TITLE: The sensitivity of US wildfire occurrence to pre-season soil moisture conditions across ecosystems

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KEY POINTS:
- Data from NASA’s Gravity Recovery and Climate Experiment (GRACE) holds information that could aid national fire potential assessments
- A high frequency of small fires tends to occur when pre-season soils are wet while larger fires are more frequent when soils are dry
- Surface soil moisture and fire occurrence data were combined to produce annual probable wildfire occurrence and burned area maps
ABSTRACT

It is well accepted that drought and low moisture conditions are linked with increased wildfire occurrence. However, quantifying the sensitivity of wildfire to surface moisture state has been challenging due to a lack of soil moisture observations at an appropriate spatial scale. Here we apply model simulations of surface soil moisture that numerically assimilate observations from NASA’s Gravity Recovery and Climate Experiment (GRACE) mission, combined in a predictive algorithm with the US Forest Service’s Fire-Occurrence Database. We estimate a relationship between historic surface moisture and wildfire occurrence to produce annual probable wildfire occurrence and burned area at 0.25-degree resolution for the contiguous United States by land-cover classification. Cross-validation indicates increased frequency of smaller fires when the months preceding fire season are wet, while larger fires are more frequent when soils are dry. This demonstrates that assimilated GRACE data holds information that could aid national-scale fire potential assessments for early decision-support.

1. INTRODUCTION

Wildfires in the United States have increasingly become larger and more frequent during the last several decades, contributing to greater environmental degradation, property damage, and economic loss [Dennison et al., 2014; Morton et al., 2003]. From 2003 to 2013, wildfires account for an average cost of $2.2 billion dollars per event in the United States [Smith and Matthews, 2015]. Wildfires are typically uncontrolled fires that occur in areas of combustible vegetation, and depend greatly on vegetation type. In the contiguous United States, 90% of wildfire ignitions are associated with human activity, but several other factors such as wind and lightning strikes can be important in ignition and growth. One of the largest contributing factors to general wildfire risk is fuel moisture content (FMC), a measure that when limited contributes to greater fire severity in a given area [Verbesselt et al., 2002]. Low FMC generally indicates higher fire risk as well as higher potential fire severity, or the degree of environmental change caused by a fire, due to plants being more resistant to fire when containing more moisture [Van Der Werf et al., 2008].

The availability and the wetness of fuels tend to be associated with precipitation and soil moisture conditions at the land surface [Chuvieco et al., 2004; Krueger et al., 2015]. However, local-scale observations of these conditions are difficult to obtain over large domains and with consistently discretized, spatially and temporally uniform structure [Famiglietti et al., 2008]. Therefore it is challenging to develop a quantitative description of the relationship between land surface wetness conditions and wildfire occurrence, and the specific impacts of surface soil moisture and fuel moisture content on wildfire occurrence across land cover types is still an open research question. The National Interagency Fire Center currently publishes seasonal fire potential outlook reports for the United States [National Significant Wildland Fire Potential Outlook, 2016]. These reports use the US Drought Monitor, past monthly temperature and precipitation averages, and one and three month weather outlooks to qualitatively assess regional fire potential. This does not account
for the quantitative relationships between fire occurrence and contributing environmental factors such as soil moisture and only offers binary assessment—above or below normal—of fire potential over broad geographic regions.

Launched in 2002, NASA’s Gravity Recovery and Climate Experiment (GRACE) mission provides monthly observations of terrestrial water storage anomalies (TWSA) that describe spatial and temporal changes in the amount of water stored in soils, groundwater and above the land surface [Tapley et al., 2004]. However, GRACE observations have an intrinsically low spatial resolution (150,000 km²), due to the limitations of the instruments and the altitude of the satellites. This makes GRACE TWSA observations difficult to apply for natural resource management. One way to circumvent the resolution limitations of GRACE is to perform a physical downscaling of the GRACE observations through numerical data assimilation. This has been done with much success for drought and flood monitoring applications [Houborg et al., 2012; Reager et al., 2015], and is currently included as an input to the U.S. Drought Monitor framework [Rodell, 2013].

