Vegetation Management and Water Yield: Silver Bullet or a Pipe Dream?

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Lee MacDonald is professor emeritus and a senior research scientist at Colorado State University. His academic training includes a BS in human biology from Stanford, an MS in resource ecology from the University of Michigan, and a PhD in forest hydrology from the University of California at Berkeley. He did a post-doc at the University of Washington, was a hydrologist for the U.S. Forest Service, and has worked as a consultant. From 1990 to 2012 he was a professor of land use hydrology in the Watershed Science Program, and he has advised more than 40 graduate students and published more than 50 peer-reviewed articles, monographs, and book chapters. His research focusses on how changes in land use and vegetation affect runoff, erosion, and sediment yields, particularly in forested areas, with special emphasis on the effects of fires, roads, and timber harvest. He also has taught and published on cumulative watershed effects, hillslope and wetland hydrology, forest management effects on stream channels, and erosion in steep agricultural areas. The bulk of his work has been in the western U.S., but he has worked and traveled in more than 60 countries on all seven continents, and given dozens of invited workshops and lectures throughout the U.S., Europe, Asia, and the Pacific. He also was appointed to a National Academy of Sciences panel to assess the hydrologic effects of a changing forest landscape. In his current positions he is leading research projects, advising graduate students, consulting, and directing a long-term curriculum development project in Vietnam. More details and links to his publications and student theses can be found on his web site http://www.nrel.colostate.edu/macdonald-lab/.

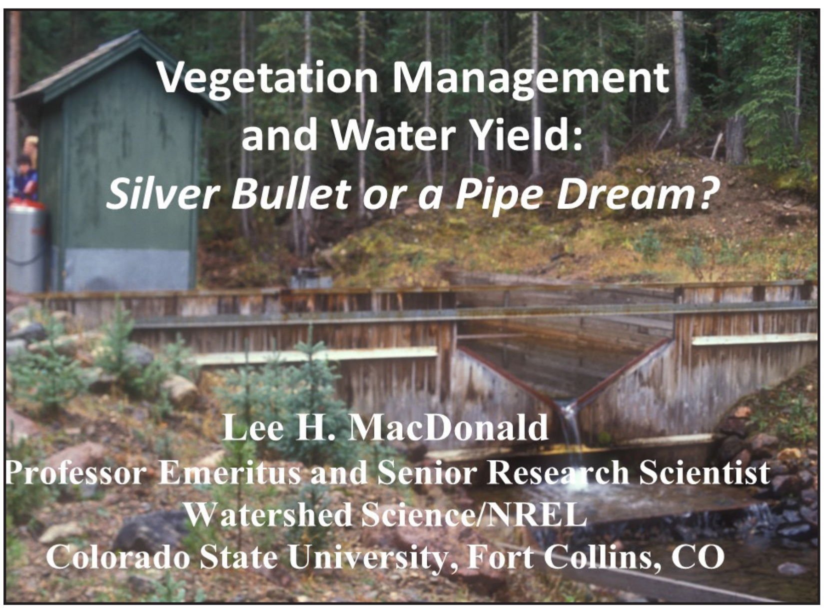

Figure 1. Introduction.

