Response to interactive comment on "Application of MODIS snow cover products: wildfire impacts on snow and melt in the Sierra Nevada" by P. D. Micheletty et al.

We thank Anonymous Referee #1 for their constructive comments. We appreciate Reviewer 1's time and effort to improve our paper. We agree that there are a few areas of the paper that need clarification and we will use your comments to improve the readability and organization of the paper. We have addressed each comment individually, in bold, below.

Anonymous Referee #1
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General comments
The authors provide an analysis of pre and post-fire conditions over the Moonlight Fire affected region using MOD10A1 and MODSCAG imagery. Their conclusions show a significant change in several SCA metrics, including CDFs and melt-out dates.

The manuscript is well written and the analyses are consistent. I would point out to a couple of moderate observations though:

1) The objective of the paper is not to compare MOD10A1 and MODSCAG in terms of accuracy of SCA. The authors should be careful when saying that one product is better than the other based on the results of this particular work. In order to say that one product is "better", a ground truth comparison is required (which is beyond the scope of this paper). The authors are on the right path when pointing out the MOD10A1 limitations though.

Thank you for bringing this to our attention. There are more rigorous comparisons of the accuracy or validity of the two products, which is outside of the scope of this paper. However, one of our objectives was to determine which product (MOD10A1 or MODSCAG) is more suitable for identifying changes in SCA, specifically, after a wildfire. We have revised areas of the paper to better clarify this distinction (changes are reflected in the introduction and conclusion).

2) The adjustment of the canopy must be performed with annually varying canopy fractions from the MOD44B product. However, I am not sure if the authors performed this for the post-fire conditions. I checked the webpage of MOD44B and it seems that the product is available only until 2010. Please check this. I don't expect the conclusions to change significantly though.

As the reviewer pointed out, the product is only available from 2000-2010. To adjust the SCA values for water years 2011 and 2012 the fraction of vegetation metric produced from the MODSCAG algorithm was used. In order to remain consistent, the MODSCAG fraction of vegetation was then adjusted to match MOD44B percent tree cover product through a linear regression. The MODSCAG fraction of vegetation product was made into annual composites and compared to the MOD44B product. The final adjusted MODSCAG fraction of vegetation product is used in equation 5 for WY 2011 and 2012.

To clarify and state our methods, the original text has been revised in section 3.1.3 of the manuscript.

3) It is important to distinguish between effects of the fire on ground SCA vs. effects on viewable SCA by the sensor. Whenever you detect and analyze changes in SCA from pre to post-fire conditions, be sure to assess if the detected change could correspond to changes in viewable SCA conditions.

We understand that there is a difference between the effects of fire on the ground SCA versus the effects on viewable SCA by the sensor. We have reviewed the manuscript and have made sure that this distinction is clear.

For example:
In the Methods section 3.2.2, "The difference maps (ΔfSCA) are used to detect spatial changes in *viewable* snow cover after the fire"

Results section 4.3, "…highlight shifts in *viewable* snow cover after the fire (Figure 5)."

Discussion section 5, "..the primary goal of this study is to evaluate the effects of wildfire on the spatial and temporal distribution of *viewable* snow cover.."

4) Is there the chance to compare the behavior of the SCA over the Moonlight fire region to a region with a lower forest cover? It would be very interesting to analyze if the post-fire SCA conditions are similar to a non-forested watershed (i.e., has the "SCA regime" changed from forested to non-forested?). I understand this analysis is difficult as probably most of the similar elevation watersheds/regions have similar forest cover.

We appreciate the reviewer's suggestion and agree that this would indeed be an interesting study. However, as the reviewer also pointed out, in order to take into account the effects of climate the comparison basin would need to be at a similar elevation range and climate zone. Through our extensive analysis of nearby basins (used to identify our control basin, Grizzly Ridge) based on elevation range, aspect, and NLCD vegetation classes, we didn't find comparable basins with large non-forested areas. Although there are small areas of grassland meadows within each study domain, they are not large enough to investigate with great confidence because the MODSCAG product is relatively course at 500 meter resolution. Our primary objectives were to first determine whether or not changes in SCA after a wildfire could be identified and quantified using current remote sensing techniques at the large watershed scale. This was accomplished by compensating for climate with a similar (geographically and geomorphologically) control basin, Grizzly. An analysis of whether post-fire SCA conditions are similar to natural non-forested SCA conditions would be an interesting follow-up paper, especially with higher resolution (~30m) products for an inter-basin/hillslope scale study.

I recommend accepting the paper with minor revisions.

Specific comments

Figure 1 - Include geographical coordinates information for each of the regions.

Figure 1 has been revised to include geographical coordinates for each region.

Figure 4 - Increase the contrast between non-canopy and canopy adjusted fSCA (it is very difficult to distinguish both).

The contrast between the non-canopy and canopy adjusted fSCA has been increased significantly in order to improve readability in Figure 4.

Page 7516

Line 22: You mention that part of the objective is to determine "the better indicator of SCA" between MOD10A1 and MODSCAG. Is this really part of the objectives? This has been studied previously, for example Rittger et al. (2011) does a comprehensive review of current MODIS snow products. I would rephrase the statement.

Thank you for this suggestion. This is similar to your first comment. One of our objectives was to determine which product is more suitable for identifying changes in SCA, specifically, after a wildfire. We rephrased the original statement to reflect this statement.

Revised Text ".. 2) Compare MOD10A1 and MODSCAG products in pre- and post-fire conditions to determine which product is more suitable for identifying changes in SCA after fire .."

Page 7517

Lines 3-4: Do you mean "total cumulative burned area"? Or "annual burned area"? This part is not clear.

We have clarified this statement as follows:

Original Text: "There is a statistically significant ($P<0.05$) increase in total area burned in the Sierra Nevada from the 1980s to the present. The 1980s decadal average of burned area increased from 300 km^2 to 900 km^2 …."

Revised Text: "There is a statistically significant ($P<0.05$) increase in total *annual* area burned in the Sierra Nevada from the 1980s to the present. The 1980s decadal average of *annual* burned area increased from 300 km^2 to 900 km^2 …"

Page 7520

Line 11: Maybe this is a question for Painter et al., but does MODSCAG include a "burned canopy" endmember in the spectral library? If it doesn't, how does it account for the reflectance of burned canopy?

Thank you for bringing up this interesting point. From our literature review it is unclear if "burned canopy" is included in the spectral library (but we hypothesize it is likely not in their endmember library). This may be a better question for the developers of the algorithm. In general, an *endmember* is a "pure" surface cover with a distinctive spectral signature. The library used for MODSCAG is not described in detail in Painter et al., 2009 or Painter et al., 2003. It is stated that the spectral library was developed from field and

laboratory data using an ASDI spectroradiometer, and includes various classes of vegetation, rock, soil, and lake ice. Burned or charred vegetation or soils are not specifically mentioned. The model output data that is available through NASA JPL, however, does not distinguish between vegetation classes or rock types, etc. but rather outputs a fraction of vegetation, fraction of snow cover, etc. Therefore it is unclear how well the model identifies burnt vegetation. We argue that having burnt canopy within a pixel would not inhibit the models ability to clearly identify the areas with snow, based on the shape of snow's spectrum and the large grainsize library, which is ultimately what we are investigating. It could be the case that as the fraction of snow diminishes within a pixel and the burnt area increases, the accuracy of the model may decrease, but this is true in general with the MODSCAG algorithm (regardless of the vegetation, soil, or rock type) and is discussed in our manuscript.

Page 7521

Lines 18-19: Why do you apply a vegetation correction to MODSCAG and not to MOD10A1? By applying the correction to MODSCAG you are scaling up the MODSCAG fSCA values, while leaving MOD10A1 untouched. I wouldn't recommend doing this as the results are not comparable if the correction is not applied to both values.
It would be interesting to extend the analyses you perform in this paper to canopy adjusted MOD10A1.
Furthermore, what is the effect of fire in the MOD44B product? Is this a continuously updated dataset? I would expect that a fire would introduce a significant difference in tree cover, and thus correcting post-fire fSCA with pre-fire MOD44B would result in an error.

The MOD10A1 was not adjusted for canopy cover using equation 5 in the manuscript for the following reasons: Version 5 (used here) of the MOD10A1 contains a fSCA product which is based off of a linear fit to binary Landsat TM snow cover data to the NDSI of MODIS. NDSI relies on the absolute reflectance of each individual pixel and (unlike MODSCAG) does not distinguish how much of that pixel is vegetated (or not snow). To account for this, Klein et al. (1998) developed a method to map more snow in vegetated areas based on a threshold of NDVI and NDSI (described in our manuscript). These thresholds are used to "screen" the fractional snow cover results from the linear regression. Therefore, the fSCA values from the MOD10A1 product are already "corrected" for vegetation based on the NDSI and NDVI threshold explicitly integrated in the NASA algorithm. As we discuss in section 4.1, MOD10A1 tends to overestimate snow in densely vegetated areas (pre-fire) due to this exact vegetation correction. We advocate that performing an additional canopy correction to MOD10A1 using equation 5 would be redundant. Based the concern that you have raised, we have revised the text in Methods section 3.1.1 to make this more apparent to the readers.

To further address your comment, the MOD44B product is based on annual composites of MODIS images. Therefore, vegetation change from one year to the next is captured. This product is commonly used to investigate changes in forest canopy cover, due to disturbances such as deforestation or fire. The MODSCAG fSCA (including post-fire years) is corrected for each year based on annual estimates of fraction of vegetation (fVeg). FVeg is estimated using MOD44B for years 2000-2010 while 2011 and 2012 estimates are estimated from the adjusted MODSCAG fVeg (previously discussed in Comment #2). This section (3.1.3) of the manuscript has been revised to provide more detail in this area.

Page 7524

Lines 1-2: Is this relationship between exceedance probability and SCA calculated with your data? If it is, explicitly mention that you already did that calculation. Lines 3-4: A basin average of 10% fSCA doesn't necessarily include many individual pixels with relatively high fSCA. This statement must be backed up with observations first.