Building upon these successes, we investigate the relationship between GRACE-assimilated soil moisture (as a proxy for fuel moisture content) and seasonal wildfire occurrence and severity. We apply GRACE-assimilated soil moisture simulations from the Catchment Land Surface Model (CLSM) and in-situ wildfire observations over the continental United States during the 2003-2012 period, and at 0.25-degree spatial resolution [Houborg et al., 2012; Short, 2015]. We disaggregate the study domain by land cover type [Homer et al., 2015], under the hypothesis that wetness should modulate different land cover responses to wildfire ignition differently. We then determine the historic relationship between wildfire occurrence and surface soil moisture across land cover types, and cross-validate a predicted response to show the strength of the relationship. In doing so, this study reveals complex nonlinearities in the influence of fuel moisture content on wildfire severity, and further establishes the need to incorporate accurate surface moisture information in the quantitative assessment of fire risk and potential in the United States.

2. DATA

NASA’s GRACE mission is comprised of a pair of Earth-orbiting satellites flying in tandem at over 400 km altitude, spaced about 220 kilometers apart. Distance variations between the two satellites are measured using a K-band Ranging System (KBR), which provides precise (within 10 µm) measurements of the distance changes between the two satellites caused by temporal and spatial fluctuations in the Earth’s gravity field [Tapley et al., 2004]. The measurements are used to determine changes in the Earth’s mass distribution at horizontal resolutions greater than 150,000 km², with higher measurement accuracy at larger spatial scales [Wahr et al., 2004]. The monthly to decadal temporal changes in the gravity field are attributed to mass redistribution in the atmosphere, ocean, continents and solid earth. After isolation and correction of ‘unwanted’ signals (i.e. ocean, atmosphere, and postglacial rebound), these measurements are assumed to represent the movement of water mass over time, referred to as terrestrial water storage anomalies. Swenson
and Wahr [2004] and Wahr et al. [1998] provide general post-processing details and Landerer and Swenson [2012] provides details on signal restoration, scaling, and regional error calculation. The GRACE dataset used for this project is a monthly, global, one-degree gridded, scaled GRACE land data product, which is processed by the Texas Center for Space Research [CSR; version CSR-RL05] and NASA’s Jet Propulsion Laboratory and available for download at grace.jpl.nasa.gov. The time period of data for this project is from April 2002 to December 2013.

The Catchment Land Surface Model (CLSM) was developed at the NASA Goddard Space Flight Center and is a physically based, apportioned land surface model [Koster et al., 2000]. The subgrid horizontal structure of a rectangular atmospheric grid is divided into topographically-defined catchments with an average area of approximately 4000 km². Water is redistributed spatially and vertically based on the topography of each basin or watershed. The model’s hydrologic processes are based on each catchment’s topographical statistics. For the assimilation, the model-generated terrestrial water storage moisture components are corrected toward the GRACE observational estimate with the degree of correction determined by the levels of error associated with each using and Ensemble Kalman Smoothing Filter method (EnKS) [Zaitchik et al., 2008]. Monthly GRACE anomaly fields are converted to absolute values by adding the time-mean total water storage field from the CLSM output. Assimilation increments are calculated based on the relative uncertainty in the model and the observations where a two-step smoother is applied to handle GRACE’s monthly temporal resolution. These increments are applied directly to the column-integrated prognostic variable (the catchment deficit) and the primary non-equilibrium prognostic (the root zone excess moisture), without need for arbitrary vertical disaggregation. The CLSM-DA time series used here covers January 2003 to December 2014. Outputs are reported on 0.25-degree grid cells for the contiguous United States (domain: -126.875 23.875, -66.125 51.625), including portions of Canada and Northern Mexico. This gridded analysis is an interpolation of catchment tiles to a model grid.

The USDA Forest Service’s Fire Program Analysis Fire-Occurrence database (FPA FOD) is a comprehensive geospatial database of wildfires in the United States from 1992 to 2013. It includes 1.73 million geo-referenced wildfire records, representing a total of 126 million acres burned during the 22-year period [Short, 2015]. It also contains vital information for each of these fires, including date, cause, fire size, fire class, burned area, and coordinates. This data was imported into a geographic information system and processed into two separate raster datasets that matched the spatial and temporal resolution of the GRACE derived soil moisture data. The first dataset aggregated the annual number of fires in each 0.25 × 0.25 degree cell for May through April of the following year, while the second summed the total burned area (in acres) for each cell in that timeframe.

