THE LANDFIRE REFRESH STRATEGY: UPDATING THE NATIONAL DATASET

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ABSTRACT

The LANDFIRE Program provides comprehensive vegetation and fuel datasets for the entire United States. As with many large-scale ecological datasets, vegetation and landscape conditions must be updated periodically to account for disturbances, growth, and natural succession. The LANDFIRE Refresh effort was the first attempt to consistently update these products nationwide. It incorporated a combination of specific systematic improvements to the original LANDFIRE National data, remote sensing based disturbance detection methods, field collected disturbance information, vegetation growth and succession modeling, and vegetation transition processes. This resulted in the creation of two complete datasets for all 50 states: LANDFIRE Refresh 2001, which includes the systematic improvements, and LANDFIRE Refresh 2008, which includes the disturbance and succession updates to the vegetation and fuel data. The new datasets are comparable for studying landscape changes in vegetation type and structure over a decadal period, and provide the most

RESUMEN

El programa LANDFIRE proporciona datos detallados sobre vegetación y cargas de combustibles en todos los EUA. Como suele ser necesario en las bases de datos ecológicas, las condiciones del paisaje y la vegetación deben de ser actualizadas periódicamente para incorporar perturbaciones, crecimiento y sucesión natural. El programa LANDFIRE Refresh ha sido pionero en la actualización de estos productos a nivel nacional. Incorporó una combinación de mejoras específicas sistemáticas a los datos del programa LANDFIRE a nivel nacional, métodos de detección por satélite de perturbaciones, datos sobre perturbaciones con verificación en campo, modelizaciones de sucesión y crecimiento de vegetación y procesos de transición de la vegetación. Esto resultó en la creación de dos bases de datos completas para los 50 estados: LANDFIRE Refresh 2001, que incluye las mejoras sistemáticas y LANDFIRE Refresh 2008, que incluye la actualización de los datos sobre perturbaciones y sucesión a los datos de vegetación y combustibles. Estos conjuntos de datos nuevos son comparables y permiten el estudio de los cambios de la vegetación y su estructura para periodos de una década, y ofrecen la caracterización más reciente a nivel na-

recent characterization of fuel conditions across the country. The applicability of the new layers is discussed and the effects of using the new fuel datasets are demonstrated through a fire behavior modeling exercise using the 2011 Wallow Fire in eastern Arizona as an example.

cional sobre cargas de combustibles. Se presenta la aplicabilidad de las nuevas capas, y se demuestran los efectos de la utilización de las bases de datos sobre combustibles a través de una demostración mediante un ejercicio de modelización de comportamiento del fuego basado en el ejemplo del incendio Wallow, ocurrido en el este de Arizona en el año 2011.

INTRODUCTION

Terrestrial landscapes are in a constant state of change caused by a variety of factors including vegetation succession, disturbance, climatic changes, and land use patterns. Many landscape scale ecological analyses require large area spatial datasets that are consistently developed and provide a current characterization of the biotic and abiotic resources in the study area. Therefore, regional to national scale ecological spatial data products must undergo regular updating to maintain relevance. Often this updating involves using change detection methods with airborne or satellite imagery to detect and characterize landscape disturbances and update data products accordingly. While disturbances such as forest harvest or wildfire are only one element of landscape change, they often have substantial impacts on the ecosystems in which they occur. By focusing on disturbance detection and characterization, large scale ecological data producers can account for many of the changes visible on the landscape.

One source of large scale ecological data in the US is the interagency Landscape Fire and Resource Planning Tools (LANDFIRE) Program, which provides consistent and comprehensive spatial data describing potential and existing vegetation type, vegetation structure, wildland fuels, and fire regimes across the entire US (Rollins 2009). LANDFIRE was developed collaboratively between the US Department of Agriculture (USDA) Forest Service (FS) and the US Department of Interior (DOI) in response to the National Fire Plan and the recognized need for consistent spatial data nationwide to evaluate fire risk, behavior, effects, and departure from historical fire regimes. LANDFIRE data are freely available and distributed through the Program website at http://www.landfire.gov. Since the release of the LANDFIRE National dataset in 2009, which provided baseline data at a nominal 2001 timeframe, LANDFIRE has transitioned to providing periodic updates. The first comprehensive update, termed LANDFIRE Refresh, was completed in 2011 for all 50 states. The goals of the LANDFIRE Refresh effort were to provide systematic improvements and updates to the LANDFIRE data products, and also to design and build tools and processes to facilitate future updating.

LANDFIRE data are used for a myriad of applications including fire and land management, resource assessment, and wildlife habitat modeling. Fire behavior analyses have compared LANDFIRE fuel layers with other available datasets in California (Pierce *et al.* 2012), Colorado (Krasnow *et al.* 2009), and South Carolina (Hollingsworth *et al.* 2012). A study

of fuel treatment effectiveness was conducted using LANDFIRE data to simulate fire behavior pre and post fuel treatment implementation (Wimberly *et al.* 2009, Cochrane *et al.* 2012). Finney *et al.* (2011) used LANDFIRE data to simulate large fire probabilities and fire size distributions across the coterminous US, and Scott *et al.* (2012) used LANDFIRE data to model the probability of "resource objective" fires reaching Wildland-Urban Interface (WUI) areas near the Bridger-Teton National Forest of Wyoming. Studies have used potential vegetation and fire regime layers from LAND-FIRE to compare with local map data (Provencher *et al.* 2009), dendrochronological analyses (Swetnam and Brown 2010), and historical fire occurrence records to evaluate current fire regimes (Reid and Fuhlendorf 2011). LANDFIRE data have also been used to quantify extent of rangelands across the coterminous US (Reeves and Mitchell 2011), simulate fire regimes in China through relationships between LANDFIRE fire regime data and climate variables (Krawchuk and Moritz 2009), infer pine densities to model mountain pine beetle dynamics (Crabb *et al.* 2012), and model biological carbon sequestration capacity (Sundquist *et al.* 2009, Zhu *et al.* 2010). Wildlife habitat modelers have used LANDFIRE data to determine habitat suitability and value for several species including northern goshawk (*Accipiter gentilis*; Zarnetske *et al.* 2007), grizzly bear (*Ursus arctos*; Graves *et al.* 2011), and wild bee pollinators (Chaplin-Kramer *et al.* 2011). Additional innovative examples of LANDFIRE data applications are reported on the LANDFIRE website. The data are also integrated into several national-level fire management, risk assessment, budgeting, and carbon assessment systems, including the Wildland Fire Decision Support System (WFDSS; wfdss.usgs.gov; Noonan-Wright *et al.* 2011), Fire Program Analysis (FPA; www.forestsandrangelands.gov/FPA), the joint DOI and USDA FS Cohesive Wildfire Management Strategy (Calkin *et al.* 2011), the West Wide Wildfire Risk Assessment (www.westwideriskassessment.com), and the US Geological Survey (USGS) LandCarbon Program (www.usgs.gov/climate_landuse/land_carbon). For all of these programs, LANDFIRE data provide a consistent base to support assessment, analysis, and decision making at regional to national scales.

With the variety of applications and national programs relying on LANDFIRE data products, it is important that they be maintained, by both incorporating user feedback to improve the existing layers, and by updating the data to reflect more current landscape conditions (Ryan and Opperman 2013). LAND-FIRE Refresh addressed several specific issues through systematic changes based on review by end users. Additionally, time series stacks of Landsat imagery were used to detect disturbances and reflect their impacts in the vegetation and fuel data. An overview of the issues addressed, methods used to address them, and impacts of the changes made to the LAND-FIRE data products is presented. The impact to end users of maintaining updated data is illustrated in part by presenting the results of a fire behavior modeling exercise using LAND-FIRE National and Refresh data products for the 2011 Wallow Fire in Arizona. More technical details about the Refresh processes, including comparisons of regional statistics for several data layers, are provided in the LAND-FIRE Refresh GeoArea Reports available on the Program website.

