Final report

Multi-spectral remote sensing of brush fire scars in arid urban regions: analysis of future fire and flooding hazards

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Research problems

Partitioning precipitation between infiltration and runoff and the movement and convergence of that runoff over the land surface strongly depend on the mechanical properties of that surface. Not only is the infiltration capacity important, but also its roughness can diminish the rate of flow. These surface conditions will be strongly altered as a result of a fire. Significant research on the effects of fire in humid-temperate systems (forests) has shown that indeed the runoff and sediment transport regime changes because of fire (e.g., Meyer, et al., 1992; Cannon, et al., 2001, Cannon, 2001). Such changes can come directly from fire (vegetation removal; burning of litter, production of duff, changes in rock properties from extreme heat), fire fighting (bull dozing and plowing), or changes triggered by those direct effects. Studies of fire damaged areas in chaparral landscapes in California and Spain showed that sediment transport rates from small catchments also generally increase following burns (e.g., Flosheim, et al., 1991 and Brown, 1990). While fuel loads in deserts are lower, brush fires there can be significant. In particular, continuing urban growth in places like Phoenix, AZ increase the exposure of the urbanized fringe to the direct and indirect effects of brush fires.

In this project, we addressed a number of research questions. Those related to fire behavior and the geomorphic responses to brush fire in arid systems are:

1) What are the factors that control the timing and behavior of desert brush fires and what is the importance of the proximity of the urban fringe?
2) Given the high variability in surface process rates and the relatively low fuel loads in desert environments, what are the geomorphic effects of brush fires and what are the implications for flood hazards?

Study area

Because a number of fires had occurred along the northeastern urban fringe of the Pheonix area and because of the availability of data there, we focused our efforts on the area shown in Figures 1 and 2. Figure 2 is a Landsat image of the area north of the McDowell Mountains and east of North Scottsdale showing areas of major brush fires since 1988. Those major fires include the Carefree, Pinnacle, Camp, Buckhorn, Dynamite, and Rio events. We focused significant effort along the northern edge of the Rio fire scar in the McDowell Mountain Park. The area is one of numerous firefighting jurisdictions with US Forest Service, Arizona State Lands, the US Bureau of Land Management and numerous municipal entities all involved.

Methods

Fire reporting from various agencies

In order to better characterize the occurrence of fires in the study area and beyond, we contacted the major fire fighting agencies with jurisdiction in the area: US Forest Service, US Bureau of Land Management, and the Arizona State Lands Office. We received more overall data from the BLM, but the USFS were more detailed. The Arizona State Lands Office data came from their prime fire fighting contractor: Rural-Metro and were somewhat incomplete. The data cover the period from 1962 to 1998, but is not complete for all of that period. BLM reported 172 fires, ASL reported 16, and the USFS reported 30 fires during this period in the study area (note that the BLM data cover all lands in Arizona). Our major efforts were then to merge the datasets and to characterize them. See Figure 3 and the results section below.

Aerial photography

We flew over the study area in order to better document the relationship between the geography and the fire scars. Figure 4 shows two views of fire scars on the north western side of the McDowell Mountains.

Balloon photography

In order to better document the geometry, landforms, and vegetative differences of burned and unburned portions of the landscape, we employed low altitude vertical aerial photography from helium balloon platforms (Figures 5 and 6). This system includes a remotely triggered camera suspended about 10m along the line from the balloon. These high resolution images are quite valuable at bridging the resolution gap between our ground observations and those from aircraft or satellite.

Important urls for reference include:

http://activetectonics.la.asu.edu/kites/balloon.html (Balloon photgraphy overview)

http://activetectonics.asu.edu/Fires_and_Floods/10_24_00_photos/, http://activetectonics.asu.edu/Fires_and_Floods/6_13_01_photos/, http://activetectonics.la.asu.edu/Fires_and_Floods/6_14_01_balloon, http://activetectonics.asu.edu/Fires_and_Floods/6_14_01_balloon2/, http://activetectonics.asu.edu/Fires_and_Floods/07_03_01_Photos/, http://activetectonics.asu.edu/Fires_and_Floods/8_25_01_photos/, http://activetectonics.asu.edu/Fires_and_Floods/2002/MMPBalloonforweb/ (Balloon photography of fire scars).

Analysis of sediment movement

In order to assess any differences in sediment flux and type between burned and unburned catchments, we installed 8 sediment traps (3 on burned and 5 on unburned sites) at the McDowell Mountain Park study site (Figures 2 and 6). The underlying geology across the burn edge that we studied is the same: a Plio-Pleistocene well inderated granitic sourced alluvial fan gravel and sand unit. Figure 7 shows the design of the devices. These traps were monitored and materials collected over the course of monsoon and winter runoff events. Monitoring continues and the information so far gathered provides an important baseline for future studies.

Topographic analyses

Our field observations suggested to us subtle differences in the landscape structure that we tried to quantify topographically. The first activity was a high resolution topographic survey (>6900 points over a 10^4 m^2 area) using a Real Time Kinematic GPS system in the area of the Cave Creek fire spanning the fire scar edge (Figures 2, 8, and 9). The second was a detailed study of landscape curvature versus regolith thickness at the McDowell Mountain Park study site (Figure 2).

Results

The geography and temporal activity of brush fires in central Arizona

Figure 3 shows the US Forest Service, US BLM, and Arizona State Lands (ASL) fire report data for the Greater Phoenix area. These data are generally complete from 1962-1998. Most fires are less than 100 acres and thus are shown as points. The larger fires in the northeast Phoenix/Scottsdale area are shown with outlines (compare with Figure 2 and note that the Rio fire was not recorded in these databases). The majority of the fires occur in the urban fringe and to the north where elevations are higher and thus fuels are increased. We examined the timing, cover, elevation, aspect, and causes of these fires.

- Timing. Figure 4 and Table 1 show the number of fires for each reporting year. Prior to about 1980, there were less than 5 fires reported each year. While this may result from incomplete reporting, it may also indicate a decreased influence of direct urbanization-related triggers or land use changes. Many of the big years for fires after 1980 were also in El Nino periods (1982-1983, 1994-1995-Largest fire in this time-Rio). Most fires were also reported in the afternoons (when it was the hottest and presumably when they were triggered or fast moving).

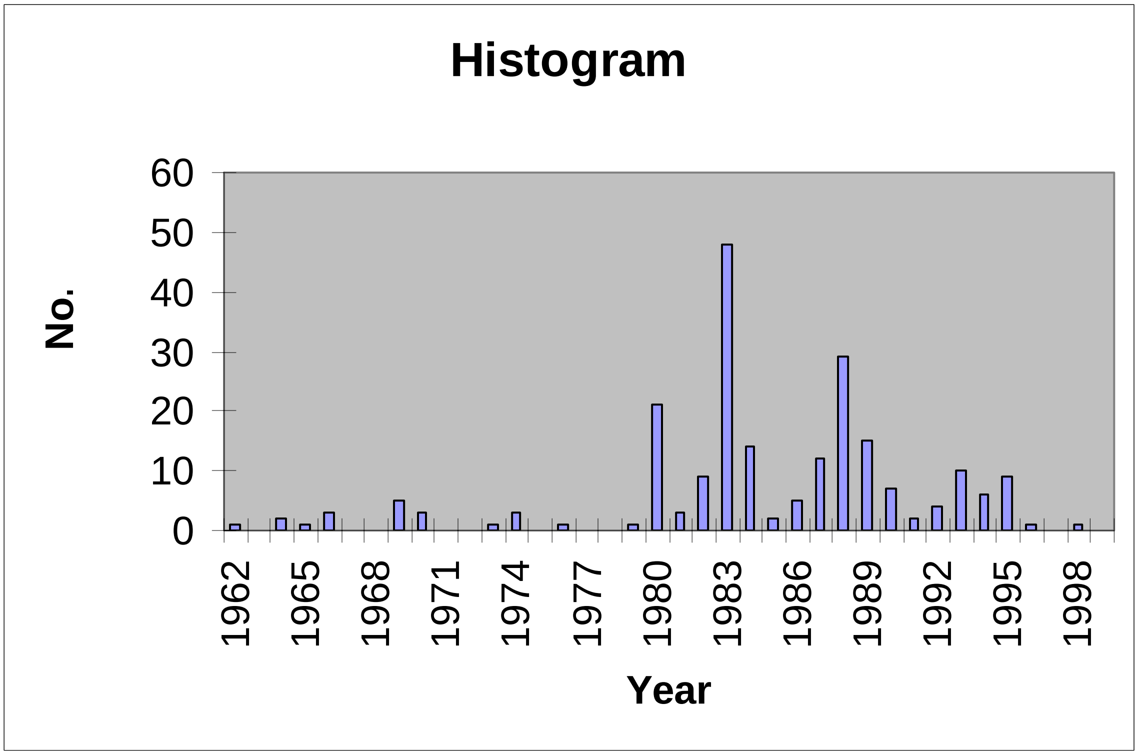


Figure 4. Number of fires reported per year by USFS, BLM, and ASL combined.

Table 1.. Number of fires reported per year by USFS, BLM, and ASL combined.

- Cover

USFS is the only agency that reports cover, but 14 fires were on grass while only 7 for which the information was recorded occurred in the cover type brush. The most common fuel types that were noted were grass, and sagebrush with grass.

- Elevation

The majority of fires reported are within the 1501 to 3500 feet elevation categories. This probably correlates with the elevation of the fringe area and recreational areas and the human-ignited fires. See Table 2.

Table 2. Number of fires versus elevation classes reported by USFS, BLM, and ASL combined.

	Elevation	*No. of Fires*
501-1500	1	2
1501-2500	2	9
2501-3500	3	9
3501-4500	4	4
4501-5500	5	4
5501-6500	More	2

- Aspect

The most common aspects reported for the fires were southwest and west. This could be potentially attributed to two things: prevailing winds in this area are WSW; and the slopes facing civilization have a WSW aspect. See Table 3

Table 3. Number of fires versus aspect classes reported by USFS, BLM, and ASL combined.

	Aspect	*No. of Fires*
Flat	0	3
North	1	3
Northeast	2	0
East	3	3
Southeast	4	0
South	5	4
Southwest	6	7
West	7	6
Northwest	8	2
Ridge	9	2
	More	0

- Cause

Year	*No. of Fires*
1962	1
1963	0
1964	2
1965	1
1966	3
1967	0
1968	0
1969	5
1970	3
1971	0
1972	0
1973	1
1974	3
1975	0
1976	1
1977	0
1978	0
1979	1
1980	21
1981	3
1982	9
1983	48
1984	14
1985	2
1986	5
1987	12
1988	29
1989	15
1990	7
1991	2
1992	4
1993	10
1994	6
1995	9
1996	1
1997	0
1998	1
More	0

The most common cause for fires was lightning (Table 4). Heavy monsoon related lighting activity is a reasonable expectation for the area. However, as Table 4 shows, almost all other reported causes were human-related. Lumping them, there were 19 human-caused fires and 21 total “natural” fires with 7 undetermined. This observation dilutes to some extent the inference of direct interaction with the urban fringe to trigger more fires. However, changes in land use and land cover due to human activity (and thus increased grass cover) are indirectly related to the proximity of the urban environment.

