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Key Points:

- Quantitative generalizations are derived for logging impact on sediment yield
- Postlogging sediment yield increase lies within an order of magnitude
- Sediment yield seems generally unrelated to the proportion of catchment logged

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Quantitative generalizations for catchment sediment yield following forest logging

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Abstract Published data for temperate forests across the world are analyzed to investigate the potential for generalized quantitative expressions of catchment sediment yield impact in the years immediately following logging. Such generalizations would be useful in a variety of forestry and engineering tasks and would aid the spread of knowledge amongst both relevant professionals and new students. Data were assembled for paired catchment studies (51 catchments including 16 controls) that enabled the postlogging sediment yield impact to be compared with both the prelogging period and an undisturbed control catchment, using a specially defined relative response factor. Three categories of impact were derived: low-moderate, high, and very high, defined by specific ranges in the maximum value of the relative response factor. The maximum increase in specific sediment yield (in t km^{-2} yr^{-1}) following logging is 1 order of magnitude above the control sediment yield at both the annual and storm event scales, at least under normal circumstances of Best Management Practice. There is no apparent relationship between sediment yield and the proportion of catchment logged, at least at the general scale. A cumulative probability distribution for the year in which the maximum postlogging sediment yield occurs, shows the majority of cases falling in the first 2 years. These generalizations refer to the broad response to logging as a function of ground disturbance, for example, by logging technique, roads, and burning. Although limited to order of magnitude quantification, they provide a basis for first estimates and for a general appreciation of an impact problem.

1. Introduction

Scientific curiosity, engineering need, environmental concern, and economic interest all drive research into the quantitative prediction of the impact of forestry activities on soil erosion and catchment sediment yield. Design of infrastructure such as road culverts, criteria for environmental impact assessments and standards for environmental certification are all strengthened through the use of quantitative information. In specific cases, such information can be obtained from experimental catchments or computer modeling. However, a methodology is missing that provides a broader perspective and a more generalized means of making quantifications. In particular, while there is a reasonably clear *qualitative* understanding of the impact of forestry activities on sediment yield, there is a lack of *quantitative* generalizations, of the sort available for the impact of forests on water yield. Examples of this latter capability include:

1. Forested catchments have around 15% less annual runoff than equivalent grassland catchments in the upland UK [e.g., *Marc and Robinson*, 2007].
2. Forest cover must change over at least 20% of the catchment area to cause a measurable effect on annual runoff [e.g., *Bosch and Hewlett*, 1982].
3. More tentatively, forest cover has little moderating effect on the magnitudes of storm peak discharges for rainfall event return periods greater than about 10 years for sites in Chile [e.g., *Bathurst et al.*, 2011].

If such generalizations could be developed between forests and sediment yield, they would be very helpful in estimating the impacts of proposed forestry operations and ensuring compliance with environmental standards. Easily remembered generalizations would also aid the spread of knowledge amongst both relevant professionals and new students.

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The lack of generalizations reflects the observation that, while a considerable number of studies of forest impact on sediment yield have been published over the last few decades, there does not seem to have been any attempt to integrate their results and draw appropriate lessons. This paper therefore analyzes data from past studies in the literature to determine the extent to which quantitative statements can be established. Given the substantially greater difficulties of determining sediment relationships compared with water relationships, and noting also the limitations of the past studies, the research is restricted to the impact of forest logging on catchment sediment yield in the years immediately following logging, in temperate countries with well-established forestry sectors, principally the UK, U.S. Pacific Northwest and Texas, Japan, New Zealand, and Chile. After considering the types of generalizations that are appropriate for this impact, the paper reviews the available literature data and draws conclusions at the annual and event temporal scales as well as considering spatial scale dependencies.

2. Generalized Expressions

To be of practical use, sediment-related generalizations should incorporate an understanding of erosion processes and how they are affected by logging activities. In the natural state, catchment sediment yield is derived from hillslope and channel sources and varies with catchment geology, vegetation cover, topography, climate, and other such factors. In most cases, although not always, forest logging causes an increase in suspended sediment concentrations, bed load transport, and sediment yields along the stream network [e.g., *Amaranthus et al*., 1985; *Davies and Nelson*, 1993; *Guthrie*, 2002; *Bruijnzeel*, 2004], although much of this may be attributed to ground disturbance by logging technique and forest roads rather than simple exposure of soil to the elements [e.g., *Reid and Dunne*, 1984; *Grayson et al*., 1993; *Croke et al*., 1999]. The increase in runoff consequent upon the reduced interception and transpiration caused by logging can also increase transport of material already in the channel, even without inputs from the hillslope. On the other hand, channels may become clogged with woody debris produced during logging and, in line with woody debris impacts elsewhere [e.g., *Comiti et al*., 2008], potentially this could trap sediment and therefore reduce sediment yield. Similarly, measures such as buffer strips can reduce sediment input to channels [e.g., *Lacey*, 2000]. A first major question that should be addressed by a quantitative generalization is therefore:

> *What is the impact on annual sediment yield in the years following logging, as a function of logging technique, road construction, and other intervention practices?*

As most sediment transport takes place during storm events, a second generalization should answer the question:

> *What is the impact on storm event sediment yield in the years following logging, as a function of logging technique, road construction, and other intervention practices?*

As shown by *Bosch and Hewlett* [1982], the change in *water yield* depends on the proportion of the catchment that is logged. For *sediment yield*, the location of the logged area and its connectivity to the stream network may be more important than the proportion of catchment affected. Nevertheless, as forest logging is often now practiced on a patch basis, affecting only a proportion of a catchment, a further generalization should at least consider, even if only to reject, the question:

> *Is it possible to identify a relationship between sediment impact and the proportion of the catchment that is logged?*

And in a related vein:

> *How far downstream of a logged area does the sediment impact remain significant?*

Finally, it would be helpful to answer the question:

> *How long after logging does the peak sediment impact occur and how long does recovery to prelogging conditions take?*

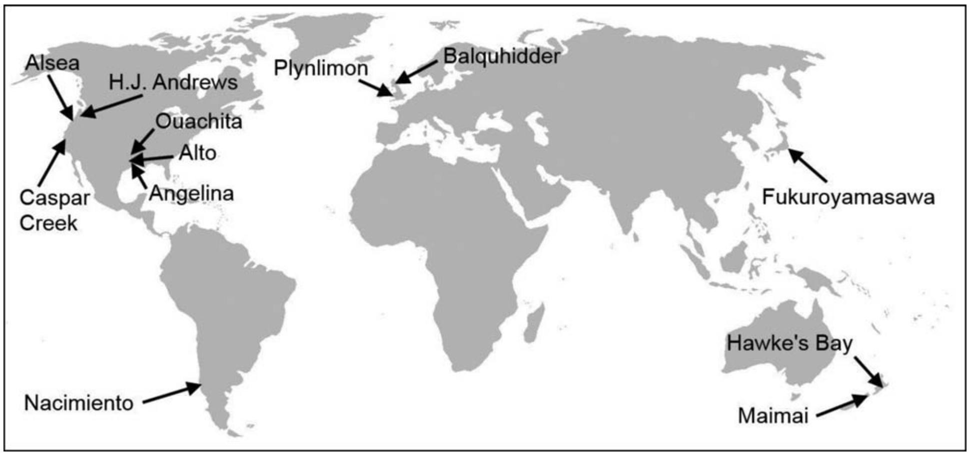

Figure 1. Location of paired catchment studies.

3. Data Source

Addressing the above questions requires data from catchments that have undergone logging, enabling the sediment yields from the pre and postlogging periods to be compared. However, the natural changes that might have taken place between these periods need to be removed from the comparison. For example, an increase in rainfall (and thence stream discharges) from the pre to postlogging periods would be expected to increase sediment yield even without any logging. Similarly, comparison of logging impacts between catchments requires the effect of differences in catchment characteristics to be discounted. Data from undisturbed control catchments are therefore needed to standardize the logging impacts, both between pre and postlogging periods and between catchments. A literature search was therefore carried out to identify paired catchment studies that included both pre and postlogging measurement periods of sediment yield.

The search was constrained by the number of publications that provided the actual data or for which the data could be accessed on a web site. It is likely that other data sources exist but in reports not easily accessible to researchers. Sixty-five individual test catchments (including 20 individual control catchments) were eventually identified, from 14 studies (Figure 1 and Table 1). However, the studies at Ouachita, Oklahoma, and Alto-A and B, Texas, include replicate sites, the data for which are averaged, so that this analysis effectively considers 51 catchments, of which 16 are controls:

1. In many cases, there is only a limited period of prelogging data but in all cases there are at least 2 years except for Alto-A and Plynlimon-B (1 year) and Maimai and Ouachita (no data).
2. In all cases, the analyzed sediment yield impact is that arising from the various logging interventions in the years immediately following the logging, typically four or five. As such, it is essentially a ground surface (including roads) and stream channel impact and does not include the yield that might arise in steep catchments from the increased probability of landsliding following decay of the roots of the felled trees, which typically peaks at around 7 years after logging [e.g., *Amaranthus et al*., 1985; *Sidle et al*., 1985, pp. 63–65; *Sidle and Ochiai*, 2006, pp. 94–95]. In some cases, the available data cover much longer periods (e.g., the H.J. Andrews Forest and Caspar Creek studies) in which there may be additional contributions to the impact.
3. Within the studies, the annual data are provided for a variety of water year definitions and for calendar years.

