Post-fire Erosion and Rehabilitation: A Process-based Understanding

Lee H. MacDonald

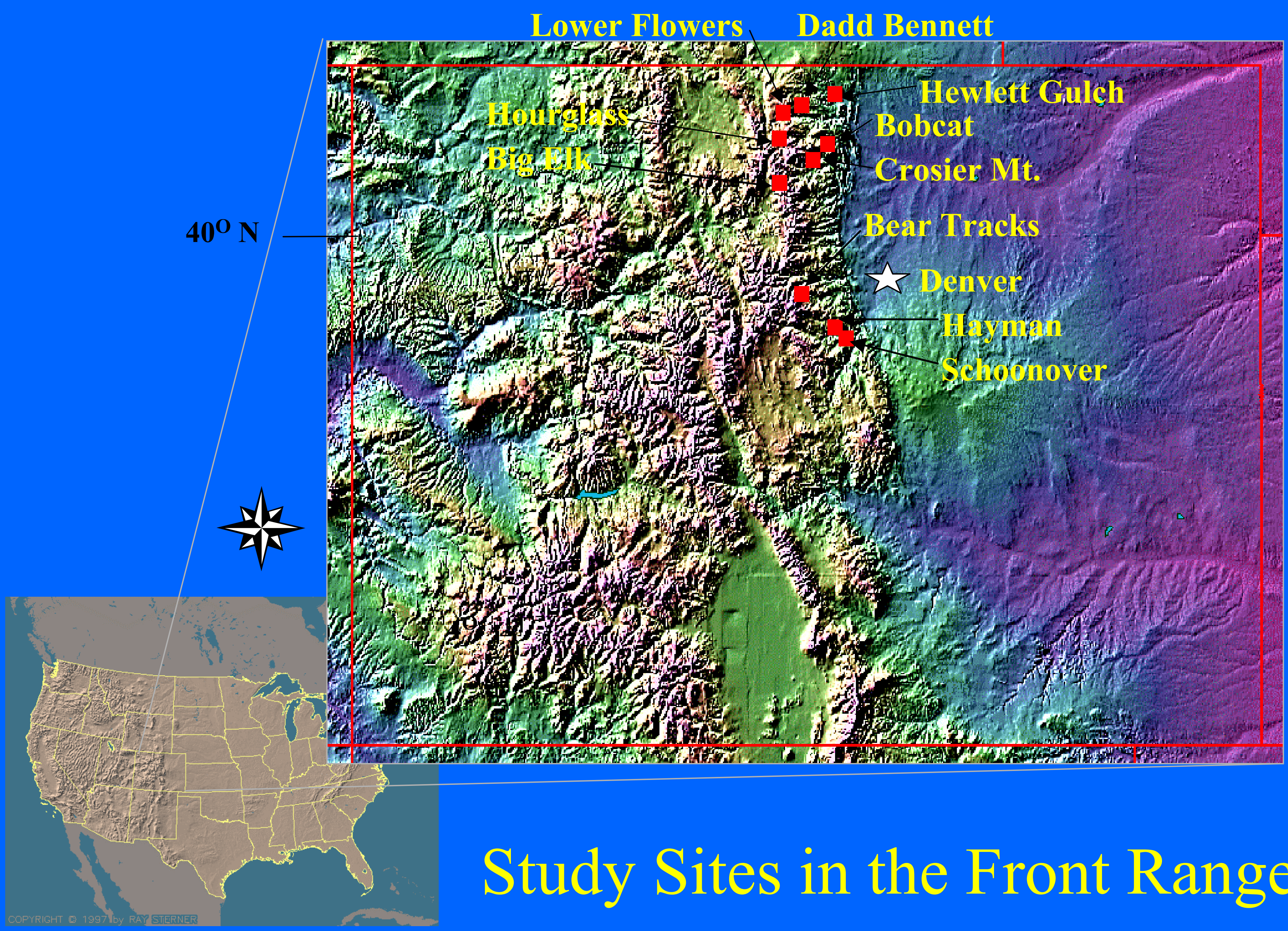
Department of Forest, Rangeland, and Watershed Stewardship

Colorado State University

Fort Collins, CO

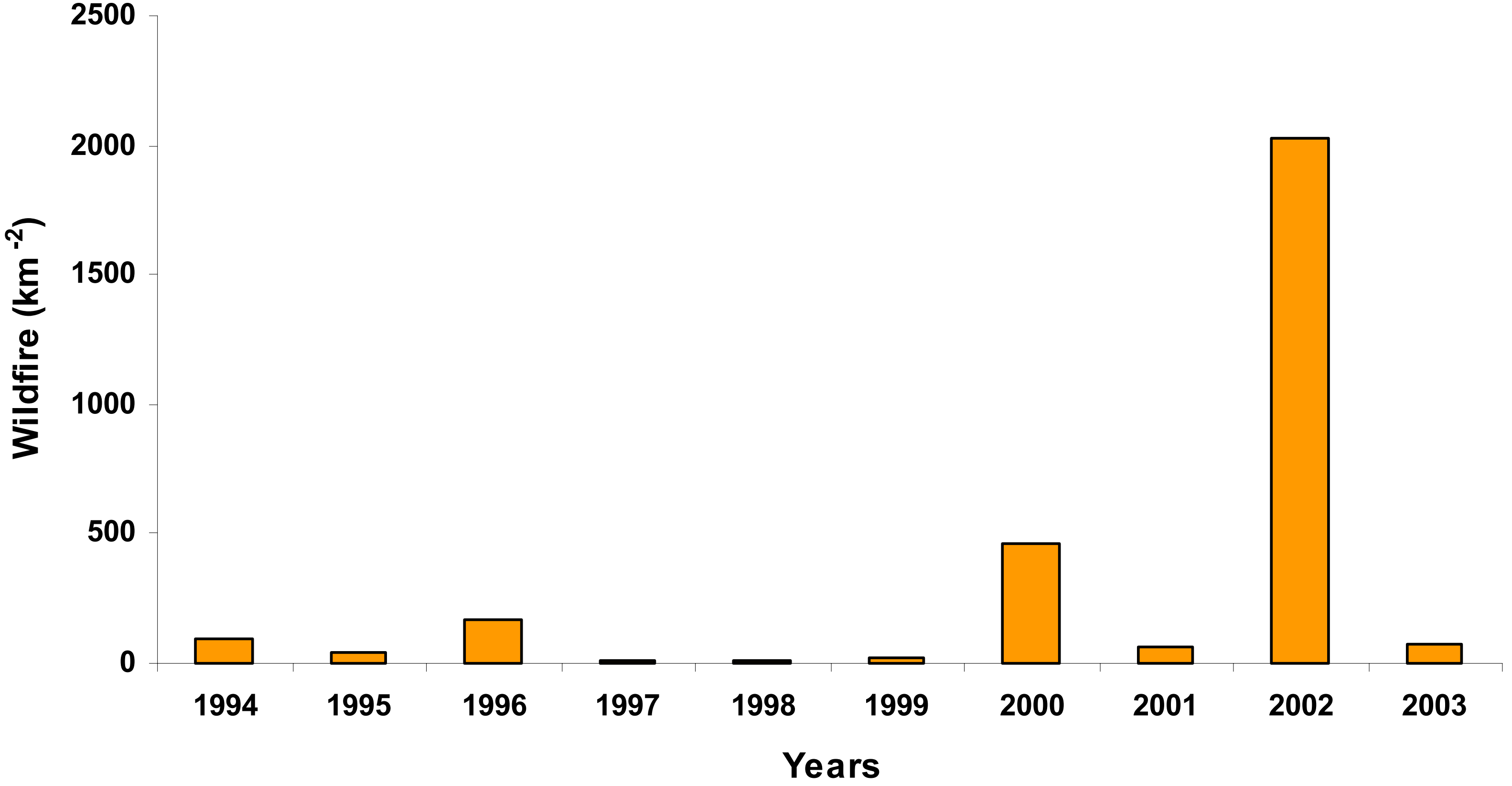
Contributors

- Tedd Huffman (M.S., 2002);
- Juan Benavides-Solorio (Ph.D., 2003);
- Joe Wagenbrenner (M.S., 2003);
- Matt Kunze (M.S., 2003);
- Zamir Libohova (M.S.,2004);
- Jay Pietraszek (M.S., 2005);
- Daniella Rough (M.S.,2005);
- Darren Hughes (M.S., 2005);
- Ethan Brown (M.S., 2005);
- Dr. John Stednick.

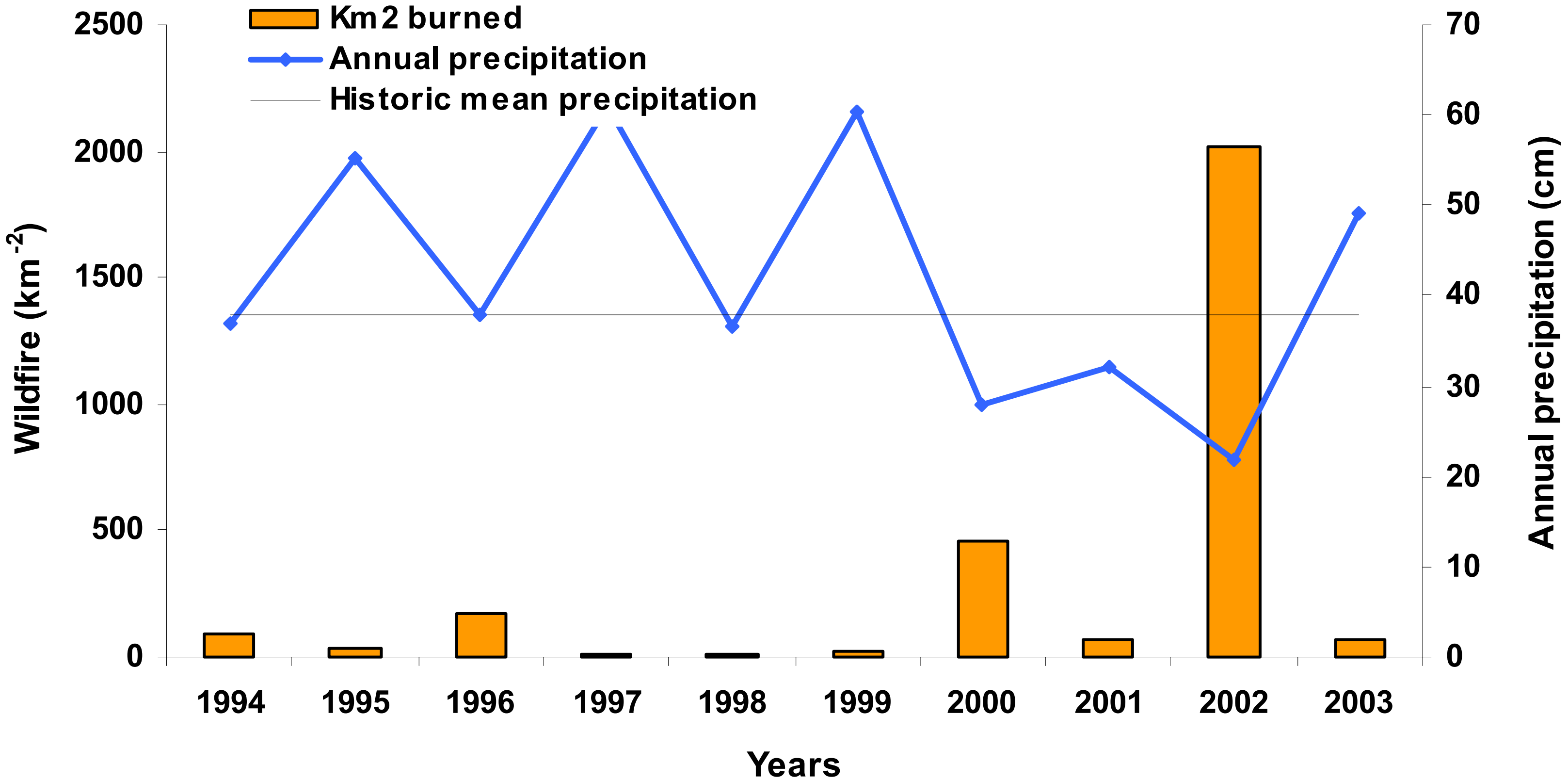


Study Sites in the Front Range

Area Burned in USFS Region 2, 1994-2003



Area Burned and Precipitation, 1994-2003



Erosion after a 100-year storm on the 1996 Buffalo Creek fire southwest of Denver, Colorado

Photo by John Moody, USGS

High flows from a storm with a 30-minute rainfall intensity of 19 mm/h one year after the Buffalo Creek fire.

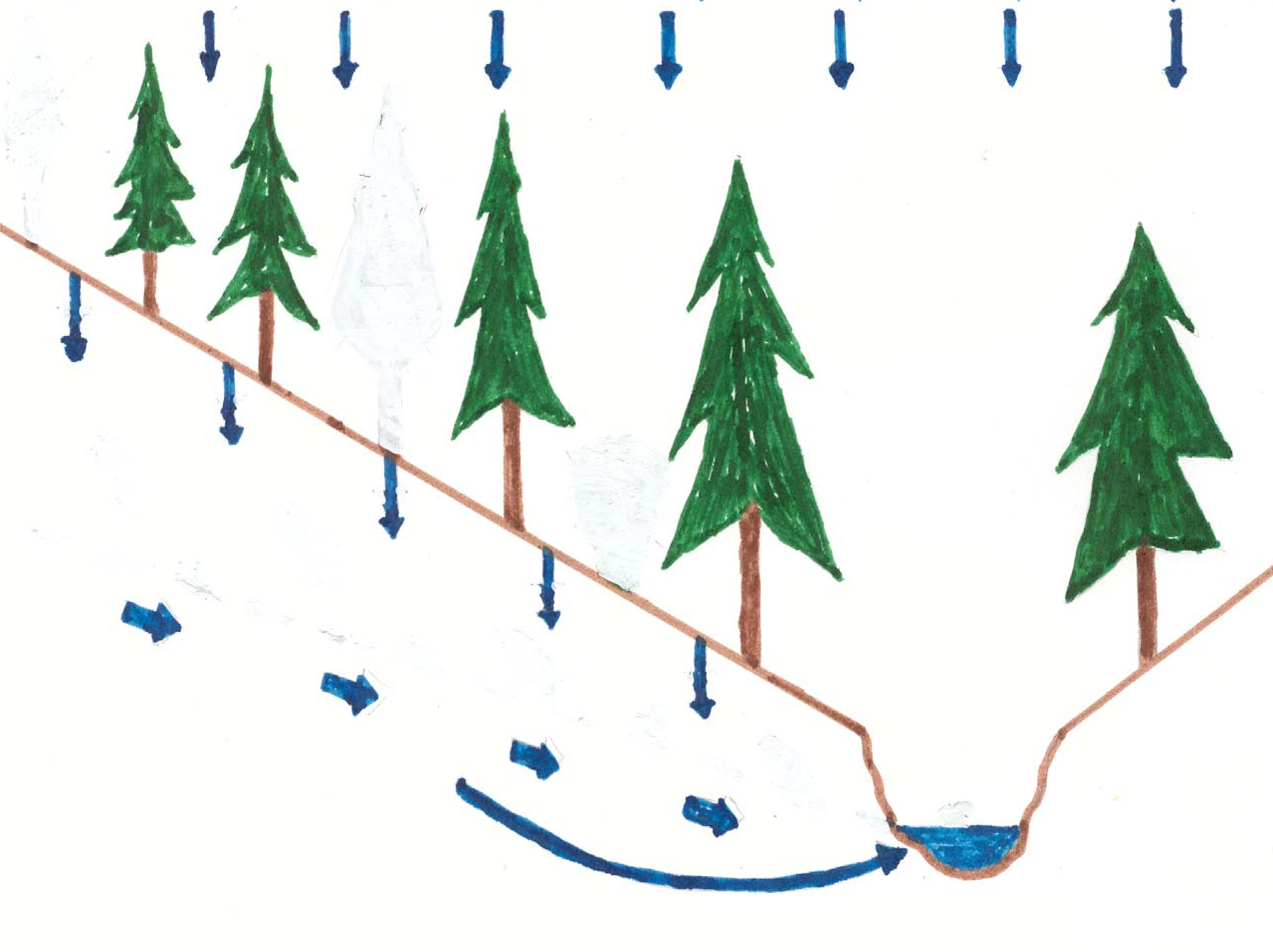
Photo by John Moody, USGS

Channel incision from a 20 mm/hr rain event after the Cerro Grande Fire near Los Alamos, NM.

Photo by John Moody, USGS

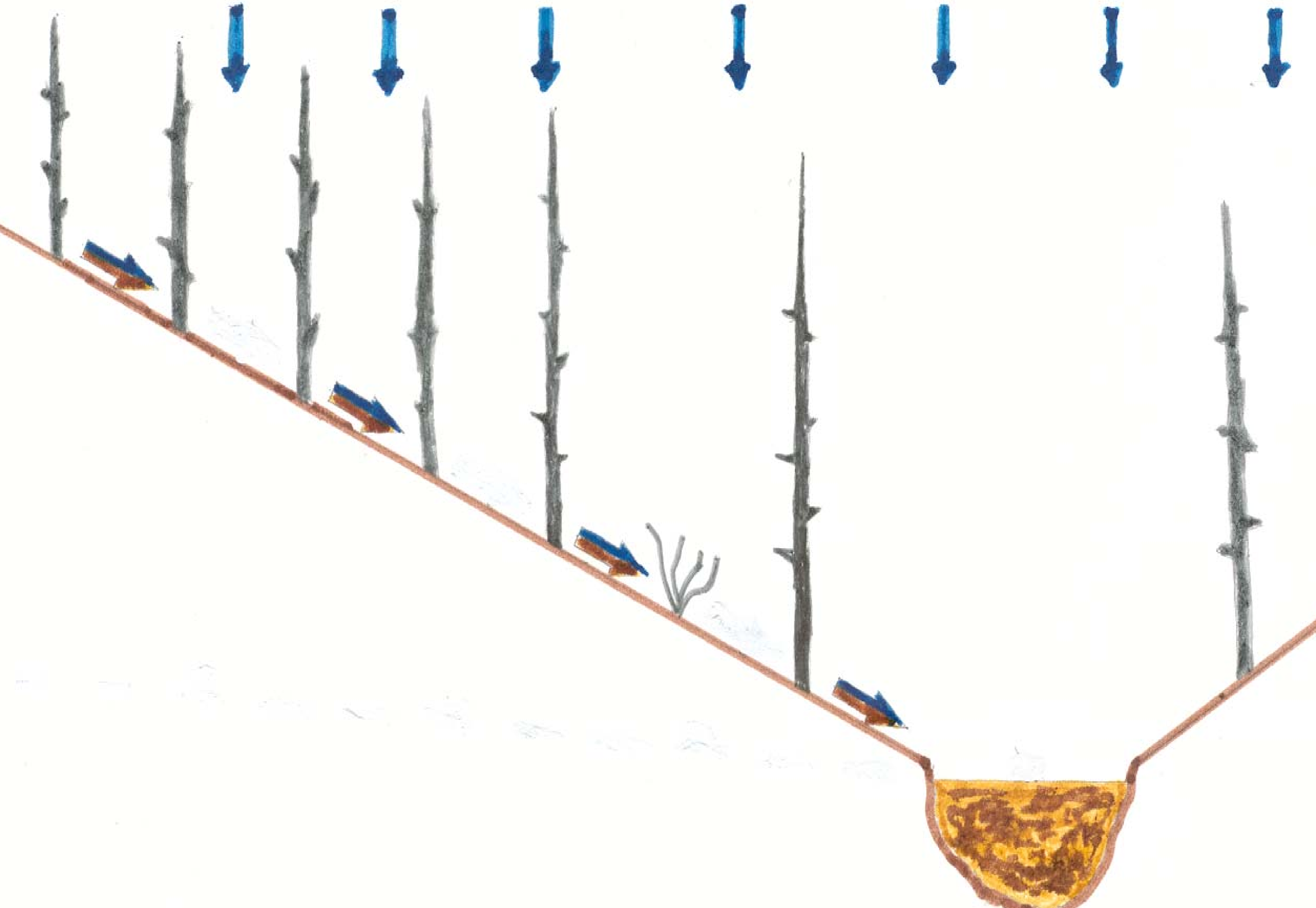
Deposition of coarse sand and gravel after the Cerro Grande fire in northern New Mexico.

Photo by John Moody, USGS



Hydrology of Unburned Forests

- Coarse-textured soils (>60% sand);
- Generally good ground cover (usually $\geq$ 80%);
- Storm runoff generated primarily by subsurface stormflow;
- Low peak flows from all but highest-magnitude storm events;
- Very low mean erosion rates (<0.1 t ha^{-1} yr^{-1});
- Clean, high quality water.



Post-fire Hydrology

- Loss of surface cover;
- Possible water repellent layer in the soil;
- Shift in runoff processes from sub-surface stormflow to infiltration-excess (Horton) overland flow;
- Large increases in peak flow and erosion rates;
- Downstream sedimentation;
- Degradation in water quality (turbidity, suspended sediment, nitrate, manganese, dissolved organic carbon) and aquatic habitat.

Overall Objectives

1. Quantify the effect of wild and prescribed fires on runoff and erosion rates in the Colorado Front Range;
2. Determine the rate of recovery to pre-fire conditions;
3. Quantify the relative importance of different controlling factors on post-fire erosion rates;
4. Evaluate the effectiveness of different rehabiliation techniques, using a process-based understanding to explain the results;
5. Use the results and understanding to guide land managers and help design more effective rehabilitation treatments.

Collecting Data at Different Spatial Scales

- Point scale: soil water repellency;
- Small plot scale:
  - Runoff and sediment yields from rainfall simulations on 1 m^2 plots;
- Hillslope scale:
  - Sediment production from planar hillslopes and swales (zero-order catchments) using sediment fences;
  - Using paired-swale design to compare rehabilitation techniques against untreated controls;
- Small catchment scale:
  - Runoff, suspended sediment yields, water quality, and channel morphology.

Fortuitous Collection of Pre-fire Data

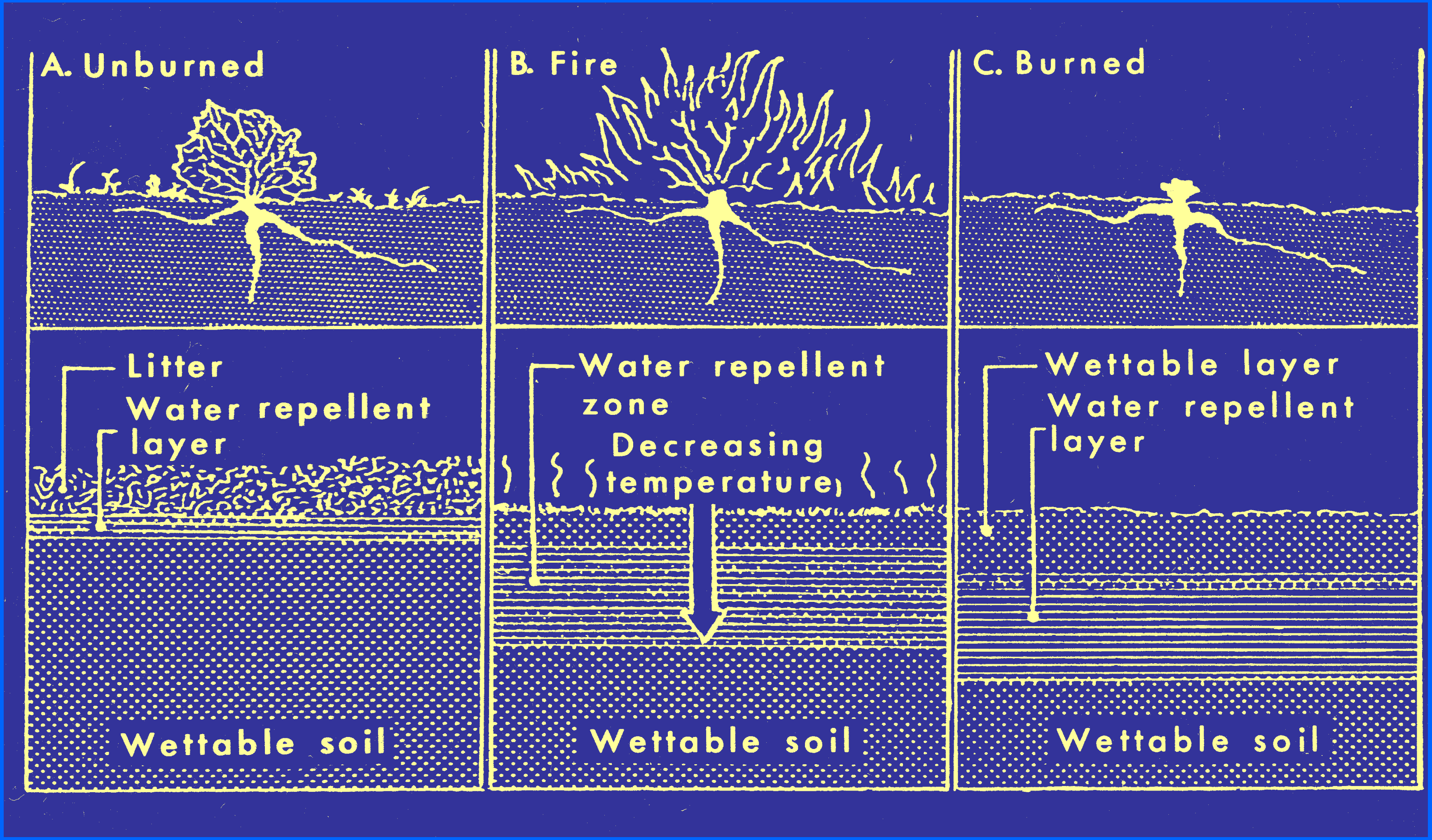
- Goal was to evaluate the effects of a proposed thinning project;
- Began monitoring percent cover, erosion rates, water quality, and channel morphology in mid-2001 on sites southwest of Denver;
- Majority of study sites burned in June 2002 Hayman fire, so have pre- and post-fire data at hillslope and small catchment scales.

Post-fire Effects Vary with Burn Severity

- Burn severity classified as high, moderate or low, depending on consumption of litter and soil organic matter;
- High severity: complete consumption of organic horizon and alteration of the structure or color of the underlying mineral soil; loss of aggregates ("pulverization"):
- Moderate severity: consumption of litter layer but no visible alteration of the surface of the mineral soil;
- Low severity: only partial consumption of the surface litter;
- Severity is not equal to intensity (heat loss per unit width per unit time), but severity and intensity often assumed to be closely correlated.


Soil Water Repellency

Fire-induced soil water repellency



(DeBano, 1981)

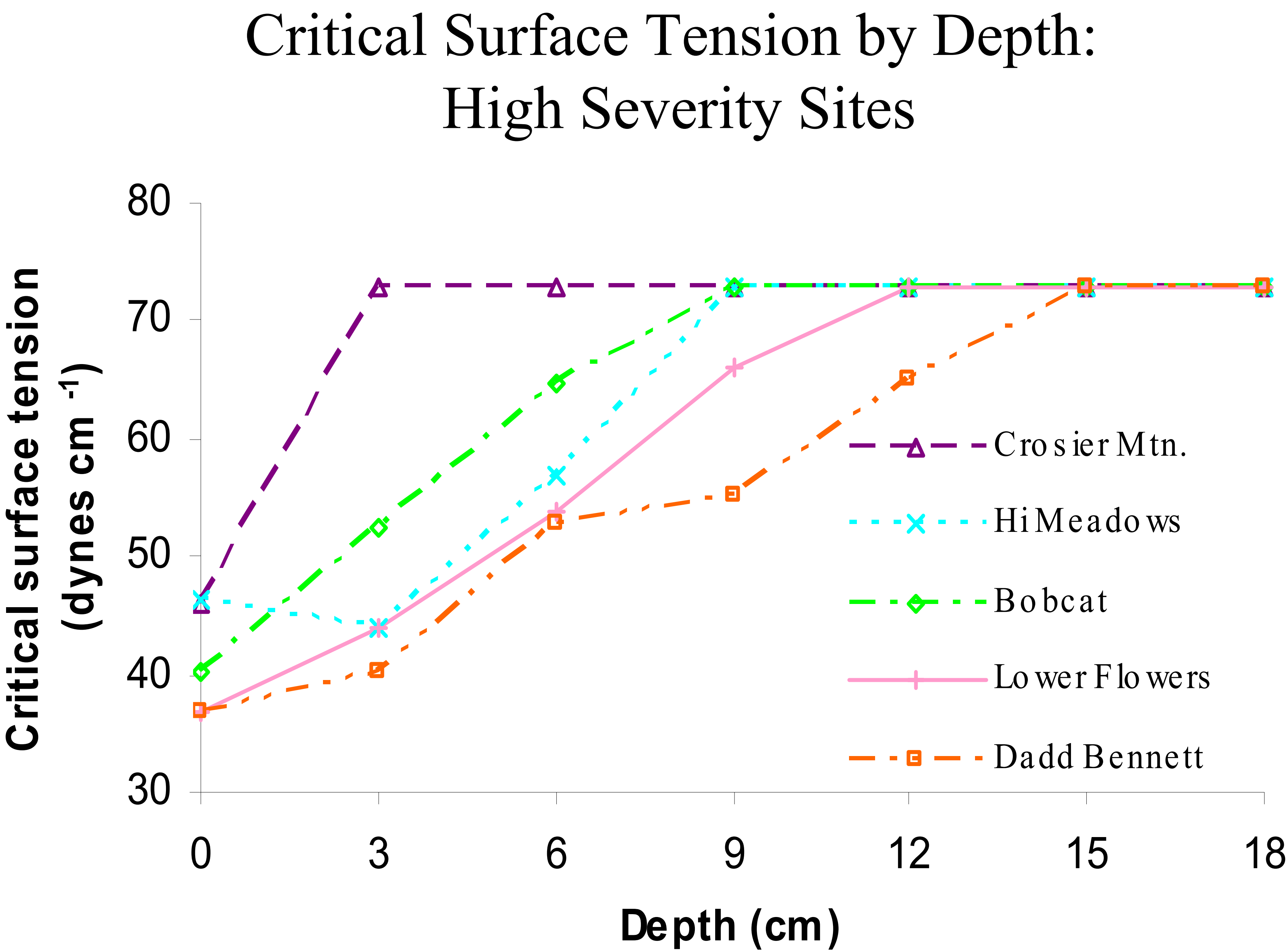
Methods of Analysis

Water drop penetration time (WDPT):

- Apply drops at 3-cm depth increments beginning at mineral soil surface;
- Indefinite waiting time.

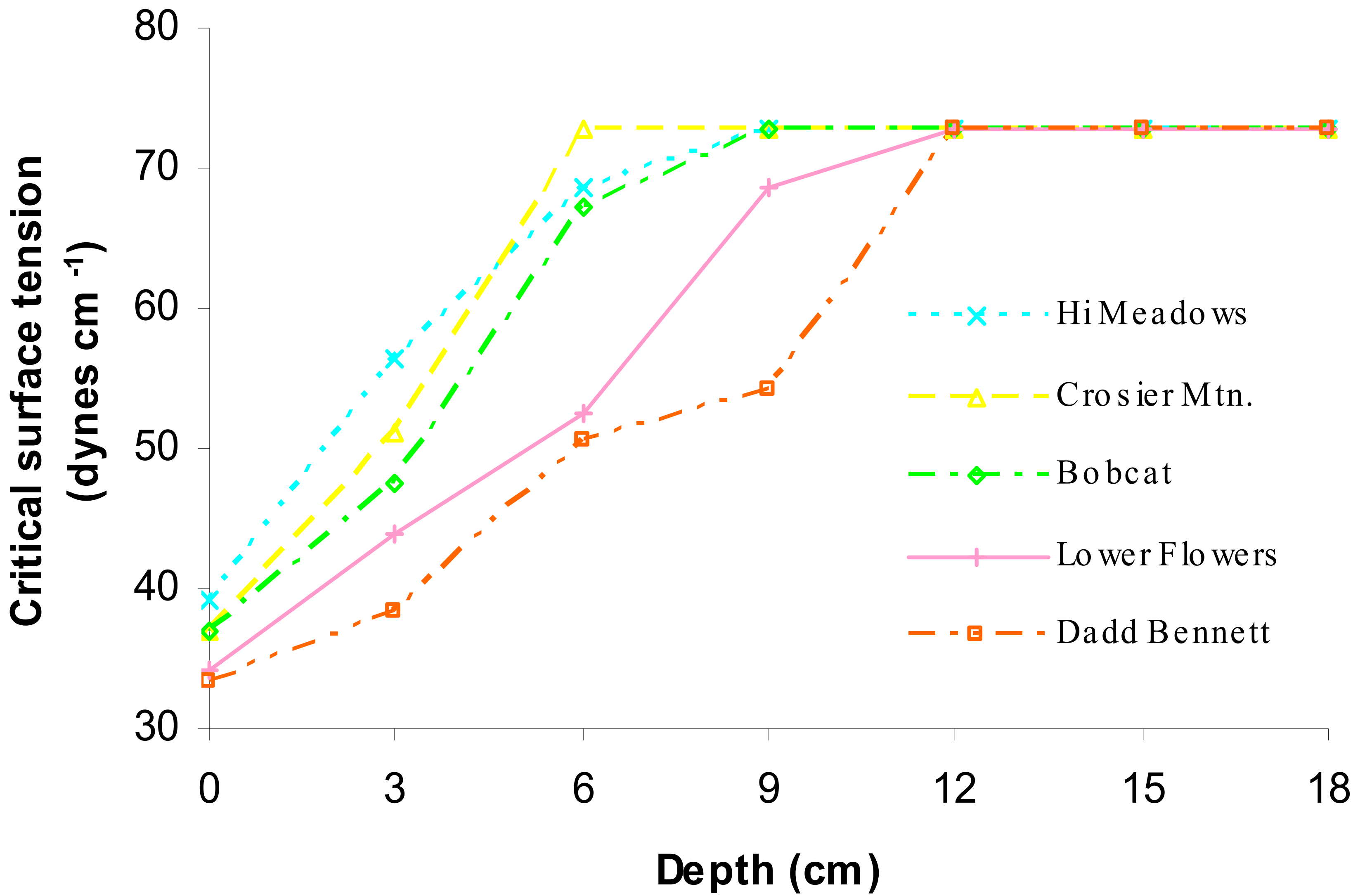
Critical surface tension test (CST):

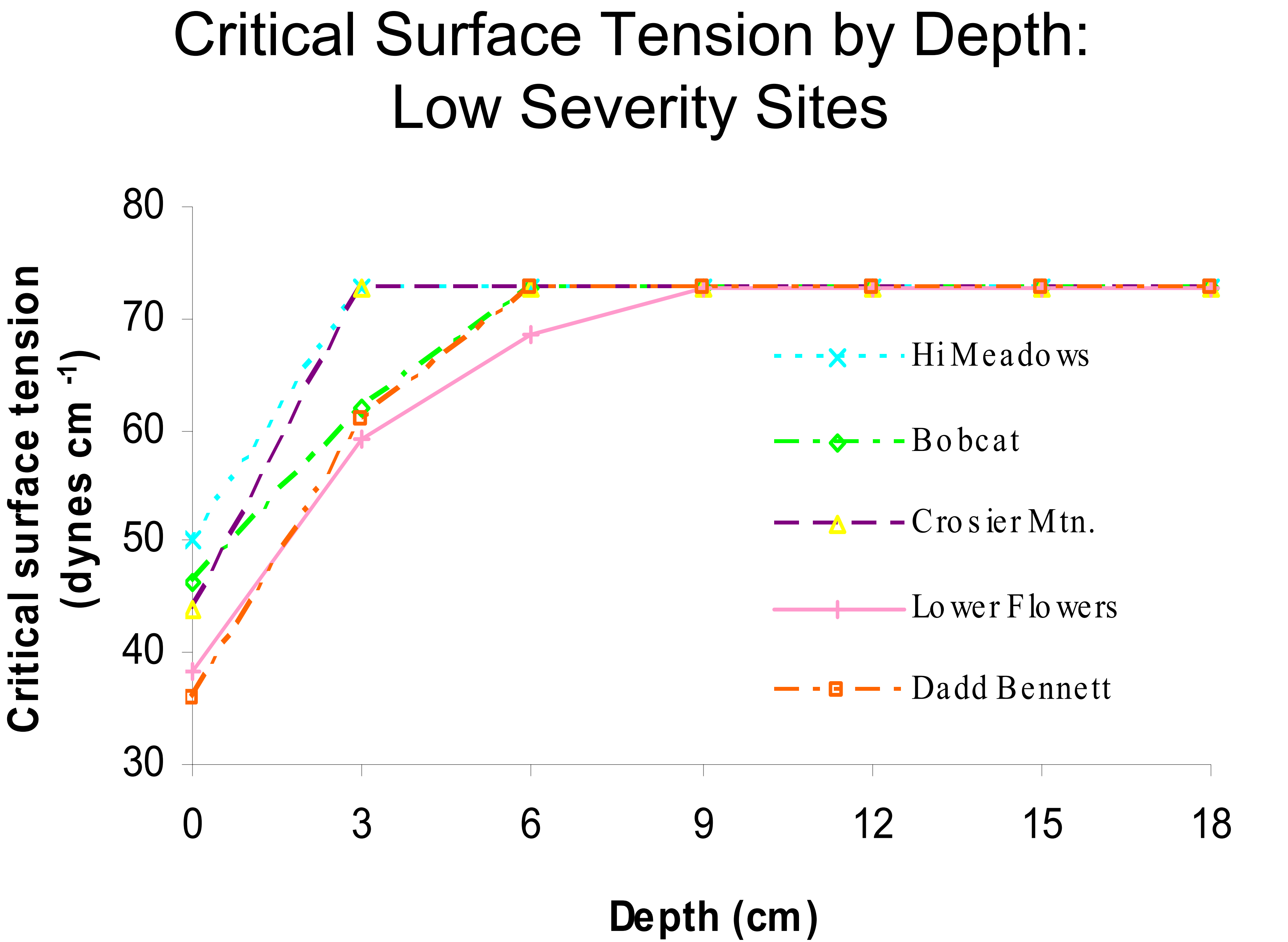
- Apply 5 drops of de-ionized water;
- If pure water is not absorbed within 5 seconds, test solutions with progressively higher ethanol concentrations (increasing ethanol concentrations decrease surface tension);
- Critical surface tension (CST) is the tension of the first solution that is readily absorbed into the soil.



