Appendix C. Characterization and Modeling of Major Ecosystem Disturbances

The assessment of the Nation's ecosystems for biological carbon sequestration will explicitly address disturbances such as wildfires (resulting from natural causes and human activity), as required by section 712 of the Energy Independence and Security Act (EISA; U.S. Congress, 2007). The national assessment disturbance methodology also will include tornadoes, damaging winds, hurricanes, and insect and disease outbreaks (table C1). Additionally, management activities, such as fuel treatments, designed to affect disturbances also will be considered by the disturbance methodology. For each disturbance type or management activity, the national assessment will follow a similar series of steps (fig. C1). First, recent disturbance patterns will be characterized as the number of events and area affected each year by ecoregion. The characterizations of recent trends will then be used to identify relations with climate, biophysical, and anthropogenic variables using statistical methods. When the resulting relations are statistically significant and ecologically relevant, they will be used to project future disturbance patterns.

The characterization of recent trends and statistical relations will capture broad-scale patterns, but additional methods are needed when projecting to locate and simulate the effects of each individual disturbance event; therefore, the national assessment will incorporate a second suite of methods to simulate the spread or placement of individual disturbance events at the pixel level when possible. These components of the disturbance model will include fire spread, empirical wind-fields, and habitat-suitability models for insects and disease. Some disturbances, especially insects and diseases, will lack the data or ecological understanding needed to build predictive relations at the 30-meter (m) pixel scale. In these cases, the summaries of recent disturbances and projections will be used to provide ecoregion-level disturbance probability distributions to the biogeochemical model (appendix D of this report), which will incorporate the spatial uncertainty inherent to the ecoregion-scale probabilities. The disturbance modeling will be adaptive and will incorporate new scientific understanding, data, and methods as they become available during the national assessment.

C.1. Characterizing Past and Current Ecosystem Disturbances

C.1.1. Events Database

The national assessment will leverage the fire-disturbance data compiled and used to maintain the Landscape Fire and Resource Management Planning Tools Project (LANDFIRE) data products. Additionally, several key datasets, not currently (2010) utilized by LANDFIRE, will be incorporated to characterize past and current nonfire disturbances. An events database will be constructed to hold data describing major ecosystem disturbances from the LANDFIRE refresh data call; burn perimeter and severity data from Monitoring Trends in Burn Severity (MTBS) (Eidenshink and others, 2007); data describing insects and diseases from the Forest Health Monitoring (FHM) program of the U.S. Forest Service (USFS); data from the National Oceanic and Atmospheric Administration (NOAA) National Hurricane Center's hurricane archive; and data from NOAA's National Weather Service Storm Prediction Center tornado track and damaging wind event archives (table C1). Data from the National Fire Plan Operations and Reporting System (NFPORS) also will be incorporated into the events database to characterize fuel treatments (table C1).