All the sites are in temperate climatic zones. According to the updated Köppen-Geiger classification of *Peel et al*. [2007], the climate types are: Csb (H.J. Andrews, Alsea, Caspar Creek, and Nacimiento), Cfa (Ouachita, Alto, Angelina, and Fukuroyamasawa), and Cfb (Maimai, Hawke's Bay, Balquhidder and Plynlimon), where C = temperate, s = dry summer, f = without dry season, a = hot summer, and b = warm summer.

Between them, the studies cover over 50 years from around 1959 to the present day. During this time, the techniques that characterize Best Management Practice (BMP) for logging and subsequent land treatment have

Table 1. Test Catchments and Data Sources[a]

Catchment	Area (km^2)	Data Period	Date of Logging	Tree Type[b]	Logging Technique and Extreme Events	Percent Catchment Logged[c] (%)	Sediment Yield Measurement Technique
H.J. Andrews, OR, USA[d]							
					All: Major storm Dec 1964		
WS1	0.96	1959–1988	1962–1966	Largely Douglas fir	SS. BR 1966. PR.	All	Depth integrated SSL sample; bed load in sediment basin
WS3	1.01	1959–1988	1962		R 1959. CL. BR 1963. PR.	25	
WS2	0.60	1959–1988	None		Control catchment	0	
Alsea, OR, USA[e]							
Needle Branch	0.75	1959–1969	1966	Douglas fir and alder	R 1965. BR 1966.	82	SSL samples but no details
Deer Creek	3.04	1959–1969	1966		PC. RC 1965. BPL 1966. BS.	25	
Flynn Creek	2.02	1959–1969	None		Control catchment	0	
Maimai, New Zealand[f]							
M7	0.0414	1977–1978	1976	Beech/ podocarp/ hardwood	CL. BR 1977. PR.	All	SSL manual and automatic samplers; bed load in sediment trap
M9	0.0826	1977–1978	1977		SL. BR 1978. BS.	All	
M6	0.0164	1977–1978	None		Control catchment	0	
Ouachita, OK, USA[g]							
Three pairs of logged/control sites							
Mean logged	0.016–0.042	1979–1982	1978	Shortleaf pine	SL. BR1978. PR 1979	All	Automatic pump sampler; Coshocton wheel
Mean control	0.016–0.042	1979–1982	None		Control catchment	0	
Alto-A, TX, USA[h]							
					All: RT. SL. BR. BS. PR1981.		
Mean SW1, SW2, SW3	0.0257–0.0272	1980–1984	1980	Shortleaf pine and mixed hardwoods	Shearing, windrowing, burning	All	Automatic pump sampler; Coshocton wheel; sediment trap
Mean SW5, SW7, SW9	0.0257–0.0272	1980–1984	1980		Roller chopping, burning	All	
Mean SW4, SW6, SW8	0.0257–0.0272	1980–1984	None		Control catchment	0	
Angelina NF, TX, USA[i]							
ANF2	0.039	1981–1988	1983–1984	Loblolly longleaf, shortleaf pine/ sweetgum/ S. red oak	Roller chopping	All	Coshocton wheel; sediment trap
ANF3	0.039	1981–1988	1983–1984		Shearing, windrowing	All	
ANF1	0.039	1981–1988	1983		Shearing, windrowing, grazing	All	
ANF4	0.039	1981–1988	1983–1984		Shearing, windrowing, grazing	All	
ANF5	0.039	1981–1988	None		Control catchment	0	
Balquhidder, UK[j]							
Kirkton	6.85 (2.81 forest)	1983–1989	1986–1989	Norway and Sitka spruce	High rainfall postlogging. SS. R.	36 (forest) 15 (total catchment)	Automatic and manual SSL samples; turbidity monitoring
Plynlimon-A, UK[k]							
Hore	3.17	1983–1990	1985–1989	Norway and Sitka spruce	FL, CL, SL. R.	28.9	Manual SSL samples; turbidity monitoring
Hafren	3.67	1983–1990	None		Control catchment	0	
N. Fork, Caspar Creek, CA, USA[l]							
KJE	0.15	1986–1995	1989	Redwood and Douglas fir	SS. BS	97	Automatic pump sampler; turbidity monitoring
MUN	0.16	1986–1995	None		Control catchment	0	
JOH	0.55	1986–1995	1989		SS.	30	
HEN	0.39	1986–1998	None		Control catchment	0	
IVE	0.21	1986–1998	None		Control catchment	0	
LAN	1.56	1986–1995	1989–1990		SS. BR 1990 (20% area). BS.	32	
GIB	0.20	1986–1995	1991		SS. BR 1991 (98% area). BS.	100	
FLY	2.17	1986–1995	1989–1991		SS. BR 1991 (30% area). BS.	45	
EAG	0.27	1986–1998	1990–1991		SS. BR 1991 (98% area). BS.	100	
DOL	0.77	1986–1998	1990–1991		SS. BR 1991 (34% area)	36	
CAR	0.26	1986–1998	1991		SS. BS.	96	
BAN	0.10	1986–1995	1991		SS. BS.	95	
ARF	3.84	1986–1998	1989–1992		SS. BR 1990–1991 (24% area). BS	46	
NFC	4.73	1986–1998	1985–1992		SS. BR 1985–1992 (20% area). BS.	50	
Plynlimon-B, UK[m]							
Nant Tanllwyth	0.89	1995–1997	1996	Norway and Sitka spruce	SS. CL. RC.	15	Automatic pump sampler; turbidity monitoring
Hafren	3.67	1995–1997	None		Control catchment.	0	
Hawke's Bay, New Zealand[n]							
Pakuratahi	3.45	1995–2001	1998–1999	Radiata pine	SS. SL. R.	All	Automatic pump sampler
Tamingimingi	7.95	1995–2001	None	Pasture	Control catchment	0	

Table 1. (continued)

Catchment	Area (km^2)	Data Period	Date of Logging	Tree Type[b]	Logging Technique and Extreme Events	Percent Catchment Logged[c] (%)	Sediment Yield Measurement Technique
Alto-B, TX, USA[o]							
					All: RT. SL. PR2002. Major storms 2001, 2003		
Mean SW1, SW6, SW7	0.025	1999–2003	2002	Loblolly pine	Intensive	All	Automatic pump sampler; sediment trap
Mean SW2, SW4, SW9	0.025	1999–2003	2002		Conventional	All	
SW3	0.025	1999–2003	None		Control catchment	0	
LW2	0.8–1.2	1999–2003	2002		RC. Conventional	All	
LW3	0.8–1.2	1999–2003	2002		RC. Herbicide, fertilizer	All	
LW4	0.8–1.2	1999–2003	2002		RC. Intensive	All	
LW1	0.8–1.2	1999–2003	None		Control catchment	0	
Fukuroyamasawa, Japan[p]							
B	0.0109	1996–2002	1999	Japanese plantation trees	SS. PR 2000.	All	Automatic pump sampler; turbidity monitoring
A	0.008	1996–2002	None		Control catchment	0	
Nacimiento, Chile[q]							
					Earthquake 2010. Dry years		
N04	0.077	2008–12	2010	Radiata pine	SL. PR seed plough 2010.	All	Automatic SSL sampling
N01	0.126	2008–12	None		Control catchment	0	

[a]SS, skyline suspension; BR, residual burning; PR, replanted; CL, cable logging; R, roads; RC, roads with careful design and use; PC, patch cut; BPL, partial light burning; BS, buffer strip; SL, skidder logging; RT, rubber-tyred feller bunchers; FL, forwarder logging; SSL, suspended sediment load.
[b]The inclusion brackets mean that the tree type applies to all the sites at each catchment.
[c]The term "All" is used where the entire catchment has been logged but the respective authors have not specified a percentage. It is assumed that the percentage is 100 but it could be a little less.
[d]*Grant and Wolff* [1991] and *HJA* [2013a, 2013b] website.
[e]*Brown and Krygier* [1971].
[f]*O'Loughlin et al.* [1980].
[g]*Miller* [1984].
[h]*Blackburn et al.* [1986].
[i]*Blackburn et al.* [1990].
[j]*Johnson* [1993, 1995].
[k]*Leeks* [1992] and *Roberts and Crane* [1997].
[l]*Lewis et al.* [2001] and *CC* [2013] website.
[m]*Leeks and Marks* [1997] and *Stott et al.* [2001].
[n]*Fahey et al.* [2003].
[o]*McBroom et al.* [2008].
[p]*Hotta et al.* [2007].
[q]*Huber et al.* [2010] and A. Iroumé (Disponibilidad y calidad del recurso agua en cuencas hidrográficas en la zona de Nacimiento, report to Forestal Mininco S.A., Universidad Austral de Chile, Valdivia, unpublished report, 2012).

changed and the order in which the studies are listed in Table 1 is therefore roughly chronological. The Alto-B study of *McBroom et al*. [2008], for example, was a deliberate attempt to compare the impacts of current BMP with the practice used in the previous logging cycle (Alto-A) at the same site [*Blackburn et al*., 1986].

