

applied over thousands of hectares, and forest managers need to ensure that money has been spent appropriately and effectively to stabilize the areas at greatest risk (Groen and Woods 2008; Robichaud and others 2000).

Remote sensing is a potential solution to this uncertainty because of the ability to rapidly acquire a relatively cheap and accurate “snapshot” of post-fire conditions. High spatial resolution satellite sensors such as QuickBird (DigitalGlobe Inc., Longmont, Colorado) and IKONOS (GeoEye, Dulles, Virginia) can provide a clear picture of ground conditions after the fire that is similar in quality and scale to a traditional aerial photograph (Goetz and others 2003) but with the advantage of greater spectral information. QuickBird and IKONOS satellites collect four spectral bands of data (visible through the near infrared region of the electromagnetic spectrum), whereas Landsat, which is most often used for post-fire mapping, collects seven spectral bands (visible through shortwave infrared). The shortwave infrared band is highly sensitive to the changes in soil after fire, which makes it so useful for mapping burn severity. However, the pixel size of a QuickBird image is much finer (2.4-m (8-ft) versus 30-m (100-ft) Landsat pixels), allowing for greater spatial discrimination of ground components. The spatial resolution of QuickBird imagery is more closely matched to the spatial variability of the post-fire environment, which makes it well-suited for mapping fine-scale characteristics such as straw mulch coverage.

QuickBird imagery has been used to help guide post-fire treatments, determine immediate post-fire tree mortality, and refine soil burn severity maps (Chirici and Corona 2005; Corona and others 2008). These high-resolution images give users the ability to identify vegetation patches, roads, bodies of water, and other resources at risk and allow users to assess the color and char condition (green, brown, or black) of any remaining vegetation. IKONOS was used to measure crop residue on agricultural fields with modest success (Bannari and others 2006) using a linear spectral unmixing model of soil, crop (green vegetation), and residue (senesced crop). This model is comparable to a post-fire scene in that there are few ground cover components and the major spectral signatures are live and dead vegetation and exposed soil. If a treatment is applied, such as straw mulch, it has a similar spectral signature to crop residue. To improve results, Bannari and others (2006) suggest that the ideal time to spectrally discriminate crop residue is early in the growing season before there is abundant green vegetation so that soil and crop residue are the primary contributors to the

spectral signature. Thus, the ideal time to detect mulch in a post-fire scene is immediately after it is applied and before green vegetation has had a chance to re-establish.

Due to the limited scale of this project, QuickBird imagery was primarily collected over areas that were known to have been burned at high severity, were considered at risk for increased runoff and erosion, and were treated with a helicopter-applied mulch treatment. The objectives of this study were: 1) to determine if satellite imagery could be used to detect straw mulch cover on the ground; and 2) to learn whether straw mulch cover could be measured with satellite imagery.

Methods

Study Area

Lightning storms ignited the Spur and Tripod Fires on 3 July and 24 July 2006, which eventually burned together and became the Tripod Complex (called the Tripod Fire hereafter) (USDA 2007). The fire was declared contained on 31 October 2006 after 71,000 ha (175,000 ac) burned. Mean annual precipitation is 150-300 mm (6-12 in), depending on elevation. Tree species composition of the burned areas at the low- to mid-elevation was generally mixed coniferous stands of ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), and western larch (*Larix occidentalis*), with pockets of Engelmann spruce (*Picea engelmannii*) and lodgepole pine (*Pinus contorta*). The high-elevation montane forests were dominated by Engelmann spruce, lodgepole pine, and subalpine fir (*Abies lasiocarpa*).