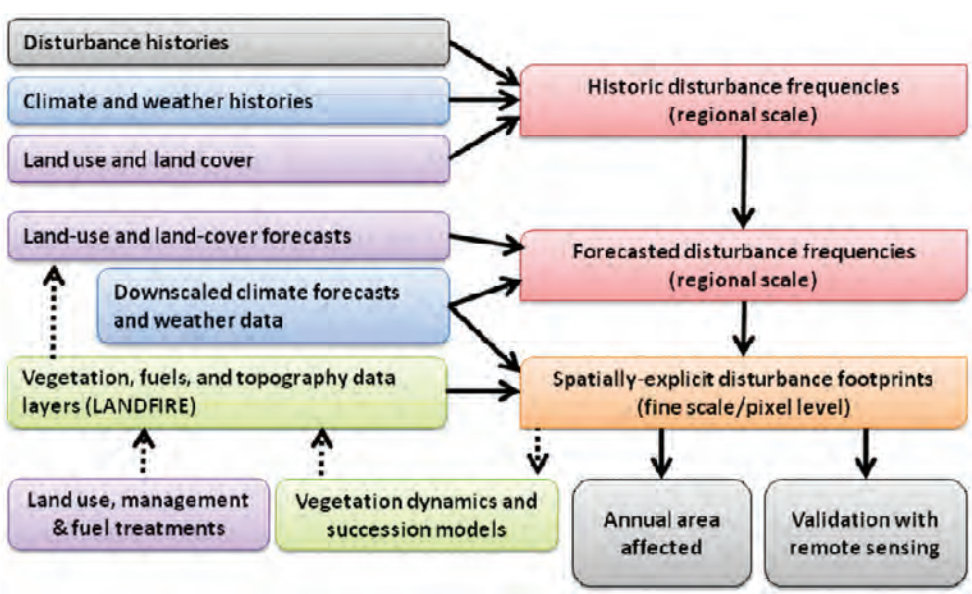

Figure C1. Generalized process and data flow chart showing disturbance modeling component tasks. Solid lines represent processes linking input datasets, models, and output datasets. Dashed lines indicate processes that update data sources required for disturbance modeling. Because each disturbance type differs in terms of the driving forces and the scales over which they operate, this streamlined modeling approach will be modified for each disturbance type. These distinctions will necessitate that the disturbance methodology be adaptive and include components that operate at different spatial and temporal scales.

Table C1. Summary of major ecosystem disturbances resulting from both natural causes and human activities, including disturbance-related management activities, to be assessed for effects on carbon sequestration and greenhouse-gas fluxes, spatial resolution of disturbance forecasts, disturbance projections reported, input data sources, explanatory variables, and potential management options implemented under the reference and enhanced scenarios.

[m, meter; MTBS, Monitoring Trends in Burn Severity; LANDFIRE, Landscape Fire and Resource Management Planning Tools Project; NFPORS, National Fire Plan Operations and Reporting System; NOAA, National Oceanic and Atmospheric Administration; RSLC, remote sensing of landscape change; USFS, U.S. Forest Service]

Disturbance type	Spatial scale	Attributes	Data sources	Broad-scale explanatory variables	Fine-scale explanatory variables	Scenario and management options
Wildland fires (human-caused and natural)	250-m pixels	Fire size, severity, and emissions	MTBS LANDFIRE	Climate Land use Population	Weather Vegetation Topography Distance from urban area	Active fire suppression.
Fuel treatments (including prescribed fires)	250-m pixels	Areas and types of treatment	NFPORS LANDFIRE		Vegetation Land ownership	Increased or decreased number and area of treatments.
Hurricanes, tornadoes, damaging winds	250-m pixels	Storm tracks and areas of mortality	NOAA RSLC		Vegetation Topography	
Insects and diseases	250-m pixels	Areas of defoliation and mortality	USFS Forest Health Monitoring Aerial Surveys RSLC	Climate Past outbreaks	Climate Vegetation Topography Distance from previously affected areas	

For many disturbance types, the existing data incorporated into the events database will contain only point and line vector information. For example, hurricane, tornado, and damaging wind data consist of lines and points of the approximate storm locations; additional information is needed to characterize the area affected. Remote sensing of landscape change can help fill these information gaps. Dramatic vegetation changes, such as stand-replacing fires and forest clearcuts, are easily identified in imagery; however, less severe types of disturbances, such as insect outbreaks and storm damage, are more difficult to distinguish (Ahren, 1988; Franklin and others, 2003; Skakun and others, 2003; Kennedy and others, 2007; Vogelmann and others, 2009). Therefore, disturbed areas will be identified by using vegetation change-detection algorithms that (1) take advantage of the rich temporal information in Landsat and Moderate Resolution Imaging Spectroradiometer (MODIS) time-series stacks, and (2) that search for anomalies in spectral reflectance and vegetation indices trends across all image dates (Huang and others, 2009, 2010).

The results of the vegetation change analysis will be used to augment the events database and provide additional data about the locations of fuel treatments, insect and disease outbreaks, and storm damage to vegetation. For instance, the FHM aerial-survey data are provided as polygons indicating disturbance cause; for example, the mountain pine beetle. There is heterogeneity in disturbance severity within the FHM polygons—healthy trees are interspersed among unhealthy trees. This heterogeneity will be captured by assigning attribute information about the disturbance cause provided by the FHM polygons to disturbed areas identified by the vegetation change analysis. Similarly, disturbed patches in the imagery that are spatially coincident with storm locations would be attributed as storm damage.