Thank you for the comment. This statement has been revised: "Exceedance probabilities are derived from the pre-fire fSCA CDF curves and are used to establish high and low thresholds for analysis." And lines 3-4 have been removed.

Lines 5-6: Is the concept of exceedance probabilities used in SCA analyses in other papers? Even though 70% might be used for low-flow analyses, the choice of the value should be justified. A short analysis relating SCA CDF and streamflow CDF would be useful to justify the choice of exceedance probability.

To our knowledge, this is the first instance of this technique on snow covered area. Our method is based on statistical measurements based on the literature referenced in our manuscript. The thresholds represent quartiles in distributions and natural inflection points in the data (regardless of the type of data set). To perform an unbiased analysis on our snow covered area dataset, we incorporated the most common thresholds for upper and lower quartiles. We revised the text in this section to help clarify our approach.

Page 7526

Line 17: Please define how "duration of the winter precipitation" is calculated.
Line 17: How do you relate fSCA ensembles to duration of the winter precipitation? I am not sure if I am understanding this statement.

The duration of the winter precipitation is calculated based on the dates in which precipitation fell primarily as snow. We used an average temperature of 0 or below to guide the winter period selection. The larger fSCA years correlate to longer snow seasons, not necessarily larger (total depth wise) snow seasons. We revised the text to reflect this.

Page 7527

Lines 1-10: See comment for Page 7521, Lines 18-19. Clearly state what are the limitations of the MOD44B product in terms of representation of annual conditions. I am not sure if the MOD44B is updated annually. If it isn't, is the canopy adjustment valid after the fire?

Thank you for this comment. We have revised our manuscript to clarify your concern in section 3.1.3 describing the MOD44B product.

Lines 11-25: This is an interesting analysis. Could it be repeated using the CDFs for the entire time periods? For example, calculate the CDF for the entire pre-fire SCA time series, and do the same for the entire post-fire SCA. I am not sure if you mean this in lines 14-16, please clarify if this is what you calculated.

We did estimate a CDF for the entire pre-fire and entire post-fire records. However, the results were similar, and decided that the current presented analysis is more rigorous. We have clarified the text in the manuscript to express which CDF is analyzed.

Page 7528

Line 5: Does this result imply that there is more SCA on the ground, or only SCA viewed by the sensor? It is important to clarify this point: the larger number of days with higher SCA can be interpreted as “the sensor is seeing SCA that didn’t see before”.

Thank you for this comment. This is SCA viewable by the sensor. We do not have any field verification data; therefore, our analysis is based on snow seen by the MODIS sensor. We have reviewed our entire manuscript and have incorporated this important distinction between on the ground and viewable SCA as you have mentioned.

Page 7530

Line 21-23: Have you quantified the number of storms over the season? How do lower temperatures affect the persistence of SCA? These statements must be quantified.

These results are based on visual interpretation of figure 4 and table 2. This paragraph has been revised to make this more apparent and improve readability.

Page 7531:

Line 14-21: Again, check how frequently MOD44B is updated. Be explicit in the methodology of which MOD44B years are used to correct canopy. I checked the MOD44B website ttps://lpdaac.usgs.gov/products/modis_products_table/mod44b and it states that the availability is from 2000 to 2010.

A more explicit explanation has been added in the methods section 3.1.3 describing the MOD44B product.

Page 7534

Lines 11-13: What do you mean by “active and continuous spectral mixing analysis”? MODSCAG is based on spectral mixing analysis, however I do not understand what you mean by “active and continuous”.

This syntax, “active and continuous spectral mixing analysis” is commonly used and based on Painter and NASA JPL’s snow team. Active and continuous spectral mixing means that the product is updated daily for a smoothed time series. However, we removed the phrase to reduce confusion from readers who are unfamiliar with the product.

Application of MODIS snow cover products: Wildfire impacts on snow and melt in the Sierra Nevada

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Abstract

The current work evaluates the spatial and temporal variability in snow after a large forest fire in northern California ~~with~~ using Moderate Resolution Imaging Spectroradiometer (MODIS) snow covered area and grain size (MODSCAG)~~ algorithm~~. MODIS MOD10A1 fractional snow covered area and MODSCAG fractional snow cover products are utilized to detect spatial and temporal changes in snowpack after the 2007 Moonlight Fire and an unburned basin, Grizzly Ridge, for water years (WY) 2002-2012. Estimates of canopy adjusted and non-adjusted MODSCAG fractional snow covered area (fSCA) are smoothed and interpolated to provide a continuous timeseries of daily basin average snow extent over the two basins. The removal of overstory canopy by wildfire exposes more snow cover; however, elemental pixel comparisons and statistical analysis show that the MOD10A1 product has a tendency to overestimate snow coverage pre-fire, muting the observed effects of wildfire. The MODSCAG algorithm better distinguishes sub-pixel snow coverage in forested areas and is highly correlated to soil burn severity after the fire. Annual MODSCAG fSCA estimates show statistically significant increased fSCA in the Moonlight Fire study area after the fire (WY 2008-2011; $P < 0.01$) compared to pre-fire averages and the control basin. After the fire, the number of days exceeding a pre-fire high snow cover threshold increased by 81%. Canopy reduction increases exposed viewable snow area and the amount of solar radiation that reaches the snowpack leading to earlier basin average melt-out dates compared to the nearby unburned basin. There is also a significant increase in MODSCAG fSCA post-fire regardless of slope or burn severity. R~~Alteration of r~~egional snow cover change has~~s~~ significant implications for both short and long-term water supply~~ies~~ for ~~downstream~~impacted ecosystems, downstream communities and resource managers.

Key words: *Wildfire, MODSCAG, MODIS, snow cover, snowmelt, Sierra Nevada*

1 Introduction

The last several decades have been marked by distinct increases in large-wildfire frequency as well as fire duration and season across the western U.S. (Westerling et al., 2006). Soil and vegetation change after fire result in increased flooding, mass-wasting, increased runoff intensities, long-term changes in ~~the~~ energy and water budgets, and increased air pollutants (Swanson, 1981; Kattelmann et al., 1983; Stednick, 1996; Webb et al., 2012). Storm runoff also liberates atmospherically deposited contaminants and mobilizes particulate-bound constituents, degrading post-fire water quality (Stein et al., 2012; Burke et al., 2013). Vegetation recovery significantly controls long-term hydrologic conditions and elevated discharged has been observed for nearly ten years post-fire (Kinoshita and Hogue, 2011). Similarly, forest canopy considerably influences snowpack properties and snowmelt response (Faria et al., 2000). Given the dependency of the Western U.S. on snowpack and mountain runoff for water supply (NRCS, 2012) and the assumption of stationarity, under which water reservoir systems are designed and managed (Milly et al., 2008), minimal forest structure alterations will have critical implications for regional and state water resources and management.

Field-based studies have found that disturbance in forest structure considerably impacts snow accumulation and melt properties, altering water yield from snow dominated basins (Kattelmann et al., 1983; Stednick, 1996; Faria et al., 2000; Stephens et al., 2012; Webb et al., 2012). Post-fire changes in snowpack energy balance include increased e exposure to radiation ~~exposure~~, decreased snow albedo due to surface alterations from charred soils, dust, or vegetation, and changes in soil temperature (Painter et al., 2007; Burles and Boon, 2011; Ebel et al., 2012; Gleason et al., 2013; Harpold et al., 2013). The opposing effects of increased snow accumulation but increased snow ablation have been documented at the plot scale for the first year following a wildfire (Gleason et al., 2013; Harpold et al., 2013). Plot-scale studies generally reported significant increases in snow accumulation in burned areas compared to nearby control plots due to the lack of canopy interception (Burles and Boon, 2011; Harpold et al., 2013). Decreased canopy cover reduces snow interception, increases solar radiation exposure, and alters sublimation of the exposed snowpack (Faria et al., 2000; Varhola et al., 2010; Harpold et al., 2013). Harpold et al. (2013) showed winter season ablation reduced snowpack depths by 50% prior to melt and a 10% reduction in snow water equivalent in burned areas the first year after fire. Gleason et al., (2013) showed a 40%

decrease in snow albedo accompanied by a 200% increase in net shortwave radiation in burned forest plots compared to unburned forests. However, effects are undocumented at the watershed scale and there is a ~~need for additional~~paucity of studies on snow accumulation and melt variability from forest cover change (Varhola et al., 2010).

Remote sensing products, including NASA Moderate Resolution Imaging Spectroradiometer (MODIS) MOD10A1 and MODIS Snow Covered Area (SCA) and Grain size (MODSCAG), a spectral mixing product, provide the spatial and temporal resolution necessary for monitoring large-scale wildfires that often impact inaccessible and ungaged snow-dominated basins. To our knowledge, no study has investigated pre-fire and post-fire snow cover change using satellite imagery. The current study facilitates identification of remote sensing tools capable of detecting spatial and temporal changes in post fire snowpack through application of MODIS MOD10A1 and MODSCAG fractional snow covered area (fSCA) products to the 2007 Moonlight Fire in northern Sierra Nevada, California. Specifically, the objectives of our work are to: 1) Understand spatial and temporal variability of pre- and post-fire fSCA with MODIS (MOD10A1 and MODSCAG)products, 2) Compare MOD10A1 and MODSCAG products in pre- and post-fire conditions to determine which product is more suitable for identifying change~~s~~ in SCA after fire~~the better indicator of SCA~~, 3) Investigate the influence of aspect, burn severity, and general climate patterns on post-fire snow behavior (using fSCA as a proxy), and 4) Evaluate post-fire recovery patterns in a snow-dominated basin over several years.