A Forest Service Burned Area Emergency Response (BAER) team mapped soil burn severity and determined emergency stabilization needs within weeks of the fire's containment. Twenty-three percent of the burned area was classified as high soil burn severity, 39% as moderate, and 38% as low or unburned. BAER treatments prescribed after the Tripod Fire included seeding, fertilizing, and mulching to protect watersheds at risk for erosion and runoff (USDA 2007). Wheat straw mulch was applied to 5500 ha (13,500 ac) via helicopter at the rate of 2 Mg ha⁻¹ (1 ton ac⁻¹) beginning in October 2006. Treatment application resumed in June 2007 and was completed the first week of July 2007. The majority of this straw came from certified weed-free, wheat-grain fields in Washington that had inspection reports or from Montana, Idaho, and California, which have state weed-free certification programs (USDA 2007).

Field Sampling

On 8 August and 19-20 October of 2007, 10 field sites were sampled for validation of the straw heli-mulching application rate. The areas that were known to have high straw coverage were the focus areas for the field validation. On selected heli-mulched hillslopes, a 60- by 60-m (200- by 200-ft) sampling area (called a site) was established with nine plots arranged with the slope aspect and across the hillslope (fig. 1). The location of the center of each site (plot A) was recorded with a GPS (Garmin GPSMap-76S, Garmin International Inc., Olathe, Kansas). Within ~ 5 m (16 ft) of each plot center, five 1- by 1-m (~ 3- by 3-ft) square subplots were sampled for ground cover. A string-gridded plot frame with 100 string intersections was laid on the ground, and the ground cover type (mineral soil, vegetation, litter, or straw mulch) was recorded at each intersection. The mean ground cover of the five subplots was assigned to each of the nine plot locations to create a spatial representation of mean ground cover types across the hillslope. This sampling scheme was repeated on 10 hillslopes, for a total of 90 ground cover plots on the Tripod Fire study area.

QuickBird Imagery Analysis

QuickBird imagery was acquired on 26 July 2007 over an 8000-ha (20,000-ac) portion of the burned area.

The imagery was delivered as multiple geotiff files that were combined into a single, orthorectified image mosaic. Preliminary examination of the color (red-green-blue color composite) image allowed for the identification of the major ground cover components: blackened (charred) vegetation, brown (scorched) vegetation, green (unburned) vegetation, soil, and straw mulch. The straw mulch cover was easily identified because the straw was highly visible against the otherwise black background.

Spectral mixture analysis (SMA) was used to model the percent cover of the mulch in the treated areas. Spectral endmembers for image processing were selected from the most homogenous patches of green, scorched, and charred vegetation, soil, and straw mulch located in the imagery (fig. 2). By examining the spectral signature of the purest pixels and given our knowledge of the fire area, we were able to select endmember spectra for spectral mixture modeling. Once endmember spectra were identified, spectral unmixing of individual pixels was used to estimate the fractional component spectra (spectral fractions) of the pixels (ENVI 2007) and, in turn, the physical fractional component of the materials on the ground (Adams and others 1985; Roberts and others 1993; Theseira and others 2003). The outputs of SMA are grayscale fractional cover images that are scaled 0 to 1 (or 0 to 100%).