C.1.2. Field-Reference Database

The field-reference database will be a compilation of all existing georeferenced field data available for the United States in the Fire Effects Monitoring and Inventory Protocol (FIREMON) database structure compiled for LANDFIRE. It includes Forest Inventory and Analysis (FIA) data from the USFS, fire monitoring data from the National Park Service, and data from the U.S. Geological Survey's Gap Analysis Program (GAP). Data will be acquired and compiled as the assessment progresses geographically across the Nation. Data in the field-reference database will be used to validate the disturbance and management information in the events database (section C.1.1 of this report).

C.1.3. Annual Summaries of Past and Current Disturbances

Using the disturbance data described above, participants in the national assessment will start by characterizing past disturbances into annual summaries using records of recent wildfires, storms, and insect and disease outbreaks by ecoregion. These annual summaries will include disturbance type, cause, number of events, and total area affected. Fire summaries will include additional ecoregion-level estimates for emissions, and individual estimates for each fire calculated will be totaled using the Consume model (Prichard and others, 2006) and the First Order Fire Effects Model (FOFEM) (Reinhardt and others, 1997) with the fuel-loading model (FLM) and fuel-characteristic classification system (FCCS) data produced for the LANDFIRE project (Rollins, 2009). The annual disturbance summaries will be provided as tables and further summarized as probability distributions for each U.S. Environmental Protection Agency (EPA) Level II ecoregion (modified from Omernik, 1987) (table C2).

Table C2. Example of an output table showing recent disturbance summary data for the Mississippi Valley Loess Plains ecoregion.

[*N*, number; MTBS, Monitoring Trends in Burn Severity]

Disturbance type	Year	*N*	Hectares	Source
Wildfire, human	1984	0	0	MTBS
Wildfire, human	1985	0	0	MTBS
Wildfire, human	1986	1	239	MTBS
Wildfire, human	1987	0	0	MTBS
Wildfire, human	1988	2	518	MTBS
Wildfire, human	1989	0	0	MTBS
Wildfire, human	1990	2	529	MTBS
Wildfire, human	1991	0	0	MTBS
Wildfire, human	1992	1	223	MTBS
Wildfire, human	1993	3	705	MTBS
Wildfire, human	1994	4	2,666	MTBS
Wildfire, human	1995	0	0	MTBS
Wildfire, human	1996	6	4,367	MTBS
Wildfire, human	1997	0	0	MTBS
Wildfire, human	1998	2	383	MTBS
Wildfire, human	1999	1	202	MTBS
Wildfire, human	2000	2	731	MTBS
Wildfire, human	2001	0	0	MTBS
Wildfire, human	2002	0	0	MTBS
Wildfire, human	2003	0	0	MTBS
Wildfire, human	2004	0	0	MTBS
Wildfire, human	2005	0	0	MTBS
Wildfire, human	2006	0	0	MTBS
Wildfire, human	2007	0	0	MTBS
Wildfire, human	2008	2	599	MTBS

C.2. Identifying Drivers of Ecosystem Disturbances

To project future disturbance events, the critical driving variables determining occurrence patterns need to be identified. Within the disturbance-modeling framework, these relations will be identified for ecoregions and for individual disturbance events. This two-scale approach will allow incorporation of broad-scale climatic drivers as well as fine-scale land-use, vegetation, and topographic patterns that affect individual disturbance events.

