FINAL REPORT

The response of algal communities in streams of the Jackson Demonstration State Forest to timber harvest activities

by

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Abstract

Significantly more of the nuisance filamentous alga *Cladophora* was found in Hare Creek (logged stream) than in NFSF Noyo (unlogged). Minimum levels of solar radiation and water velocity required for the establishment of *Cladophora* were significantly lower on Hare than on NFSF Noyo, and *Cladophora* on Hare Creek initiated growth earlier in the spring than on NFSF Noyo. The greater range of suitable habitats and the earlier initiation of growth on Hare are indicative of higher nutrient levels. Logging can act to increase Cladophora in two ways, either by opening the canopy and increasing solar radiation above the threshold level needed for establishment or by increasing nutrients and lowering the threshold levels of solar radiation and velocity.

Non-filamentous algal biomass growing on artificial substrates was significantly lower in Hare Creek than in NFSF Noyo, and this difference in non-filamentous algal biomass could not be ascribed to either lower total invertebrates, or lower invertebrate grazers. Variations in solar radiation had little effect on algal biomass.

Peak suspended sediment levels were five times higher on the logged stream, Hare Creek, than on the unlogged stream, NFSF Noyo, during a storm in March 1985. Comparison of algal biomass growing on ceramic tiles, sampled before and after the storm, revealed that suspended sediment had no effect on the periphyton of the unlogged stream but completely abraded the periphyton on the logged stream.

INTRODUCTION

The concern for stream protection during logging operations is reflected in numerous studies documenting the deleterious effects of timber harvesting on stream biota (Gibbons and Salo, 1973). A preponderance of this research has been directed towards fish and invertebrates with the result that relatively less is known about the possible effects of logging on primary producers. Our research in the Jackson Demonstration State Forest has focused on the primary producers and on what factors associated with timber harvesting may affect their population structure.

Responses of fish and invertebrates have been suggested by some to reflect changes in food pathways as a result of logging (Murphy et al., 1981; Hawkins et al., 1982). Hence the algal community should be a sensitive indicator of subsequent changes in higher trophic levels.

BACKGROUND

Logging can produce many potentially damaging changes to the stream environment resulting in economic and aesthetic losses. The water quality problems associated with logging include: increased fine sediment; increased light; 'increased nutrients; larger temperature fluctuations; larger peak flows and the introduction of small organic debris (Hall and Lantz, 1969; Gibbons and Salo, 1973; Erman et al. 1977).

Because these physical-chemical alterations often occur in concert and there are many potentially confounding interactions, one often cannot identify the primary causative agents of deleterious changes in the stream biota. Therefore, it is also difficult to determine management remedies. Bufferstrips are often the only practical means of protecting a stream as buffers theoretically can eliminate all the effects of logging by removing the operation to a prescribed distance from the stream.

The general objective of this study was to ascertain how the various potential changes introduced by logging, in particular increases in light and fine sediment, individually and together, affect stream plant communities. This knowledge could then be applied towards designing more effective bufferstrips or devising other mitigating strategies.

The study examined three aspects of the possible effects of logging on stream plant communities. The first area of research explored the relationship between logging and algal species composition changes; specifically whether or not logging favors the growth of filamentous green algae. The second aspect was the influence of forest practices on diatom algal standing crop in streams. The third major objective of the study was to determine the effect of suspended sediment in streams on algal communities. These three aspects are discussed in order.

STUDY SITE

Hare Creek, whose watershed was logged continuously from 1974 to 1984 and the North Fork of the South Fork of the Noyo River (NFSF Noyo) which has not been logged for at least 50 years were chosen as the treatment and control streams respectively (Fig. 1 and 2). These two streams were selected because they provided the greatest contrast of logged and unlogged conditions found on the Jackson State Demonstration Forest, they have similar vegetation and drainage area, and are in close proximity. In addition, these two streams were examined by Erman et al. (1977) in a previous study on the biological effects of logging on streams.

The vegetation on both watersheds is typical of forests on the north coast of California, composed mainly of Douglas-fir (*Pseudotsuga menziesii*) and coast redwood (*Sequoia sempervirens*). The parent material for each watershed is primarily Franciscan sandstone. The drainage area above the Hare Creek study section is 12.8 km^2 and above the Noyo 10.9 km^2. Hare Creek has a narrow buffer and a road adjacent to this buffer for much of its length.

SECTION I

LOGGING AND ALGAL CHANGES

Introduction

A thin (4 to 5 cells thick) brown film of unicellular diatoms attached to the substrate of the stream is the most common algal community found in northwestern coastal streams that have relatively closed canopies. Hansmann and Phinny (1973) observed the growth of large mats of green algae in an Oregon stream in the years following logging where previously there were only diatoms. Long strands or mats of filamentous green (Chlorphyta) algae are visually and ecologically a distinctly different type of algae from diatoms. These mats of filamentous algae can be composed of several species or, as is more common in streams, they are monospecific. In this portion of our study we determined the abundance of filamentous green algae in a logged and unlogged stream and examined ecological conditions necessary for its presence or absence.

In Jackson State Forest the only filamentous algae observed was *Cladophora* sp. *Cladophora* is a very common algal taxon found in many environments worldwide. It is a green algae capable of growing several meters long, and is usually considered a nuisance (Blum, 1956; Whitton, 1970). Some reasons why it is considered a nuisance algae **are** aesthetic (long green algae are often referred to as pond scum); it is slippery to walk on (a common problem for anglers); it can clog waterways; it can reduce night time oxygen levels from respiration; and it can clog interstices of rocks and decrease microhabitat for insects when it decays (Whitton, 1970).

The prevalence of Cladophora has been greatly increased by human disturbance (Whitton 1970). This increase stems from the fact that Cladophora is usually limited by either light or nutrients (particularly phosphorus), both of which may be significantly increased by many types of land use, in particular, logging. Our objective was to determine if logging had enhanced the growth of Cladorphora in Hare Creek.

It is well known that logging can, through canopy removal, increase the light reaching a stream and may therefore increase the growth of Cladophora in this way. But Cladorphora is more abundant and robust in areas of high velocity and is often confined to them. Thus stream velocity is also important, primarily for the delivery of nutrients, which also limit its growth. Our approach was to determine the minimum requirements of light and water velocity required for the growth of Cladorphora. After establishing these thresholds we compared the thresholds between the logged and unlogged streams to see whether or not there are effects that might be ascribed to logging irrespective of changes in light due to nutrient increases.

Methods

To determine under what conditions Cladophora was established, a study reach of approximately 0.5 km was chosen on each stream (Fig. 2). Two surveys were conducted between July 2 and July 15, 1984. One. was concerned with the effects of light on Cladophora and the other was concerned with the effects of velocity on Cladophora.

The survey to determine the minimum light requirements of Cladophora was confined to riffles so that velocity would be similar and because Cladophora was only present in riffles on NFSF Noyo. At six riffles on each stream the percent cover of Cladophora, the total daily solar radiation (photosynthetically active radiation 400 to 700 nm waveband hereafter referred to as solar radiation), stream velocity and depth were measured. Solar radiation was determined using the photometer (Li-Cor 192S) method (Appendix 1). Percent cover of Cladophora was determined for each riffle by randomly selecting four plot centers and placing a grid (25.4 x 25.4 cm) with 100 squares over the selected point. For each square the predominant algal taxa was recorded. At each plot center depth and velocity (Gurley pigmy current meter) were measured.

The photometer method is extremely time consuming and another procedure was used to complete the survey of the effects of light on Cladophora. For all remaining riffles within the study reaches, light was determined using the modified angular canopy density method (Appendix 1). A single velocity measurement was taken in the center of the riffle using the Gurley pigmy current meter.

To determine the minimum threshold velocity for the presence of

Cladophora a second survey was conducted to supplement the velocity data obtained in the first survey. As all riffles had been previously sampled this survey was confined to pools and runs. Presence or absence of Cladophora was recorded and water velocity was measured and a qualitative rating of the amount of light reaching the stream was made.

The minimum threshold velocity for the establishment of Cladorphora for each stream was taken to be between the fastest velocity that did not contain Cladophora and the slowest that did contain Cladophora. Minimum threshold levels of light *were* established similarly.

Dates of the first initiation of growth of Cladophora were noted during preliminary visits to the streams.

Orthophosphate and nitrate in both streams *were* measured in July and August 1984. Water samples were taken (in iodine treated plastic bottles) before dawn directly below a riffle in the center of each study reach.

Orthophosphate was determined using the ascorbic acid method and nitrate using the cadmium reduction method (Standard Methods, 1980). Temperature extremes were measured using maximum-minimum thermometers.

Results

The results of the initial survey to determine the minimum light requirements of Cladophora are presented in Table 1. Figure 3, using the data from Table 2 and the supplementary surveys, shows the range of total daily solar radiation for which Cladophora was present or absent on each stream. Cladophora on Hare Creek grew in reaches of stream with much less light than it did on NFSF Noyo. The threshold total daily light on Hare Creek was between 3.9 x 10^6 μ E/m2 and 5.7 x 10^6 $\mu E/m^2$. The threshold total daily light on NFSF Noyo was between 9.8 x $10^6 \mu E/m^2$ and 12.2 x $10^6 \mu E/m^2$.