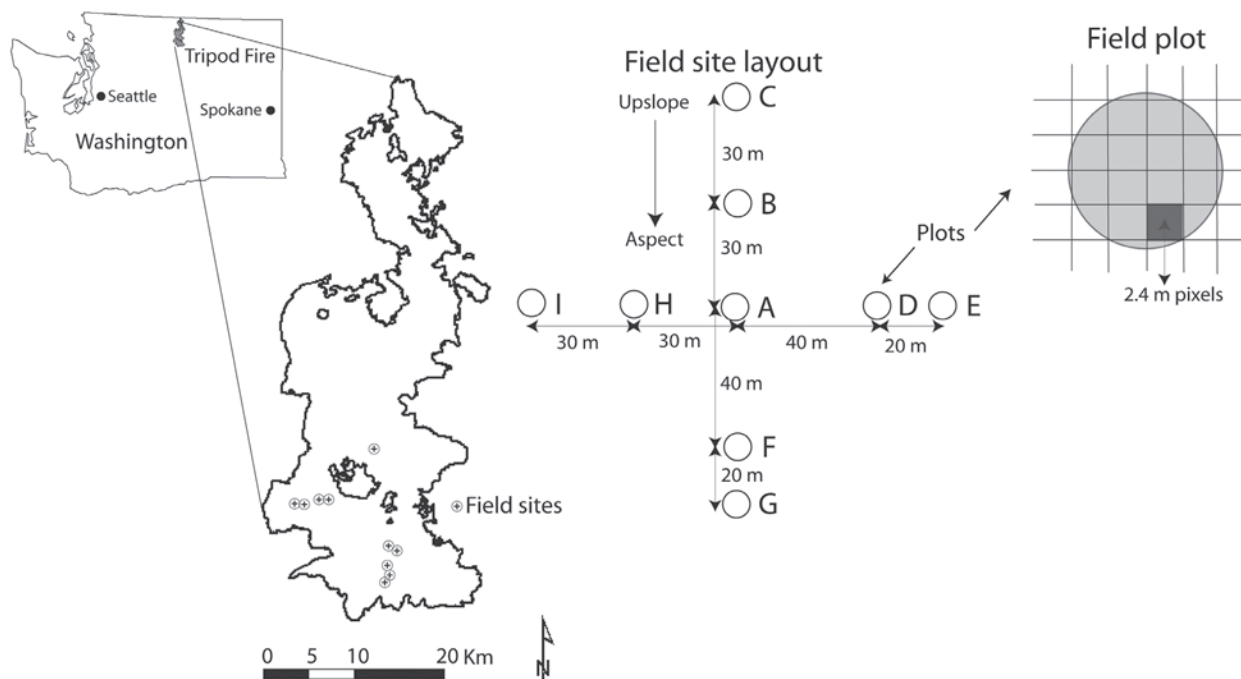


Figure 1—The location of the field sites and the field plot layout on the Tripod Fire located on the Wenatchee-Okanogan National Forest in north-central Washington State.

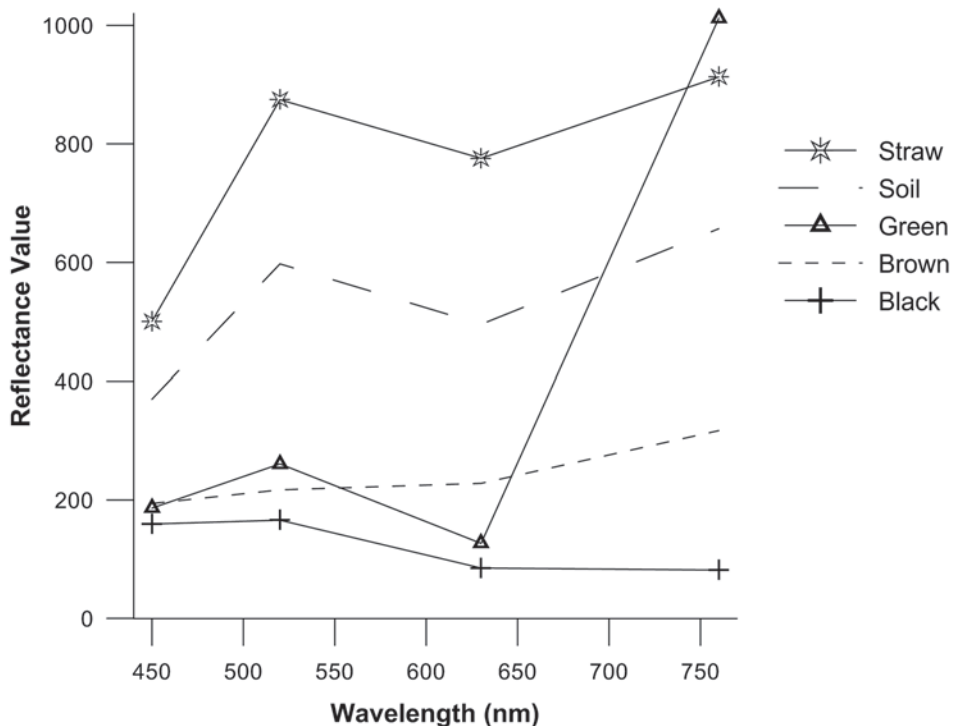


Figure 2—QuickBird spectral signatures of the five endmembers used in the spectral mixture analysis.