C.2.1. Ecoregion-Level Relations

The ecoregion annual disturbance summaries will be used to identify relations between disturbances and broad-scale climate, biophysical, and anthropogenic drivers using empirical methods. For example, inter-annual variability in fire occurrence has clear relations to extreme weather (Bessie and Johnson, 1995) and climate variables capturing drought and moisture availability and vegetation productivity in the preceding year (Swetnam and Betancourt, 1990; Westerling and others, 2006; Falk and others, 2007). Similarly, severe insect outbreaks often are related in part to climate conditions (Gan, 2004; Aukema and others, 2008). Broad-scale patterns of land use and land cover (LULC), topography, and population also may play significant roles in explaining disturbance patterns, especially for human-caused wildfire ignitions (Cardille and others, 2001; Syphard and others, 2007). By using previously identified relations, researchers will use statistical methods to test ecoregion-scale relations among recent disturbance occurrence, weather, climate, LULC trends, and population trends. General linear models will be used with negative binomial and Poisson responses for the number of disturbances and Gaussian responses for area affected; however, other statistical techniques may be used where appropriate. For certain disturbance types, such as hurricanes, where there is little evidence of a long-term trend, relations with climate and other broad-scale predictors may not be identified. In such cases, the recent annual disturbance summaries will be used to simulate future disturbance occurrence patterns.

C.2.2. Fine-Scale Relations

Ecoregion-level relations will explain broad-scale patterns in terms of the number of disturbance events and total area disturbed each year; however, they provide minimal information about exactly where within ecoregions the individual disturbance events are most likely to occur. These patterns will be explained by using a second suite of empirical methods that predict the probability of disturbance at fine spatial resolutions (250-m pixels) and will incorporate fine-scale relations between disturbance-occurrence patterns and vegetation types, topography, and land use—especially from human pressures. For instance, abiotic and anthropogenic variables have been shown to be effective predictors of human-caused wildfire ignitions (Cardille and others, 2001; Syphard and others, 2008). Similarly, many of these same variables also have been shown to affect insects and disease because of preferential selection for certain hosts or vegetation types and transport by humans to previously unaffected areas (Prasad and others, 2010) in addition to topographic position, climate conditions, and previous outbreak locations (Dodds and others, 2006; Aukema and others, 2008; Santos and Whitham, 2010). In contrast, the likelihood of hurricane, tornado, and wind damage is largely dependent on vegetation type and topographic position (Boose and others, 2001; Kramer and others, 2001; Ramsey and others, 2001; Schulte and others, 2005). For each disturbance type, potential predictors will be identified from existing studies, and the relation between disturbance locations and predictors will be tested and quantified using statistical methods.

C.3. Future Ecosystem Disturbance

For the national assessment, projections of future disturbance events will be made for each of the reference and enhanced carbon-sequestration scenarios. The number of events and area affected by each disturbance will be projected using the previously identified ecoregion-scale and fine-scale methods (sections C.2.1 and C.2.2 above). To incorporate management activities, model parameters, probabilities, and predictions may be altered. For example, an increase in a prescribed fire-use scenario may simply double the number of prescribed fires simulated in any given year. Ecosystem disturbance modeling will be conducted and reported for EPA Level II ecoregions. The details of the modeling steps for each disturbance type and incorporation of mitigation and management actions are provided in the following sections.

C.3.1. Wildfire (Human Caused and Natural)

Simulations for wildfires will be made for each EPA Level III ecoregion for each reference and enhanced scenario. Predictions of annual ecoregion fire activity (*n* wildfires per year) will be based on previously developed empirical relations with broad-scale climate and LULC variables (section C.2.1 above). Ignition locations of individual fire events will be based on an additional set of probability surfaces based on empirical relations with weather, climate, vegetation, topography, and LULC (section C.2.2 above). Once ignition locations are determined, individual fire spread will be simulated using the minimum-travel-time (MTT) algorithm (Finney, 2002), the LANDFIRE fuels and topography layers (Rollins, 2009), and the fire-weather climatology derived from the NOAA North American Regional Reanalysis (NARR) weather data. Following fire spread, emission estimates will be summarized for each fire using the Consume and FOFEM models and the FCCS and FLM data produced by LANDFIRE (Rollins, 2009).