Table 4. Number of fires versus causes reported by USFS, BLM, and ASL combined.

	Cause	*No. of Fires*
Campfire	1	1
Equipment	2	1
Escaped fire	3	1
Exhaust	4	1
Fireworks	5	1
Harvesting	6	1
Lightning	7	19
People	8	6
Power lines	9	2
Recreation	10	1
Smoker	11	5
Trash burning	12	1
Undetermined	13	7

- Anecdotal information about the desert brush fires from interviews with Fire personnel

We interviewed staff from Maricopa County, Arizona State Lands (Scott Hunt (Phoenix District Forester) and David Behrens (Fire Management Officer)), USFS (Tim Bos (Fire Management Officer)), and BLM (Mike Fisher (Fire Management Specialist)). Major points that they made about the brush fires in this area include:

1) Usually human-caused (some arson, cigarettes).
2) Lots of annuals, especially grass is the major indicators of brush fire risk in the desert. A fire will move through, clear the native vegetation, and the replacement vegetation will be exotics (Cheatgrass/Junegrass) which regrow rapidly, are very flammable, and can reburn. Wet winters followed by lots of growth are big fire years.
3) The fires may go out at night, especially if the dew point is >30.
4) Fire fighting tactics try to employ roads or other natural boundaries. They typically use hand crews or put a single on a fire. They try not to use heavy equipment. A bulldozed "Cat Line" will last for a long time in the desert environment. They often use a small plane or helicopter for suppression.
5) These areas are low fuel and "offer low to medium resistance to control."
6) There is almost no prescribed burning in these environments because there can often be too much build up of fuel for safe prescribed burning.
7) There is a conflict among the greater populace between concerns about air quality and smog and fires also about letting fires burn versus preserving the fragile desert.

8) Fuels persist in the dry climate.
9) From their perspective and experience, there was no clear association between fire effects and obvious geomorphic processes (esp. flooding or debris flows).
10) These fires are important because of the high value of the lands that are burn from a scenic standpoint. For example, the Troon fire (July 1995) decreased some lot values by 20%. The wildland/urban interface is a location of high scenic value.
11) Hazard of burning is seasonally dependent on the annual fuel loads. The risk depends on the ignition sources which goes up as the number of people.
12) While many ecosystems naturally depend on the regular occurrence of fire, the Sonoran/Mojave desert systems do not. However, the exotic plants (red brome/cheat grass) hat have been introduced are often fire dependent. This “Type Conversion" will be aided with wetter years and slightly hire elevations, thus further promoting the grass growth and increasing hazard with devastating potential for habitat.

High resolution documentation of fire scar geomorphology and vegetation from balloon-based aerial photography

The high spatial resolution from our balloon photography was valuable at depicting the highly heterogeneous structure of the landscape and the degree to which it was burned. Figures 5 and 6 show several views of the fire scars from this vantage. These images are valuable measures of the sub pixel structure of satellite imagery of these sites. The patchiness of the fire scarring is clear, particularly in Figure 5. Semi-quantitative assessment of these images and field checking of them indicate a higher drainage density on the burnt surfaces, as expected by our hypotheses.

Analysis of sediment movement

The sediment trap data we gathered from the McDowell Mountain Park study site showed an interesting and somewhat unanticipated result that the unburned watersheds produced evacuated more sediment in the events we studied relative to the burned watersheds. These results require refinement with respect to determination of average denudation rate (correction for drainage basin area), but the areas are similar enough that the factor of 2 difference should be significant. We also examined the collected materials with respect to grain size (the burned watersheds produced less clay and the sediments were relatively coarser grained). Finally, the other interesting difference that we observed was that the unburned watersheds produced more organic material (42% vs. 13% of the sediments), and that material was obviously recent (unburned) litter (twigs, leaves, roots). The burned watersheds produced larger and typically burned organic debris including bark, twigs, and sticks.

The sediment transport observations support one of the major conclusions: changes due to fires in the desert system occur early—probably within a year or so of the event. Since that time, the transportable material has largely been stripped and newly produced materials are not easily stored in the burned landscape.

Topographic analyses

Our first topographic analysis was performed by measuring more than 6900 elevation points in an area spanning the edge of the Cave Creek fire scar. Figures 8 and 9 show the site and the observations. In particular, Figure 9 shows a Triangular irregular network (TIN) of surveyed data (white dots) for which we calculated the slopes shown in B. No obvious increase in slope in the burnt portion of the landscape is evident. Future work will include further quantitative analyses of these data to test for differences.

Our second topographic analysis is presented in the attached pdf document (Appendix B: "Curvature and regolith calculations from the McDowell Mountain Park Rio burn fire site"). The hypothesis we wanted to test was that the burned landscape should show relatively thinner regolith for given slope or curvature because of recent flushing of the sediment from the system (immediately following the fire—see comments above about analysis of sediment movement). While our observations are solid, we could not quantitatively differentiate between the two sites. Thus, our intuition and hunch that was developed in the field—and still appears reasonable—is either not really there, or is too subtle for us to measure so far. I suspect that it is the latter, or at least that we have not yet figured out how to measure it.

References

Brown, A. G. (1990). Soil erosion and fire in areas of Mediterranean vegetation; results from chaparral in Southern California, USA, and matorral in Andalucia, southern Spain. Vegetation and erosion; processes and environments. J. B. Thornes, John WIley and Sons.

Cannon, S. H. (2001). "Debris-flow generation from recently burned watersheds." Environmental and Engineering Geoscience **VII**(4): 321-341.

Cannon, S. H., R. M. Kirkham, et al. (2001). "Wildfire-related debris-flow initiation processes, Storm King Mountain, Colorado." Geomorphology **39**: 171-188.

Florsheim, J. L., E. A. Keller, et al. (1991). "Fluvial sediment transport in response to moderate storm flows following chaparral wildfire, Vetura County, Southern California." Geological Society of America Bulletin **103**: 504-511.

Meyer, G. A., S. G. Wells, et al. (1992). ",Response of alluvial systems to fire and climate change in Yellowstone National Park." Nature **357**(6374): 147-150.

Planned publications

Two publications are in preparation from this portion of the project: One summarizing the geomorphologic results (the bulk of this report), and the second emphasizing the geography of these desert brush fires. See Appendix A for a possible outline for the latter. It will emphasize a presentation of the results from the survey of fire report data from the various fire fighting agencies that we performed.

Funded students

The ASU portion of this project had very modest funding available for students. Nevertheless, Mimi Diaz was employed for several months and she assisted in the analysis of the sediment trap data and in the development of the Fire Report database. In addition, Aaron Redman, a high school student, volunteered with us and assisted significantly in some of the balloon photography data collection.

Presentations
The major presentation of this portion of the project is the data-rich web site: http://activetectonics.la.asu.edu/Fires_and_Floods/index.html. This site is full of the raw and interpreted data from much of the project and receives more than 80 hits per month.

Appendix A. Possible outline for manuscript: The geography and timing of desert brush fires

Definitions
- Brush fire
- Rangeland
- Desert

Spatial occurrence (expand to greater Phoenix area?)
- GIS data
  - BLM state wide
  - USFS NE Scottsdale (other fires in Apache Junction area—get from USFS; also look to the south in Gila River/San Tans/Sierra Estrella—maybe there is a real dearth there and that would be interesting)
- RS
  - Initial detection issues

Temporal occurrence
- NE Scottsdale
- BLM statewide

Firefighting practice
- USFS fire reports
- TIMS from Rio fire
- Master from San Diego fire

Causes
- Lightning data
- Yahoo factor (urbanization)
- Association with growth

Effects/recovery
- Vegetation, type (grasses), landcover change
- Geomorphic
- Need to get rain gauge data

Figure 1. Shaded relief of Arizona with 2002 ASTER image of northwest Phoenix showing the encroachment of the urban system on the increasing elevations of the Transition Zone. Our study area and Figure 2's location are indicated by the yellow rectangle.