Data

LANDFIRE utilizes several data sources to maintain the products, including georeferenced field plots, disturbance event features, Landsat imagery, elevation data and derivatives, and ancillary geospatial data layers. To date, the LANDFIRE Reference Database (LFRDB) stores information about more than 800 000 field plots representing vegetation and fuel characteristics from across the US. Many

of the data points are provided through data sharing agreements with programs such as the USDA FS Forest Inventory and Analysis (FIA) program, the USGS national Gap Analysis Program (GAP), and state natural heritage programs. Other data are provided by local, state, federal, and tribal agencies, as well as non-profit and private organizations. The LFRDB is constantly evolving as data are received and integrated. Similarly, the LANDFIRE Events database stores point and polygon data indicating natural and anthropogenic disturbance events. Data are integrated from the Monitoring Trends in Burn Severity program (MTBS; Eidenshink *et al.* 2007), which provides fire perimeters and burn severity data for large fires in the US. In addition, LANDFIRE solicits geospatial disturbance data from federal, state, tribal, local, and private agencies that describe wildfire, silvicultural activities, fuel treatments, insect and disease damage, weather damage, and other landscape altering events. Each event lists, at a minimum, the type of disturbance, year of occurrence, and spatial location. Many disturbance events also include severity information. The raw features are overlaid and overlaps between events, such as salvage logging after a fire, or multiple fire perimeters submitted from different agencies, are reduced through a hierarchical topology process to yield one unique event per year per location. In the case of multiple disturbance types in the same year, the disturbance with the most impact on vegetation or fuel composition is retained. The result is a nationwide spatial Events layer that specifies the date, type, and severity of disturbances.

LANDFIRE relies on Landsat 5 Thematic Mapper (TM) and Landsat 7 Enhanced Thematic Mapper Plus (ETM+) imagery to provide a spectral base for detecting and characterizing landscape disturbance. For Refresh, LANDFIRE built Landsat time series stacks (Huang *et al.* 2009) incorporating annual imagery from 1984 to 2008 for every Landsat path and row combination in the coterminous US, totaling over 11 000 scenes. We converted the images to at-sensor reflectance, reprojected, and resampled them to a common data frame and mask. In addition to the imagery, we used elevation data from the National Elevation Dataset (ned.usgs.gov) and land cover data from the National Land Cover Database 2001 (NLCD; Homer *et al.* 2007) to detect disturbances across the landscape and characterize the magnitude of vegetation change. We used data from the National Agricultural Statistics Survey (NASS; Johnson and Mueller 2010) and the USGS GAP Protected Areas Database (PAD; www.protectedlands.net) to delineate and characterize agricultural land use classes where available. Roads and urban areas were defined by the National Transportation Statistics (NTS) layer (http://www.bts.gov).

METHODS

The LANDFIRE Refresh effort was divided into two parts and two separate sets of data layers were produced. In the first part, termed LANDFIRE Refresh 2001 (LF 2001), a series of improvements was made to the LANDFIRE National products. In the second part, termed LANDFIRE Refresh 2008 (LF 2008), the LF 2001 products were updated to *circa* 2008 conditions by incorporating disturbance and vegetation transition data.

LANDFIRE Refresh 2001

As use of the LANDFIRE National data products grew, end users of the data identified issues concerning their utility, four of which were addressed in LF 2001. First, gaps in data coverage were found and corrected along international borders, caused by differences in boundary definitions between input layers. Second, delineation of non-vegetated land use classes (e.g., water, barren land), wetland, and riparian zones were updated. In LANDFIRE National, NLCD land cover data were used to

determine non-vegetated classes and inform wetland and riparian mapping. However, NLCD 2001 final products were not available for all areas in time to inform LANDFIRE mapping in the coterminous US. Therefore, preliminary NLCD 2001 data were used in some areas, while in other areas NLCD 1992 land cover data (Vogelmann *et al.* 2001) were used. Because the two NLCD products used different thematic legends and somewhat different mapping methods, inconsistencies existed between areas where different data were used. Therefore, we revised areas for which the final NLCD 2001 data were not available during LANDFIRE National mapping to reflect the final data. In Alaska, the NLCD land cover data were not used directly in LAND-FIRE National; non-vegetated, riparian, and wetland classes were mapped alongside other vegetated classes, which tended to cause confusion in the classification. For LF 2001, several Alaskan riparian and wetland classes were combined to simplify the legend. These classes were then remapped using NLCD 2001 land cover data. Non-vegetated classes were also remapped using NLCD and Web-enabled Landsat Data composites (weld.cr.usgs.gov; Roy *et al.* 2010). In Hawaii, the final NLCD land cover data were available for LANDFIRE National mapping and no systematic concerns existed with the non-vegetated, riparian, or wetland classes.

The third issue addressed in LF 2001 concerned the inclusion of burnable agriculture and urban classes. In LANDFIRE National, all agricultural and urban areas were assigned non-burnable surface fuel models, causing fire behavior models to not propagate fire through these areas. In reality, many agricultural areas do burn, as do WUI areas. Therefore, we separated agricultural and urban areas into burnable (e.g., senesced grassland pastures and WUI areas) and non-burnable (e.g., some irrigated crops or the centers of large cities). For agricultural areas in the coterminous US, we used crop type data from NASS and protected

area status from PAD to determine burnability, generally assuming most irrigated and some non-irrigated crop types were not burnable while pasture and other crop types were burnable. In Alaska and Hawaii, NASS and PAD data were not available, and agricultural lands are not as prevalent; therefore, we used NLCD land cover to differentiate between unburnable cultivated crops and burnable pasture land. All burnable agriculture areas were assigned surface fuel models appropriate for that landscape. For urban areas, the NLCD 2001 natural vegetation classes were modeled in areas masked as urban to determine the type of vegetation prevalent in that area. The NTS layer was used to define roads and urban areas that were retained as non-burnable; all other areas were considered burnable and surface fuel models were assigned based on the modeled vegetation type.

Fourth, external review and feedback from end users indicated that, in many areas, forest height values tended to be too low and forest canopy cover values too high in the LAND-FIRE National products, which had substantial impacts on fire behavior modeling systems (see Scott 2008, Krasnow *et al.* 2009, LAND-FIRE 2011*a*). Therefore, as part of LF 2001, we remapped both forest height and canopy cover for the coterminous US. The NLCD 2001 forest cover data were used directly as the LANDFIRE National forest canopy cover product, which was mapped by deriving reference data from high resolution imagery, creating canopy cover models based on the reference data, and extrapolating the models to 30 m resolution Landsat imagery (Huang *et al.* 2001, Homer *et al.* 2004). This top down approach tends to fill smaller gaps within and between canopies, leading to higher estimates of canopy cover than a bottom up approach may produce (Jennings *et al.* 1999). While this difference may be negligible for some applications, it is critical for fire behavior modeling, where canopy cover is used to compute fuel shading and wind adjustment factors in opera-

tional fire behavior modeling systems (Albini and Baughman 1979, Rothermel *et al.* 1986). For LF 2001, we remapped forest canopy cover using stem map derived canopy cover estimates from FIA plots (Toney *et al.* 2009) as the reference data and built regression tree models relating the canopy cover estimates to Landsat imagery, elevation and topographic derivatives, and land cover. Likewise, we remapped forest height using stand height values derived from FIA plots to build regression tree models. Along with the input used to remap canopy cover, we also incorporated the National Biomass and Carbon Dataset's (NBCD) basal area weighted height product, derived from Shuttle Radar Topography Mission (SRTM) data (Kellndorfer *et al.* 2004). NBCD products are available for all forested areas in the coterminous US. We used the SRTM derived products for remapping forest height because synthetic aperture radar backscatter has been shown to be sensitive to forest structural parameters and, because radar can penetrate through a forest canopy, it can be used to develop profiles of forest structure in ways that passive optical cannot (Dobson *et al.* 1995).