Critical Surface Tension by Depth:
High Severity Sites
Critical surface tension
(dynes cm -1)
80
70
60
50
40
30
0
3
6
9
12
15
18
Depth (cm)
Crosier Mtn.
Hi Meadows
Bobcat
Lower Flowers
Dadd Bennett

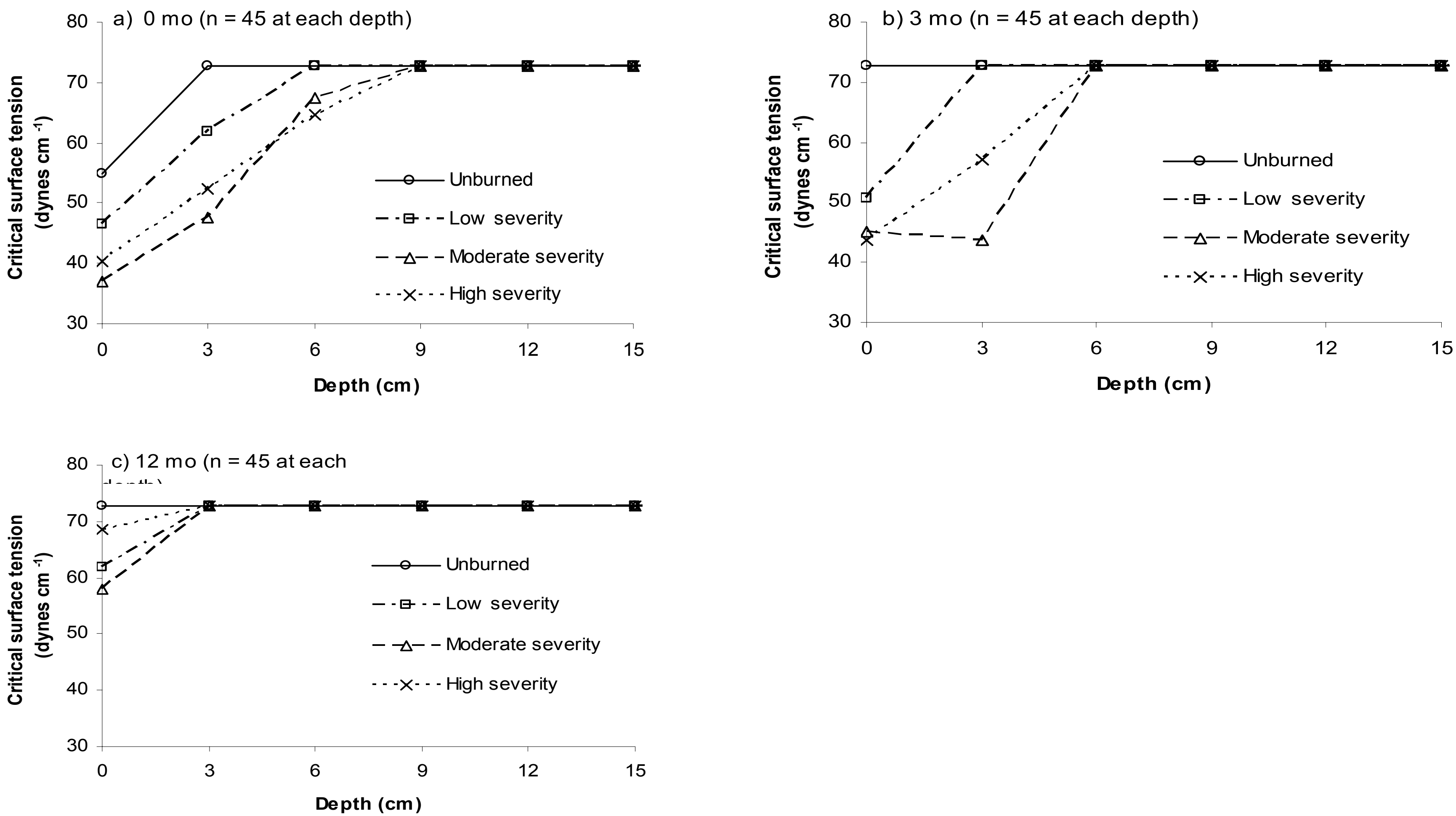
Critical surface tension by depth: Moderate severity sites



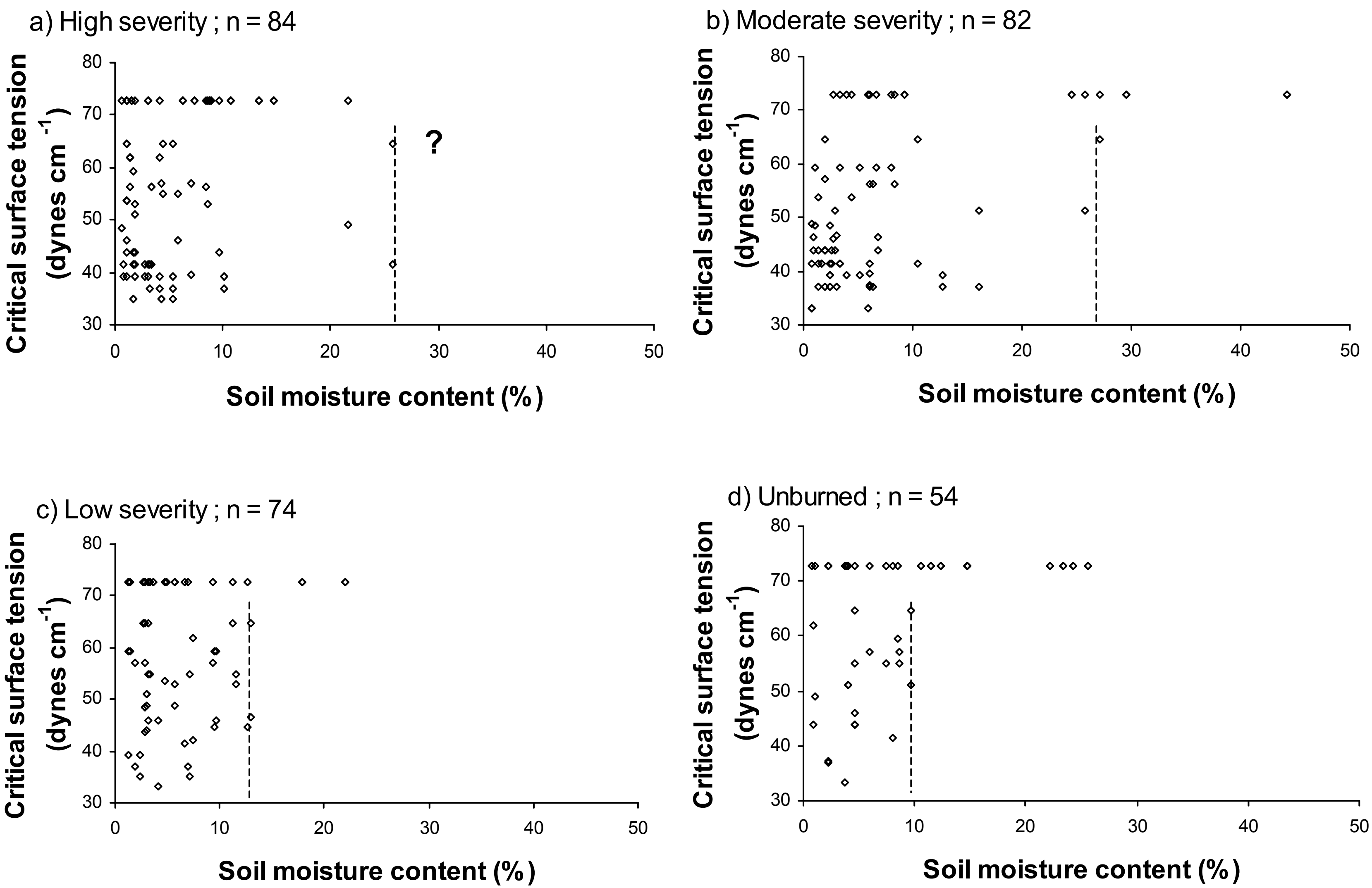


Critical Surface Tension by Depth:
Low Severity Sites
Critical surface tension (dynes cm -1)
80
70
60
50
40
30
0
3
6
9
12
15
18
Depth (cm)
Hi Meadows
Bobcat
Crosier Mtn.
Lower Flowers
Dadd Bennett

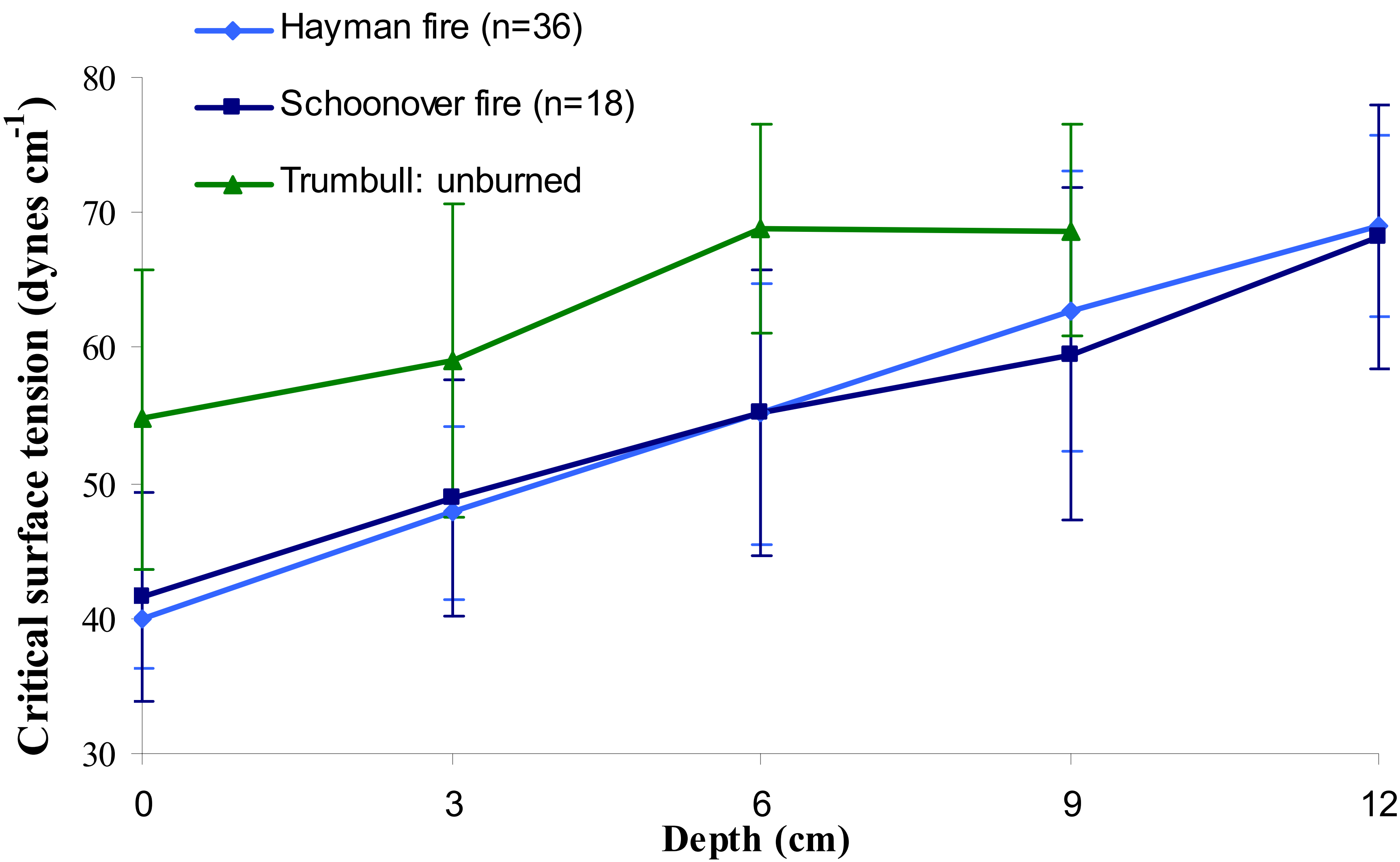
Soil water repellency over time: Bobcat fire



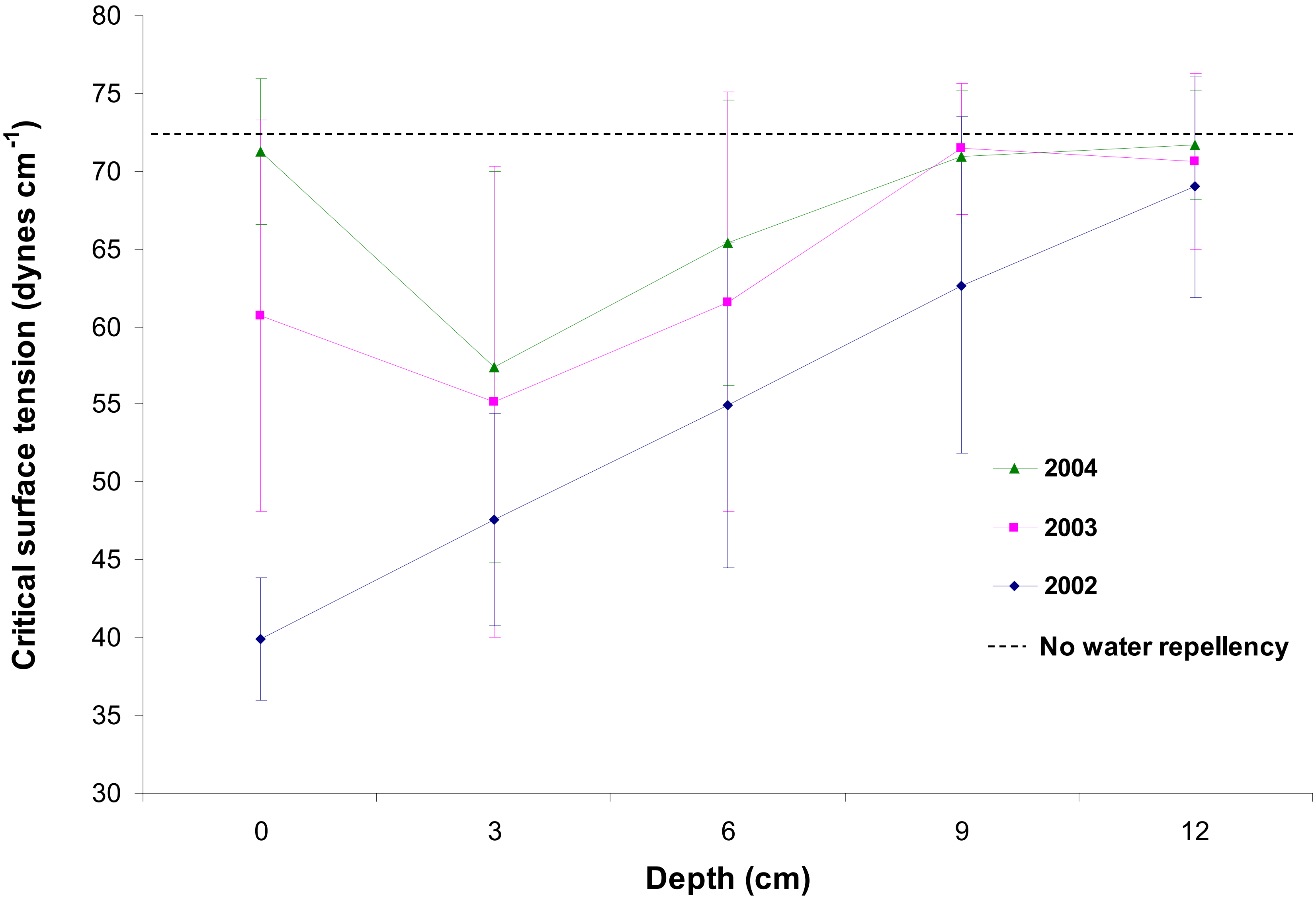
Effect of soil moisture on water repellency



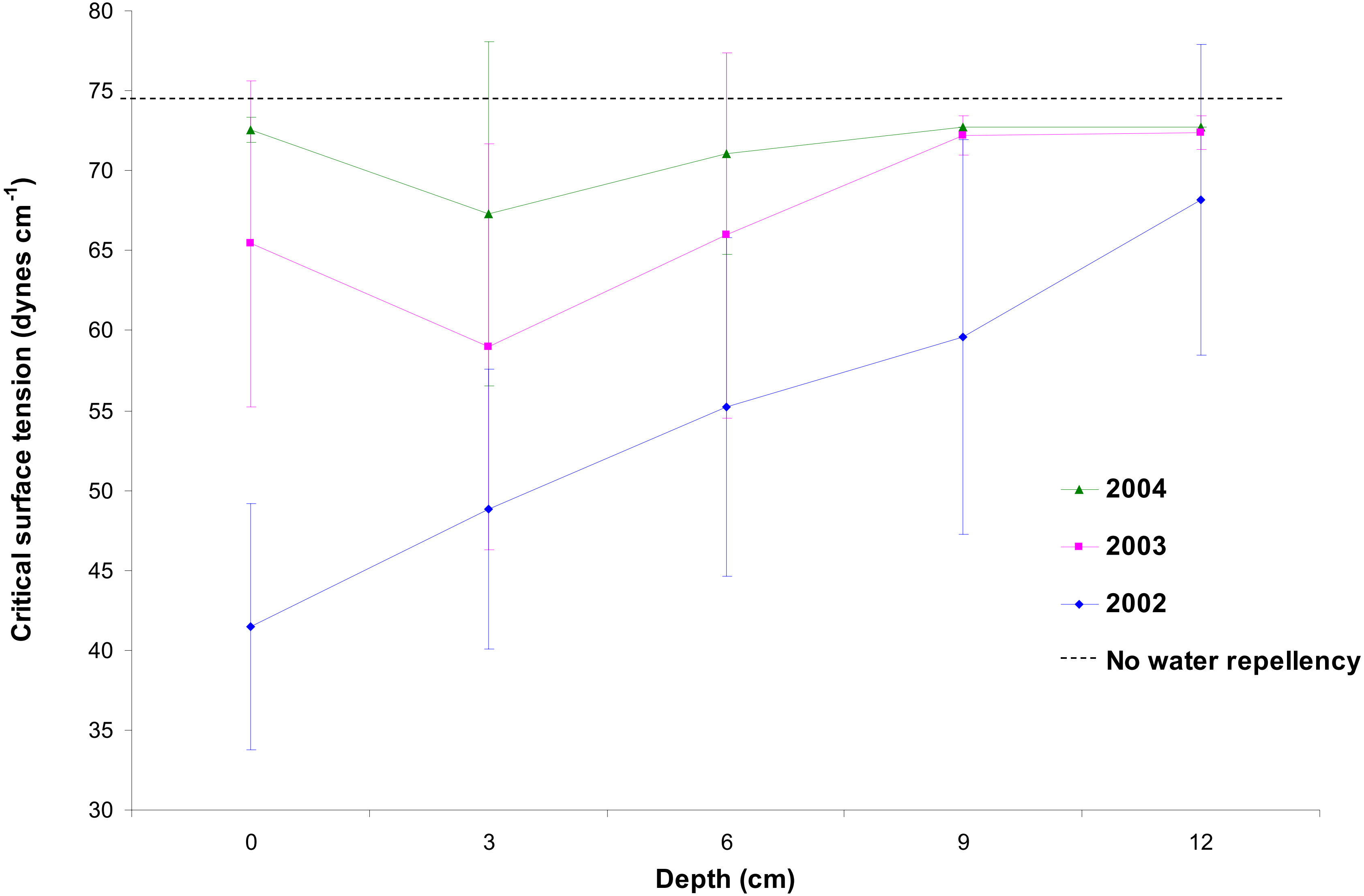
Mean soil water repellency by depth: Burned and unburned swales in 2002



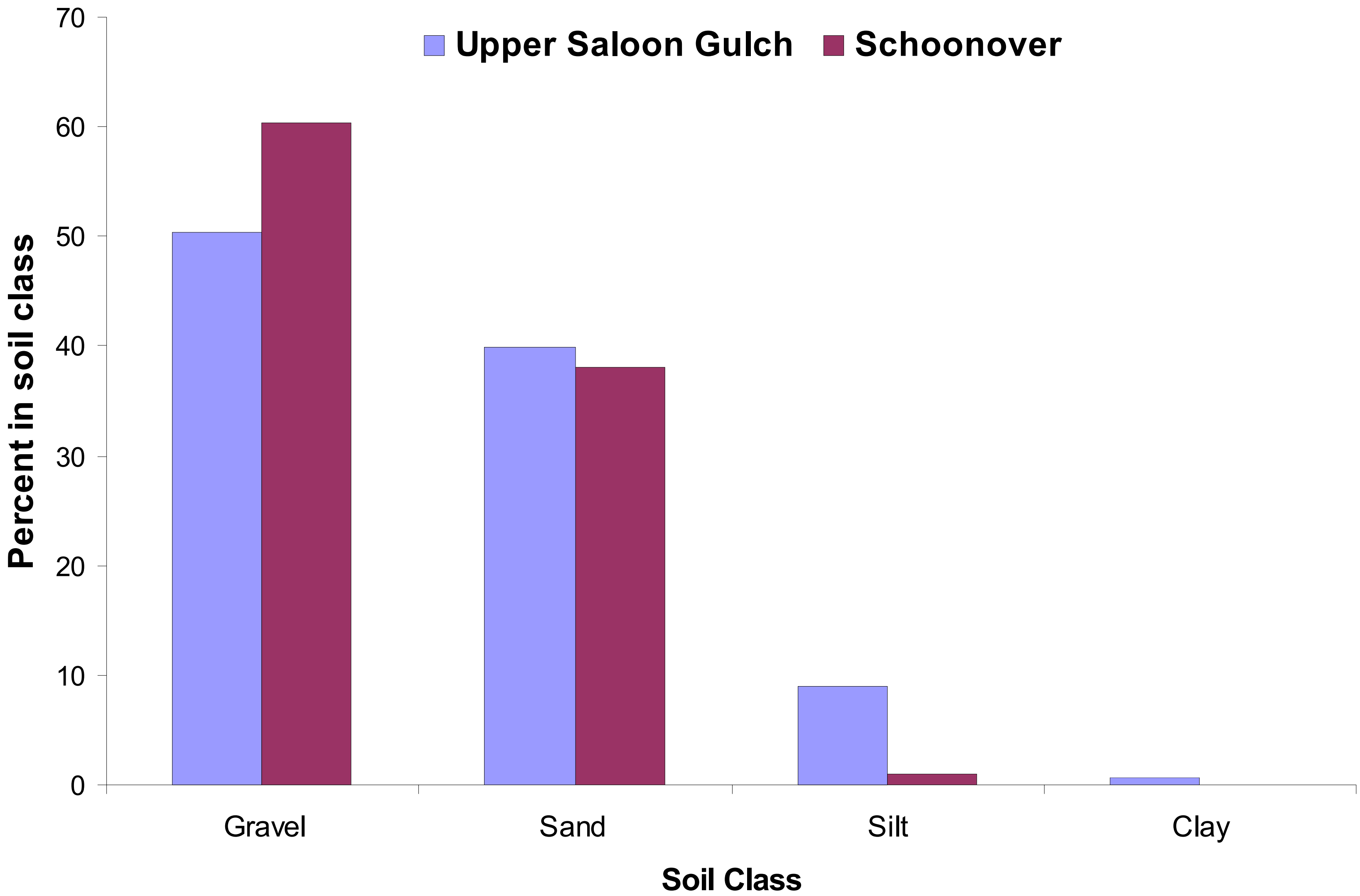
Water repellency over time: Upper Saloon Gulch, 2002-2004



Water repellency over time: Schoonover fire, 2002-2004



Soil particle-size distribution



Conclusions: Soil Water Repellency

- Surface in unburned areas naturally water repellent;
- Fire-induced water repellency is relatively shallow (maximum of 9 cm);
- May be stronger in prescribed fires due to higher fuel loadings and slower rate of fire spread;
- Very high spatial variability;
- Relatively rapid recovery (≤ 2 years);
- Not present under wet conditions (12 to 30+ percent soil moisture), depending on fire severity;
- CST faster and more consistent than WDPT.

Rainfall Simulations

Advantages of Rainfall Simulations

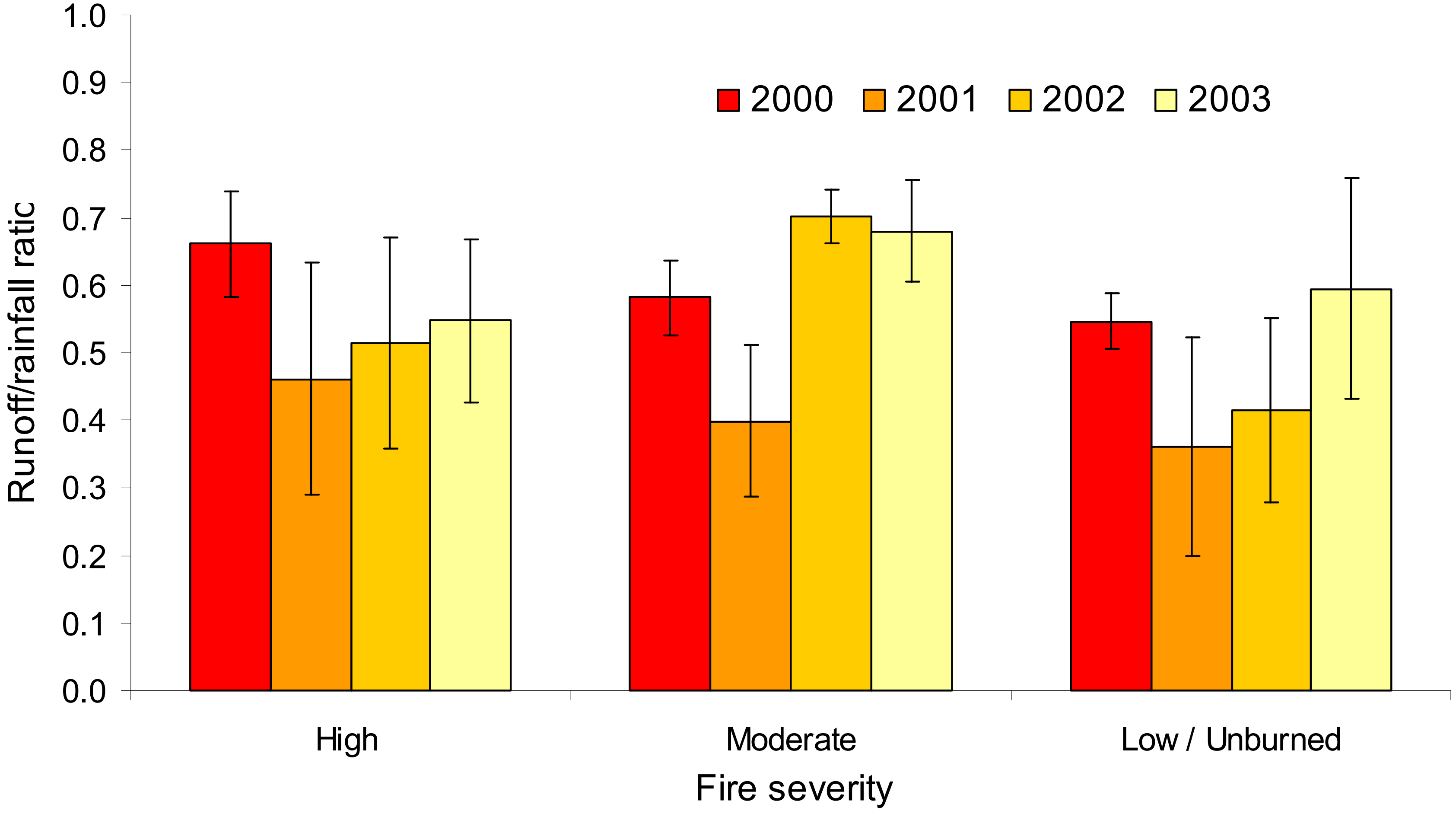
1. Not dependent on natural rain events (or lack thereof);
2. Provides comparable data between sites;
3. More rigorous evaluation of selected factors (e.g., soil type, fire severity, etc.).

Number of Simulations by Severity and Fire

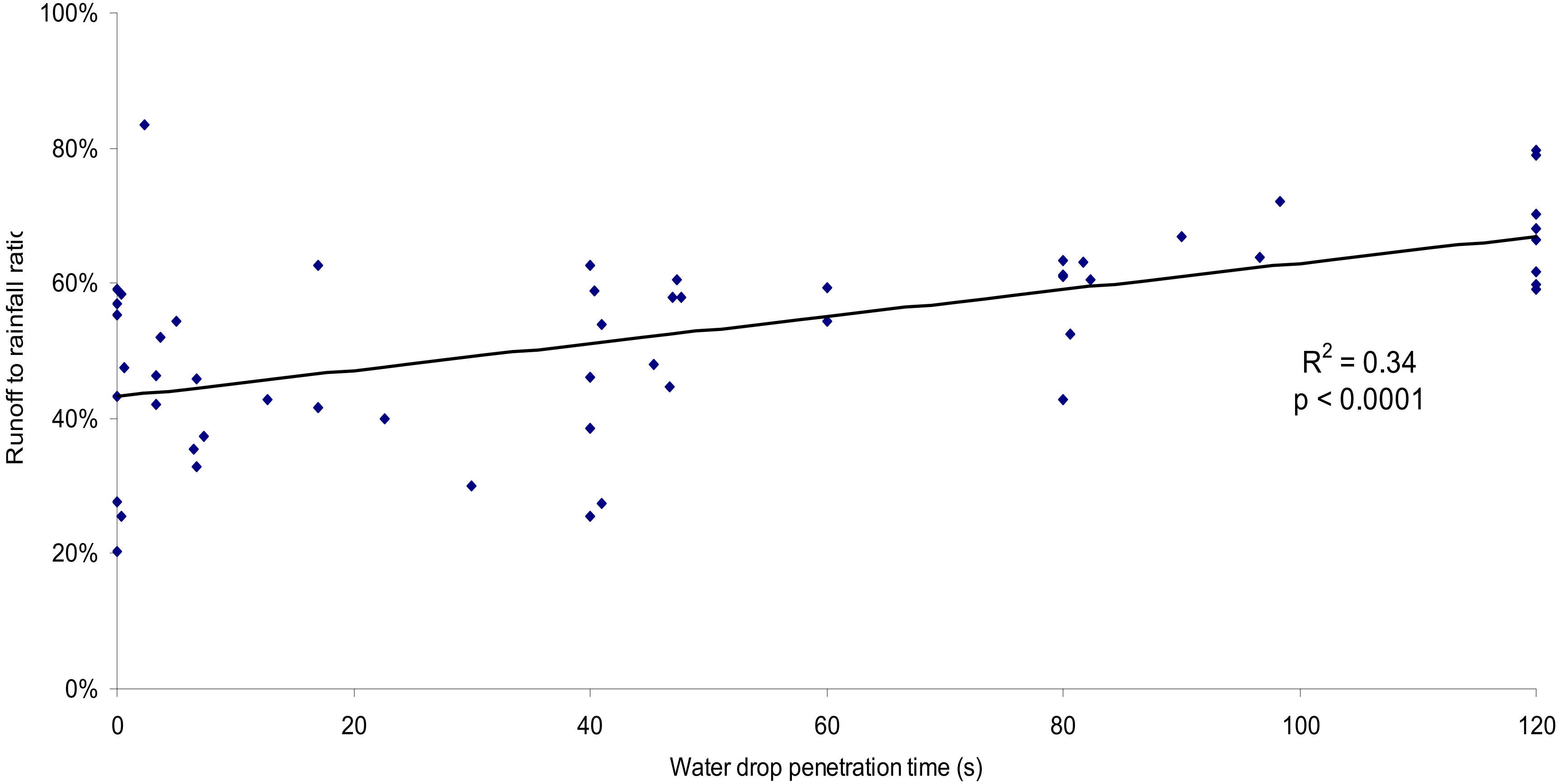
Fire	2000			2001			2002			2003			Totals
	Severity			Severity			Severity			Severity			
	High	Mod.	Low/ unb.	High	Mod.	Low/ unb.	High	Mod.	Low/ unb.	High	Mod.	Low/ unb.	
Bobcat	7	5	4	6	4	4	11	3	4	5	2	2	57
L. Flowers *	2	2	2	3	3	3	-	-	-	-	-	-	15
Hourglass	2	0	2	-	-	-	-	-	-	-	-	-	4
Hayman	-	-	-	-	-	-	-	-	-	20	-	-	20
	11	7	8	9	7	7	11	3	4	25	2	2	96

* Prescribed fire

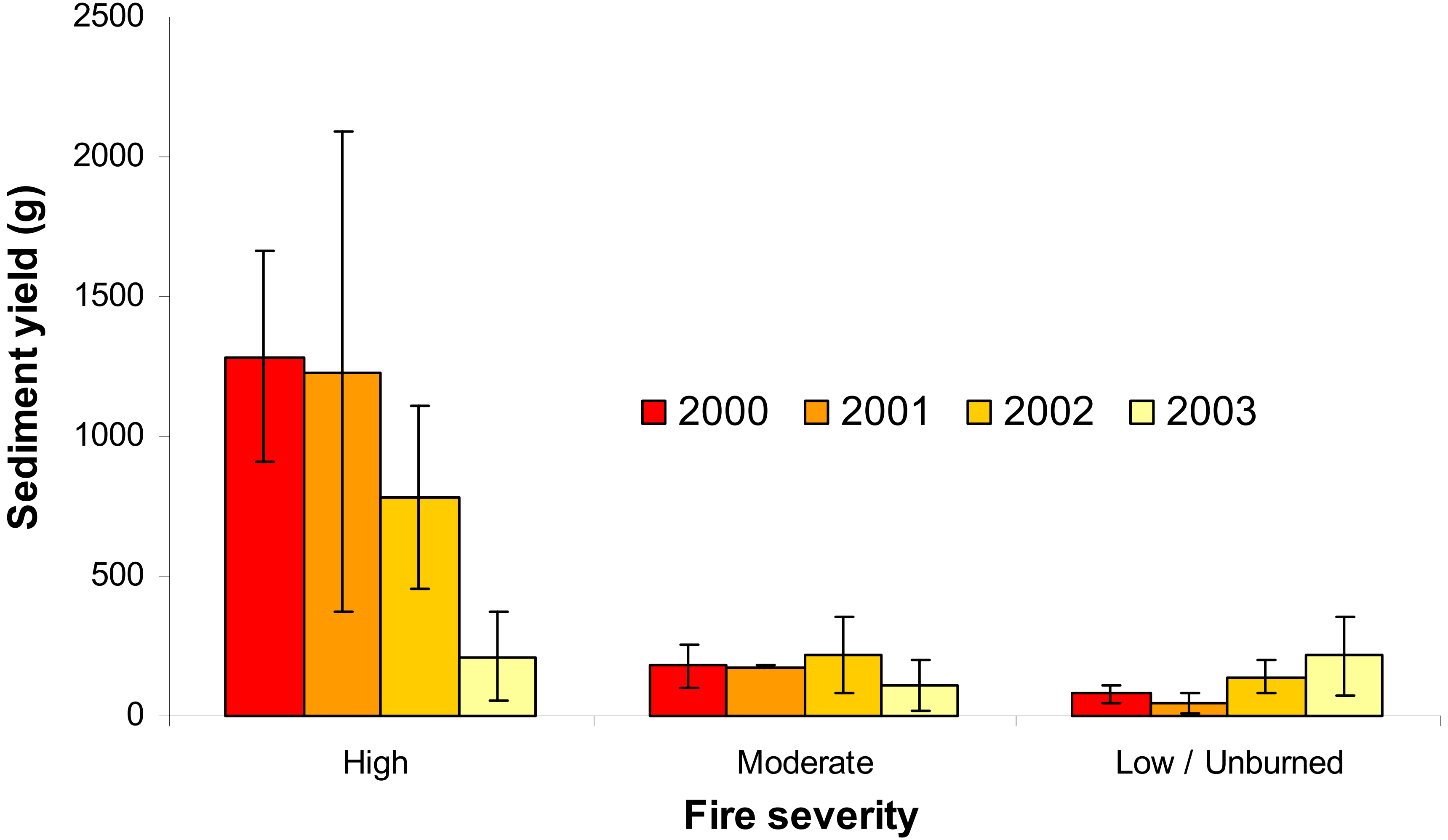
Mean Runoff/Rainfall Ratio by Fire Severity and Year: Bobcat Fire, 2000-2003



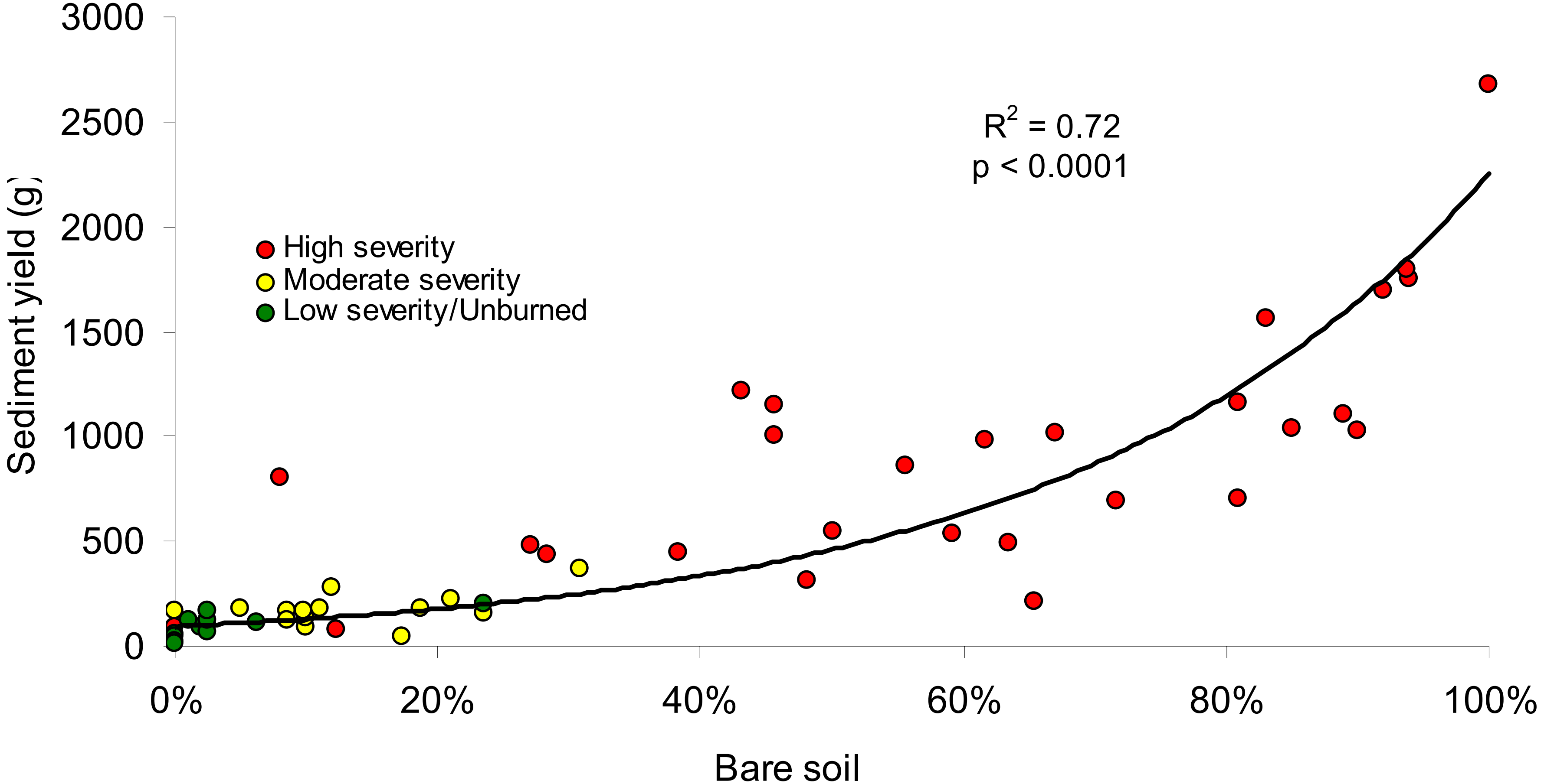
Soil Water Repellency vs. Runoff/Rainfall Ratio: High Severity Sites



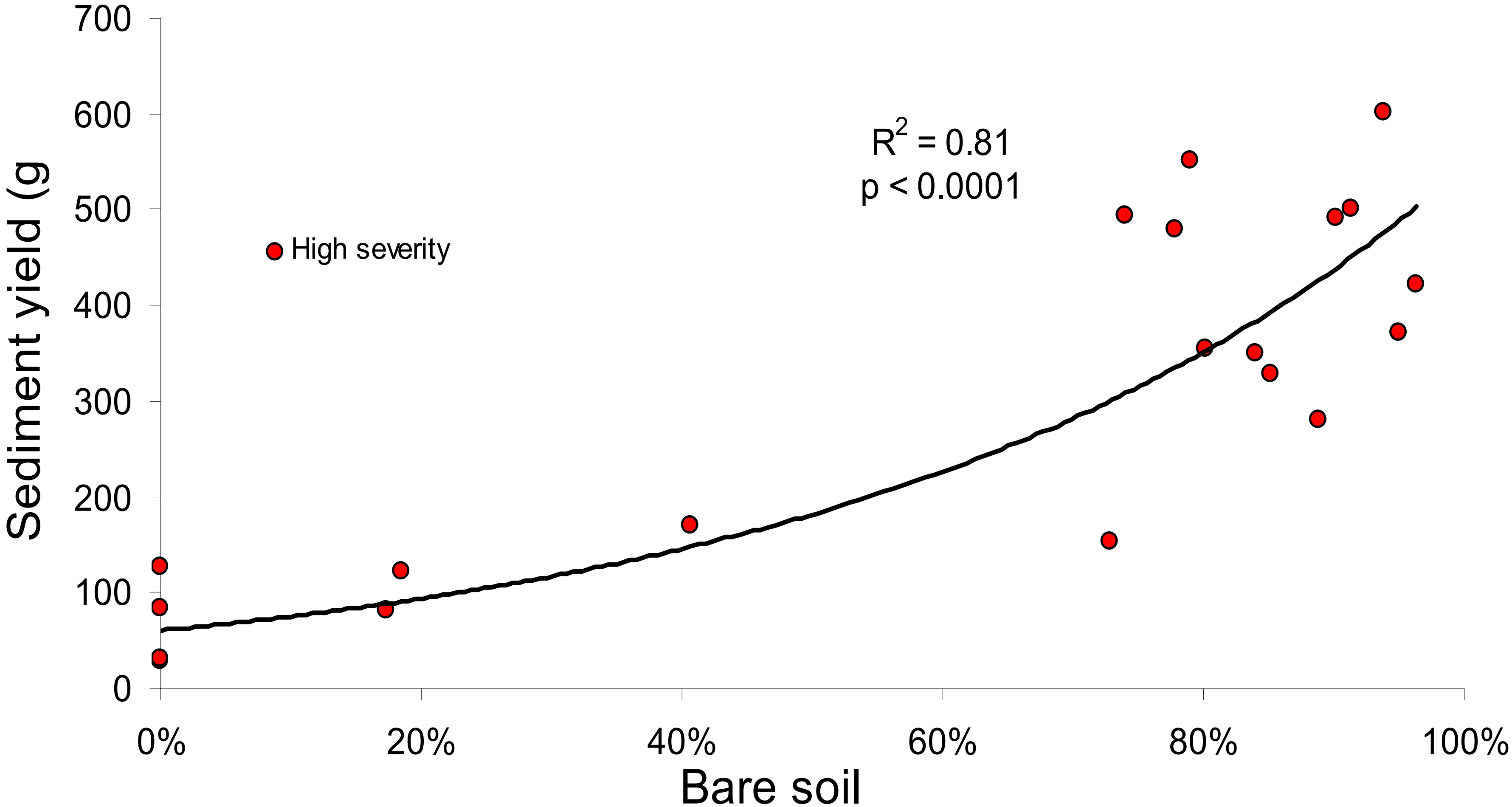
Mean Sediment Production by Fire Severity and Year: Bobcat Fire, 2000-2003