Relevant information, additional to that in Table 1, is as follows.

The Maimai and Ouachita studies do not include prelogging data and therefore are not used in the comparisons of pre and postlogging yields.

For the Balquhidder Kirkton study, there is no undisturbed control catchment. However, *Johnson* [1993] applied the 1983–1985 prelogging suspended sediment rating curves to the 1986–1989 postlogging period to generate a "natural" sediment load that is used here as a surrogate for a control catchment.

The Casper Creek study is the most extensive of those considered here. Thirteen subcatchments (including three control catchments) and the main outlet provide sediment data for a range of logging treatments (especially contrasting burned and unburned sites) and proportions of catchments logged. The catchments lie along the spine of the creek in such a way that: MUN (0.16 km^2) and KJE (0.15 km^2) are nested within JOH (0.55 km^2); JOH, IVE (0.21 km^2) and HEN (0.39 km^2) are nested within LAN (1.56 km^2); LAN and GIB (0.2 km^2) are nested within FLY (2.17 km^2); FLY, DOL (0.77 km^2), CAR (0.26 km^2), and BAN (0.1 km^2) are nested within ARF (3.84 km^2); and ARF is nested within NFC (4.73 km^2). Additionally EAG (0.27 km^2) is nested within DOL. The sequence KJE (97% logged), JOH (30%), LAN (32%), FLY (45%), ARF (46%), and NFC (50%) thus represents a variation in the proportion of catchment logged along a nested system. (See *Lewis et al*. [2001] for a relevant map.)

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For the Alto-A study, two different postlogging treatments were assessed: shearing, windrowing (i.e., contour lines of wood debris) and burning; and roller chopping and burning. In each case (including the control catchments), there were three replicates.

For the Alto-B study, two different postlogging treatments were assessed at small (0.025 km^2) and large (0.8–1.2 km^2) scales, with the small catchments involving three replicates in each case. The intensive treatment allowed more rapid stand establishment and higher productivity than the conventional treatment. At the larger scale, a third treatment involving herbicide release and fertilizer was also studied.

For the Angelina National Forest study, four different postlogging treatments were assessed. From 1986, the third year after logging, catchment ANF1 was subjected to semicontinuous grazing while ANF4 was subjected to rotational grazing.

For the Fukuroyamasawa study, *Hotta et al*. [2007] provide ratios of the pre and postlogging sediment yields between the catchments but do not provide the yields themselves.

The Nacimiento study is comparable in scale to the Caspar Creek study. Eleven catchments ranging from 0.077 to 4.144 km^2 with various forest covers and undergoing logging under a variety of circumstances have been monitored since 2008. At the current stage, though, only one catchment has a sufficient length of pre and postlogging data to support the analysis of this paper. The study area was affected by a magnitude 8.8 earthquake centered about 180 km to the north on 27 February 2010. The effect on the discharges is described by *Mohr et al*. [2012] but it is not clear if there was a significant impact on sediment yield, for example, through bank collapses. Logging took place in the 2 months following the earthquake and any earthquake impacts were therefore subsumed within the logging impacts. Both the control and the logged catchments showed a similar increase in sediment yield in 2010 (see Figure 5) but the increase in the control catchment was probably caused by the increased passage of logging vehicles on a road through the catchment.

All the control catchments have the same vegetation cover (either natural or plantation forest) as the associated prelogged catchments, except for the Hawke's Bay study in New Zealand, where the Tamingimingi control catchment has a pasture cover.

Overall the assembled data provide a sufficient basis for addressing the questions raised in the previous section. Paired catchment data incorporating several years of data from both the pre and postlogging periods enable the impact of logging to be quantified for a range of catchment treatments, at both the annual and the event scale. They also allow the recovery to prelogging conditions to be studied, at least within the limited period of the postlogging records. Data on partial logging, from 0 to 100% of the catchment, enable the sediment yield impact to be investigated as a function of the proportion of catchment logged. Importantly, quantifying the logging impact relative to a control catchment enables the effect of local catchment characteristics such as soil, geology, and topography that might otherwise dominate the variation in sediment yields between studies to be largely eliminated. This provides confidence that the (relative) impacts can indeed be generalized across the various catchments. The range of catchment scales (over $>$2 orders of magnitude, from 0.01 to 8 km^2) further increases confidence in the generalized nature of the analysis. However, because of the advances in BMP over the period of data availability, there is potentially an element of nonstationarity in the recorded sediment impacts. This would suggest that, all other effects being equal, the logging impact should decrease from the earlier to the later studies. It is not clear, though, if this variation is significant. For example, the sediment yields for Alto-A and Alto-B indicate both increases and decreases over the 20 years between the studies.

4. Analysis

The data were analyzed for each of the proposed generalized expressions in turn.

4.1. Impact of Logging on Annual Sediment Yield—Absolute Impacts

While recognizing that absolute values of sediment yield are affected by a range of factors, it was nevertheless of interest (a) to categorize the range of yields across the sites and establish general limits at a world scale, and (b) to see if similarities existed between the sites, given the general similarities in climate and forest cover between most of them. Considering that the interest is likely to be in the worst case conditions, the maximum specific annual yields in the years immediately following logging were therefore extracted from the data (Table 2 and Figure 2). Most refer to suspended sediment only but some include

Table 2. Test Catchment Data

Catchment	Area (km^2)	Maximum Annual Sediment Yield (t km^{-2} yr^{-1})	Maximum Annual Relative Response SY^*_{max}	Occurrence of Maximum Annual Sediment Yield (Year After Logging)	Occurrence of Maximum Annual Relative Response SY^*_{max} (Year After Logging)	Recovery Period (Years After Logging)
H.J. Andrews, OR, USA						
WS1	0.96	471[a]	151	3	1	No recovery in data period
WS3	1.01	18,090[a]	45.3	2	2	10–13
WS2	0.60	159[a]	Control	Control	Control	Control
Alsea, OR, USA						
Needle Branch	0.75	317	10.1	2	3	Trending to recovery by year 4
Deer Creek	3.04	259	2.3	1	1	4
Flynn Creek	2.02	105	Control	Control	Control	Control
Maimai, New Zealand						
M7	0.0414	80[a]	No data	No data	No data	No data
M9	0.0826	449[a]	No data	No data	No data	No data
M6	0.0164	56[a]	Control	Control	Control	Control
Ouachita, OK, USA						
Three pairs of logged/control sites						
Mean logged	0.016–0.042	28[a]	No data	1	No data	Trending to recovery by year 4
Mean control	0.016–0.042	4[a]	Control	Control	Control	Control
Alto-A, TX, USA						
Mean SW1, SW2, SW3	0.0257–0.0272	294[a]	48.3	1	1	No recovery in data period
Mean SW5, SW7, SW9	0.0257–0.0272	2.51[a]	2.43	1	3	4
Mean SW4, SW6, SW8	0.0257–0.0272	3.29[a]	Control	Control	Control	Control
Angelina NF, TX, USA						
ANF2	0.039	26.2[a]	4.67	4	1	3-5
ANF3	0.039	30.6[a]	6.87	1	2	3-5
ANF1	0.039	14.7[a]	5.76	4	2	3-5
ANF4	0.039	70.5[a]	2.27	4	2	3-5
ANF5	0.039	27.5[a]	Control	Control	Control	Control
Balquhidder, UK						
Kirkton	6.85 (2.81 forest)	635 (104 natural)	11.3	1	3	Continuous logging, variable response
Plynlimon-A, UK						
Hore	3.17	141	13.0	2	2	Variable, trending to recovery by year 6
Hafren	3.67	48	Control	Control	Control	Control
N. Fork, Caspar Creek, CA, USA						
KJE	0.15	181	0.78	1	5	Post-logging reduction in sediment yield
MUN	0.16	>53	Control	Control	Control	Control
JOH	0.55	>141	0.95	1	3	Post-logging reduction in sediment yield
HEN	0.39	80	Control	Control	Control	Control
IVE	0.21	>16	Control	Control	Control	Control
LAN	1.56	83	1.63	6	5	Post-logging reduction in sediment yield
GIB	0.20	72	4.76	2	3	Fluctuating response
FLY	2.17	>106	2.39	4	5	Near recovery, except peak year
EAG	0.27	165	4.43	6	3	No recovery
DOL	0.77	>317	3.13	2	2	Slow trend to recovery
CAR	0.26	44	6.67	2	3	Trending to recovery by year 7
BAN	0.10	16	8.29	4	3	Near recovery, except peak year
ARF	3.84	111	1.95	4	5	6
NFC	4.73	134	2.27	6	5	8
Plynlimon-B, UK						
Nant Tanllwyth	0.89	57	2.1	No data	No data	No data
Hafren	3.67	23	Control	Control	Control	Control
Hawke's Bay, New Zealand						
Pakuratahi	3.45	282	8.1	3	2	4
Tamingimingi	7.95	142	Control	Control	Control	Control
Alto-B, TX, USA						
Mean SW1, SW6, SW7	0.025	23[a]	14.2	2	1	Trending to recovery by year 2
Mean SW2, SW4, SW9	0.025	11[a]	4.7	2	1	Trending to recovery by year 2
SW3	0.025	12[a]	Control	Control	Control	Control
LW2	0.8–1.2	24[a]	1.9	2	2	Unclear
LW3	0.8–1.2	5[a]	0.205	1	1	Post-logging reduction in sediment yield
LW4	0.8–1.2	74[a]	4.75	2	1	No recovery
LW1	0.8–1.2	4[a]	Control	Control	Control	Control

Table 2. (continued)

Catchment	Area (km^2)	Maximum Annual Sediment Yield (t km^{-2} yr^{-1})	Maximum Annual Relative Response SY^*_{max}	Occurrence of Maximum Annual Sediment Yield (Year After Logging)	Occurrence of Maximum Annual Relative Response SY^*_{max} (Year After Logging)	Recovery Period (Years After Logging)
Fukuroyamasawa, Japan						
B	0.0109	No data	1	No data	No data	Little impact
A	0.008	No data	Control	Control	Control	Control
Nacimiento, Chile						
N04	0.077	55	5.4	1	3	Near recovery, except peak year
N01	0.126	56 (road effect?)	Control	Control	Control	Control

[a]Total load; others suspended load only.

bed load. Data are not available for all the Caspar Creek catchments for all the postlogging years as some storm events were not recorded; the values are therefore limited to years with no, or almost no, missing data.