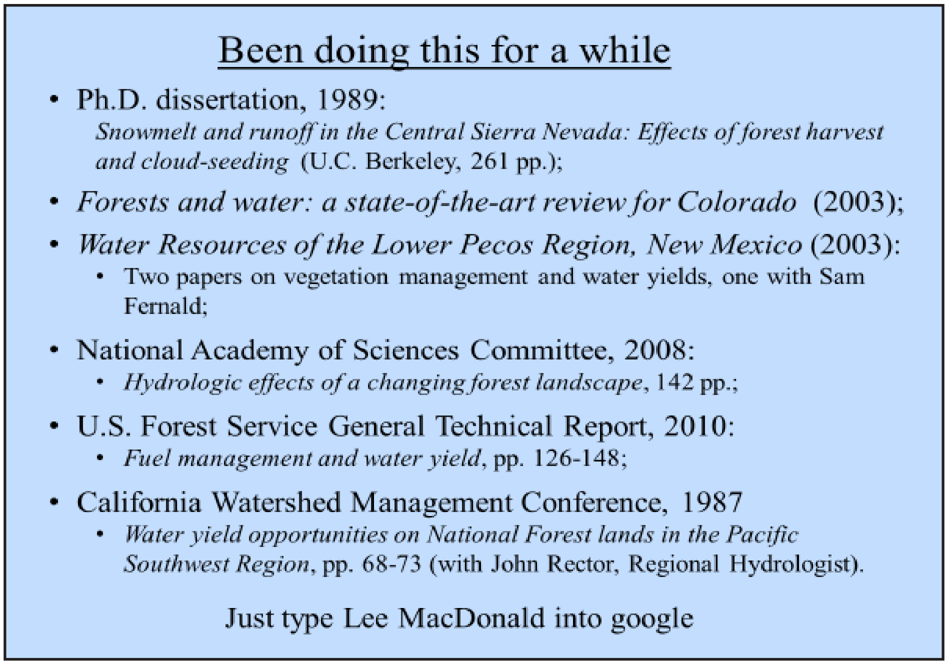

Figure 2. Lee MacDonald selected publications.

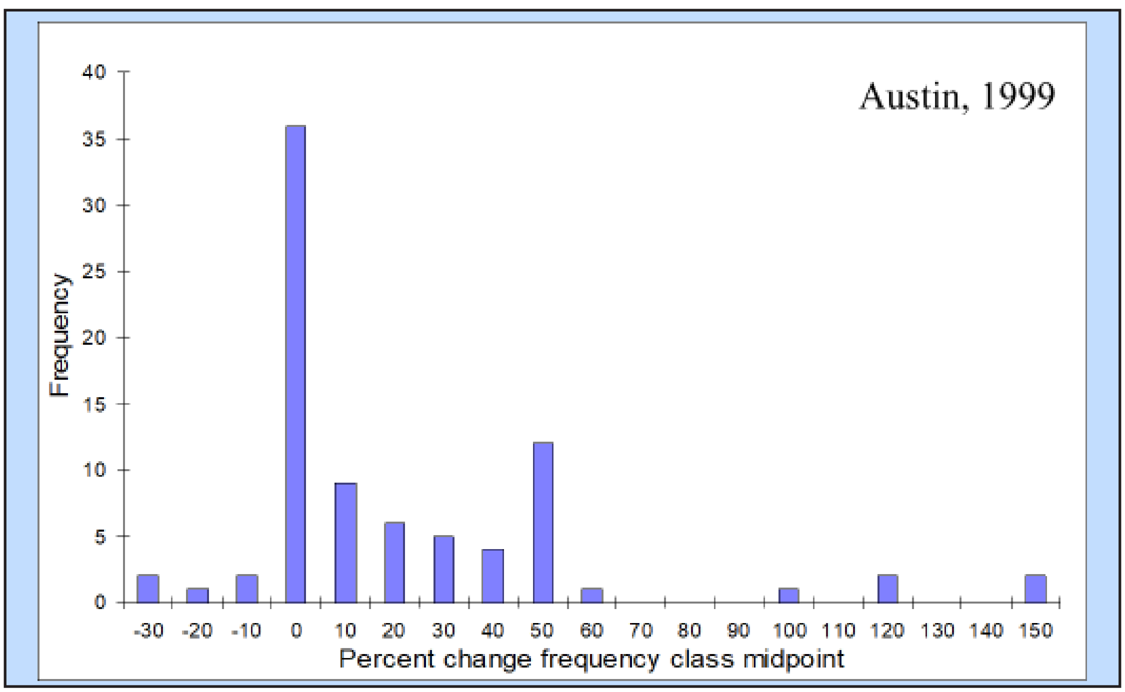

Figure 3. Percent water yield change from forest harvest.

