Evaluating Cumulative Effects of Logging and Potential Climate Change on Dry-Season Flow in a Coast Redwood Forest

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Abstract

Comparisons based on pretreatment calibrations between summer flows and antecedent precipitation indices (APIs) at the Caspar Creek Experimental Watersheds show increased dry-season flow for 8 yr after selective logging, followed by at least 27 yr of depressed flow. In contrast, summer flow in a partially clearcut watershed remained higher than expected for 18 yr after logging. The API-based models were used to evaluate the effects of selected climate change scenarios when combined with logging-related hydrologic changes, with the effects assumed to act independently. Changes in rainfall late in the wet season have a disproportionate effect on dry-season flows, while autumn rains have little effect.

Keywords: cumulative effect, low flow, climate change, logging, instream flow

Introduction and Study Area

Low-flow changes associated with forest management can affect downstream water supply and alter habitat quality for instream biota. Quantification of the long-term effects of various silvicultural strategies on dry-season flows would provide information needed to assure desired flow in target stream reaches. However, such an analysis requires lengthy flow records after silvicultural treatments and also generally requires that analogous records be available from a control site. Although logging has long been known to augment runoff over the short term (Moore and Wondzell 2005), studies in the Pacific Northwest and elsewhere show that flow may eventually decline to below pretreatment levels as forest regrows (Hicks et al. 1991). Earlier work at the Caspar Creek Experimental Watersheds in northwest California (Keppeler 1998, Figure 2) suggested that such a pattern may also have been emerging after selective logging of a coast redwood (*Sequoia sempervirens*) forest.

Flow has been measured since 1962 at gaging weirs in the North and South Forks of Caspar Creek (Figure 1, 39°21' N., 123°44' W.). The 424-ha South Fork watershed underwent 67 percent volume-selection logging in 1971–73 for a study of the effects of tractor yarding. In 1985–86, about 13 percent of the 473-ha North Fork watershed was clearcut, and in 1989–92 an additional 37 percent was clearcut and mostly cable-yarded during a study of cumulative watershed effects. The 48-yr flow records thus provide an opportunity to compare summer flow responses to contrasting silvicultural strategies in a pair of matched watersheds.

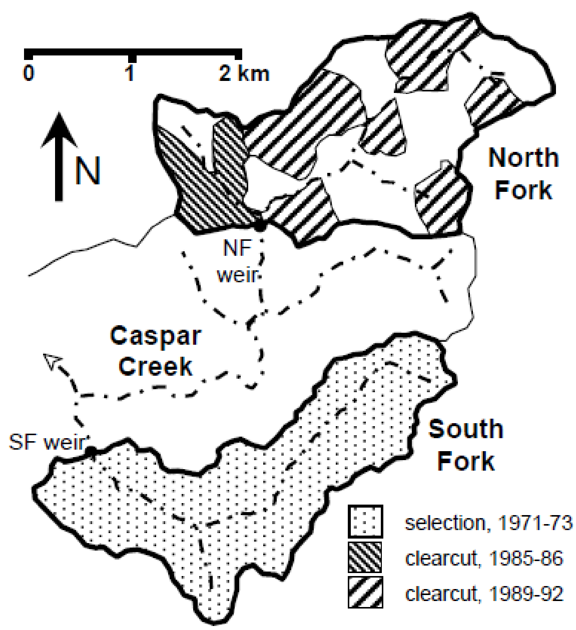

Figure 1. Caspar Creek Experimental Watersheds.

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The watersheds are underlain by marine sandstones and siltstones, and most slopes are mantled by 0.5- to 1.5-m-deep clay-loam to loam soils, often with high gravel components. Annual rainfall averages 1,170 mm, and about half runs off as streamflow; snow is negligible. About 95 percent of the rain at Caspar Creek falls in October–May, a period that also accounts for 95 percent of runoff. The minimum flow usually occurs in early October, but most streams draining <20 ha are dry by June. Old-growth forest in the area was logged in the mid to late 1800s, and by 1960 the watersheds supported 60- to 100-yr-old second-growth stands dominated by coast redwood and Douglas-fir (*Pseudotsuga menziesii*).