In order to compensate for some of the geolocational uncertainty in the imagery associated with locating field plots on the imagery (6 to 15 m (20 to 50 ft) accuracy), pixel values within a 5-m (16-ft) radius around each plot location were averaged (~24 pixels). These spectral fractions were compared to the ground data at the same spatial scale to evaluate how well the image model compared to the conditions on the ground.

Statistics

Correlations were first assessed between the ground cover and the spectral fractions (image model) using the Pearson correlation statistic (SAS proc CORR) (SAS Institute Inc. 2008) at the site scale ($n = 90$) and then at the plot scale (the mean of five subplots, $n = 9$). Correlations were considered significant if $p < 0.05$. In order to analyze trends in the data and account for the likely under-prediction of straw mulch in the imagery, the Spearman rank correlation was also calculated. Scatterplots with ground data as the independent variables and image data as the dependent variables were used to further examine the ground and image relationships. Linear regressions (SAS proc REG) (SAS Institute Inc. 2008)

were calculated from these data, and linear regression estimator lines and coefficients of determination were reported on the scatterplots.

Results and Discussion

Detection of Straw Mulch After the Tripod Fire

The straw mulch appeared on the image in two patterns: wide swaths from the helicopter flight paths, and smaller patches from individual straw bales (fig. 3). In the first post-fire growing season, minimal vegetation returned to the most severely burned areas. The resultant vegetation cover averaged only 6% and was not a key contributor to the overall color (reflectance) of the scene. The dominant spectra in the mulched areas were charred (black) and scorched (brown) trees, soil, and straw mulch. These were ideal conditions for detection of the mulch because the mulch was much lighter and brighter (higher albedo) than the charred background, which was primarily dark (fig. 2). Fewer spectra contributing to the overall scene leads to a higher chance of target spectrum (straw mulch) detection (Bannari and others 2006).