To understand and predict changes in runoff due to vegetation management requires us to:

- Understand the changes in each underlying process;
- Understand how site conditions affect each process;
- Quantify each change over time;
- Sum each predicted change over time to estimate the total net change.

Without a process-based understanding we will be confused and just endlessly argue!

Figure 4. Basic precept.

First principle: Use the Law of Continuity (i.e., basic water balance):

$$\text{Inputs} = \text{Outputs} \pm \text{Change in storage} \qquad (1)$$

$$\text{Precipitation} = \text{Interception} + \text{Evaporation} + \text{Transpiration} + \text{Runoff} \pm \text{Change in storage} \qquad (2)$$

$$P = I + E + T + Q \pm \Delta S \qquad (3)$$

Figure 5. Predicting the effect of vegetation management on runoff using the Law of Continuity.

$$P = I + E + T + Q \pm \Delta S \qquad (3)$$

Usually lump evaporation and transpiration;

Change in storage on annual basis ≈ 0;

Runoff is output of interest, so rearrange to get:

$$\mathbf{Q = P - I - ET} \qquad (4)$$

Figure 6. Law of Continuity.

What is the effect of forest harvest on interception?

What is the effect of forest harvest on transpiration?

If forest harvest usually decreases interception and transpiration, by equation 4:

$$\uparrow \mathbf{Q = P - \downarrow I - \downarrow ET} \qquad (5)$$

There are some exceptions (e.g., cloud forests; increased baseflows due to increased infiltration with more woody vegetation).

Figure 7. Law of Continuity (cont.).

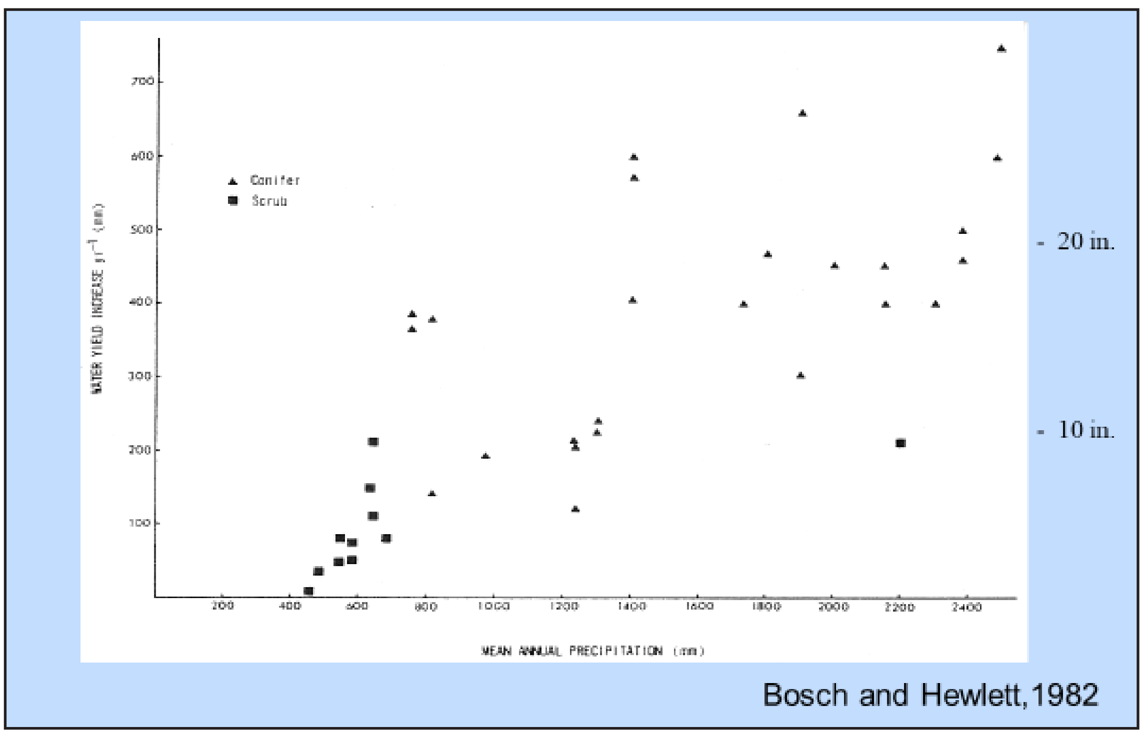

Figure 8. First-year water yield increase due to forest harvest v. mean annual precipitation.