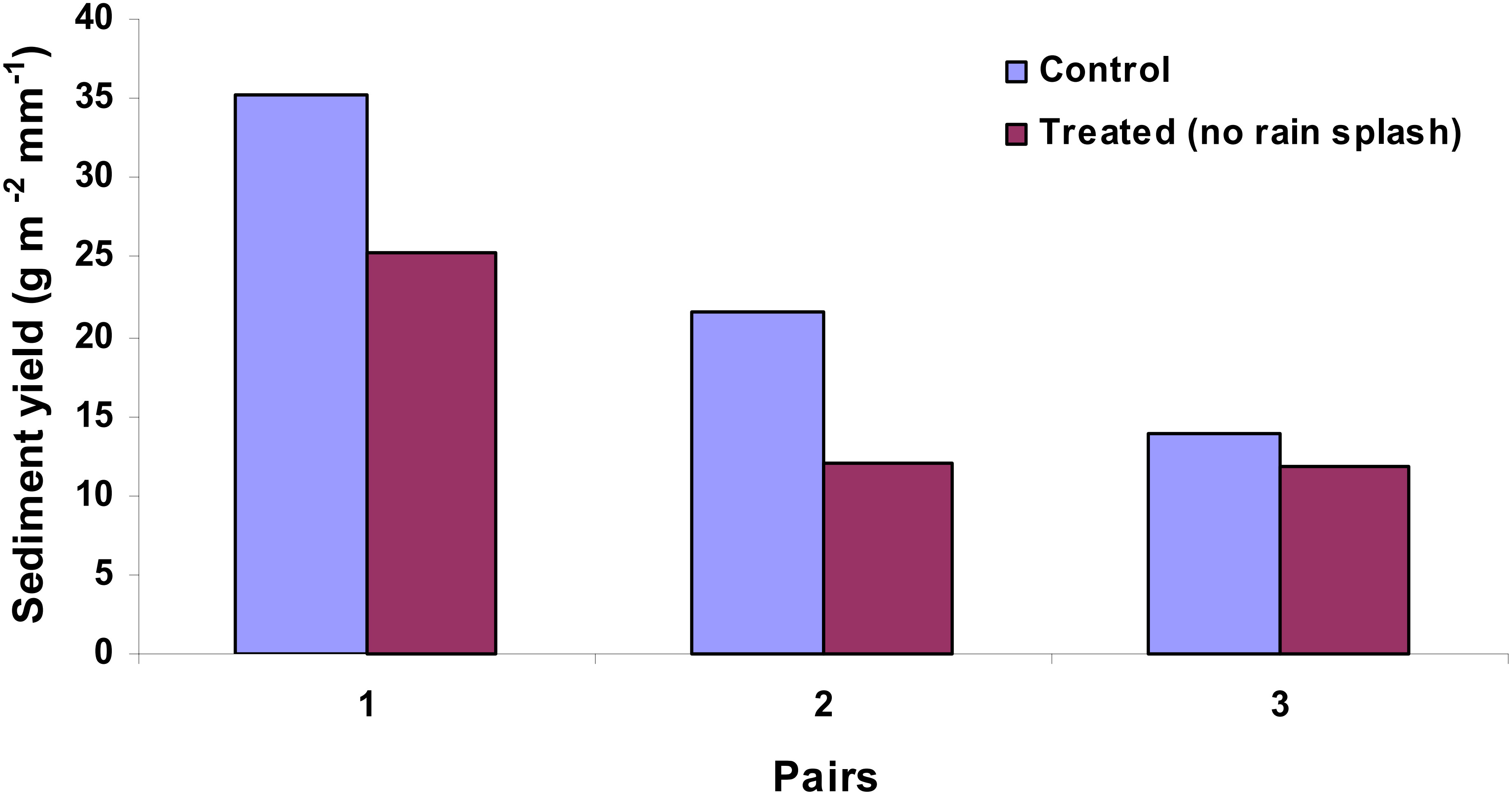
Sediment Yield vs. Percent Bare Soil for Rainfall Simulations, Bobcat Fire



Sediment Yield vs. Percent Bare Soil for Rainfall Simulations, Hayman Fire



Erosion rates with and without rainsplash at high-severity sites: Bobcat fire




Sediment Production at the
Hillslope Scale
9. 7. 2002

Number of untreated sites by fire and severity

Fire	Date burned	Size of fire (ha)	Primary vegetation type	Sediment fences per severity			
				High	Moderate	Low	Total
Big Elk	Aug-02	1,760	Lodgepole pine	3	2	1	6
Hayman	Jun-02	55,700	Ponderosa pine	31	1	0	32
Schoonover	May-02	1,490	Ponderosa pine	6	0	0	6
Hewlett Gulch	Apr-02	200	Ponderosa pine	3	0	0	3
Bobcat	Jun-00	4,289	Ponderosa pine	13	2	1	16
Dadd Bennett*	Jan-00	200	Ponderosa pine	0	3	2	5
Lower Flowers*	Nov-99	300	Ponderosa pine	4	4	2	10
Crosier Mountain*	Sep-98	1,011	Lodgepole Pine	4	1	0	5
Bear Tracks	Jun-98	196	Subalpine fir	3	0	2	5
Hourglass	Jul-94	516	Lodgepole pine	5	1	1	7
* Prescribed fire			**Totals**	**72**	**14**	**9**	**95**

Site Data

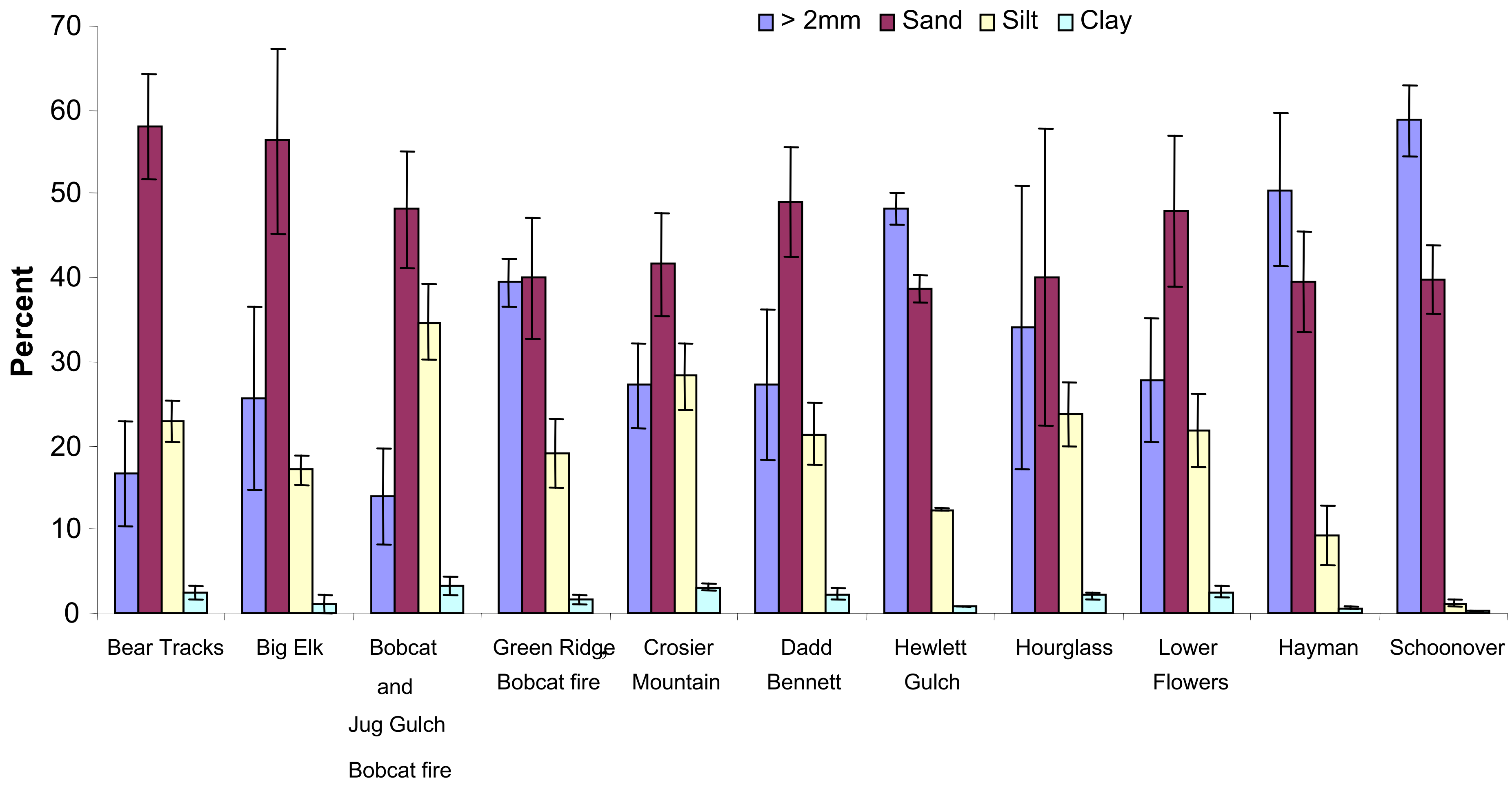
- Measuring sediment production using sediment fences;
- Measuring key factors for each study site:
  - Contributing area;
  - Slope and aspect;
  - Soil texture;
  - Soil water repellency;
  - Percent ground cover in spring and fall;
  - Precipitation amounts, intensity, and erosivity with tipping bucket rain gages.

Site Characteristics

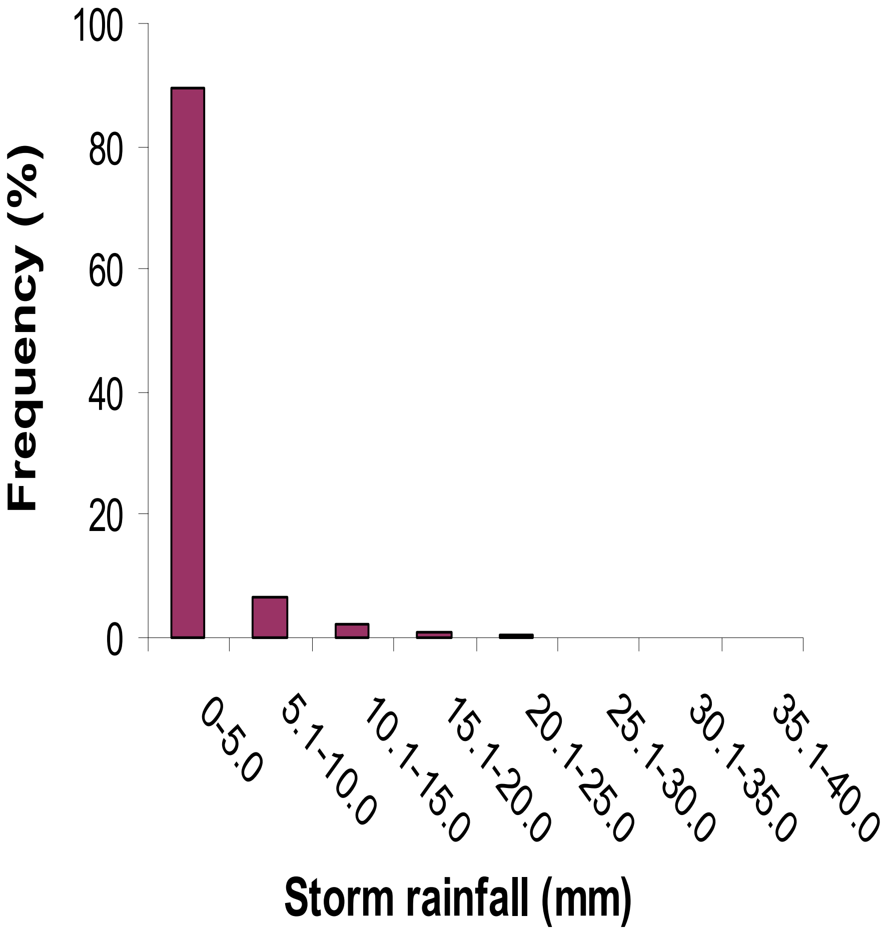
- Contributing areas of 0.01-0.5 ha;
- Slopes typically 20-40%;
- All aspects;
- Annual precipitation typically 400-600 mm, with about half as snow;
- Most of erosivity comes from localized summer thunderstorms in July and August;
- Generally coarse-textured soils.

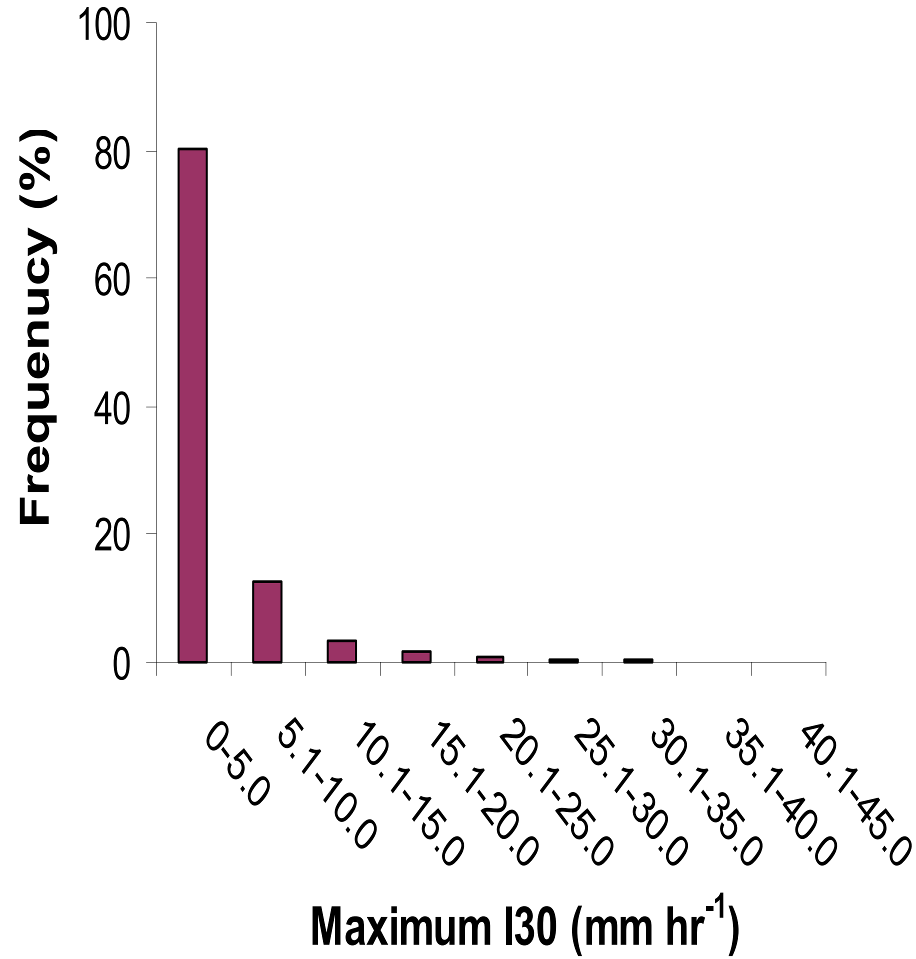
Soil Particle-Size Distribution by Fire

Bars indicate one standard deviation

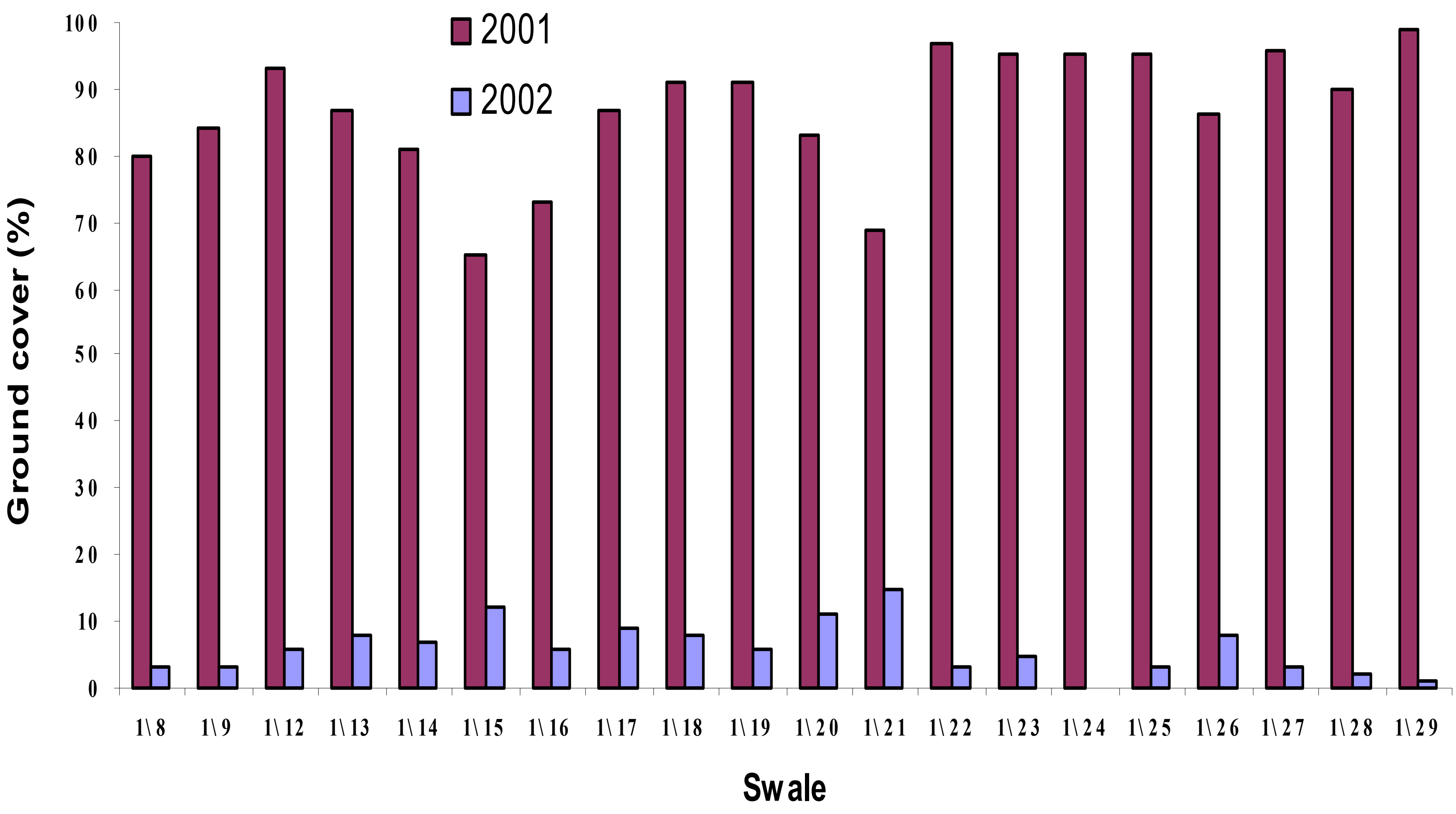


Frequency Distribution of Storm Rainfall and Maximum I_{30}

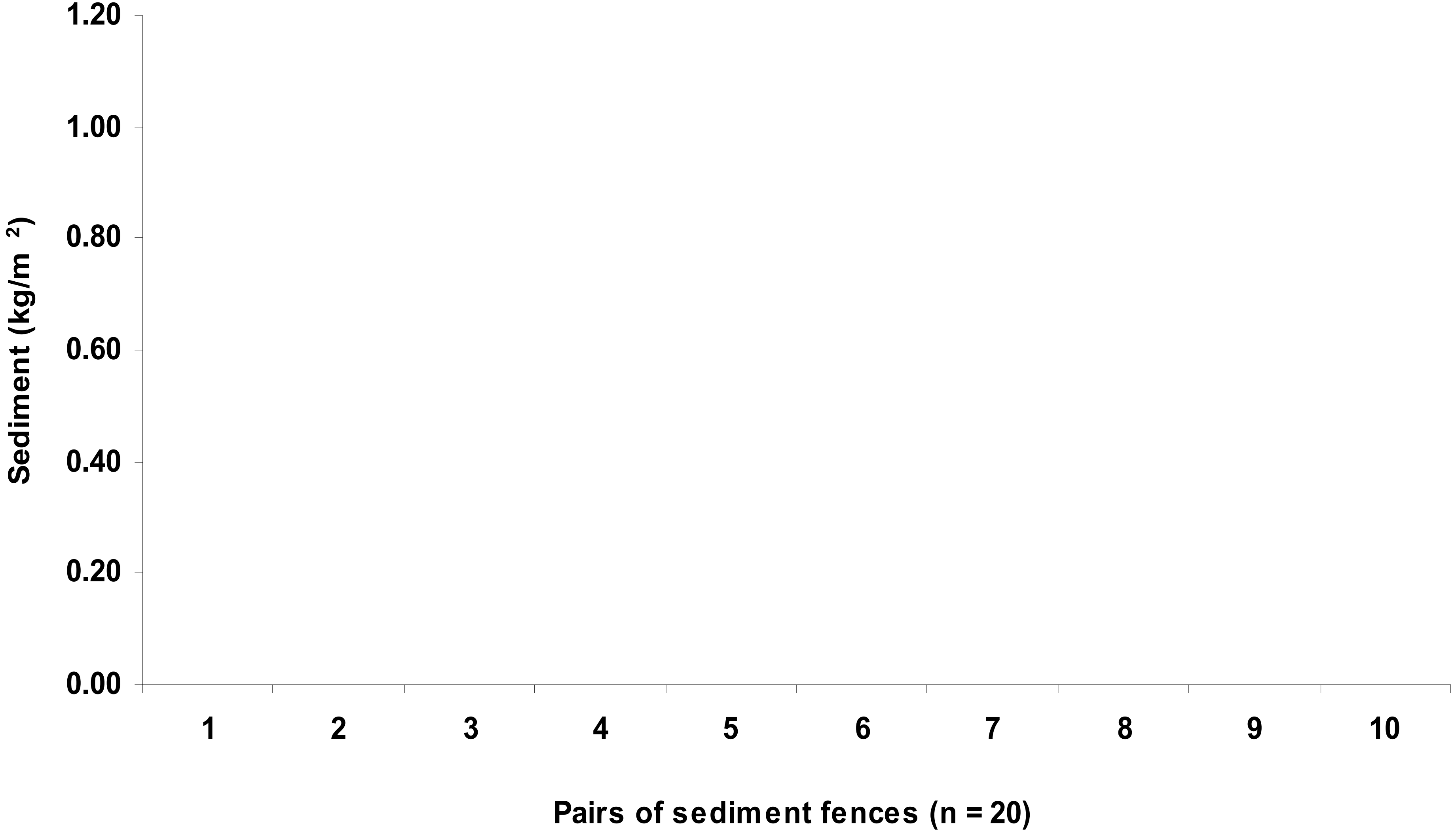




Mean percent ground cover in Upper Saloon Gulch in 2001 (prior to burning) and 2002 (after the Hayman fire)

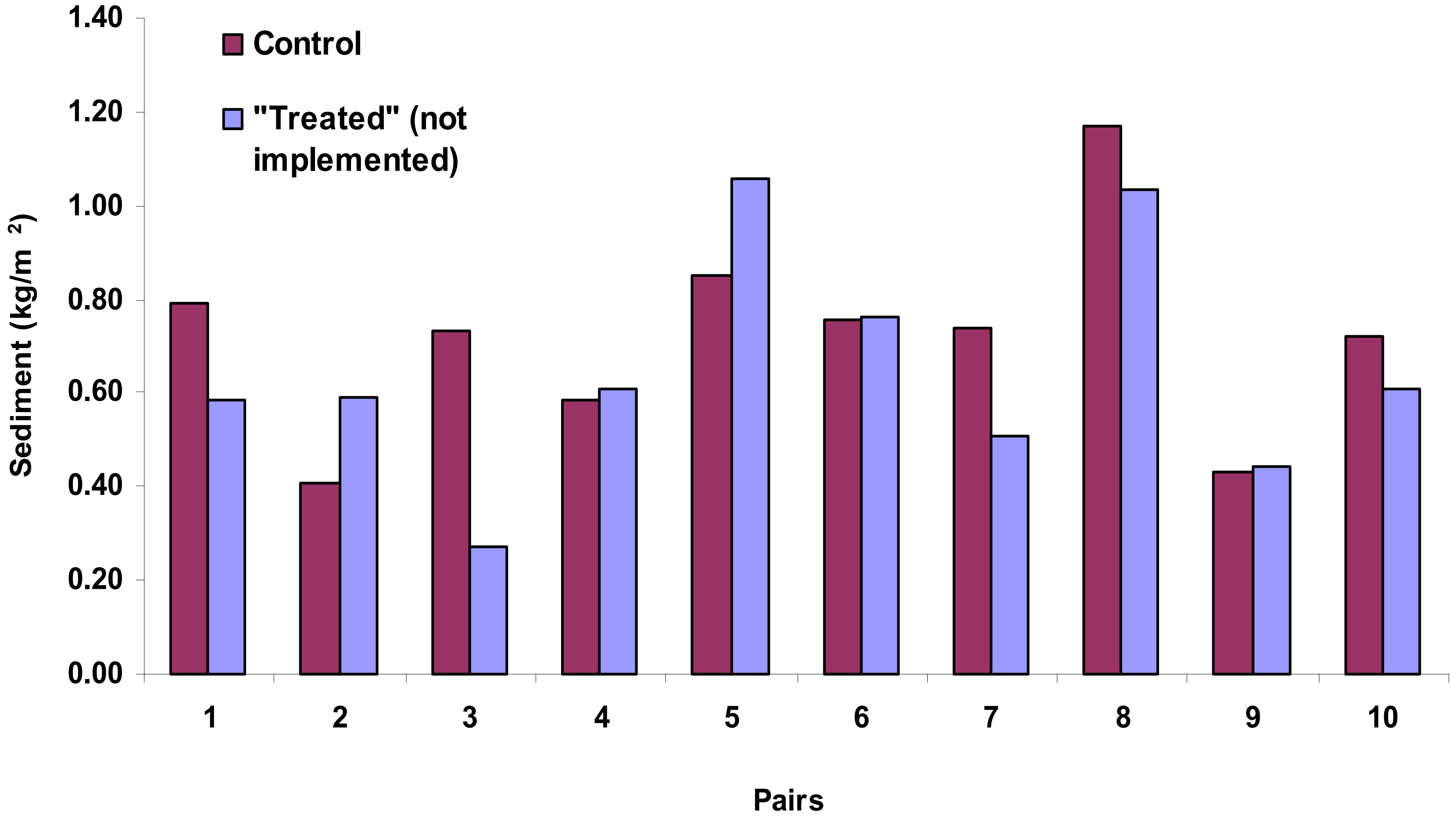


Sediment production: Summer 2001 (before Hayman fire)

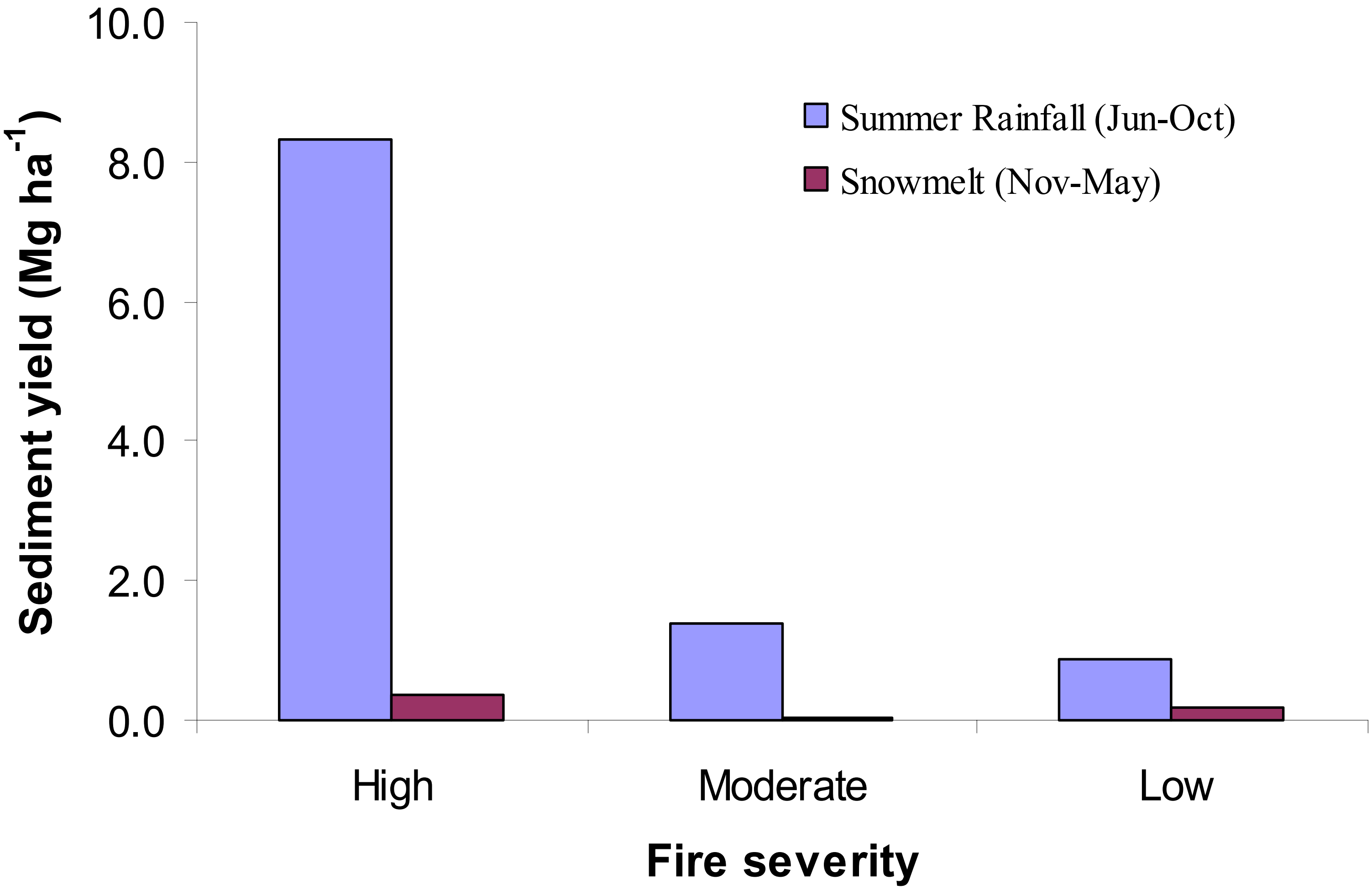


Sediment from 11 mm of precipitation in 45 minutes on 21 July 2002

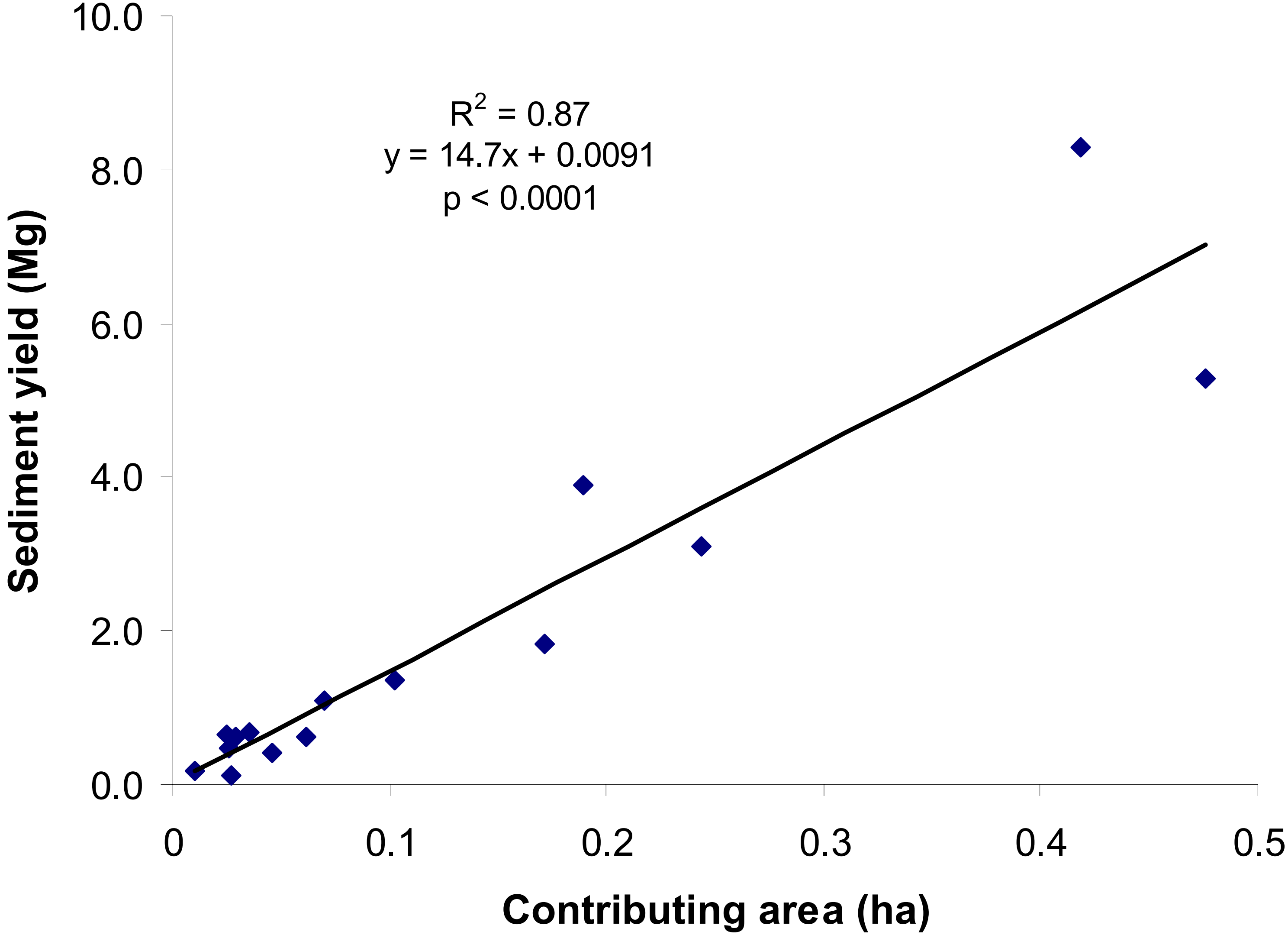
Sediment production after Hayman fire: 21 July 2002 storm (11 mm in 45 minutes)



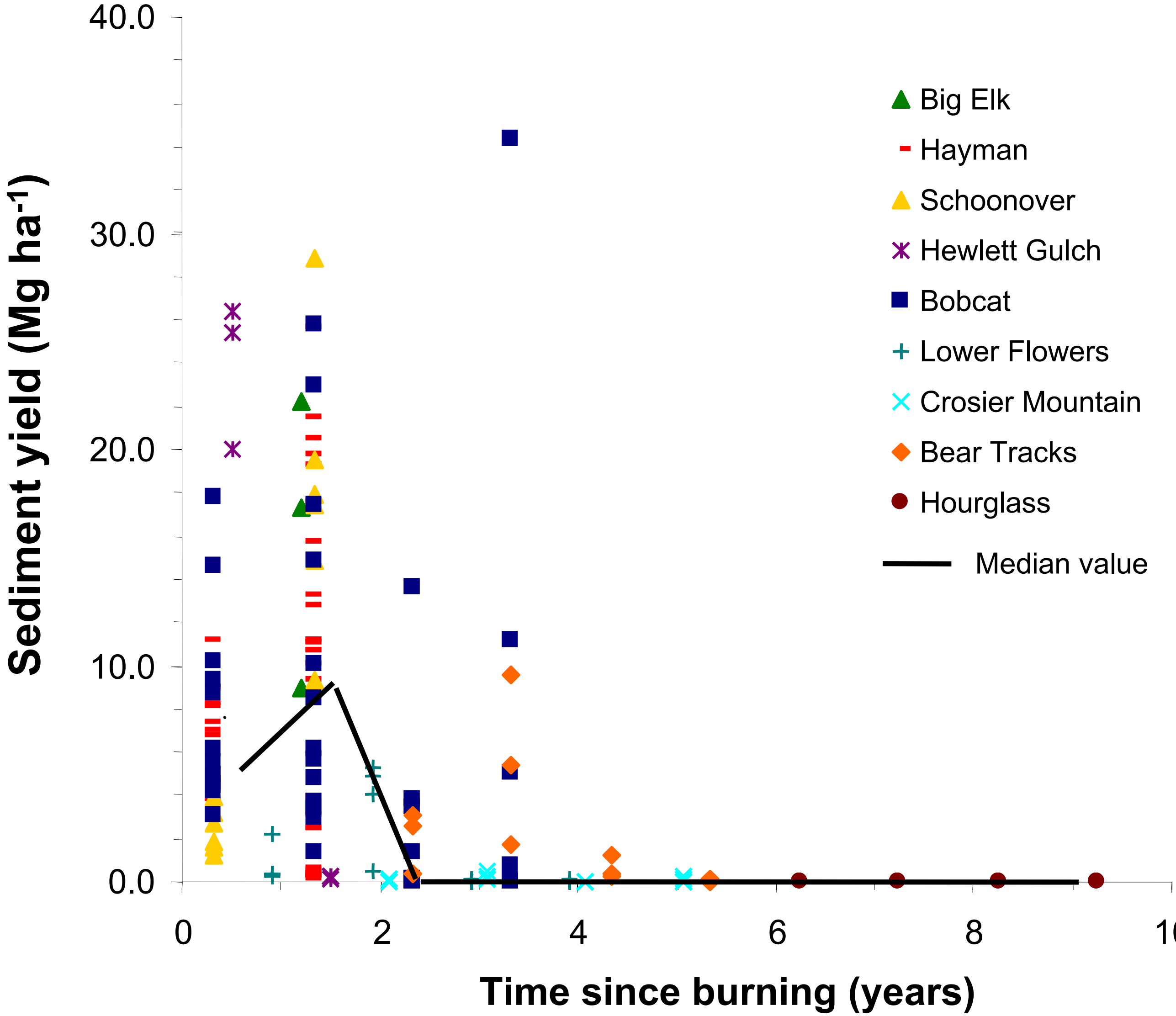
Sediment Yield vs. Fire Severity and Season: First Two Years After Burning