Anadromous coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*Oncorhynchus mykiss*) often spawn in the watersheds, but portions of the channel system used for summer rearing are constrained in part by the extent of dry-season flow. Salmonid populations have declined in the area, and there is concern that potential effects from broad-scale climate change may augment the effects of silviculturally-induced flow changes. We here adapt methods used by Reid (in press) to model the potential effects of altered rainfall regimes on dry-season flows at Caspar Creek when combined with changes due to selective and clearcut logging.

Methods

The South and North Fork weirs are concrete sharp-crested compound weirs, and flow has been measured there using a sequence of float gages (recorded using strip charts) and data-logged pressure transducers. For the first experiment, calibrations established between North and South Fork flows for the pre-logging period were used to estimate expected South Fork flows after logging, and the observed deviations from expected values allowed characterization of the initial South Fork dry-season flow response to selective logging (Keppeler 1998).

This analytical strategy was no longer useful after 1985, when logging began in the North Fork. In addition, because South Fork flows had not reliably returned to pretreatment levels by 1985, the North Fork now lacked a paired control watershed, and treatment effects from the new North Fork experiment thus could not be evaluated at the weir gage. The experimental design instead employed subwatersheds as controls, and the weir gage was not directly used in the experiment. Subwatershed gaging flumes were installed in 1984, and part of the watershed was logged soon after. Subwatersheds are not gaged during summer months because many of the gage sites run dry. Consequently, dry-season flow analysis must rely on gaging records from the North and South Fork weirs.

A method was thus needed to estimate expected dry-season flows at the weirs after the 1985 logging. Rainfall has been measured nearly continuously in the South Fork and in nearby Fort Bragg for the duration of the study period. If pretreatment flows at each weir could be predicted using the rainfall record, it would be possible to calculate expected flows after logging in the absence of a flow record from a control watershed.

Preliminary analyses suggested that an antecedent precipitation index (API) might be a useful predictor. The Fort Bragg gage provides the most complete record of summer rain, while winter rains are well represented by the South Fork gage. Summer rainfalls for events >0.6 mm are strongly correlated at the two gages ($SF\ Rain = 1.03\ FB\ Rain - 0.73$ mm, $r^2 = 0.89$). Smaller events generally represent fog drizzle, which is more common at coastal Fort Bragg than at the South Fork gage, located 6 km inland. We thus combined the October–May record from the South Fork with the June–September Fort Bragg record (with daily rainfalls <0.6 mm set to 0) to construct a continuous rainfall record from 1962 through 2008. A suite of APIs with recession coefficients ranging from 0.993 to 0.600 was then calculated from the rainfall record.

Late-summer flow data are unavailable for years when weir ponds were drained to remove sediment. For years with dry-season data, we selected three to five dates in August and September that had no rainfall during the previous 3 days, had <9 mm of rain during the previous 30 days, and, when possible, were more than 6 days apart. Mean daily flows on the selected dates during the pre-logging periods were then regressed against the suite of APIs to identify the API that best predicts observed flows at each site. The resulting calibrations allow estimation of expected August and September flows at the South Fork (L_{eS}, L/km^2-s) and North Fork (L_{eN}) weirs for pretreatment (unlogged) conditions:

$$L_{eS} = 0.0143\ API_{0.985} - 0.0320 \qquad (1)$$

$$L_{eN} = 0.0272\ API_{0.977} + 0.0366 \qquad (2)$$

with $API_{0.985}$ (mm) calculated using a recession coefficient of 0.985 and $API_{0.977}$ using a coefficient of 0.977 (Figure 2). Flow changes after treatment were then described using ratios of observed flows to those expected for forested conditions.