The highest yields by far come from the H.J. Andrews Forest catchments [*Grant and Wolff*, 1991]. Following residue burning in October 1966, WS1 yielded 419 t km^{-2} yr^{-1} in WY1967, 471 t km^{-2} yr^{-1} in WY1969, 574 t km^{-2} yr^{-1} in WY1971, and 1210 t km^{-2} yr^{-1} in WY1972. The value of 471 t km^{-2} yr^{-1} is used as the maximum postlogging yield (Table 2) on the grounds that the value of 1210 t km^{-2} yr^{-1} appears to have occurred in a wet year with raised yields in all three catchments (i.e., including the control) and that (along with the value of 574 t km^{-2} yr^{-1}) it is sufficiently distant from the period of felling that it might represent sediment derived from landslides triggered as the root systems decayed. WS3 was burned in September 1963 and yielded 18,090 t km^{-2} yr^{-1} in WY1965, largely as a result of a major event in December 1964. Only 4413 t km^{-2} yr^{-1} was supplied by suspended load, the rest moving as bed load; the majority of the sediment came from roadfill with the rest from channel erosion [*Grant and Wolff*, 1991]. The next highest yields were 219 t km^{-2} yr^{-1} in WY1964 and, again more distantly from the time of logging, 439 t km^{-2} yr^{-1} in WY1972. WS2 shows the highest control yield (159 t km^{-2} yr^{-1}).

Out of 34 logged catchments (there are no data for Fukuroyamasawa in Japan), 28 (82.4%) have a maximum specific yield of <300 t km^{-2} yr^{-1}, while 53% have yields of <100 t km^{-2} yr^{-1} (Figure 2). Of 16 control catchments (including the "natural" Balqhidder control but not Fukuroyamasawa), all have yields of <160 t km^{-2} yr^{-1}, 75% have yields of <100 t km^{-2} yr^{-1}, and half are <50 t km^{-2} yr^{-1}. The highest yields in the logged catchments appear to be associated with treatment involving burning, heavy road use, and extreme events. In general, though, logging in the regions considered seems to provoke maximum yields of less than a few hundred t km^{-2} yr^{-1} and modern BMP appears capable of reducing this below 100 t km^{-2} yr^{-1} and even below 10 t km^{-2} yr^{-1} in some cases. Such figures contrast with, for example, typical maximum yields of high hundreds to thousands of t km^{-2} yr^{-1} in areas affected by wildfire, especially in semiarid and steepland areas [e.g., *Lavabre and Martin*, 1997; *Martin and Lavabre*, 2000; *Moody and Martin*, 2001, 2009; *Desilets et al.*, 2007].

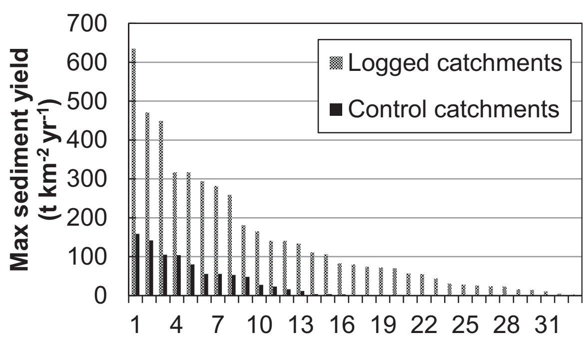

Figure 2. Summary of maximum annual sediment yields in the years following logging, ranked by size. The rankings of the logged and control catchments are independent of each other. The yield for H.J. Andrews Forest catchment WS3 (18,090 t km^{-2} yr^{-1}) is not shown to avoid distorting the scale.

Yields for undisturbed natural forest seem to vary over a similar range to the control catchments, with the higher values related to landslides and major storm events. Values may otherwise fall well below 10 t km^{-2} yr^{-1} [e.g., *O'Loughlin et al.*, 1978; *Miller*, 1984].

The maximum postlogging annual yields were also plotted against catchment area (Figure 3). In the case of partially logged catchments, the area is the total catchment area corresponding to the outlet at which the sediment yields were measured. As in Figure 2, there is considerable overlap of the yields between the logged

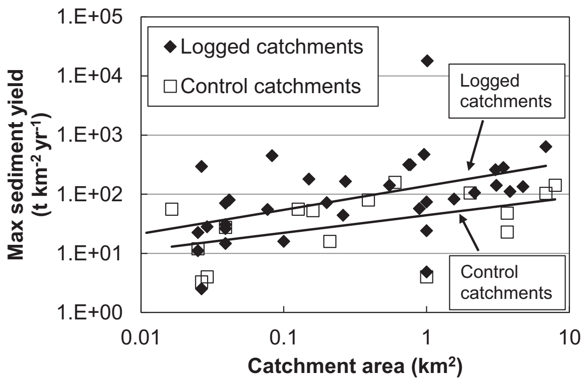

Figure 3. Summary of maximum annual sediment yields in the years following logging, as a function of catchment area. The fitted equations are given in the text.

and control catchments, although the control catchment data tend to lie at the lower edge of the logged catchment data. In both cases, there is a weak dependency on area but with significant scatter. Regressing maximum specific sediment yield (SY_{max}) in t km^{-2} yr^{-1} on catchment area (A) in km^2 gives:

$$\text{logged catchments } SY_{max} = 138.3A^{0.405} \quad r^2 = 0.215 \tag{1}$$

$$\text{control catchments } SY_{max} = 44.1A^{0.298} \quad r^2 = 0.249 \tag{2}$$

The exponents in these equations are significantly different from zero [regression analysis: $P = 2.66 \times 10^{-17}$ (logged) and 1.49×10^{-8} (control)] but are not significantly different from each other (t test: $P = 0.5415$). However, the relationship for the control catchments may be biased by the data for the small catchments (<0.04 km^2) in Texas and Oklahoma (Alto-A, Alto-B, Angelina National Forest, and Ouachita). Removal of these sites from the analysis leaves the relationship almost horizontal (exponent 0.076). Analysis elsewhere has suggested that a positive relationship between specific sediment yield and catchment area may be indicative of the channel and its banks being the dominant sediment source, while an inverse relationship may indicate that the hillslopes are the dominant source [*Dedkov and Moszherin*, 1992; *Dedkov*, 2004]. *De Vente and Poesen* [2005] have also proposed a model in which specific sediment yield increases with area from plots to the small catchment scale (not well defined but around 1 km^2 or so), as a function of the increase in active erosion processes and in connectivity. The relationship becomes inverse at larger scales. Care must be taken in adopting these interpretations in this case, though, as relationships between sediment yield and catchment area are usually determined for single catchments or for catchments within a region of homogeneous characteristics, rather than at a world scale. Also, they are usually derived on the basis of mean, rather than maximum, sediment yields. Further, the maximum catchment scale considered here (<10 km^2) is small compared with that in many analyses of area dependency.

4.2. Impact of Logging on Annual Sediment Yield—Impact Relative to Control Catchments

The control catchments provide the basis for quantifying the relative impact of logging. Figure 4, therefore, plots the annual specific sediment yields for the logged catchments against the corresponding yields for their respective controls, for those cases where there was a sufficiently long prelogging period to establish a baseline (generally 3 years or more), namely the H.J. Andrews Forest, Hawke's Bay, Caspar Creek, Alsea, and Balquhidder catchments. Apart from the Hawke's Bay control, which was grassland, and the Balquhidder control, which was estimated, the controls are plantation, rather than natural, forest catchments. The comparison, therefore, quantifies the impact of logging relative to catchments which have not been logged, within the same period. In the case of Caspar Creek, annual totals were obtained from the data record by summing the individual storm totals over the year. However, not all the storms were measured and the same storms were not all measured across all the catchments. Therefore, only those storms that were measured in all the catchments were summed. In some years, this was only one event, although usually a large one. Thus, the total yields used for Caspar Creek in Figure 4 are likely to be less than the actual annual yields but it is assumed that they are valid for showing relative effects. Also for Caspar Creek, the control catchment data (denominated HI) are the average for two catchments (HEN and IVE) as recommended by *Lewis et al.* [2001]. As it was impractical to show all the Caspar Creek catchments only two are shown in the figure, representing the extremes in relative postlogging response for the fully logged headwater catchments. For each catchment, a baseline relationship is shown for the prelogging period; for the purposes of the exercise, it was sufficient to establish these by eye. The data for the postlogging period, and for the logging period itself where this was relatively extended, are then compared with the baseline. Clearly, there are variations from year to year but, with one exception, all the postlogging data lie within an order of magnitude of the baseline.