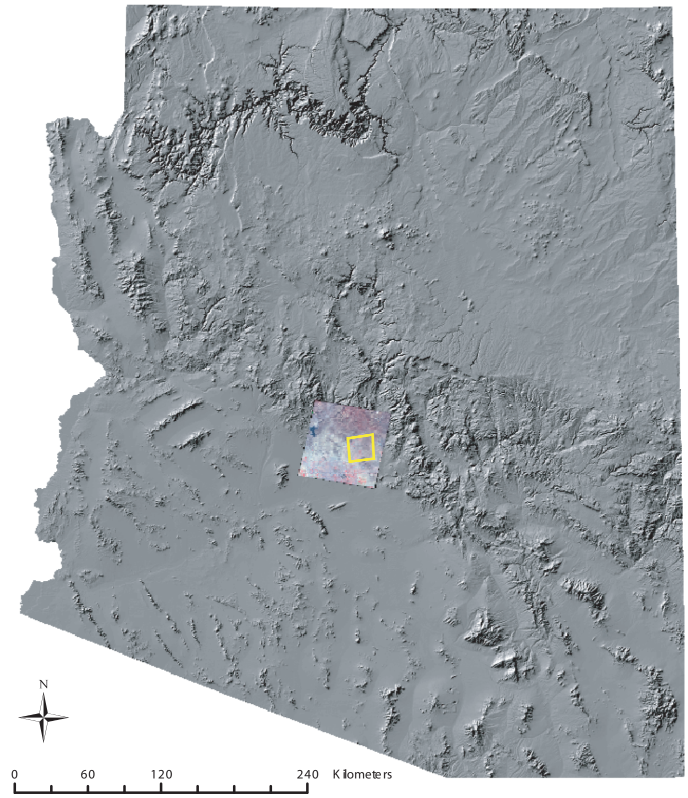
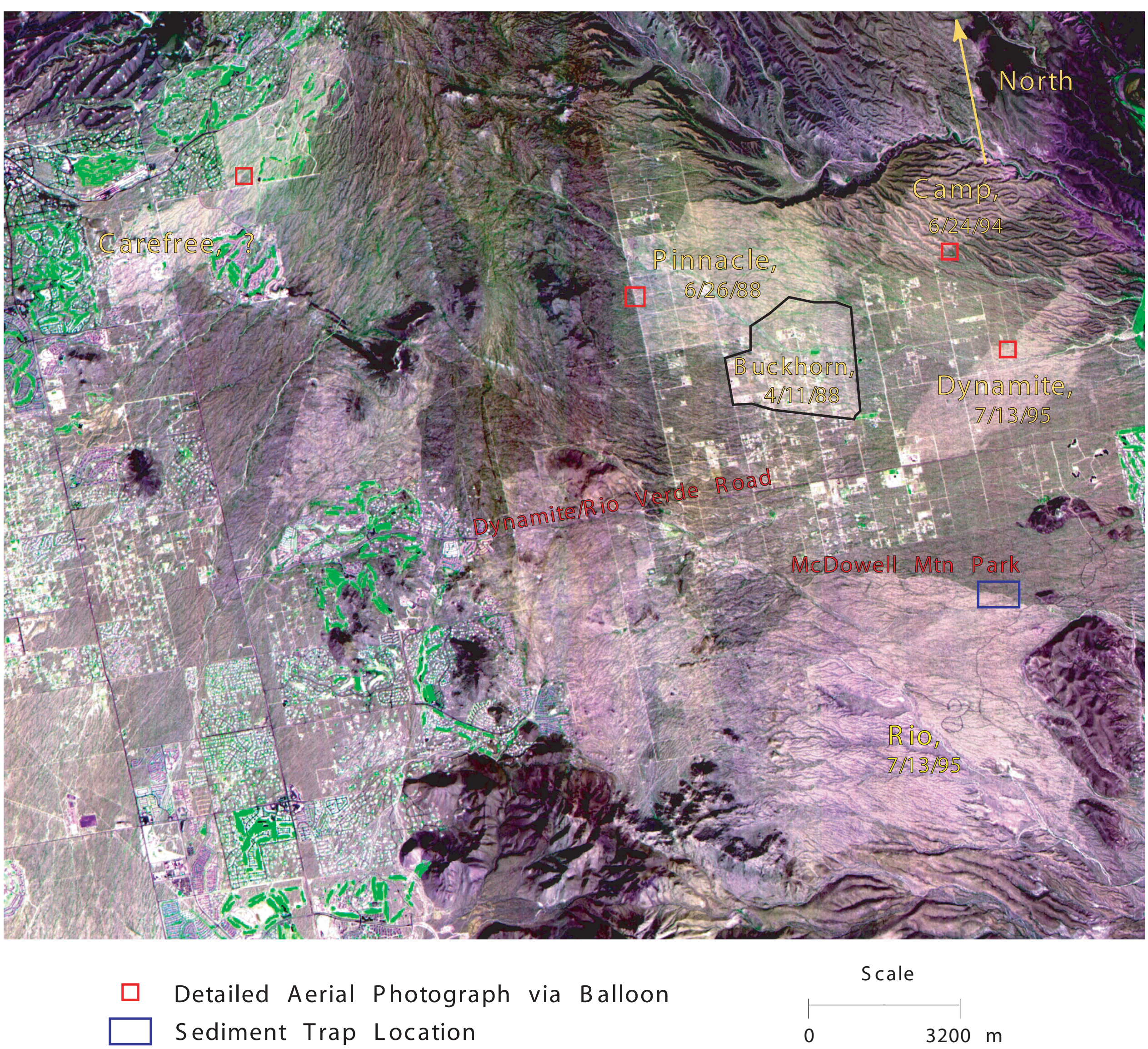


Figure 2 (below). Landsat image of the area north of the McDowell Mountains and east of North Schottsdale showing areas of major brush fires since 1988. Those major fires include the Carefree, Pinnacle, Camp, Buckhorn, Dynamite, and Rio events. We focused significant effort along the northern edge of the Rio fire scar in the McDowell Mountain Park. The area is one of numerous firefighting jurisdictions with US Forest Service, Arizona State Lands, the US Bureau of Land Management and numerous municipal entities all involved.



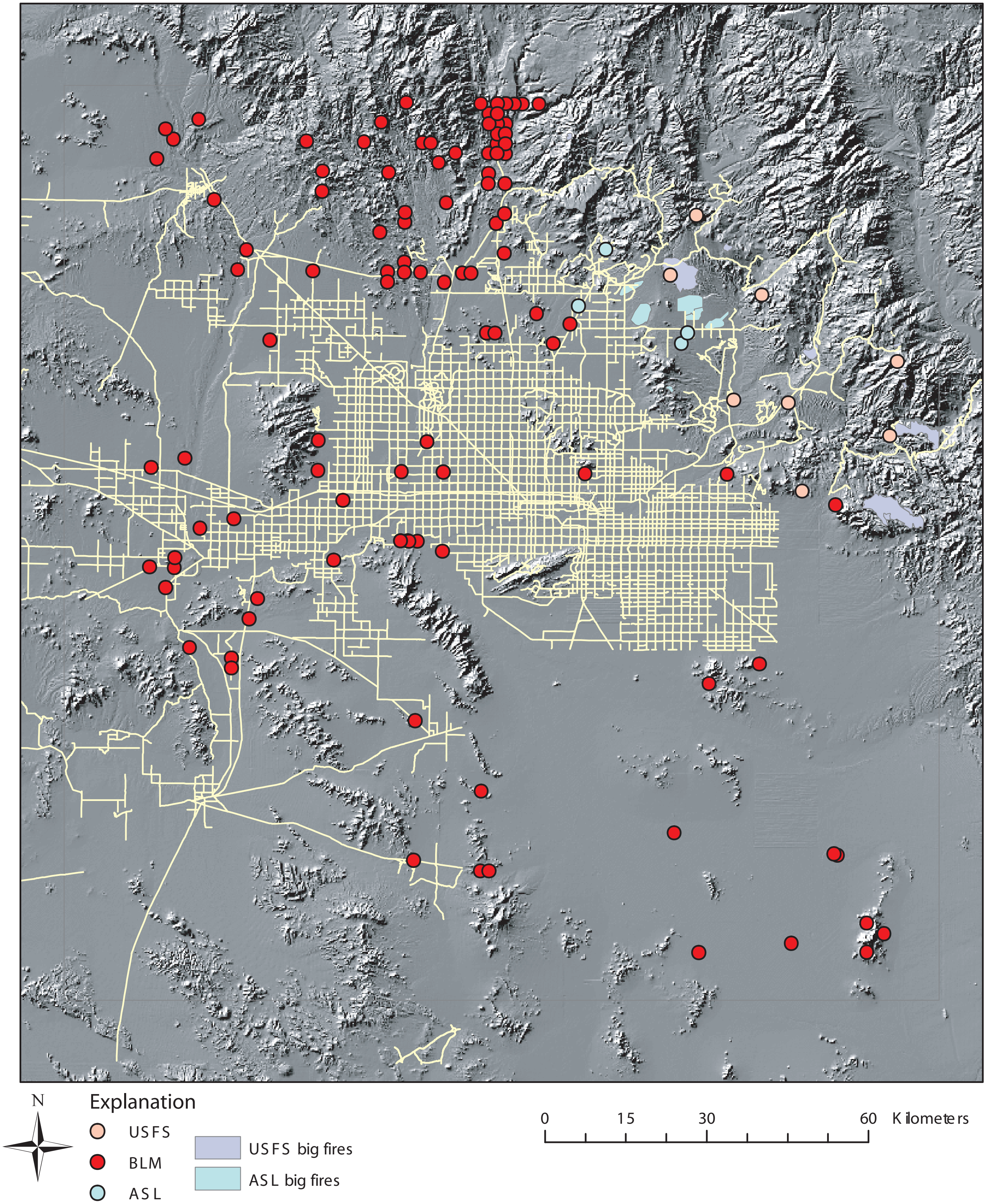


Figure 3. US Forest Service, US BLM, and Arizona State Lands (ASL) fire report data for the Greater Phoenix area. These data are generally complete from 1962-1998. Most fires are less than 100 acres and thus are shown as points. The larger fires in the northeast Phoenix/Scottsdale area are shown with outlines (compare with Figure 2 and note that the Rio fire was not recorded in these databases). The majority of the fires occur in the urban fringe and to the north where elevations are higher and thus fuels are increased.

Figure 4. Oblique aerial photography of fire scars in the area of the McDowell Mountains. A) View to the west over the northern edge of the Rio fire. Immediately west of the hill in the foreground is the area of the sediment trap locations. B) View south over Camp, Dynamite, and Rio fire scars illustrating their importance from an areal and albedo standpoint (see Figure 2).

