Erman and others 1977; Erman and Mahoney 1983). Shannon diversity is defined as:

$$H = -\Sigma [p_i \times (\ln p_i)]$$

where p_i is the proportional abundance of the ith taxa (n_i/N), n_i is the individual abundance, and N is the total abundance (Magurran 1988). Relative dominance was estimated by two techniques: (1) the most abundant taxa; and (2) the five most abundant taxa per stream reach.

Table 3. Roaded area for watershed or streamside impact zone (SIZ), photograph date, watershed areas (entire basin and SIZ), control (C), and treatment (T) for Taylor, New York, and Bit blocks

Photo date	Roaded area in basin	SIZ area	Roaded area in basin	SIZ area	Roaded area in basin	SIZ area	Roaded area in basin	SIZ area	Roaded area in basin	SIZ
	Lower Taylor (T) (601 ha/116 ha)		Upper Taylor (C) (113 ha/11 ha)		E. Branch Lights (C) (828 ha/132 ha)					
1941	3.0	0.5	1.2	0.3	0.8	0.0				
1953	3.0	0.5	1.2	0.3	2.0	0.2				
1966	3.0	0.5	1.2	0.3	25.4	5.6				
1972	10.4	3.2	1.2	0.3	25.6	5.3				
1977	10.4	3.2	1.2	0.3	25.1	5.3				
1982	10.4	3.2	1.2	0.3	24.5	6.3				
1987	10.4	3.2	1.2	0.3	23.6	6.3				
	Mid. New York (T) (466 ha/124 ha)		New York Trib. (T) (92 ha/24 ha)		Upper New York (C) (347 ha/89 ha)		Empire (C) (532 ha/127 ha)			
1972	5.6	0.3	0.2	0.0	5.4	0.3	3.0	0.6		
1977	7.9	0.7	0.5	0.2	6.7	0.1	3.0	0.6		
1982	8.0	0.7	0.8	0.8	6.5	0.2	3.0	0.6		
1987	11.1	1.5	2.5	0.5	7.9	0.3	3.0	0.6		
	Lower Four Bit (T) (101 ha/21 ha)		Lower Two Bit (T) (120 ha/38 ha)		Upper Four Bit (C) (86 ha/15 ha)		Upper Two Bit (C) (61 ha/18 ha)		E. Fork Indian (C) (87 ha/15 ha)	
1944	0.8	0.0	1.7	0.5	0.8	0.0	1.2	0.0	1.1	0.0
1955	0.5	0.0	1.7	0.5	0.5	0.0	1.2	0.0	1.1	0.0
1964	3.7	1.0	3.5	1.3	2.9	0.3	1.2	0.0	1.7	0.0
1971	5.8	1.0	4.0	1.3	3.3	0.3	1.5	0.0	2.0	0.0
1975	5.8	1.0	4.0	1.3	3.3	0.3	1.5	0.0	2.0	0.0
1980	6.3	1.0	4.0	1.3	3.9	0.3	1.5	0.0	4.9	0.0
1986	6.3	1.0	4.0	1.3	3.9	0.3	1.5	0.0	4.9	0.0

Results and Discussion

Equivalent Road Area Trends

All study watersheds had either roads or logging activities throughout the length of the photographic period (Table 3). Some watersheds, such as Upper Taylor, had constant, nonzero ERA values that persisted throughout the photo record, which indicated the presence of roads but not harvests (e.g., Upper Taylor in Figure 3). In the mid-1950s, ERA values rose from near zero on the Taylor and Bit basins, reflecting significant logging activity in these areas (Figures 3 and 4). Major increases in harvesting and road building occurred in the 1960s in some control watersheds (Tables 3–6). In the mid-1950s and 1960s, ERA values for the treatment watersheds reached 10% on the Taylor, Bit, and New York blocks, and percentages of disturbed area reached 20–30%. Percentages of disturbed area in the New York block were very high and reached 86% (Table 5). However, these percentages included areas that were harvested more than once. Some control watersheds experienced heavy disturbances prior to the 1960s, but we concluded they were generally distant enough from the channel to not invalidate the classification as a control. Figures are not shown for the New York block because there were no photographs prior to