Sediment Yield vs. Contributing Area: Hayman Fire, 2003



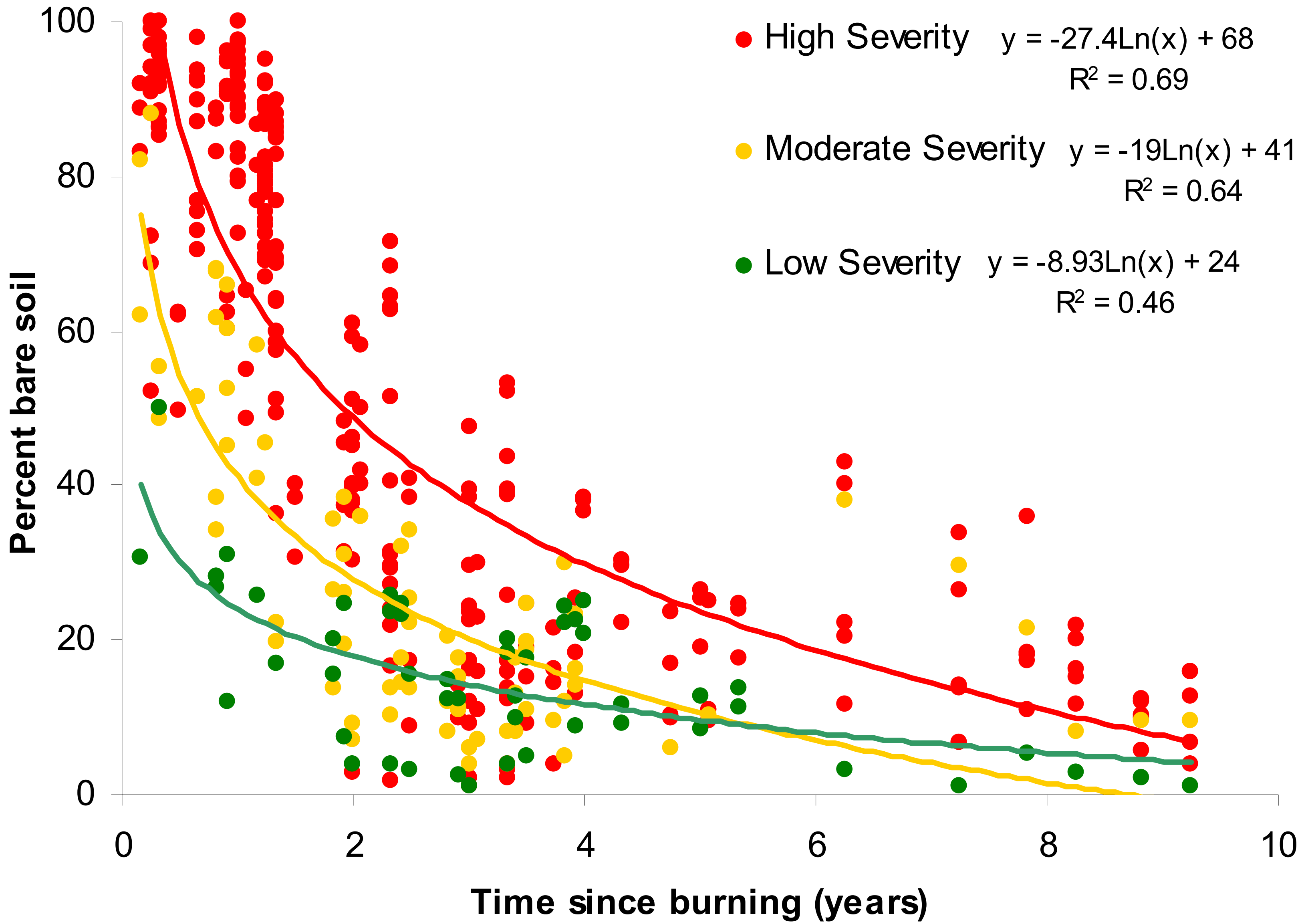
Sediment Yield vs. Time Since Burning: High-severity Sites



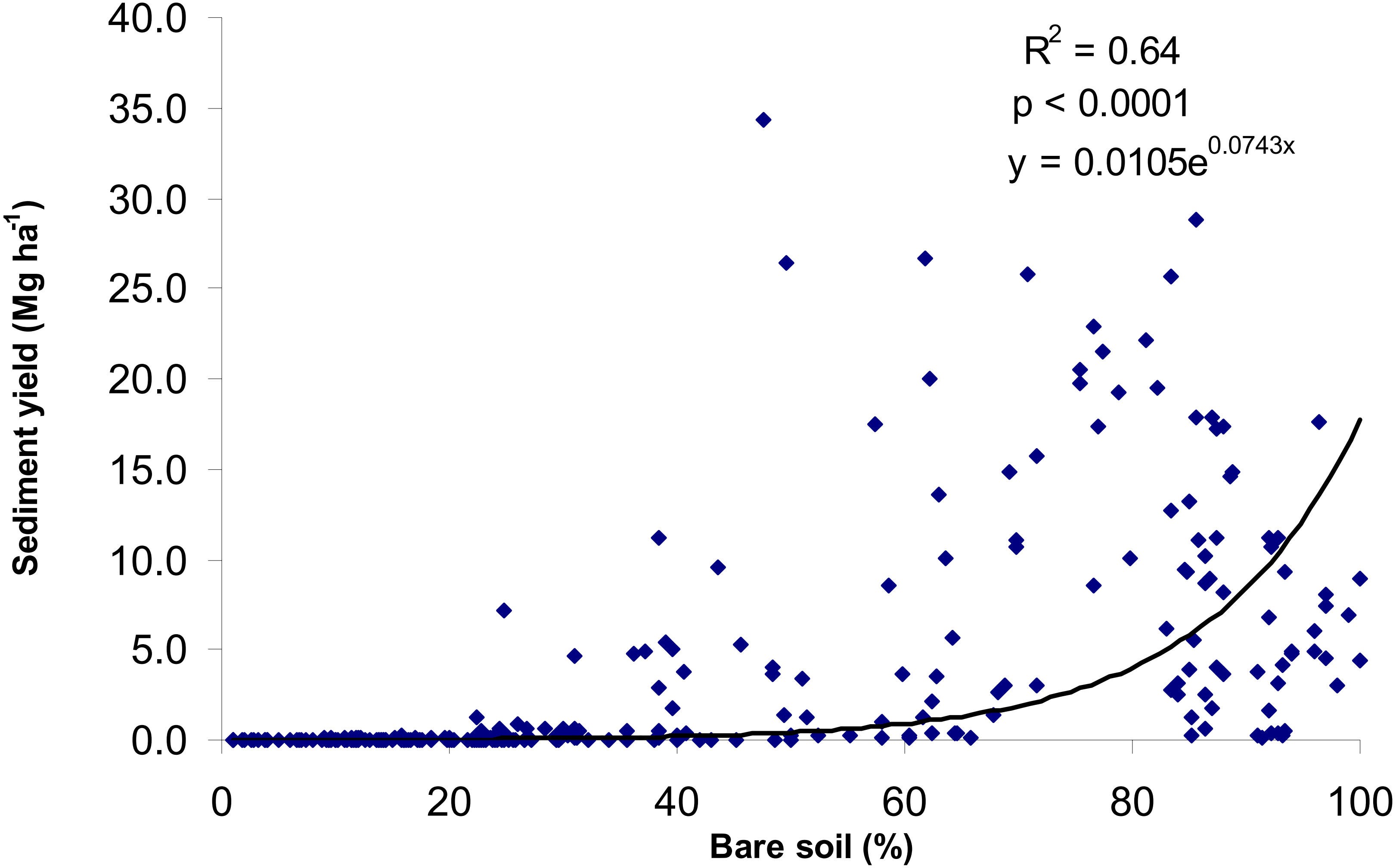
Vegetation recovery over time

Bobcat fire, sediment fence #9

Percent Bare Soil vs. Time Since Burning

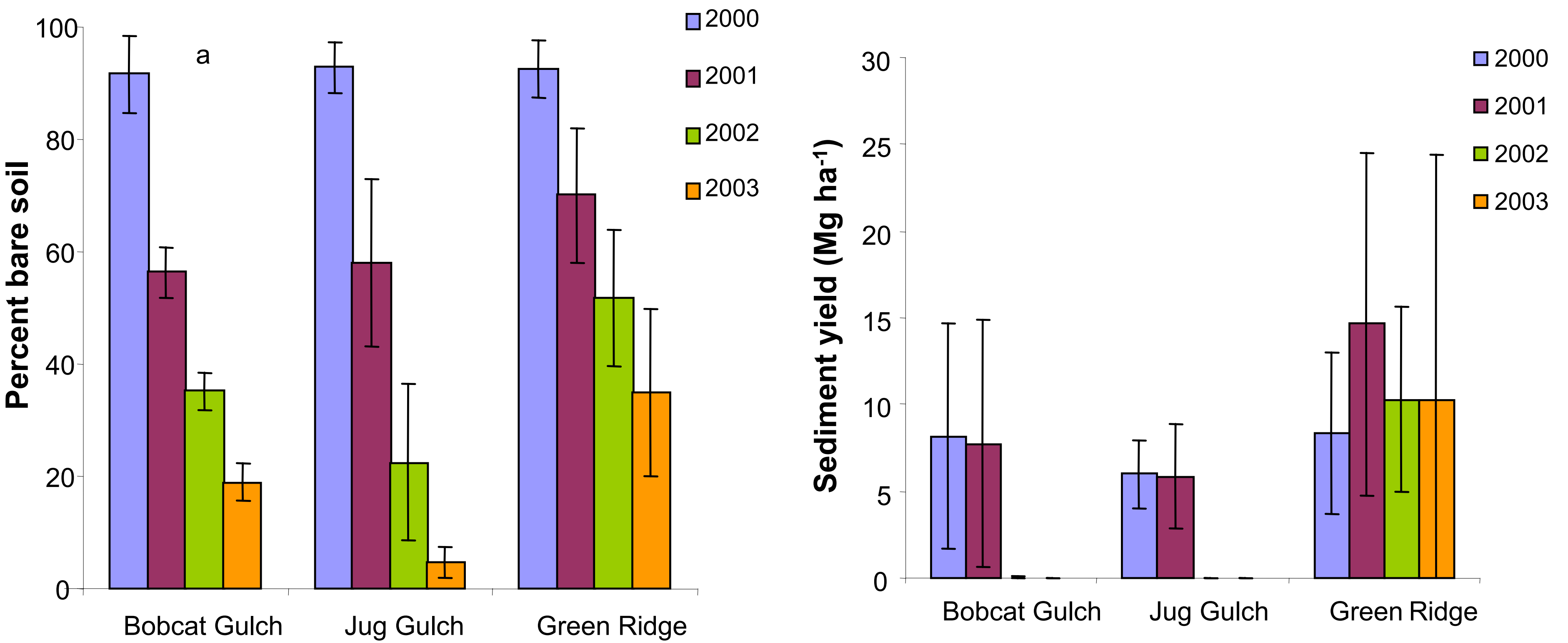


Sediment Yield vs. Percent Bare Soil

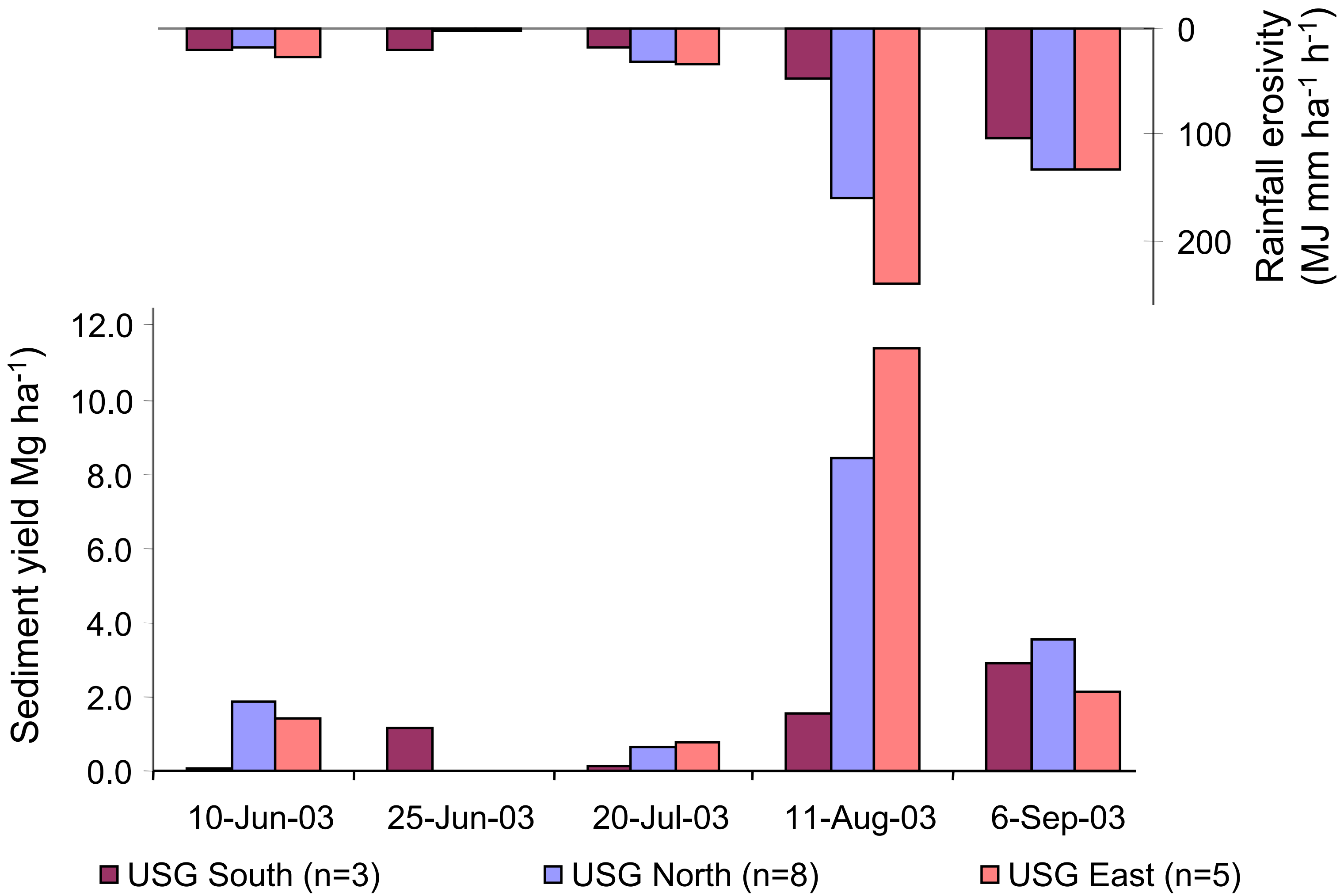


Percent Bare Soil versus Sediment Yields for Three Areas in the Bobcat Fire

High severity burns; Bars indicate one standard deviation.

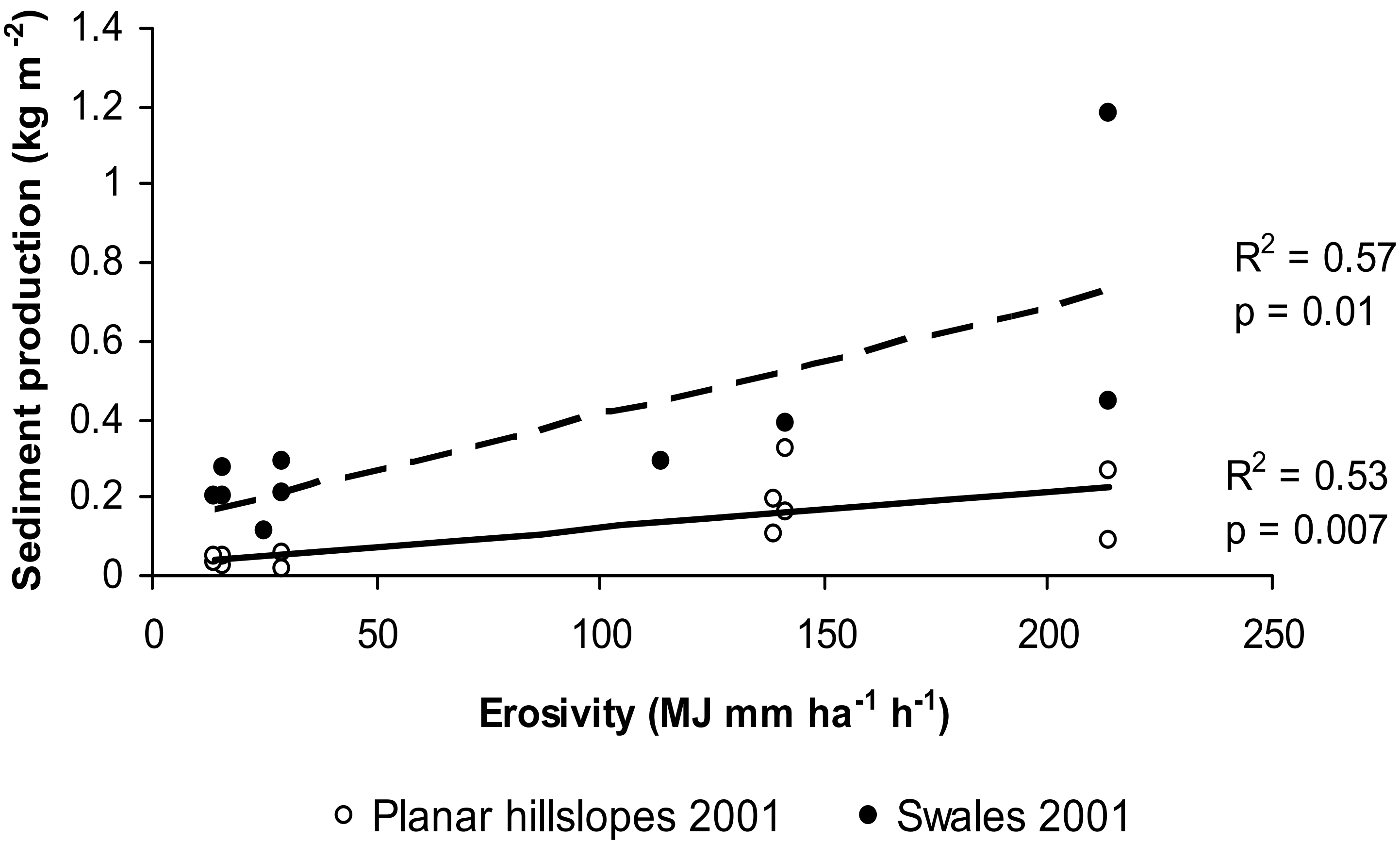


Rainfall Erosivity versus Mean Sediment Yields: Five storms in the Hayman fire

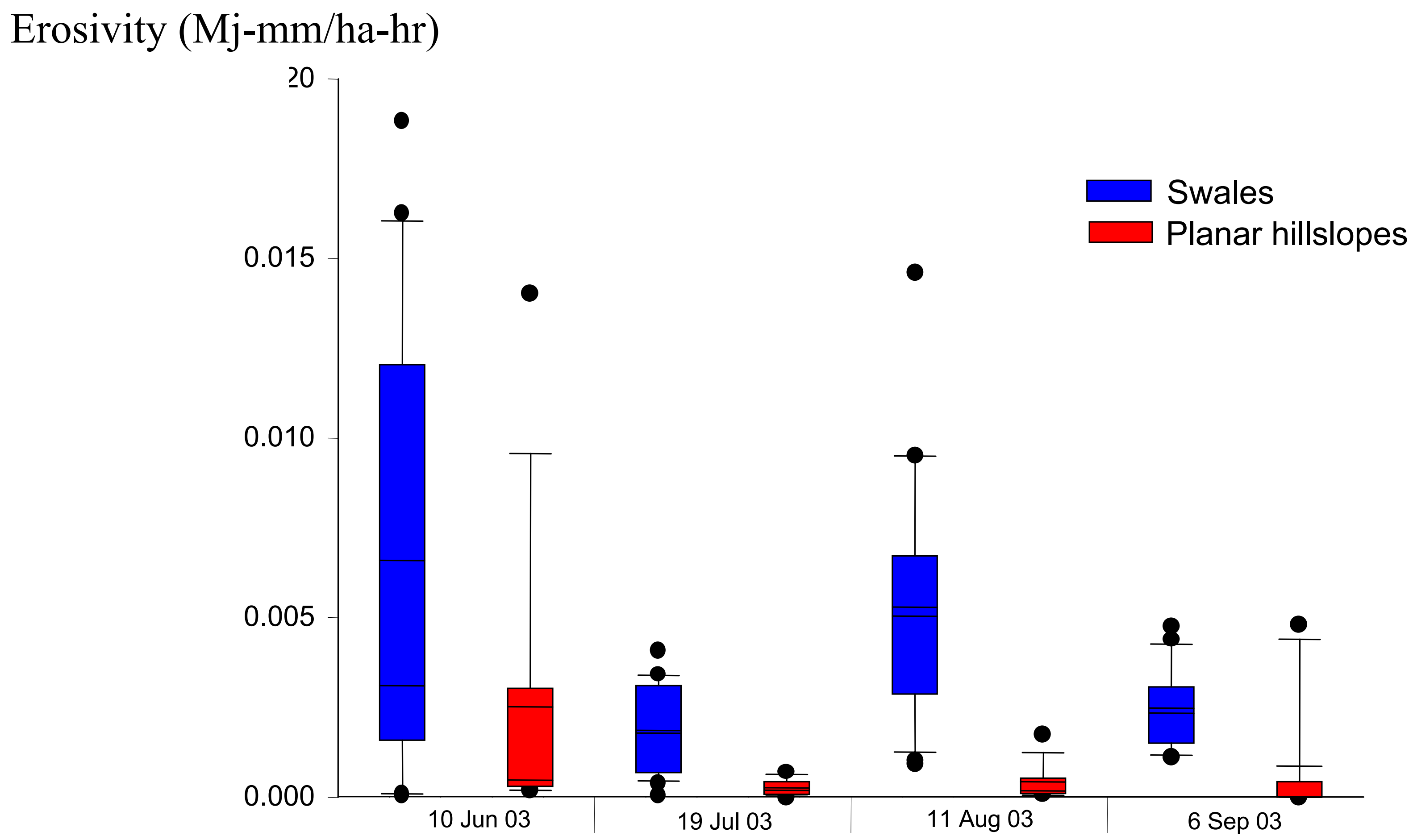



Upper Saloon Gulch: 10 July 2002
17 mm rain in 1 hour 56 minutes

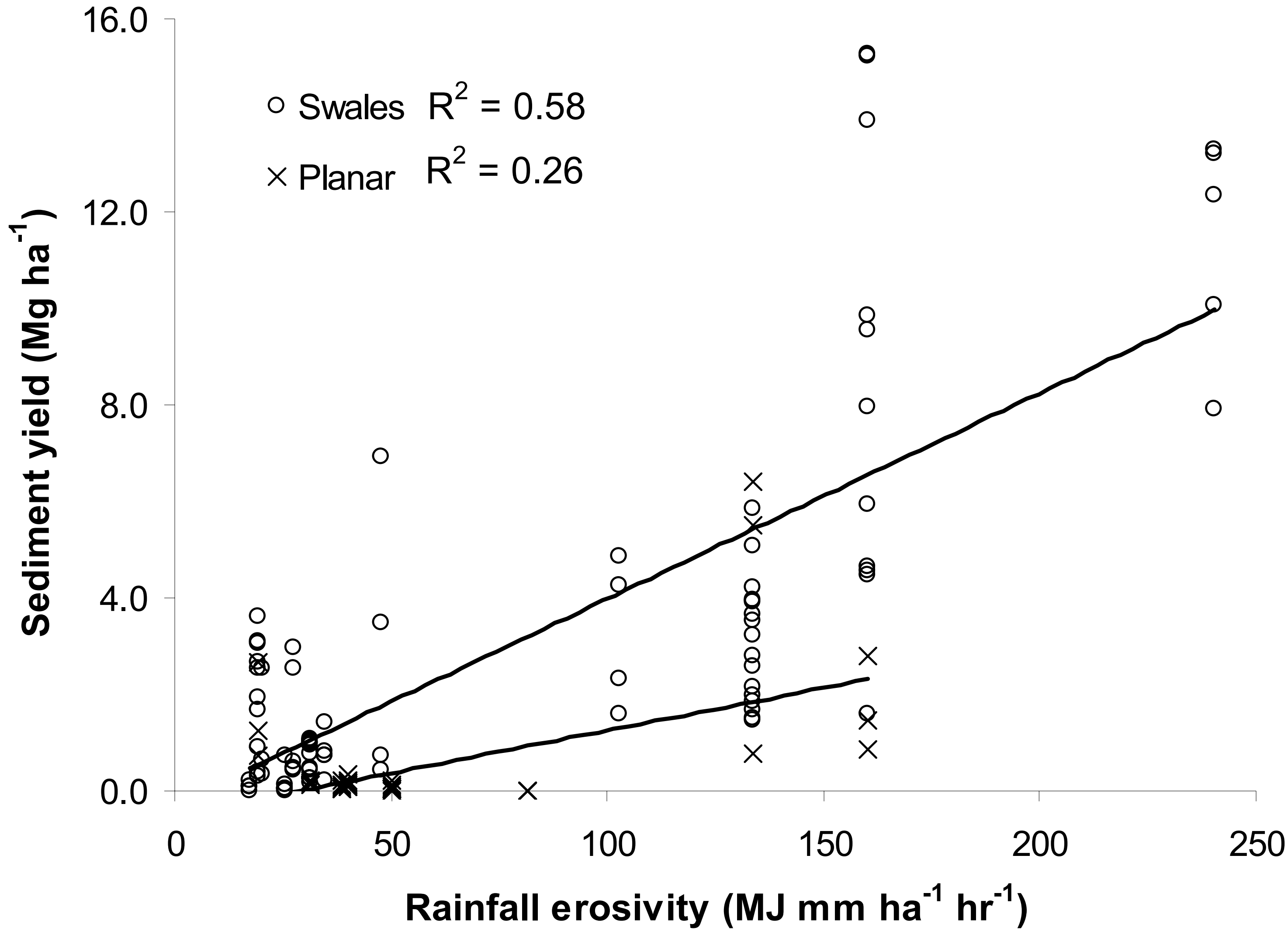
Sediment yields from swales vs. planar hillslopes in 2001: Bobcat fire



Sediment yields by storm for swales vs. planar hillslopes: Hayman fire, 2003

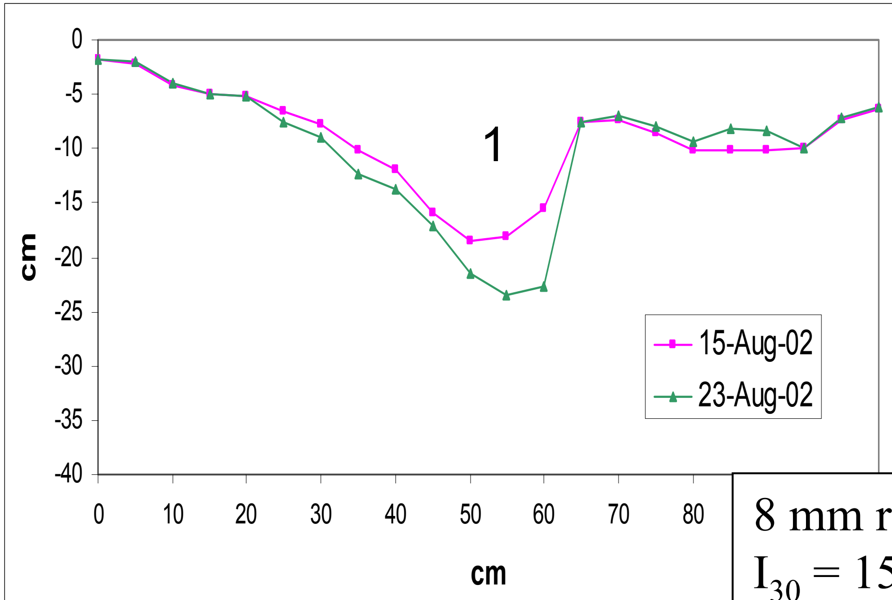


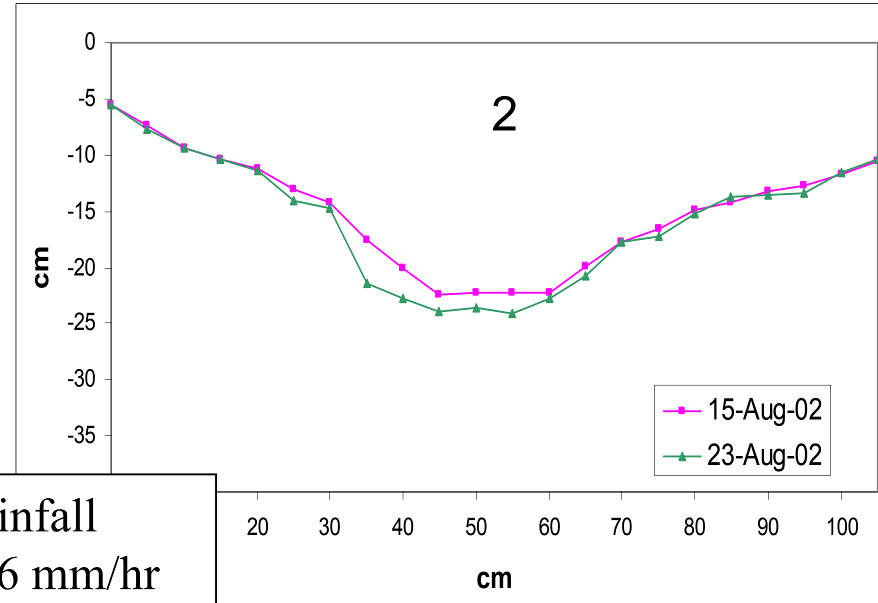
Sediment yields vs. rainfall erosivity for planar hillslopes and swales: Hayman fire, 2003



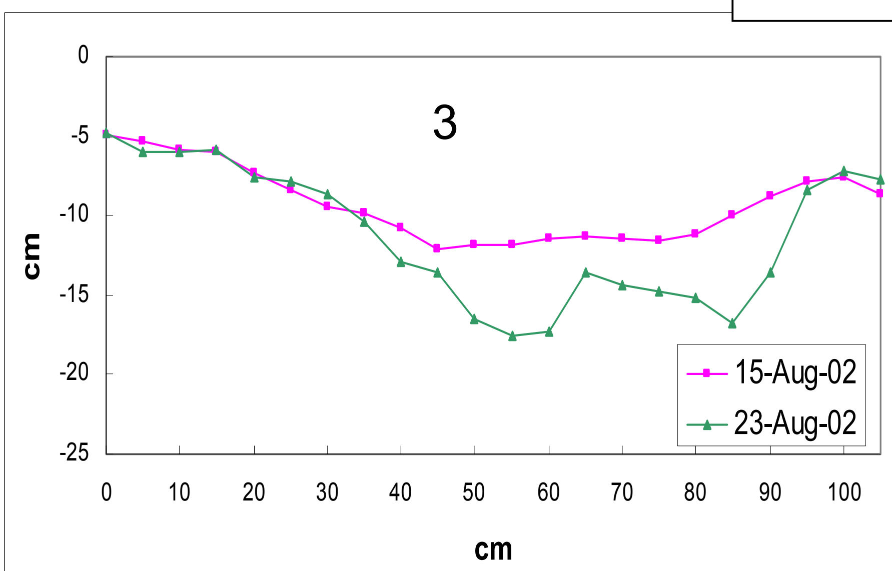
Measuring rill erosion, Hayman fire

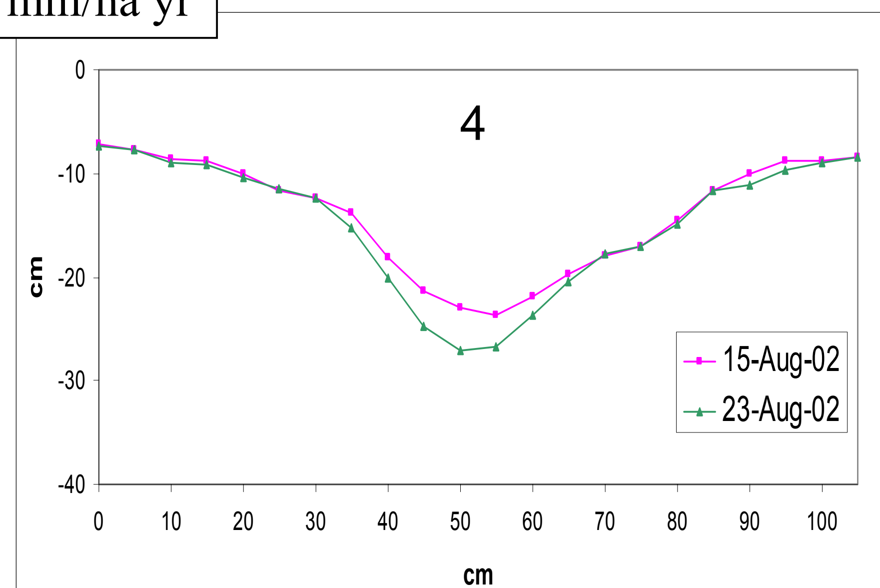
Rill erosion in Swale 4: Storm on 21 August



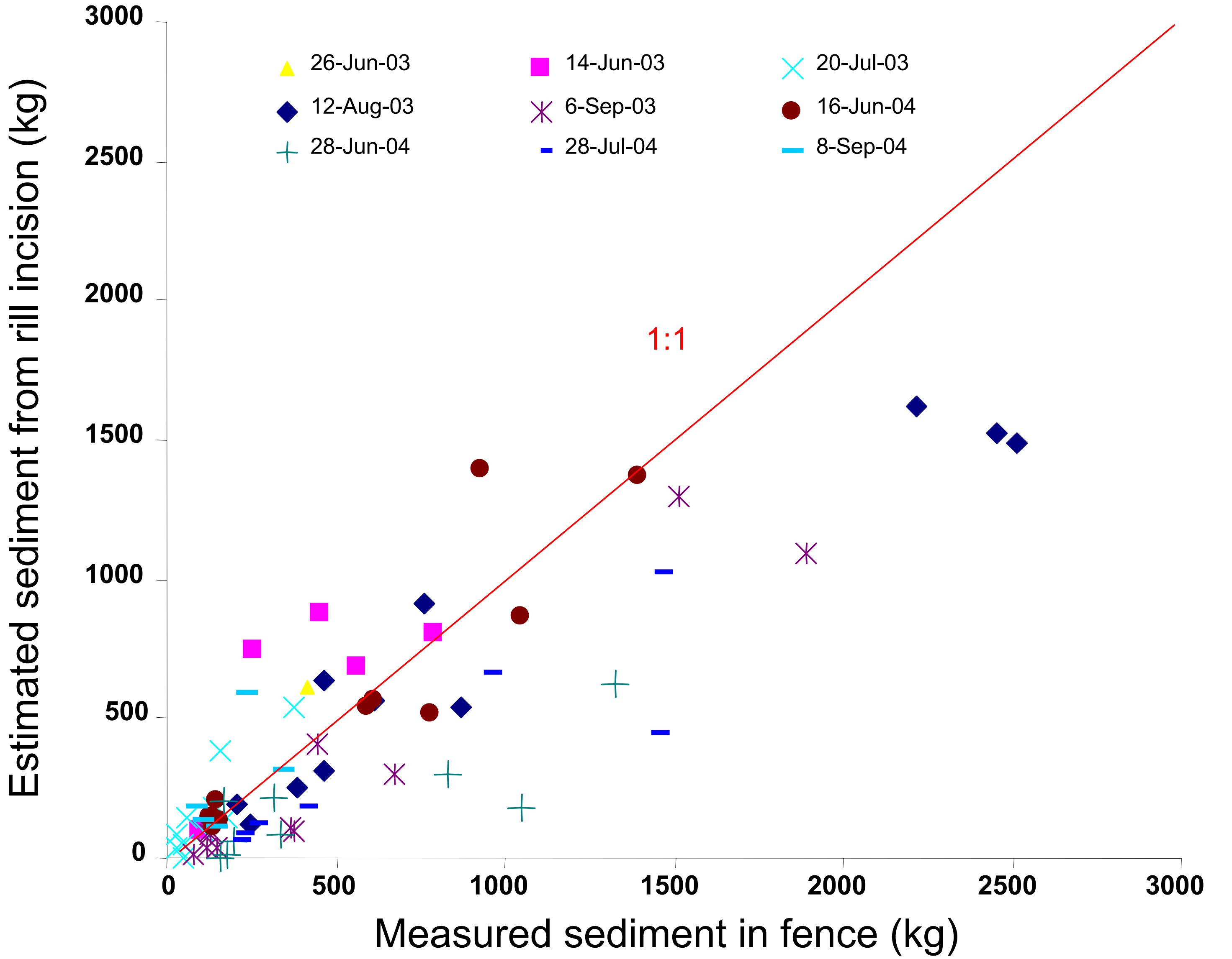


8 mm rainfall
I_{30} = 15.6 mm/hr
27.4 MJ mm/ha yr





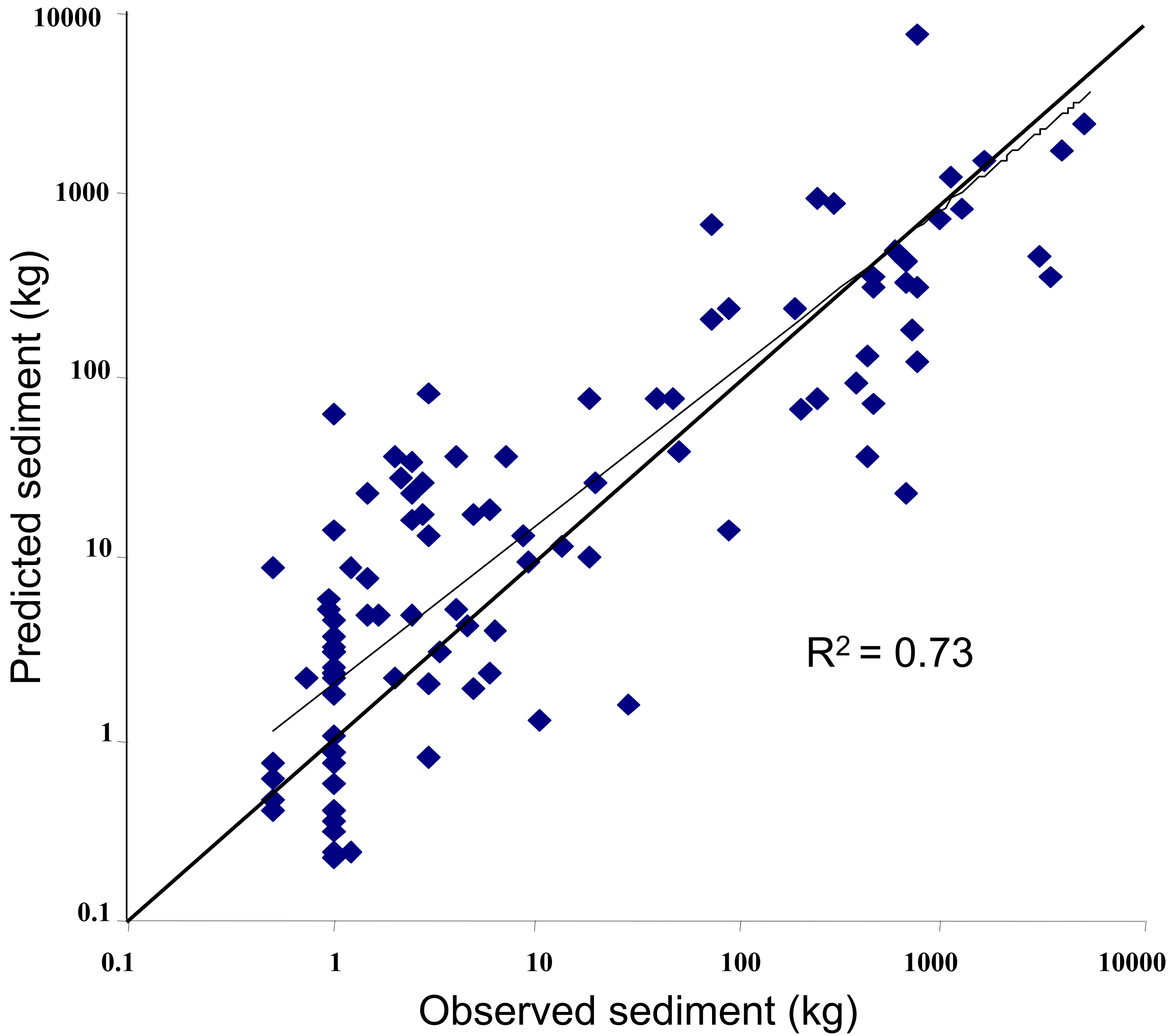
Estimated Sediment from Rill Erosion vs. Measured Sediment: Hayman fire