- Need at least 450-500 mm (18-20 inches) of annual precipitation to get a runoff response from clearing the woody vegetation;
  - In wetter areas may get a water yield increase from cutting as little as 20%;
  - In drier areas have to cut more, as residual vegetation and evaporation readily scavenge any "extra" water;
- Potential increase in water yield is directly related to annual precipitation;

$$Q = P - ET \pm \Delta S \qquad (4)$$

Figure 9. Limitation #1.

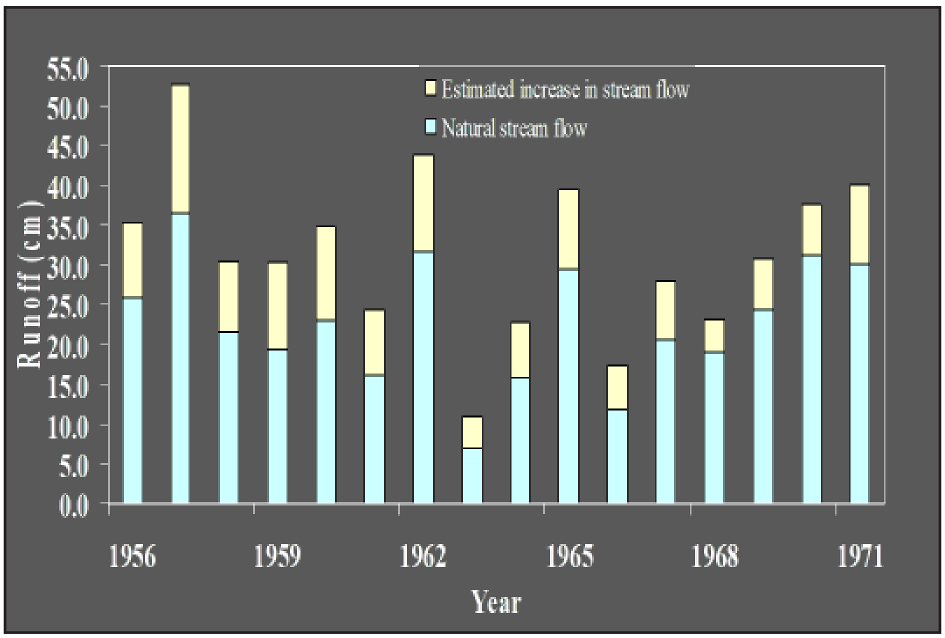

Figure 10. Increased runoff by water year in Fool Creek, CO, 1956-1971.

- Biggest increases occur in the wet years when they are least needed, and smallest increases in the dry years when they are most needed;

Figure 11. Limitation #2.

- Biggest increase comes at the beginning of the wet season as less water needed to recharge soils;
  - IF the soils are deep enough to allow the "saved" water to be stored below the rooting depth of the remaining vegetation;
- In rain-dominated areas some of the additional water comes during the wet season due to reduced interception;

Figure 12. When will the increase in runoff occur?