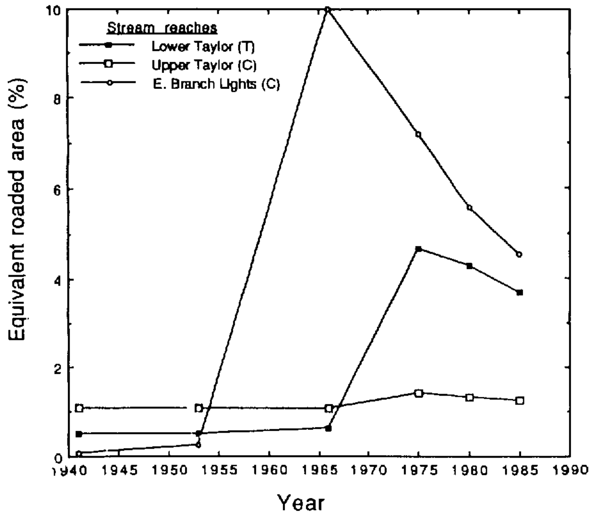

Figure 3. Trend in equivalent roaded area index for the Taylor block using a 30-year recovery period.

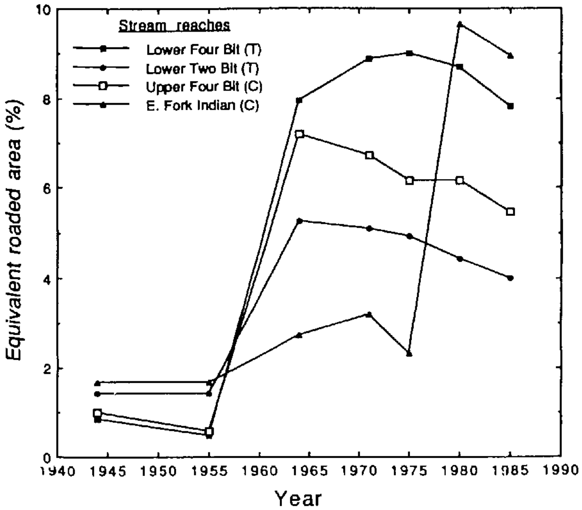

Figure 4. Trend in equivalent roaded area index for the Bit block using a 30-year recovery period.

1966. However, the New York watersheds had extensive cutting and mining prior to 1966. A similar pattern of disturbance occurred in the SIZs as occurred in the entire watersheds (Figures 5 and 6). Maximum ERA levels exceeded 8% for the Taylor and Bit blocks, and 10% for the New York block (no figure).

For the plots of ERA values, only the 30-year recovery curves are shown because the general pattern of declining ERA after harvest was similar when the 20- and 50-year recovery rates were used. ERA values dropped more quickly when the 20-year recovery rate was used, unlike the slow declines that resulted from using the 50-year rate. With the 50-year recovery rates, ERA values peaked slightly higher in a few cases when new harvests occurred before past harvest areas had recovered completely.

Near-Stream Activities

The modified ERA method emphasized activities within 100 m of the stream. For our sample of watersheds and using a Spearman correlation test, this refinement yielded significant correlation between some of the ERA values and community parameter indices derived from the UCB studies (Table 7). The nonparametric Spearman correlation was used to avoid making distributional assumptions about the data. The sample correlations between the modified ERA values and Shannon diversity were higher than they were with the standard ERA method. Comparison of ERA values and community dominance yielded similar results. Proximity of the disturbance to the channel increases the chance that the aquatic ecosystem will be affected. By limiting the effective watershed to a 200-m strip along the length of the channel, our refined method increased the proportional effect of any disturbances in that area. Alternately, an ERA method could be formulated that included the entire watershed but had different, much higher disturbance factors for areas within the SIZ. This revision would incorporate the management in the upland areas of the basin but reflect the sensitive nature of the near-channel zone.