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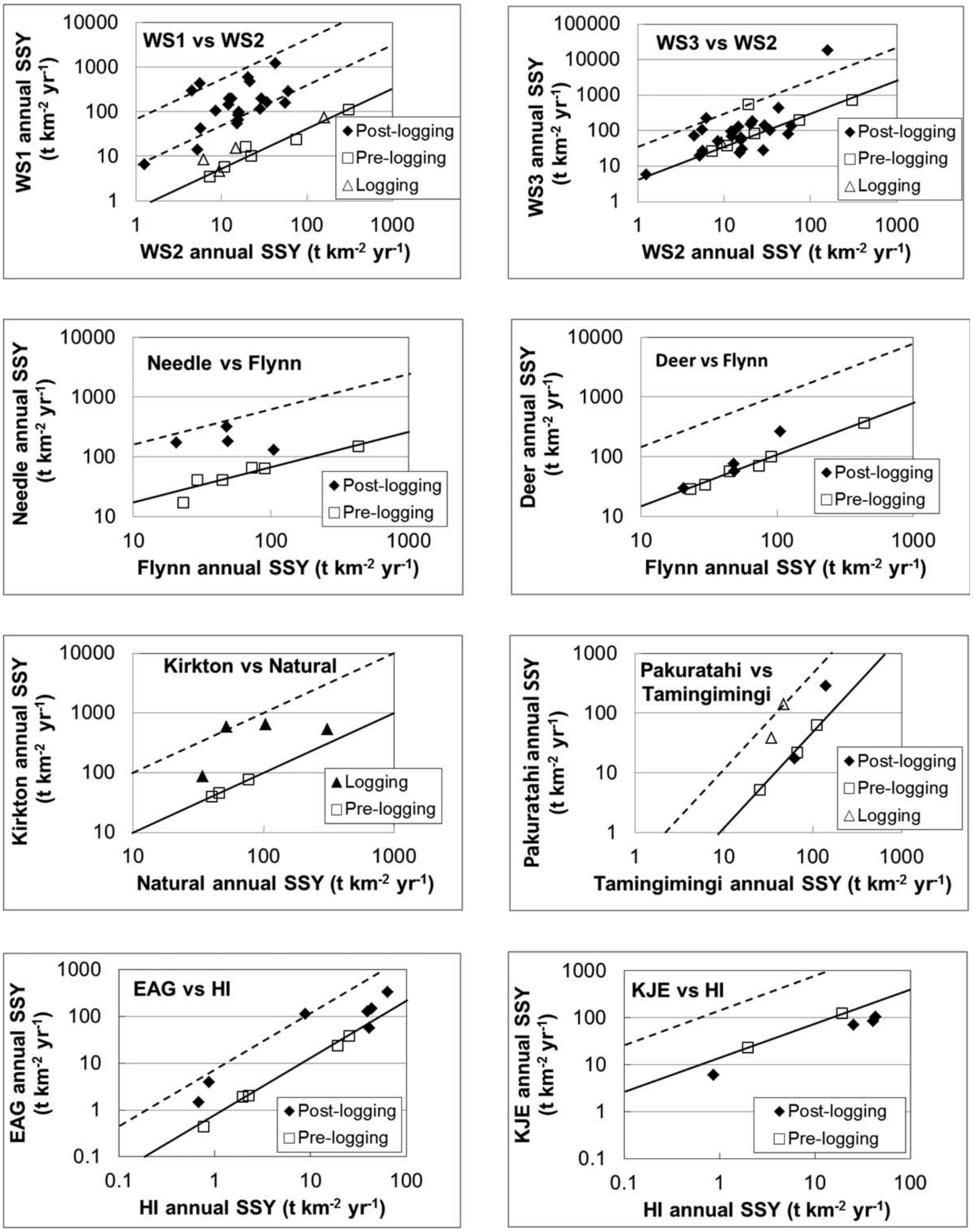

Figure 4. Comparison of the annual specific sediment yields for a selection of the logged catchments with the corresponding yields for their respective controls. The solid line is the baseline prelogging relationship; the dashed line is displaced up the abscissa by 1 order of magnitude.

The exception is the H.J. Andrews WS1 catchment, where the postlogging data spread over 2 orders of magnitude. For the WS3 catchment, only the 1 year with an exceptional storm produced a sediment yield of >1 order of magnitude greater than the baseline. The Kirkton catchment produced one annual yield that is just over the boundary of an order of magnitude. The logging period in this catchment involved heavy road use and was also a relatively wet period.

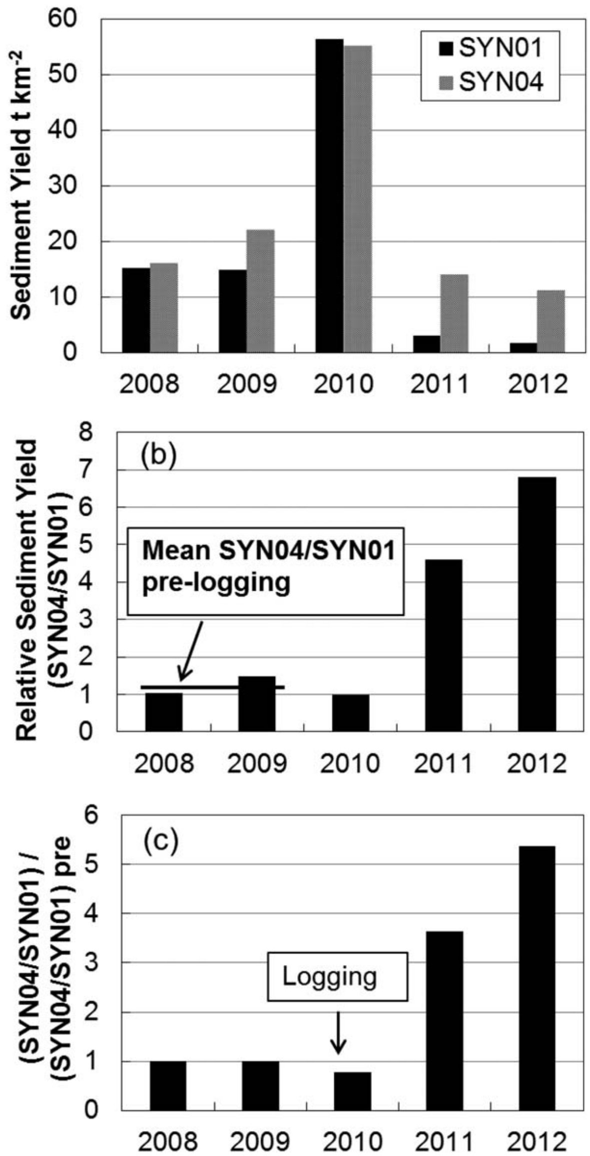

Figure 5. Calculation of relative response SY^* for the Nacimiento catchment N04. (a) Annual sediment yields for the logged and control catchments. (b) Ratio of annual yields (logged/control) and the mean value for the prelogging period. (c) Ratio of annual yields divided by the mean prelogging ratio.

This comparison suggests that the maximum additional impact on sediment yield does not exceed 1 order of magnitude under normal circumstances of BMP. However, poorly practiced burning, heavy road use, or extreme events can push the impact up by another order of magnitude.

4.3. Impact of Logging on Annual Sediment Yield—Impact Relative to Control Catchments and Prelogging Period

Full quantification of the impact of logging requires the postlogging response to be compared simultaneously with not only the response in the control catchment but also the prelogging response. A relative response factor for annual specific sediment yield was therefore calculated as $SY^* = (SY_l/SY_c)_i/(SY_l/SY_c)_{pre}$, where SY is specific sediment yield in t km^{-2} yr^{-1}, subscript l refers to the logged catchment, subscript c refers to the control catchment, subscript i refers to a year in the postlogging period and subscript pre refers to the mean value for the prelogging period. In other words, the ratio of the sediment yields for the logged and control catchments for a year in the postlogging period is compared with the mean ratio for the prelogging period (Figure 5). Thus, for example, if the sediment yield following logging is twice the yield in the prelogging period but the yield in the control catchment also doubles, then the relative response is unity and the impact is effectively zero.

The reliability of the relative response factor clearly depends on the length of the prelogging period and a period of 3–5 years will provide a sounder base for comparison than 1–2 years.