Figure 4 shows all values of velocity for which Cladophora was present or absent in the study reaches. On the NFSF Noyo Cladophora was found in riffles where the stream velocity was at least 0.35 m/s, never in runs or pools. On Hare Creek Cladophora was found not only in riffles and runs but in essentially standing water where the current was unmeasurable.

cladophora initiated growth on Hare Creek in mid-May but growth on NFSF Noyo did not begin until late June.

Phorphorus and nitrogen levels measured in the months of July and August *were* never significantly different between the two streams, nor were maximum and minimum temperatures different (Appendix 2).

Discussion

Cladophora was found in only six extremely well-lit (>12 x $10^8 \mu E$) riffles in the entire 0.5 km study area on the NFSF Noyo and was never observed on any other site in the watershed. In Hare Creek Cladophora was present on all but the very darkest riffles and in many runs and pools. Cladophora also initiated growth a month earlier on Hare Creek than on NFSF Noyo. These results all indicate that logging has significantly increased the growth of Cladophora on Hare Creek.

Hare Creek watershed was selectively logged and a bufferstrip was left, thus an increase in light was minimal and therefore not the reason that Cladophora was more abundant on Hare Creek than on NFSF Noyo. The factors responsible for the greater abundance of Cladophora on Hare Creek, lower minimum thresholds of light and stream velocity (and to some degree the earlier growth initiation), are not related directly to increased light, but are indicative of higher levels of nutrients, most likely phosphorus (Whitton, 1971). When nutrients were measured in July and August there was no significant difference. But phosphorus is transported into streams adsorbed on sediments during winter storm events. As will be shown in Section 3, Hare Creek has a much greater sediment load and therefore a much greater potential for higher phosphorus levels than NFSF Noyo. Winter and spring would be the periods when Hare Creek would have higher phosphorus concentrations than NFSF Noyo. Cladonhora is capable of luxury consumption of phosphorus when it is available (Whitton, 1971), thus the limited period in the spring when *Cladophora* is growing with high phosphorus levels probably may be sufficient to support *Cladophora* throughout its growing season.

SECTION II

DIATOM RESPONSE TO LOGGING AND SOLAR RADIATION

Introduction

An increase in solar radiation to small order streams by canopy reduction has often been considered a major effect of logging on streams (Hansmann and Phinney, 1973; Murphy et al., 1981; Hawkins et al. 1982). Any study looking at primary productivity in streams must be concerned with solar radiation because of its predominant role in photosynthesis.

This part of the study was designed to examine whether differences in solar radiation on a single stream affect the diatom periphyton community (filamentous algae was addressed in the previous section), and to examine logged and unlogged streams under conditions of similar solar radiation to determine whether there are differences between the stream diatom production of the two streams that can be ascribed to changes introduced by logging other than solar radiation.

We are assuming because of the similarity and proximity of the two streams that the primary differences between them are due to treatment effects, i.e., logging on Hare Creek. Therefore we will hereafter ascribe differences between the two streams to logging but acknowledge that differences may be due also to intrinsic differences between the streams.

The assumption that solar radiation was the most important factor controlling primary production in forested streams was the basis for the following working null hypotheses: (1) There is no relationship between logging and diatom.biomass; (2) There is no relationship between solar radiation and diatom biomass. Invertebrate grazing pressure was also considered an important factor because of the possibility of erroneously accepting the null hypotheses due to differential grazing between streams.

Methods

Two stations were established with approximately equal high levels of solar radiation, one on each stream, and two stations with approximately equal low levels of solar radiation, one on each stream. Initially five riffles were chosen that appeared to be the lightest and darkest on each stream. Total daily solar radiation was determined using the photometer method in early July (Appendix 1). Then the Modified Angular Canopy Density Method (Appendix I) was used to determine what the solar radiation levels would be at these riffles at the end of the study (approximately one month).

From these measurements a high solar radiation station was chosen on each stream that most closely matched at both the beginning and the end of the study period. The same method was used to select the two dark stations.

Unglazed ceramic tiles were chosen as the best artificial substrate to sample algae and invertebrates (Lamberti and Resh, 1985). On July 11, 1984, five 15.2 by 15.2 cm tiles cemented to separate cinder blocks were placed in the streams with the tiles flush with the substrate at each of the four stations. Current (measured with a Gurley pigmy current meter) and depth were then measured over the center of each tile. The tiles were left in place for 36 days. Just before tiles were removed, invertebrates on the tiles were caught in a fine mesh net (noseum netting) which fit tightly over each tile and preserved in 70% ethanol. Macroinvertebrates were identified to genus (Merritt and Cumming, 1984). Tiles were scraped with razor blades to remove the algae. The ash-free dry weight of algal biomass on each tile was determined by collecting the algae on pre-ashed (550° for 15 min.) and tared Whatman GF/C filters. The filters were dried at 70° for 48 hours, cooled in a dessicator, and weighed to the nearest 0.1 mg. The filters were then burned at 550°C for 25 minutes, cooled and reweighed.

Statistical Design

A stepwise multiple regression analysis was used to determine the most important factors effecting the variation of algal biomass. The independent variables included two dummy variables: (1) whether the sample was from the logged stream or the unlogged stream, (2) whether the sample was from a high solar radiation or a low solar radiation, and six numerical variables: current, depth, numbers of total invertebrates, numbers of grazers, numbers of large grazers, and numbers of small grazers. (The last two are subjective categories but seemed appropriate as all the mayflies were less than 1 mm long but very numerous, and the *Glossosoma* and Lymnaea were 10 mm long but occurred in low numbers.) The criteria for a variable's inclusion in the regression equation are an F ratio greater than 0.01 and tolerance greater than 0.001.

Results

The total daily solar radiation on the high solar radiation station on the NFSF Noyo was 25 x $10^6 \mu E/m^2$ and 15 x $10^6 \mu E/m^2$ on Hare Creek. The total daily solar radiation on the low solar radiation station on NFSF Noyo was 1.6 x $10^6 \mu E/m^2$ and 3.0 x $10^6 \mu E/m^2$ on Hare Creek. The mean algal ash-free dry weight on the high solar radiation station on the NFSF Noyo was 1.06 g/m^2 (s = 0.57) and was 0.32 g/m^2 (s = 0.11) on the high solar radiation station on Hare Creek. The mean algal ash-free dry weight on the low solar radiation station on NFSF Noyo was 0.76 g/m^2 (s = 0.28) and was 0.24 g/m^2 (s = 0.13) on the low solar radiation station on Hare Creek.

Table 2 presents a summary of the stepwise regression. Fifty--two percent of the variation was explained by the negative relationship between algal biomass and logging (r = 0.72, p = 0.001). Solar radiation accounted for a relatively small marginal increase in R^2 (0.056) and its partial coefficient of regression was significant only at p = 0.25. All invertebrate variables, current, and depth had statistically indiscernible effects on algal biomass.

There were no statistical differences between the nitrogen and phosphorus levels measured in mid-summer on NFSF Noyo and those measured on Hare Creek. The maximum and minimum temperatures on each stream were also similar (Appendix 2).

Discussion

The significant negative relationship between logging and algal biomass, which accounted for 52% of the variation, indicates that logging activity surpassed algal biomass independently of differences in solar radiation, grazing invertebrates, current or depth. This relationship probably reflects not only a lower standing crop of algae but also lower production in the logged stream because under conditions of equal grazing (grazers were only marginally correlated with algal biomass), standing crop can be used as a relative measure of production.

An original working hypothesis used in this. study was that because logging can increase invertebrates (Erman et al., 1977) increased grazing might be responsible for a lower algal standing crop in logged streams. But if the invertebrates found on the tiles were representative of the invertebrates that grazed the tiles during their 36 day exposure, then this hypothesis is false. Lamberti and Resh (1985) showed that invertebrate populations sampled from unglazed ceramic tiles were identical in relative numbers and species composition to those present naturally in the substrate, and we assumed that invertebrate grazers captured on our tiles were also representative of invertebrates in the vicinity. If this assumption were not true, differences in grazing pressure among the four stations may still be responsible for differences in algal biomass.

Although solar radiation had a positive effect on algal biomass, it was not very significant despite the high and low solar radiation stations representing the greatest contrast in total daily solar radiation available within the study reaches. Solar radiation apparently is not as important as we previously thought especially in relation to the large differences in algal biomass accounted for by logging.

Since the response of diatom biomass on the logged stream cannot be attributed to changes in solar radiation, temperature, nutrients at the time of sampling, or substrate (as these variables were similar on each stream and artificial substrates were used), it must be attributed to some undetermined change in the stream environment produced by logging or to some intrinsic but undetectable difference between the two streams studied. One possibility discussed above is that invertebrate grazing was higher on the logged stream than on the unlogged stream and we failed to detect it. Another possibility, discussed in the next section, is that diatoms were scoured by suspended sediment during winter floods more heavily in the logged stream than in the unlogged stream. Since floods carrying suspended sediment may occur as late as March or April, this may give diatom communities in the unlogged stream a comparative advantage throughout the summer growing season.

SECTION III

THE RESPONSE OF STREAM ALGAE TO SUSPENDED SEDIMENT

Introduction

Often in the course of silvicultural or other land management activities large amounts of fine sediment are introduced into streams, most frequently from landslides, bank cutting, or surface erosion off roads. This introduction of fine sediment can increase the suspended sediment, wash load, and bedload, and can cause biologically significant changes in the composition or morphology of the stream substrate. The deposition or intrusion of fine sediment is one of the most significant deleterious impacts of logging on stream biota. The rearing capacity of pools, often a factor limiting fish populations, is greatly diminished by reductions in' pool volume. Changes in size distribution of riffle gravel can, through habitat alteration, adversely affect algae, invertebrate fauna, and fish reproduction.