Recovery Period

Following the cessation of logging activities, the physical and biological environment recovers and ERA values decline based on the assumed recovery schedule. Using a Spearman rank correlation test, the 30-year recovery period used by the FS produced significant correlations between ERA and diversity or dominance from the UCB studies (Table 7). Conversely, the 50-yr recovery period yielded lower, nonsignificant correlations (Steel and Torrie 1960). In one case, a significant correlation was determined for a 20-year recovery period but not for a 30-year period. These results suggest that shorter recovery periods better describe the association between recovering forest systems and aquatic response, as represented by the ERA and diversity or dominance, respectively.

Either the 20- or 30-year period allows for substantial vegetative and hydrologic recovery on the study watersheds. Revegetation typically reduces the risk of erosion and mass failure, and hydrologic recovery is furthered by litter accumulation, decreases in soil compaction, and recovery from soil surface armoring. Based on sampling of plants taller than 1.4 m in quadrats at 5 and 10 m from the channel along transects spaced at 40-m intervals, densities in the cut areas equaled or exceeded control areas in less than 15–17 years for the New York, Bit, and Taylor blocks (Fong 1991). Similarly, ten years after logging, harvested sites along Carnation Creek, British Columbia, contained vegetative cover equal to prelogging levels (Hartman and Scrivener 1990).

Thresholds for Detectable Change

We compared standard and modified ERA values with the UCB dominance and Shannon diversity data to determine if ERA and invertebrate community condition could be correlated. If ERA is linked to channel and aquatic ecosystem health, then such a correlation should exist. We hypothesized that as ERA increased, dominance of certain taxa should increase and diversity should decrease. We anticipated a curve with a moderate slope for low and moderate

Table 4. Dates and sizes of tractor-harvested areas in watersheds and streamside impact zones (SIZ) on control (C) and treatment (T) basins of the Taylor block

Watershed	Photo date	Year of harvest	Watershed cut area (ha)	SIZ cut area (ha)	Harvest method
Lower Taylor (T)	1941	None			
(601 ha/116 ha)	1953	None			
	1966	1964	4	1	Clear-cut
	1972	1966–1972	13	0	Clear-cut
	1972	1968–1969	3	0	Clear-cut
	1972	1970	36	2	Heavy selective
	1972	1972	25	5	Light selective
	1972	1972	30	13	Heavy selective
	1977	None			
	1982	1979	12	1	Light selective
	1987	1986	35	7	Cear-cut
Sum/% of area			158/26%	29/25%	
Upper Taylor (C)	1941	None			
(113 ha/11 ha)	1953	None			
	1966	None			
	1966	1968–1969	2	0	Clear-cut
	1972	None			
	1977	None			
	1982	None			
	1987	None			
Sum/% of area			2/2%	0/0%	
E. Branch Lights (C)	1941	None			
(828 ha/132 ha)	1953	None			
	1966	1958	335	32	Heavy selective
	1966	1958	97	17	Light selective
	1966	1958	6	0	Clear-cut
	1972	None			
	1977	None			
	1982	1981	3	0	Light selective
	1982	1981	3	0	Clear-cut
	1982	1982	53	4	Light selective
	1987	None			
Sum/% of area			497/60%	53/40%	

ERA values and then a steeper slope for ERA values past a threshold value of 15% or 20%. The comparison does show a decline in diversity with increasing disturbance levels (Figure 7). The comparison did not reveal an upper-limit threshold, possibly because the disturbance was not sufficiently severe, e.g., the ERA values did not exceed 10.5%.

The results do suggest, however, the presence of a minimum ERA threshold. Assuming a normal distribution of errors and using a two-phase linear regression model, successive fittings were made to find the join point that minimized the sums of squares (Hinkley 1971). For our sample, the join point between the two phases corresponded to an ERA value of 5.1%. The 95% confidence interval for this minimum ERA threshold was from 3.7 to 6.5%. Although the slope of line A is positive in Figure 7, the slope is *not* significantly different than zero and we *cannot* conclude that minor disturbances increase aquatic species diversity. The negative slope of line B is significant, however, at the 5% level, supporting the hypothesis of an inverse relationship between diversity and land disturbance for our sample. The minimum threshold value suggests that only low levels of disturbance in the streamside zone can be tolerated without at least a temporary effect on the aquatic community.