Lastly, in addition to these four improvements, further changes were made in Alaska and Hawaii. In Alaska, the vegetation type legend was condensed by combining several similar classes. This was done to simplify the detailed legend and increase agreement with field data for several vegetation types. In Hawaii, a review workshop was conducted with local data users who identified many specific individual areas that were misclassified in the vegetation type layer. Given the small geographic size and detailed feedback provided by the local users in Hawaii, these areas were remapped to correct the errors.

LANDFIRE Refresh 2008

Once LF 2001 was completed, the LF 2008 effort brought the improved products to a more current state. In the coterminous US, LAND-

FIRE implemented the Vegetation Change Tracker (VCT; Huang *et al.* 2010), which utilizes stacks of Landsat imagery to track vegetation signals through time and detect disturbances. We selected Landsat TM or ETM+ scenes nominally for every year between 1984 and 2008; one image per year was selected that ideally represented peak vegetation greenness with minimal cloud cover. The VCT algorithm provided year of disturbance and disturbance magnitude data for every Landsat path and row combination. We filtered the VCT outputs, combined VCT-detected changes with the Events data, and compared the resultant layers to the Landsat imagery to ensure that the final Remote Sensing of Landscape Change (RSLC) product matched the spatial patterns and time periods of the imagery. This methodology is further described in Vogelmann *et al.* (2011). The RSLC product includes disturbance layers for each year from 1999 to 2008 because LANDFIRE National data were mapped using Landsat imagery from as early as 1999. We also captured the type and severity of each disturbance from the Events data where available. Disturbance types include: biological (the use of predators, parasites, or pathogens to control weeds, insects, or disease); chemical or herbicide treatments; development (involving permanent land clearing); fire; insects or disease; silviculture treatments; and weather damage. For VCT-detected disturbances that were not co-incident with Events data, we buffered the nearby events to 1 km and used event information from the buffered events to provide the potential type and severity. If a disturbance fell within a single buffered event, that event's information was used; if the disturbance fell within multiple buffers, a prioritization scheme was devised based on the persistence of the disturbance type and the highest priority event was used. If a disturbance did not fall within any buffered events, the type was labeled as unknown. Severity was determined using VCT output if there were no events or if there were events without severity information nearby.

We added a confidence attribute to each disturbance that listed a qualitative measure of confidence in the disturbance type and severity labels based on the method used to obtain them. We then used the RSLC products to inform vegetation transitions.

In Alaska and Hawaii, the Landsat data and algorithms were not sufficient to complete the same RSLC process as for the coterminous US. Issues such as historical data acquisition and availability, persistent cloud cover, extreme sun angles and short growing seasons in Alaska, and lack of Landsat 5 data in Hawaii since the early 1990s prevented the assembly of time series stacks necessary for running VCT. However, in contrast to the coterminous US, relatively little active landscape management occurs in these states and the majority of disturbances in both areas are attributed to fire. Therefore, with the cooperation of local expert personnel, we used spatial events layers from MTBS and information provided by local land management agencies to define disturbance time, type, and severity.

Once we identified disturbed areas, we updated the existing vegetation layers based on modeled vegetation transitions. We defined vegetation transitions by first intersecting the existing vegetation data with the disturbance products to list unique combinations of vegetation and disturbance across the map. Then, in forested areas, we modeled ten years of growth for each vegetation-disturbance combination using the Forest Vegetation Simulator (FVS; Dixon 2002) and FIA plot data from the LFRDB. The plot data were grouped into their respective FVS variants and separate FVS runs were conducted for each variant and disturbance combination. This approach gave us average growth and transition parameters based on all available FIA plots for a particular variant and disturbance combination. We used the vegetation conditions predicted by FVS to define vegetation type and structure transitions in disturbed areas, based on the time since disturbance. We also ran FVS without disturbances

and used those results to define transitions in undisturbed areas to capture vegetation growth and succession. In Hawaii and all but the southeastern portion of Alaska, there were no FIA plot data available to run FVS. Therefore, in these states and all non-forested areas, staff ecologists and regional experts made expert opinion determinations of the vegetation transitions in each vegetation-disturbance combination. For undisturbed non-forested areas, we developed a ruleset based on the LANDFIRE National Environmental Site Potential layer and the VCT output in the coterminous US, and expert opinion in Alaska and Hawaii, to again capture vegetation growth and succession. All of the transition definitions were stored in a custom database and were applied to the existing vegetation layers to produce the updated products.

We also updated the surface and canopy fuel layers based on the disturbance products. We developed transition rules based on updated existing vegetation, disturbance type, severity, and time since disturbance to assign surface fuel models to disturbed areas. Input and review was sought from regional fuel experts before the rules were implemented to create LF 2008 surface fuel model layers. We used the Fire and Fuels Extension module for FVS (FVS-FFE; Reinhardt and Crookston 2003) to model coefficients of change in canopy base height (CBH) based on landscape disturbance. We applied the coefficients to the CBH calculations in the updated products. We recalculated canopy bulk density based on the updated existing vegetation using a previously developed generalized linear model (Reeves *et al.* 2009). In non-disturbed areas, we also modeled vegetation growth using FVS-FFE and FIA plot data, then used those outputs to update the canopy fuel layers.

Fire Behavior Modeling

To assess the impacts of the newly created products, we completed several fire behavior

modeling exercises using historical fire incidents in each geographic area. For these analyses, we used LANDFIRE National, LF 2001, and LF 2008 layers separately to model the fires using weather data from Remote Automated Weather Stations (RAWS) near each fire. We used the Fire Area Simulator (FARSITE) fire behavior modeling system to predict the fire perimeter over a given period of time (Finney 2004). The intent of these analyses was not to try to replicate the exact perimeter of the fire, but to show the differences in how fire behavior is predicted when using the three fuel data sources. Detailed discussion of the methods, results, and implications of these exercises are included in the LANDFIRE Refresh GeoArea reports available on the Program website. Presented here is one of the exercises, the Wallow Fire, which burned in east-central Arizona, USA, in the summer of 2011. Between 1 and 2 June, the Wallow Fire moved approximately 19 km, threatening the town of Alpine, Arizona. Two fuel treatments had previously been completed on the edges of the valley outside of Alpine and the fire moved toward these areas, which we simulated with FARSITE. We obtained representative wind and weather conditions from 2 June from the Strayhorse and Mountain Lion RAWS, and used the same weather conditions for all three model runs, substituting each of the three fuel datasets to simulate fire behavior for this period.

Key differences between the three fuel datasets existed in both the surface fuel models and the canopy fuel layers. There were generally two distinct vegetation types in the area of the Wallow Fire: ponderosa pine and mixed conifer. The surface fuel models, as defined by Scott and Burgan (2005), in the ponderosa pine areas were nearly all Timber Litter 8 (TL8) in all three datasets. In the mixed conifer areas, the LANDFIRE National fuel models showed a mixture of Timber Understory 1 (TU1), TL3, TL5, and TL8. In LF 2001 and LF 2008, most of the mixed conifer areas were

TL3, due mostly to the reassignment of fuel models following the remapping of forest height and canopy cover. The two fuel treatment areas captured in the LF 2008 data moved from a ponderosa pine type with a TL8 fuel model to a mixed conifer type with a TL3 fuel model. CBH in the LANDFIRE National layer was generally 2 m to 4 m for the ponderosa pine type and 1 m to 2 m for the mixed conifer type. In LF 2001 and LF 2008 outside of the fuel treatment areas, the CBH was generally 1 m to 2 m in the ponderosa pine type and 0.1 m to 1 m in the mixed conifer type. CBH in the fuel treatment areas in LF 2008 was generally 2 m to 3 m.