The land cover type dataset used in this study was the USGS’ National Land Cover Database 2011 (NLCD 2011) [Homer et al., 2015]. This dataset maps land cover and land use across the United States at a 30 meter resolution. The NLCD data was first reclassified for generalization and
resampled to the same spatial extent and resolution as the previous two datasets. This allowed each
grid cell to have a unique land cover classifier, which could then be programatically used to
extract values and characterize each relevant vegetation type’s relationship between soil moisture
and wildfire. For the purposes of this study, only vegetated land cover types are of importance to
wildfires. Accordingly, the Developed/Urban, Barren Land, and Planted/Cultivated classes were
not considered in the analysis. The Mixed Forest class was not considered due to its unsuitably
small number of pixels. Additionally, even though model simulations of wetland soil moisture may
not be accurate due to missing physical processes, we include this class to represent general
wet/dry responses in wetland environments. Figure 1 shows a visualization of this processed land
cover data along with the other two datasets mentioned above.

3. METHODS

The first step in algorithm development was to disaggregate the fire data by size class as defined
in Table 1. Annual January through April soil moisture data were averaged into single two-
dimensional maps (latitude x longitude) for each year. Annual total fire occurrence and cumulative
burned area maps were produced for each wildfire class, for the period ranging May through April.
This time period was selected in order to delineate a nominal fire season in line with the beginning
of the Western US fire season, although true fire season tends to vary in time and by location
[Westerling et al., 2003]. Each burned area and fire frequency value was plotted against its
corresponding soil moisture value for the entire population of 0.25 degree grid cells within each
land cover classification. This produced a distribution of fire occurrence and burned area as a
function of soil moisture for each land cover class. These data were then binned by soil moisture
ranges to calculate average fire occurrence and burned area values over each range. These
distributions reveal the unique relationship in each land cover class between occurrence of
wildfires of increasing severity classification as a function of soil moisture state.

We also investigated whether the information contained in these relationships with soil moisture
demonstrated predictive utility. Comprehensive deterministic prediction is challenging, because
we don’t include all of the information required to determine the comprehensive source and forcing
for all fire occurrence and severity; variables such as lightning strikes, human activity, and wind
gusts all contribute substantially to actual wildfire predictability. Instead, we investigate a
statistical tendency of soil moisture to affect wildfire occurrence by lumping a large population of
observations into a single model, and evaluating how the population responds as whole to this
single factor. We assume that the population captures the probable best estimate of the relationship
that would occur at a single location under different conditions and across time. A comprehensive
fire prediction model could likely include other forcing variables.

The distributions were compiled as look-up tables to be referenced for mapping fire probability
and predicted burned area. A simple equation for calculating fire probability and probable burned
area were applied by referencing the look-up table corresponding to each land cover type for the
relevant fire size class based on the pre-season soil moisture value. The expected number of fires is thus estimated. Burned area (Equation 1) is then estimated by multiplying the best estimate of the fire occurrence by the average burned area value for the bin that each cell’s soil moisture value belongs to by land cover type.

\[
\text{Probable Burned Area}(i) = \text{Average Fire Occurrence}(i) \times \text{Average Burned Area}(SM_i, LC_i)
\]

(1)

In Equation 1, \(i\) is a given 0.25 degree grid cell, and \(SM_i\) and \(LC_i\) are the corresponding values of soil moisture and land cover classification. Maps for both predicted number of fires and predicted burned area were thus created for each fire size class. These 7 maps for each parameter can be added together to create maps for a year’s total predicted number of fires and total burned acreage.

4. RESULTS

Figure 2 shows that within each land cover type, there are different distributions of fire occurrence as a function of soil moisture for each fire class. For example, within the evergreen forest type, the smaller fire classes B, C, and D tend to be more frequently associated with a higher average number of fires following high pre-fire season soil moisture. Meanwhile, the larger fire classes E, F, and G, show the opposite trend whereby dryer soil moisture conditions in January – April are associated with more fires. Some distributions are relatively uniform or not well organized. This indicates the absence of a clear relationship between soil moisture and fire occurrence, or that other factors tend to mask that relationship. Table 2 shows that each vegetation type differs from the other in its surface soil moisture and fire climates, as shown by the average and standard deviation values. These values were calculated by compiling the pre-season surface soil moisture and fire occurrence values across all cells within each land cover type for each year in the study period.