The maximum annual value of the relative response factor from the postlogging period (denominated SY^*_{max}) was calculated for 32 logged catchments (excluding the Maimai and Ouachita sites but including the Fukuroyamasawa site, relative to the data used for Figure 2) (Table 2 and Figure 6). The Caspar Creek values are based on annual yields determined from only those storms that were measured in all the catchments and the control catchment is HI, the average of HEN and IVE. Comparing the relative response values with the catchment treatments allows three specific impact ranges to be delineated, one of which can be further subdivided into two. The boundary values of the ranges are selected for numerical convenience but lie within the data gaps separating the different impact ranges (see Figure 6). There is, therefore, a small degree of both arbitrariness and empiricism in the selected values, which can be reduced only with more data.

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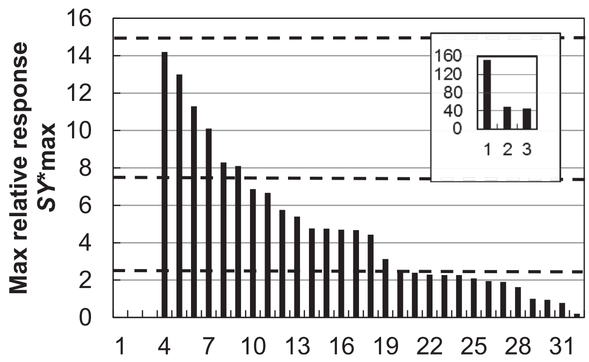

Figure 6. Summary of maximum relative responses *SY** in the years following logging, ranked by size. The responses for the H.J. Andrews Forest (1 and 3) and Alto-A (shearing) (2) catchments are shown inset to avoid distorting the scale. The dashed lines indicate the boundary values of *SY** as defined in the text and Table 3.

1. $SY^*_{max} < 7.5$: low-moderate impact. The relevant catchments are most of the Caspar Creek and Alto-A and B sites, the Angelina National Forest sites, Fukuroyamasawa, Nacimiento 4, Tanllwyth, and Deer Creek. These correspond to treatments according to modern BMP, including careful use of burning and roads, cable or skyline logging, and dry season logging or coincidence of logging with relatively low or average rainfall. (For the Angelina National Forest rainfall was mostly above normal but in the prelogging as well as postlogging periods.) The SY^*_{max} range may be subdivided about the value of 2.5. Lower values, given the margin for error in the basic data, must effectively indicate little or no impact or an inverse impact (e.g., where logging debris in the stream channels acts to trap sediment and the sediment yield impact declines following logging). Higher values indicate a moderate impact. Separation of these subdivisions is partly a function of the logging methods and subsequent land treatment but is also a function of the ratio of the sediment yields for the logged and control catchments for the prelogging period. Thus, the Angelina National Forest catchment ANF4 has a low SY^*_{max} value (2.27) while ANF1 has a higher value (5.76) despite undergoing the same logging treatment, because ANF4 has a relatively high sediment yield in one of the prelogging years and this has the mathematical effect of reducing its SY^*_{max} values.
2. $SY^*_{max} = 7.5$–15: high impact. The relevant catchments are Hore, Kirkton, Needle Branch, Pakuratahi, and Caspar Creek BAN. Apart from BAN (considered in section 5), these correspond to sites with extensive ground disturbance from burning, roads and landings, skidder logging and timber harvester machinery, and intensive treatment for rapid stand reestablishment. They may also include sites with relatively wet (but not extreme) conditions postlogging.
3. $SY^*_{max} > 15$ very high impact. This corresponds to the two H.J. Andrews Forest sites, which suffered from intensive burning and (for WS3) roads and an extreme event, and the Alto-A site that underwent shearing, which apparently left little mulch or vegetation to protect the soil and also resulted in scalping of the soil on steeper slopes [*Blackburn et al*., 1986].

Figure 7 shows that SY^*_{max} does not necessarily vary as the maximum specific sediment yield, nor do these two maxima necessarily occur in the same year. There is also no clear dependency of relative response on catchment area. For example, for catchments of about 1 km^2, SY^*_{max} ranges from 0.2 to 151 (Table 2).

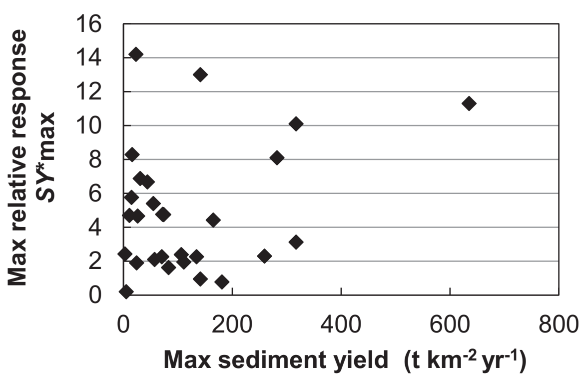

Figure 7. Comparison of maximum annual relative response *SY** with maximum annual sediment yield in the years following logging. The responses for the H.J. Andrews Forest (WS1: 471, 151; WS3: 18,090, 45.3) and Alto-A (shearing) (294, 48.3) catchments are not shown to avoid distorting the scale.

4.4. Impact of Logging on Storm Event Sediment Yield

Instantaneous sediment transport is as important as annual yield in characterizing water quality for compliance with BMP. In particular, the high yields that might breach any quality thresholds are most likely during storm events. Storm sediment yield data are available only for the Caspar Creek and Hawke's Bay catchments and Figure 8, therefore, plots the yields for these catchments against the corresponding control yields, separating events before, during and after logging. For Caspar Creek, the control

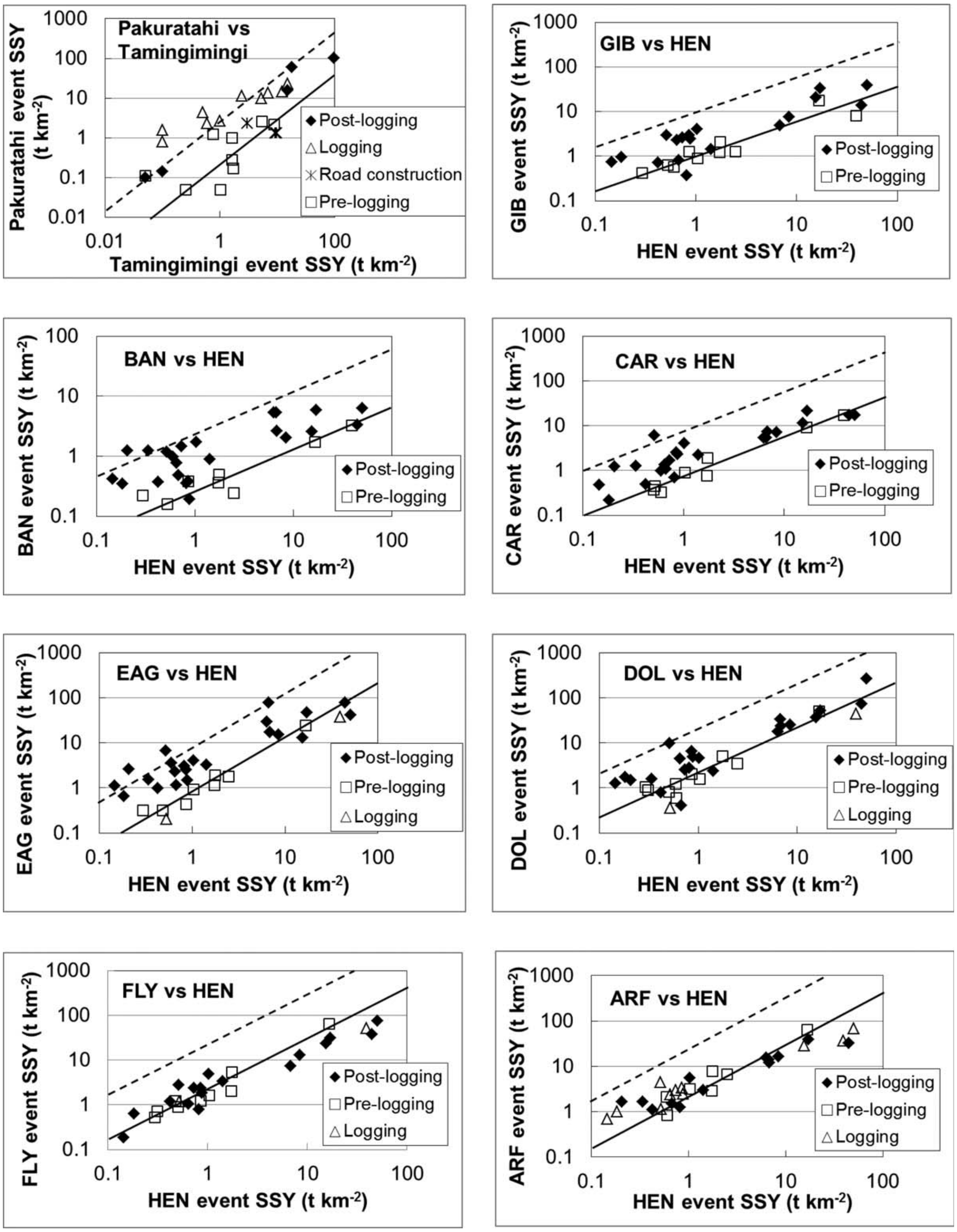

Figure 8. Comparison of the event-specific suspended sediment yields (SSY) for a selection of logged catchments with the corresponding yields for their respective controls. The solid line is the baseline prelogging relationship; the dashed line is displaced up the abscissa by 1 order of magnitude.