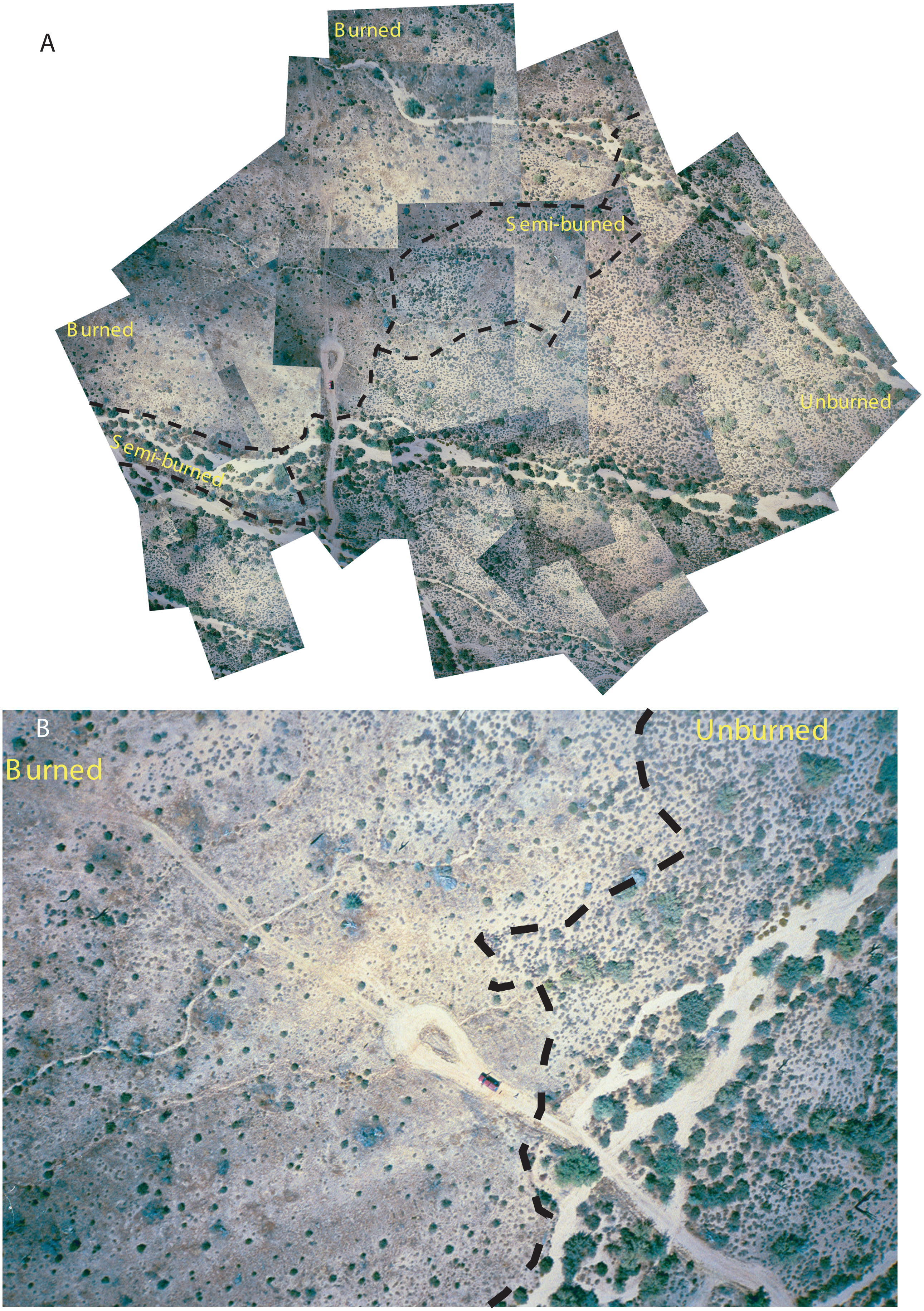


Figure 5. Balloon aerial photography of the Dynamite fire scar edge. Note the heterogeneous structure of the burn. Aaron Redman assisted in the collection and presentation of these data.

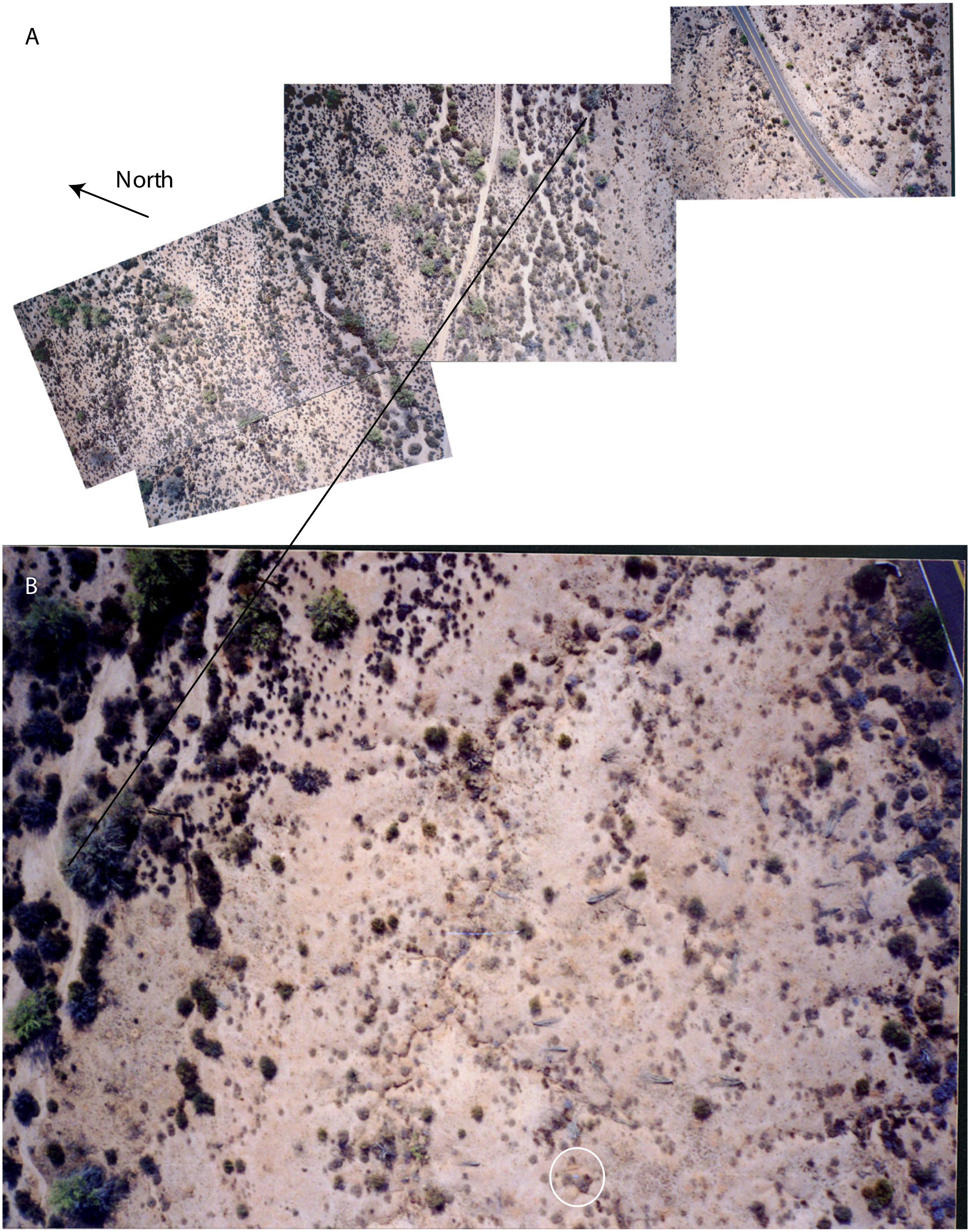


Figure 6. Balloon aerial photography of the northern edge of the Rio fire scar in McDowell Mountain Park. A) Overview mosaic showing the transition from fire scar (right side) to unburnt desert (on the left or north). B) Detailed view including setting of sediment trap (circled). Fire scar edge is along right side of channel system on left.

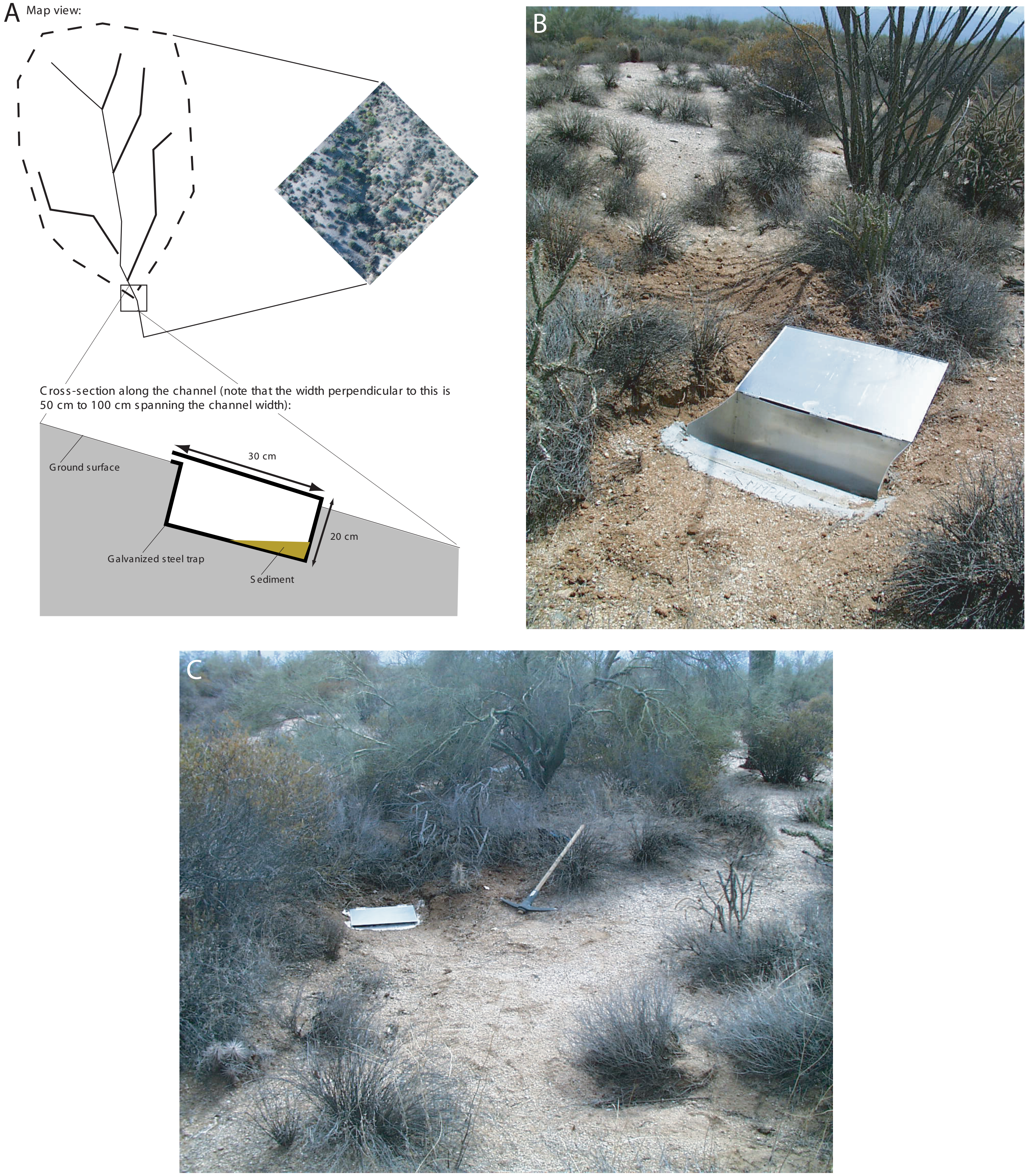
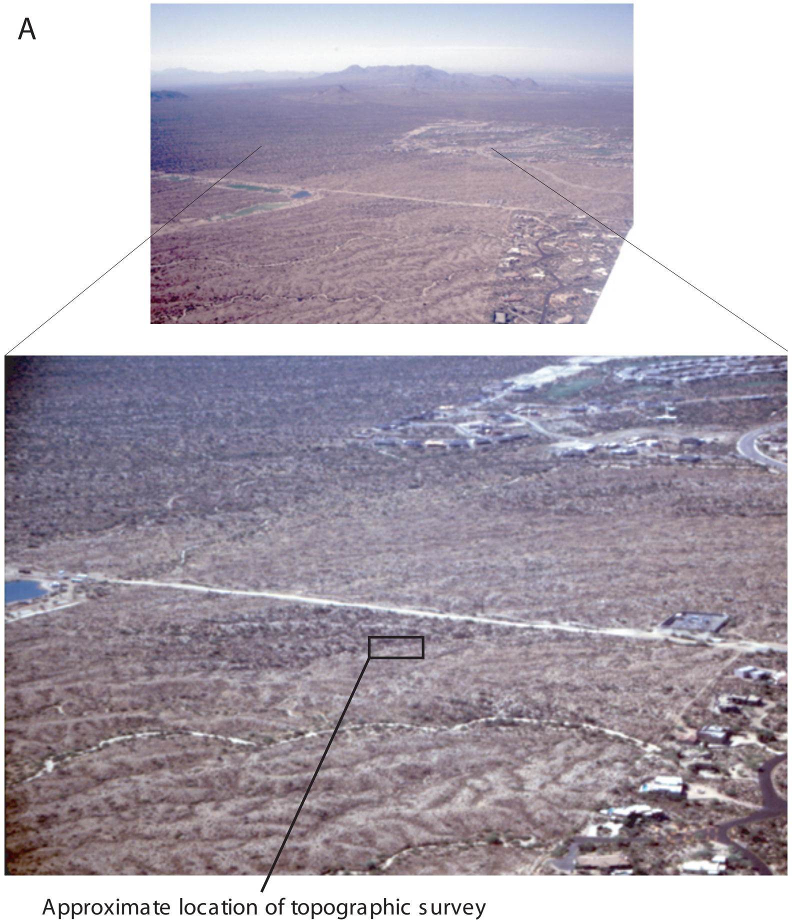