2 Study Areas

2.1 Moonlight Fire

There is a statistically significant ($P<0.05$) increase in total annual area burned in the Sierra Nevada from the 1980s to the present. The 1980s decadal average of annual burned area increased from 300 km^2 to 900 km^2 in the current decade (Wildland Fire Incidents, 2013). The Moonlight Fire burned over 250 km^2 (27,370 ha) in the Plumas National Forest (about 190 km north of Sacramento) from September 3-15, 2007 on the eastern side of the northern Sierra Nevada divide (Figure 1). Since the late 1800s, this was the first major wildfire recorded in this area (California Department of Forestry and Fire Protection, 2012). Steep terrain and high winds caused a mosaic of soil burn severities resulting in concentrated areas of high surrounded by moderate to low/unburned areas (USDA Forest Service RSAC, 2007; Figure 1). Pre-fire vegetation consisted of mostly evergreen forest (90%) with some riparian and shrub/scrub areas (Fry et al., 2013; Table 1). The slope aspects within Moonlight Fire are relatively evenly distributed~~, with a dominant south facingslope, followed closely by west, north, and east~~ (Table 1). The Moonlight Fire burn area has an elevation range of 1090 – 2290 meters and receives on average 680 mm of precipitation a year, the majority of which falls in the winter months as snow (Table 1).

2.2 Grizzly Ridge

To evaluate the fire signal relative to regional climate variability a complimentary regional control basin, Grizzly Ridge, was chosen for comparison. The Grizzly Ridge area has not burned within the last 100 years of record (California Department of Forestry and Fire Protection, 2012). It is 150 km^2 (14,800 ha) approximately 24 km south of Moonlight Fire on the same side of the divide in the Sierra Nevada (Figure 1). Vegetation within the Grizzly Ridge area is comprised of mostly evergreen forest (80%) and shrub/scrub in the lower elevations (Fry et al., 2013; Table 1). The slope aspects exhibits similar patterns as Moonlight Fire, although Grizzly Ridge has roughly 10% more south facing slopes (Table 1). The Grizzly Ridge area has an elevation range of 1300-2320 meters and receives an annual basin average of 880 mm of precipitation.

3 Methods

MODIS MOD10A1 and MODSCAG products were gathered for both areas, Moonlight Fire and Grizzly Ridge, from October 1, 2001 to September 30, 2012 (water year (WY) 2002 – 2012). Both products only identify areas covered by snow, not snowpack depth – a longer snow season will distinguish more fSCA, but not depth changes or snow water equivalent. Annual and monthly precipitation and maximum and minimum temperatures for Moonlight Fire and Grizzly Ridge were estimated from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) climate data set (Daly, 1994; 1997; 2002). Conterminous U.S. products are downloaded from the PRISM Climate Group (http://www.prism.oregonstate.edu/) and the monthly 4 km pixels are extracted within Moonlight Fire and Grizzly Ridge and averaged over both domains for WY 2002-2012.

3.1 Remote Sensing Products

3.1.1 MODIS MOD10A1

The Terra MODIS SCA product (MOD10A1) provides atmospherically corrected daily fractional snow cover at 500 m spatial resolution based on the normalized difference snow index (NDSI). The preprocessed MODIS product includes spectral thresholds that mask and screen for clouds and low reflectance surfaces such as water (Salomonson and Appel, 2004). To account for snow in densely vegetated areas Klein et al., 1998 developed a method that uses a combined snow reflectance model and canopy reflectance model to map more snow in forested areas using normalized NDSI and the normalized difference vegetation index (NDVI; Klein et al., 1998). The NDVI normalizes ~~the~~ reflectance~~s~~ in the near-infrared and visible (red) wavelengths to differentiate vegetation where there is chlorophyll absorption of red light for photosynthesis and reflection of near-infrared light (Tucker, 1979):

$$NDVI = \frac{R_{NIR} - R_{VIS}}{R_{NIR} + R_{VIS}} \quad (1)$$

where R_{NIR} is near-infrared reflectance and R_{VIS} is red reflectance in the visible spectrum. The NDSI is evaluated as (Dozier, 1989):

$$NDSI = \frac{R_{VIS} - R_{SWIR}}{R_{VIS} + R_{SWIR}} \quad (2)$$

where, R represents spectral reflectances in the visible and shortwave infrared bands. The vegetation correction is used to map snow when NDSI < 0.4 and NDVI > 0.1.

The newest publicly available version [005] of MODIS fractional snow covered area, MOD10A1 is a daily, 500-m product, available from 2000 to the present (Hall et al., 2006). MOD10A1 fSCA is based on an empirical snow mapping algorithm developed from a linear regression between binary Landsat Thematic Mapper snow cover and MODIS NDSI (Salomonson and Appel, 2004; Hall et al., 1995):

$$fSCA = -0.01 + 1.45 NDSI \quad (3)$$

This algorithm is used to map fractional snow cover and performs relatively well in the winter months in mountainous regions compared to other remote sensing products and ground-based observations (Maurer et al., 2003; Pu et al., 2007).

3.1.2 MODSCAG

MODSCAG is derived from a physically-based algorithm which uses a multispectral mixing analysis to identify sub-pixel snow covered area and grain size (Painter et al., 2009). The MODSCAG model has been validated over the Sierra Nevada, Rocky Mountains, high plains of Colorado, and Himalayas using Landsat fSCA, field data, and in situ albedo observations (Painter et al., 2009). The MODSCAG algorithm solves a combination of linear equations to identify the best mixture of endmember components that make up the surface reflectance of a pixel from the MODIS atmospherically corrected surface spectral reflectance product, MOD09GA (Painter et al., 2009):

$$R_{S,\lambda} = \sum_{k} F_k R_{\lambda,k} + \varepsilon_\lambda \tag{4}$$

where $R_{S,\lambda}$ is the average surface reflectance from MODIS in wavelength λ, F_k is the fraction of endmember k (i.e. snow, vegetation, soil, rock, etc.), $R_{\lambda,k}$ is the surface reflectance of endmember k in wavelength band λ, and ε_λ is the residual error at λ for all endmembers. Non-snow endmembers are gathered from a library of hyperspectral field and laboratory observations. MODSCAG uses a library of spectral reflectances generated from the hemispherical-directional reflectance factor with a discrete-ordinates radiative transfer model to identify snow endmembers (Painter et al., 2009). This method utilizes the shape of the snow's spectrum rather than absolute reflectance. A simultaneous solution of sub-pixel snow surface grain size and fractional snow cover is necessary, assuming that spectral reflectance of snow endmembers are sensitive to surface grain size.

MODSCAG analyzes the linear mixtures of endmember spectral libraries and selects the optimal model with the smallest error relative to MOD09GA surface reflectance and the fewest number of endmembers. If snow endmembers are identified, MODSCAG will attribute a snow-covered area and grain size based on the fraction of the snow endmember in the pixel. The MODSCAG snow mapping algorithm for fSCA results in an average root-mean-square error (RMSE) of ~5% (Rittger et al., 2013). MODSCAG shows less sensitivity to regional canopy cover and is noted to more accurately identify snow cover throughout the year compared to MOD10A1 (Rittger et al., 2013). The current study incorporates MODSCAG to evaluate pre- and post-fire snow covered area relative to the MOD10A1 product for Moonlight Fire and Grizzly Ridge.

3.1.3 Canopy Adjustment

Forest canopy obstructs the view of the ground by MODIS, causing underestimates of snow cover in dense forests (Raleigh et al., 2013). Hence, forest cover density data is used to indicate snow cover masked by canopy and improve MODSCAG estimates of viewable snow cover (Molotch and Margulis, 2008):

$$fSCA_{Adj} = \frac{fSCA_{Ob}}{1 - fVeg} \tag{5}$$

where $fSCA_{ob}$ is the observed MODSCAG fSCA and fVeg is the annual density of forest cover or the fraction of vegetation. For 2000 to 2010, fVeg is estimated from the MODIS (MOD44B) percent tree cover product (DiMiceli et al., 2011). The percent tree cover product from MOD44B is derived from annual composites of MODIS data using an automated supervised regression tree algorithm and is available for years 2000-2010. The MOD44B product is updated annually and has been used extensively to investigate landcover change~~s~~ and forest disturbance~~s~~ (Hansen et al., 2003; Morton et al., 2005). For years 2011 and 2012, the MODSCAG fraction of vegetation product is used to estimate fVeg. For consitency, 2011 and 2012 MODSCAG fraction of vegetation is adjusted based on a linear regression of annual composites of MODSCAG fraction of vegetation and MOD44B percent tree cover. The canopy adjusted fSCA (Equation 5) assumes that the distribution of snow under a canopy is equivalent to viewable open areas between trees or in clearings. This assumption that spatial distribution of snow in viewable gaps can be interpolated to nearby canopied forests is not as reliable during the accumulation and melt periods (Raleigh et al., 2013). A rigorous correction to improve estimations of snow under canopy using optical sensors remains an area of active research for remote sensing in forested terrains, and is outside the scope of this study. In the current study, MODSCAG fSCA is adjusted for canopy cover (Equation 5), whereas the MOD10A1 SCA is distributed with vegetation corrected fSCA (Klein et al., 1998) and does not require further modification.

3.2 Spatial and Temporal Analysis

3.2.1 Basin fSCA Interpolation

Temporal analysis for WY 2002-2012 uses daily basin averaged MODSCAG fSCA for both Moonlight Fire and Grizzly Ridge. The daily data initially has gaps and errors from cloud cover, sensor viewing geometry, or imperfections in the retrieval algorithm. A combination of noise filtering, snow/cloud discrimination, and interpolation and smoothing improves the MODSCAG daily snow cover timeseries (Dozier et al., 2008). Dozier et al. (2008) view the snow data as a space-time cube, which can be filtered, smoothed, and interpolated. In the current study, the space-time cube is filtered to remove cloudy or noisy values; the remaining data is used to interpolate and smooth gaps within the cube.