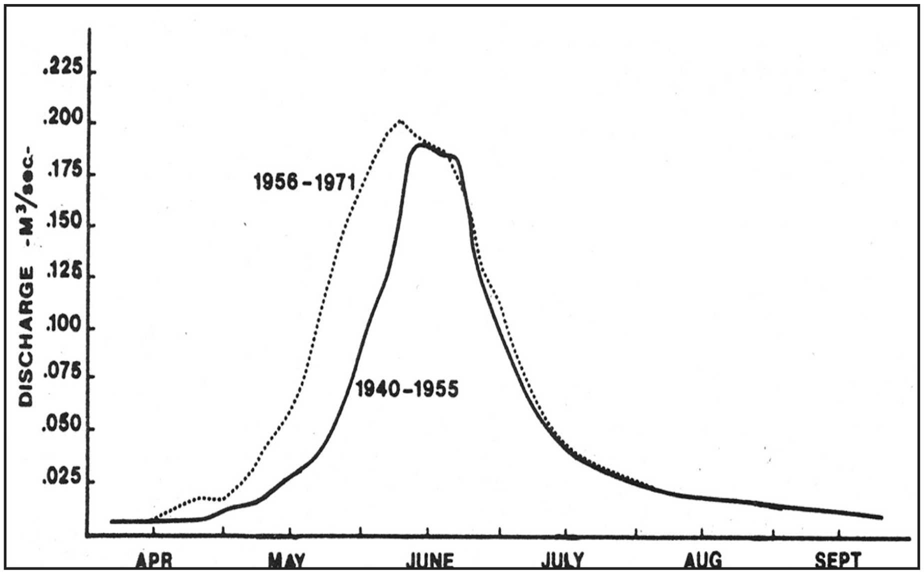

Figure 13. Pre- and post-treatment hydrographs in Fool Creek, CO.

- Soil water and groundwater must be stored below the rooting depth of the residual vegetation and the depth of soil evaporation;
- Since most of the water comes during the wet season, downstream reservoir storage is needed if the extra water is to be used at a time different from when it is produced (e.g., summer irrigation);

Figure 14. Limitations #3 and #4: timing, soil depth, and storage.

What happens to the water yield increase over time?

Figure 15. What happens to the water yield increase over time?

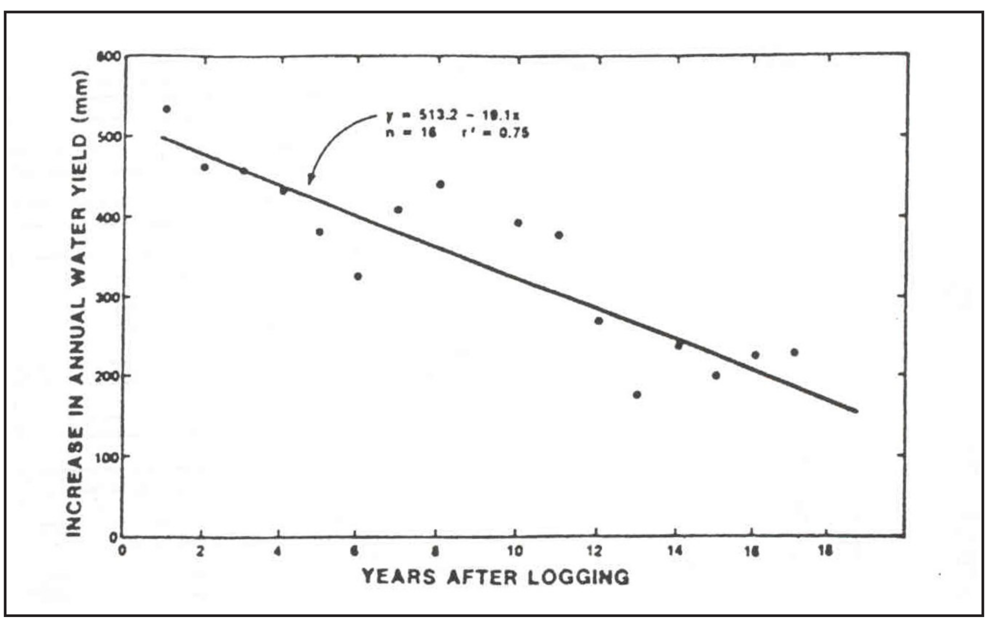

Figure 16. Time-varying increase in annual water yields at watershed 1 in H.J. Andrews experimental forest in Oregon.