Figure 7. Sediment trap installation. A) Basic design and situation within drainage basin. B) view of open trap with cement lip. C) Closed trap at narrow portion of shallow channel.

A



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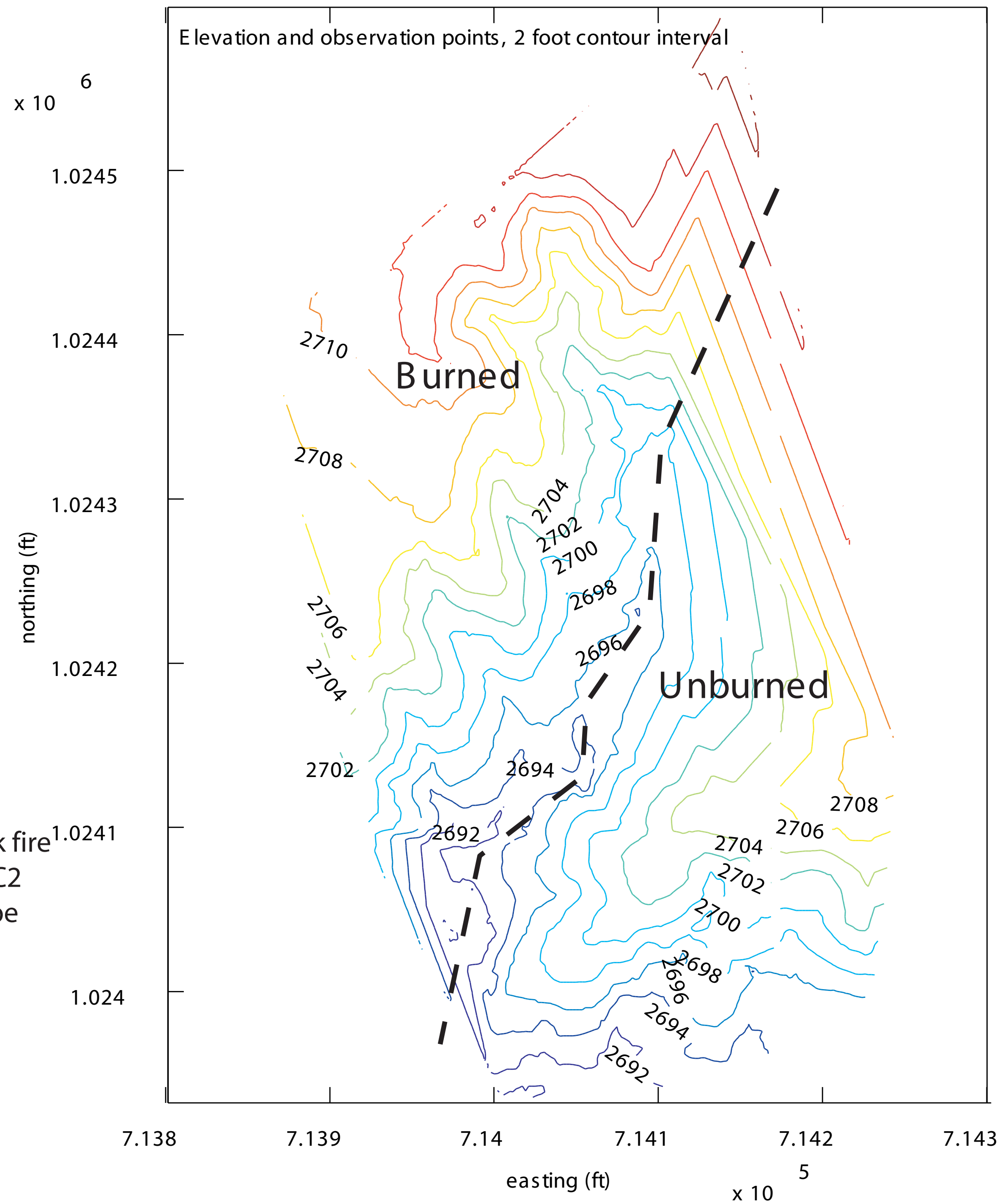
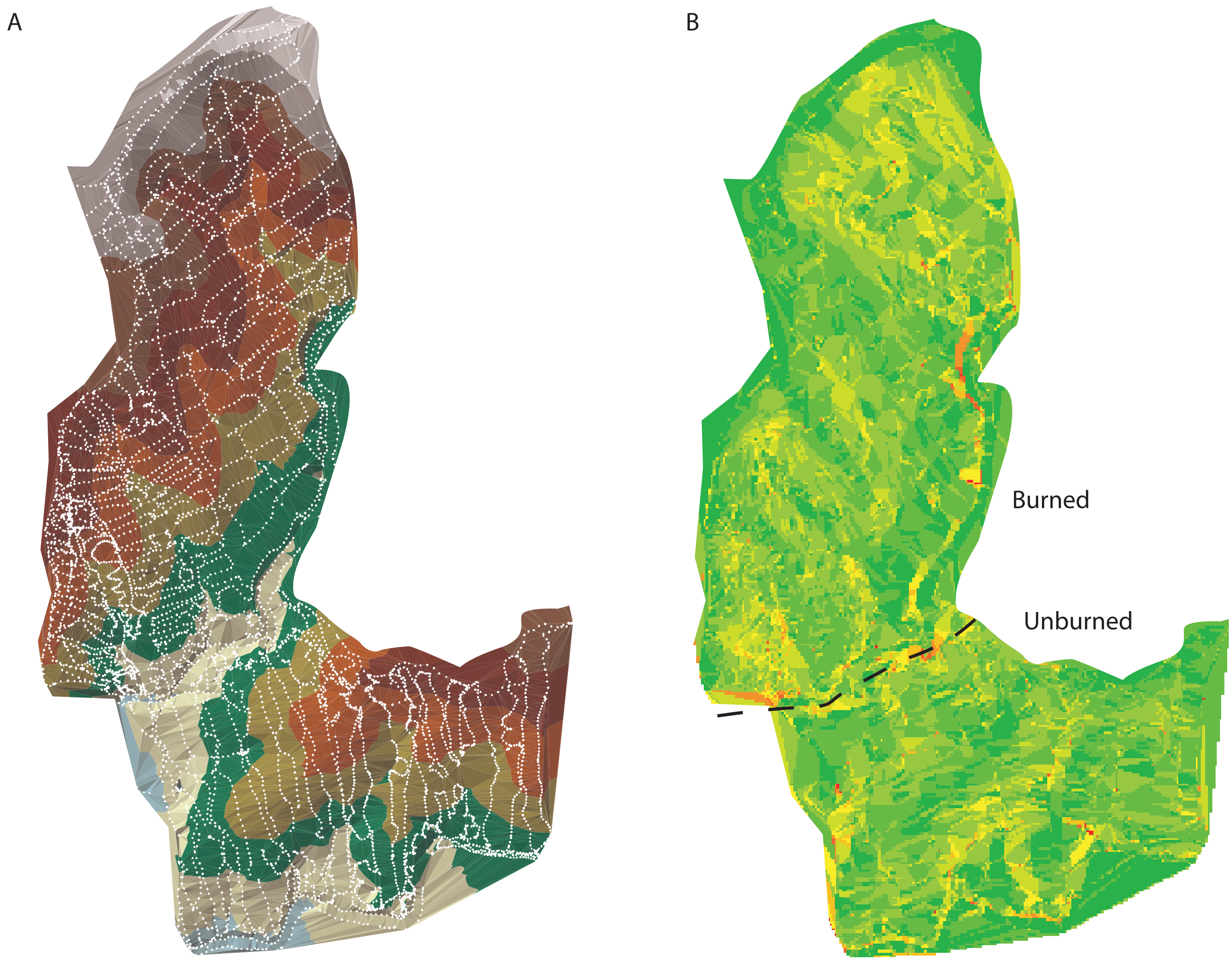


Figure 8. Topographic survey across fire scar edge at the Cave Creek fire (see figure 2 for location). A) Oblique aerial photographs of site. B) C2 foot contour map across scar edge. No clear differences in landscape form are evident.

Figure 9. Topographic analysis of Cave Creek Fire scar boundary. A) Triangular irregular network (TIN) of surveyed data (white dots). B) Slopes of TIN shown in A. No obvious increase in slope in the burnt portion of the landscape is evident. Future work will include further quantitative analyses of these data to test for differences.



Appendix B: “Curvature and regolith calculations from the McDowell Mountain Park Rio burn fire site”

Curvature and regolith calculations from the McDowell Mountain Park Rio burn fire site

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1 Curvature calculations

We use an 1 meter diameter template in the field to survey the central point of interest and 8 points at 50 cm radii every 45° for curvature calculations (Figure 1).

1.1 Synthetic curvature and algorithm testing

Figure 2 shows the survey geometry and synthetic elevation data with surveyed horizontal positions with approximately 45° slopes. The data are these:

My curvature calculation algorithm follows the following steps for each "wheel" of 9 points:

1. Determine distance (*dist*) between central point and *i*th outer point.

2. For the first four outer points, determine the slope S_i between them and the interior one as: $S_i = \frac{H_0 - H_i}{dist}$ where H_0 is the height of the central point and H_i is that of the ith outer point. For the second set of four outer points, determine the slope between them and the interior one as: $S_i = \frac{H_i - H_0}{dist}$. For the example case shown in Figure 2, the slopes are thus shown in table 1. The slopes are not exactly 1 because the diameter of the circle is not exactly 1 m.