C.3.2. Fuel Treatment (Including Prescribed Fire)

Simulations for fuel treatments will be run for EPA Level III ecoregions for each reference and enhanced scenario. Predictions of annual ecoregion treatment activities will be based on a random selection from the recent probability distribution of fuel-treatment activity (*n* treatments and area treated per year), but may be modified in terms of the number of treatments per year or area treated per year under the different enhanced scenarios. Individual fuel treatments will be restricted to public lands and randomly placed within wildland vegetation types depending on the type of treatments; for instance, forest-fuel thinning cannot occur in grasslands. Nonfire treatments will expand using a patch-grow algorithm until a final predicted treatment size is reached, or an entire contiguous wildland vegetation patch is treated. For prescribed fire-fuel treatments, the MTT fire-spread algorithm used by the wildfire modeling will be used (section C.3.1 above). The LANDFIRE fuel data layers will be updated after placement of fuel treatments, to account for treatment effects on fire behavior and spread.

C.3.3. Insect and Disease Activity

Simulations will be run for EPA Level III ecoregions for each reference and enhanced scenario. Predictions of annual ecoregion-level insect and disease activity (area affected per year) will be based on ecoregion empirical relations derived from epidemiological and species distribution modeling techniques (section C.2.1 above; Elith and others, 2006; Phillips and others, 2006; Elith and Leathwick, 2009) using climate, vegetation, topography, and previous outbreaks as predictors. Because of the potentially large number of unique insect species and diseases that could be simulated, spatially explicit species-occurrence modeling will be prioritized on the basis of the amount of area currently (2010) affected and the effect on standing biomass; example insects include the mountain pine beetle (*Dendroctonous ponderoseae*), the southern pine beetle (*Dendroctonus frontalis*), and the gypsy moth (*Lymantria dispar*; Krist and others, 2007). In cases where it is not possible to generate statistically and ecologically significant, spatially explicit probability surfaces, ecoregional probability distributions will be used instead.

C.3.4. Tornado and Damaging Wind Events

Tornado and damaging wind simulations also will be made for EPA Level III ecoregions under each reference and enhanced scenario. Ecoregion-level predictions of tornado activity (*n* storms per year) will be based on a random selection from regional summaries of recent occurrences. Then for each simulated tornado, an empirical storm-track generator (Vickery and others, 2000) will establish the tornado path. The width of the tornado-disturbance footprint will be determined from the recent distribution of storm track widths measured using remote sensing of landscape change (section C.1 above). If wind damage to vegetation can be effectively monitored from remote sensing of landscape change, then damaging wind models will be made similarly to tornado methods. Historic frequencies of the number of damaging wind events and area affected will be used to simulate future occurrence patterns.

C.3.5. Hurricane Events

Hurricane effects often occur over areas larger than the EPA Level III ecoregions used for other disturbance types; therefore, hurricane simulations will run annually, but for the entire United States for each reference and enhanced scenario. Predictions of hurricane activity (*n* storms per year) will be based on a random selection from regional summaries of recent occurrences. As with tornadoes, an empirical storm-track generator will create a storm path and wind speeds along the path for each hurricane (Vickery and others, 2000). A surface wind-field and exposure probability surface based on topography and vegetation, calibrated with remote sensing of landscape change data, will determine areas where vegetation damage will occur (Boose and others, 1994).

C.4. Disturbance Model Outputs

Disturbance model outputs are listed in table C1 and will include tabular annual summaries of the number of events and area affected for each disturbance type or management activity for each assessment unit. Additionally, tabular summaries of annual greenhouse-gas emissions (methane, carbon monoxide, carbon dioxide, and nonmethane hydrocarbons) will be produced for wild and prescribed fires. Disturbance maps with 250-m spatial resolution also will be generated annually, with unique labeling for specific disturbance types. These outputs will be provided for recent disturbances (1984–2010) and future disturbances (2011–2050). Outputs for projections will be presented as probability distributions to represent the range of values observed under a number of simulation replicate runs.