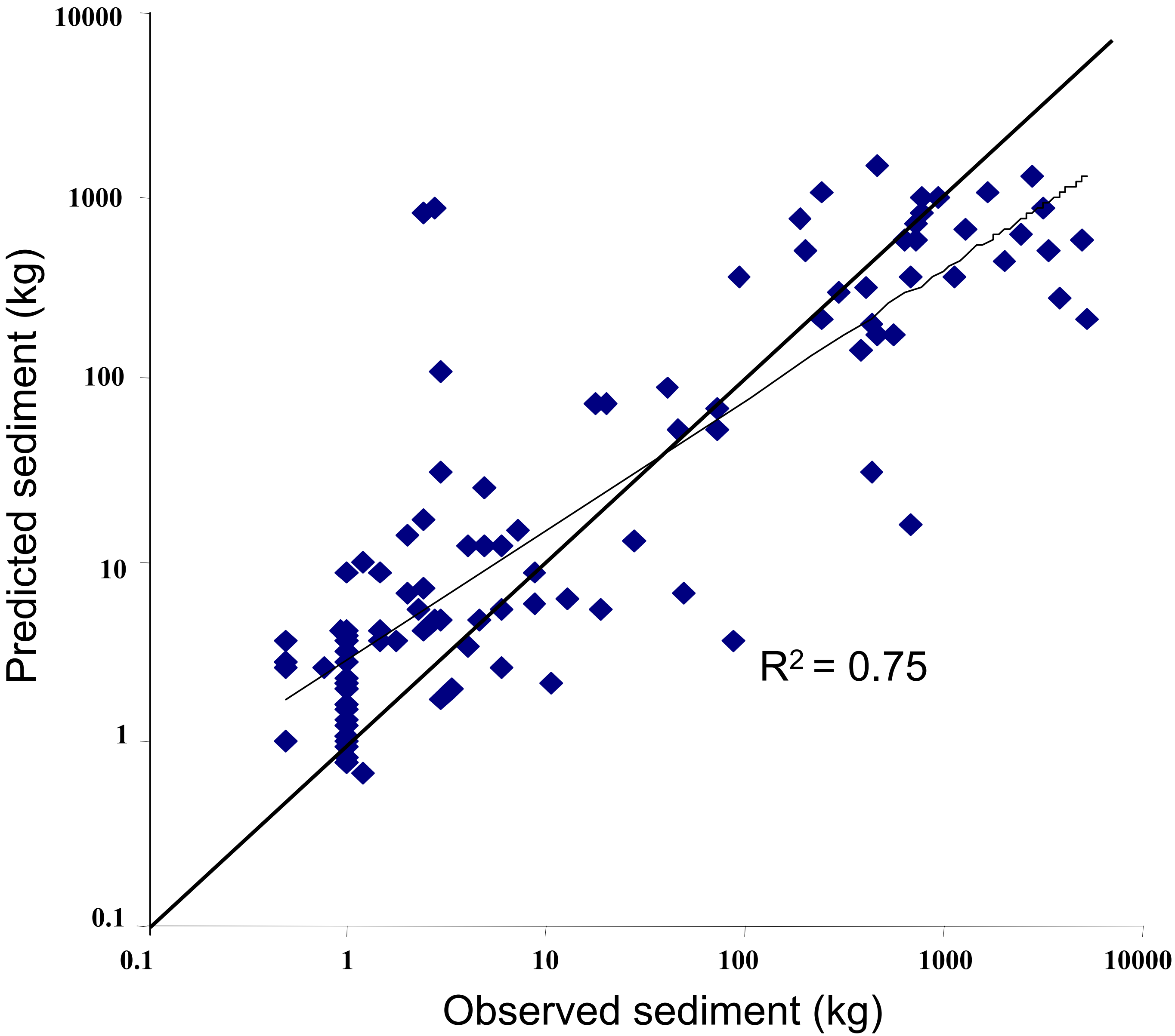
Model Calibration (50% of data; n=120)

Model	Parameter	R^2	RMSE
Complete	Bare soil, rainfall erosivity, soil D_{84}, hillslope position, aspect	0.83	0.54
4-parameter	Bare soil, rainfall erosivity, soil D_{84}, hillslope position	0.72	0.68
3-parameter	Bare soil, rainfall erosivity, hillslope position	0.68	0.71
2-parameter	Bare soil, rainfall erosivity	0.63	0.76
1-parameter	Bare soil	0.58	0.81

Validation of Complete Model



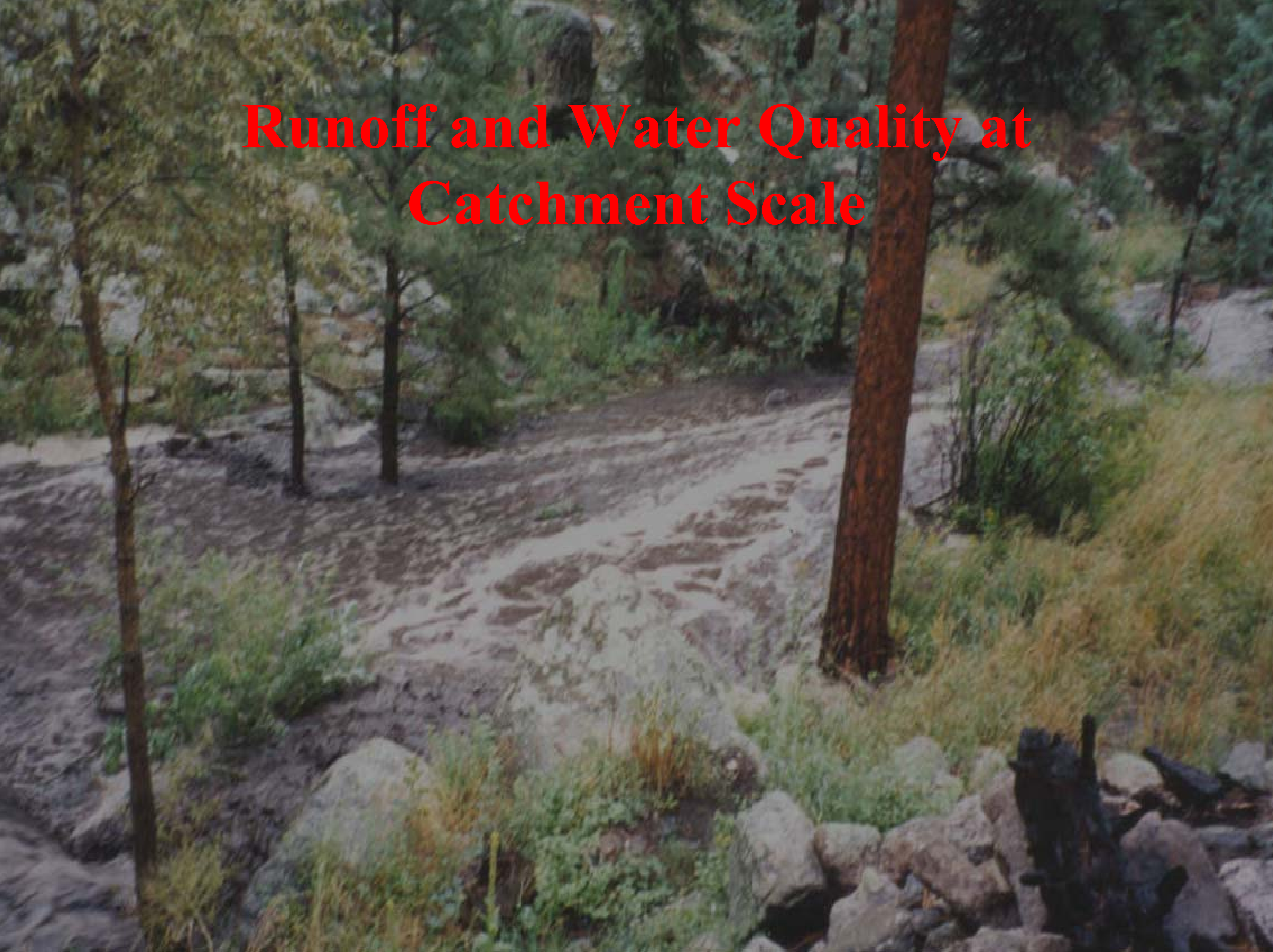
Validation of Two-parameter Model



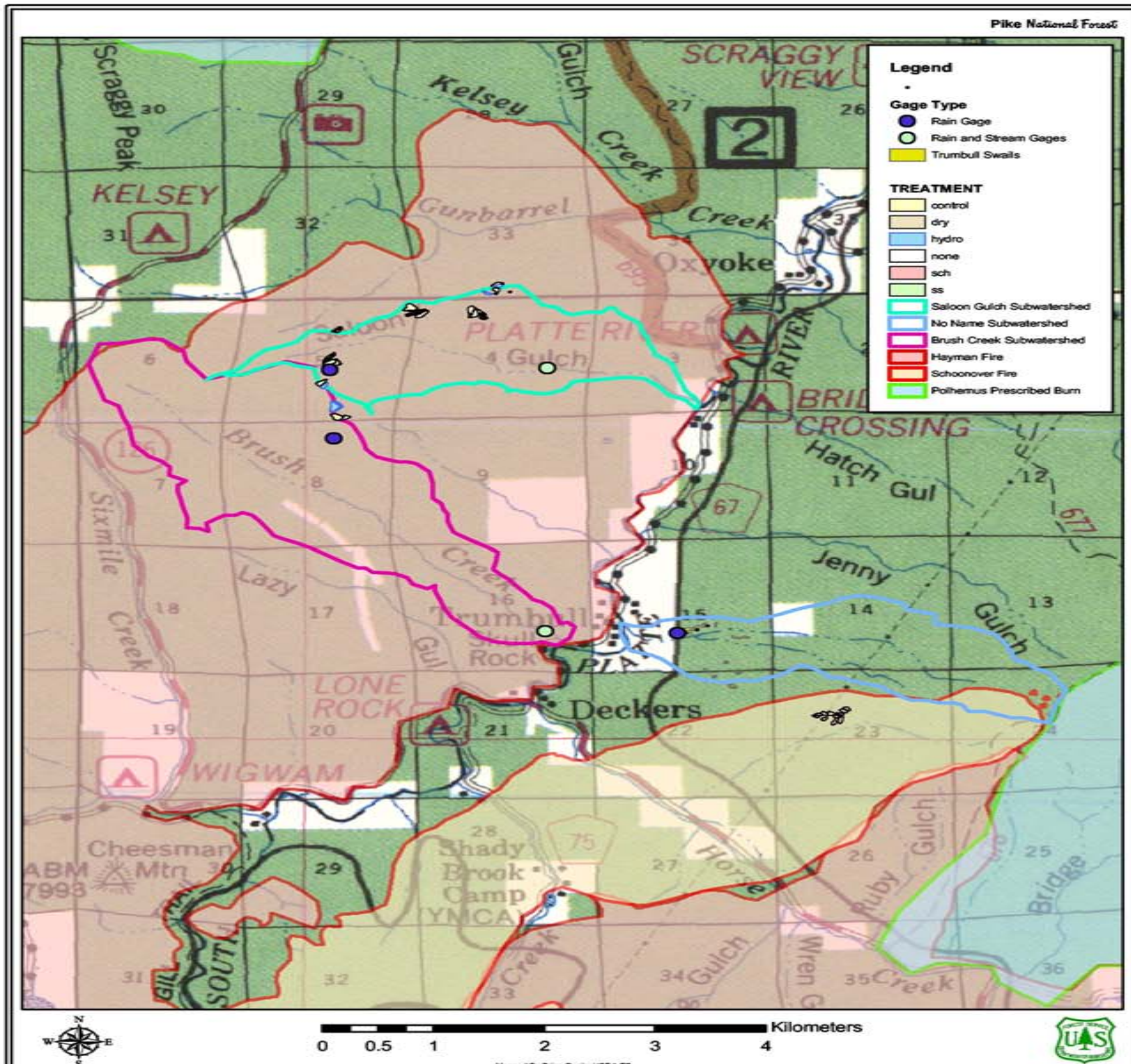
Model Validation

1. For the calibration dataset, adding four other variables in addition to percent bare soil increased the R^2 from 0.58 to 0.83 and reduced the RMSE from 0.81 to 0.54;
2. For the validation data set, there was relatively little difference in model performance between the simplest and most complete models;
3. For all models the RMSE for the validation data set was 0.65-0.73 log units (i.e., a factor of ~5).

Runoff and Water Quality at Catchment Scale



Saloon Gulch and Brush Creek Watersheds



Stream reaches: Summer 2001

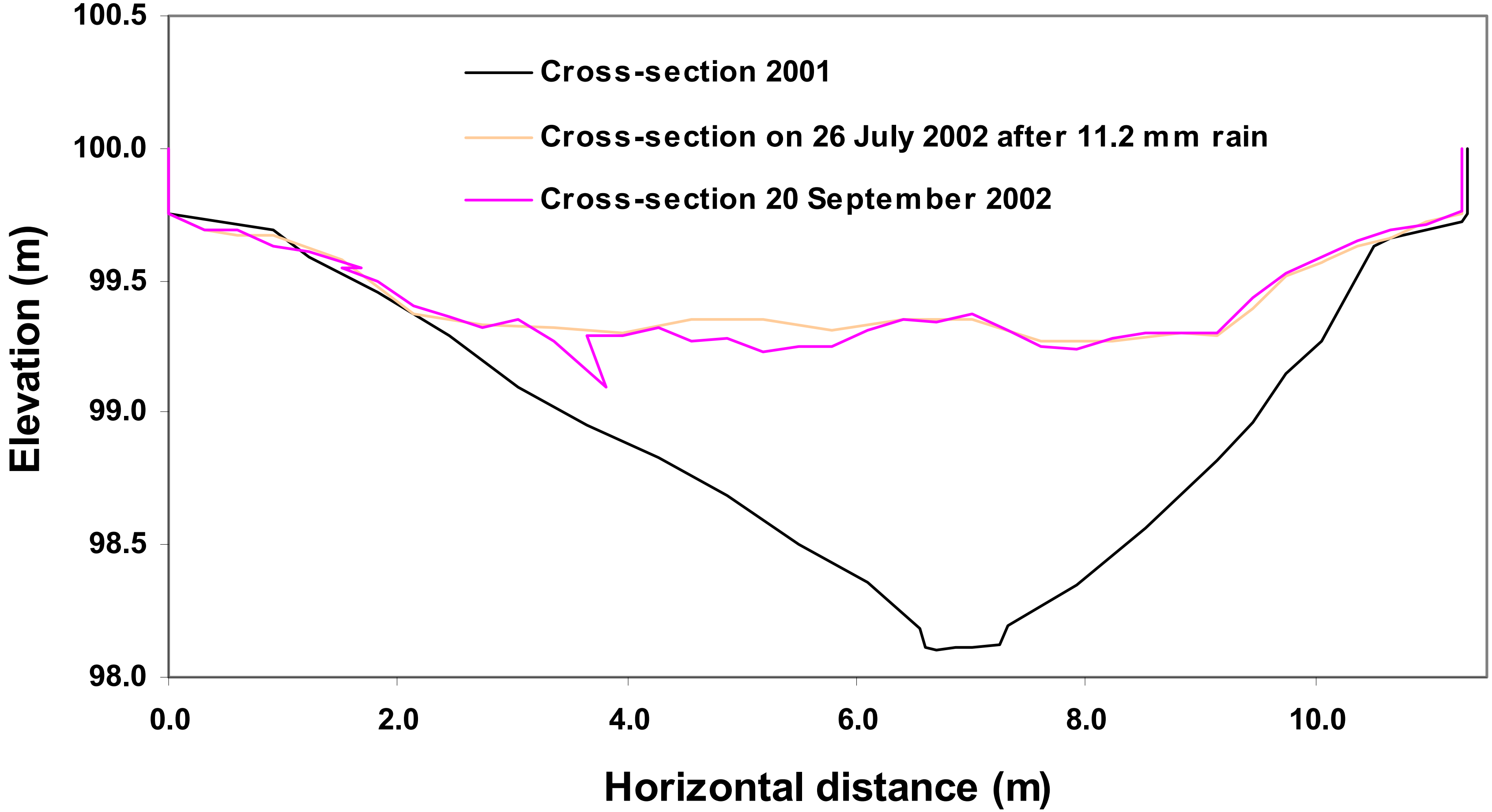
Saloon Gulch

Brush Creek

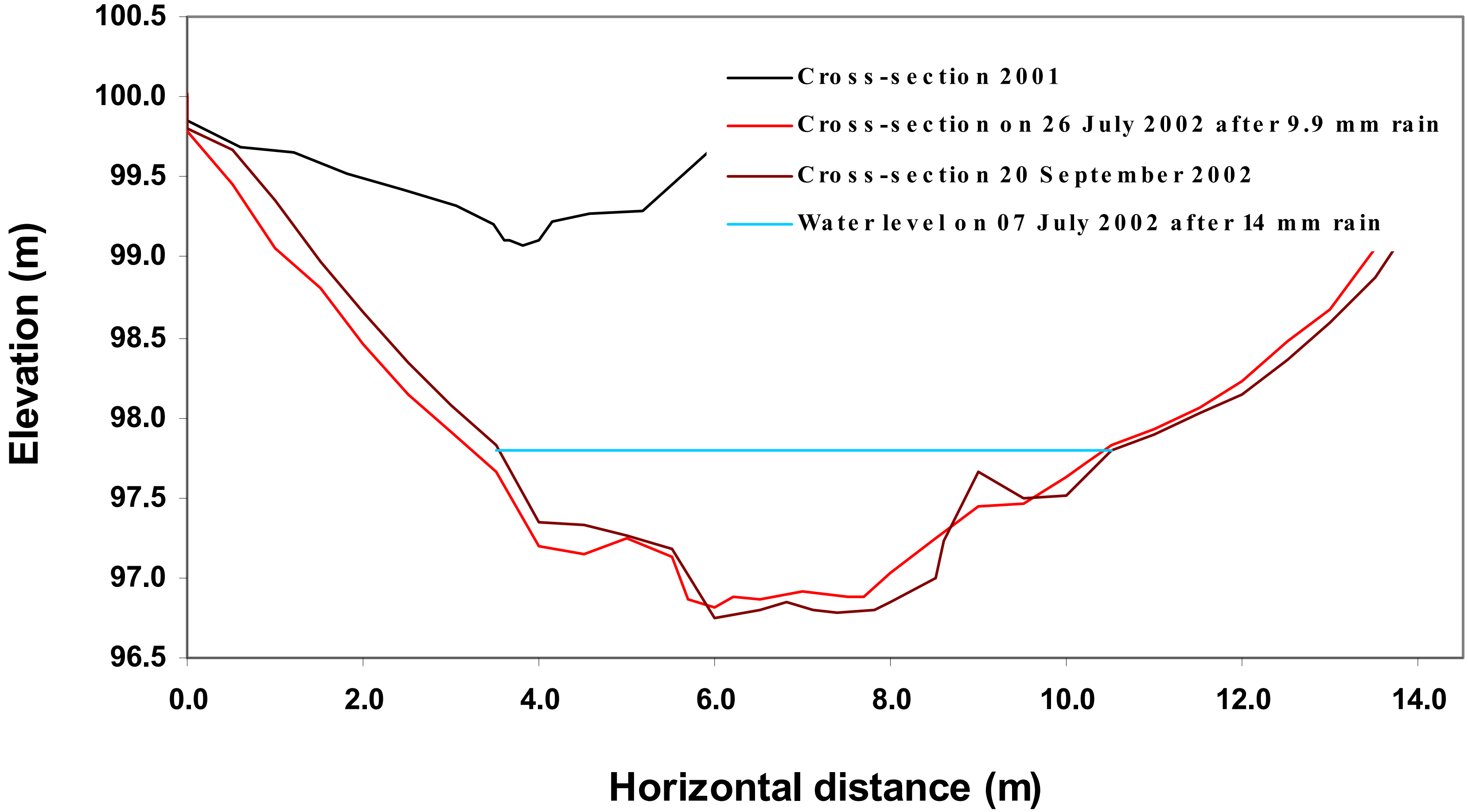
Brush Creek flume before the Hayman fire

Saloon Gulch flume after the Hayman fire: 17 mm of rain on 6 July

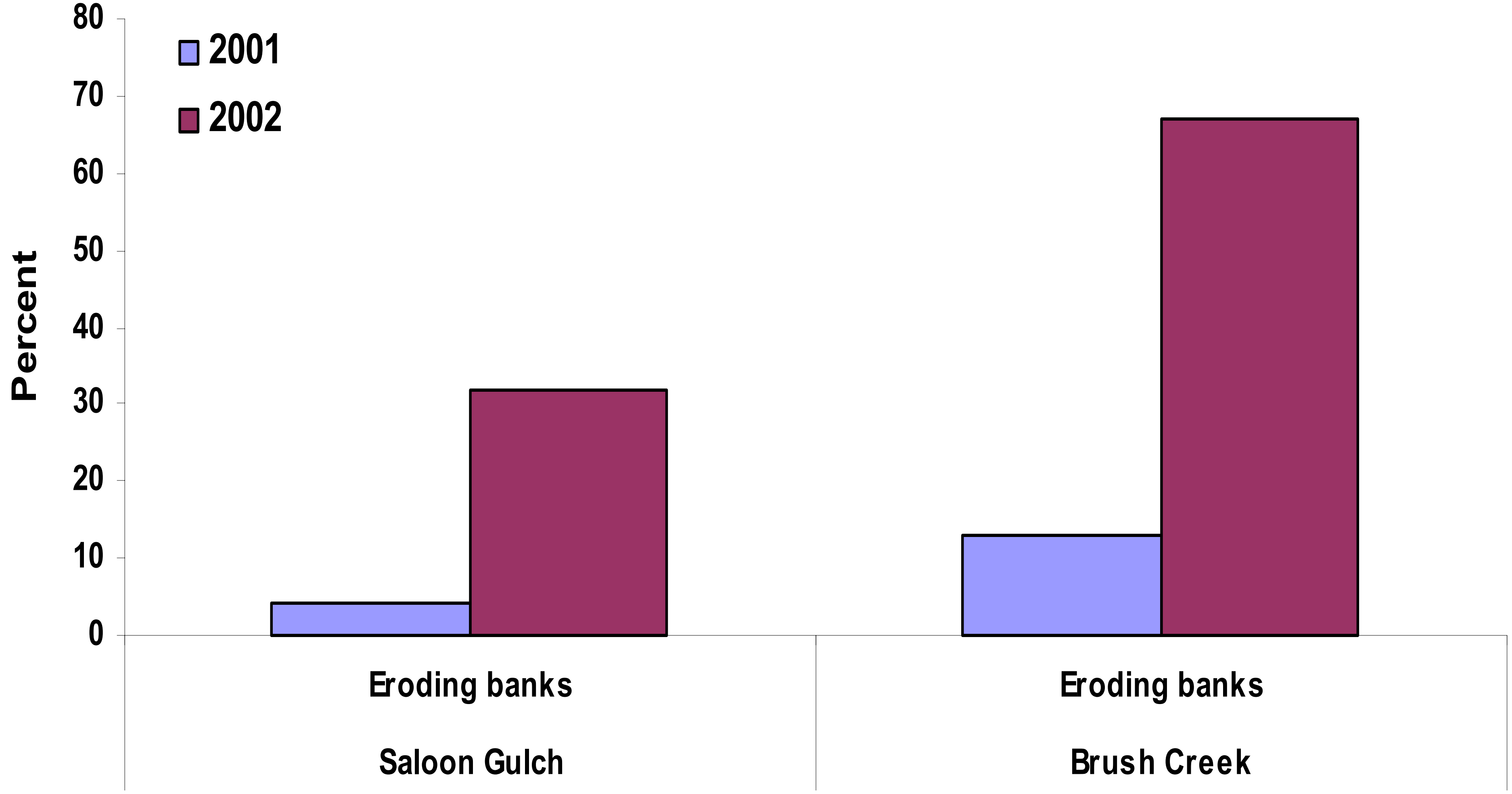
Channel Cross-section: Saloon Gulch



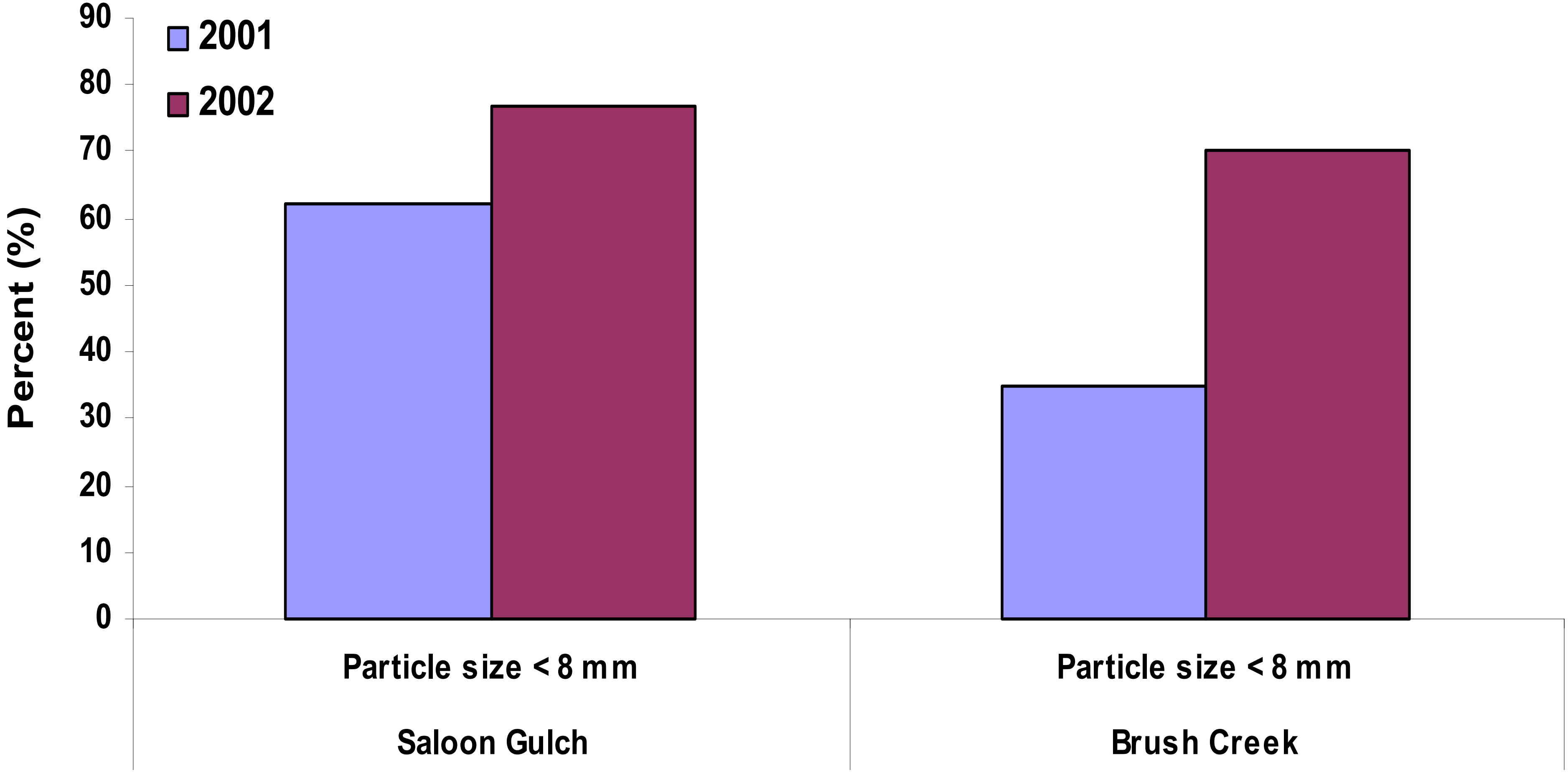
Channel cross-section for Brush Creek



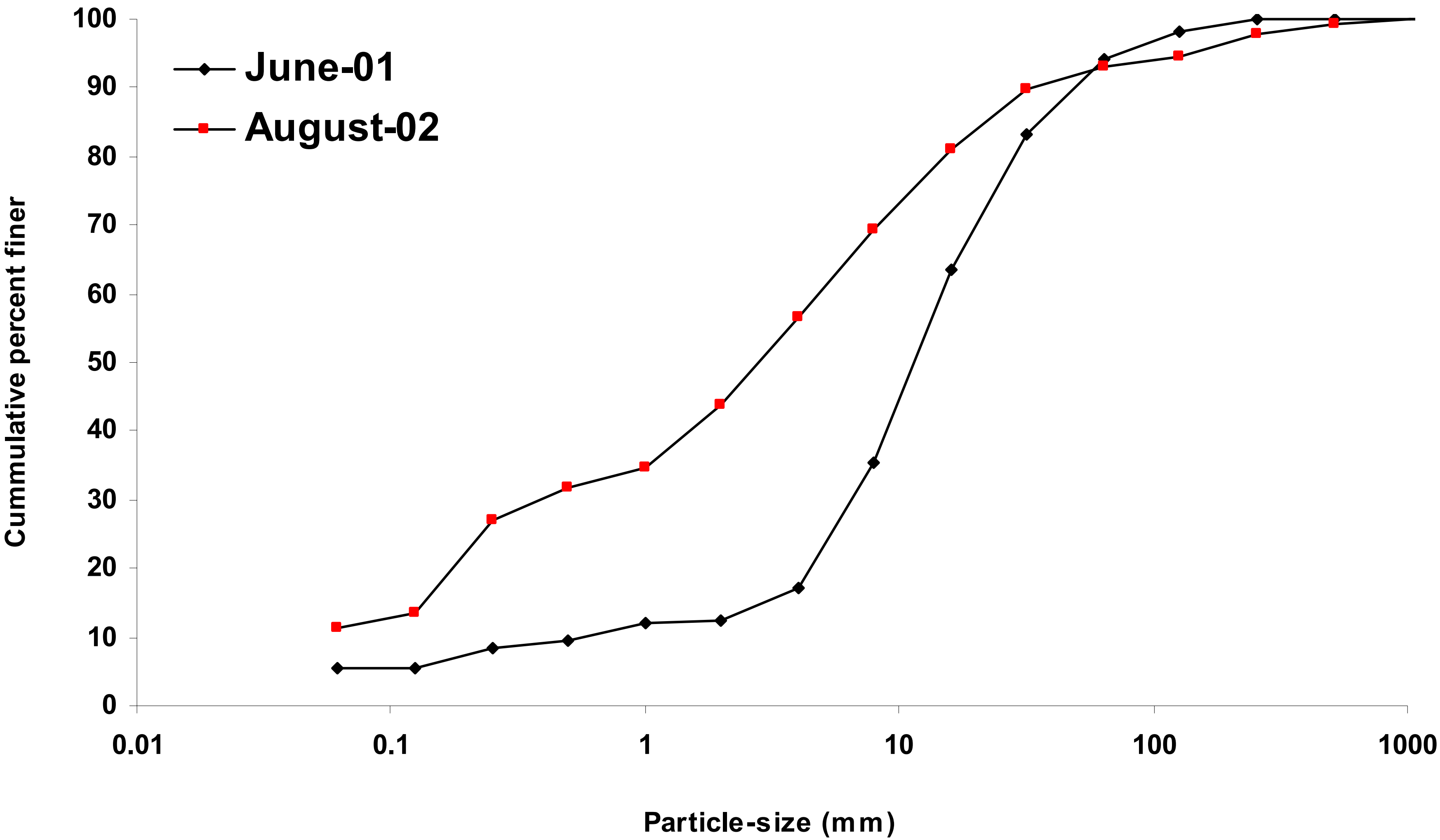
Percent eroding banks in 2001 and 2002: Saloon Gulch and Brush Creek



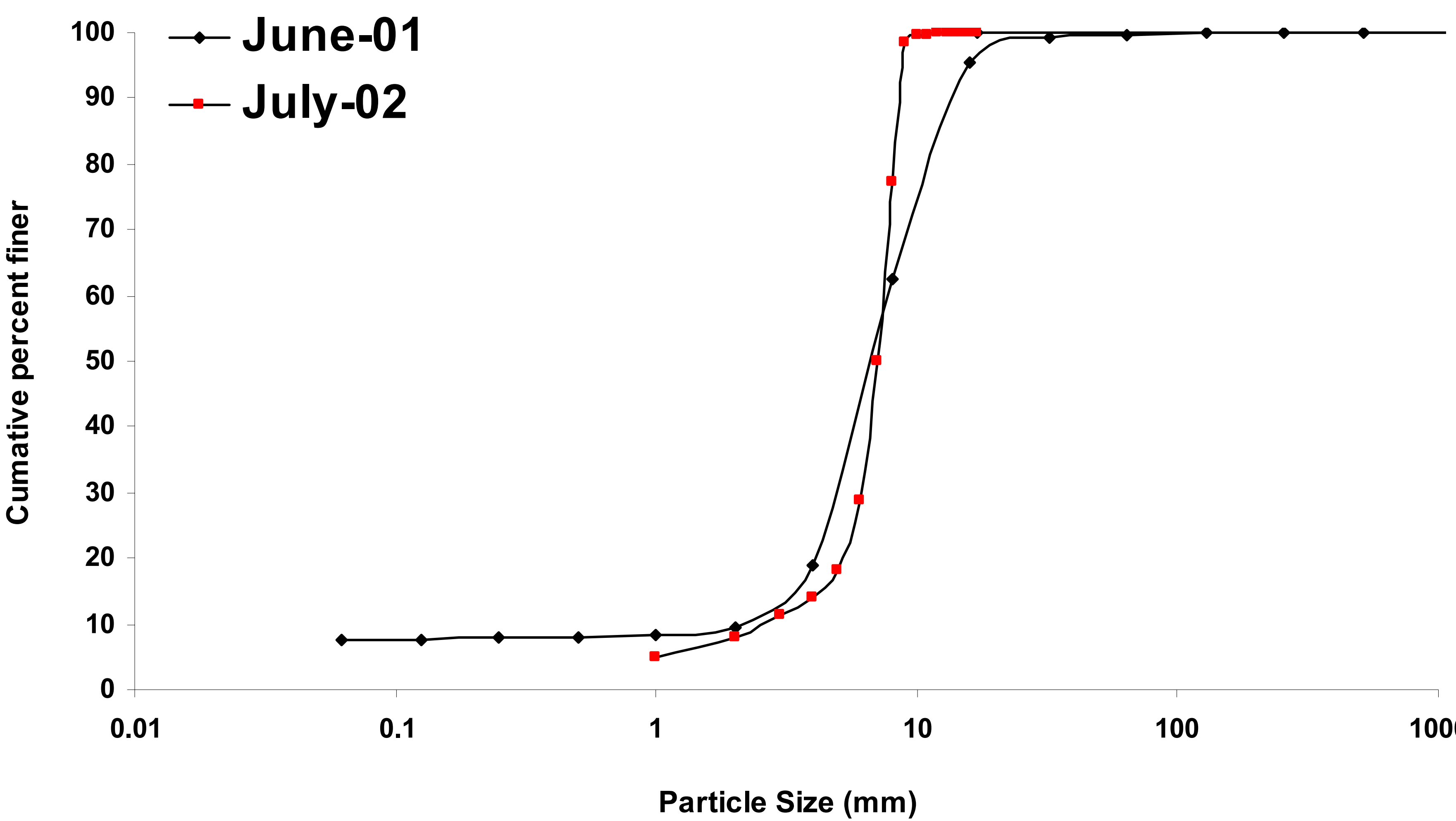
Percent of Bed Material less than 8 mm in 2001 vs. 2002: Saloon Gulch and Brush Creek



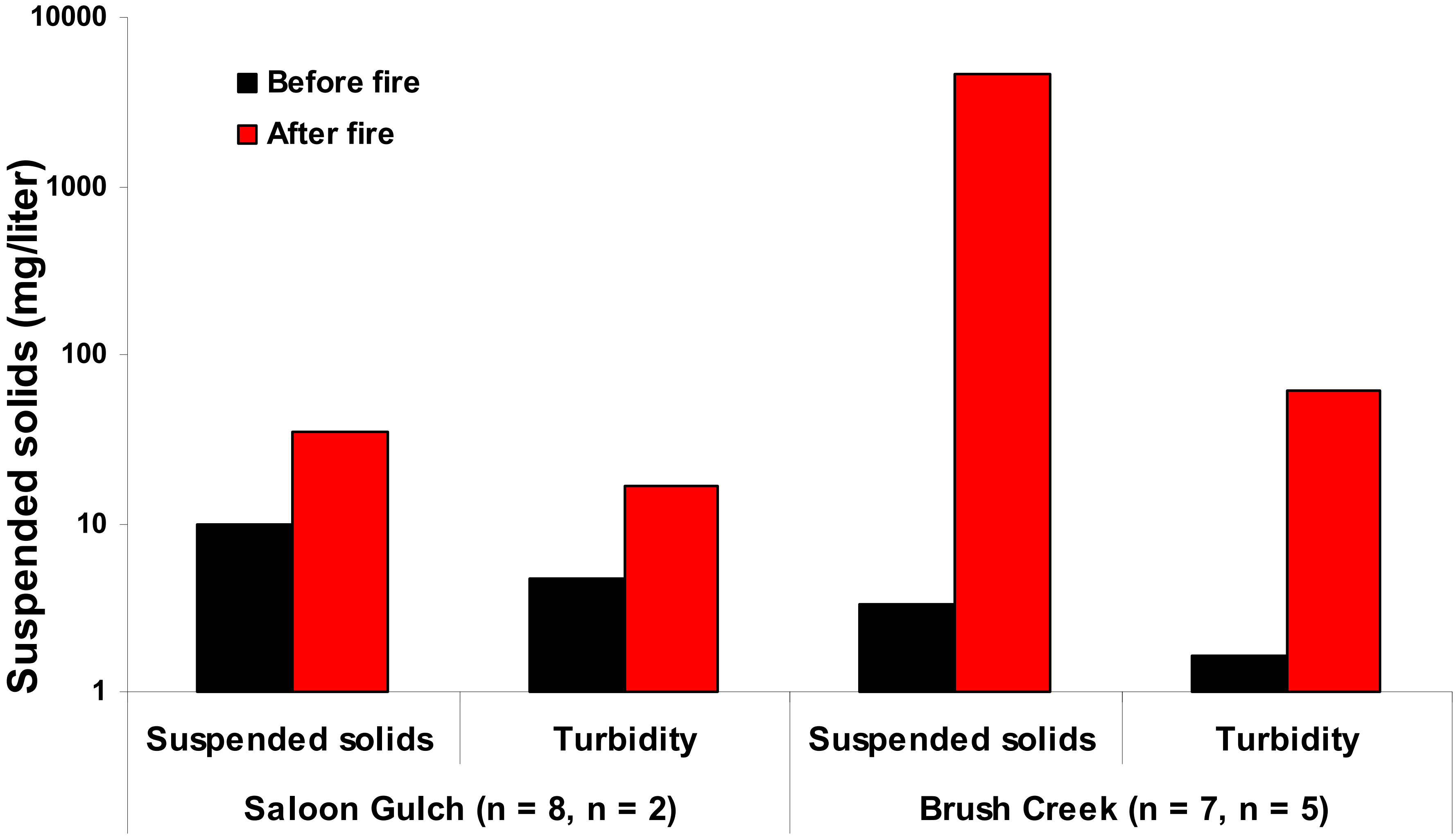
Change in particle-size distribution:

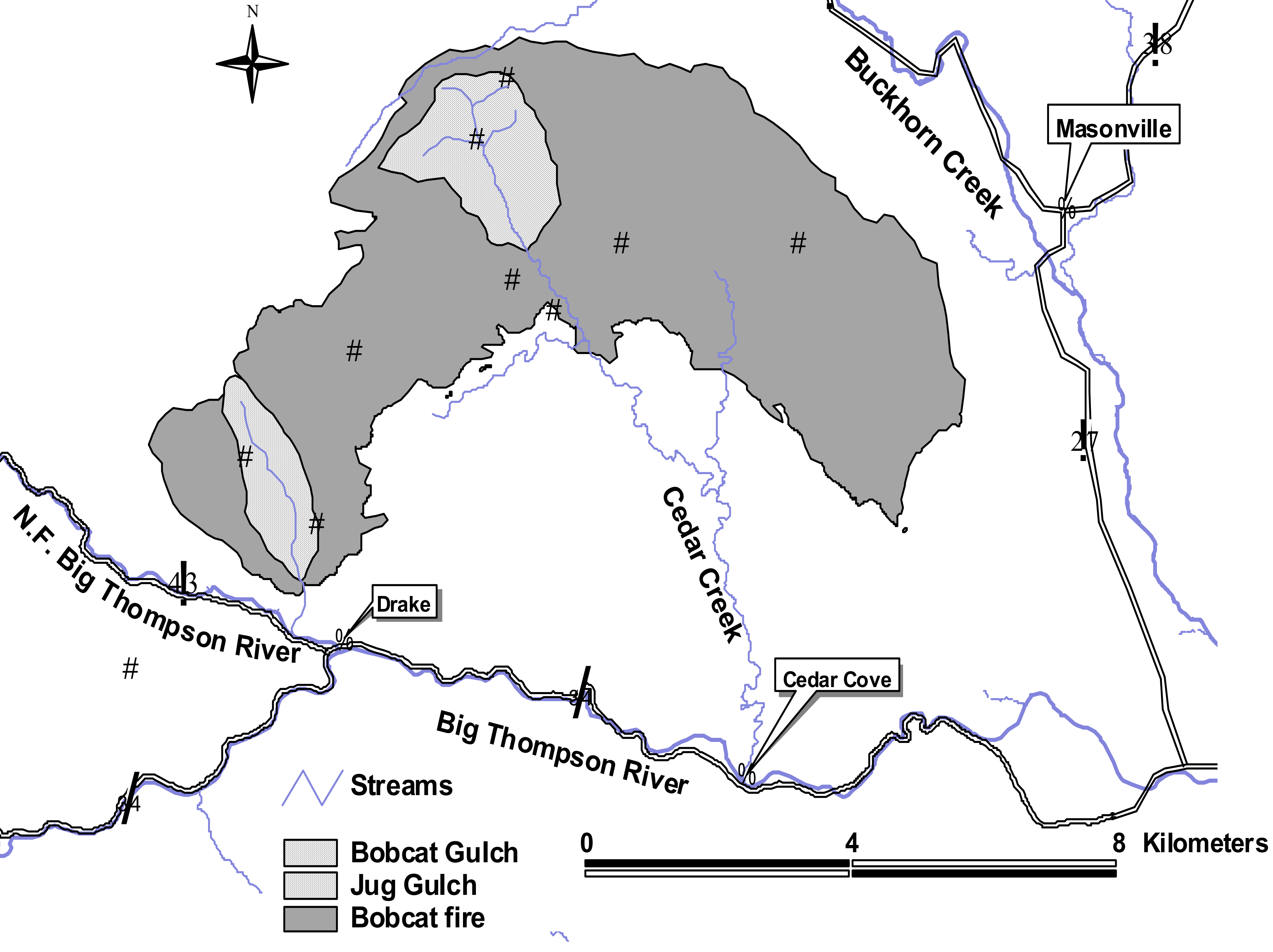


Change in particle-size distribution: Saloon Gulch



Mean total suspended sediment (TSS) and turbidity before and after the Hayman fire: Saloon Gulch and Brush Creek