Along with increases in deposited sediment one of the most commonly noted and measured changes in the stream environment (and also the basis of many water quality standards) is an increase in suspended sediment, or turbidity. A cursory reading of the literature would suggest suspended sediment has a tremendous direct impact on the biota of streams. Decreased photosynthesis, abrasion of algae and insects, and death of fish due to clogged gills are examples of what has been assumed and implied to occur with increased suspended sediment. But some of these effects are simply deduced and have never been demonstrated; and those axioms related to suspended sediment that have been examined often prove to be equivocal. Sorenson et al. (1977) remarked, "As will be seen in the review of the literature that follows, only occasionally do suspended solids have drastic acute effects on the biology of most freshwater systems."

Fish can tolerate very high levels of suspended sediment before adverse reactions occur. Salmon in Alaska often migrate upstream through glacial four for many miles with no ill effect (Cordone and Kelly, 1961). Fish apparently secrete enough mucous to clean their gills even under abnormally high levels of suspended sediment

(Cordone and Kelly, 1961). Sight feeding fish are thought to be unable to forage effectively in highly turbid waters. This is commonly inferred by relative angling success in clean and turbid water (Buch, 1956). Cordone and Kelly (1961) claim that "cutthroat trout and salmon fingerlings can feed and grow apparently very well in very muddy water."

Abrasion is the most frequently cited effect of suspended sediment on stream invertebrates. In this case there is evidence that invertebrates are affected although many authors ascribe the effects of deposited sediment to suspended sediment and do not necessarily make this distinction (examples found in Sorenson, 1977; and Iwamoto et al., 1978). Gammon (1970), however, has demonstrated a linear increase in insect drift with increasing suspended sediment (drift is an escape mechanism for aquatic insects, and increases are a sign of stress). Support can be found for either side of the question of whether suspended sediment adversely affects invertebrate communities (Sorenson, 1977; Iwamoto et al., 1978). In general, the negative reaction by invertebrates seems to be the best supported, although not proven, of all the assumed problems with suspended sediment.

Decreased photosynthesis due to high turbidity is the most common undocumented effect of suspended sediment. Often studies that are cited as evidence of this phenomenon actually were studying a different aspect of water quality and only mentioned the possible connection between photosynthesis and suspended sediment as an aside (e.g., Chapman, 1962; Cairns et al., 1972). But it hardly seemed necessary to test this relationship because by definition high turbidity means less light penetration and therefore less potential photosynthesis. But there are several problems with this analysis. First, in the streams usually encountered during logging operations and most critical for salmonid and forest production (less than fifth order streams], high levels of turbidity only occur during relatively short periods when there would be little photosynthesis anyway because of storm clouds. This may not be true in larger rivers where high turbidity can occur year-round regardless of stage. A second problem is that in many small forested streams there may not be much photosynthesis naturally due to canopy cover, and the primary sources of energy for the stream ecosystem may be allochthonous (Vanote et al., 1980). No studies could be found that quantifiably show that photosynthesis has been significantly affected by suspended sediment.

Abrasion of algal communities by suspended sediment is also assumed, but not quantified. Although this effect seems possible, it could also be true that most algal communities must be adapted to occasional high levels of suspended sediment and may be resistant to abrasion. In addition, many algal species or communities, especially filamentous algae, have only seasonal existences and are naturally decimated by the first winter storm (Blum, 1956).

This phase of the study was designed to examine the question of whether or not suspended,sediment abrades periphyton and to see if there is any difference in the reduction of periphyton caused by suspended sediment from logged and unlogged watersheds. Since the sediment discharge of northern Californian coastal streams is the highest in the United States (Curtis et al., 1975) and is among the highest in the world (Holeman, 1968), it seems likely that streams in this area of the United States would have the greatest potential for algal scouring. Natural levels of suspended sediment might be sufficient to fully abrade the periphyton community and, therefore render undetectable silviculturally induced effects from increases in fine sediment.

Methods and Materials

To determine the effect of transported sediment on algal communities it was necessary to sample algae immediately before and after a storm of sufficient magnitude to cause the stream to entrain sediment. Unglazed ceramic tiles (as discussed previously) were used as artificial substrates. Each tile was cemented to a cinder block and then anchored in the substrate to prevent them from being carried away or rolled as natural substrates might during floods.

Ten tiles, each on separate cinder blocks, were placed in each stream on October 20, 1984. Current over each tile was measured with a Gurley pigmy current meter. Depth was also measured for each tile.

Whenever weather reports indicated rain, sites were observed to see if stream discharge was of sufficient magnitude to cause sediment transport. If sediment -transport seemed likely, tiles were randomly selected on each stream and removed prior to sediment movement. Each tile was then scraped with a razor blade to removal algal biomass. After the storm the remaining tiles were removed and the algae similarly removed. Ash-free dry weight of algal biomass was determined as in Section 2.

During storms suspended sediment was sampled from bridges (Fig. 2) with a USDH-48 suspended sediment sampler. Suspended sediment samples were taken approximately every 15 to 20 minutes near the peak flow and at greater intervals 1 to 2 hours from the peak. Stage and current velocity were measured after each suspended sediment sample was taken. Current velocity was measured at 30 cm intervals at the surface of the stream with a Gurley pigym current meter. Crest gauges were placed above and below the bridge where sediment was sampled. From the crest gages the height of the peak flow at the two points could then be used to determine the slope of the water surface at the peak flow. The crest gages were also used to determine the height of the peak flow at flood events that were missed.

Discharge data from the U.S.G.S. gaging station on the Noyo River at Fort Bragg were used to estimate the reoccurrence interval of the floods sampled and to estimate stream discharges not measured.

Results

The winter of 1984-85 had few freshets that were of sufficient magnitude to entrain sediment. Only one flood which occurred on March 26 and 27, 1985, was successfully sampled. One half the tiles were removed the morning of March 26. The remaining tiles were removed on March 30. This flood had two distinct peaks: one on March 26 and one on March 27. We sampled suspended sediment on Hare Creek during the peak flows on March 26. On March 27 stream discharge again increased and suspended sediment was sampled on NFSF Noyo. A hydrograph from the U.S.G.S. gaging station on the Noyo River (Fig. 5) indicates that the peak flows on both days were approximately the same. Because the NFSF Noyo would show the same relative difference in the two peak flows, we feel it is reasonable to use the flood on March 27th as a proxy for the flood which occurred on the 26th and therefore treat the suspended sediment measurements taken on Hare and NFSF Noyo as if they were synoptic measurements.

Figures 6 and 7 present discharge, suspended sediment concentration and suspended sediment discharge as a function of time for both streams. The peak discharge on Hare was 3.2 m^3/s and NFSF Noyo 2.1 m^3/s (Fig. 6 and 7). The flood's recurrence interval was approximately 1.0 year and less than the estimated bankfull discharge on both streams.

The pattern of the hydrograph and sediment data (discharge and concentration) were similar on both streams. A small peak in suspended sediment occurred close to the peak discharge, but the largest peak in sediment came on the declining limb of the hydrograph.

Hare Creek had a much higher peak suspended sediment concentration (4.0 g/l) than NFSF Noyo (0.82 g/l). On a sediment discharge basis Hare Creek was eight times higher (9,800 g/s> than NFSF Noyo (1,220 g/s). Differences between streams in these values were similar at the *lower* peak as well. Before the storm the mean ash-free dry weight of the algal biomass on Hare Creek was 0.74 g/m^2 and after the storm the tiles had no measurable biomass. On NFSF Noyo there was no difference in algal biomass sampled before (0.23 $\pm$ 0.07 g/m^2) and after the storm (0.21 $\pm$ 0.02 g/m^2).

Discussion

In any study which relies on a comparison of two streams without background data there is a chance, no matter how similar the streams, that the differences observed are due to inherent differences between the two streams and are not related to the treatment. In this regard this study was conservative because considering natural geomorphic characteristics NFSF Noyo should have a much larger sediment load. Hillslopes in the NFSF Noyo watershed are commonly over 50% while those in the Hare Creek watershed are most commonly between 20-25%. NFSF Noyo's channel gradient, 2.2%, is twice that of Hare Creek's 1.1%. Aerial photographs showed NFSF Noyo had approximately ten large (> 2,100 m^2), recent (< 10 years old) slope failures and numerous small failures (< $10m^2$) all depositing sediment into the stream. No slope failures were found on either photos or on the ground in the Hare Creek watershed. In Hare Creek there was a borrow pit that was apparently contributing sediment to the stream but this can be considered logging related. From this information one would expect that NFSF Noyo would have much more background suspended sediment than Hare Creek. We can therefore attribute with some confidence the greater amount of suspended sediment on Hare than Noyo to logging and associated activities such as roads and borrow pits.

Despite the fact that the results in this section are based on only one flood, several important conclusions can be drawn: (1) Suspended sediment was capable of scouring and decimating periphyton communities; (2) Naturally occurring suspended sediment levels (i.e., with little human caused additions) during commonly occurring floods (1.0 year recurrence interval) in the redwood region did not scour algae. Thus our hypothesis that natural suspended sediment levels in the Redwood region of California would already be able to completely abrade the periphyton is not always true. (It may be true with storms of greater magnitude.)