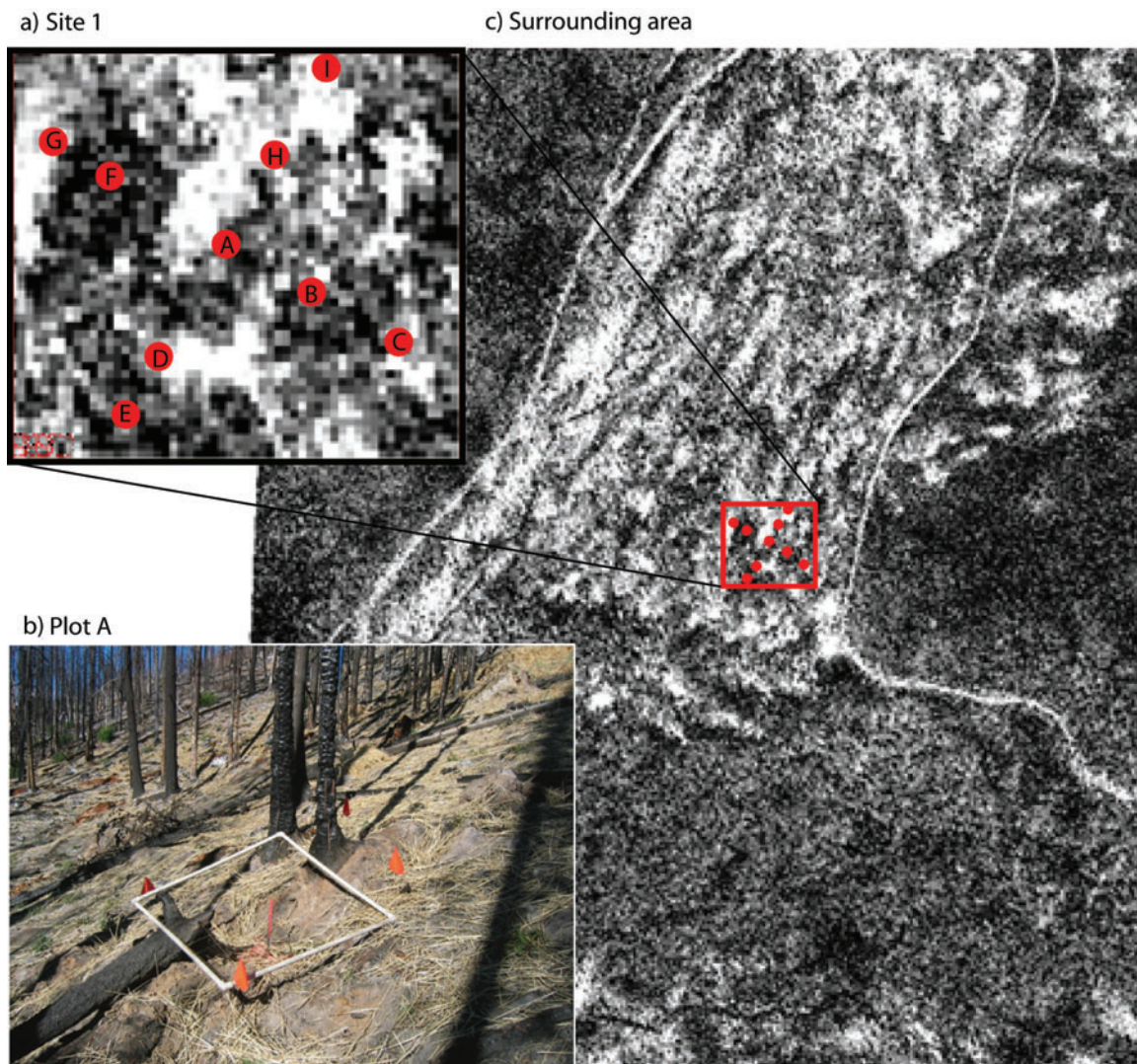


Figure 3—Fractional cover predictions of the straw mulch cover in an area approximately 1 km² (250 ac) surrounding Site 1. In c), white pixels indicate ~100% straw mulch cover, gray pixels indicate ~50% straw mulch cover, and black pixels indicate 0% straw mulch cover. Inset figures: a) a close-up of the pixels with the Site 1 plots overlaid; and b) a photograph of a typical plot. The plot frame is 1-m² (3.3-ft), and the four flags surrounding the rebar are the other subplot locations.

Predicting Straw Mulch Cover

When all data were analyzed together ($n = 90$), the correlation between straw mulch on the ground and modeled in the image was significant ($r = 0.47$; $p < 0.001$). The regression line on the scatterplot (fig. 4a) indicates considerably more mulch was measured on the ground (range 4% to 94%) than was predicted in the image (2% to 35%). This result is fairly typical in remotely sensed field studies; the image often shows less of the target material than is measured on the ground (Lewis and others 2007;

Mundt and others 2006; Robichaud and others 2007). Predicted cover fractions are more likely to be relative amounts (for example, the ratio of exposed soil to litter or straw mulch cover) rather than absolute values. The ranked data (fig. 4b) have a greater scatter than the raw data (fig. 4a), but the correlation is similar ($\rho = 0.40$), which indicates there is a significant trend between straw mulch cover on the ground and modeled in the image. The ranked data provide a relative straw mulch cover prediction compared to the other plots (that is, higher than or less than), rather than a percent cover.