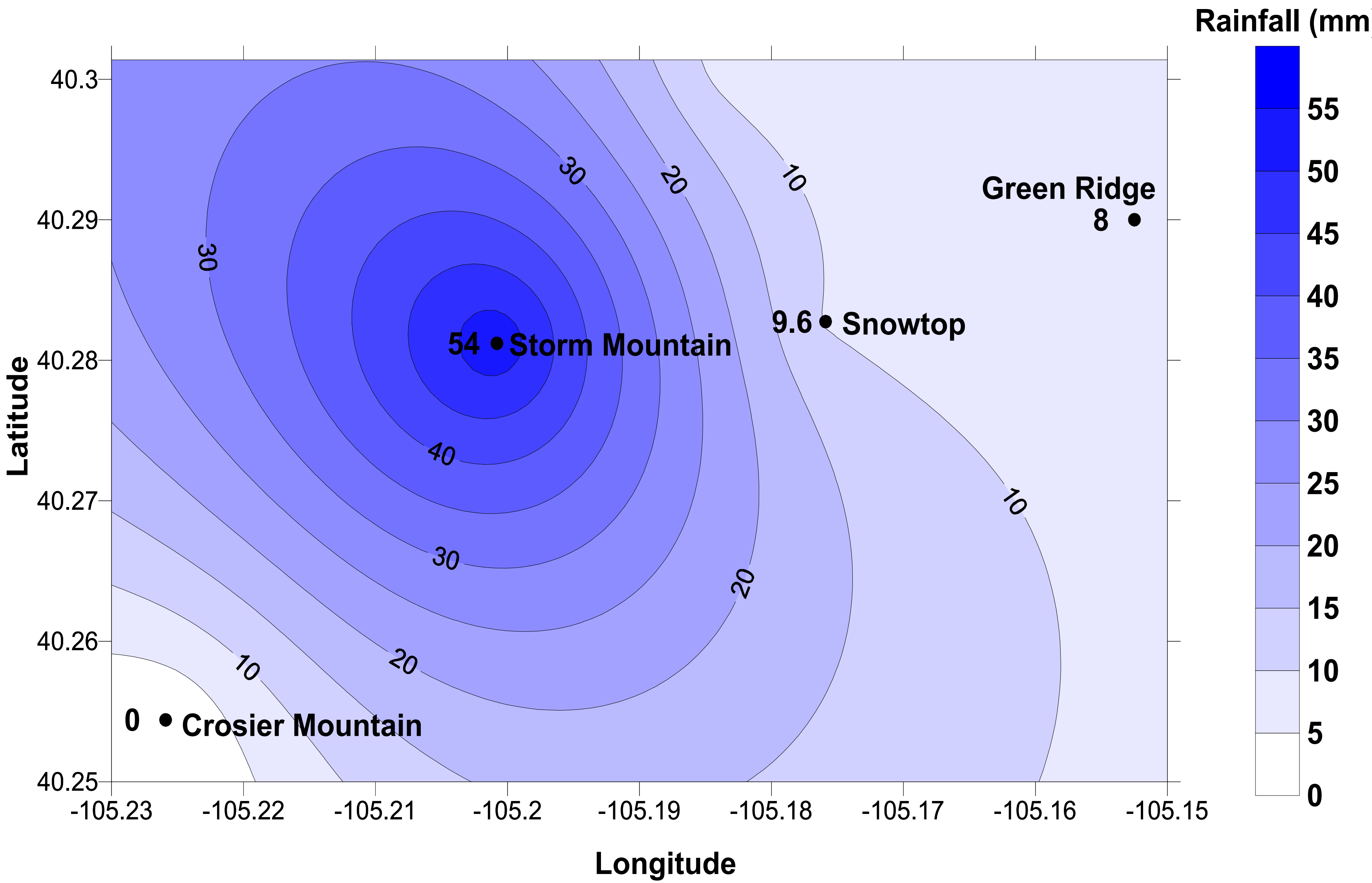


N
Buckhorn Creek
Masonville
Cedar Creek
N.F. Big Thompson River
Drake
Big Thompson River
Cedar Cove
Streams
Bobcat Gulch
Jug Gulch
Bobcat fire
0
4
8
Kilometers

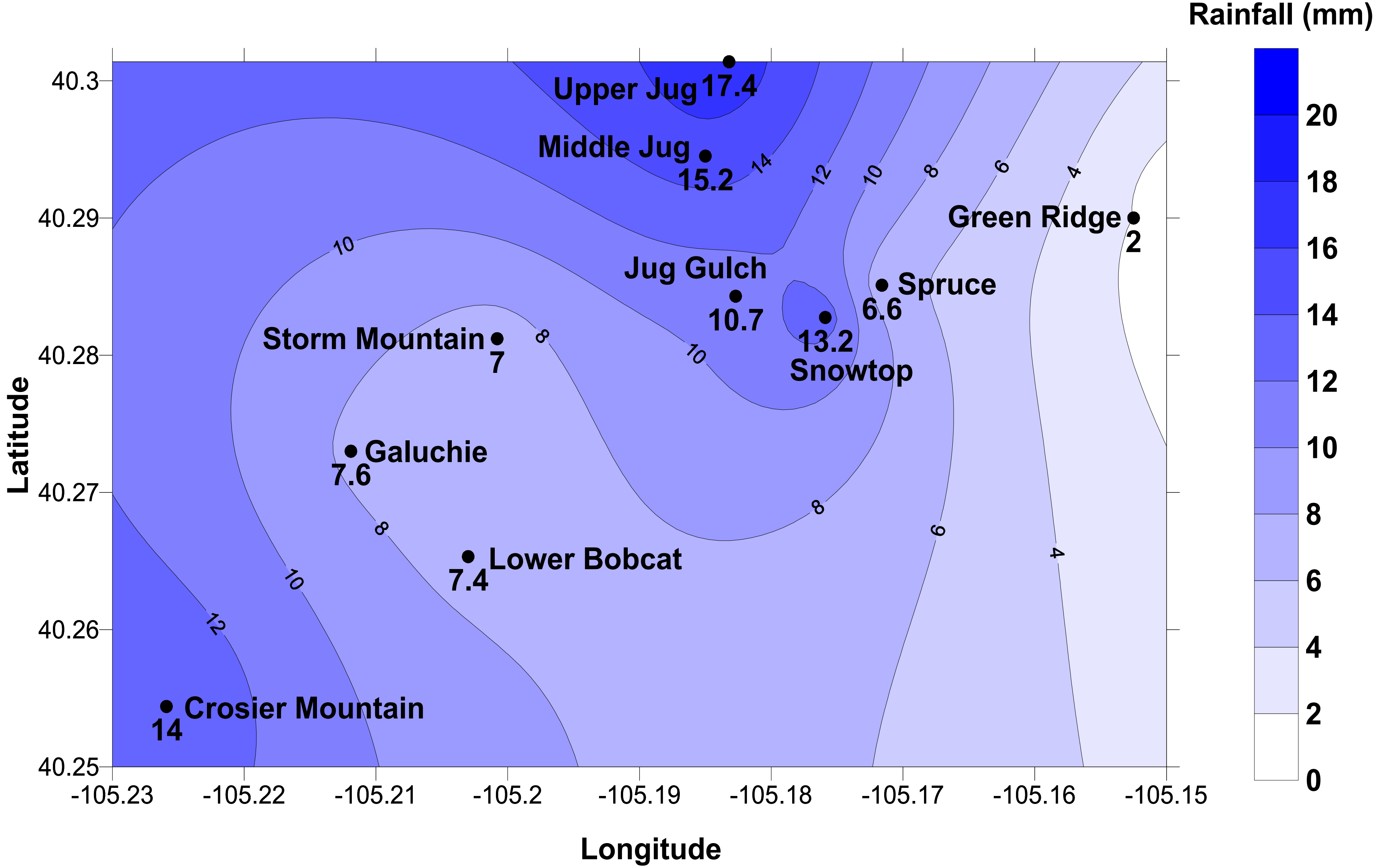
Bobcat Gulch

Jug Gulch

Spatial variability of rain on Bobcat Gulch: 16 August 2000



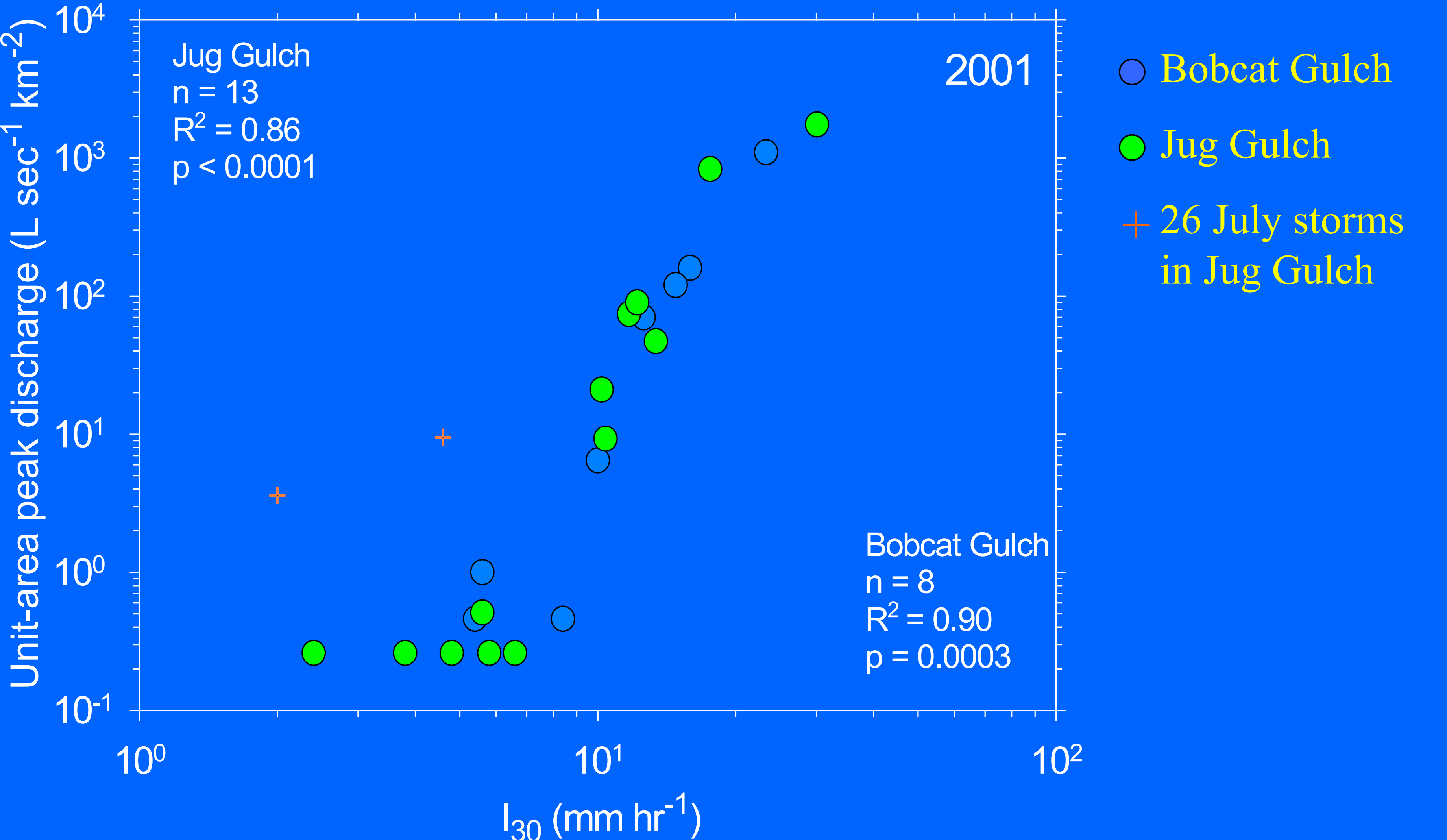
Spatial variability of rain on Bobcat Gulch: 15 August 2001



Storm Characteristics and Peak Runoff Rates: Bobcat fire, 2000-2001

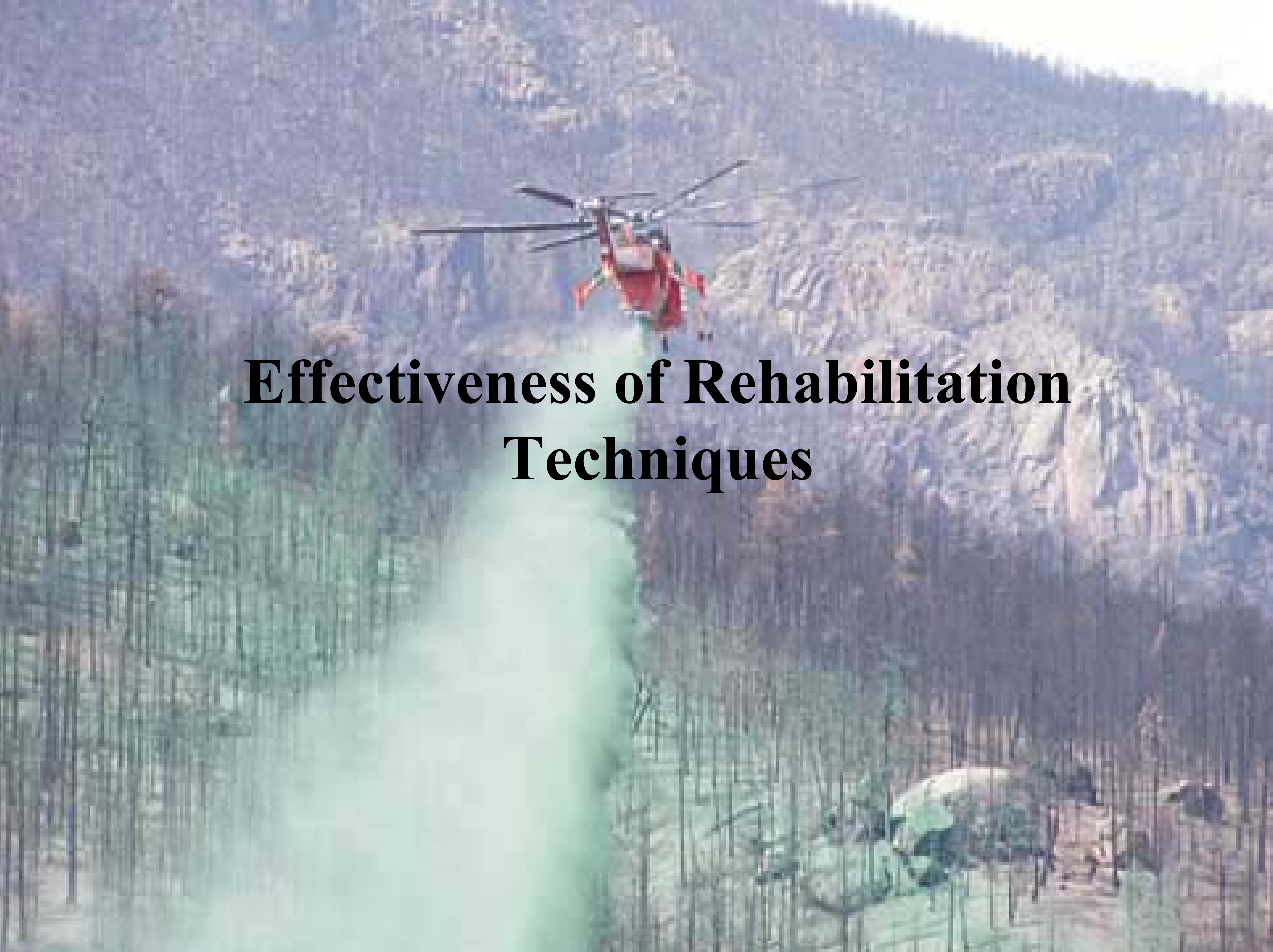
Date	Watershed	Depth (mm)	I_{30} (mm hr^{-1})	Peak discharge (L sec^{-1})	Return period
16 Aug 2000	**Bobcat Gulch** Jug Gulch	**54** 9.6	**42** 14.8	**8500** < 18	**25-yr 3-hr** <1-yr
15 Aug 2001 (#2)	Bobcat Gulch **Jug Gulch**	7.5 **16.3**	14.8 **31.6**	250 **6800**	<1-yr **2-yr 30-min**
16 Aug 2001	**Bobcat Gulch** Jug Gulch	**13.0** 7.2	**23.3** 13.8	**2300** 180	**1-yr 30-min** <1-yr
3 June 2002	**Bobcat Gulch** Jug Gulch	**17.9** 14.8	**12.7** 9.6	**< 25** < 18	**<1-yr** <1-yr

Peak discharge vs. 30-minute rainfall intensity (I_{30})



Storm Characteristics and Suspended Sediment: Bobcat fire

Date	Watershed	Depth (mm)	I_{30} (mm hr^{-1})	Sediment yield (kg ha^{-1})	Return period
8 July 2001	**Bobcat Gulch** Jug Gulch	**6.3** 4.5	**12.6** 9.0	0.3 **1.2**	<1-yr <1-yr
15 Aug 2001 (#2)	Bobcat Gulch **Jug Gulch**	7.5 **16.3**	14.8 **31.6**	1.4 **950**	<1-yr **2-yr 30-min**
16 Aug 2001	**Bobcat Gulch** Jug Gulch	**13.0** 7.2	**23.3** 13.8	**370** 25	**1-yr 30-min** <1-yr



Effectiveness of Rehabilitation Techniques

Typical Emergency Rehabilitation Treatments

Other Techniques

Hydromulch
(aerial and ground-based)

Soil binding agents
(e.g., polyacrylamides)

Background

- Large amounts of money spent after most major fires (e..g, $25 million after Cerro Grande, $17 million after Hayman);
- Strong political pressure to do something;
- Very few data on effectiveness;
- USFS review stated that effectiveness generally poor (Robichaud et al., 2000).

Treatments on Bobcat fire

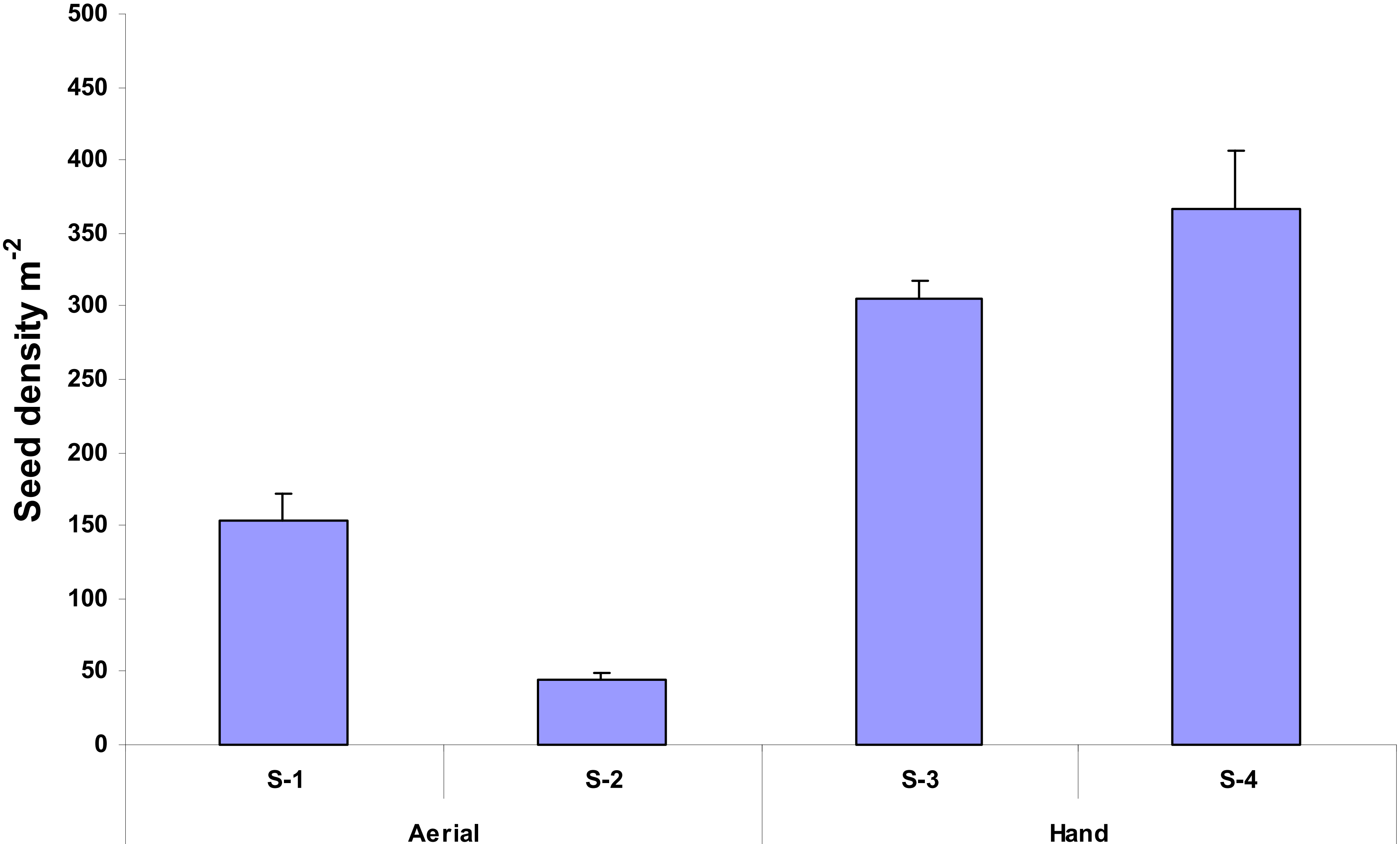
- Mulching: July 2000; Fall 2000;
- Aerial seeding: July 2000
- Contour-felling: July 2000; Fall 2000

Treatments on Hayman fire: 2002

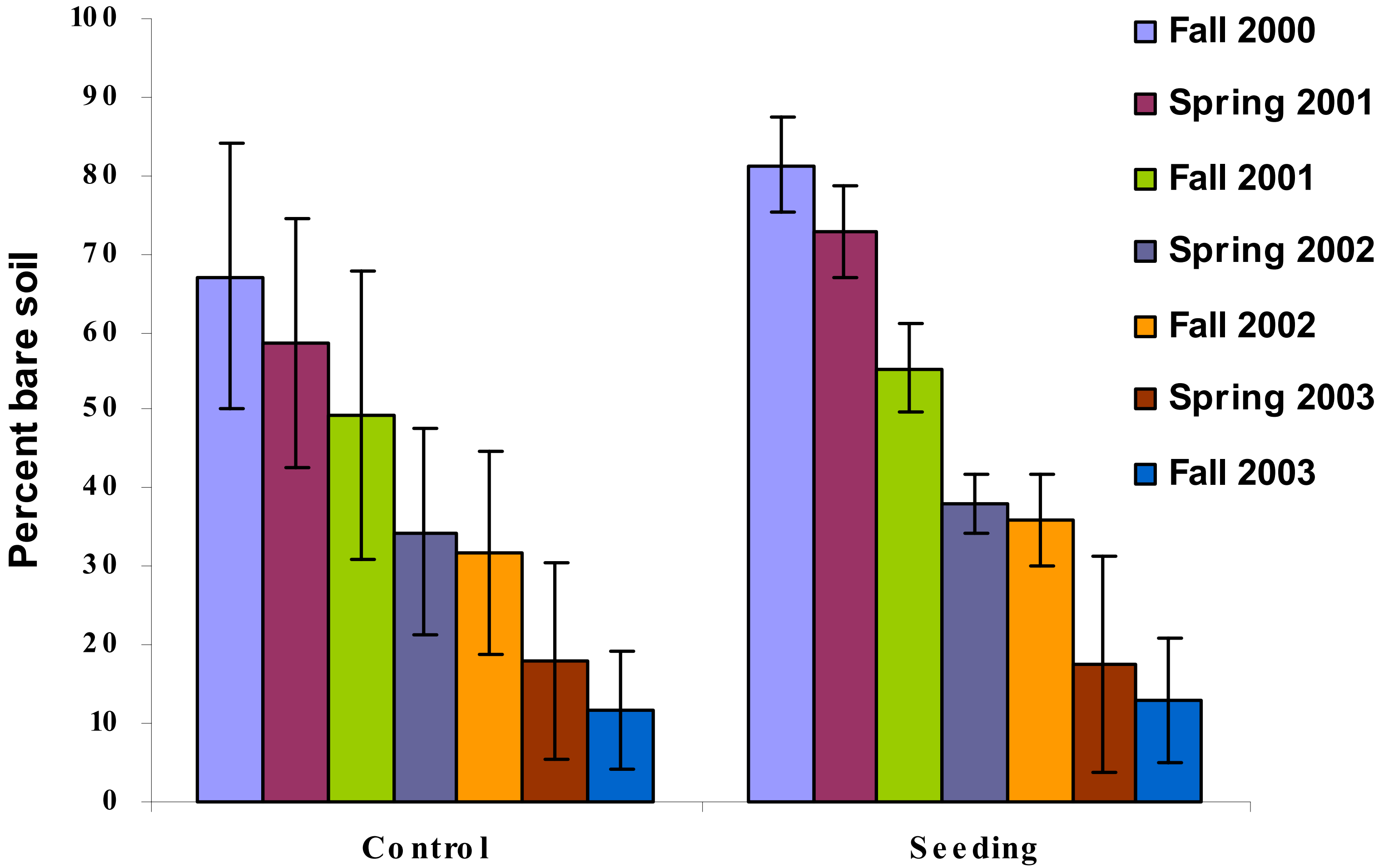
- Scarifying and seeding
- Dry mulching
- Hydromulching
  - Ground based
  - Aerial
- Polyacrylamide

Seeding

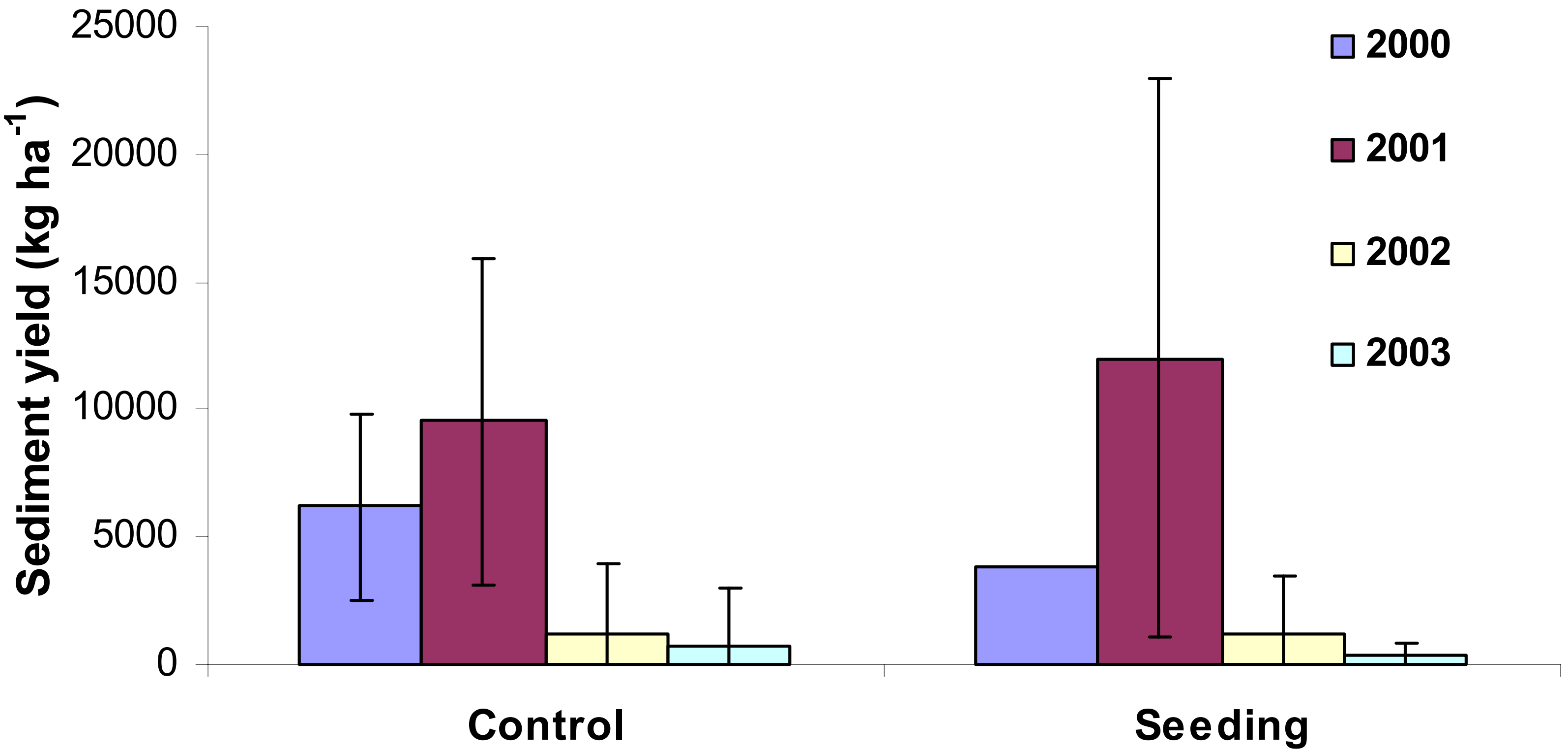
Seed density in Bobcat fire (target: 430 seeds m^{-2} or 30 lbs $acre^{-1}$)



Changes in percent bare soil on controls and seeded plots: Bobcat fire, 2000-2003

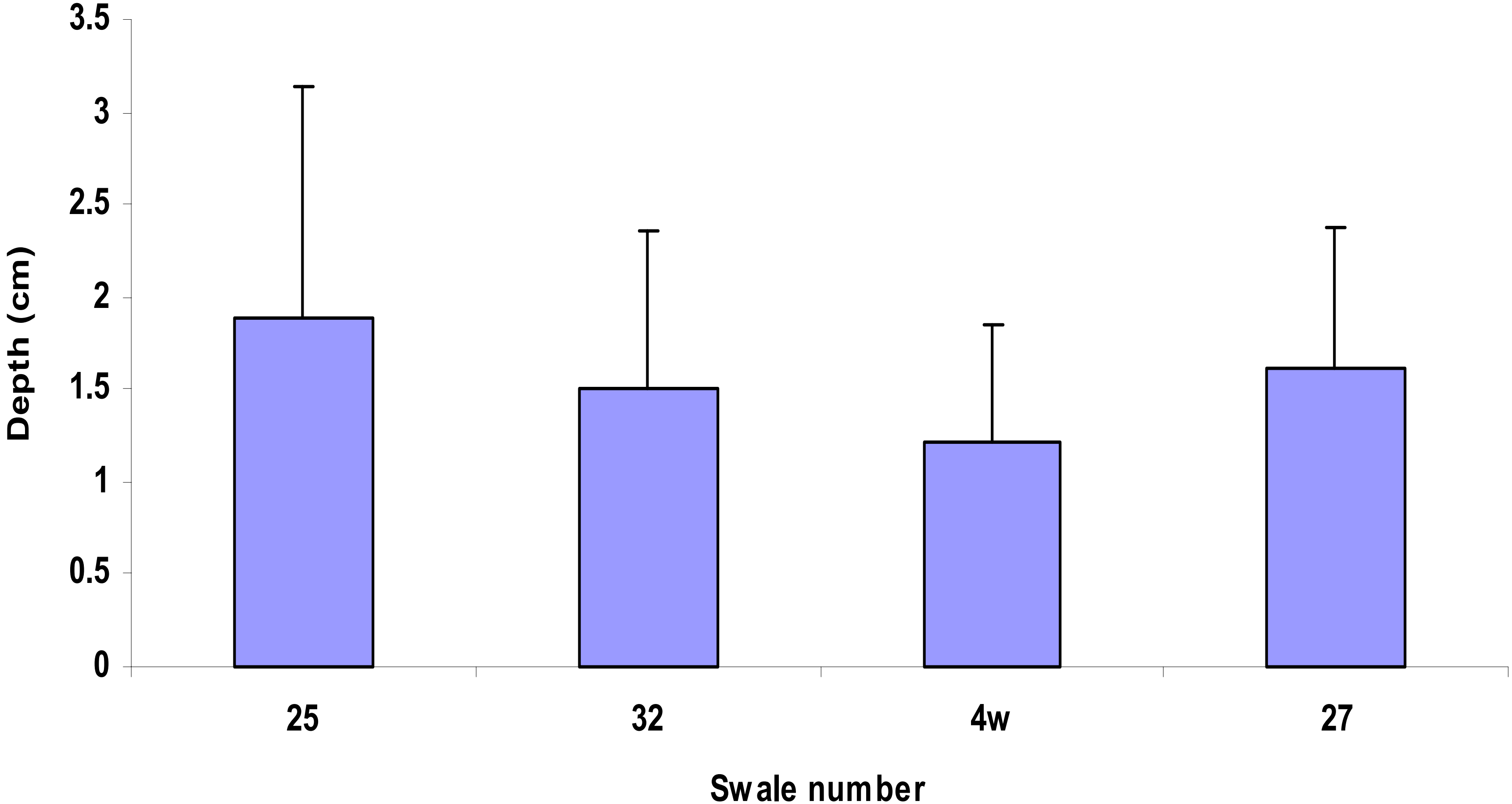


Sediment yields on controls and seeded plots: Bobcat fire, 2000-2003

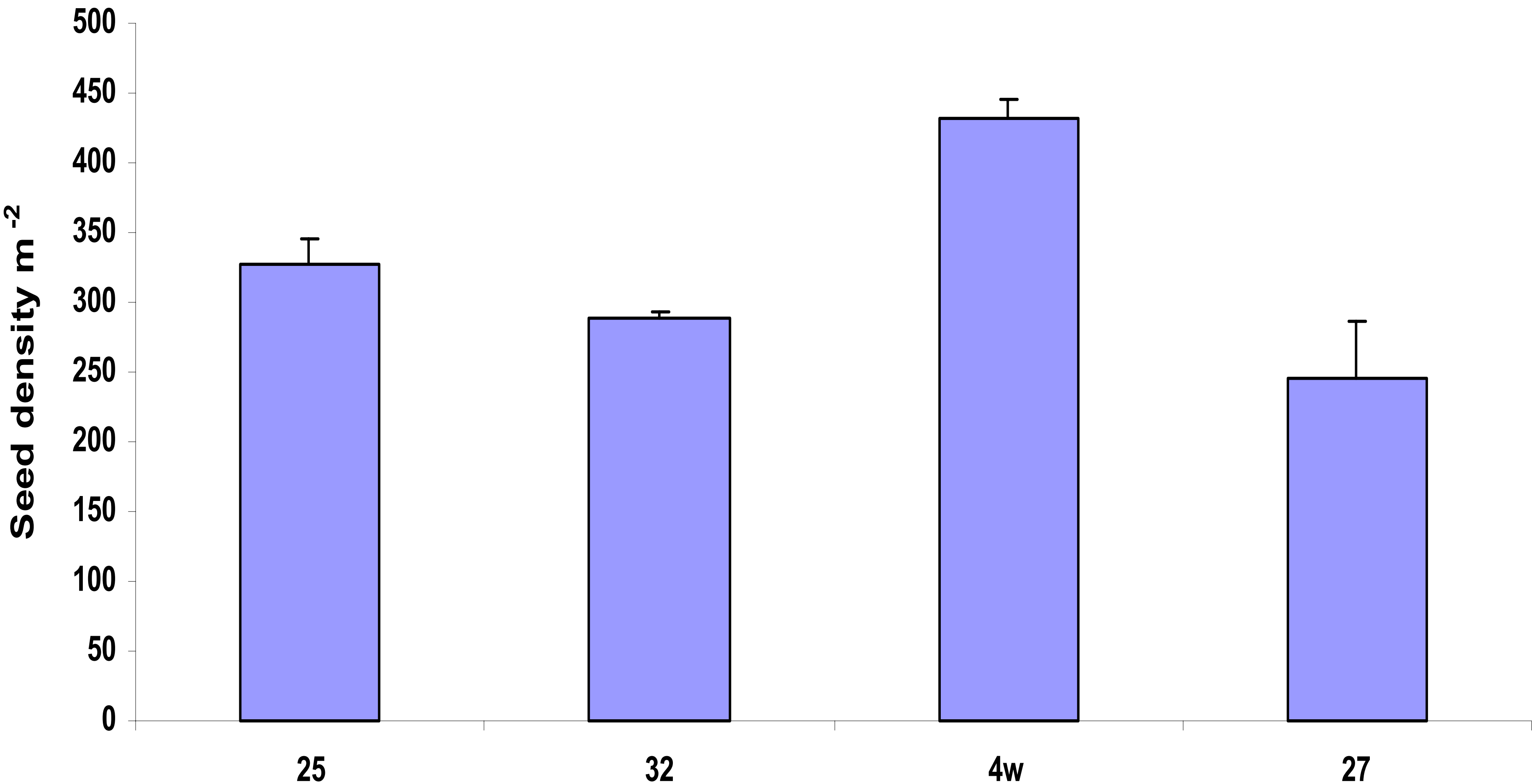



Scarification and Seeding

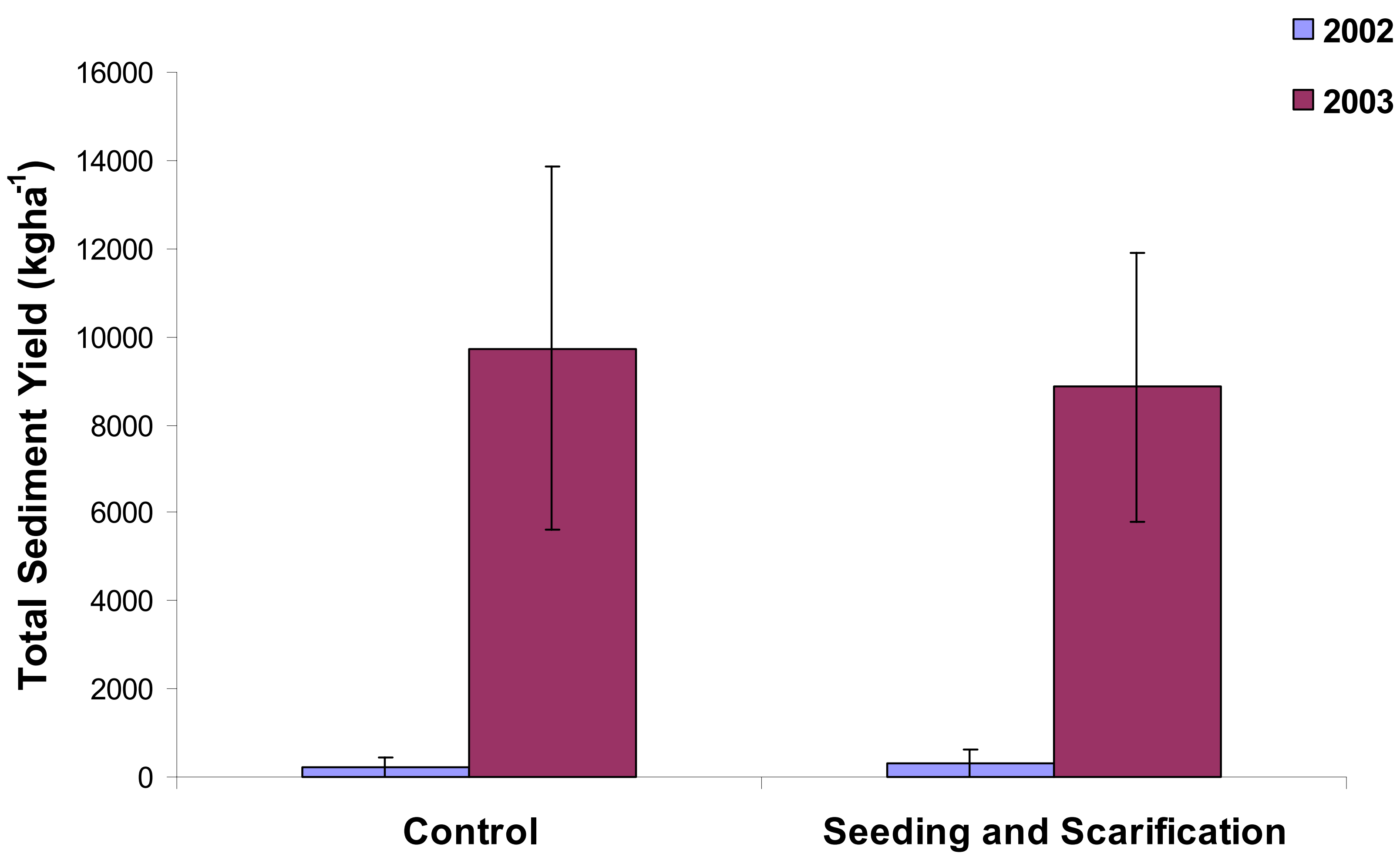
Depth of hand scarification in Hayman fire