Because our design separated the effects of substrate movement (by anchoring artificial substrates) from suspended sediment we also showed that suspended sediment is independently capable of deleterious biological effects in streams. This result is the first instance where a clear separation of these effects has been demonstrated. Increased suspended sediment damaged the lowest trophic level, and it can be assumed that its effects are translated through higher trophic levels perhaps ultimately affecting the stream's capability to produce fish.

This aspect of the study also suggests a mechanism that explains lower algal biomass later in the year in Hare Creek. Even a relatively mild storm causing a peak discharge less than bankfull can entrain sufficient sediment from a logged watershed to virtually eliminate non-filamentous periphyton. By showing, what many have suspected to he true, that suspended sediment can scour algae and that some naturally occurring levels of suspended sediment do not scour algae, we have documented another reason why care must be taken when harvesting timber to avoid increasing the erosion of suspended sediment into streams.

Conclusion

We feel that the preceding studies can be integrated to present a picture of one way in which logging may affect stream plant communities. While speculative, this explanation could serve as a model for future research.

One of the most frequently cited water quality problems associated with timber harvesting is the increased amounts of fine sediment introduced into streams (Chapman, 1962; Burns, 1972; Gibbons and Salo, 1973; Rice et al., 1979; Cederhom et al. 1980). Our results indicate that increased suspended sediment is also the case on Hare Creek.

During frequently occurring (recurrence interval less than one year) winter floods of relatively low discharge (less than bankfull) which entrain sediment, the diatom community on Hare Creek is decimated because of logging induced higher levels of suspended sediment, while the diatom community on NFSF Noyo is little affected. Substrate movement during intense storms can also be expected to bury and decimate diatom communities on both streams, but the flows necessary for substrate movement have a much larger recurrence interval (5 to 10 years) than the flows necessary to transport suspended sediment. Since our studies separate the effects on diatoms of substrate movement from suspended sediment, it can be concluded that the diatom community in Hare Creek is destroyed at least annually while the diatom community in NFSF Noyo is decimated less frequently.

If the last flood capable of scouring algae occurs in the spring (1 out of every 2 years), then the diatoms in Hare Creek are scoured off at approximately the same time as the initiation of growth of *Cladophora.* The *Cladophora* (which like other opportunistic species does best in disturbed environments) is then presented with a cleaned substrate on which to grow and high levels of nutrients (adsorbed to sediments during the storm), in particular phosphorus, which it can store for future use. The diatom community in Hare Creek must re-establish itself in the spring from any remaining cells and from upstream colonization in the face of competition and shading by Cladophora. In contrast the diatom community in NFSF Noyo would not be scoured by the spring flood and would start the late spring and summer growing season already well established. There would also be much less Cladophora on NFSF Noyo because of the later initiation of growth and higher minimum thresholds of solar radiation and stream velocity, due we assume to fewer nutrients.

These relationships would explain why there was a lower standing crop of diatoms in mid-summer in Hare Creek than in NFSF Noyo. This is because the source of colonizers for the artificial substrates would be the diatom community upstream from them which would for the reasons outlined above be depressed.

Management Implications

There are two ways that logging operations act to *increase* the spread of Cladophora: increased solar radiation from canopy removal and nutrient loading due to increased erosion and sediment yield to the stream. It is difficult before or during timber harvesting to assess how much more sediment will be delivered to a stream. It is therefore also difficult to keep nutrient enrichment below a level which would not encourage Cladophora However, it is possible to predict the increased level of solar radiation which would occur with the opening of the canopy by using the Modified Angular Canopy

Density Method. Because the effect of nutrients on the growth of Cladophora is accounted for by the lowered minimum threshold of solar radiation, determining total daily solar radiation before and after timber harvesting would completely assess the potential for the enhancement of Cladophora To use the lowered solar radiation threshold as a proxy for nutrients one must assume that the nutrient enrichment in Hare Creek is typical of modern logging operations and therefore use the threshold solar radiation values established on Hare Creek for other streams nearby.

The implication of these results is that in order not to significantly alter the periphyton community, then any opening of the canopy must be carefully controlled. At present, general guidelines recommend 50% of the canopy must be retained during timber harvesting, primarily as a precaution against deleterious stream temperature increases. Our research shows that in some cases this is inadequate for maintaining periphyton community integrity.

In contrast to Cladophora the diatom algal standing crop is not greatly increased by large increases in solar radiation. This would be important in situations where Cladophora is not a nuisance and canopy removal is desired.

The scouring of algae by suspended sediment can be added to the list of means by which fine sediment additions to streams have deleterious biological effects and is one more reason that great care must be taken when harvesting timber to avoid increasing the erosion of sediment into streams.

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APPENDIX I

Two METHODS FOR DETERMINING THE AMOUNT OF LIGHT REACHING A STREAM

Light is a critical factor in the study of primary production because of its driving *role* in photosynthesis. Determining the amount of light reaching a stream has its own unique problems. First there is almost always variability in canopy cover along a stream requiring separate measurements for every area of concern. On a smaller scale, short reaches of stream, 3 to 5 m long, with fairly homogeneous canopy cover, can exhibit patchiness of sunshine at any given time due to variable shading by branches and leaves. In addition in the course of a day there can be huge variations in the amount of light reaching the stream as the sun moves behind trees or into open areas. Both problems assure that a single light measurement would probably have little relation to the light status. of that reach of stream.

Our first method (measuring instantaneous radiation with a LiCor photometer at frequent intervals and many locations over a day) for determining the amount of total daily light reaching a section of stream successfully avoided these problems but was extremely time consuming. Using the values obtained by the first method as a reference, a second method was developed that is less costly. These two methods are described in detail below.

Method 1 Photometer Method

In our study a reach of stream was commonly a riffle approximately 3-5 m long. Light was determined by (1) randomly choosing 10 points in each riffle, (2) flagging these points, (3) measuring with a Licor Model 192S photometer the light reaching the riffle surface at each point over the course of a day at 15 to 30 minute intervals, (4) averaging the values of all 10 points for each 15 minute interval, (5) plotting the average light against time of day, and (6) integrating this graph to obtain total average light reaching a riffle. By averaging 10 points each time light was measured we accounted for variations in shading at a reach over the course of a day. This procedure would need to be repeated for different seasons as sun angle changed.

Method 2 A Modified Canopy Density Method

An angular canopy densiometer was developed (Brazier and Brown, 1973) to predict temperature increases in streams resulting from canopy removal during timber harvesting. It is a square mirror divided into 36 smaller squares. The mirror is placed on a tripod with adjustable brackets so that it can be positioned at various angles relative to horizontal. The Brazier and Brown method required pointing the mirror due south and setting the angle of the mirror so that it would point directly at where the sun would be at noon (solar time) on a critical date for stream heating (a high angle for the sun but stream discharge is near its lowest, thus later than spring equinox). Then while looking directly into the mirror the number of squares completely or partially covered by canopy are counted and percent angular canopy density (ACD) is determined. This value was successfully correlated (Brazier and Brown, 1973) with predicted stream temperature increases.

This method was modified in the following manner for use in predicting light reaching a stream, not just for stream heating at a critical time. The Brazier and Brown method takes one reading with the mirror pointed due south (noon, solar time) and the angle of the mirror set at the complement of the angle of the sun. We took ACD readings with the mirror directed at where the sun would be at 0900, 1030, 1200, 1330, 1500.

The angles of sun above the horizon and the compass direction of the sun for these times of day were obtained from a solar engineering handbook for the latitude and time of year.

Since we were seeking a correlation between actual light measured with the photometer, we used the current positions of the sun on the day of measurement, July 6, 1964. But angular canopy density reading can be taken for any date light information is desired (canopy may change over the course of a year as happens in deciduous forests but corrections are possible).

ACD reading must be adjusted when sunlight is less intense at angles below solar noontime. We used the Li-Cor photometer to measure light in the open at 1200, 1330, 1500 (the angles of the sun at 1330 equal those at 1030 as does 1500 equal 0900 so adjustments are the same) and then adjusted each angular canopy density (ACD) measurement by the ratio of its corresponding open sunlight value to open sunlight value at noon. The correction factors for mid-July at 39° latitude were 1 0 for noon, 0.789 for 0900 and 1500 and 0.878 for 1030 and 1530.

The final value of the Modified Angular Canopy Density method (MACD) is obtained by summing the adjusted values for each period.

To determine how well the MACD estimated actual light over the course of an entire day measured with a photometer, we chose 10 riffles and performed both methods. The MACD was highly correlated (r = 0.95) with photometer estimates of average daily light (Fig. Al). Because the angular canopy densiometer measures the canopy that intercepts sunlight, the relationship between MACD and average daily light is inverse. When only noon values of the ACD were used, the correlation coefficient was 0.71, thus showing the need for measurements at other times -- four in our case were adequate.

Either Fig. Al or the equation of the regression line (Total Daily Light = $5.68 \times 10^7 - 1.35 \times 10^5 \times$ MACD) can be used to obtain total daily light values (in $\mu E/m^2$) from MACD measurements. Although Fig. Al and the regression equation are latitude and date specific, a difference in latitude and/or time of year can be accounted for by measuring the light with a photometer in an open area at 1200, 1330 (or 1030), and 1500 (or 0900), computing a ratio with the sum of these measurements and the sum of corresponding measurements taken on July 6 at 39°N latitude, and then using this ratio to adjust the value obtained from Fig. Al.