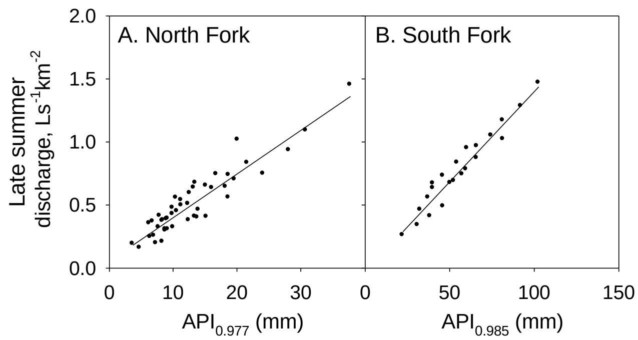

Figure 2. Calibration relations between late-summer flows and APIs in the (a) North Fork (n = 46, r^2 = 0.87) and (b) South Fork (n = 22, r^2 = 0.94).

We wanted to evaluate interactions between logging-related flow changes and those arising from potential climate change, but no significant trends in annual, spring, or autumn rainfall were evident over the 48-yr record, and climatic projections for the area are uncertain. We decided to test outcomes from six plausible rainfall regimes constructed by modifying the existing rainfall record to reflect altered annual rainfalls and changes in the seasonal rainfall distribution. We selected change scenarios within the observed range of variability so that they could reasonably be described by the API model. We did not consider indirect interactions between altered rainfall and logging effects, and we did not evaluate changes in other climatic attributes.

The 24 wettest years on record show an annual average 22 percent higher than the 48-yr average, so we constructed one 48-yr record by multiplying the recorded daily rainfalls by 1.22 and a second record by multiplying daily totals by 0.78. Rainfall in April and May accounts for an average of 10.4 percent of the annual rain over the 48-yr record and 14.9 percent during the 24 yr of that record with the highest percentages. We constructed a third record by increasing April–May daily rainfalls by a factor of 14.9/10.4 while multiplying rainfalls in other months by 85.1/89.6 to maintain the observed annual average. A fourth record was constructed by multiplying April–May rainfalls by 5.8/10.4 and rain in other months by 94.2/89.6.

Summer rainfall is minimal at Caspar Creek, with June and July accounting for only 1 percent of the annual rainfall. Years with lower than the median proportion of summer rain show a mean percentage 77 percent lower than average, so we constructed two additional records that reflect a 77 percent increase and decrease in June–July rainfall without modifying annual rainfall totals.

For each constructed 48-yr rainfall sequence, rainfall in August was set to 0 (a mean reduction of 6 mm), and values of $API_{0.977}$ and $API_{0.985}$ were calculated for September 1 of each year. Equations 1 and 2 were then used to estimate expected flow under unlogged conditions at each weir on that date for each of the six API sequences. The proportional logging-related changes in flow, having been defined as a function of time after clearcutting or selective logging, were then applied to the climatically altered flows predicted for unlogged conditions to estimate the combined effects of logging and hypothetical changes in rainfall.

Results and Discussion

Influence of Logging

Ratios between observed and expected flows show different post-logging trajectories for the partially clearcut and selectively logged watersheds (Figure 3). Late summer flows increased soon after selective logging began in the South Fork and remained high for 8 yr. By 1986, 15 yr after the 3-yr logging period began, flows had consistently dropped to below levels expected for unlogged conditions. Flows continued to drop until 1992, 21 yr after logging began. Flows have increased since then, but after 2000 they have remained slightly lower than pre-logging levels.

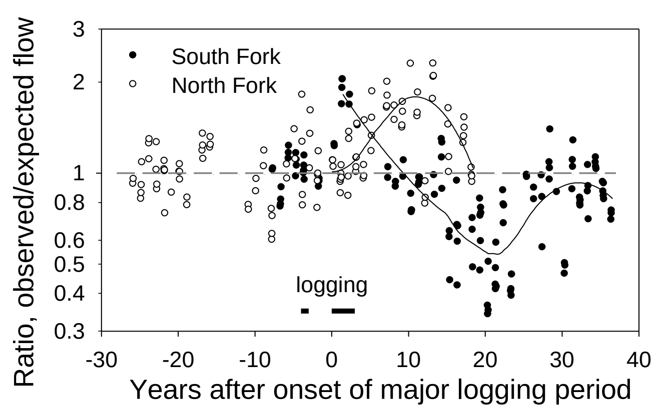

Figure 3. Late-summer flow changes after South Fork selective logging and North Fork clearcutting. Post-logging curves are fitted by loess regression. North Fork 12-yr and South Fork 30-yr values are considered outliers due to an unusual 50 mm/day June storm.