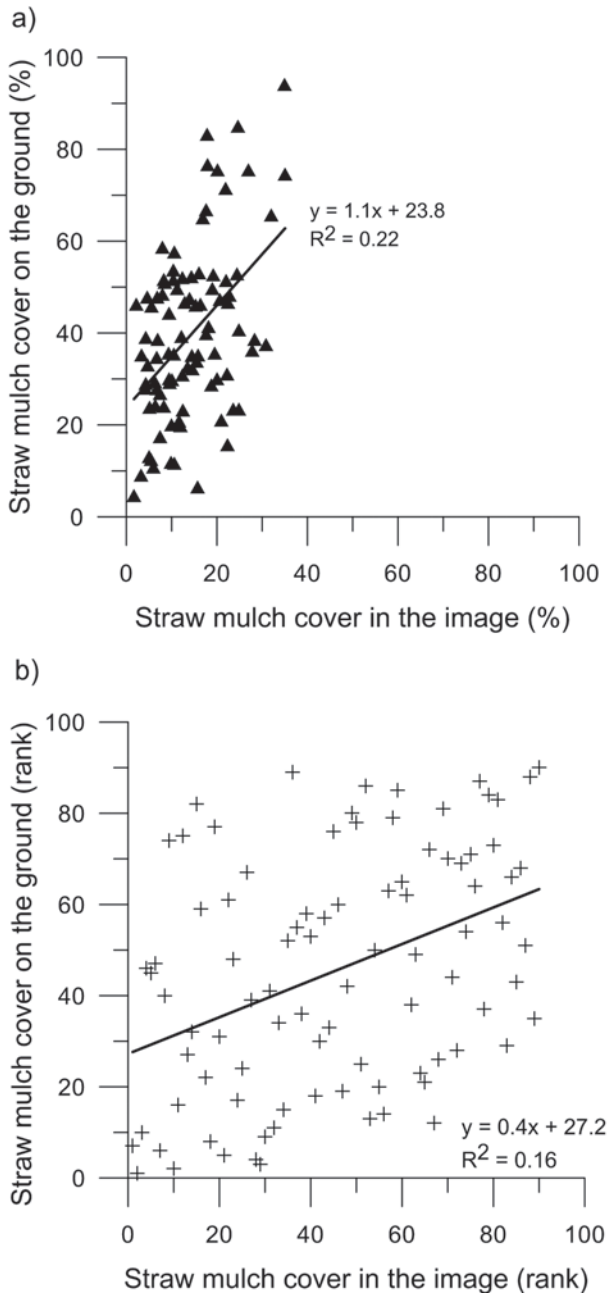


Figure 4—Measured straw mulch cover on the ground versus straw mulch cover in the image from the SMA for all data at the plot scale ($n = 90$). a) is the raw data (percent straw mulch cover); and b) is the ranked data.

When analyzed at the plot level, correlations between straw mulch measured in the field and predicted in the image had a wide range ($r = 0.1$ to 0.7). Rank correlations (Spearman) also spanned a similar range ($\rho = 0$ to 0.65) and were as strong or stronger on most of the plots. The best result from both correlation analyses was on Site 3 ($r = 0.73$; $\rho = 0.65$). On Site 3, plots A and G had the least amount of straw measured on the ground and in the

image, and overall, the ranks of the data show a strong agreement (table 1). Plots C and H were the biggest outliers (in terms of rank) on this site. Plot C had the third smallest amount of measured straw mulch but had the second largest (eighth smallest) amount predicted in the imagery; however, these values only differed by 10%. Plot H had the most measured straw (83%), but only 18% predicted straw (sixth smallest). This site had more remaining canopy than most of the sites, and the large

Table 1—Straw mulch cover on Site 3 at individual plots, sorted by lowest to highest measured coverage.

Plot	Ground (%)	Ground (rank)	Image (%)	Image (rank)
A	10	1	6	2
G	12	2	5	1
C	30	3	20	8
F	35	4	9	4
E	38	5	7	3
I	39	6	12	5
B	41	7	18	7
D	75	8	27	9
H	83	9	18	6

under-prediction of straw values was probably a result of occlusion of the ground by the canopy.