There are two principal advantages of the MACD over the photometer method. First it is much faster and therefore cheaper. The photometer method requires for each reach an entire day of measurements and then an hour of calculations. The MACD requires 0.5 hour to determine the angles and compass directions for the date and latitude desired, and these positions of the mirror are used for all stations. Once at a reach where light information is needed, it takes approximately 10 minutes to record the data. The second advantage of the MACD is that light levels can be determined for any time of the year regardless of when a reach is visited (keeping in mind any seasonality of canopy cover). With the photometer method light levels can only be determined for a date when one is at the stream.

Table 1. Mean percent cover of <u>Cladopora,</u> total daily light, **and mean** water and velocity.

Stream	Station	Cladophora % Cover	S.D.	Total Daily Light	Velocity (m/sec)	S.D.	Depth (cm)	S.D.
NFSF Noyo	A	0	0	4.0	.30	.06	8.6	1.7
NFSF Noyo	B	0	0	6.3	.38	.12	11.5	3.1
NFSF Noyo	C	0	0	1.9	.27	.13	14.3	1.3
NFSF Noyo	D	28.3	14.6	24.7	.47	.11	11.3	11.7
NFSF Noyo	E	0	0	1.6	.47	.17		
NFSF Noyo	F	20.0	9.1	34.9	.48	.17	14.2	1.1
Hare	A	20.5	9.6	12.2	.46	.19	8.1	1.5
Hare	B	20.5	22.1	0.7	.31	.10	10.6	2.1
Hare	C	60.3	26.6	5.7	.17	.07	14.6	2.7
Hare	D	26.5	11.4	10.7	.39	.02	8.5	1.0
Hare	E	12.75	11.0	14.7	.30	.16	0.4	1.4
Hare	F	1.25	2.5	3.0	.52	.34	11.6	2.2

Table 2. Multiple correlation analysis of non-filamentous algal biomass on tiles with four independent variables.

Variable	Multiple R	R Square	RSQ Change	Simple R	B	P
Logging Status	0.72297	0.52266	0.52268	-0.72291	-3.957737	0.001
Light Status	0.76054	0.57841	0.05574	-0.15429	-1.347449	0.25
Total Numbers Larqe Grazers	0.76714	0.58851	0.01009	-0.13592	0.51558150-01	us
Depth of Stream (cm)	0.76757	0.58917	0.00066	0.15736	-0.39741370-02	NS

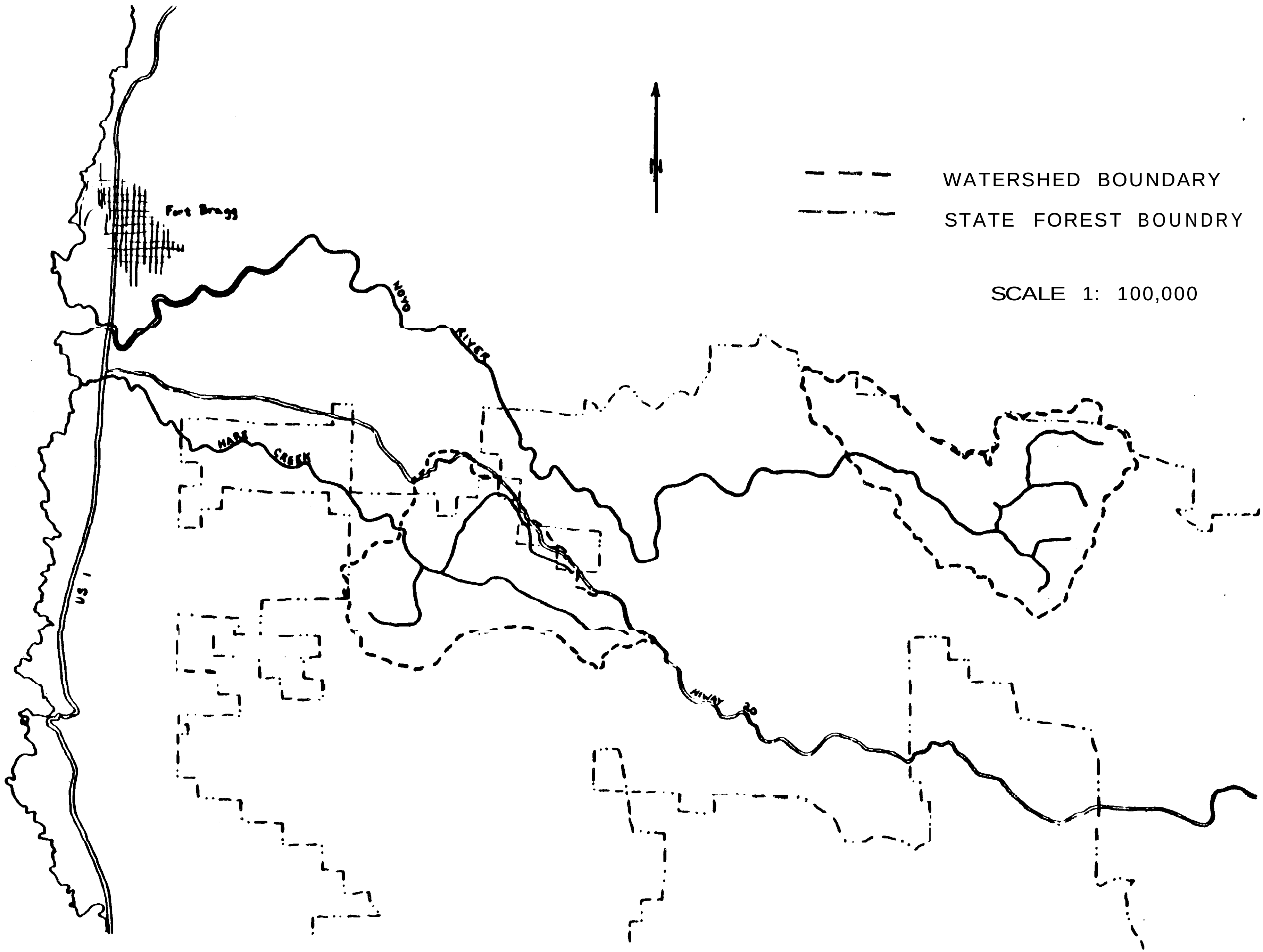
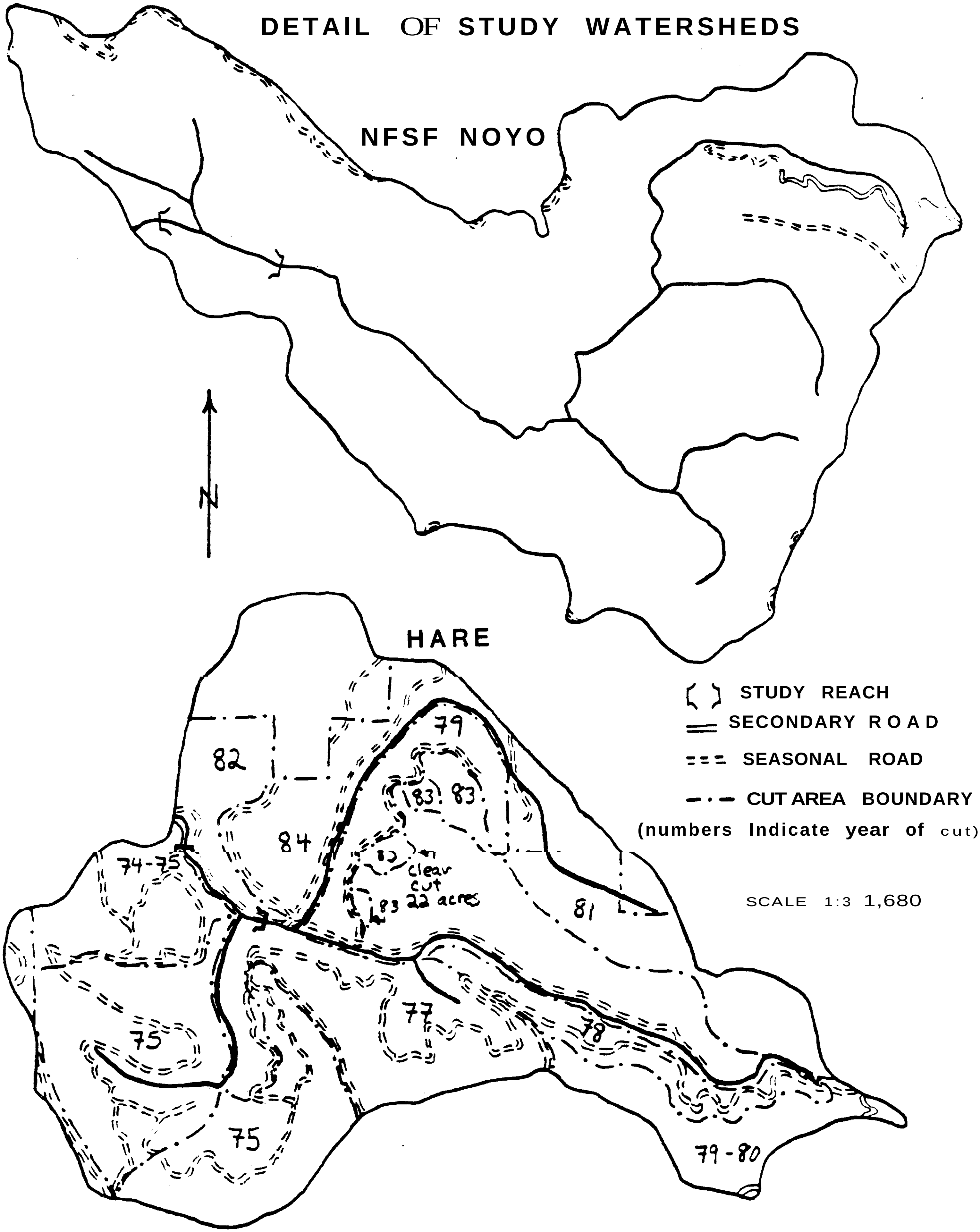