3. Go around the 8 node wheel, determining the four individual curvatures $IC_i$by subtracting the the two slopes that make up each of the four diameters of the wheel and divide by the distance over which that occurs (half the diameter because the slopes are really at the midpoints of each radius): $IC_i = \frac{(slope(i+4) - slope(i))}{(dd(i+4)+dd(i))/2}$. The curvatures in this example are thus:

4. The curvature for that central point is the mean of the 4 individual curvatures calculated above (for the example, -0.9682).

Positive curvature indicates concave up and negative curvature is concave down.

#	e (m)	n (m)	H (m)	Slope
13	999.494	1004.786	0.5	n/a
14	998.987	1004.649	0	0.9520
15	999.047	1005.027	0	0.9846
16	999.377	1005.257	0	1.0303
17	999.745	1005.198	0	1.0364
18	999.982	1004.881	0	-1.0057
19	999.917	1004.496	0	-0.9749
20	999.609	1004.279	0	-0.9618
21	999.21	1004.33	0	-0.9307

Table 1: Surveyed data and synthetic elevations used to calculate slopes and curvature in the example.

#s	Slope1	Slope2	Distance/2	Curvature
14-13-18	0.9520	-1.0057	0.5112	-0.9575
15-13-19	0.9846	-0.9749	0.5103	-0.9599
16-13-20	1.0303	-0.9618	0.5026	-0.9909
17-13-21	1.0364	-0.9307	0.5098	-0.9646

Table 2: Slopes, distances over which they change, and individual "spoke" curvatures.

2 Regolith thickness determination

We determined regolith thickness at the center of each of the surveyed wheels by qualitatively determining the greatest change in induration with depth. This was done using a shovel or screwdriver (Figure 3). Usually, a strong change in color to more reddish below corresponded with the interpreted depth.

3 Results

3.1 Burnt transect from August 4

See Figures 1 and 4 for a view of the transect site and a map respectively of the burnt transect that Tamara Misner and I worked on August 4, 2002. Figure 5 shows the basic measurement distribution for curvature and regolith. The curvature distribution shows a mode in the small negative (convex upward) curvature and a longer tail to the positive (concave upward) curvature side. Mean and standard deviation of the curvature are 0.0231 ± 0.0788. The regolith distribution has a mode between 5 and 10 cm and the mean and standard deviation are 13.2653 cm $\pm$ 7.3308 cm.

No clear trend in the plot of regolith versus curvature is evident (Figure 6). The outlier of high positive curvature and high regolith thickness was measured in a large Paloverde near a channel. The negative curvature measurements show a slightly more clustered regolith distribution and a lower maximum.

3.2 Unburnt transect from August 25

See Figures 7 and 8 for a view of the transect site and a map respectively of the unburnt transect that Caitlin Schrein and I worked on August 25, 2002. Figure 9 shows the basic measurement distribution for curvature and regolith. The curvature distribution shows a mode in the small negative (convex upward) curvature and is not significantly skewed. Mean and standard deviation of the curvature are 0.0197 ± 0.0564. The regolith distribution is centered around 10 cm and the mean and standard deviation are 11.8725 cm $\pm$ 7.3620 cm.

No clear trend in the plot of regolith versus curvature is evident (Figure 10). The negative curvature measurements show a slightly more clustered regolith distribution.

3.3 Comparisons and preliminary conclusions

Figures 11 and 12 and Table 3.3 compare the two datasets. Qualitatively, they are very similar. Tentatively, I have performed a t-test to see if the means are statistically different (assuming things like the distributions are normal–standard for the t-test). I used an online t-test two sample calculator (`http://ebook.stat.ucla.edu/calculators/`) and used the calculated p-value to evaluate the significance. The null hypothesis in both cases was that the means were equal. "Small p-values suggest that null hypothesis is unlikely to be true." Rejection of the null hypothesis is usually done at $p<0.05$. The p-value for the regolith comparison is 0.35 and for the curvature comparison, it is 0.81; both are well above the rejection level, implying that with the assumption of normal distributions, the means are likely to be the same.

We might look more deeply at the data and the secondary levels that were noted. That takes away a bit from the relative objectiveness of the current effort, but we don't see much of either internal trends or significant differences between the datasets. We might also look at those points that were deemed sufficiently close to vegetation and do some comparisons with and without.

I do wonder if the grain size distribution will show a difference that is significant?

Regolith	Mean	Standard deviation
Burnt	13.2653	7.3308
Unburnt	11.872	7.3620

Curvature	Mean	Standard deviation
Burnt	0.2306	0.078774
Unburnt	0.019743	0.05642

Table 3: Comparison of datasets.

Figure 1: Surveying along the burnt transect. We used the 1 m template to better control the curvature point survey. We sampled at the central point for regolith and grain size.

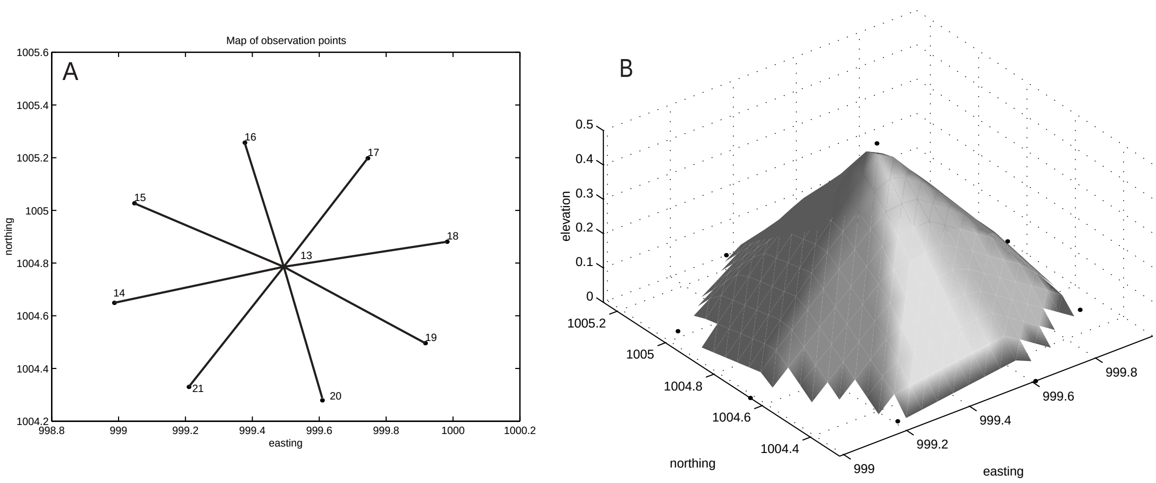

Figure 2: A) Surveyed array for curvature calculations. B) Synthetic elevation data with surveyed horizontal positions with approximately 45° slopes.

Figure 3: Regolith thickness measurements were made in pits like this. We used the shovel or screwdriver to determine the depth of the largest change in induration (screwdriver tip). Sometimes we would note a second level where the induration changed (at the base of the hole in this picture).

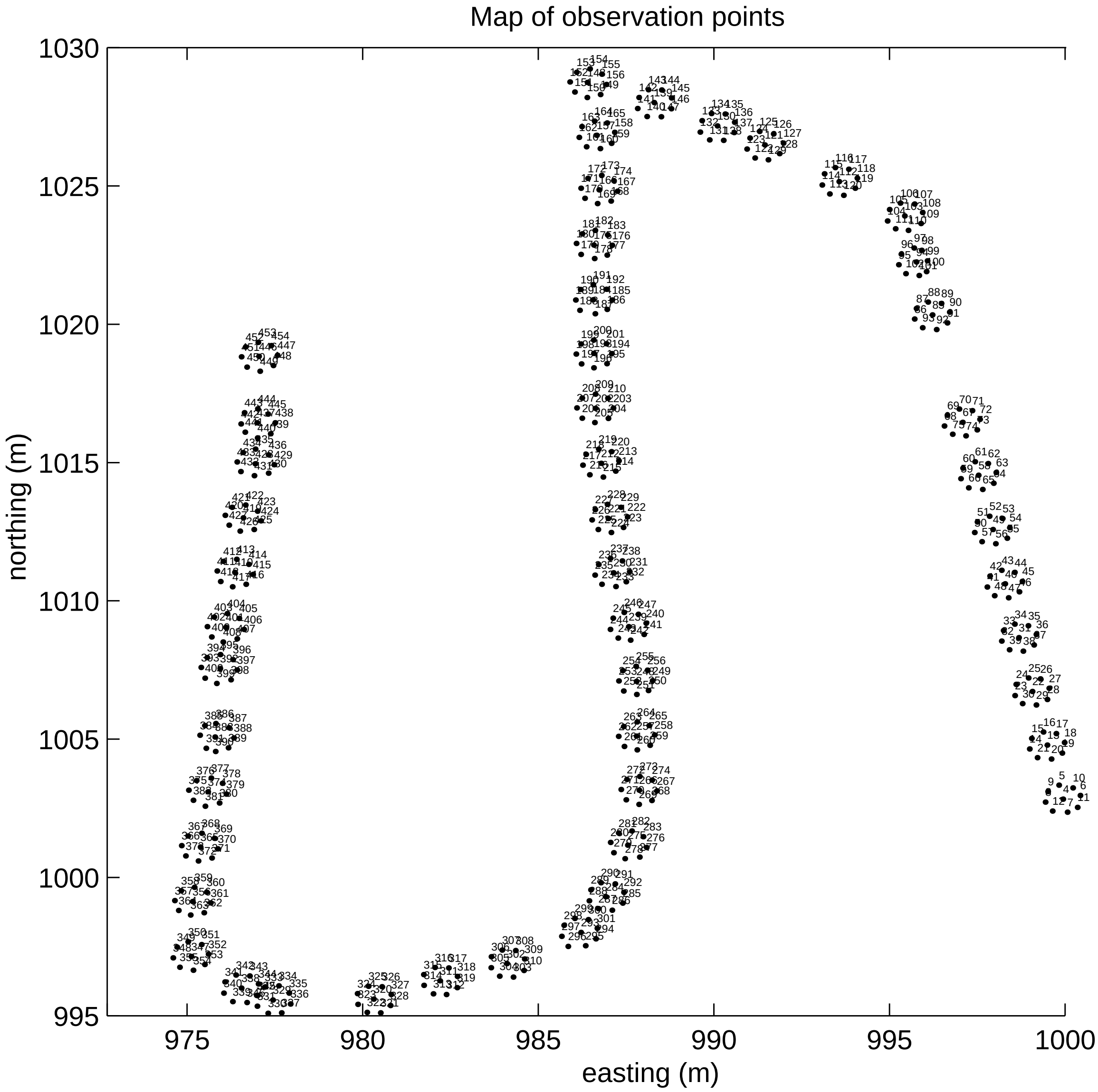

Figure 4: Map of surveyed points for transect in burnt area on August 4, 2002.