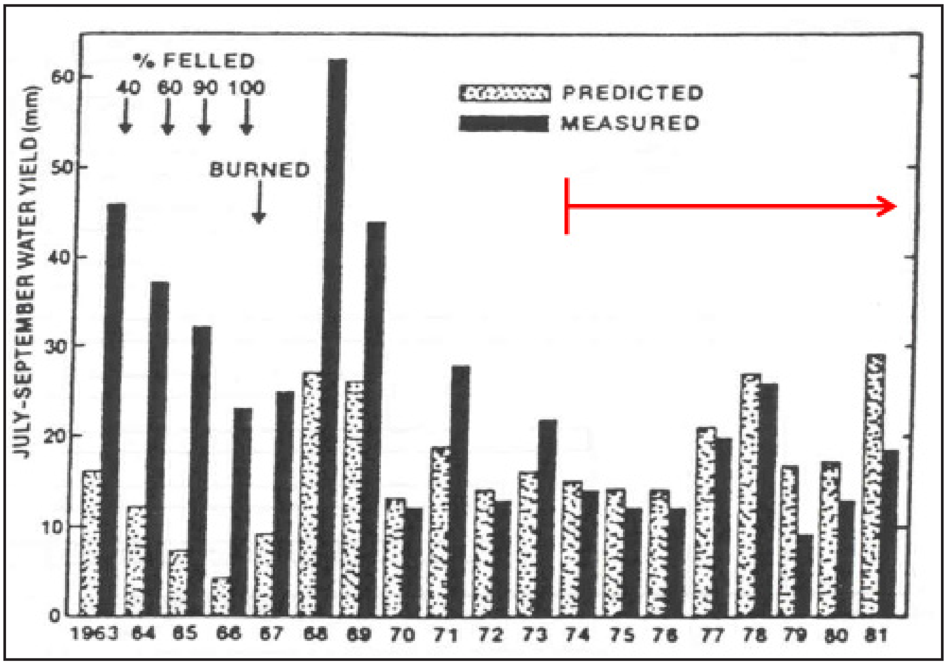

Figure 17. Summer streamflow over time at watershed 1 in H.J. Andrews experimental forest in Oregon.

- Have to keep removing the vegetative regrowth, or else the increase in water yield will disappear or even decrease;
- More rapid disappearance in:
  - In drier areas;
  - Areas with very rapid regrowth (e.g., species that resprout, wet tropical forests);
  - In low flows.

Figure 18. Limitation #5: regrowth.

- Limited precipitation in New Mexico means that water yield increases from vegetative treatments will generally be relatively small;
- A small increase times a large area can yield a big number, but:
  - How much of a given watershed is suitable for treatment (precipitation, soils, vegetation)?
  - How much of a given watershed can be treated given ownership and other resource constraints?

Figure 19. Limitation #6: area suitable for treatment.

- Treatment threshold of 20-25% applies to:
  - Paired-watershed experiments;
  - Very accurate discharge measurements;
- Change more difficult to detect over time:
  - At one location;
  - Using typical gauging stations given their lower accuracy;

→ Highly unlikely to detect a statistically significant change in flows in most management situations;

→ Is it ok to just act on theory and faith?

Figure 20. Limitation #7: detectability.

- A reduction in woody vegetation will reduce snow interception and increase the snowpack, but:
  - Large openings may be subject to wind scour, so one needs either small openings (<6 H) or sufficient roughness to hold the snow;
  - Increased sublimation may compensate for the reduction in interception (Dahm et al., 2013; Jemez Mountains).

Figure 21. Limitation #8: snowpack effects.

- Potential trade-off between increasing water yield and increasing erosion;
  - Watershed managers must maximize infiltration and ground cover in order to minimize overland flow and surface erosion;
  - Should not create more than 30-35% bare soil!

Figure 22. Limitation #9: trade-off between runoff and erosion.