Figure 1

Location of Study Watersheds

Figure 2

DETAIL OF STUDY WATERSHEDS



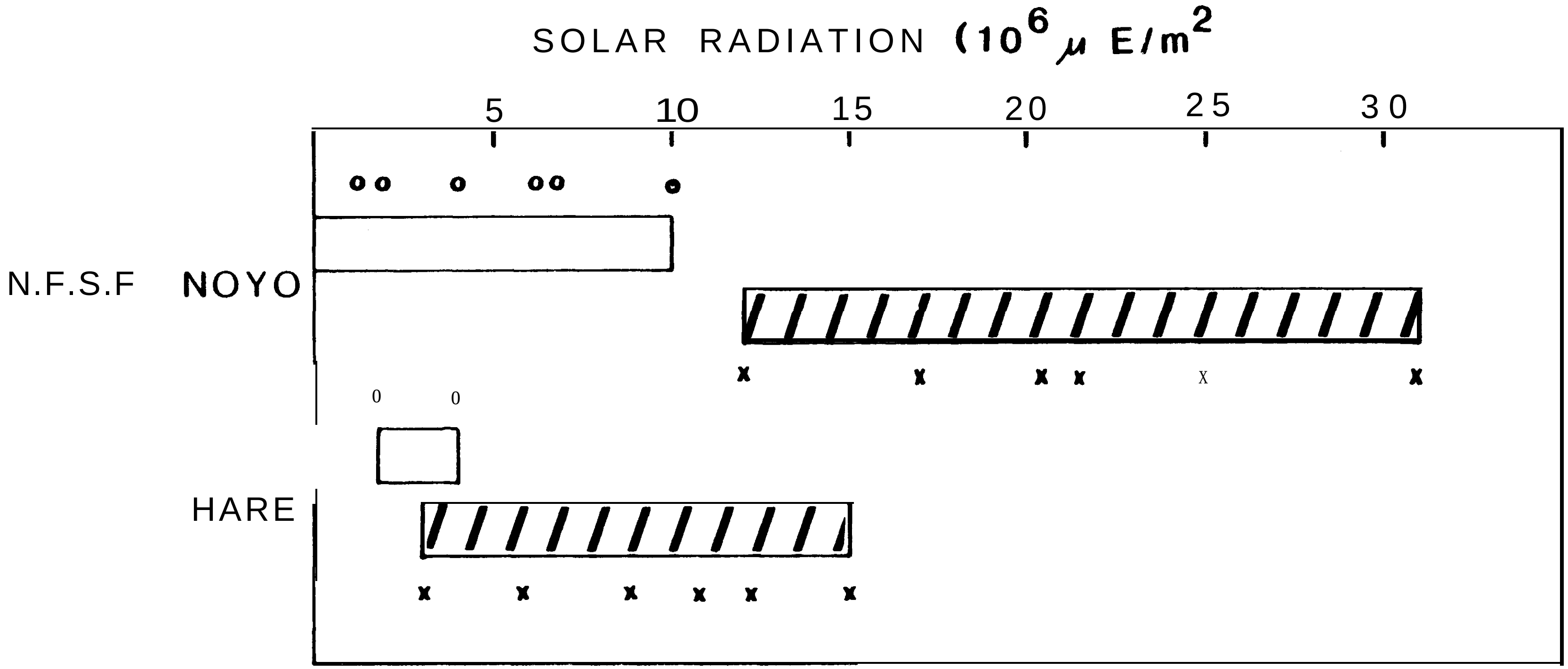


Figure 3. Presence or absence of Cladophora in relation to total daily solar radiation. Hatched bars indicate the range of solar radiation for stream reaches where Cladaphora was present, with x's representing actual data. Open bars indicate the range of solar radiation for stream reaches where Cladaphora was absent, with o's representing actual data.

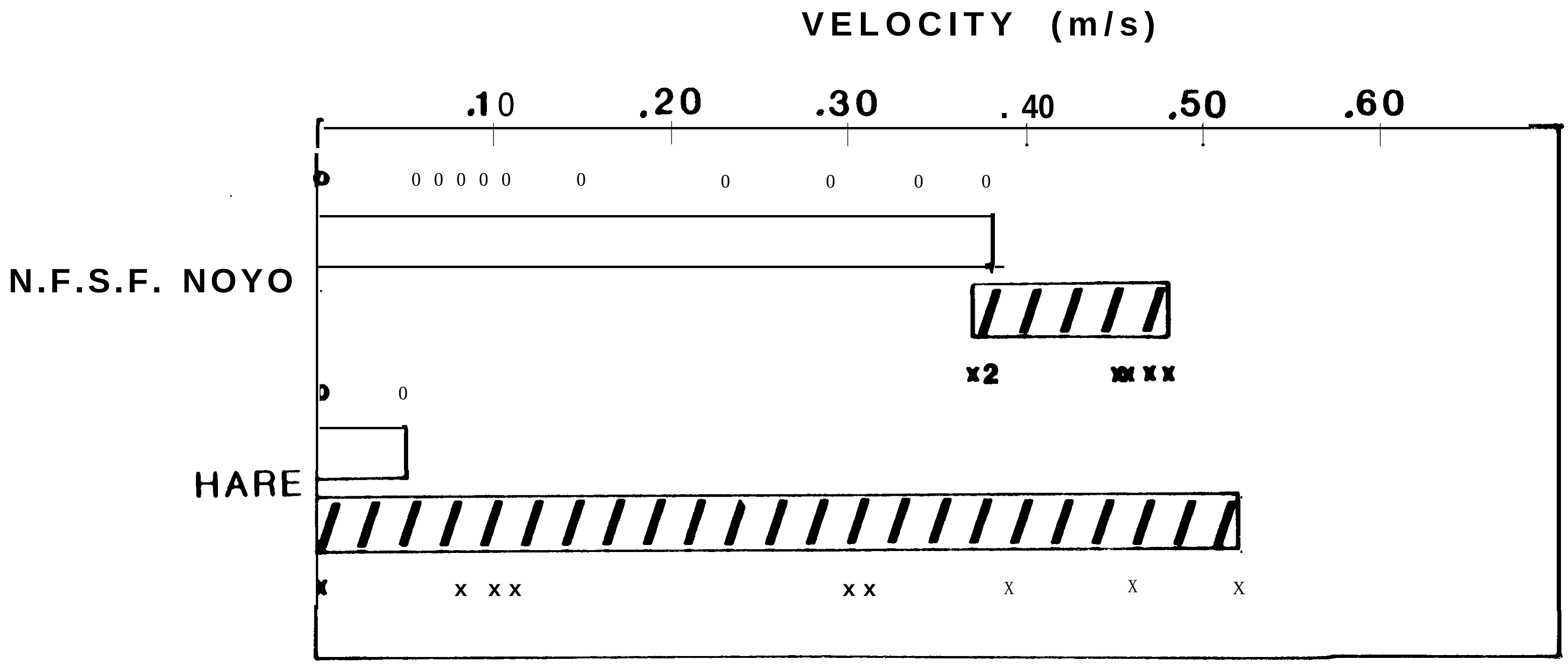


Figure 4. Presence or absence of Cladaphora in relation to stream water velocity. Hatched bars indicate the range of velocity for stream reaches where Cladaphora was present, with x's representing actual data. Open bars indicate the range of velocity for stream reaches where Cladaphora was absent, with o's representing actual data.