catchment is HEN on its own, as this maximizes the number of storms that can be used. As in Figure 4, the prelogging data form a baseline against which the subsequent data can be checked. Also as in the annual case, an approximate order of magnitude rule seems to apply, at least for the given conditions, i.e., the maximum increase in storm sediment yield following logging is 1 order of magnitude larger than the control

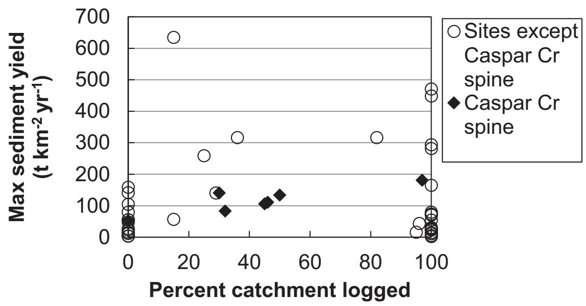

Figure 9. Variation of maximum annual sediment yield in the years following logging against the percentage of catchment logged. The yield for H.J. Andrews Forest catchment WS3 (18,090 t km^{-2} yr^{-1} at 25% logged) is not shown to avoid distorting the scale.

sediment yield. However, as noted by *Lewis et al*. [2001] in their analysis of the Caspar Creek data, the yields for the smaller storms tend to have a wider range than the yields for the larger storms (in relative terms) and are more likely to achieve the 1 order of magnitude increase.

4.5. Variation of Sediment Yield With Proportion of Catchment Logged

The variation of maximum annual sediment yield against the percentage of catchment logged (Figure 9) suggests that, overall, the maximum yield increases as the percentage of catchment logged increases. However, the scatter in the data is too great to enable a generalized relationship to be quantified. In particular, there is considerable overlap between the yields at 0 and 100% logging. Also, the diagram does not include the point for the H.J. Andrews catchment WS3, which is far off the scale (18,090 t km^{-2} yr^{-1} at 25% logged). If only the data for the Caspar Creek spine (MUN, KJE, JOH, LAN, FLY, ARF, and NFC shown as solid points in the diagram) are considered, though, there is a rather firmer suggestion of a relationship, showing an increase in maximum yield with percentage of catchment logged.

Plotting SY^*_{max} against the percentage of catchment logged (Figure 10) does not improve over Figure 9. There is no clear relationship for any data grouping and there is a wide range of SY^*_{max} values for fully logged catchments. The Caspar Creek spine data are shown separately and form a coherent group but the pattern is distorted by the presumed influence of the KJE headwater catchment. That catchment featured a reduction in sediment yield relative to the control catchment after logging, a point that was noted but not explained by *Lewis et al*. [2001]. By reducing relative sediment yield at the head of the spine, though, it is likely to have had a knock-on effect on the values further down the system, so that, for example, the main spine relationship for SY^*_{max} lies below the relationship for the separate tributary system of DOL and EAG.

4.6. Period of Significant Impact

In the years following logging, the sediment yield will be determined by the logging technique itself, the presence of forest roads, any postlogging treatment, any replanting schedule, weather variations, in-channel erosion or blockage, and the rate at which revegetation occurs. In general it might be expected that an initially high sediment impact in the years immediately following logging would be followed by a period of declining annual yields, tending toward the regime in place before the logging. Two key times to identify are therefore the year following logging in which the maximum sediment yield impact occurs and the period over which the impact declines to a negligible value.

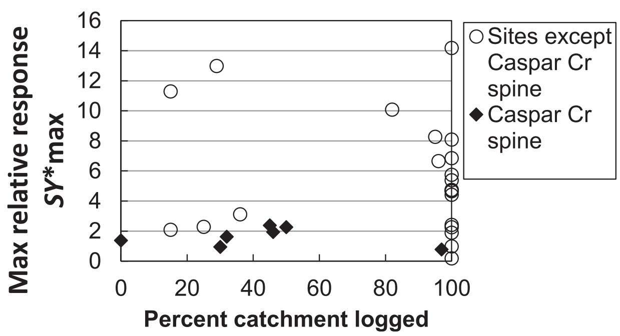

Figure 10. Variation of maximum relative response *SY** in the years following logging against the percentage of catchment logged. The responses for the H.J. Andrews Forest catchments WS1 (151 at 100% logged) and WS3 (45.3 at 25% logged) and the Alto-A (shearing) catchment (48.3 at 100% logged) are not shown to avoid distorting the scale.

The limited length of the available postlogging data series restricts this analysis, especially for the period of recovery. Nevertheless, Figure 11 shows that the majority of catchments (about two thirds) did indeed deliver their maximum postlogging sediment yield in the first 2 years after logging. However, a significant proportion of catchments still

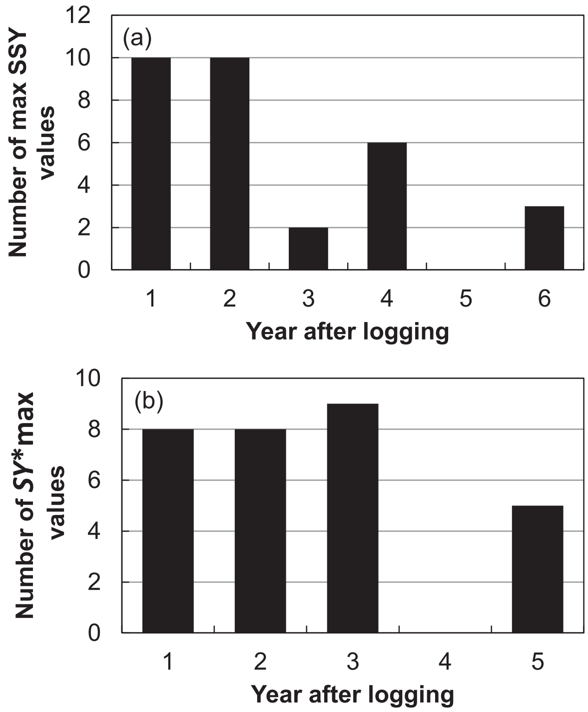

Figure 11. The distribution through time of the occurrence of (a) the maximum sediment yield and (b) the maximum relative response *SY** in each logged catchment following logging. Number of occurrences is shown for each year after logging.

delivered their maximum yield over the subsequent years. This distribution can be converted into a cumulative probability distribution, which allows a quantitative estimate of the year in which the maximum postlogging sediment yield will occur (Figure 12). (This is restricted by the available data to an overall period of only 6 years.) For the maximum relative response *SY**, though, there is a more even distribution and similar numbers of catchments deliver their peak values in years 1, 2, and 3.

The information in Table 2 shows that the recovery time is very variable between the catchments. Some catchments have a lower sediment yield after logging than before. Others do not recover in the period of data (over 20 years in the case of WS1). Some show relatively little impact except for one exceptional year. Others show fluctuations from year to year. A few suggest recovery in around 4 years. There is no obvious general pattern and it seems that the multiple effects noted above preclude the possibility of a general quantified relationship for the recovery period.

5. Discussion

Limitation of the field sites to those from temperate forests appears to provide an overall data set sufficiently coherent and internally consistent to permit the development of expressions that are generally applicable to temperate regions around the world. The analysis indicates the extent to which the generalized expressions proposed earlier in the paper can be represented in quantitative terms.

The impact of logging on annual sediment yield in the years immediately following logging, as a function of intervention, is quantified in terms of the absolute values of specific sediment yield, the values relative to those in control catchments for the same period and the values relative both to the control catchment and the period before logging (using the relative impact factor *SY**). Maximum values of sediment yield and *SY** in the postlogging period are used to quantify worst case conditions. At the annual scale, three categories of impact can be distinguished with quantifiable limits: low-moderate impact, high impact, and very high impact (Table 3). The quantitative limits are based on the data.

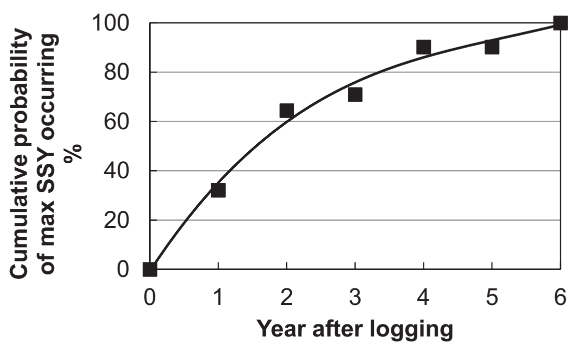

Figure 12. Cumulative probability of the occurrence of the maximum sediment yield in the years immediately following logging. Three-order polynomial fitted to the data points.