- How many roads will be needed for management, and how will these be managed to minimize erosion and sediment delivery?

Figure 23. Limitation #9: trade-off between runoff and erosion (Cont.).

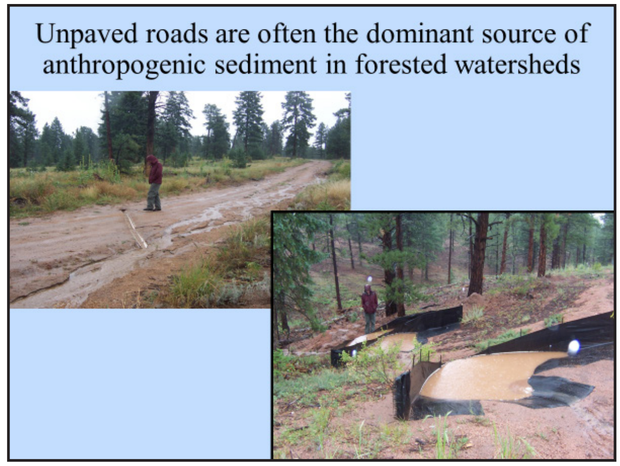

Figure 24. Unpaved roads are often the dominant source of anthropogenic sediment in forested watersheds.

Figure 25. Fires increasing runoff.

Figure 26. Fires increasing flooding.

Figure 27. Fires increasing erosion.

- People have been discussing the potential to increase water yields by vegetation management for decades, but how many operational projects can you name?
- Thinning projects are being justified by reducing fire risk and possibly forest health concerns, not their potential increase in water yields;
  - Water yield increases do not justify costs;
  - Is there a mechanism to capture the economic value?
- Much easier to reduce demand than increase supply (e.g., more efficient irrigation systems).

Figure 28. Empirical evidence.

- Increasing water yields through vegetation management is good in theory, but subject to many limitations;
- The biggest control on the amount of runoff is the amount of precipitation, and we have very little control over that;
- Theoretical potential for small, very localized increases;
- Relatively high cost means that an increase in water yield will generally be a by-product rather than a primary objective;

You decide: pipe dream or silver bullet?

Figure 29. Conclusions.

Figure 30. Questions?

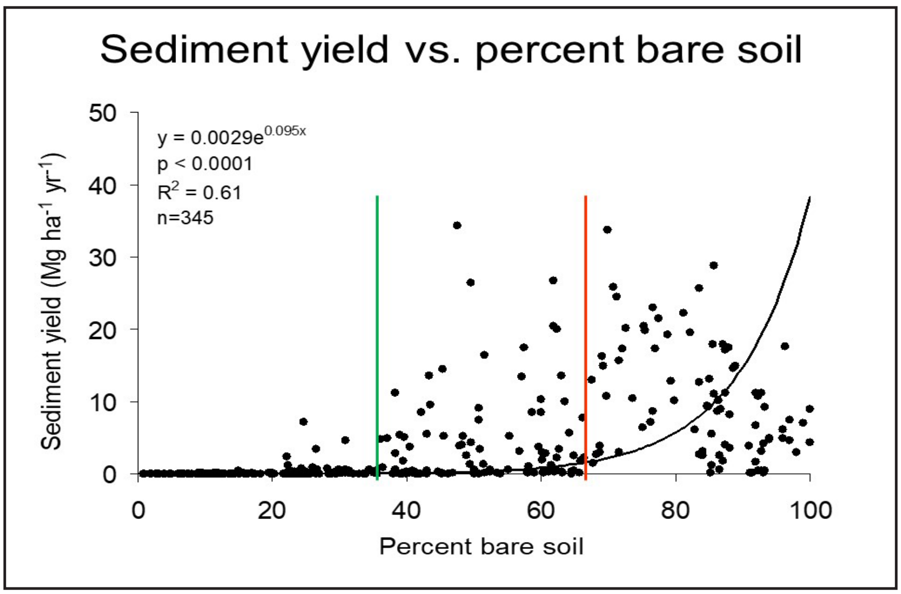

Figure 31. Sediment yield v. percent bare soil.