RESULTS

LANDFIRE Refresh 2001

LF 2001 resulted in product layers that had specific errors addressed, including extension of data products to definitive international borders and consistent mapping of non-vegetated land use classes, riparian areas, and wetland areas. The assignment of burnable fuel models to agricultural and urban areas resulted in the conversion of 15.6 million hectares, or 41.3 %, of urban land from unburnable to burnable, and 73.8 million hectares, or 40.3 %, of agricultural land from unburnable to burnable, which has substantial impacts on fire behavior modeling in these areas. The remapped forest height layers showed generally better distribution among the height classes relative to FIA plot data, with differences varying by geographic region (Figure 1). The remapped forest canopy cover layers resulted in a substantial decrease in the amount of land mapped in the highest canopy cover classes and also showed better agreement with FIA plot distribution compared to LANDFIRE National (Figure 2). The LF 2001 dataset provided an improved base layer from which comprehensive updates could be incorporated in LF 2008.
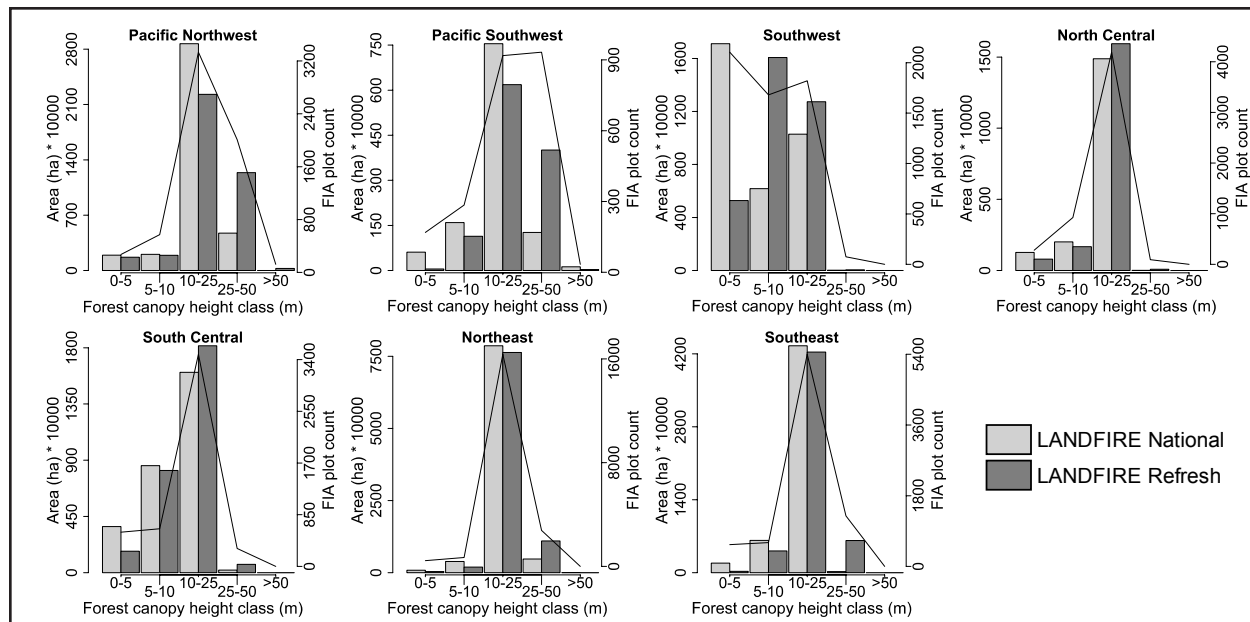
Figure 1. Changes in forest canopy height distribution between LANDFIRE National and Refresh (LF 2001) data by geographic area, overlaid with distribution of FIA plot counts (line) in each class.
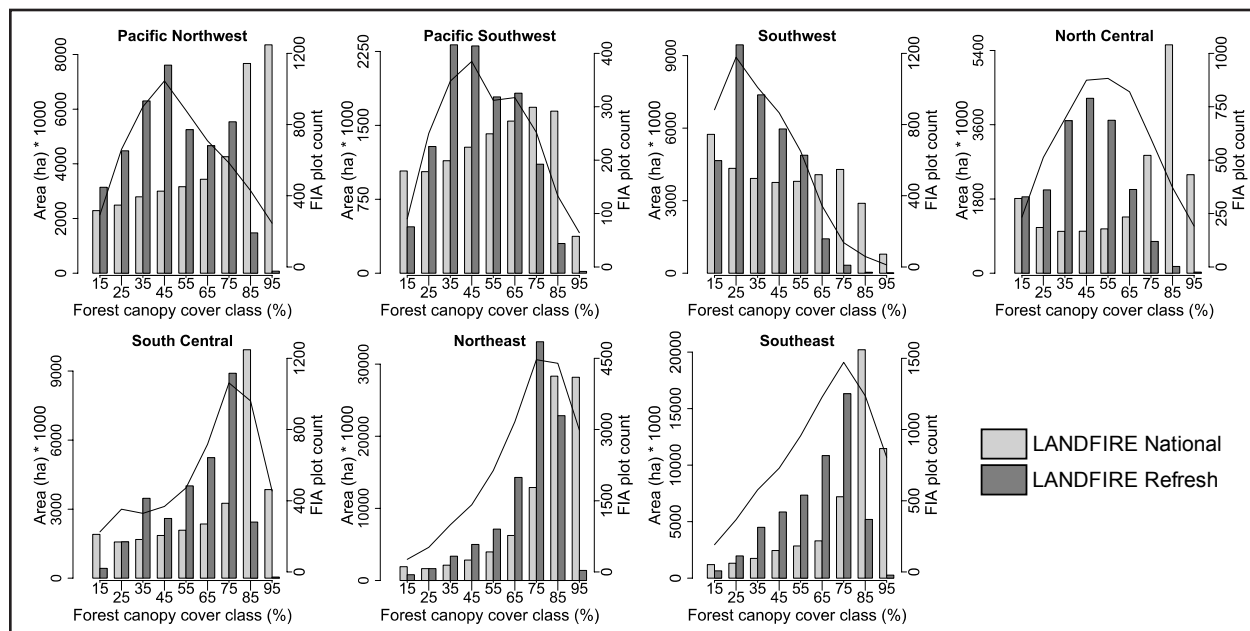

Figure 2. Changes in forest canopy cover distribution between LANDFIRE National and Refresh (LF 2001) data by geographic area, overlaid with distribution of FIA plot counts (line) in each class.

LANDFIRE Refresh 2008

The results of LF 2008 included a publicly available database of disturbance events, a new suite of disturbance products, and updated existing vegetation and fuel layers. We compiled a database of geospatial disturbance events totaling nearly 600 000 records from over 300 different sources across the country. We have made public versions of this database avail-

able, including all non-proprietary records for which we have permission to distribute. The disturbance products are also being distributed and provide detailed information about landscape change across the country. There were a total of almost 50 million hectares mapped as disturbed between 1999 and 2008, with the most prevalent disturbance sources identified as fire, insects or disease, and silviculture (Table 1). The amount of area disturbed and proportions of disturbance agents varied by geographic area (Figure 3). In the eastern US, disturbance was primarily caused by silviculture, followed by fire. In the central and western US, including Alaska and Hawaii, the most dominant disturbance agent was fire. Area disturbed between 1999 and 2008 varied between 1.23 % of land area in Hawaii and 11.74 % of land area in the Pacific Northwest (Figure 3). We used the disturbance information and vegetation transition process to update every landscape across the US.