Filtering consists of several steps: 1) a two-dimensional adaptive Wiener filter (Matlab wiener2 function) is used to identify noise and data dropouts in all seven land reflectance bands, where the Boolean variable is set to 1 for raw fractional snow-covered area that is 0; 2) quality flags from the MOD09 product are used to identify snow-covered pixels as cloudy. False positives and false negatives are identified from MODSCAG snow cover (fSCA) and grain size (r) processing. Then thresholds (false positives: $fSCA > 0.6 \wedge r \geq 100$ μm and false negatives: $fSCA > 0.6 \wedge r \leq 100$ μm) are used to reduce misidentification; 3) to correct for values obscured by MODIS scan angles (the primary source of error), the time dimension of the space-time cube is interpolated using a cubic smoothing spline (Matlab csaps function). The current study uses 16 days (representing a MODIS viewing angle cycle) for the limits of integration; the smoothing parameter is adaptive and varies spatially depending on the extent of cloud cover or missing data. The weight varies from 0 to 1 and is based on the viewing angle (determined from the corresponding MOD09GA) such that the near-nadir views have the greatest weights. If the cubic smoothing spline yields unrealistic values from gaps in data, the smoothed fSCA values are interpolated using a piecewise interpolant; and 4) after steps 1-3, the whole cube is smoothed with a Gaussian filter, providing a continuous data stream of snow covered area.

3.2.2 Elemental Pixel Comparison

Differencing maps for each gridded fSCA product, MOD10A1 and MODSCAG, are developed by taking the difference between winter (January – March) pre-fire average fSCA (WY 2002-2007) and post-fire average fSCA (WY 2008-2012); the domain includes 1099 pixels. The difference maps (ΔfSCA) are used to detect spatial changes in viewable snow cover after the fire. An elemental pixel comparison (EPC) between MODSCAG fSCA and MOD10A1 fSCA is evaluated using a least-squares linear regression analysis of individual pre- and post-fire winter pixels. EPC is also used to investigate temporal changes in snow cover based on corresponding basin attributes including burn severity and slope aspect.

Gridded daily fSCA is disaggregated over each domain by slope aspects (north, south, east and west) derived from a USGS National Elevation Dataset (NED) 30 meter Digital Elevation Model (DEM). Daily basin average estimates are then produced for each slope aspect for WY 2002 to 2012 for Grizzly Ridge and Moonlight Fire. For Moonlight Fire, daily fSCA was also disaggregated to match a 30 meter soil burn severity map (based on Landsat burned area reflectance from the USDA Forest Service RSAC, 2007) for EPC ~~(USDA Forest Service RSAC, 2007)~~. A time series of basin averaged fSCA is made based on each burn severity (i.e. high, moderate, and low-unburned) from WY 2002 to 2012 for statistical analyses.

3.3 Statistical Analysis

3.3.1 MODSCAG Cumulative Distribution Function

Annual cumulative distribution functions (CDFs) are developed using daily basin averaged fSCA for both Moonlight Fire and Grizzly Ridge to investigate annual shifts in snow cover after fire. Fractional SCA cumulative distribution functions are similar to flow duration curves, which are used to investigate annual changes in flow regimes due to forest disturbance (Lane et al., 2006; Brown et al., 2005). Fractional SCA CDFs are used to determine the probability that a specific basin averaged fSCA will be equaled or exceeded during a given time period. Exceedance probabilities are derived from the pre-fire MODSCAG fSCA ~~duration~~ CDF curves and are used to establish high and low thresholds for analysis. High snow cover days are defined based on the pre-fire long-term CDFs with an exceedance probability of 10% or less.

During the beginning and end of the snow season, as MODSCAG and MOD10A1 pixels approach an fSCA value of 15% (very low fractional snow covered area), there is increased uncertainty and larger errors in positively identifying snow (Rittger et al., 2013). This study uses an exceedance probability of 70% (representing 10% basin average snow cover) to identify an unbiased low SCA melt-out threshold and reduce error from misidentification of snow. This 70% exceedance probability threshold commonly represents lower quartiles in CDFs and also corresponds to the most widely used definition of low flow as derived from flow duration curves (70-99%; Smakhtin, 2001).

To quantify the change from pre-fire to post-fire, a two-sample Kolmogorov-Smirnov (K-S) test is used to compare the distributions of pre- and post-fire fSCA CDFs. The K-S null hypothesis is that the pre- and post-fire fSCA CDFs are from the same continuous distribution at α=0.01 (Massey, 1951), where the K-S test statistic is the maximum vertical distance between the two curves being evaluated (Cowpertwait et al., 2013).

3.3.2 Analysis of Variance

An Analysis of Variance (ANOVA) is used to determine the statistical significance of temporal changes in snow cover after fire. Daily basin averaged fSCA estimates are separated annually based on the water year, excluding summer months (July to September), and by basin attributes (burn severity and slope aspect). The fSCA is then evaluated for statistical differences from the pre-fire period and compared to the control domain (Grizzly Ridge). The null hypothesis that the mean of each post-fire annual fSCA (WY 2008-2012) is similar to the pre-fire annual mean (WY 2002-2007) is tested at α=0.01.

4 Results

4.1 MODSCAG and MOD10A1 Comparison

Non-canopy adjusted MODSCAG and MOD10A1 differencing maps for Moonlight Fire show a distinct difference in fSCA after the fire (Figure 2). Generally, the spatial pattern of the increased fSCA for both products follows the high soil burn severity in the Moonlight Fire. Higher soil burn severity near the center of the domain results in reduced canopy cover and more visible snow and snow covered area. An EPC and linear regression of ΔfSCA and soil burn severity shows a stronger correlation of non-canopy adjusted MODSCAG ΔfSCA to soil burn severity (r=0.56) than MOD10A1 ΔfSCA (r=0.43). Non-canopy adjusted MODSCAG has a basin average increase in fSCA of 0.3 (Figure 2, right) after the fire whereas MOD10A1 displays smaller differences throughout the burned domain and increases, on average by 0.2 (Figure 2, left). For the MODSCAG product, 44% of the Moonlight Fire domain exhibited ΔfSCA values of least 0.3, while MOD10A1 has 21% of the domain with values of 0.3 or higher.

The least-squared linear regression analysis of MOD10A1 fSCA and MODSCAG fSCA established from the EPC shows a distinct difference between pre- and post-fire correlation (Figure 3). MOD10A1 tends to produce higher estimates of fSCA compared to MODSCAG across the entire domain pre- and post-fire. MOD10A1 is biased high compared to MODSCAG, but the pre-fire linear correlation between the two products is relatively high (r=0.85). After the fire there is an increase in variability and the linear relationship between MOD10A1 and MODSCAG decreases (r=0.69). The linear regression line is also higher post-fire (Figure 3). The upward shift in the regression line in the MODSCAG direction is consistent with the increase in visible fSCA (Figure 2). Decreases in the correlation coefficient after the fire are most likely due to differences in the amount of increased fSCA identified by each product.

Product assessment studies have shown that MOD10A1 fSCA overestimates snow cover in densely vegetated areas (Rittger et al., 2013). These results are consistent with our linear regression analysis. This can be attributed to the MOD10A1 snow-mapping algorithm and NDVI threshold indices (Klein et al., 1998) that are used to identify snow in forested areas. NDVI is a greenness index based on surface reflectances and does not differentiate vegetation types. Therefore, the current NDVI threshold (> 0.1) increases mapped snow cover in areas with shrubs and grasses the same as forested areas. Reduced canopy cover from wildfire should lead to increased viewable snow cover from satellite observations. Due to overestimates in SCA before the fire, this signal is muted in MOD10A1. The EPC results prompted the utilization of MODSCAG fSCA for the remainder of the current study because of the overestimation biases associated with the MOD10A1 fSCA product as well as its lower spatial correlation to soil burn severity. The combination of these results and MODSCAG's more rigorous snow-mapping algorithm, which also takes into account snow grain size, provides us with higher confidence in pre- and post-fire fSCA estimates that will be used for further analysis.

4.2 MODSCAG Timeseries Analysis

Daily basin averaged canopy adjusted and non-canopy adjusted MODSCAG fSCA, monthly precipitation, and temperature (maximum and minimum) are plotted for the Moonlight Fire and Grizzly Ridge for the entire study period (Figure 4). Pre-fire average annual precipitation for Moonlight Fire is 730 mm and for Grizzly Ridge is 900 mm. Post-fire annual precipitation totals are less for both Moonlight Fire and Grizzly Ridge (560mm and 800 mm respectively). Temperature trends for each domain are very similar, with Moonlight Fire and Grizzly Ridge averaging around 9 $^{\circ}$C before the fire and 8 $^{\circ}$C after. Over the ten year time series, the fSCA ensembles are more sensitive to the duration of the winter precipitation season (season in which precipitation occurred at temperatures below 0 $^{\circ}$C) than the total snowfall. The largest fSCA year before the fire (WY 2005) was not from the period with the highest total winter precipitation (710 and 990 mm for Moonlight and Grizzly, respectively) but rather, exhibited the longest snow season (Figure 4; Table 2).

Daily averaged MODSCAG fSCA estimates are uniformly increased based on the annual fraction of vegetation within the canopy adjustment algorithm (Equation 5; Figure 4). The pre-fire average fSCA for Moonlight Fire and Grizzly Ridge is 0.13 and 0.15, respectively; while the post-fire average fSCA is 0.23 for the Moonlight Fire and 0.18 for Grizzly Ridge. Prior to the fire, both fSCA ensembles follow very similar trends (r=0.96). After the fire, the non-adjusted fSCA values in Moonlight fire increase and approach the canopy adjusted fSCA curve due to significant reductions in canopy cover. Pre-fire, the average difference in canopy-adusted and non-adjusted fSCA ensembles is approximately 0.30 for both Grizzly Ridge and Moonlight, while after the fire the difference is decreased in the Moonlight Fire, on average, to 0.18. The non-adjusted MODSCAG fSCA values show a significant increase in basin averaged fSCA (or exposed snow cover) after the Moonlight Fire in 2007 ($P<0.01$) due to the stand replacing fire (Figure 4). MODSCAG fSCA increased, but the canopy adjustment has no statistically significant increase in annual fSCA. However, exposed areas with increased viewable fSCA exhibit altered accumulation and melt behavior due to changes in the snowpack energy budget and are further analyzed with both canopy adjusted and non-adjusted fSCA.