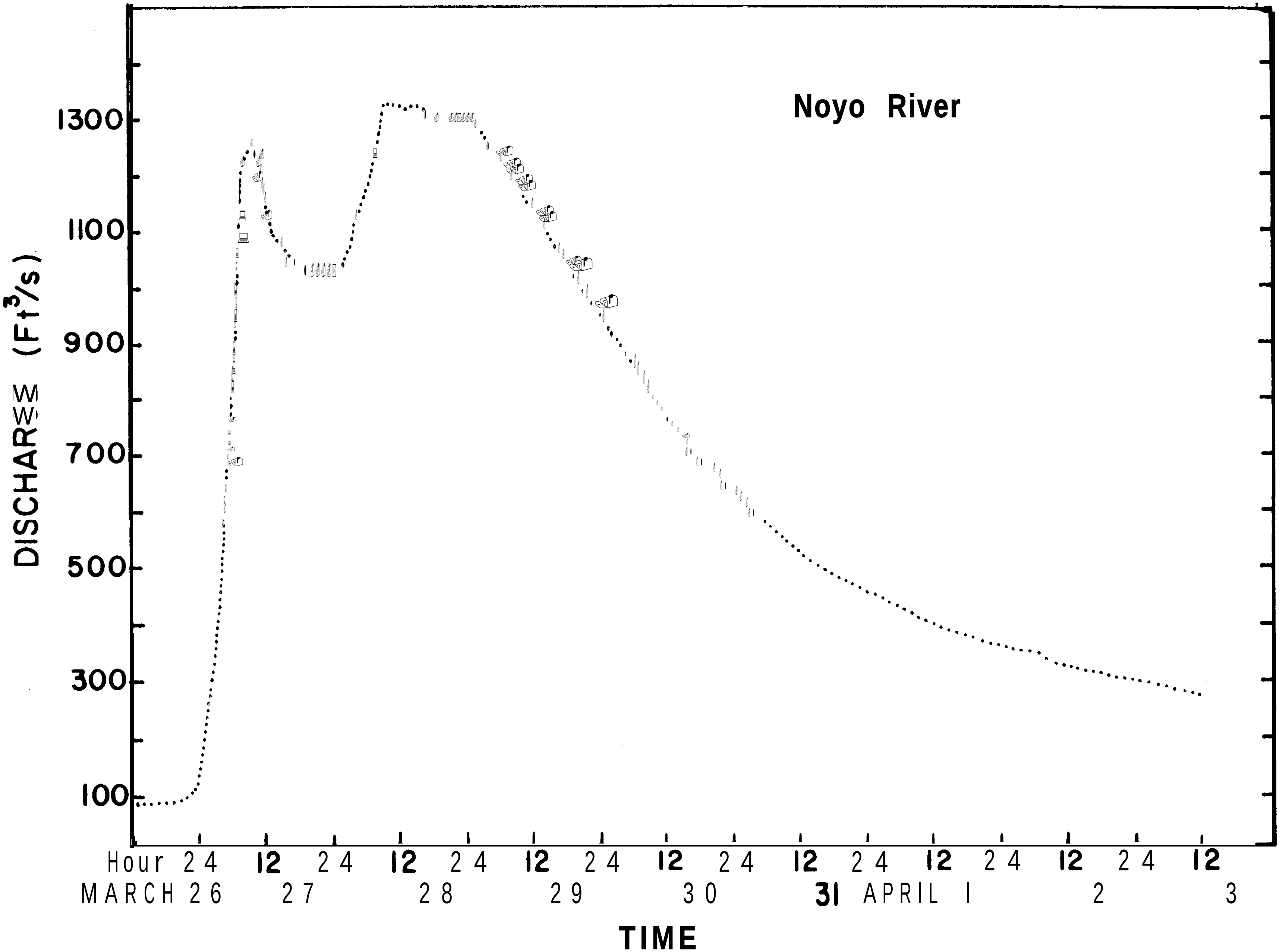


Figure 5. Hydrograph of the Noyo River at Fort Bragg, March 26-April 2, 1985.

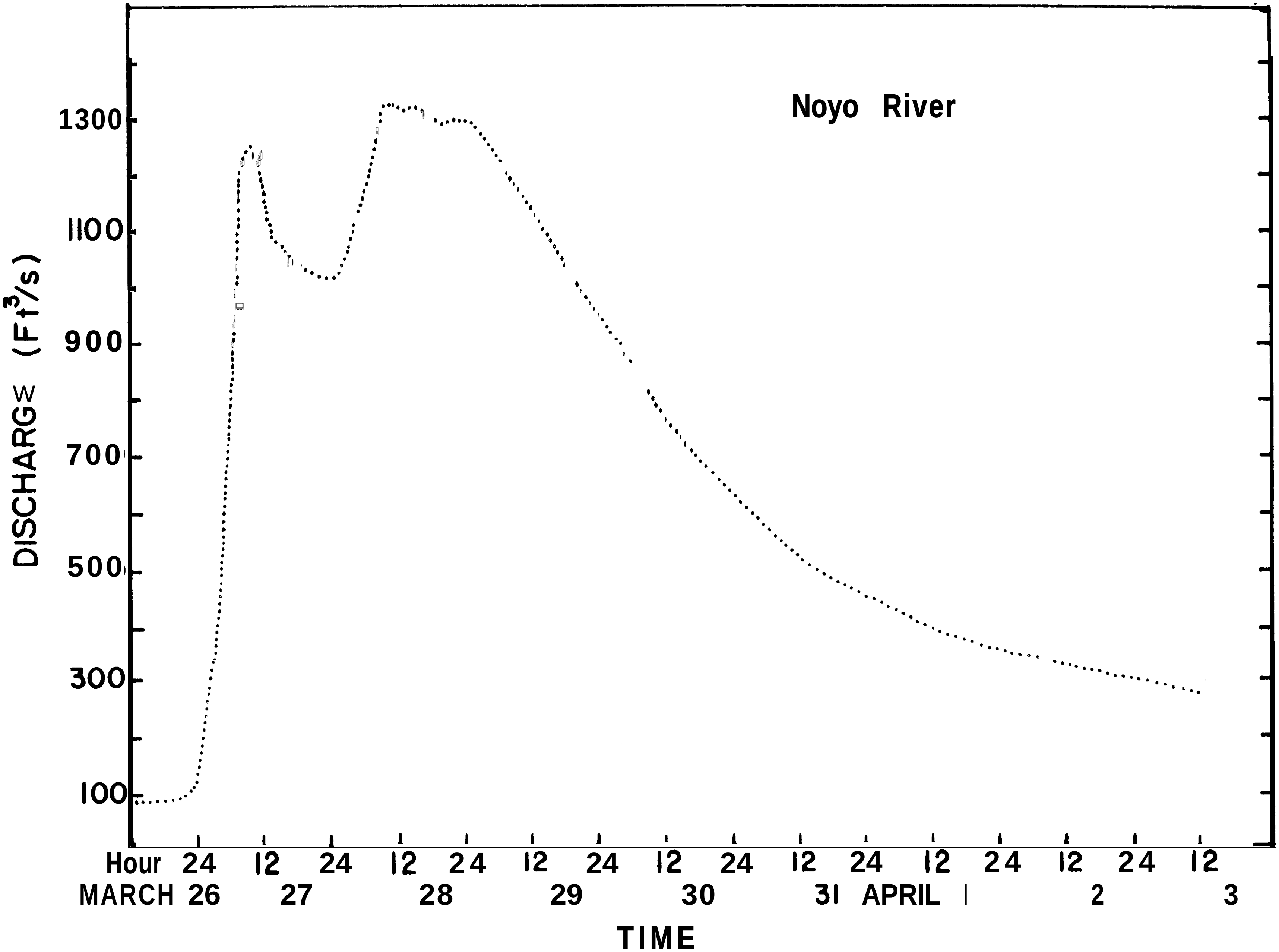


Figure 5. Hydrograph of the Noyo River at Fort Bragg, March 26-April 2, 1985.

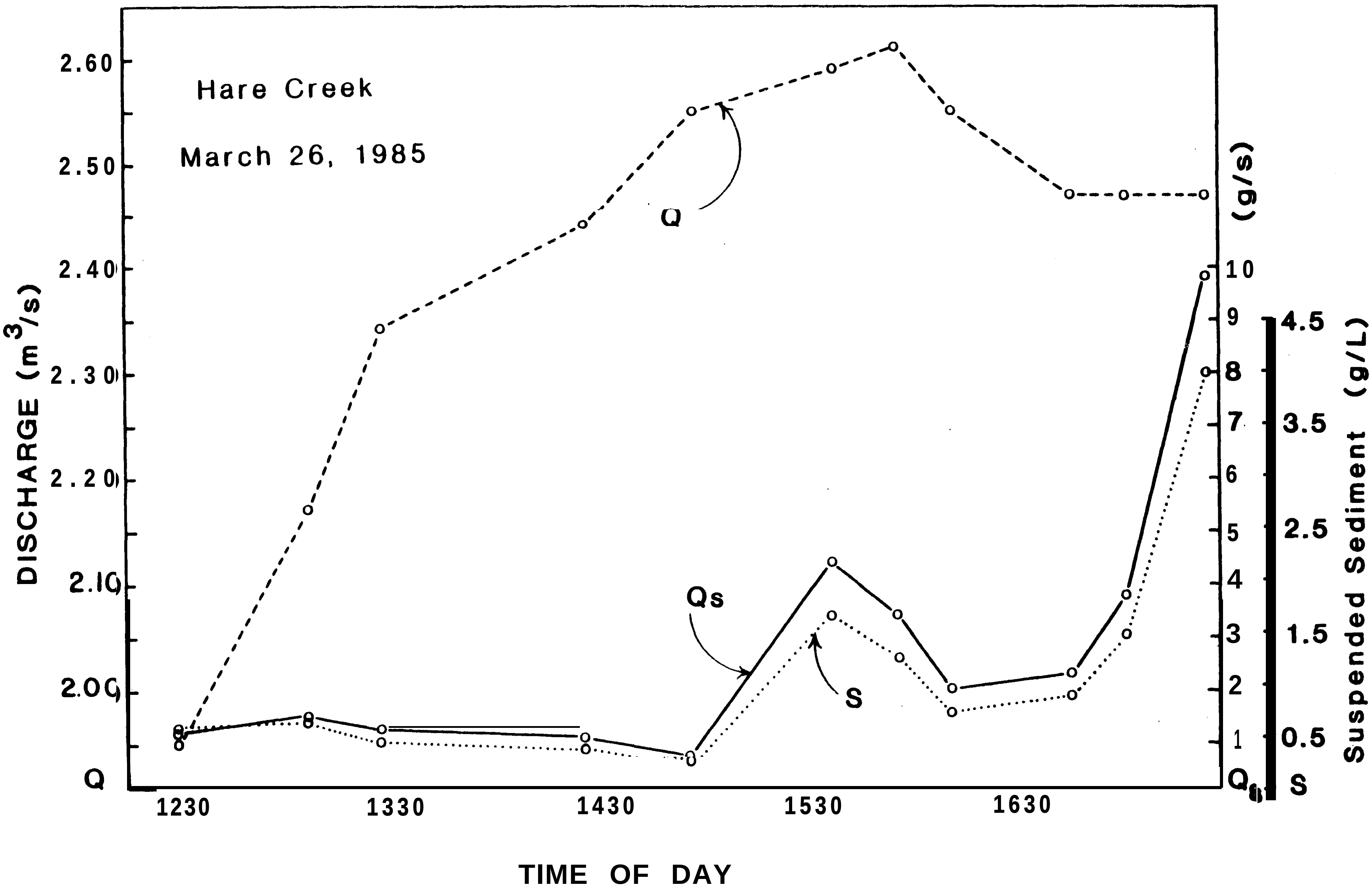


Figure 6. Discharge (Q), Suspended sediment discharge (Qs) and Concentration of suspended sediment (s) on Hare Creek on March 26, 1985.