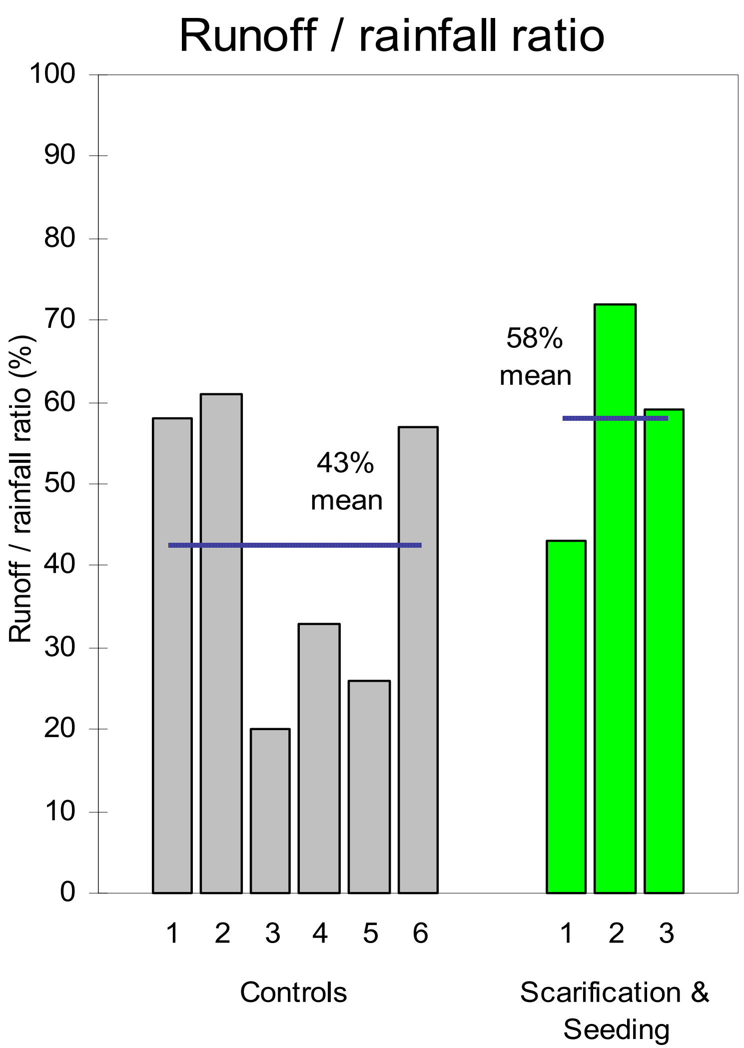
Seed density in Hayman fire (target: 280-380 seeds m^{-2})

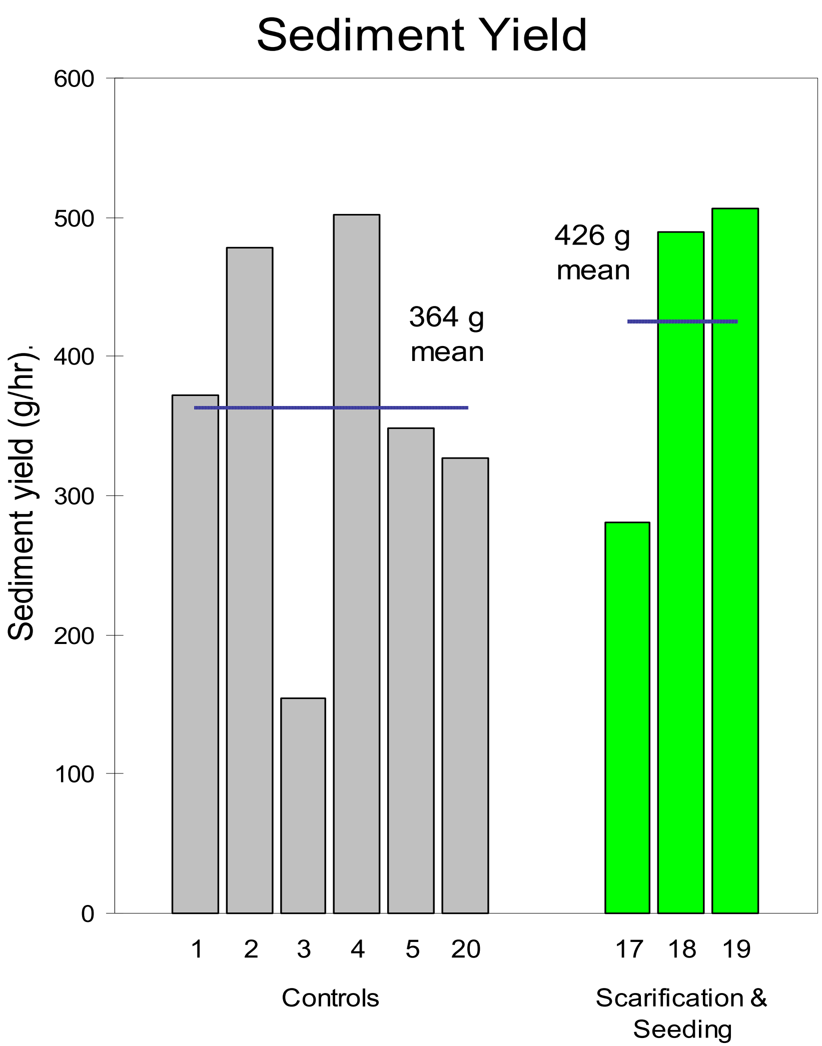


Sediment yields for control plots vs. seeding and scarifying: Hayman fire, 2002 and 2003



Runoff and Sediment Yields from Simulations on Seeded and Scarified Plots: Hayman Fire, 2003

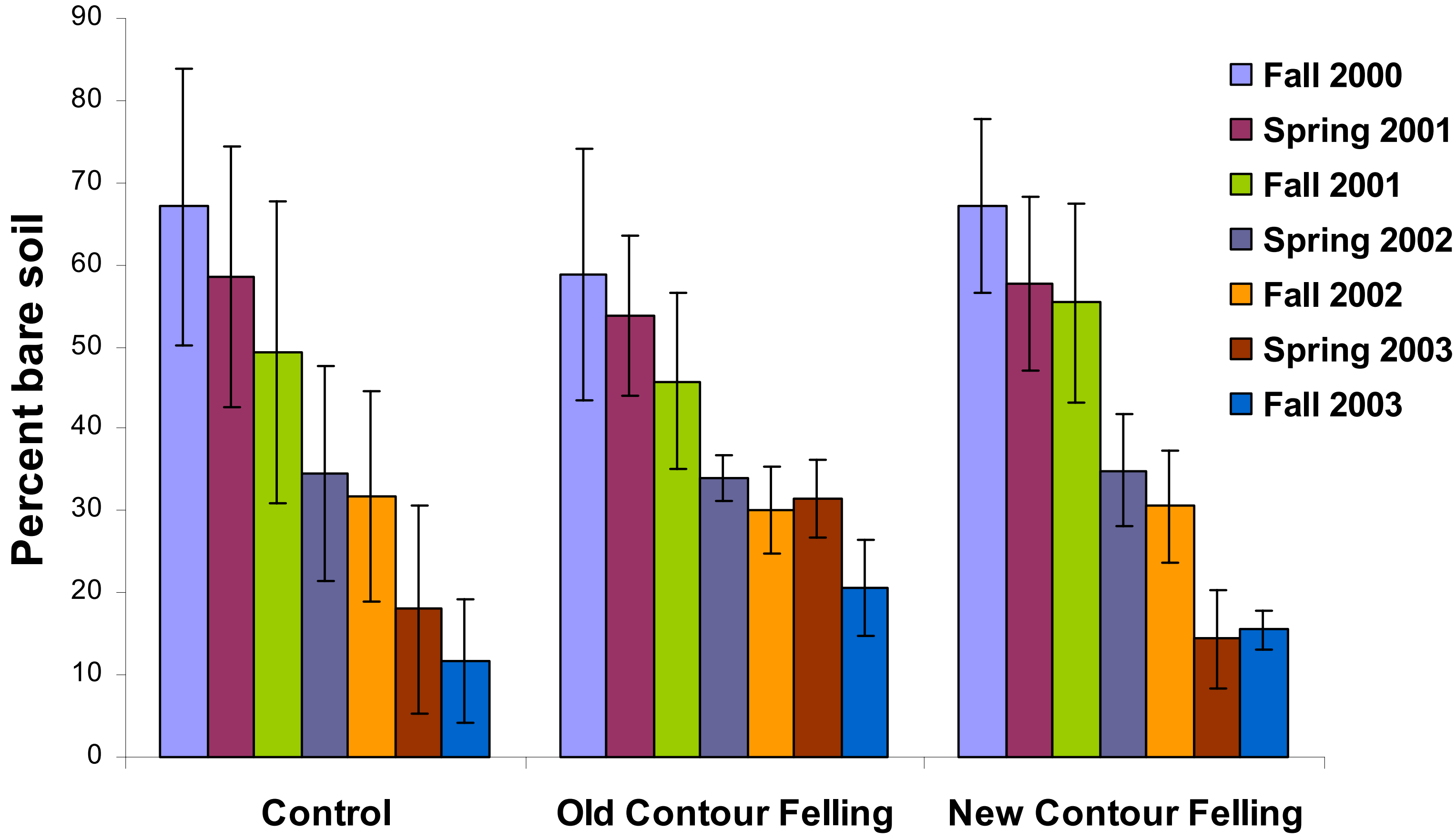




Seeding: Summary

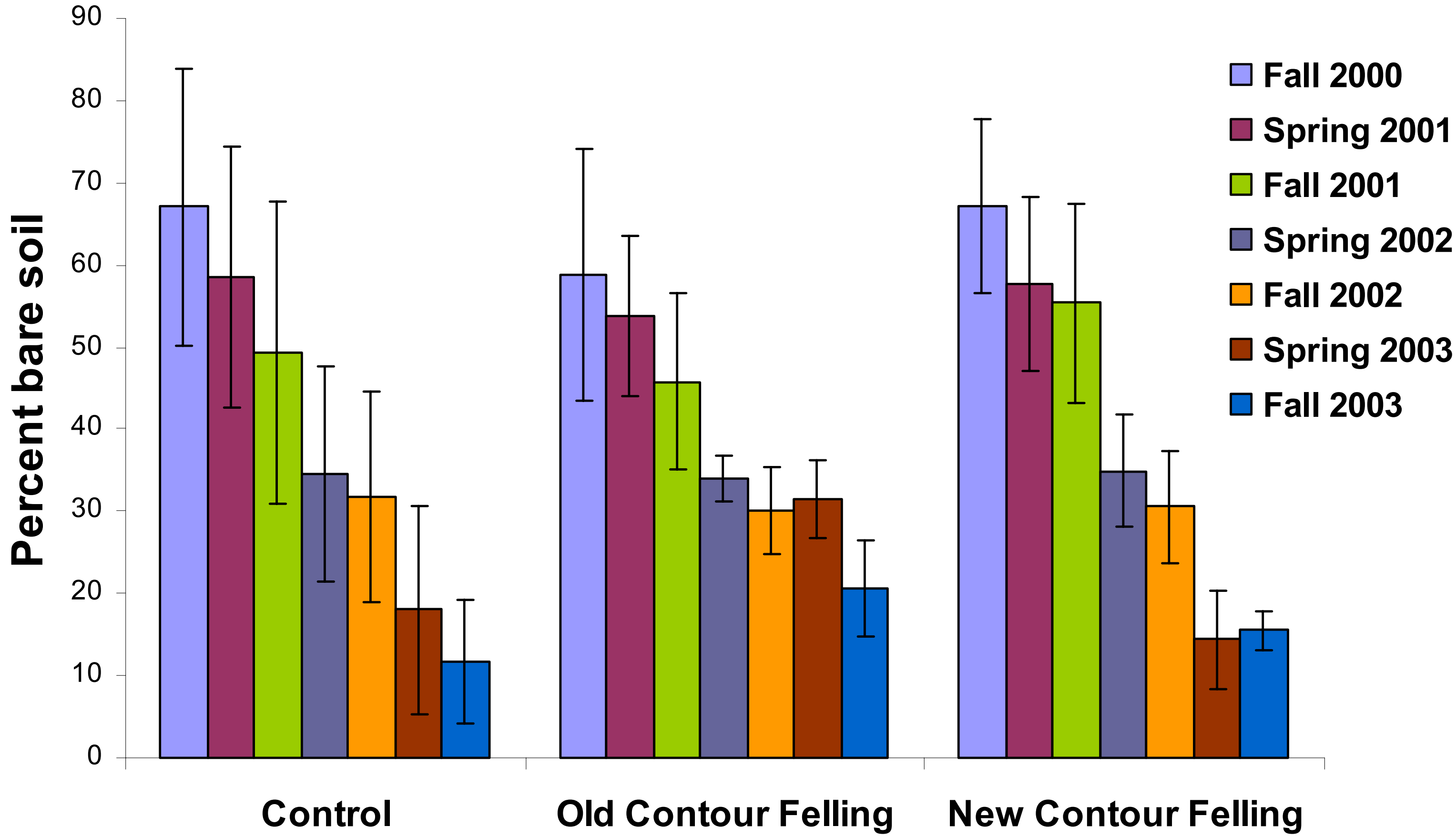
- Uneven seed distribution;
- Depth of scarification probably too shallow to break up water repellent layer;
- No evidence that it increases cover;
- No evidence that it reduces erosion;
- Surface runoff can redistribute seeds;
- Need ideal sequence of storms and lack of natural regeneration for seeding to be effective.

Changes in percent bare soil on contour-felled plots: Bobcat fire, 2000-2003

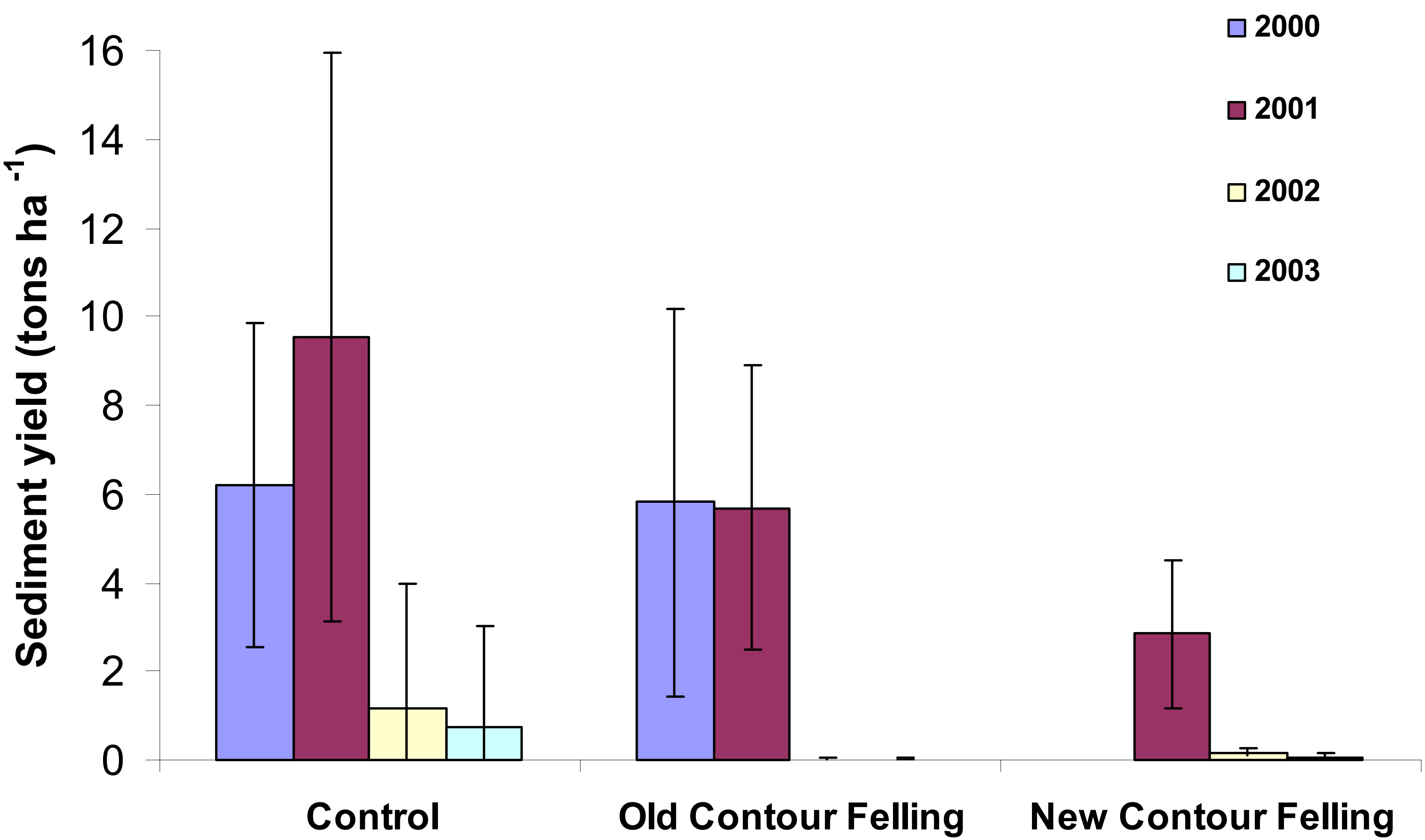



Contour Felling

Percent bare soil on contour-felled plots: Bobcat fire, 2000-2003



Sediment yields on contour-felled plots: Bobcat fire, 2000-2003

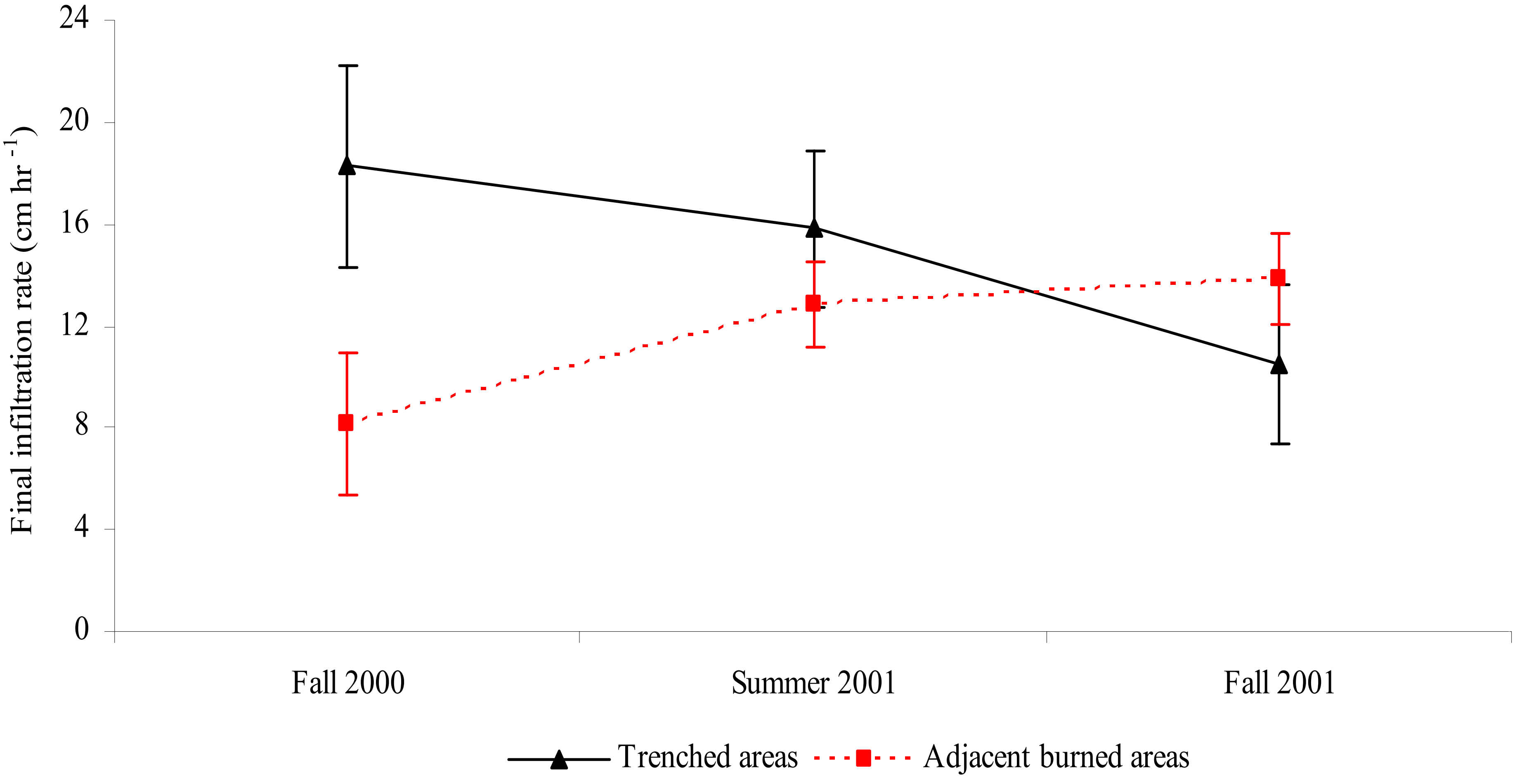


Contour-felling Effectiveness

(values in red are minimums, values in blue are maximums)

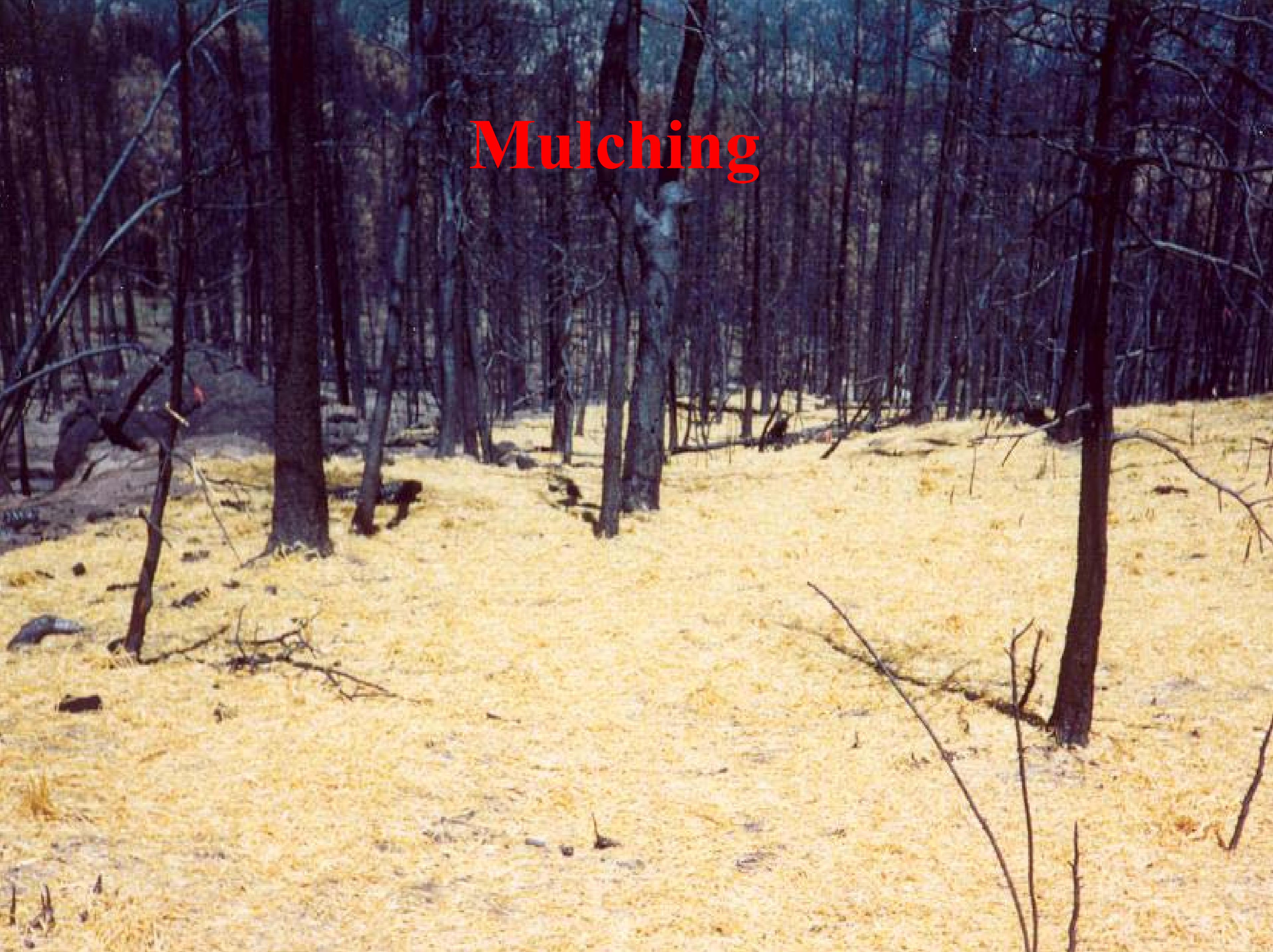
Site	Mean value for each site			Total failures (percent)	Site storage capacity (m^3 ha^{-1})
	Log density (m log ha^{-1})	Log length (m)	Log diameter (m)		
Bobcat	161	5.6	0.25	27	6.8
Galuchie	147	4.4	0.27	27	7.2
Spruce	538	6.6	0.25	10	18
Eldorado B-1	939	3.2	0.18	27	12
Eldorado G-1	855	2.9	0.19	23	29
Hi Meadows HST-3	776	5.8	0.20	40	32
Hi Meadows HST-2	1,310	6.2	0.23	70	9.0
Overall mean	**676**	**5.0**	**0.23**	**32**	**16**

Infiltration rates over time, Bobcat fire

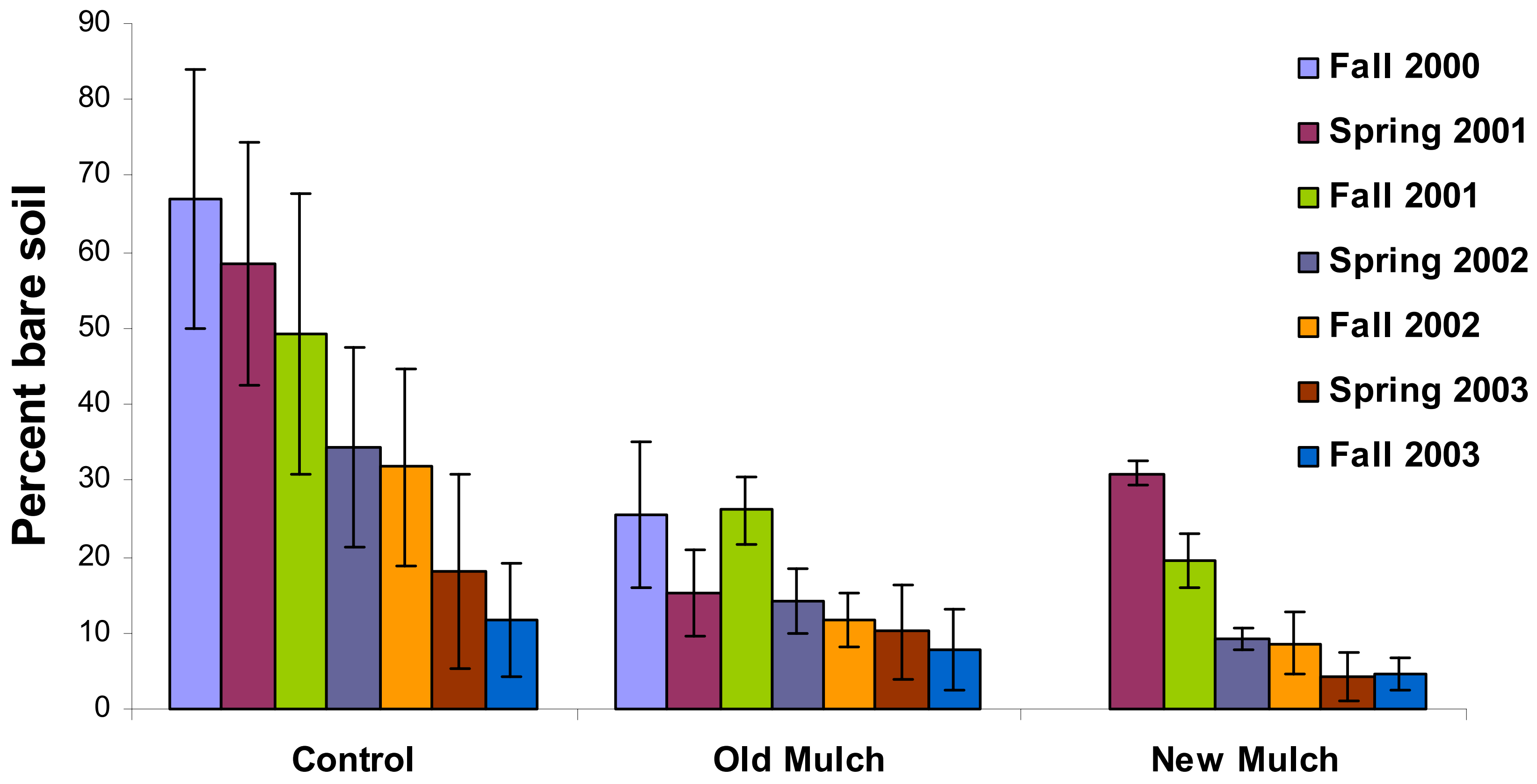


Contour-felling: Summary

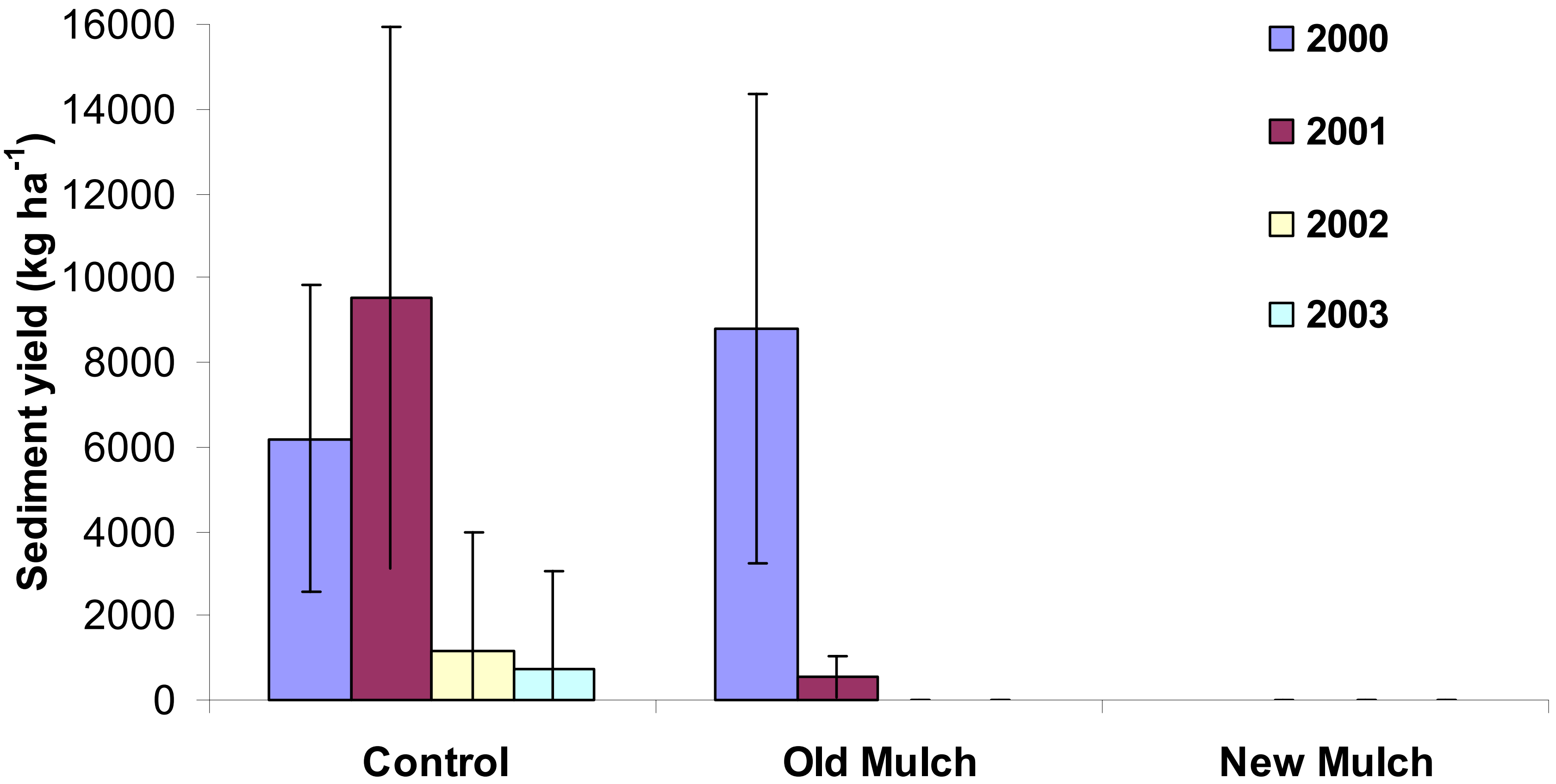
- Increase in infiltration capacity short-lived and limited in area;
- Potential to capture only 2-3 mm of runoff;
- Wide range of potential sediment storage values varying with:
  - Size of contour-felled logs;
  - Density of contour-felled logs;
  - Quality of installation;
- Could potentially capture most of sediment from an average summer;
- Poor installation can increase rill erosion;
- Not very cost-effective.


Mulching

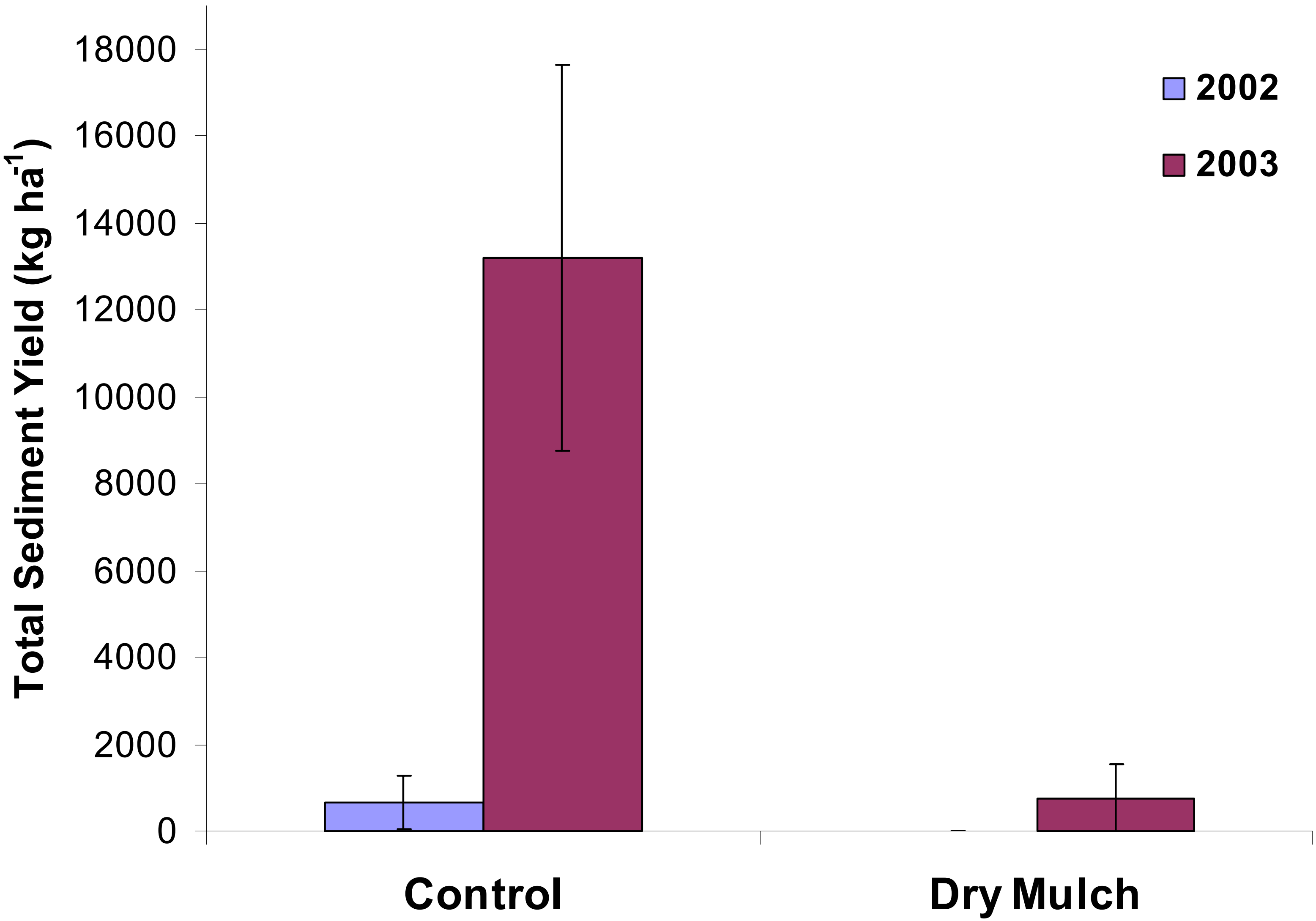
Percent bare soil on control and mulched plots: Bobcat fire, 2000-2003



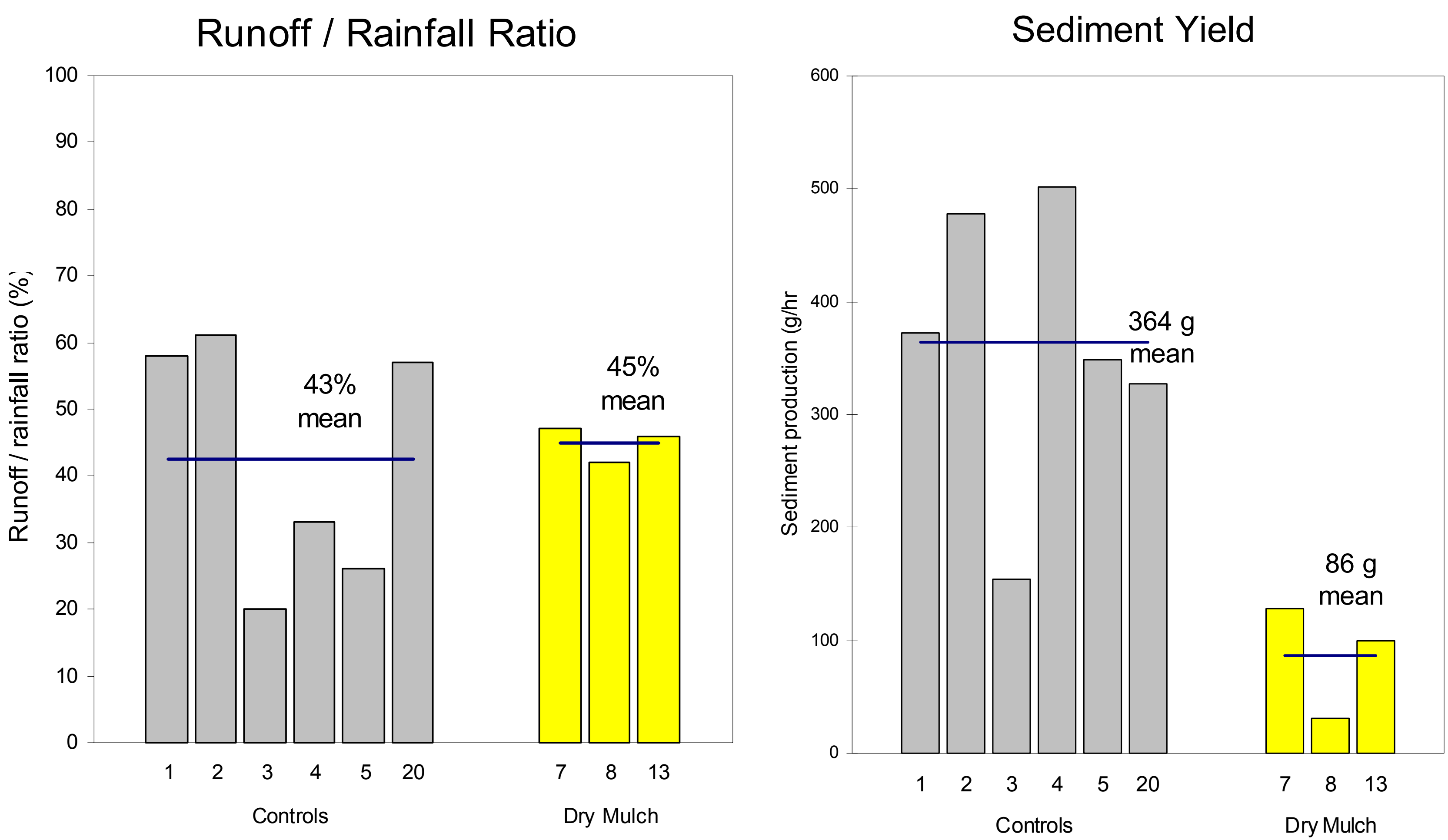
Mean sediment yields on control and mulched plots: Bobcat fire, 2000-2003