The percent straw mulch cover and the ranks of the straw mulch cover from Site 3 were plotted to visually compare the raw and ranked data (fig. 5). The coefficients of determination were similar ($R^2 = 0.53$ and 0.42), as expected from the correlation analysis. The biggest differences in the scatterplots were the slopes of the linear regression estimator lines. By ranking the data, the range of the ground and image data are the same (1 to 9); therefore, the slope of the linear regression estimator line is similar to an imagined 1:1 line. Whereas on the percentage cover graph, the slope was steep (slope = 2.4), highlighting the discrepancy in the range of straw mulch cover values found on the ground and in the imagery. Thus, the relationship between the percent straw mulch cover on the ground and in the image is significant, but the ability to predict a percent straw mulch cover accurately is weak. The ranked data indicate a relative increasing relationship between the straw mulch cover on the ground and compared to the amount modeled in the imagery. Therefore, the straw cover modeled in the image can be validated by field plots that have adequate straw mulch cover for erosion mitigation, and the image can then be used to determine which areas outside of the field plots also have sufficient straw mulch cover.

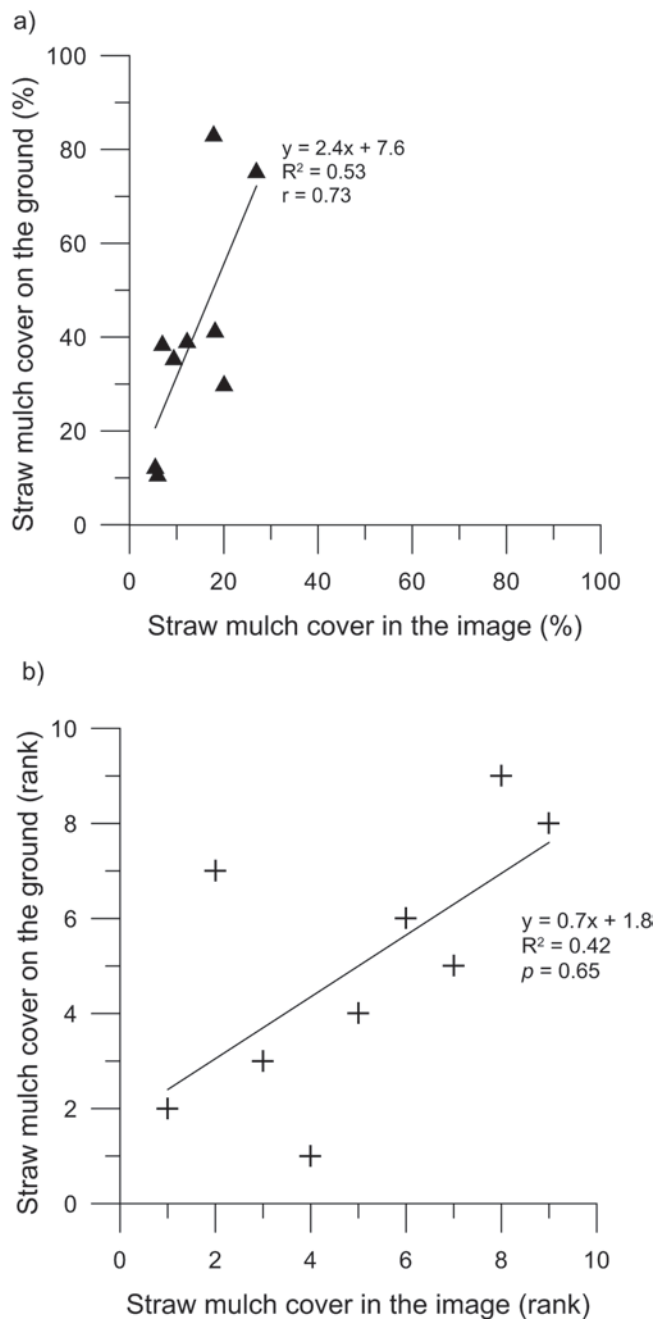


Figure 5—Measured straw mulch cover on the ground versus straw mulch cover in the image from the SMA for the data at Site 3 (n = 9). a) is the raw data (straw mulch cover); and b) is the ranked data.