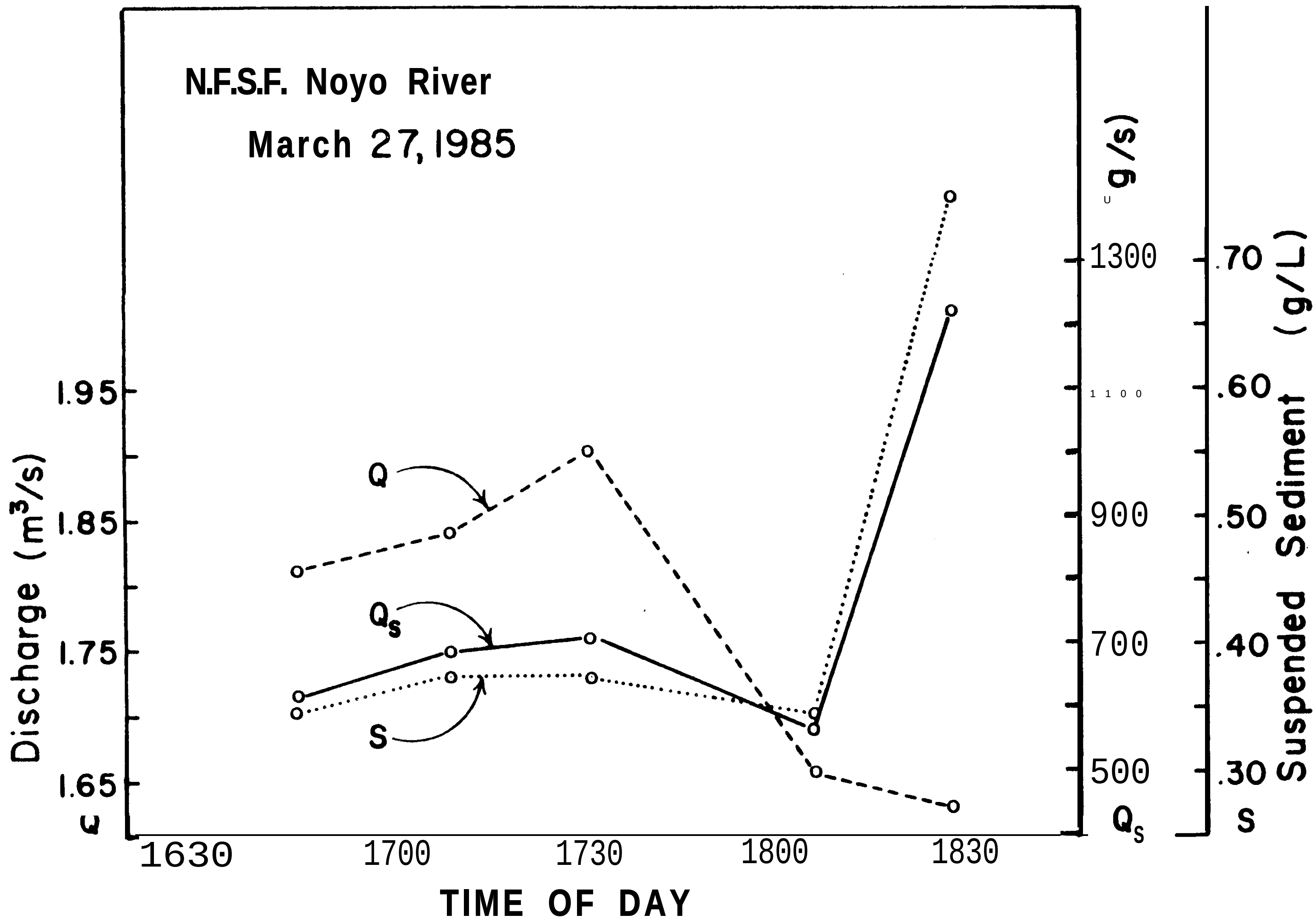


Figure 7. Discharge (Q), Suspended sediment discharge (Q_S) and Concentration of suspended' sediment (S) on NFSF Noyo on March 27, 1985.

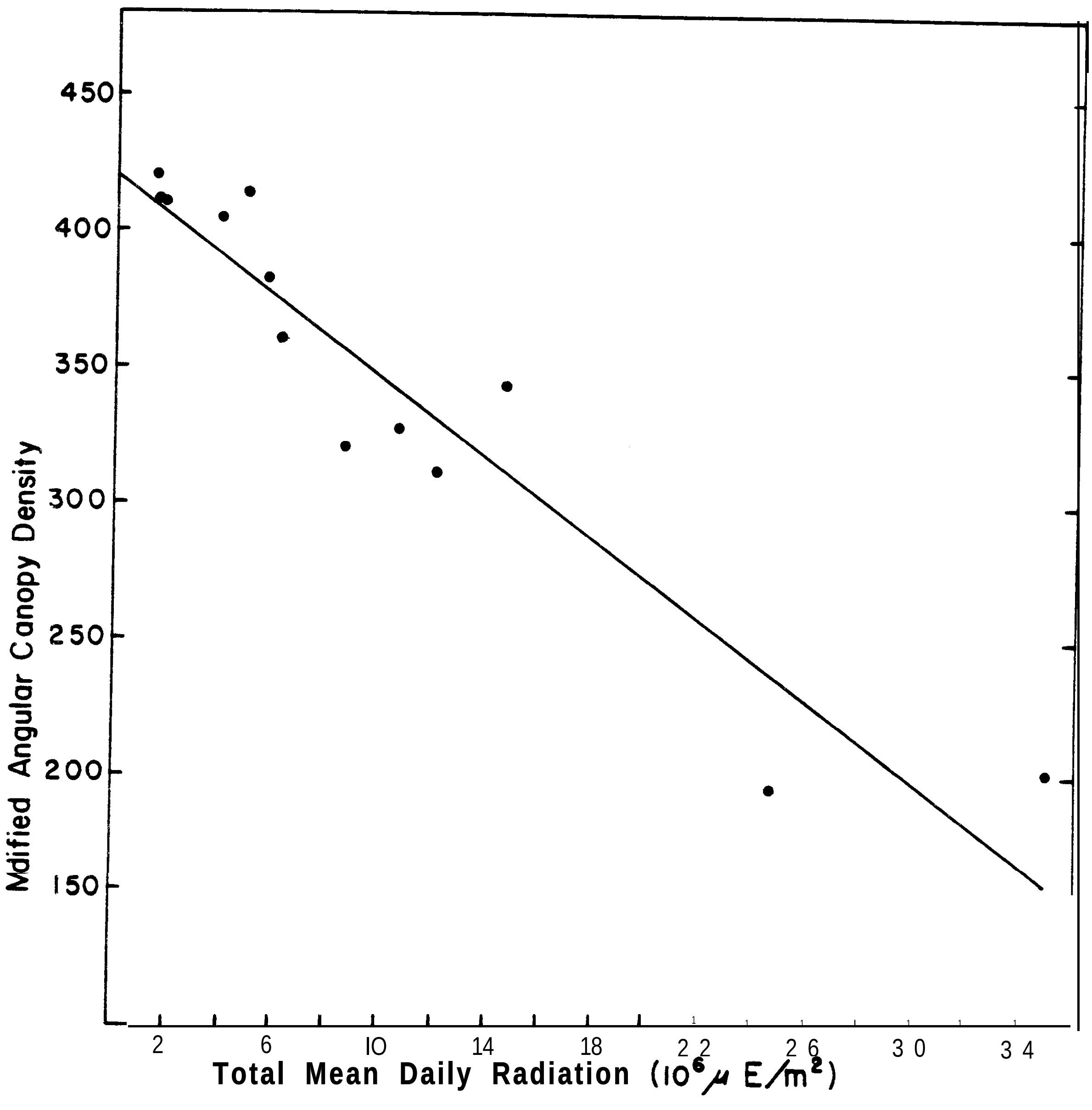


Figure A1. Modified angular canopy density measurements regressed against total mean daily solar radiation (r = 0.95).