The updated surface fuel models show distinct trends in disturbed and non-disturbed areas. The non-disturbed landscapes had less area in grass and shrub fuel models and more area in the timber fuel models, which indicates

that vegetation growth and succession were captured (Figure 4). In landscapes disturbed by fire, there was less area in timber and shrub models and substantially more area in grass models. In areas disturbed by silvicultural activities, there was more area mapped in grass and shrub models and less area in timber models, all of which capture the post-disturbance changes in vegetation type (Figure 4). Canopy structure was also updated, and changes among structure classes also varied between disturbed and non-disturbed areas. The taller forest height classes increased in area mapped along with the shortest forest height class, while grass, shrub, and mid-forest height classes were reduced in non-disturbed areas (Figure 5). This was the result of vegetation succession and conversion from grass and shrub to forest communities and growth of forested areas from shorter to taller trees. While growth and succession occur within grassland and shrubland ecosystems, the areal magnitude of rangelands in the US is much smaller compared to forested lands, so those changes are not readily visible in the nationwide summaries. In burned areas, there is less area mapped in the forest and shrub height classes and sub-

Table 1. Total number of hectares disturbed per year, by disturbance type, for the US.

|	Area disturbed per year by each disturbance type (ha)								
Year	Bio- logical	Chemical or herbicide	Devel- opment	Fire	Insects or disease	Silviculture	Unknown	Weather	Total
1999	0	24 380	690	2 565 741	218 770	236 533	1 212 286	59 213	4 317 613
2000	6	51 467	329	3 080 467	127 444	216 624	1 001 114	1 901	4 479 352
2001	5	89 150	1087	1 555 095	318 272	219 127	1 138 873	2 489	3 324 098
2002	68	108 629	145	3 001 186	185 693	225 215	959 352	62 733	4 543 021
2003	7	87 550	103	2 151 991	155 645	261 293	1 068 440	4 940	3 729 969
2004	0	95 108	218	3 701 915	364 508	302 183	1 113 701	914	5 578 547
2005	0	105 600	350	4 286 368	445 740	249 015	1 150 379	9 606	6 247 058
2006	69	52 099	130	4 390 539	388 165	256 065	990 026	4 082	6 081 175
2007	0	192 480	272	4 216 351	535 471	283 144	977 274	8 308	6 213 300
2008	105	124 968	74	2 358 701	605 314	153 493	1 344 627	24 720	4 612 002
Total	260	931 431	3 398	31 308 354	3 345 022	2 402 692	10 956 072	178 906	49 126 135
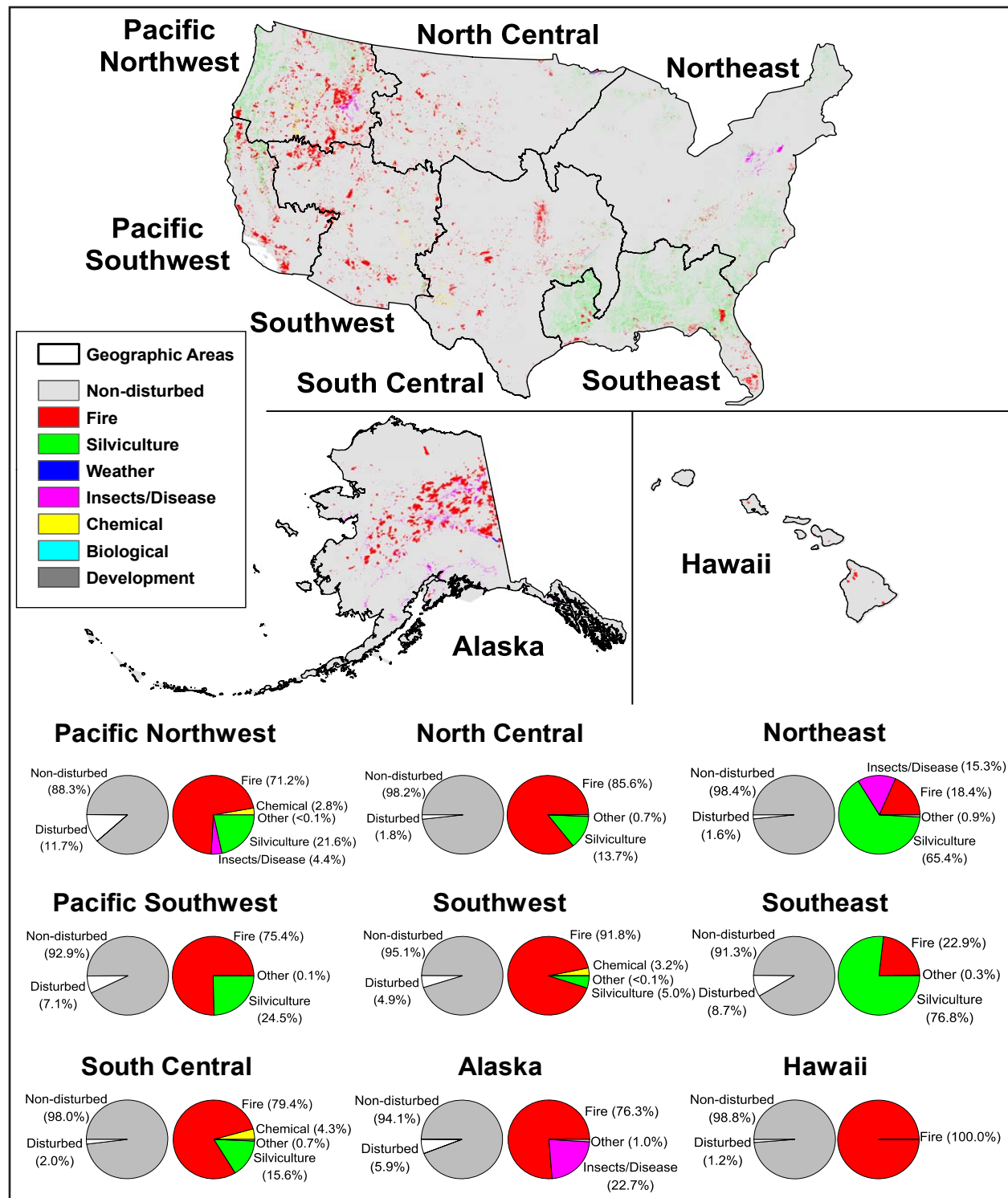
Figure 3. LANDFIRE Refresh disturbance products for the US showing spatial distribution of disturbances across the country, percentage of area disturbed, and proportions of disturbance types per geographic area.
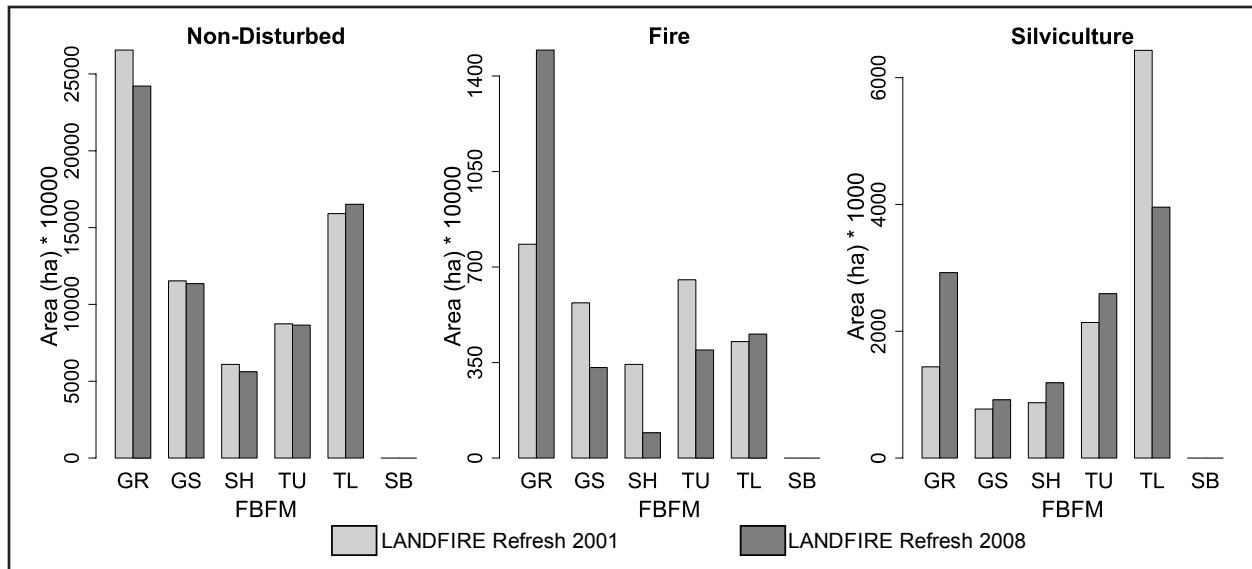
Figure 4. Changes in fire behavior fuel model distribution between LANDFIRE Refresh 2001 and 2008 data for non-disturbed, fire, and silviculture disturbances. GR = grass, GS = grass and shrub, SH = shrub, TU = timber understory, TL = timber litter, SB = slash and blowdown.
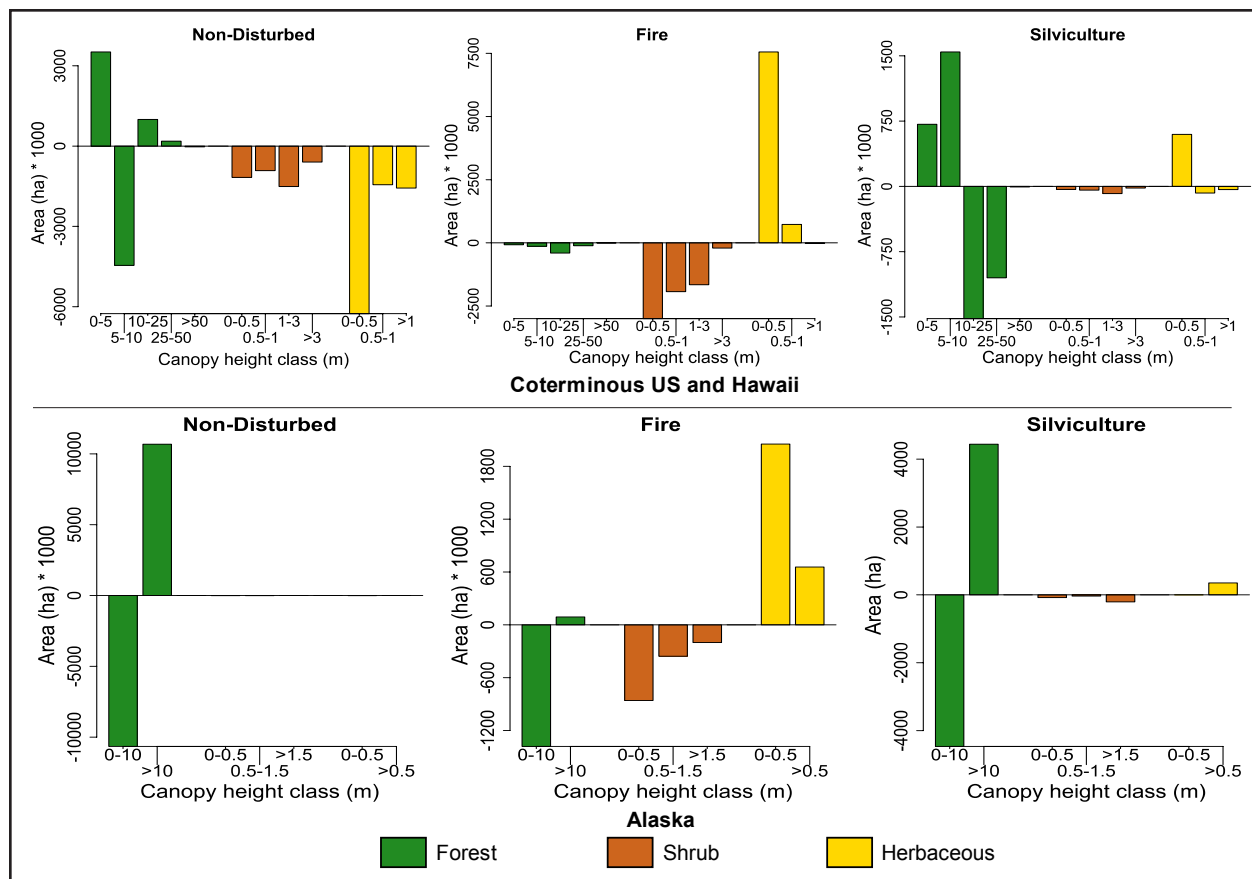