4.3 MODSCAG Cumulative Distribution Functions

Annual CDFs of basin averaged non-canopy adjusted and canopy adjusted MODSCAG fSCA for both Moonlight Fire and Grizzly Ridge highlight shifts in viewable snow cover after the fire (Figure 5). The spread in the pre-fire (Figure 5; black) cumulative distribution functions are attributed to snow season climate variability. For post-fire water years 2008-2011 the annual cumulative distribution functions are statistically different from the pre-fire curve ($P<0.01$), and the null hypothesis is rejected. However, WY 2012 falls within the pre-fire distributions and is not statically different. The K-S statistic indicates post-fire non-adjusted fSCA distributions are elevated, on average, by 40% compared to pre-fire non-adjusted curves. The canopy adjusted fSCA curves are not as sensitive, but still increase by 14% after the fire. The distribution of the post-fire curves in Moonlight is generally higher compared to Grizzly Ridge and is especially apparent using the non-adjusted fSCA (Figure 5a). The shape of the fSCA curves significantly change after the fire due to the upward shift in inflection points. This shifting distribution indicates a higher post-fire probability that the basin will have larger areas of exposed snow coverage.

Using the thresholds established from the cumulative distribution functions, the consecutive number of high snow cover days with respect to the length of snow season are shown for Moonlight Fire (Figure 6a and b) and Grizzly Ridge (Figure 6c and d). Post-fire, there are more days with high snow cover in Moonlight Fire than pre-fire and compared to Grizzly Ridge for both canopy adjusted (Figure 6c and d) and non-canopy adjusted fSCA values (Figure 6a and b). On average, there were 13 days that exceeded the high snow cover threshold in the Moonlight Fire before the fire, whereas after the fire there are on average 70 days classified as high snow cover. Temporal distributions highlight daily basin averaged SCA patterns throughout each year for both canopy adjusted and non-adjusted (Figure 6, right). Larger fSCA patterns are noticeable during winter months (December (12) through April (5)) after the fire. The canopy adjusted fSCA plots (Figure 6b and d) have larger values relative to the non-canopy adjusted due to the linear scaling based on the vegetation fraction (Figure 6a and c); and is congruent with the annual cumulative distribution functions (Figure 5).

4.4 ANOVA

An ANOVA of non-adjusted MODSCAG fSCA shows that post-fire annual basin averaged fSCA for WYs 2008-2011 are significantly higher than pre-fire averages in the Moonlight basin at $\alpha=0.01$ ($P < 0.01$; Figure 7). For the pre-fire years (WY 2002-2007), both Moonlight Fire and Grizzly Ridge follow similar annual basin averaged fSCA trends ($r=0.92$). Before the fire the Moonlight Fire area had, on average, 17% less basin averaged fSCA than Grizzly Ridge. After the fire, however, the Moonlight Fire area had an average of 26% more fSCA than Grizzly Ridge. The Moonlight Fire and Grizzly Ridge domains are also sensitive to winter precipitation, including amount of precipitation and duration of the snow season. Total precipitation as well as the length of snow season in Moonlight Fire and Grizzly Ridge were above average in WY 2005 (Table 2) and yielded more fSCA; while WY 2007 was dry and resulted in less basin averaged fSCA (Figure 7). For the Moonlight Fire, WY 2012 lies within the pre-fire interval and is similar to the pre-fire average, but may be climate induced. Annual precipitation in WY 2012 is 380 mm (Moonlight Fire) and 520 mm (Grizzly Ridge), which corresponds to the lower fSCA. Annual basin average fSCA estimates in Grizzly Ridge note only one (WY 2011) statically significant increase in fSCA during the post-fire period of WY

2008-2012, which is attributed to the larger than average annual precipitation and length of snow season (1200 mm).

After the fire, there are significantly higher annual basin averaged fSCA estimates based on slope aspect and soil burn severity (bold values denote statistical significance; Table 3). Regardless of slope aspect and burn severity, statistically significant increases in fSCA for Moonlight Fire are observed from WY 2008 to 2011 ($P < 0.01$). WY 2012 in all aspects and burn severity is not significantly different than pre-fire fSCA values, but is still relatively high considering that it also received the lowest amount of total precipitation in the 11 year study period. Generally, the high soil burn severity areas within the Moonlight Fire domain have slightly larger annual average fSCA values than moderate and low-unburned (Table 3).

4.5 Annual Melt-out Dates

Annual melt-out dates are estimated for Grizzly Ridge and Moonlight Fire based on the 70% exceedance (10% basin averaged fSCA) threshold established from the canopy adjusted MODSCAG fSCA cumulative distribution functions. At 10% coverage, the domain will have lost the vast majority of its snowpack due to melt. Annual melt-out dates for Grizzly Ridge and Moonlight Fire are compared for pre-fire and post-fire years (Figure 8). Although the melt-out dates are variable from year to year based on annual snow conditions, Grizzly Ridge and Moonlight Fire melt-out dates are relatively similar pre-fire, where it is observed that Moonlight typically melts out an average of 1.5 days after Grizzly Ridge and ranges from -0.5 to 7 days with a standard deviation of 3 days (Figure 8b).

The average long-term pre-fire difference in melt-out dates (1.5 days) between Moonlight Fire and the control basin, Grizzly Ridge, are used to estimate the expected melt-out day for WY 2008-2012 assuming no fire (Figure 8a; red solid diamonds). With the fire, the observed annual difference in melt-out dates between Moonlight Fire and Grizzly Ridge show an average decrease of 7.5 days and more variability post-fire, with a standard deviation of 11 days (Figure 8b). Thus relative to pre-fire averages, Moonlight melts out an average of 9 days earlier. After the fire, Moonlight melts out 1-23 days before Grizzly Ridge each year except for 2012 which has melt-out 5 days after Grizzly Ridge (Figure 8).

5 Discussion

Daily remote sensing products MODCSCAG and MOD10A1 were used to evaluate spatial and temporal changes in snow cover extent over Moonlight Fire and Grizzly Ridge from WY 2002 to 2012. MOD10A1 generates higher fSCA estimates than MODSCAG, which concurs with other studies that show the linear snow-mapping algorithm and the current NDVI threshold (Klein et al., 1998) do not differentiate between vegetation types and results in overestimates of fSCA (Rittger et al., 2013). Elevated pre-fire fSCA estimates dampen the fire signal which should increase viewable snow cover seen from MODIS. The MODSCAG product has a higher linear correlation to soil burn severity than MOD10A1 (r=0.56 and r=0.43, respectively) and on average identifies larger increases in post-fire fSCA than MOD10A1 due to its ability to un-mix a combination of spectral signals within each pixel. As the primary goal of this study is to evaluate the effects of wildfire on the spatial and temporal distribution of viewable snow cover, the results prompted the use of MODSCAG fSCA estimates for the remaining analysis.

Long-term basin averaged MODSCAG fSCA estimates demonstrate statistically significant increases fSCA in the Moonlight Fire domain after the fire (WY 2008-2011; P < 0.01) compared to pre-fire averages. Based on observations, ~~Y~~years with high pre-fire fSCA estimates (i.e. WY 2005), ~~are~~ are more representative of the snow season duration than the~~a~~ ~~function of~~ total winter precipitation~~ and the length of snow season. Multiple smaller storms spread throughout the winter season (rather than fewer larger storms) resulted in a relatively larger extent of snow covered area through the year~~. However, non-canopy adjusted MODSCAG fSCA values in the Moonlight Fire had an average of 43% more fSCA than pre-fire years due to the stand replacing fire and the removal of forest canopy, despite a decrease in annual precipitation of 100 mm and average annual temperature of 1 °C from pre- to post-fire. Pre-fire, non-canopy adjusted fSCA ensembles in both basins followed similar trends (r=0.96), but there is a notable increase from non-canopy adjusted MODSCAG fSCA in Moonlight Fire as compared to Grizzly Ridge of 26%, post-fire.

A decomposition of fSCA in the Moonlight Fire area based on slope aspect and soil burn severity using the EPC is employed to investigate the influence of each attribute. Results show statistically significant increases in fSCA from WY 2008 to 2011 regardless of slope aspect and soil burn severity because of acute changes in vegetation structure and the resulting exposure of more snow cover. Water year 2012 is the only year after the fire that does not show statistically significant changes in fSCA compared to average pre-fire conditions and are attributed to the lowest recorded precipitation in the 11 year study period. Compared to the pre-fire low precipitation year (WY 2007), which received slightly more precipitation than WY 2012, and WY 2012 in Grizzly Ridge, fSCA is still increased by nearly 20% in Moonlight Fire.

In this study, it was beneficial to investigate MODSCAG fSCA estimates adjusted for canopy cover using equation 5 and non-adjusted estimates. Using the two estimates, there is a recognizable change in fSCA due to the reduced vegetation fraction which is apparent as post-fire fSCA ensembles increase and begin to approach the canopy adjusted values. This analysis identifies the importance in incorporating dynamic vegetation fractions when using the canopy adjustment. Static vegetation fractions are likely to result in large overestimates of fSCA after fire, as a result of unnecessary linear scaling of fSCA.

Cumulative distribution functions of canopy and non-canopy adjusted basin averaged MODSCAG fSCA are developed for Moonlight Fire and Grizzly Ridge to investigate post-fire shifts in snow cover and establish high snow cover and melt out thresholds. Using the K-S test, we note that annual post-fire fSCA distribution (WY 2008-2011) is elevated up to 40% compared to the long-term pre-fire distribution, and are significantly different at α=0.01. This represents a higher probability of high fSCA values across the Moonlight Fire. Before the fire, the 10% exceedance threshold (defined as high snow cover) corresponded to an average snow coverage of 33% across the domain using non-canopy adjusted fSCA estimates, and 60% coverage using the adjusted fSCA values. Using these values as thresholds, it was determined that after the fire, there is an average 81% increase in the number of high snow coverage days (i.e. days exhibiting higher than 33% snow coverage or higher than 60% snow coverage using the non-canopy adjusted and canopy adjusted fSCA estimates, respectively) compared to pre-fire conditions and the control basin. Significant changes in the number of days with high snow coverage from elevated annual fSCA cumulative distribution functions compared to both pre-fire conditions, and the control basin are a consequence of the fire and the removal of forest vegetation. It is likely that the increase in fSCA is directly related to additional exposure of the snow surface that was once hidden by forest canopy.