This finding suggests that land-management decisions based on hydrologic thresholds of concern are likely to have an effect on stream biota. For example, Haskins (1987) described a case study where the FS assessed the suitability of timber harvesting in selected watersheds of the Shasta-Trinity National Forest. Those watersheds with ERAs that exceeded a predetermined threshold of concern of 18% were not con-

Table 5. Dates and sizes of tractor-harvested areas in watersheds and streamside impact zones (SIZ) on control (C) and treatment (T) basins of the New York block

Watershed	Photo date	Year of harvest	Watershed cut area (ha)	SIZ cut area (ha)	Harvest method
Mid. New York (T)	1966	Pre-1966	245	40	Heavy selective
(466 ha/124 ha)	1972	1966–1972	7	4	Light selective
	1977	1974	28	13	Heavy selective
	1977	1974	6	0	Light selective
	1977	1974	4	3	Clear-cut
	1982	None			
	1987	1982–1987	30	0	Clear-cut
	1987	1982–1987	11	2	Heavy selective
	1987	1982–1987	27	5	Light selective
Sum/% of area			358/77%	67/54%	
New York Trib. (T)	1966	Pre-1966	44	3	Heavy selective
(92 ha/24 ha)	1972	None			
	1977	1974	19	6	Heavy selective
	1977	1974	4	3	Clear-cut
	1982	None			
	1987	1982–1987	9	0	Clear-cut
	1987	1982–1987	3	2	Heavy selective
Sum/% of area			79/86%	14/58%	
Upper New York (C)	1966	Pre-1966	200	36	Heavy selective
(347 ha/89 ha)	1972	1966–1972	7	4	Light selective
	1977	1974	3	1	Heavy selective
	1977	1974	0	0	Light selective
	1982	None			
	1987	1982–1987	22	0	Clear-cut
	1987	1982–1987	16	5	Light selective
	1987	1982–1987	11	0	Light selective
	1987	1982–1987	8	0	Heavy selective
Sum/% of area			267/77%	46/52%	
Empire (C)	1966–1987	None			
(531 ha/127 ha)					
Sum/% of area			0/0%	0/0%	

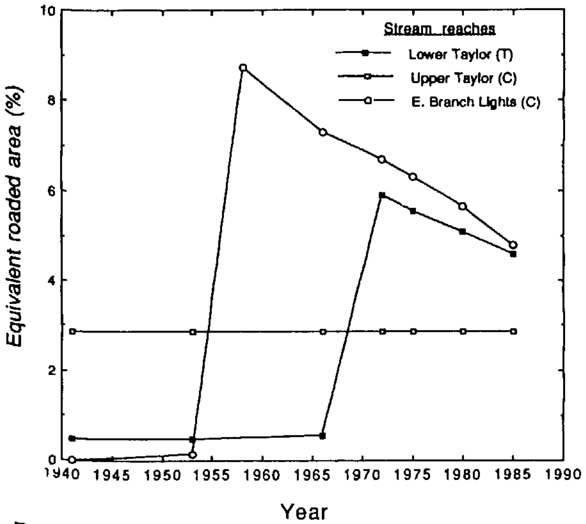

Figure 5. Trend in equivalent roaded area of the streamside impact zone for the Taylor block using a 30-year recovery period.