Figure 5. Changes in canopy height distribution between LANDFIRE Refresh 2001 and 2008 data for non-disturbed, fire, and silviculture disturbances in the coterminous US and Hawaii (top) and Alaska (bottom). Alaska data are shown separately because the class sizes were different.

stantially more area in the grass height classes. In areas with silvicultural activities, there is a decrease in the higher forest and shrub height classes and an increase in the shorter forest height and grass classes. Silvicultural disturbance includes both removal of biomass (e.g., harvesting) and addition (e.g., planting), accounting for the increase in shorter forest classes and decrease in taller forest classes (Figure 5). Canopy cover changes were similar, with increased forest canopy cover and decreases in grass and shrub cover in non-disturbed areas, and reductions of forest and shrub cover and increases in grass cover for disturbed areas (Figure 6). Together, these results illustrate the magnitude of updated LAND-FIRE vegetation and fuel data.

Fire Behavior Modeling

The Wallow Fire modeling exercise showed limited fire spread using LANDFIRE National fuel layers (Figure 7). The same simulations using LF 2001 (Figure 8) and LF 2008 (Figure 9) fuel layers show a much greater fire spread and are more representative of the actual fire perimeter on 2 June. Differences were also found between the LF 2001 and LF 2008 fuel layers in the areas where the fuel treatment activities occurred. In the LF 2001 model run, the fire burned through the treatment area and into the town of Alpine; whereas with the LF 2008 model run, the fire spread was greatly reduced in the treatment area and the fire did not reach the town in the simulation time period.
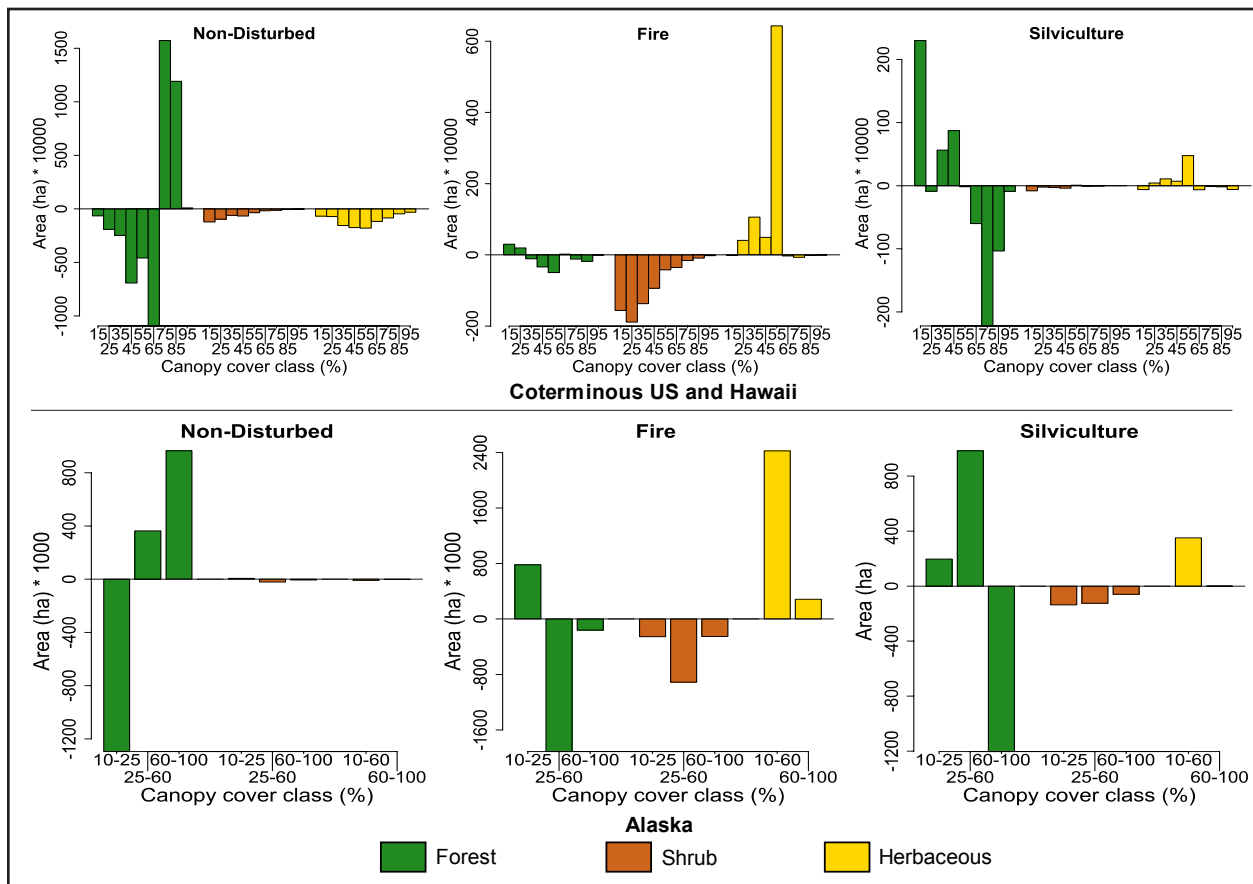