Mean sediment yields on control and mulched plots: Hayman fire, 2002-2003

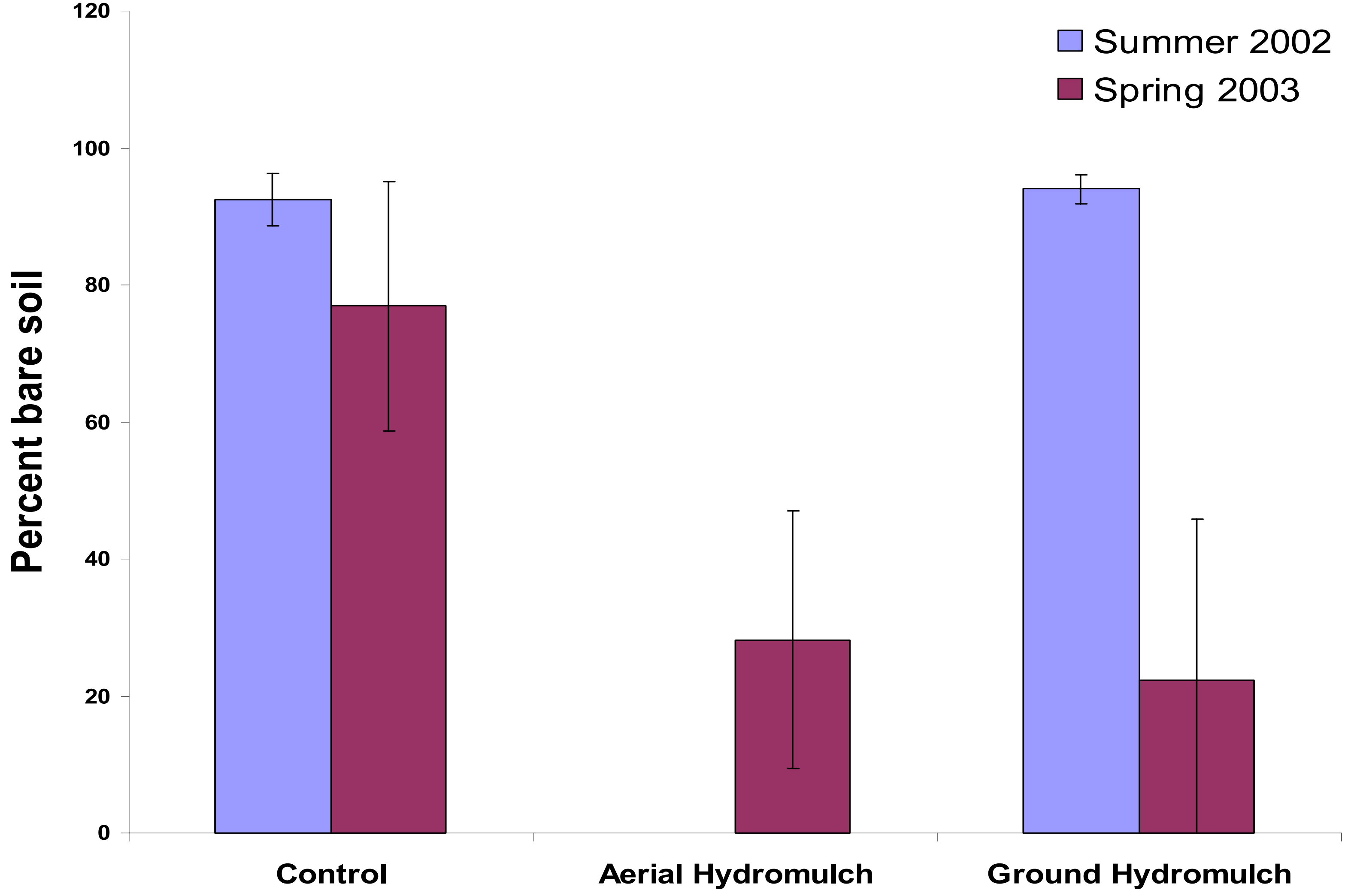


Runoff and Sediment Yields from Rainfall Simulations on Control and Mulched Plots: Hayman Fire, 2003

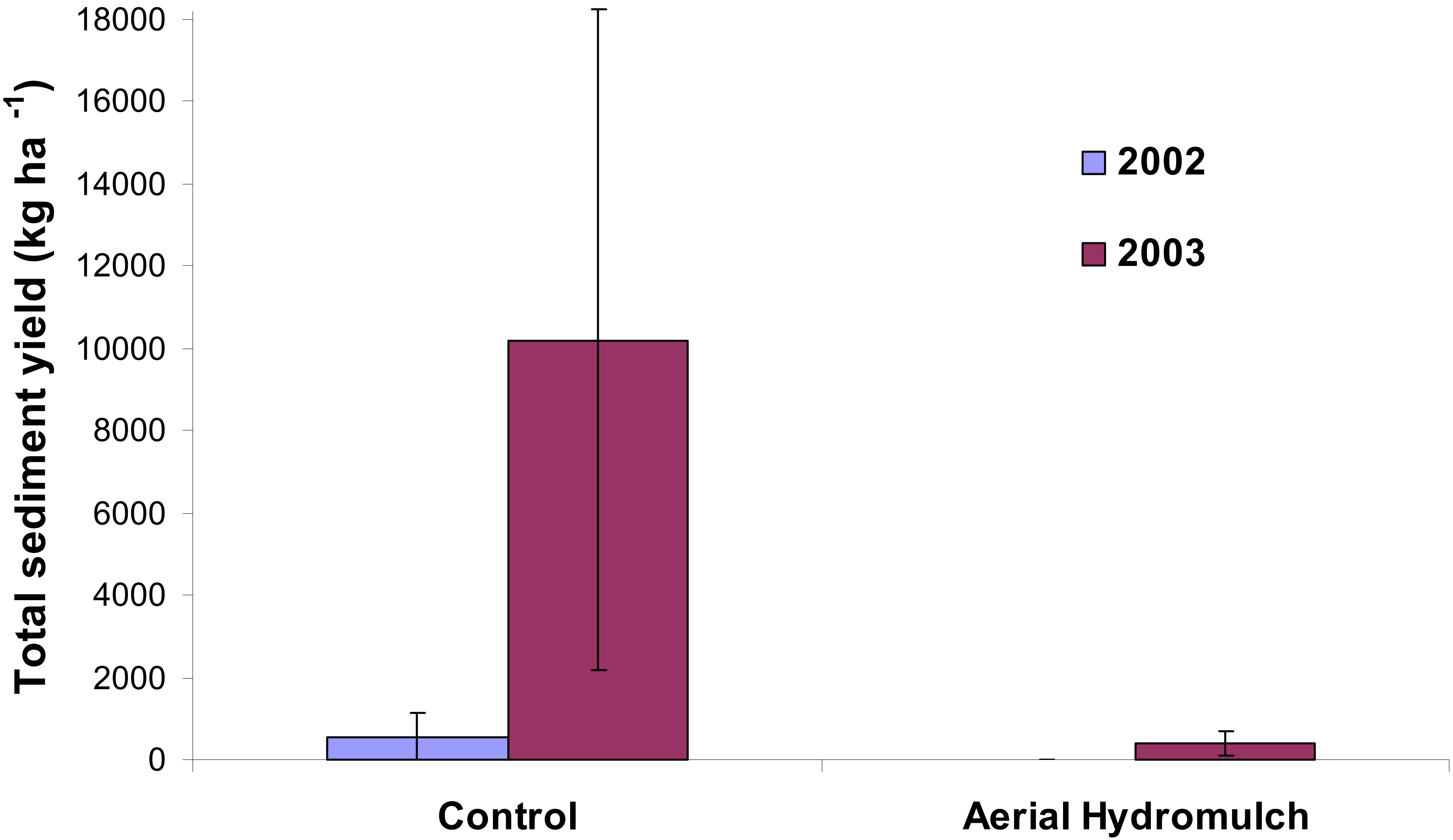



Hydromulching

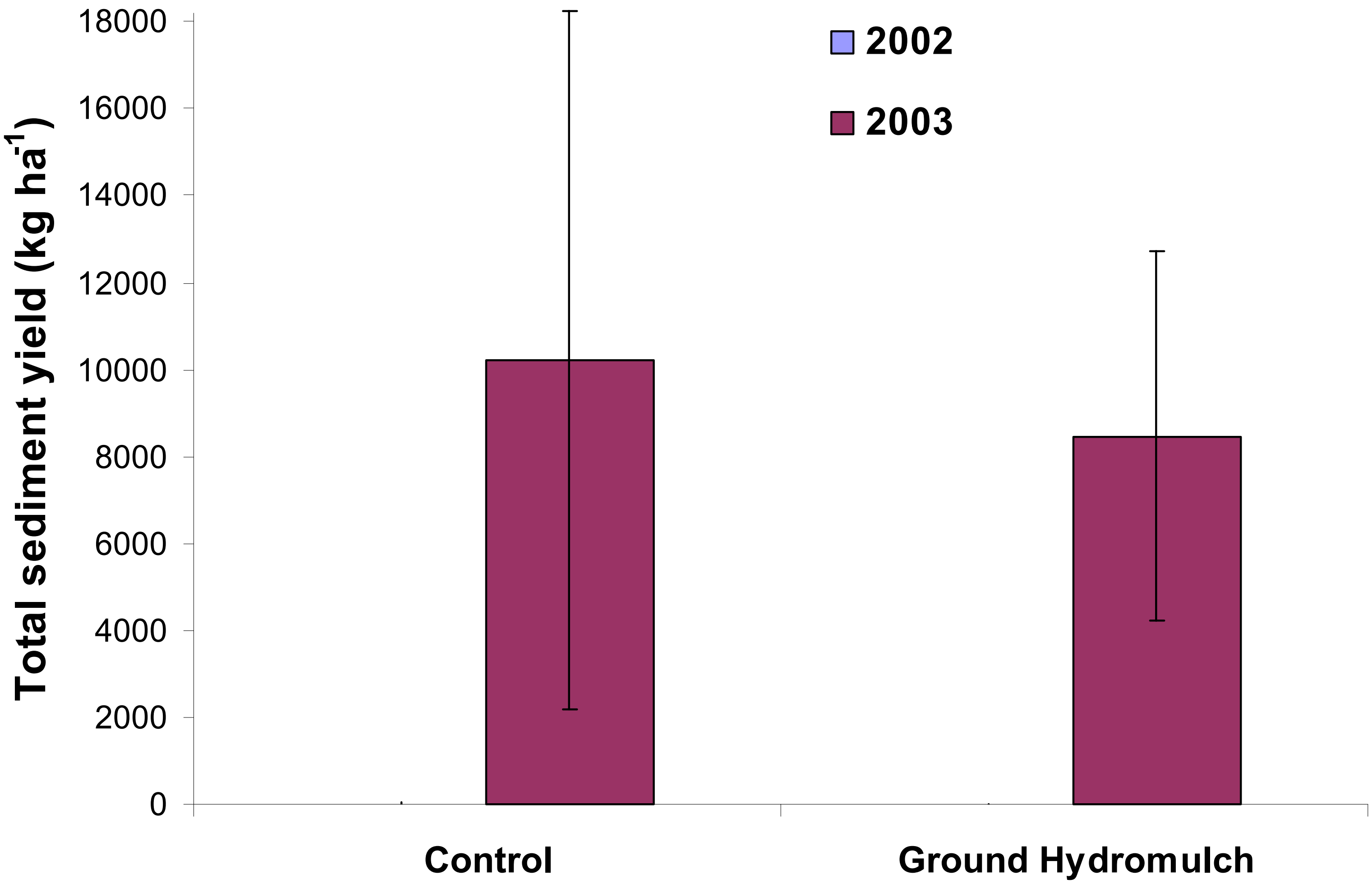
Percent bare soil for aerial and ground hydromulch: Hayman fire, 2002 and 2003



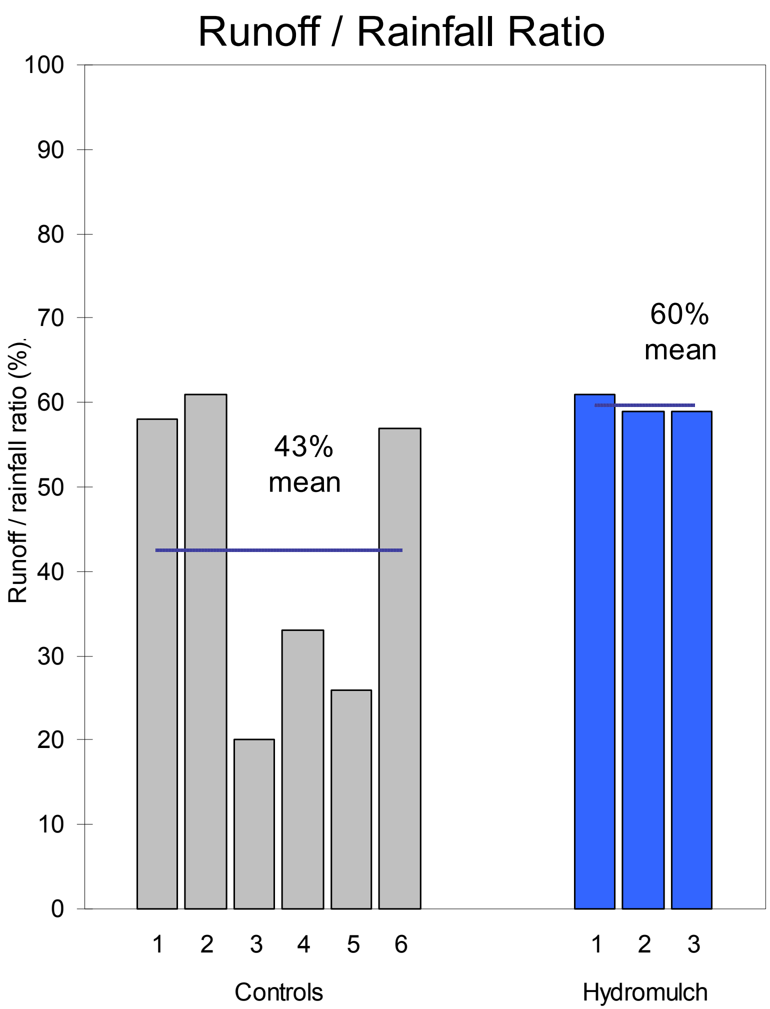
Sediment yields for aerial hydromulch: Hayman fire, 2002 and 2003

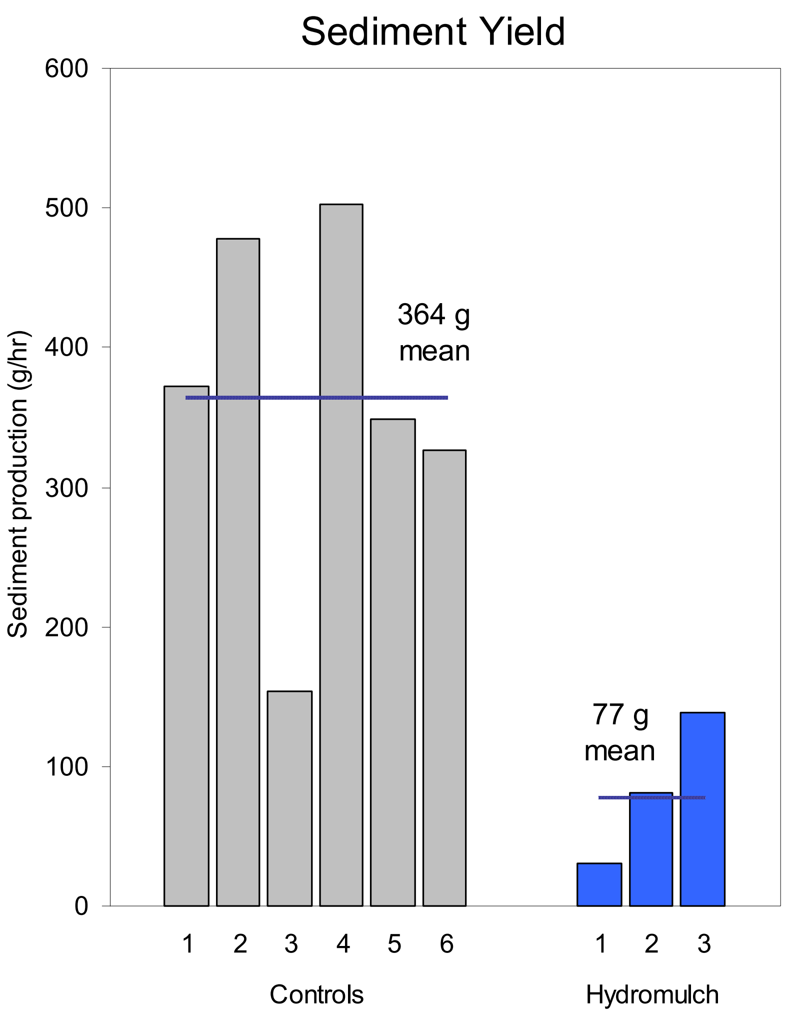


Sediment yields for ground hydromulch: Hayman fire, 2002 and 2003



Hydromulch
Rainfall Simulations, Hayman Fire





Why is percent cover so important, and mulching so effective?

- Provides immediate cover to reduce rainsplash and overland flow velocities;
- May reduce soil water repellency by increasing soil moisture;
- May improve germination;
- May reduce rill erosion.

→ Effectiveness probably decreases with increasing storm size;

→ Aerial application may provide reasonable cover.

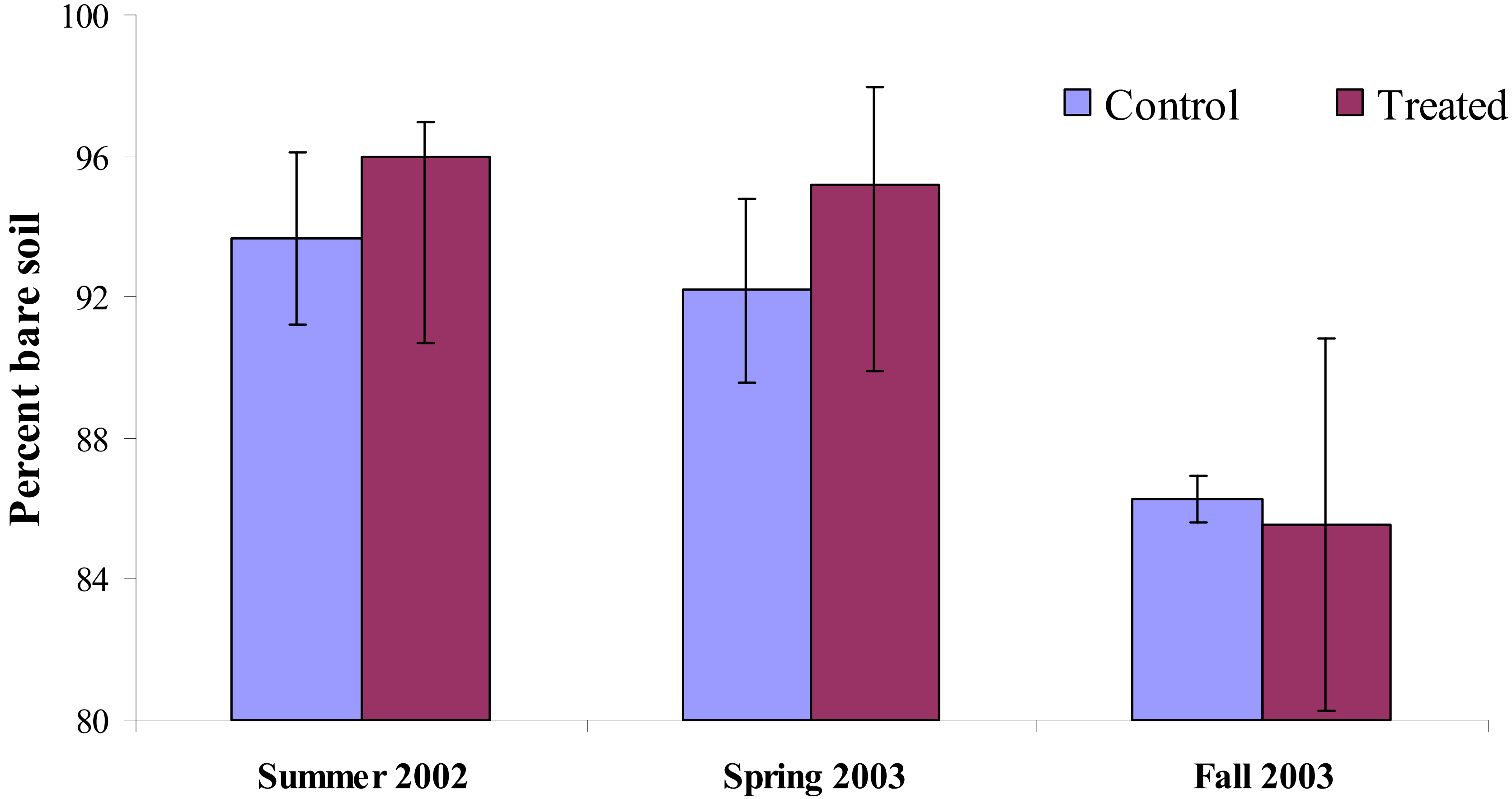
Soil Binding Agents: Polyacrylamide (PAM)

Extensively used to reduce furrow erosion and flocculation in water treatment;

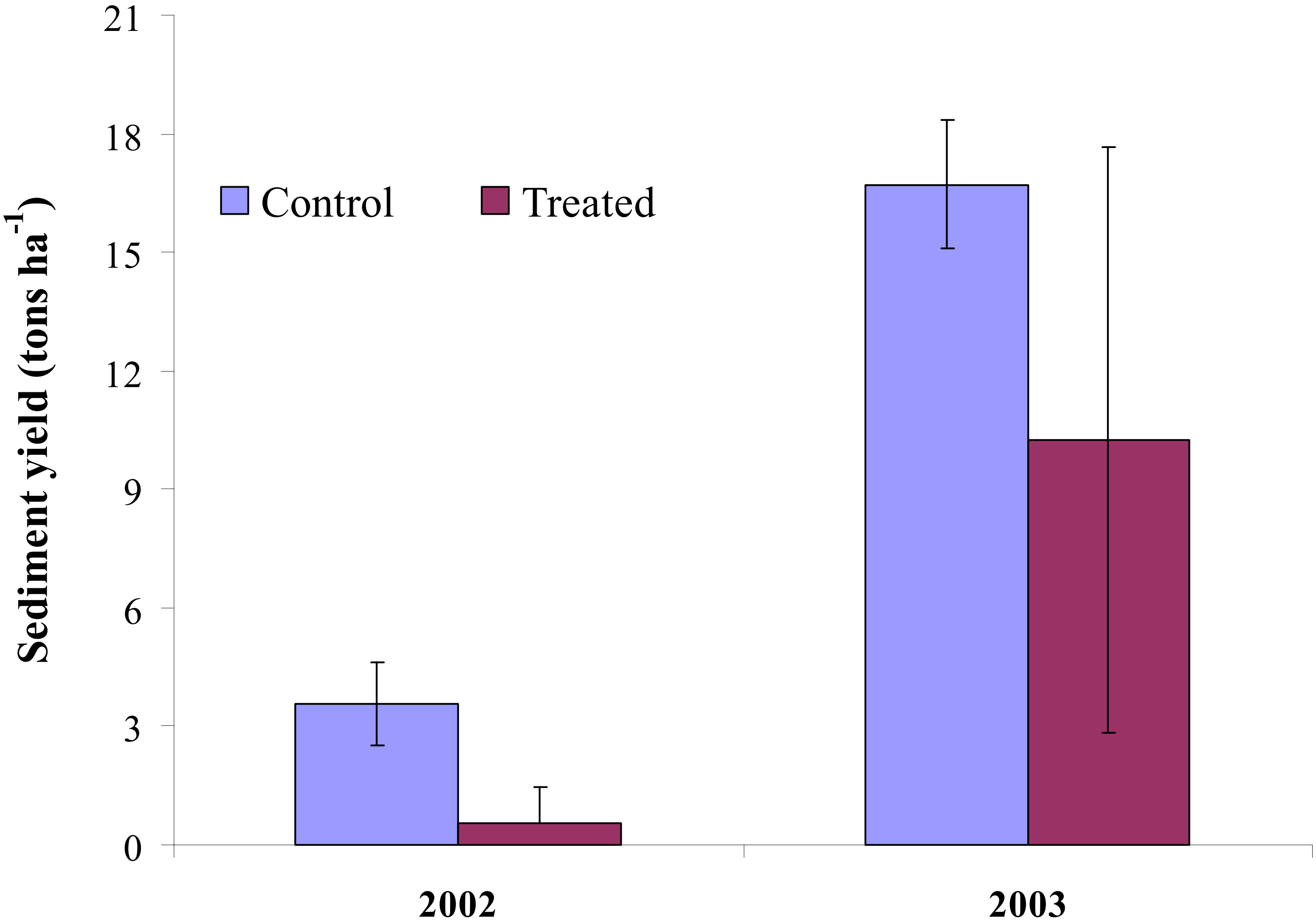
Many different types for different purposes;

Testing micronized, anoinic, long-chain polymer.

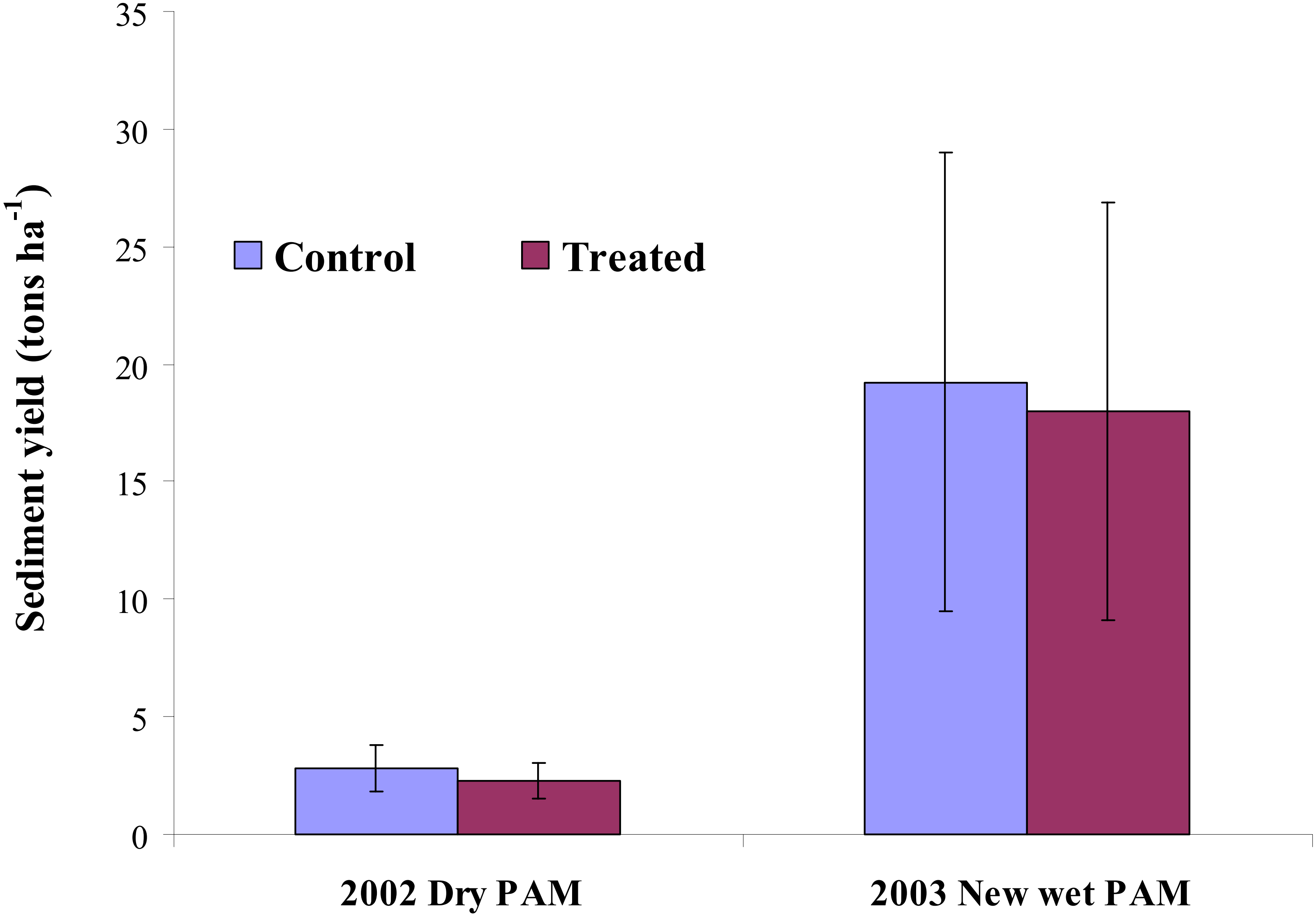
Percent bare soil changes for PAM treated swales: Schoonover fire, 2002 and 2003



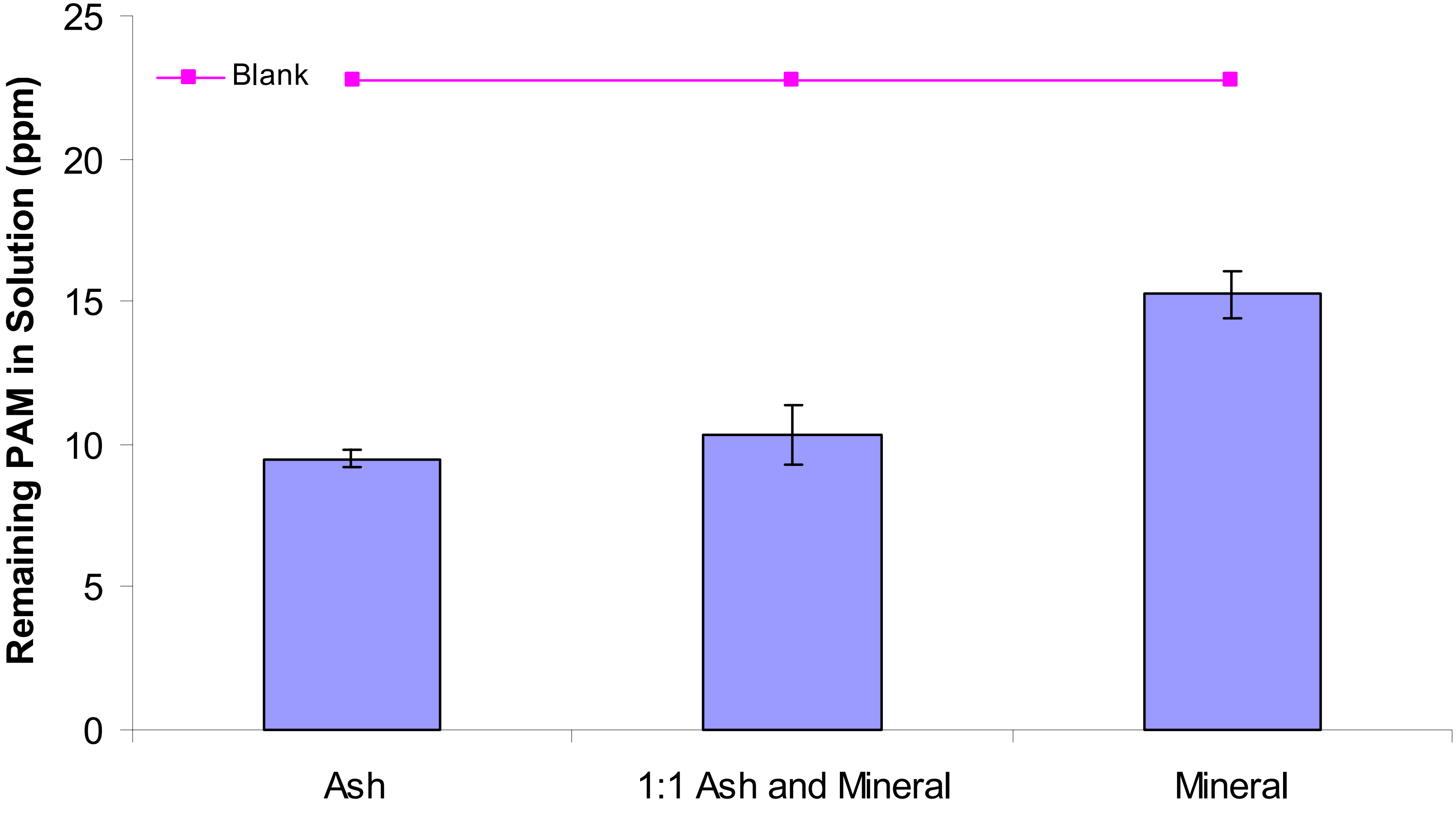
Sediment yields for wet PAM treatment 2002-2003



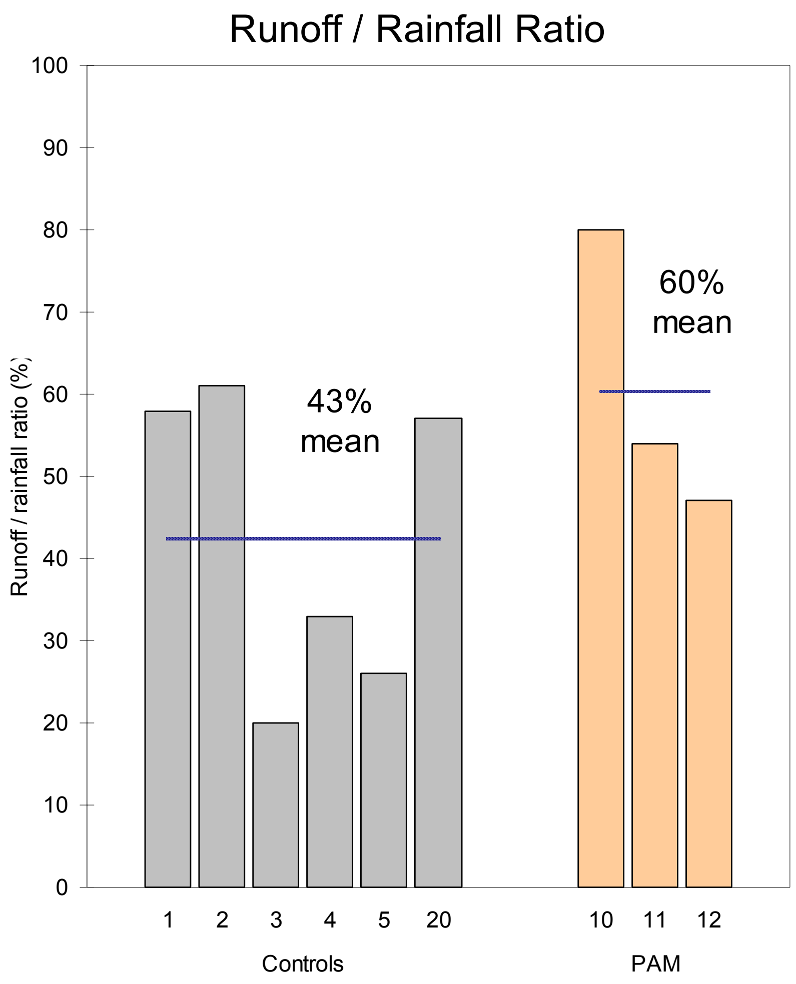
Sediment yields for dry and new wet PAM treatments 2002-2003

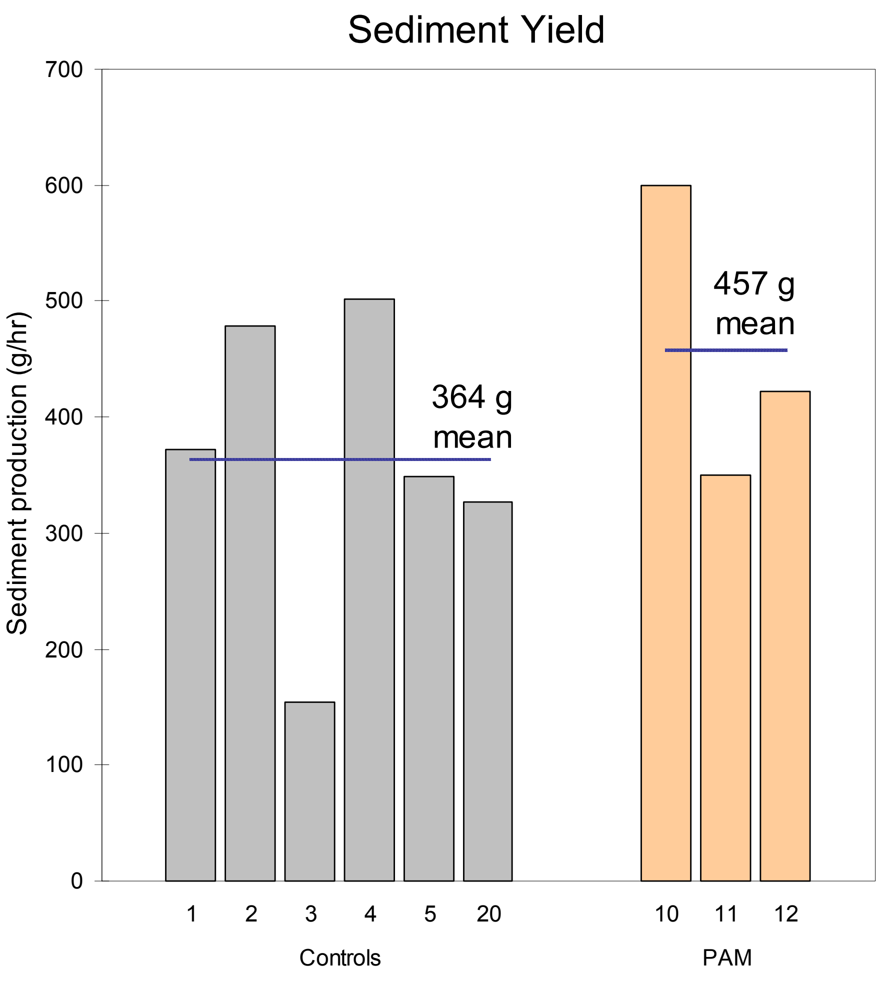


PAM attenuation in ash and mineral soil samples



PAM Treatment
Rainfall Simulations, Hayman Fire





Effectiveness of PAM: Summary

- Potential chemical interaction with ash;
- Wet formulation probably more effective than dry;
- May be most effective when mixed with hydromulch;
- Effectiveness complicated by:
  - Different formulations;
  - Different means of applications;
  - Different rates of application;
  - Effects of soil texture and ash.


Hay Bale Check Dams

Hay Bale Check Dams

- Extensively used on construction sites;
- Generally more difficult to effectively treat downstream areas than source areas;
- No quantitative data being collected, but could estimate sediment storage capacity and compare to erosion rates on untreated sites;
- Need explicit study to evaluate effectiveness.

Will the hillslope and catchment scale recover at similar rates?

Conclusions (1)

- High-severity wildfires increase runoff and sediment production rates by several orders of magnitude;
- Summer rainstorms rather than snowmelt cause virtually all of the post-fire erosion;
- Sediment production rates from high-severity sites are nearly an order of magnitude higher than sites burned at moderate or low severity;
- Sediment production rates are high in the first two summers after burning, and rapidly decline to near-background levels except in sites with exceptionally coarse soils;

Conclusions (2)

- Percent ground cover is the most important control on post-fire erosion rates;
- Rainfall erosivity, topographic convergence, and soil texture are other important controls on post-fire erosion;
- Dominant erosion process is rill incision rather than sheetwash on hillslopes;
- Soil water repellency is too short-lived to account for the observed increases in sediment production; is soil sealing the primary cause of continued high runoff and erosion rates?

Conclusions (3)

- Empirical models can predict about 60-75% of the variability in sediment production rates;
- Validation tests indicate that simple empirical models perform nearly as well as complex models, but uncertainty is still ± about 0.7 log units (± 3-4 times);
- Seeding and scarification do not increase ground cover or reduce erosion rates. Mulching is the most effective post-fire rehabilitation technique as this immediately provides ground cover.


Questions?