As an absolute value the maximum annual specific sediment yield incorporates the effects of catchment geology, topography, and other local characteristics in addition to the impacts

Table 3. Summary of Impact Categories

Category	Postlogging Qualitative Characteristics	Postlogging Quantitative Characteristics: Maximum Annual Relative Response SY^*_{max}	Number in Category	Maximum Annual Sediment Yield (Data Set Range) (t km^{-2} yr^{-1})	Annual Sediment Yield Excess Over Control Catchment	Event Sediment Yield Excess Over Control Catchment
Low-moderate	Catchments logged according to BMP, with minimal ground disturbance	<2.5 2.5–7.5	13 10	2.5–259 11–317	Within 1 order of magnitude	Within 1 order of magnitude
High	Significant ground or stream bank disturbance	7.5–15	6	16–635	Within 1 order of magnitude	Within 1 order of magnitude
Very high	Extensive ground disturbance or affected by extreme events which boost the impact in the relevant year, possibly out of character with the surrounding years	>15 Maximum value in data set 151	3	294–18,090	Within 2 orders of magnitude	Not quantified

of logging, making it too blunt an instrument for generalizing the effects of logging intervention across multiple catchments. Thus for the given data set ranges in Table 3, although both the minimum and maximum values increase from the low to the moderate to the high impact categories, there is considerable overlap. All that can be said is that (Figure 2):

> *At the world scale, the maximum postlogging yield appears unlikely to exceed hundreds of t km^{-2} yr^{-1} except in very high impact scenarios such as intense burning, heavy road use, and extreme events.*

This places the response to logging between the extremes of maximum yields of high hundreds to thousands of t km^{-2} yr^{-1} in areas affected by wildfire and maximum yields well below 10 t km^{-2} yr^{-1} in undisturbed natural forests.

Comparison of the annual specific sediment yields for the logged and control catchments provides a means of quantifying the logging impact independently of local catchment characteristics. The uniformity of results across the sites (Figure 4) enables a quantitative generalization to be defined as follows:

> *For low-moderate and high impacts, the annual specific sediment yield in the logged catchment exceeds that in the control catchment by no more than an order of magnitude. For very high impacts, annual yields may be 2 orders of magnitude higher.*

A similar generalization applies to event specific sediment yields (Figure 8).

The relative response factor SY^*_{max} was defined to account not only for the differences between the logged and control catchments but also for nonstationary conditions (e.g., in rainfall) between the pre and postlogging periods. It forms the basis for the numerical definition of the impact categories in Table 3. However, as noted earlier, the limiting values in this table incorporate a degree of arbitrariness and empiricism as a function of the available data (Figure 6) and could change as more sites are analyzed. Also, the deployment of the factor in this study involves some variation in the number of prelogging years (and therefore potential inconsistency in the basis for the impact comparison) between the test catchments. The factor should also be interpreted with care since the maximum value does not necessarily correspond to the maximum specific sediment yield. Thus, it is possible to obtain a high relative response for years with low absolute sediment yields while years with high absolute yields may have lower relative values (Table 2). For example, the highest postlogging annual specific sediment yield for Caspar Creek BAN, in 1995, was 12.82 t km^{-2} yr^{-1} but this was matched by a high yield in the control catchment (43.51 t km^{-2} yr^{-1}) so that $SY^* = 1.21$, a low value. In 1994, the yields were lower but the yield for BAN was double the control yield (1.73 versus 0.87 t km^{-2} yr^{-1}), so that $SY^* = 8.29$, a high value. The relatively high SY^*_{max} values for Caspar Creek CAR and Nacimiento 4 (Figure 5) similarly refer to impacts on relatively low yields.

The poor correlation between SY^*_{max} and the maximum specific sediment yield shown in Figure 7 is perhaps confirmation that the absolute values of specific sediment yield are an insufficient basis for forming a quantitative generalization. However, complementary use of the maximum annual values of specific sediment yield and relative response factor may provide helpful information. For example, a high relative response factor coupled with a relatively low specific sediment yield (e.g., Alto-B intensive, $SY^*_{max} = 14.2$, yield = 23 t km^{-2} yr^{-1}) could imply elevated background sediment concentrations of potential long-term harm to aquatic life. By contrast, a low relative response factor coupled with a high specific sediment yield (e.g., Deer Creek, $SY^*_{max} = 2.3$, yield = 259 t km^{-2} yr^{-1}) would imply that the logging has not greatly increased the yield but the yield is nevertheless significant and would need to be accounted for in, say, culvert design. A high relative response factor coupled with a high sediment yield (e.g., Kirkton, $SY^*_{max} = 11.3$, yield = 635 t km^{-2} yr^{-1}) would indicate a significant impact characterized by a large increase in yield.

Considering the effect of partial logging, at the collective scale:

> *There is no apparent general relationship between sediment yield impact and the proportion of catchment logged (Figures* 9 *and* 10*).*

This confirms the expectation that the relationship between sediment yield and percentage of catchment logged would not be as clear as it is for runoff and percentage logged. Nevertheless, it is important to have this negative conclusion supported by evidence. Location of logging is likely to be as important as area logged for the sediment yield as it determines the connectivity with the stream network. Currently, though, there are insufficient data with which to investigate this hypothesis, nor do there appear to have been any appropriate modeling studies.

However, the absence of a general relationship does not necessarily mean that partial catchment logging is ineffective in reducing sediment yields, as it may be possible to define *individual* relationships for nested catchment systems. Further research is needed to confirm this. Where the logging impact is affected by more intense ground disturbance or extreme events (as for the H.J. Andrews Forest sites) it seems unlikely that a relationship exists.

The data do not enable quantification of the distance downstream of a logged area at which the sediment impact remains significant. There does not seem to be any published study of the downstream effect of logging in a headwater catchment nested in a larger, otherwise unlogged, catchment. In the Caspar Creek study, for example, logging was carried out throughout the various catchment scales. However, *Bathurst et al*. [2010] describe a modeling study in which the downstream effects of a vegetation change in the 172 km^2 headwaters of a 1532 km^2 were simulated. Comparison of the downstream variation in specific sediment yield for the two vegetation cases (first with wheat in the entire catchment and then a change to forest in the headwaters) showed that sensitivity to the changed land use was high immediately downstream of the headwater catchment but decreased downstream as the proportion of the total contributing area represented by the headwater catchment decreased. Rather approximately the difference in specific sediment yield was reduced to 10% of the initial value for a catchment area 10 times the headwater catchment area. Such an order of magnitude relationship is at least consistent with the general derivation of order of magnitude relationships in other aspects of the logging impact noted above.

Considering the recovery from logging, the data are sufficient to quantify an approximate cumulative probability distribution, which allows an estimate of the year in which the maximum postlogging sediment yield occurs (Figure 12). On this basis:

> *Two thirds of logged catchments deliver their maximum postlogging sediment yield in the first 2 years after logging.*

Finally:

> *There is no obvious quantitative generalization concerning the time for recovery to prelogging conditions.*

The above generalizations should be viewed in the context of the approximate nature of the results, noting that the uncertainties in quantifying soil erosion and sediment yield are rather larger than for water yield. They refer to the broad response to logging as a function of ground disturbance, for example, by logging technique, roads, and burning. The study does not include the response to landslides that may occur some years after logging in response to decay of the tree roots in steeply sloping catchments.

Order of magnitude generalizations are inevitably rather broad rules but provide a basis for first estimates and for a general appreciation of an impact problem. To the extent that they are relatively simple, they should aid the spread of knowledge amongst both relevant professionals and new students. Given the uncertainties associated with erosion and sediment transport, they may be the most accurate that can be achieved in the general case. Greater accuracy would have to be sought in particular cases through field and/or model studies.

A limitation of the data used in this study is that the catchments are relatively small ($<$10 km^2) and in temperate regions. The research could therefore be widened to larger catchments (in which dilution and attenuation effects may complicate responses) and to tropical regions.

6. Conclusions

Until now, quantitative relationships of the type describing the impact of forest logging on water yield have not been matched by relationships linking logging and sediment yield impact. This paper has therefore brought together published data from studies in temperate forest areas of the world with well-established forestry sectors to investigate the extent to which certain general questions concerning the impact of logging on sediment yield can be answered quantitatively. The following quantitative generalizations are proposed on the basis of the analysis:

1. Three categories of impact may be specified: low-moderate, high, and very high, as shown in Table 3. These are characterized by specific ranges in the maximum value of the relative response factor SY^* in the years immediately following logging.
2. At the world scale, the maximum postlogging annual specific sediment yield appears unlikely to exceed the hundreds of t km^{-2} yr^{-1} except in very high impact scenarios.
3. For low-moderate and high impacts, the annual specific sediment yield in a logged catchment exceeds that in an undisturbed control catchment by no more than an order of magnitude. For very high impacts, annual yields may be 2 orders of magnitude higher. A similar generalization applies to event specific sediment yields.
4. A cumulative probability distribution quantifies the year in which the maximum postlogging sediment yield will occur (Figure 12).

There is no apparent relationship between sediment yield impact and the proportion of catchment logged at the general scale, although it remains to be confirmed if individual relationships can be defined for nested catchment systems. Nor is there enough information to determine how far downstream of a logged area the sediment impact remains significant. There is also no apparent generalization for the time required for recovery to prelogging condition.

Review of the quoted studies suggests that the application of modern Best Management Practice should enable the impact to be limited to the low-moderate category, unless the immediate post-logging period is so unfortunate as to coincide with a major storm event or other geophysical disaster.

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