Significant changes in fSCA over the Moonlight Fire domain influence basin melt out dates. Based on the 70% exceedance probability threshold established from the cumulative distribution functions, the differences in melt out dates between Moonlight Fire and Grizzly

Ridge are similar before the fire, only differing on average by 1.5 days. After the fire, for WY 2008-2011, the entire Moonlight Fire domain melts out, on average, 9 days earlier compared to pre-fire conditions with some years melting out up to 23 days early. The significant increases in exposed snow area from reductions in forest canopy cover increase the amount of solar radiation that reaches the snowpack. Early melt due to changes in the snowpack energy balance is consistent with smaller scale field-based studies by Gleason et al. (2013) and Harpold et al. (2013). Changes in melt-out dates can have significant implications for water resource managers in the western US who rely on ~~the~~ mountain snowpack for a majority of their water supply (Bales et al., 2006). The shifts observed in this study have important ~~ramifications~~implications for reservoir operation, downstream water rights, and overall ecosystem health and recovery. Changes in snowmelt timing can heavily influence the partitioning of snowmelt water (Molotch et al., 2009), and ultimately, downstream water availability. Early snowmelt may also result in summer soil moisture deficits (Westerling et al. 2006) further exacerbating the effects of climate change. Snow is a natural storage reservoir for water and understanding the timing of when that water is released into the system is ~~important~~critical for ~~water~~ downstream resource ~~s~~ managers. ~~After~~Following a large disturbance such as wildfire, the~~is~~ altered system can no longer be managed under typical assumptions (Milly et al., 2008). To further complicate post-fire snow dynamics, ~~S~~snowpack melt out dates are also correlated to forest types and species present in the Sierra Nevada (Barbour et al., 2002), and may ~~therefore~~ influence plant phenology and vegetation types during the recovery or regeneration period.~~Changes in melt-out dates can have significant implications for water resource managers in the western US who rely on the mountain snowpack for a majority of their water supply (Bales et al., 2006). Snowpack melt out dates are also correlated to forest types and species present in the Sierra Nevada (Barbour et al., 2002), and may therefore influence vegetation types during the recovery or regeneration period.~~

According to this study, there is ~~very~~ little evidence of canopy recovery from WY 2008-2012 over the Moonlight Fire ~~domai~~area~~n~~ to pre-fire conditions as compared to the control basin, Grizzly Ridge. Basin averaged fSCA and melt out dates for WY 2012 fall within pre-fire averages, but this apparent return or recovery to pre-fire values is partly influenced by climate; as WY 2012 had a low annual basin averaged fSCA because of lower than normal precipitation totals. The sustained post-fire increase in remotely sensed fSCA in Moonlight Fire and earlier melt-out dates is a function of canopy loss. Similar to previous post-fire ecosystem studies, recovery is not expected until there is full canopy regeneration or until the system reaches a new equilibrium (Meixner and Wohlgemuth, 2003, Kinoshita and Hogue, 2011).

6 Conclusions

Continuous mapping of mountainous snow at 500 meter resolution using remote sensing techniques has been seldom applied to answer forest disturbance related hydrologic questions. Long term analysis identified distinct differences in the pre- and post-fire snow cover and total visible snow over the burned domain (Moonlight Fire) when compared to a control basin (Grizzly Ridge). The changes in snow coverage and melt-out dates from WY 2002 to 2012 in the Moonlight Fire are attributed to the removal of vegetation after fire and are driven by corresponding changes in the snowpack energy balance. Specific key findings of this study include

- MODSCAG's spectral mixing algorithm ~~better~~ identifies snow cover in forested areas and is better correlated to soil burn severity compared to MOD10A1. MODSCAG is ~~ultimately better~~ suited to identify changes in snow cover due to reductions in canopy cover after a wildfire.
- There is significantly more basin averaged fSCA ($P < 0.01$) after fire due to reduction of canopy cover and therefore increased viewable snow area.
- There are significant increases in the total number of high snow cover days after fire, based on pre- and post-fire cumulative distribution functions.
- Using the relative difference in melt-out dates between Moonlight Fire and Grizzly Ridge, the Moonlight Fire domain melts out, on average, 9 days earlier after the fire.
- There is minimal spatial or temporal recovery of canopy and snow cover 5 years after the fire.

Climate change and increasing wildfire frequency and size have the potential to highly alter mountain snowpacks. The release of advanced snow mapping products provides a tool for improved application of remote sensing data to better understand hazards such as fire and offers a unique opportunity for future long-term monitoring and research. The successful application of MODSCAG to the Moonlight Fire burn area provides the first watershed-scale analyses of snow cover and snowmelt detection after a large forest fire.

The shifts in the spatial and temporal distribution of snow throughout the year have significant implications for snow accumulation and melt patterns. This study advocates the application of remote sensing products, such as MODSCAG, due to its rigorous ~~active and continuous~~ spectral mixing analysis, which can contribute additional insight of regional post-fire snowpack and recovery studies. Remote sensing application improves our understanding and prediction of snowmelt behavior and is crucial for water resources and management, especially in regions that are highly dependent on snowpack and subject to frequent and acute forest disturbance.

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Table 1. Domain attributes for Moonlight Fire and Grizzly Ridge

Domain Attributes	***2007 Moonlight Fire***	***Grizzly Ridge***
Area [ha]	27370	14800
Elevation Range [m]	1090 – 2290	1300 – 2320
Average Annual Precipitation [mm]	680	880
NLCD Land Cover		
Evergreen Forest	89%	78%
Shrub/Scrub	9%	21%
*Misc.	2%	1%
Soil Burn Severity		
High	37%	N/A
Moderate	18%	N/A
Low – Unburned	45%	N/A
Slope Aspect		
North	21%	17%
South	33%	42%
East	20%	16%
West	26%	25%

Table 2. Length of snow season compared to total winter precipitation for Moonlight Fire and Grizzly Ridge. Post-fire years are shaded in grey.

Moonlight Fire	**Length of Snow Season [Days]**	**Total Winter Precipitation [mm]**
WY 2002	100	610
WY 2003	120	890
WY 2004	90	760
WY 2005	160	710
WY 2006	140	1000
WY 2007	60	410
WY 2008	120	450
WY 2009	130	560
WY 2010	140	590
WY 2011	170	820
WY 2012	100	380
Grizzly Ridge	**Length of Snow Season [Days]**	**Total Winter Precipitation [mm]**
WY 2002	90	780
WY 2003	120	970
WY 2004	110	800
WY 2005	150	990
WY 2006	130	1300
WY 2007	60	560
WY 2008	140	610
WY 2009	140	790
WY 2010	160	870
WY 2011	180	1200
WY 2012	60	520

Table 3. ANOVA results based on basin attributes for Moonlight Fire. Bold font denotes statistical significance ($P < 0.01$), post-fire years are shaded in grey.

Slope Aspect	**South [fSCA]**	**North [fSCA]**	**West [fSCA]**	**East [fSCA]**
WY 2002	0.13	0.12	0.12	0.13
WY 2003	0.12	0.10	0.11	0.13
WY 2004	0.11	0.10	0.10	0.11
WY 2005	0.18	0.17	0.17	0.19
WY 2006	0.16	0.15	0.15	0.17
WY 2007	0.08	0.08	0.08	0.09
Pre-Fire Average	0.13	0.12	0.12	0.14
WY 2008	**0.22**	**0.22**	**0.21**	**0.23**
WY 2009	**0.23**	**0.22**	**0.21**	**0.23**
WY 2010	**0.29**	**0.28**	**0.27**	**0.29**
WY 2011	**0.29**	**0.29**	**0.27**	**0.32**
WY 2012	0.15	0.16	0.14	0.16

Soil Burn Severity	**High [fSCA]**	**Moderate [fSCA]**	**Low-Unburned [fSCA]**
WY 2002	0.11	0.13	0.15
WY 2003	0.09	0.12	0.14
WY 2004	0.09	0.11	0.12
WY 2005	0.16	0.18	0.20
WY 2006	0.14	0.16	0.18
WY 2007	0.07	0.08	0.10
Pre-Fire Average	0.11	0.13	0.15
WY 2008	**0.23**	**0.22**	**0.21**
WY 2009	**0.24**	**0.22**	**0.21**
WY 2010	**0.30**	**0.28**	**0.27**
WY 2011	**0.30**	**0.29**	**0.27**
WY 2012	0.15	0.15	0.15

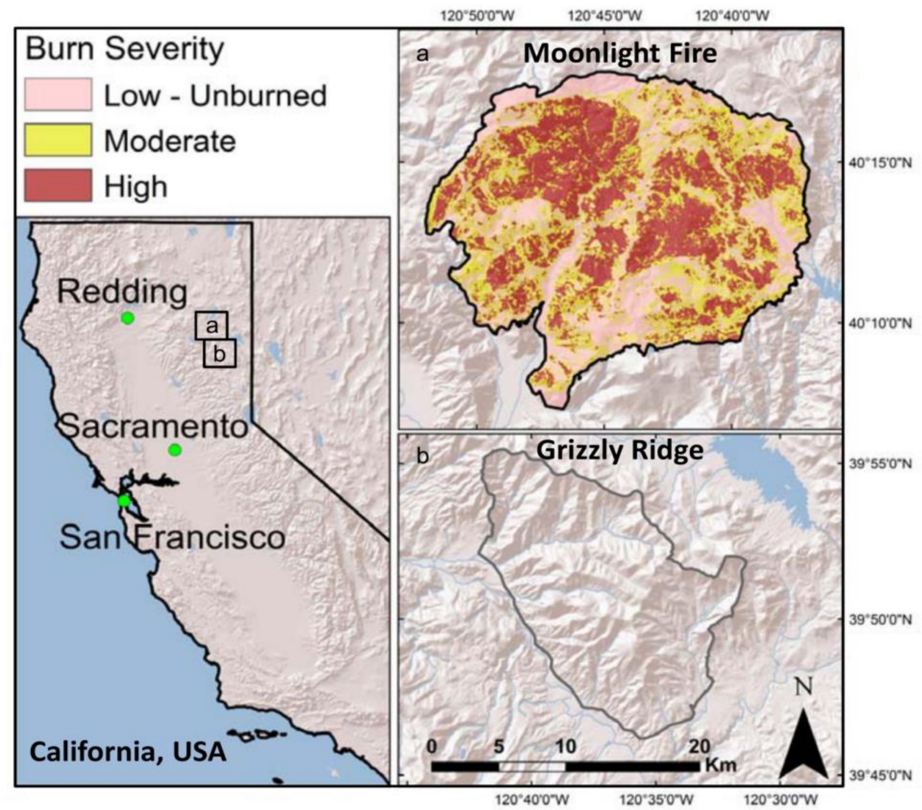

Figure 1. Map of Moonlight Fire with soil burn severity and control basin, Grizzly Ridge