Figure 6. Changes in canopy cover distribution between LANDFIRE Refresh 2001 and 2008 data for non-disturbed, fire, and silviculture disturbances in the coterminous US and Hawaii (top) and Alaska (bottom). Alaska data are shown separately because the class sizes were different.
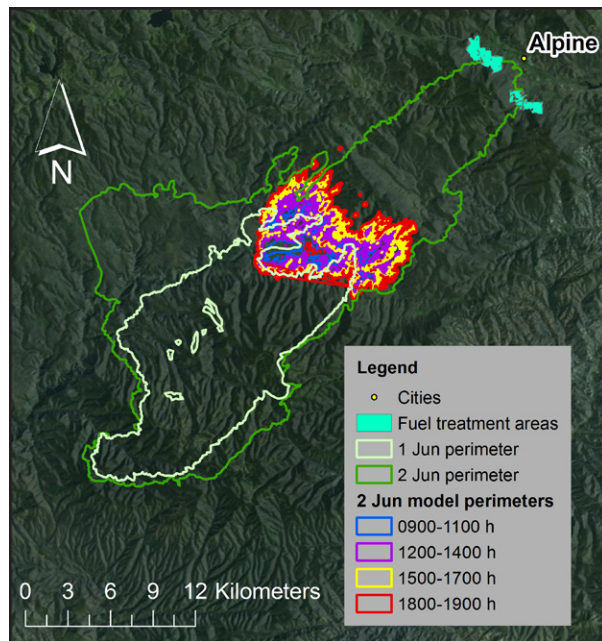
Figure 7. Simulated Wallow Fire progression for 2 June 2011, using LANDFIRE National data products.
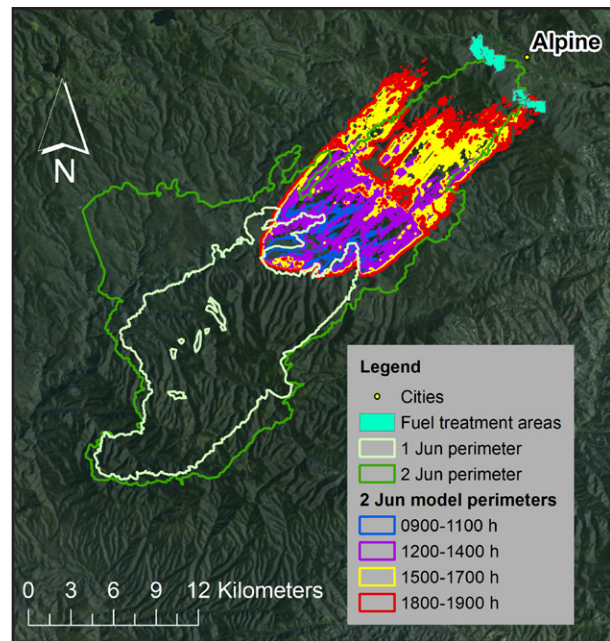

Figure 9. Simulated Wallow Fire progression for 2 June 2011, using LANDFIRE Refresh 2008 data products.
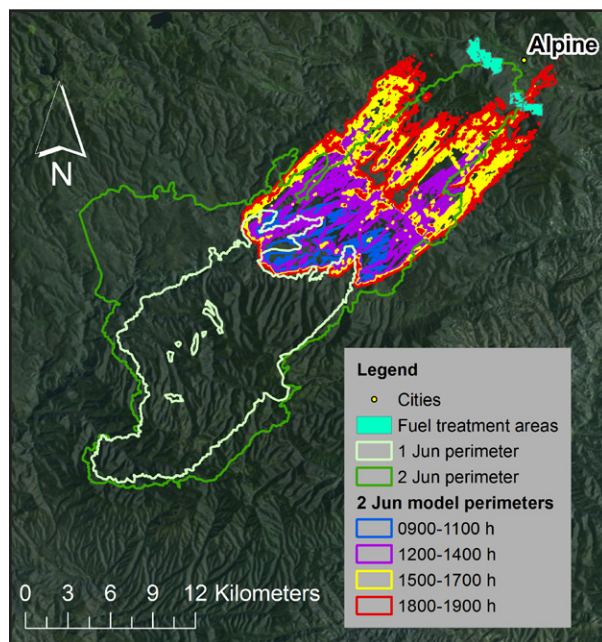

Figure 8. Simulated Wallow Fire progression for 2 June 2011, using LANDFIRE Refresh 2001 data products.

DISCUSSION

The improvements and updates to the LANDFIRE data products have a substantial effect on the utility of the data for operational fire behavior modeling. Fire behavior modeling inputs typically must be critiqued and modified before the model will adequately represent local landscape conditions (Stratton 2009). The LANDFIRE Refresh data products incorporate many of the modifications that previously were required when modeling fire behavior with LANDFIRE National data, saving time and effort on operational incidents. LANDFIRE Refresh data have been integrated into WFDSS, which is used to conduct risk analyses and probabilistic forecasts of short- to long-term fire behavior on operational incidents. WFDSS is also used to document decisions made on a fire incident derived from the risk based strategy assessments (Noonan-Wright *et al.* 2011). Through integration in WFDSS, the improvements and updates to the LANDFIRE data directly affect operational fire behavior modeling for ongoing incidents.

Updates to LANDFIRE products also affect other uses of the data. FPA uses LANDFIRE data products as input to their Large Fire Simulator, which models expected future fire

activity within a given area. Treatments and alternative strategies can be simulated to provide information to managers about the probability of future fires and the most cost effective options to manage them. This information is used for strategic planning and allocation of agency resources (Ryan and Opperman 2013). Using LANDFIRE Refresh data ensures that FPA forecasts incorporate recent disturbances and associated vegetation changes. The USGS LandCarbon Program uses LANDFIRE data products to quantify vegetation and disturbance dynamics to predict carbon fluxes at multiple scales. Updating the LANDFIRE data products allows LandCarbon to model the effects of post-disturbance vegetation transition on carbon and greenhouse gas levels (Zhu *et al.* 2010). Wildlife habitat modelers have used LANDFIRE National data to characterize the landscape conditions where various species flourish. Graves *et al.* (2011) used LANDFIRE Existing Vegetation Type (EVT) as one input to their grizzly bear abundance model in Glacier National Park, Montana, USA. Chaplin-Kramer *et al.* (2011) used LANDFIRE EVT and Existing Vegetation Cover to quantify wild bee pollinator habitats for studying the value of pollination services to the agriculture industry in California. By incorporating LANDFIRE Refresh data, these studies and others can quantify changes in wildlife patterns as a response to landscape disturbance and changes in vegetation.