Flows took longer to respond after North Fork clearcutting, but over 11 yr the proportional increase reached a level similar to the maximum at the South

Fork. The maximum mean increase at 11 yr is equivalent to a 1.57 percent increase per percent of forest logged for the 50 percent clearcut North Fork (considering both the 1985–86 and 1989–92 logging), a rate 1.2 times the maximum 1.33 percent increase per percent of forest removed by 67 percent selection logging in the South Fork. North Fork flow again dropped to pretreatment levels by 19 yr after the onset of clearcutting, but the slope of the regression (Figure 3) suggests that further decline to below pretreatment levels might soon be expected.

The large difference in response patterns for selectively logged and partially clearcut watersheds probably reflects a difference in the distribution of trees that remain after logging. Before logging, potential transpiration in this area begins to exceed actual in late spring; by June, a mature forest could utilize more water than is available. In second-growth redwood forests, many of the trees originated as stump sprouts, so clusters of trees often share a common root system. Consequently, when neighboring trees are selectively logged, the remaining trees already have the plumbing in place to take advantage of soil moisture no longer tapped by the logged trees. After an initial rise, dry-season flow thus dropped quickly to pretreatment levels as the remaining trees used up excess moisture and then continued to drop while the newly established cohort of young trees grew larger.

In contrast, on a clearcut slope, the nearest trees are off the site, and significant regrowth of foliage must occur onsite before excess soil moisture can be fully used. Dry-season flow thus remains elevated longer than in the selectively logged watershed. In addition, effects in the North Fork clearcuts are likely to have been renewed in 1995–96 by herbicide application and in 1998 and 2001 by precommercial thinning.

The contrast in initial response times may reflect differences in the distribution of logging: South Fork logging began near the weir and progressed upstream, while North Fork logging began at the headwaters. Because buffer strips left the North Fork riparian zone largely undisturbed, root networks along the full channel length could utilize the hyporheic flow associated with initial increases in dry-season runoff

Combined Effects of Logging and Climate

Of the three kinds of rainfall change modeled for the South Fork, the 22 percent change in annual rainfall produces the largest effect (Figure 4). A shift to a rainfall regime having an average annual rainfall equivalent to that of the driest 50 percent of years in the study period would lead to a 23 percent reduction in the 10^{th} percentile September 1 flow under unlogged conditions. By 21 yr after selective logging, the 10^{th} percentile flow declines to 41 percent of unlogged levels, compared to 54 percent under the present rainfall regime. For unlogged conditions under the current regime, a September 1 flow <0.55 L/km^2-s is expected an average of once in 5 yr, while lower flows would be expected nearly twice as often during the 36-yr post-logging period. Such a decrease in average flow for the post-logging period would be similar to that expected from a 10 percent decrease in mean annual rainfall under unlogged conditions.

Because recent rains affect API more strongly than earlier ones, a shift in seasonal rainfall distribution can influence dry-season flows even if annual rainfall does not change (Figure 4b). In this case, a 44 percent reduction of spring rainfall (and corresponding increases of rainfall in other months to preserve the annual average) would reduce the 10^{th} percentile flow at 21 yr after selection logging to 47 percent of forested levels.

Because of the disproportionate influence of late rainfall, a 2.5 percent increase in annual rainfall, if it occurred only by increased May rain (equivalent to an 81 percent increase in May rain), would affect September 1 flows as much as a 10 percent change distributed through the year (Figure 5). Similar calculations for other months indicate the same effect would be attained by 6.3 and 16 percent increases in annual rainfall if restricted to March and January, respectively; these would correspond to 46 and 83 percent increases in March and January rain. In effect, rainfall occurring after February has considerably more influence on dry-season flow than that occurring earlier in the wet season.