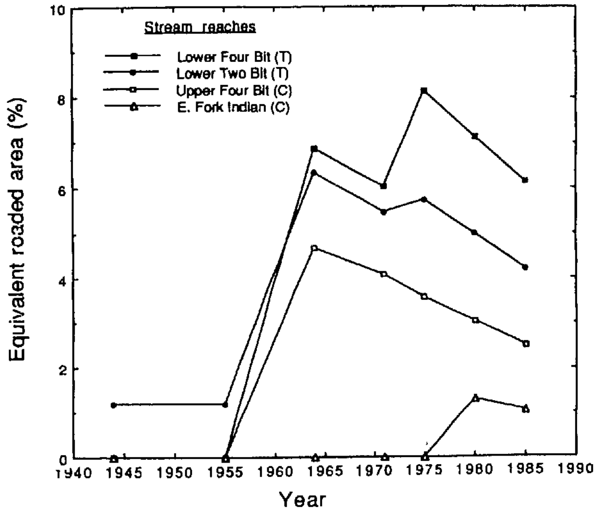

Figure 6. Trend in equivalent roaded area in the streamside impact zone for the Bit block using a 30-year recovery period.

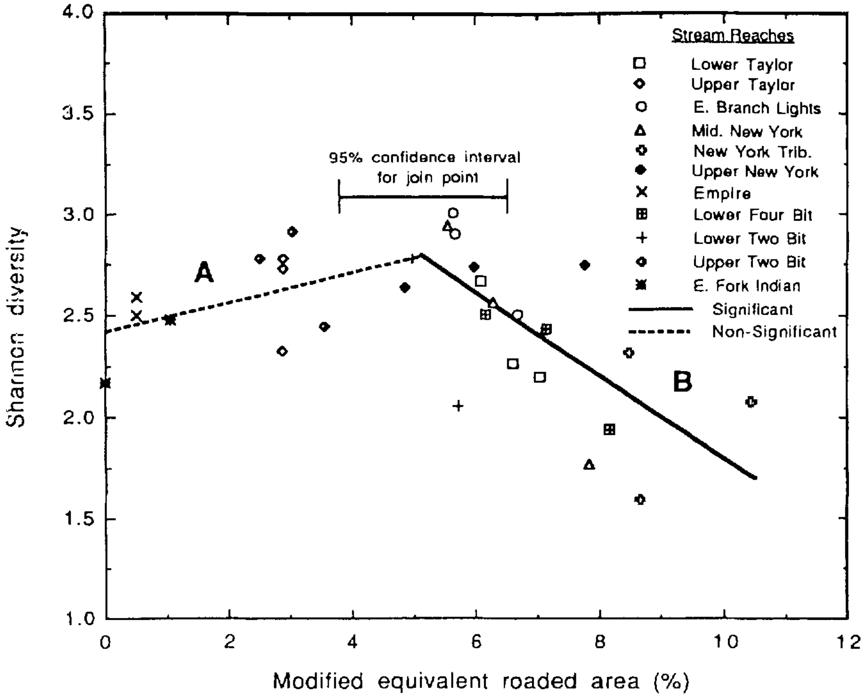

Figure 7. Beyond a minimum effect threshold, increases in roaded area result in a decreased diversity index as shown by line B (diversity data from Erman and others 1977; Erman and Mahoney 1980; Fong 1991).

sidered for further harvest activity. If a stream biota threshold of 5% had been used, fewer acres for timber harvesting would have been available, but effects on aquatic insects, and possibly the fisheries, would have been lessened. Based on the recent controversy in the Pacific Northwest over the spotted owl and the president's economic and environmental analyses, protection of near-stream zones is now much more stringent than it was in the past. With strict implementation of the new streamside protection zones, disturbances in these areas may not even reach the 5% threshold that we have correlated with declines in the diversity index.

Our results are from California, which is a Mediterranean hydrologic regime, and macroinvertebrate communities elsewhere may react differently to the same levels of disturbance. We hypothesize that land disturbance in other regions of the United States or in other countries would result in similar responses in the macroinvertebrate communities and that a method like the modified ERA would be appropriate outside of California. Analysis of the relationship between ERA and macroinvertebrate communities in other ecoregions, however, is certainly warranted. Because our study did not have ERA values in excess of 10.5%, additional research is needed to determine the influence of higher ERA values on the extent and duration of biological response.