The ability to predict a relative straw mulch cover is potentially useful when considering the efficiency and quality of the straw mulch application. It may not be necessary to know the exact percentage of straw mulch at any given spot on the ground, but rather that straw mulch was applied to enough of the area to reduce runoff

and erosion. It has been suggested that 50 to 70% straw mulch coverage is sufficient to provide erosion control and soil stabilization (Robichaud 2000). Therefore, we hypothesize if 50 to 70% of the pixels in the treated area of interest have straw mulch cover, the treatments would be considered satisfactory.

To test, using our field sites, we extracted pixels in a 120- by 120-m (400- by 400-ft, 50 by 50 pixels) area centered on each site to evaluate if sufficient mulch had been applied. All 10 sites had mulch present in at least 70% of the pixels. Nine out of 10 sites had at least 50% mulch cover predicted (greater than 15% in image; fig. 4a) in at least 70% of the pixels, and 7 out of 10 sites had at least 70% cover predicted (greater than 20% in image; fig. 4a) in at least 70% of the pixels. Thus, our analysis would have concluded that the treatment specifications had been met in these areas.

It is important to remember the field data were collected 3 to 12 months after the mulch was initially applied, and the image was acquired 3 months before the field data were collected. Redistribution and decomposition of the straw mulch is likely within this time frame, and this study was not implemented to evaluate the mulch application, rather to test methods that may be used for assessment and monitoring. Ideally, the image would be acquired immediately after the mulch was applied, and the field data would be collected within days of the image acquisition. However, such is rarely the case with field studies, and the logistics of a ground-truthing campaign often span weeks or months. Potential explanations for inconsistencies between the ground and image data include:

- Slope steepness, which may skew the view angle from the satellite.
- The heterogeneity of the straw mulch distribution—both from the helicopter’s initial application or from the redistribution over time—can lead to discrepancies between what was measured on the ground and predicted in the image.
- Geolocation of plots and sites on the ground and then in the image can cause spatial errors unless there is perfect agreement between the locations. Site centers were the only locations that were recorded with GPS; all other plot locations were calculated. Recording all plot and subplot locations would likely improve the spatial agreement between the ground and image data.

Conclusion

Straw mulch was easily identified in the QuickBird imagery because of the distinct spectral signature of the mulch against the burned background. Straw mulch coverage rates were predicted by analysis of the imagery with a correlation coefficient of $r = 0.47$, and a rank correlation of $p = 0.40$. Stronger correlations would probably occur if the image acquisition and field validation occurred closer to one another and if the locations of the individual plots were more accurately identified on the image. The correlation analysis indicated the ability to predict relative straw mulch cover beyond the sites where explicit straw cover measurements were collected. It is encouraging that we were able to identify (presence or absence) the straw mulch coverage and estimate high or low coverage from the high-resolution imagery.

Management Implications

Our results encourage further exploration of the use of high-resolution imagery for research applications and post-fire management. It is generally assumed (and minimally field-verified) that the heli-mulch treatment was applied as prescribed because it is difficult to measure treatment rates due to the spatial extent of the fire and remote nature of wildfires. This is unfortunate because of the high cost of post-fire erosion control treatments and the importance of protecting resources at risk by ensuring adequate straw mulch cover is applied to the disturbed soil. A remotely sensed image provides a means to estimate the treatment coverage and to potentially verify that the heli-mulch contract specifications were met, especially in large treatment areas. These methods probably will not be used in all post-fire treatment situations, but they are potentially useful where remote contract validation and/or monitoring are needed. The longevity of the treatment application and native vegetation response could also be monitored through the acquisition of subsequent annual or semi-annual images. This study focused on straw mulch, but the analysis techniques would probably apply to other mulch treatments such as wood shreds or wood strands or hydromulch.

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