The modeling exercise of the Wallow Fire illustrates several key impacts of the LANDFIRE Refresh data products. The simulated fire spread using LANDFIRE National fuel data was very limited compared to actual conditions. Upon inspection of the data, it was determined that fire spread was limited mostly by the lack of crown fire and spotting predicted. The majority of the landscape was mapped as surface fire only (LANDFIRE 2011*b*), while witnesses on the ground reported active crown fire during the modeled time period (Bostwick *et al.* 2012). This was primarily caused by CBH and canopy cover values being too high, which affected the initiation of crown fire, and wind and fuel shading calculations in the model, respectively, and low forest heights, which reduce spotting distance (Krasnow *et al.* 2009). The model outputs using LF 2001 products were much closer to observed fire spread, showing that the improved fuel layers, with higher forest height and lower CBH and canopy cover values, did indeed perform better in the model, with much active crown fire represented (LANDFIRE 2011*b*). However, with the fuel treatment areas not represented in the LF 2001 layers, the fire behavior was over-predicted in part of the modeled area, leading to a projection of the fire burning past the town of Alpine. The LF 2008 products corrected this over-prediction by identifying the fuel treatment areas as silvicultural disturbances, transitioning the vegetation structure, and modifying the surface and canopy fuel layers accordingly. The model output using the updated fuel layers significantly reduced fire spread through the treatment areas and showed the fire not reaching Alpine, which was more representative of actual fire conditions at that time (Bostwick *et al.* 2012).

Being able to adequately represent the landscape is also important for fire effects modeling using applications such as the First Order Fire Effects Model (FOFEM; Reinhardt *et al.* 1997). FOFEM can be used with LANDFIRE data to predict the direct consequences of a fire or for determining the conditions necessary for a prescribed burn to achieve the desired effects, including fuel consumption, soil exposure, tree mortality, and smoke production. In either case, the most accurate and up-to-date landscape data ensure validity and utility of model results.

Several limitations of the LANDFIRE Refresh data exist because of the complexities in modeling landscape conditions across the entire country. First, the performance of VCT varied among different ecosystems. VCT relies on identifying dense forest areas to cali-

brate the algorithm, which then calculates indices related to the likelihood of a pixel being forested (Huang *et al.* 2010). In open forests and rangelands, calibration of the algorithm is suspect because of the lack of dense forest pixels. In these areas, the VCT output tended to have more spurious noise pixels and may not have captured all of the disturbances visible in the imagery. In addition, VCT is proficient at recognizing sudden, stand clearing events. However, longer onset and more subtle disturbances, such as some insect and disease events, were often not fully recognized by the algorithm. It should be noted that LANDFIRE Refresh was produced using an early version of the VCT software and our experiences were used to further develop the algorithm.

In addition to the VCT outputs, geospatial events data were obtained from all available sources and used to define disturbances. The majority of these data were contributed by land management agencies or obtained from federal databases. Therefore, there is likely a bias towards public lands, especially federally managed areas, with more disturbances mapped on these lands because of the greater availability of contributed disturbance data. Contributed events data were also used to infer disturbance type, and therefore the prevalence of unknown disturbance types is greater on landscapes with fewer events, leading to uncertainty in the vegetation transitions. In Alaska and Hawaii, where VCT was not used, this bias is even more pronounced because only contributed events were used to define disturbances. Lack of data in Alaska and Hawaii (FIA, NBCD) also prevented forest height and canopy cover from being remapped in these states. These issues impact the consistency of the LANDFIRE data layers. While consistent processes were used to develop and maintain the data, dependencies on certain input data sources necessitated modifications to methods or reduction in scope of some of the improvements and updates. Greater reliance on expert opinion, which is more subjective and less repeatable, was substituted for lack of input data.

Because of the changes in legends and known issues that were addressed as part of LANDFIRE Refresh, the comparison of LANDFIRE National layers to Refresh layers for the purposes of quantifying landscape change is not recommended. Rather, the LF 2001 and LF 2008 layers provide a comparable dataset to study the dynamics of disturbance and their effects on the landscape. Few studies have recently attempted to quantify the amount of disturbance across the entire US. Masek *et al.* (2008) used Landsat image pairs from 1990 and 2000 epochs to estimate decadal forest disturbance at 25.6 million hectares for the coterminous US. He *et al.* (2011) modified the methods used by Masek *et al.* (2008) and estimated forest disturbance of 18.1 million hectares for the same time period using the same data sets. These estimates were also compared to the USFS FIA regeneration area statistics of 22.8 million hectares for the same area and time period (He *et al.* 2011). These estimates were all significantly lower than disturbed area captured in LANDFIRE Refresh in part because they did not include Alaska or Hawaii, they only considered forest lands, and they were for a previous decade. Fry *et al.* (2011) quantified changes between NLCD 2001 and NLCD 2006 land cover. They reported a total of approximately 13.5 million hectares of land cover change over the coterminous US between the two years. This included both vegetated and non-vegetated change. Considering only natural vegetation classes, the amount of change over the same period was approximately 10.7 million hectares. This is lower than the amount of disturbance reported by LANDFIRE and other studies because of the shorter time period studied, and because only changes between land cover classes were considered. For example, if an evergreen forest was affected by a moderate severity disturbance but remained a functional evergreen forest, the disturbance would be captured in the LANDFIRE, Masek *et al.* (2008), and He *et al.* (2011) datasets, but would not be counted in the NLCD change statistics. Finally, Birdsey and

Lewis (2003) estimated landscape disturbance across the US of 152 million hectares per decade, including approximately 47 million hectares from grazing, 40 million hectares from harvesting, and 16 million hectares each from fire and insects or disease. The LANDFIRE Refresh disturbance products did not capture grazing as a disturbance; mapped significantly less area as affected by harvesting, insects, and disease; but did capture significantly more burned area. In general, the Refresh disturbances only included areas with visible landscape change because of the remote sensing methods used. Therefore, low intensity harvesting or insect and disease outbreaks that did not cause substantial mortality were likely not detected, leading to some of the discrepancies between estimates. In addition, the estimates of annual burned area used by Birdsey and Lewis (2003) were through the late 1990s, which, while important, were generally less active compared to the decade mapped by LANDFIRE Refresh, leading to a relative underestimation in annual burned area.

Future updating of LANDFIRE data products is expected to take place on an annual to biennial basis. The next phase of the LANDFIRE Program is called LANDFIRE 2010 and is expected to update the data layers to a nominal 2010 state. LANDFIRE 2010 will follow much the same process as the updating phase of Refresh, reusing many of the same processes. One important difference is a partnership formed with the NLCD project to largely standardize change detection and characterization methods between partners. LANDFIRE has adopted the Multi Index Integrated Change Analysis (MIICA; Fry *et al.* 2011, Jin *et al.* 2013) model to detect and characterize landscape change for the 2010 effort. Preliminary results indicate that the MIICA model performs better in rangeland and open forested systems, where VCT was not optimal. Additional development is underway to plan a nationwide remap of LANDFIRE data using new imagery and plot data. While this effort is yet several years from commencing, the lessons learned with each successive update will help to define the requirements and processes needed for a remapping effort.

Efforts are also being made to refine mapping procedures and to explore the integration of additional data sources and methodologies to enhance LANDFIRE data products. Research on gradual change has potential to identify more subtle transitions in vegetation conditions that often are missed when focused on detecting abrupt disturbance (Vogelmann *et al.* 2009). Incorporating gradual change detection algorithms could, for example, allow LANDFIRE data products to better represent insect damage or drought stress that may occur slowly over time and may not modify vegetation type but could affect structure or fuel layers. Additional research on inclusion of light detection and ranging (lidar) data for enhancing vegetation type, structure, and surface and canopy fuel mapping is ongoing as well. Lidar data are especially useful in many parts of the country where field plot data are sparse. A prototype canopy fuel mapping project was completed for an area of interior Alaska and the results demonstrated the utility of incorporating lidar (Peterson *et al.* 2013).

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