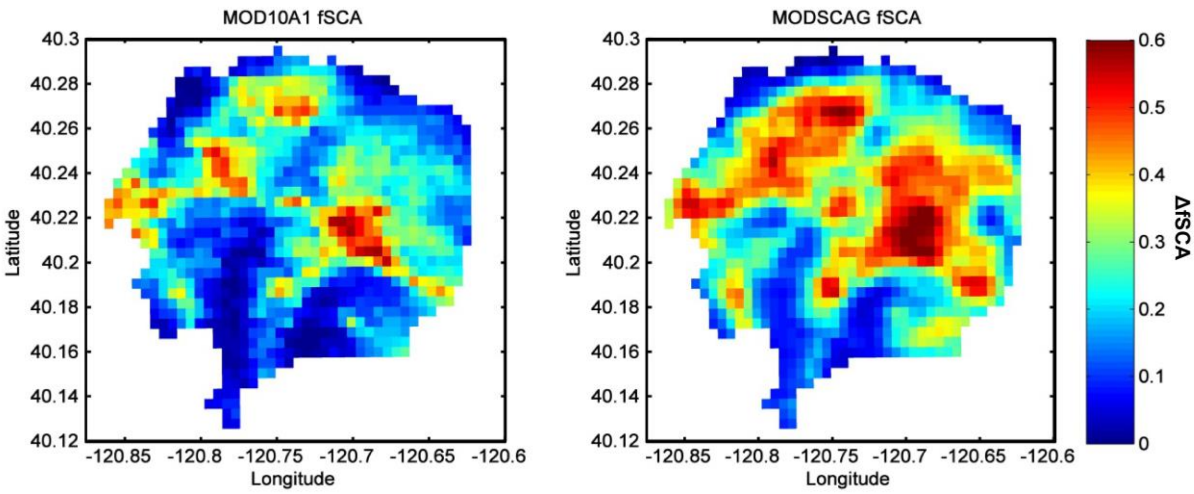

Figure 2. Pre- and post-fire MOD10A1 fSCA (left) and non-canopy adjusted MODSCAG fSCA (right) difference maps for winter (January – March) over the Moonlight Fire. Each image contains 1099 pixels.

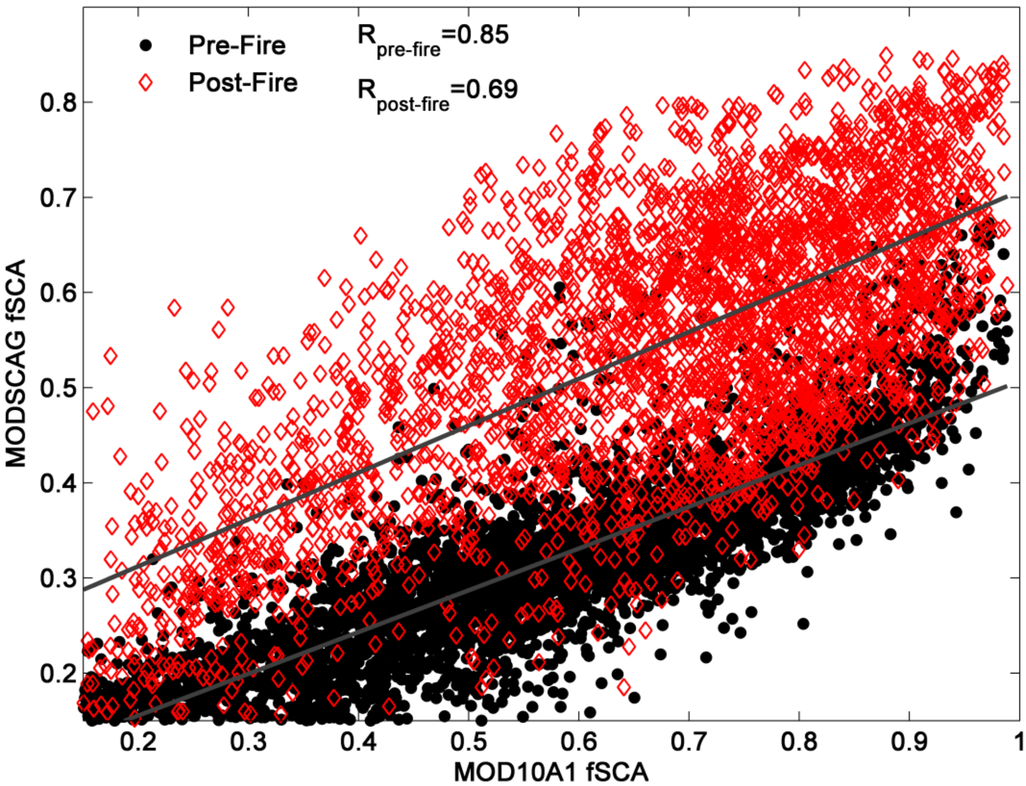

Figure 3. Least-squared linear regression analysis of MOD10A1 and non-adjusted MODSCAG over the Moonlight Fire pre- (black circles) and post-fire (red diamonds).

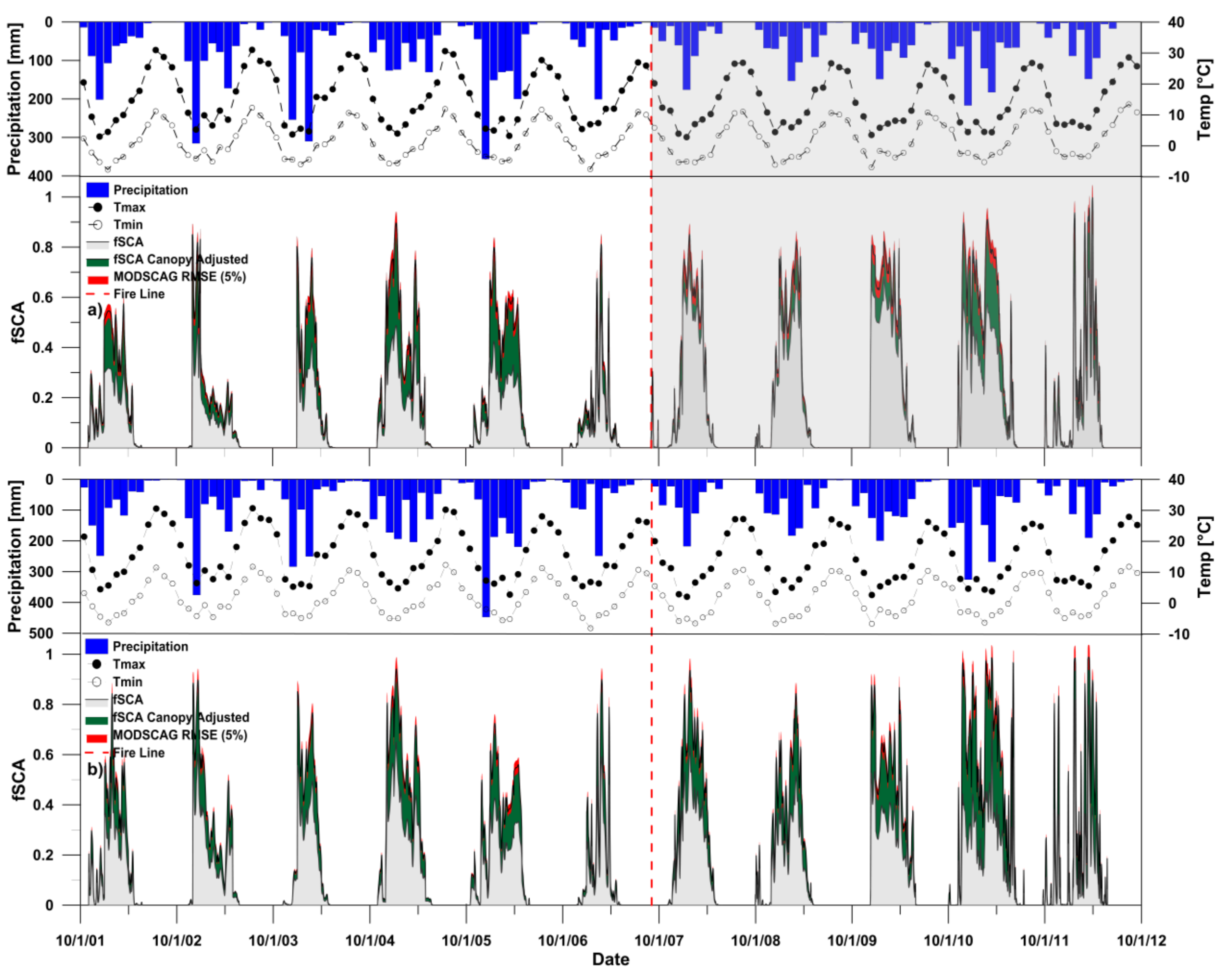

Figure 4. Timeseries of PRISM monthly precipitation totals, minimum and maximum temperatures and daily basin averaged MODSCAG fSCA for Moonlight Fire (a) and Grizzly Ridge (b) for WY 2002 to 2012.