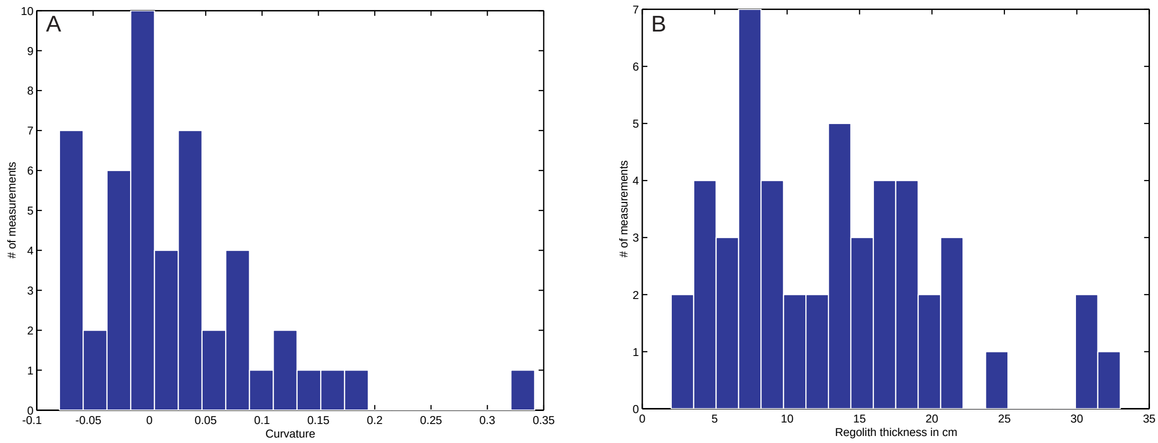

Figure 5: Histograms of August 4, 2002 measurements. A) Curvature distribution shows a mode in the small negative (convex upward) curvature and a longer tail to the positive (concave upward) curvature side. Mean and standard deviation of the curvature are 0.0231±0.0788. B) Regolith distribution has a mode between 5 and 10 and the mean and standard deviation are 13.2653 cm ± 7.3308 cm.

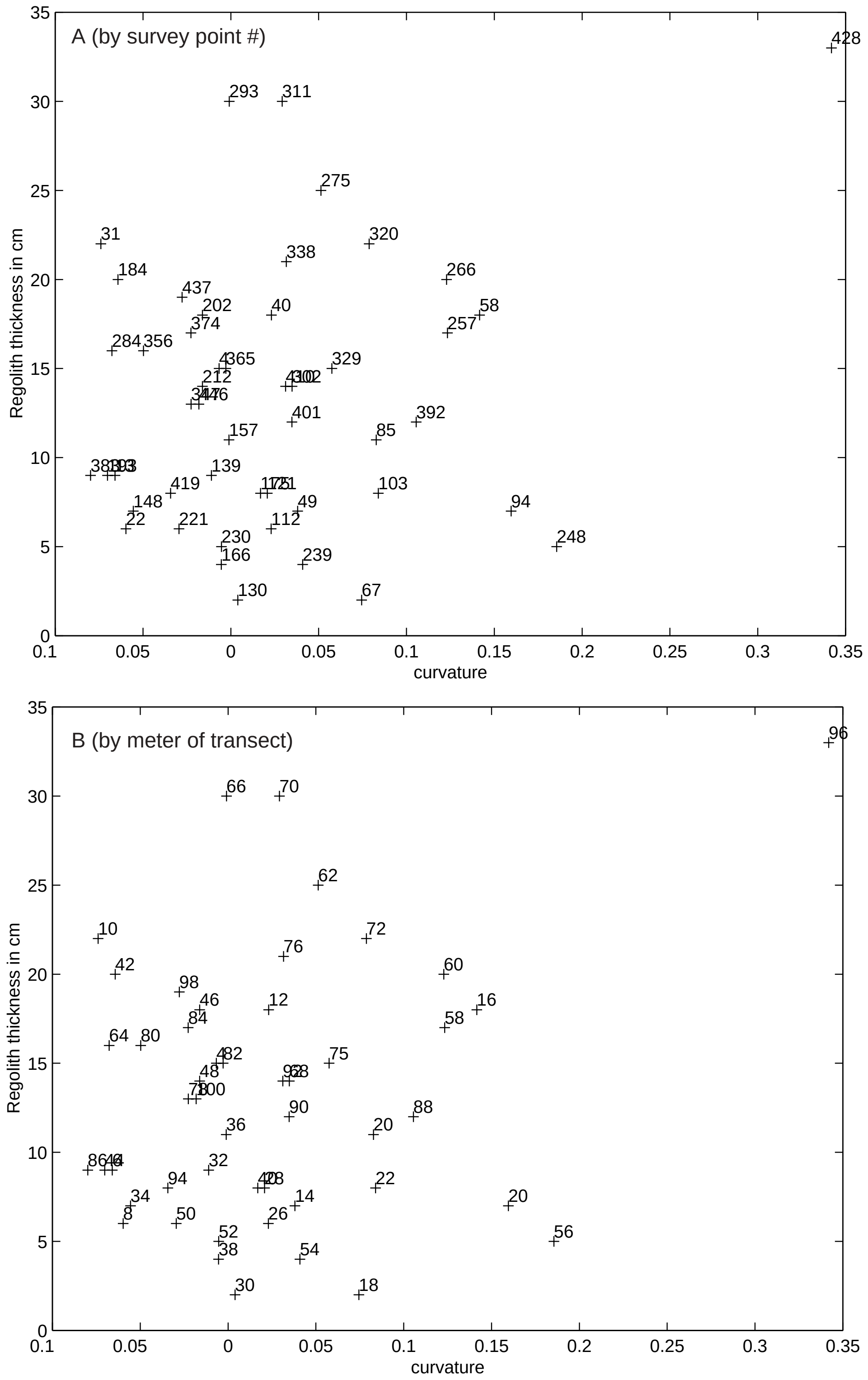

Figure 6: Regolith versus curvature. The outlier of high positive curvature and high regolith thickness was measured in a large Paloverde near a channel. No clear trend is evident. Negative curvature is convex up topography. A) Coded by survey point number. B)Coded by meter of transect.

Figure 7: Surveying in the unburnt transect. Notice the obviously larger amount of vegetation.

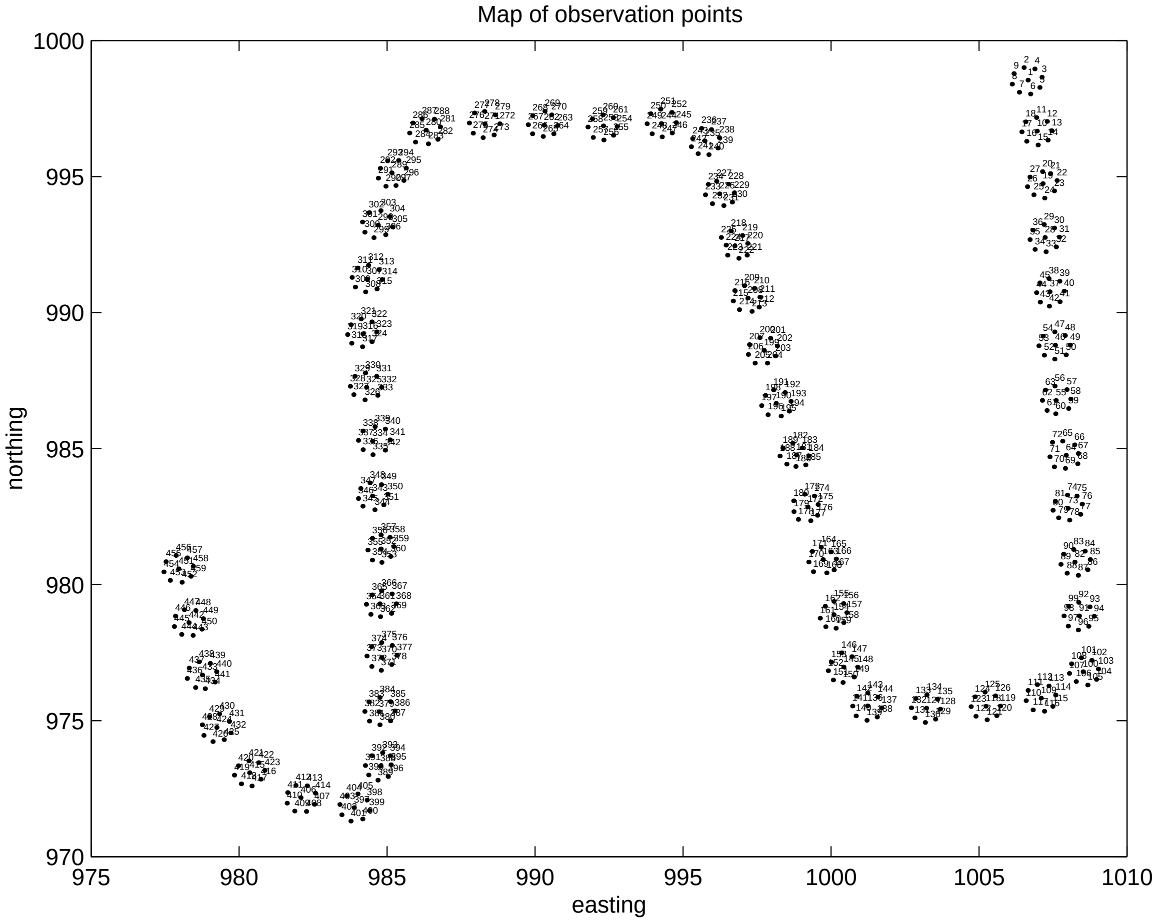

Figure 8: Map of surveyed points for transect in unburnt area on August 25, 2002.