<u>Actually, I'm a bit of a newbie!</u>

- Raphael Zon, 1927:
  Forests and water in the light of scientific investigation, USDA;
- First paired watershed experiment began in 1910 at Wagon Wheel Gap, Colorado, and published in 1928;
- Relationship between forests and water recognized in ancient Greece, China, India, …. (M. Chang, 2013, *Forest Hydrology*).

Figure 32. Past scientific invesigation into water and forests.

1) Provide a process-based understanding of how changes in vegetation can affect runoff:
   Annual water yields;
   Low flows;
   Size of peak flows;
2) Discuss the practicality of increasing water supply through vegetation management;
3) Contrast our ability to affect runoff with our effects on erosion, water quality, and water demand.

Figure 33. Objectives.

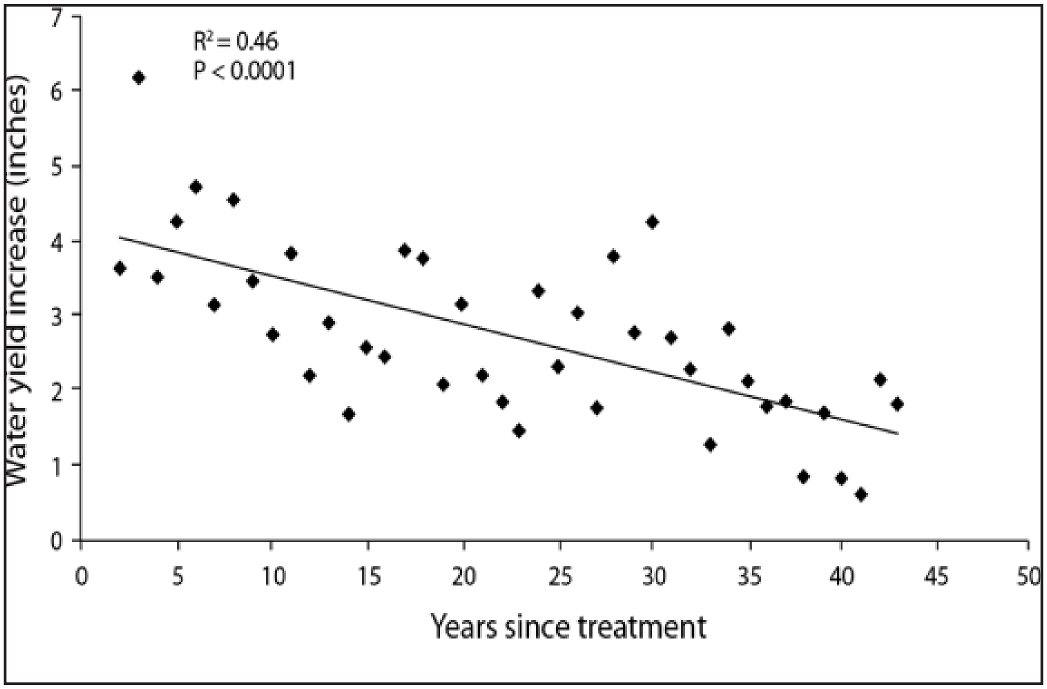

Figure 34. Time-varying increase in water yields at Fool Creek, CO.

- More rapid disappearance of any increase in low or dry season flows;
- Depending on what grows back where, water yields may even decrease compared to pre-treatment;

Figure 35. Limitation #10.

- U.S. Forest Service tried to test the results from Fool Creek at a larger scale;
  - Could only find a very few large unmanaged watersheds to be harvested;
  - Maximum area that could be clearcut was only about 23% of the watershed, plus ~3% for roads and landings;
  - Barely met the area threshold for a detectable effect in a research setting.

Figure 36. Limitation #11: treated areas.