A 77 percent reduction of June–July rainfall, with no change in annual rainfall, produces a calculated flow reduction of about half of that caused by the 44 percent decrease in April–May rain. However, the actual influence of altered summer rainfall is uncertain. Some evidence (Figure 3) suggests that summer rainfall may have less effect on dry-season flows than the API-based models predict, possibly because after a seasonal soil moisture deficit accumulates, a higher proportion of rainfall may be stored in the soil and transpired before it contributes to runoff. Field experience suggests that Caspar Creek hydrographs begin to show their characteristic responses to wet-season rainfall only after about 200 mm of autumn rain has fallen.

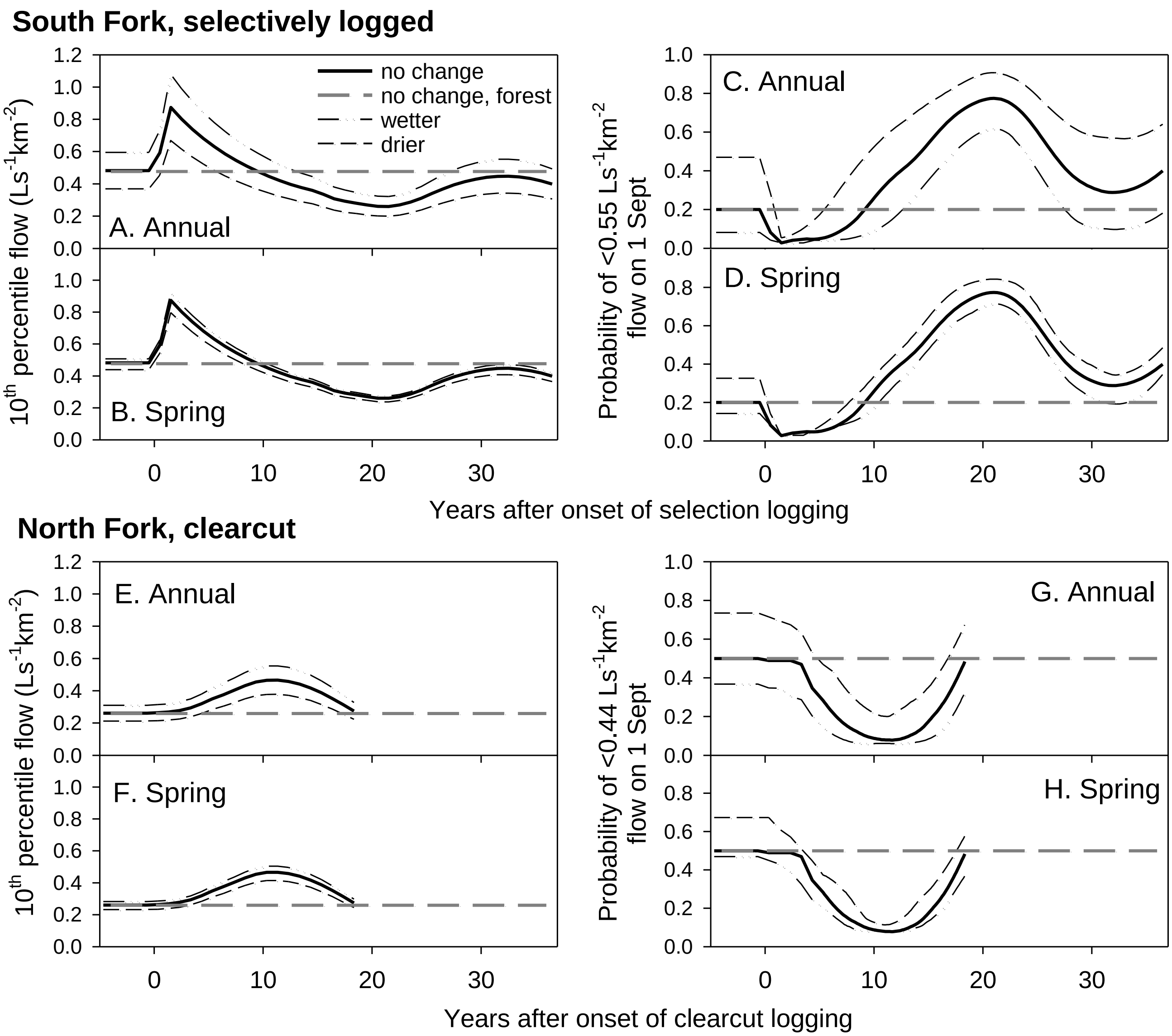

Figure 4. Modeled response of September 1 weir flows to logging and hypothetical rainfall changes. *Upper left:* Comparison of flow for which 10 percent of September 1 South Fork flows are lower for (a) a 22 percent increase and decrease in annual rainfall and (b) a 44 percent increase or decrease in April–May rainfall with no change in annual rainfall. *Upper right:* Comparison of calculated frequencies for September 1 South Fork flow <0.55 L/km^2-s (5-yr return interval) for the same changes in (c) annual and (d) spring rainfall. *Lower left:* Analogous plots for 10th percentile North Fork Caspar Creek September 1 flows after clearcut logging for the same changes in (e) annual and (f) spring rainfall. *Lower right:* Calculated frequencies for a September 1 North Fork flow <0.44 L/km^2-s (2-yr return interval) for the same changes in (g) annual and (h) spring rainfall.

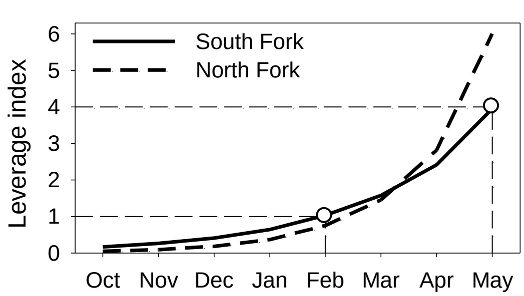

Figure 5. Influence of rainfall timing on September 1 flows. For example, a 1 percent change in annual rainfall that occurs through altered May rainfall has an effect on South Fork flow equivalent to that of a 4 percent change distributed through the year, while a 1 percent change restricted to February is equivalent to a 1 percent distributed change.

Modeling of the same hypothetical changes in rainfall regime evaluated above, but this time in combination with clearcut logging, can be carried out only for the initial 19-yr period of flow increase at the North Fork (Figure 4). Under unlogged conditions, dry-season flows are lower per unit area at the North Fork, so although the 10th percentile flows increase by a maximum factor of 1.8 at both sites, the magnitudes differ (Figure 4). For the North Fork, too, seasonal redistribution of rainfall can affect the post-logging response even without a change in annual rainfall, and the relative influence of rainfall late in the wet season is even more pronounced for the North Fork than for the South Fork (Figure 5).