Summary

Both the standard and modified forms of the ERA method yielded increases in the ERA index associated with harvests in the 1960s and 1970s, followed by decreasing ERA values after the harvest ceased. Long-term declines in ERA values should reflect revegetation and recovery of the aquatic ecosystem and increasing channel stability. Modifications to the standard ERA method that emphasized near-channel activities and contained 20- or 30-year recovery periods consistently yielded the largest correlation with diversity and dominance of macroinvertebrate communities. Changes in the ERA index were significantly correlated with changes in diversity and dominance. ERA values less than 5% were not associated with changes in diversity of aquatic insects, indicating that a minimum disturbance threshold may exist. As ERA values increased beyond 5.1%, a significant decrease in diversity was found.

Recommendations

The ERA methodology was designed primarily as a planning tool to aid Forest Service resource specialists in assessing the CWE of various management options at the forest or project level. Our experience indicates that disturbance indices for lotic systems should focus more explicitly on management activities within the

Table 6. Dates, sizes, and removal methods for clear-cut harvest areas in watersheds and streamside impact zones (SIZ) on control (C) and treatment (T) basins of the Bit block

Watershed	Photo date	Year of harvest	Watershed cut area (ha)	SIZ cut area (ha)	Removal method
Lower Four Bit (T)	1944	None			
(101 ha/21 ha)	1955	None			
	1964	1960–1964	11	3	Cable
	1964	1960–1964	6	1	Tractor
	1964	1960–1964	7	0	Cable
	1971	None			
	1975	1972	4	4	Cable
	1980	None			
	1986	None			
Sum/% of area			28/28%	8/33%	
Lower Two Bit (T)	1944	None			
(120 ha/38 ha)	1955	None			
	1964	1960–1964	10	5	Tractor
	1964	1960–1964	3	2	Cable
	1971	None			
	1975	1972	2	2	Cable
	1980	None			
	1986	None			
Sum/% of area			15/12%	9/24%	
Upper Four Bit (C)	1944	None			
(86 ha/15 ha)	1955	None			
	1964	1960–1964	18	3	Cable
	1964	1960–1964	2	0	Tractor
	1971	None			
	1975	None			
	1980	None			
	1986	None			
Sum/% of area			20/23%	3/20%	
Upper Two Bit (C)	1944–1986	None			
(61 ha/18 ha)					
Sum/% of area			0/0%	0/0%	
East Fork Indian (C)	1944–1975	None			
(87 ha/15 ha)	1980	1975–1980	12	1	Skyline[a]
	1980	1975–1980	8	0	Tractor/skyline
	1980	1975–1980	3	0	Tractor
	1980	1975–1980	1	1	Skyline
	1986	None			
Sum/% of area			24/28%	2/13%	

[a]Light selective harvest method coefficient used.

near-stream environment. This CWE analysis was based on knowledge of the long-term management history of some basins, but a comprehensive CWE program should also include long-term field monitoring of the biological characteristics of the aquatic systems. Resource managers need to have monitoring results to demonstrate that management is not adversely affecting a principal beneficial use on forested lands. As the FS shifts its focus toward integrated ecosystem management, it should expand the use of biological thresholds of concern in decisionmaking.

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Don C. Erman (University of California at Berkeley) and his students originated the long-term biotic information, ecosystem recovery concept, and block design used in this study. Funding for a portion of Dr. Erman's work was provided by the Pacific Southwest Research Station, USDA Forest Service. Ken B. Roby (Plumas National Forest, Greenville, California) provided manuscript review and insight into equivalent roaded area estimation and helped us obtain land-use information for the study sites.

Table 7. Spearman correlation coefficients and significance of ERA values versus macroinvertebrate community parameters

Community parameters	Standard ERA			Modified ERA		
	20 yr	30 yr	50 yr	20 yr	30 yr	50 yr
Shannon diversity	−0.30	−0.19	−0.10	−0.42[a]	−0.43[a]	−0.24
Dominance (top taxa)	0.21	0.13	0.07	0.27	0.28	0.14
Dominance (top 5 taxa)	0.42[a]	0.31	0.25	0.47[a]	0.51[a]	0.35

[a]Significant at $P < 0.05$.

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