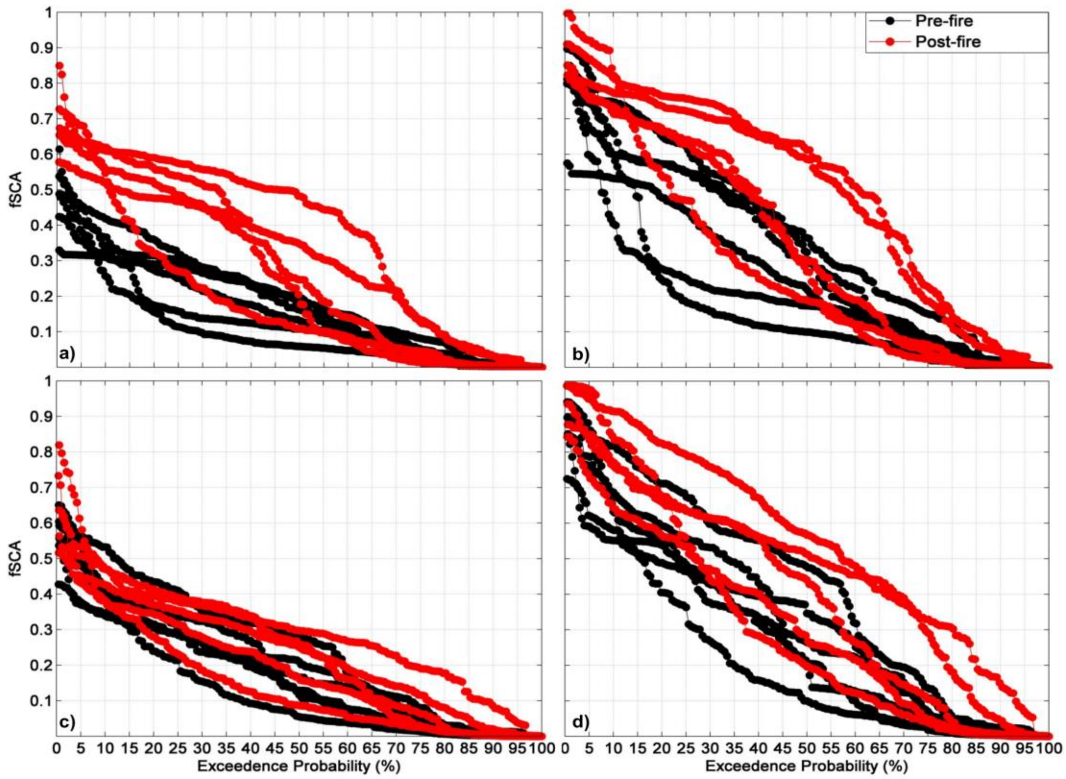

Figure 5. Annual cumulative frequency curves of daily basin averaged non-canopy adjusted MODSCAG fSCA for Moonlight Fire (a) and Grizzly Ridge (c) and canopy adjusted MODSCAG fCSA for Moonlight Fire (b) and Grizzly Ridge (d). Black lines with black circles represent extreme pre-fire fSCA years (highest and lowest annual curves) and red circles represent post-fire annual curves.

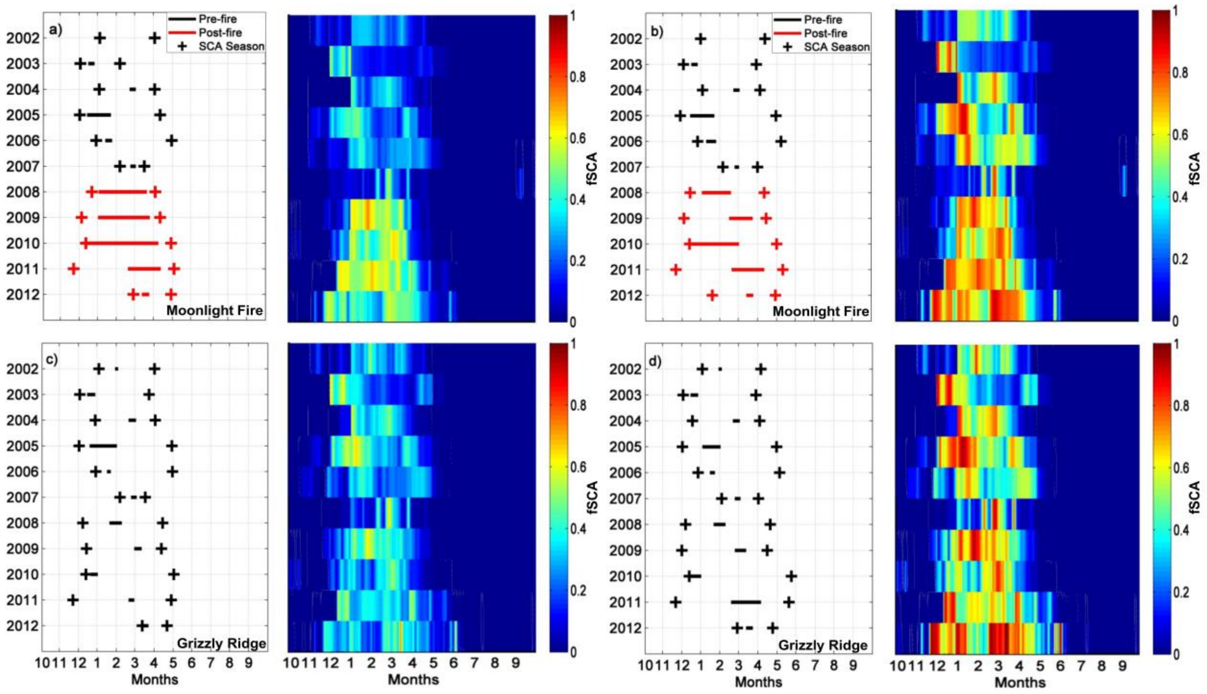

Figure 6. Temporal trends in snow cover of the consecutive number of high snow cover days (pre-fire exceedance probability ≤ 10%; [black and red lines]) with respect to the length of snow season (exceedance probability ≥ 70%; [black and red crosses]) for Grizzly Ridge (c and d) and the Moonlight Fire (a and b). Color maps show annual daily basin averaged fSCA patterns. Figures b and d are canopy adjusted MODSCAG fSCA.

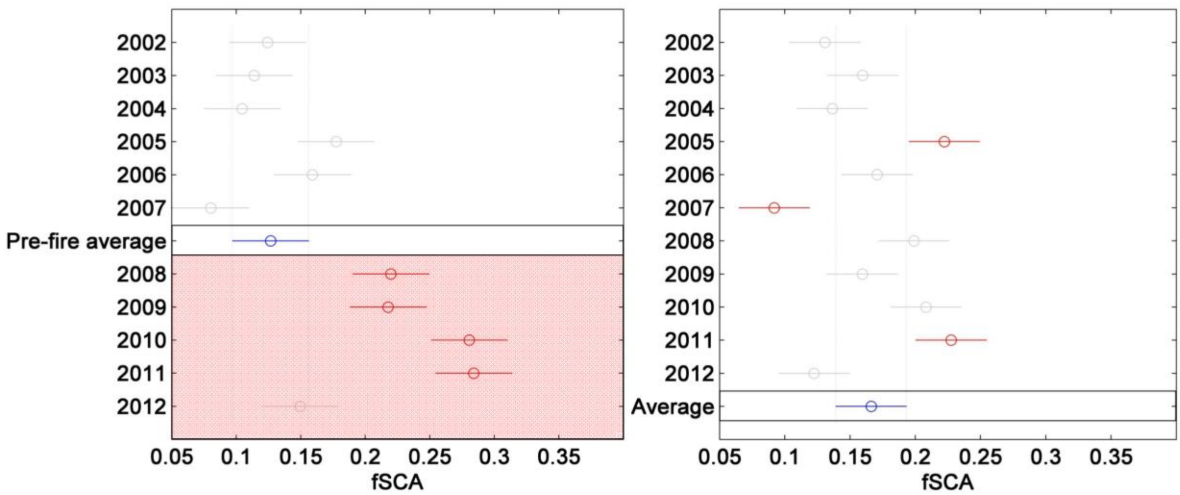

Figure 7. Basin averaged ANOVA results for Moonlight Fire (left) and Grizzly Ridge (right) (99% confidence interval). The post-fire years are shaded for Moonlight Fire.

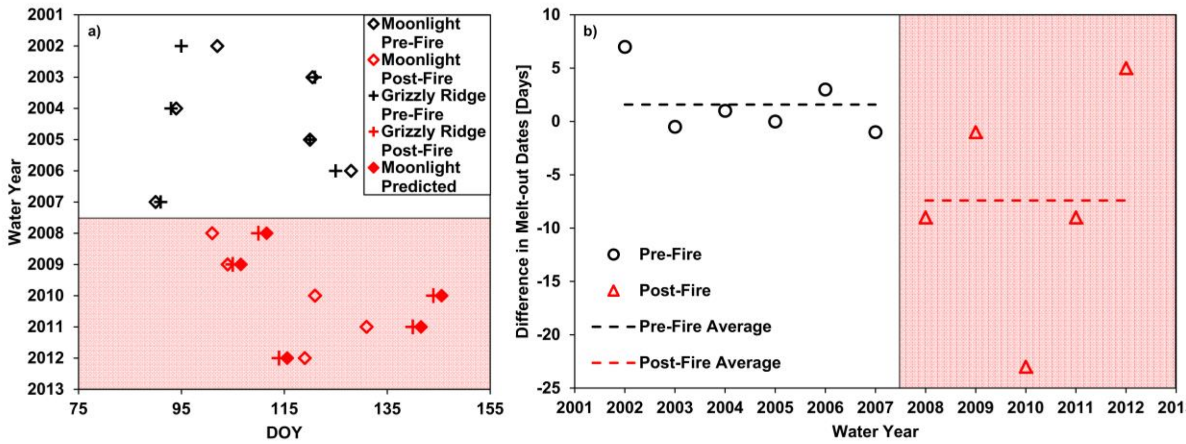

Figure 8. Basin averaged snow cover melt-out dates for Moonlight Fire and Grizzly Ridge (a). Relative difference in melt-out dates (Moonlight Fire – Grizzly Ridge) from the Moonlight Fire and Grizzly Ridge (b).