Conclusions

Data from Caspar Creek show that partial clearcutting in a coast redwood forest, in combination with forestry activities that often ensue, produced a larger (per unit area of clearcut equivalent) and lengthier increase in dry-season flow than selective logging. Results also show a long period of dry-season flow depression after selective logging. Data are not yet available to determine whether the partially clearcut watershed will also undergo a period of reduced flow.

A variety of climatic projections suggest that major changes in annual rainfall are unlikely in the area, though an analysis by Madej (pp. ##, this volume) indicates that the seasonal distribution of rainfall may be shifting. Calculations of the combined effects of logging and potential changes in rainfall regime indicate that a change in the proportion of rainfall that occurs late in the wet season may augment or reduce dry-season flows, in concert or opposition to logging effects, even if mean annual rainfall does not change.

Although we have considered only changes in rainfall regime, other kinds of climatic change may be important in the region, such as altered frequency of summer fogs and associated changes in dry-season temperature. Should conditions become warmer in the region, the major climatic contribution to an effect on summer flows may well be indirect. Increased temperatures during the growing season increase the water demands of crops, leading to increases in water diversions for irrigation. If such extractions are superimposed on a period of flow depression following logging, changes in dry-season flow might become of particular concern.

The contrasting patterns of flow change after selective and clearcut logging may allow design of watershed-scale silvicultural strategies to lessen risks of adverse dry-season flow changes in stream reaches of concern. In any case, it may be useful to employ a variety of silvicultural strategies well-dispersed through time and space to avoid synchronizing dry-season flow responses in watersheds where altered low flows may adversely affect beneficial uses in downstream reaches.

Acknowledgments

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