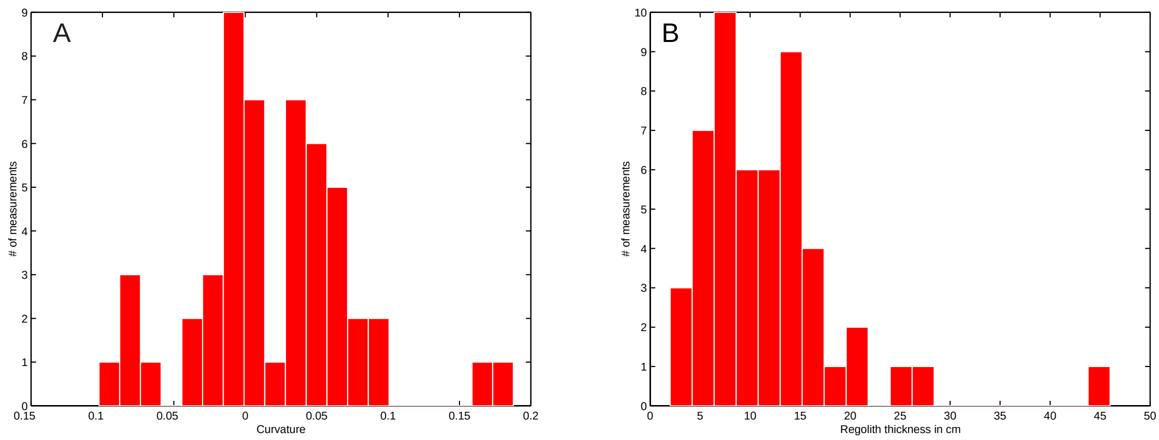

Figure 9: Histograms of August 25, 2002 measurements. A) Curvature distribution shows a mode in the small negative (convex upward) curvature and is not significantly skewed. Mean and standard deviation of the curvature are 0.0197±0.0564. B) Regolith distribution is centered around 10 cm and the mean and standard deviation are 11.8725 cm ± 7.3620 cm.

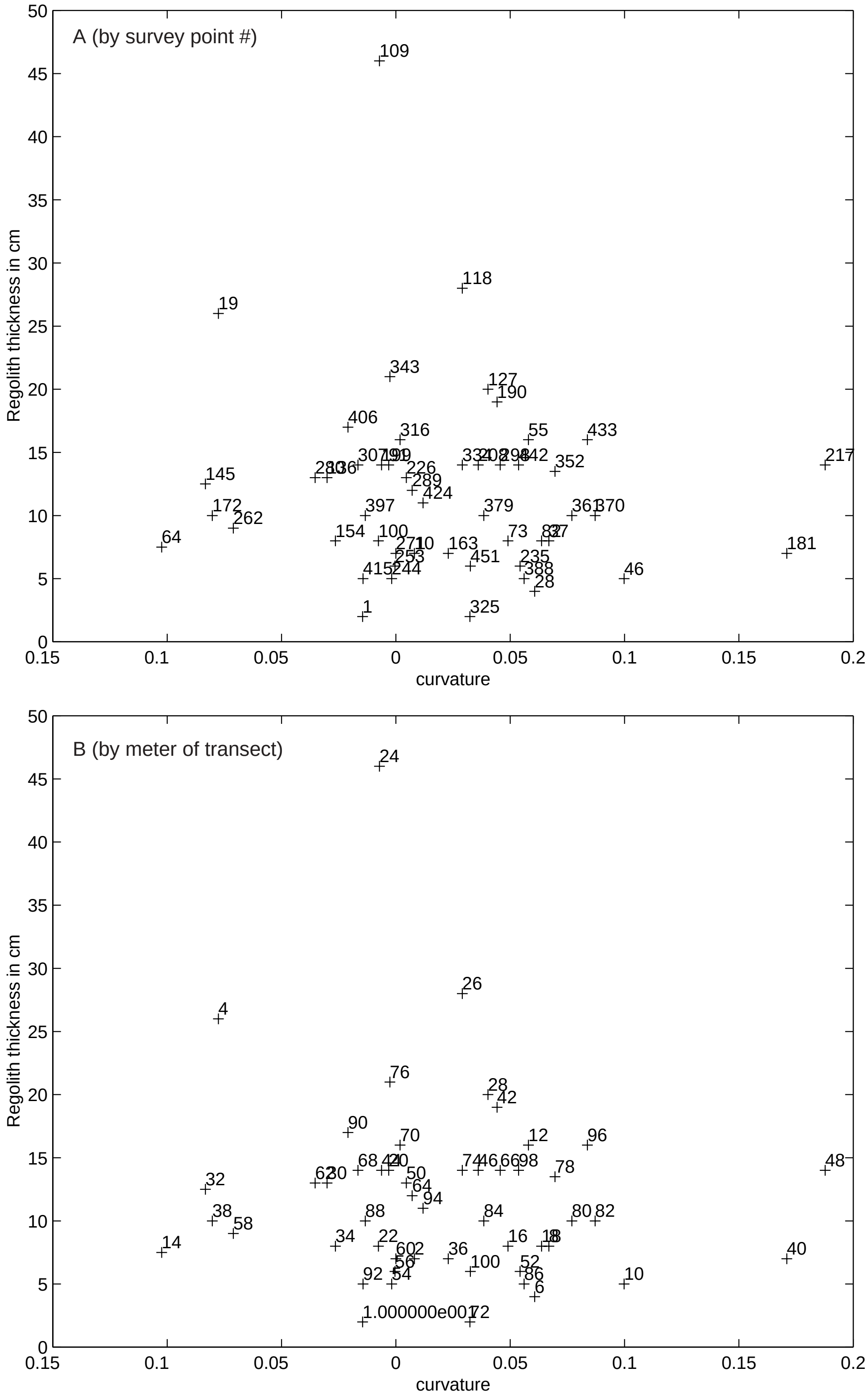

Figure 10: Regolith versus curvature. No clear trend is evident. Negative curvature is convex up topography. A) Coded by survey point number. B)Coded by meter of transect.

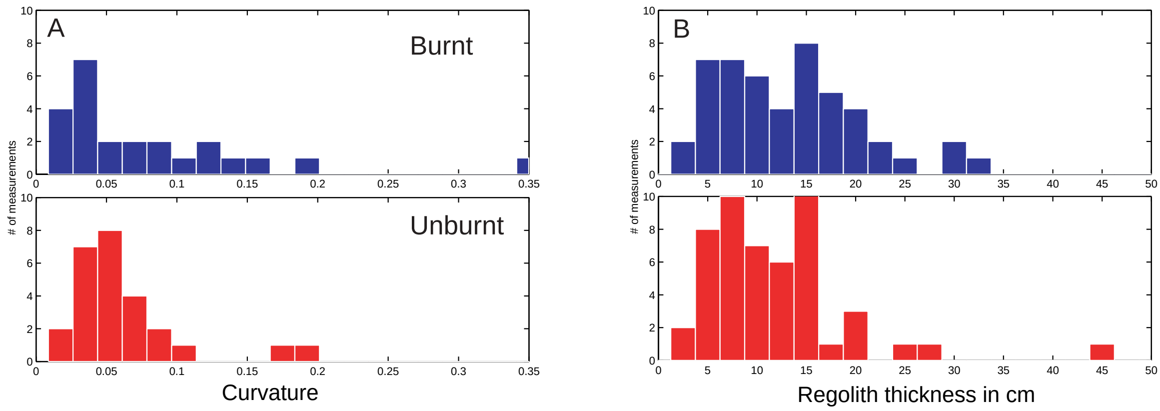

Figure 11: Comparison of burnt and unburnt curvature (A) and regolith (B) distributions.

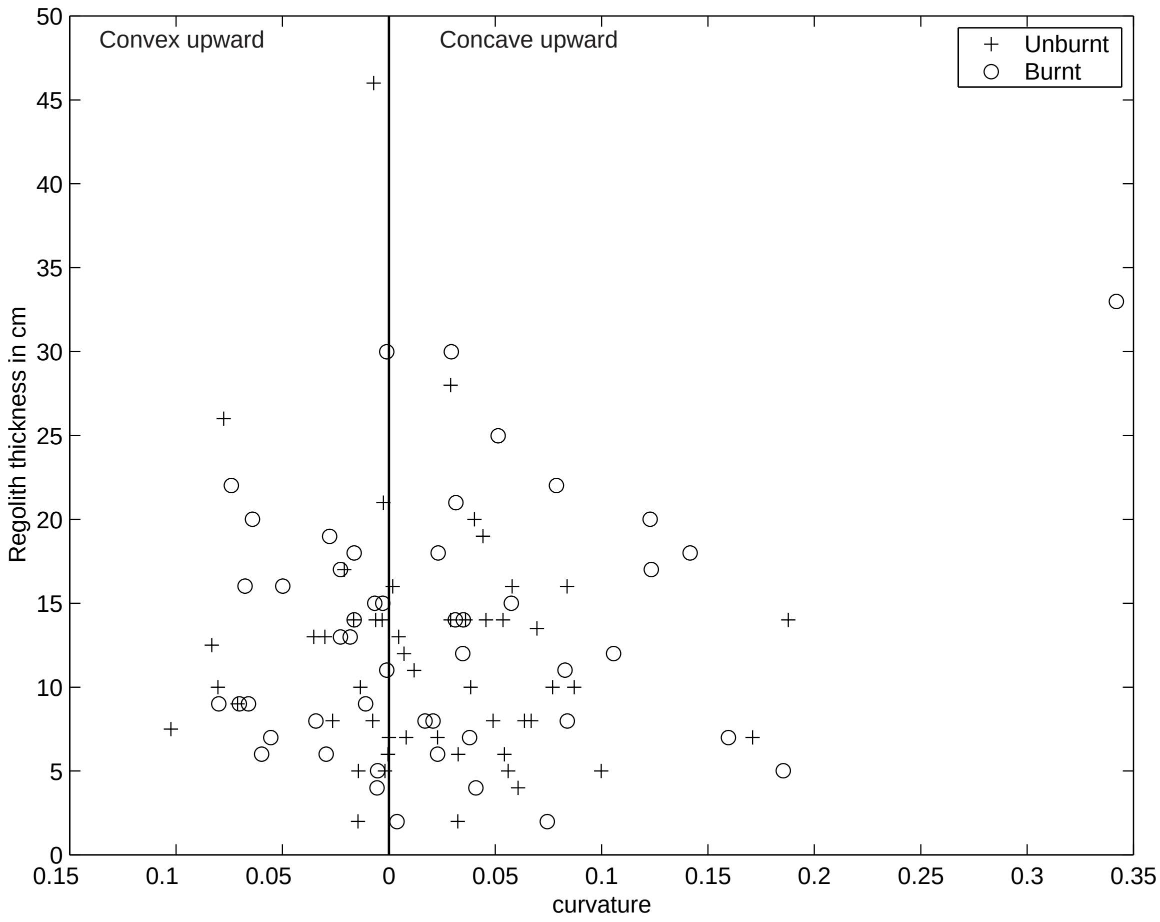

Figure 12: Comparison of burnt and unburnt regolith versus curvature.