Figure 3 provides an example of results by hindcasting the May 2012 – April 2013 fire year. The top map shows the total number of fires expected to occur in each cell that year based on the preceding January – April average soil moisture. Figure 3 (bottom) shows total predicted burned acreage. The spatial gaps in the predictive maps represent the withheld land cover classes. These maps were created for each year in the study period, and their summary statistics for predicted number of fires and total burned acres were compiled and charted in Table 3 and Figure 4.

To validate these results, predicted fire frequency and burned area maps that were generated for the 2012 – 2013 fire year (i.e. the most recent year in the FPA FOD dataset), and compared against the observations. For proper cross-validation, this fire year was held out of the algorithmic step. Results are compiled in Table 3. Additionally, the processed FPA FOD data was disaggregated by land cover type and charted next to the predicted fire data, as shown for May 2012 – April 2013 in Figure 4, showing the relative accuracy of the algorithm’s prediction for each vegetation type. Vegetation types that were deemed unsuitable for the analysis (i.e. mixed forest, agricultural, and
urban) were removed from the data sets. Figure 4 shows that in the 2012 – 2013 case study, the values for predicted fire frequency and burned area match the actual data within an error of 35.68% and 119.23% respectively, compared to an average error of 26.67% for predicted fires and 124.08% for predicted burned area for the entire study period.

5. DISCUSSION AND CONCLUSIONS

It should be noted that the predictive maps presented are not intended to offer an accurate hindcast of actual fire occurrence and severity in individual 0.25–degree grid cells. Rather they offer a qualitative assessment of the general relationship between seasonal soil moisture and wildfire potential. The validation results show that the total number of fires and burned area predicted is in fact correlated with the pre-season soil moisture data for the corresponding year, across the land cover grouping. This result simply highlights the principle importance of preseason soil moisture in governing fire risk and potential.

These results also provide the first evidence that pre-season soil moisture and wildfire occurrence can be strongly negatively correlated across land cover types. In all land covers, for the smaller classes of fires (i.e. class “D” or smaller, <300 acres), are generally (12 out of 20 pdfs) associated with higher pre-season soil moisture, not lower soil moisture as hypothesized. This likely describes a situation in which smaller and quick-growing vegetation (e.g. grasses and understory) are more prolific in wet years, and tend to contribute to wildfire persistence and propagation after ignition. This relationship has been studied before using precipitation observations [e.g. Holden et al., 2007].

While the necessity is clear, the feasibility of wildfire predictive capabilities is increasing with the advent of innovative applications of new remote sensing data. Since accurate, observation-based surface soil moisture information has been difficult to obtain over large domains, GRACE-assimilated model outputs may offer a unique contribution to fire severity prediction methods. This builds upon successes in using GRACE-assimilated model outputs for hydrologic drought monitoring [Houborg et al., 2012]. The current NASA Soil Moisture Active Passive (SMAP) mission, launched January, 2015, offers global observations of radiometer-based surface soil moisture at 36-km spatial resolution that can be used in conjunction with GRACE-assimilation efforts and should generally improve this methodology [Entekhabi et al., 2010]. This highlights the importance of the NASA hydrological data catalog for its predictive capabilities, which can further be enhanced when used in conjunction other wildfire risk indicators.

6. ACKNOWLEDGMENTS

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sources include the NASA Applied Sciences Program and the NASA GRACE Science Team. This
research was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under
contract with NASA. The data supporting this study’s conclusions consist of the included tables
and figures. The FPA FOD data [Short, 2015] can be accessed at http://dx.doi.org/10.2737/RDS-
2013-0009.3. The assimilated GRACE data is available at http://grace.jpl.nasa.gov. The NLCD

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Table 1. Fire Size Class Definitions\(^1\)

<table>
<thead>
<tr>
<th>Class</th>
<th>Burned Acres</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0 – 0.25</td>
</tr>
<tr>
<td>B</td>
<td>0.26 – 9.9</td>
</tr>
<tr>
<td>C</td>
<td>10 – 99.9</td>
</tr>
<tr>
<td>D</td>
<td>100 – 299</td>
</tr>
<tr>
<td>E</td>
<td>300 – 999</td>
</tr>
<tr>
<td>F</td>
<td>1000 – 4999</td>
</tr>
<tr>
<td>G</td>
<td>5000 +</td>
</tr>
</tbody>
</table>

\(^1\)Class size ranges are defined in [Short 2015]

Table 2. Land Cover Surface Soil Moisture and Fire Frequency Characteristics

<table>
<thead>
<tr>
<th>Land Cover Type</th>
<th>Volumetric Water Content</th>
<th>Fire Frequency (Fires/Year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>Evergreen Forest</td>
<td>0.25</td>
<td>0.07</td>
</tr>
<tr>
<td>Deciduous Forest</td>
<td>0.31</td>
<td>0.06</td>
</tr>
<tr>
<td>Shrubland</td>
<td>0.19</td>
<td>0.05</td>
</tr>
<tr>
<td>Grassland</td>
<td>0.20</td>
<td>0.05</td>
</tr>
<tr>
<td>Wetland</td>
<td>0.25</td>
<td>0.07</td>
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</tbody>
</table>
Table 3. Predicted and Actual Fire Data with Associated Prediction Errors

<table>
<thead>
<tr>
<th></th>
<th>Predicted Fires</th>
<th>Actual Fires</th>
<th>Predicted Burned Acres</th>
<th>Actual Burned Acres</th>
<th>Predicted Fires Percent Error</th>
<th>Predicted Burned Area Percent Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/2004 - 4/2005</td>
<td>68966</td>
<td>44304</td>
<td>7696006.32</td>
<td>1288883.79</td>
<td>55.67</td>
<td>497.11</td>
</tr>
<tr>
<td>5/2005 - 4/2006</td>
<td>74285</td>
<td>72461</td>
<td>8189855.53</td>
<td>6710199.52</td>
<td>2.52</td>
<td>22.05</td>
</tr>
<tr>
<td>5/2006 - 4/2007</td>
<td>66928</td>
<td>66903</td>
<td>7369845.89</td>
<td>7181219.66</td>
<td>0.04</td>
<td>2.63</td>
</tr>
<tr>
<td>5/2007 - 4/2008</td>
<td>69647</td>
<td>62238</td>
<td>7655771.51</td>
<td>8680825.32</td>
<td>11.90</td>
<td>11.81</td>
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<tr>
<td>5/2008 - 4/2009</td>
<td>67190</td>
<td>59937</td>
<td>7544476.06</td>
<td>3887901.30</td>
<td>12.10</td>
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<tr>
<td>5/2009 - 4/2010</td>
<td>67735</td>
<td>43507</td>
<td>7478052.64</td>
<td>1603893.48</td>
<td>55.69</td>
<td>366.24</td>
</tr>
<tr>
<td>5/2010 - 4/2011</td>
<td>73422</td>
<td>55468</td>
<td>8119098.39</td>
<td>4935915.82</td>
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<tr>
<td>5/2011 - 4/2012</td>
<td>70015</td>
<td>52897</td>
<td>7494680.79</td>
<td>5312742.66</td>
<td>32.36</td>
<td>41.07</td>
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<tr>
<td>5/2012 - 4/2013</td>
<td>66050</td>
<td>48679</td>
<td>7313730.04</td>
<td>8354888.73</td>
<td>35.68</td>
<td>12.46</td>
</tr>
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</table>
Figure 1. The datasets used in this study: (a) GRACE-derived surface soil moisture expressed as percent. This example shows average January – April surface soil moisture from 2003 – 2013. (b) All fires from the 2003 – 2013 study period in the FPA FOD mapped as points by fire cause. (c) The NLCD 2011 resampled to a 0.25-degree resolution.
Figure 2. Binned average fire frequencies for each analyzed land cover type by fire size class. The x-axis of each chart denotes surface soil moisture as a percentage, and the y-axis shows the average number of fires per 0.25 degree cell for that soil moisture bin.
Figure 3. Predictive maps for (a) individual fires and (c) burned area to assess fire risk and potential from May 2012 – April 2013. These predictive results are compared against the (b) actual fire distribution and (d) actual burned area for that year for validation.
Figure 4. Validation of total predicted fires and burned acres from May 2012 – April 2013.