C.5. Vegetation Dynamics

At the end of each year in the LULC-change model and disturbance-model simulations, updates will be made to vegetation-type and fuel data layers to incorporate the effects of disturbances, management actions, LULC, and vegetation succession. Initial vegetation conditions will be established from the existing vegetation-type and succession-class data layers in LANDFIRE (Rollins and Frame, 2006; Rollins, 2009). Each vegetation type has an existing vegetation-dynamics model that defines transitions among a number of succession classes. Transitions will be initiated using disturbance type, severity, and time since last disturbance. These succession trajectories are defined from historic disturbance regimes, and the vegetation dynamics are being updated to incorporate modern disturbance types; for instance, forest harvesting and invasive species. Furthermore, LANDFIRE fuel-model layers are defined using the vegetation types and succession classes, thereby allowing updates to account for vegetation change (Keane and others, 2001; Rollins and Frame, 2006). Thus, future vegetation-type, succession-class, and fuel models will be updated using the existing vegetation type and succession class and the outputs from the simulated disturbances and LULC changes.

C.6. Scenarios and Management Options

Management activities affecting fuel and ignition patterns potentially can have effects on carbon storage and greenhouse-gas emissions. The disturbance task will allow different management activities in future scenarios that incorporate a range of fire-management strategies. Specifically, fuel treatments (including fuel reduction and prescribed fire) will allow for increases or decreases in the area of different fuel treatments to be specified under alternative scenarios. The disturbance model also will incorporate fire suppression and its effect on limiting the size of wildfires using a wildfire containment probability algorithm developed by Finney and others (2009). Finally, the disturbance model's probability surfaces are sensitive to LULC changes and, therefore, may demonstrate unintended effects of land-management policies on disturbance regimes.

Management activities and the extent to which they affect disturbances will be simulated for each of the IPPC reference and enhanced scenarios. See section 3.3.1 of this report for details of the scenario development. Specifically, information will be gathered using questions such as "Within the A2 storyline, would it be feasible to double the area treated using prescribed fire in your region?" The results will be compiled into a management portfolio for each scenario and will be used to assess how different mitigation strategies might affect biological carbon storage and greenhouse-gas emissions.

C.7. Relations to Existing Disturbance Models

The modeling approach for future potential fires parallels other fire-modeling efforts in the United States, but there are some important differences. Desktop applications such as Fire Area Simulator (FARSITE) and FlamMap (a USFS fire-behavior mapping and analysis model) are used to examine individual fire events or landscape-level fire behavior. FARSITE simulates individual fire growth given an ignition point (Finney, 2004) and is considered to be "state of the art" in terms of fire-spread simulation, but the computation requirements are expensive and that prohibits its use for national-scale assessments. The MTT algorithm, which is used for the national assessment, produces similar results with less of a computational burden (Finney, 2002). The MTT algorithm is integrated into FlamMap and relies on landscape-level fire behavior outputs produced by FlamMap to simulate fire growth in addition to other fire-behavior indices across a landscape (Finney, 2006). The Fire Spread Probability model (FSPro) simulates fire spread using the MTT algorithm from thousands of randomly placed fire ignitions and stacks the results to produce burn probabilities. FSPro is integral to the wildland fire decision-support system (WFDSS) and fire program analysis (FPA). This approach is similar to FSPro in many ways because the same fire-spread algorithm is used; however, instead of generating burn probabilities like FSPro, this method generates individual burn perimeters and interacts with the LULC change model and the biogeochemical cycling model.

C.8. Integrating Land-Use- and Land-Cover-Change Modeling and Biogeochemical Modeling

There are reciprocal feedbacks among the primary modeling components, with the disturbance model, LULC-change model (appendix B of this report), and biogeochemical model (appendix E of this report) sharing data before and after each year in the simulations. At the end of each annual disturbance-model simulation, the results will be communicated to the LULC-change model and the biogeochemical model. The biogeochemical and LULC-change models do not require the level of thematic and spatial detail provided by the LANDFIRE vegetation types; therefore, the LANDFIRE vegetation-type layer will be aggregated to 250-m pixels and reclassified to National Land Cover Database (NLCD) categories using a look-up table at the end of each year in the disturbance-model simulations. The updated layer will then be transferred to the LULC-change model, and eventually to the biogeochemical model for calculating carbon stocks and greenhouse-gas fluxes for the current model-simulation year. In turn, the LULC-change modeling component will provide an updated land-cover layer to the disturbance-model component so that disturbance probability surfaces can be updated to reflect any changes that occurred. Additionally, the biogeochemical-model component will provide information on biomass-pool changes because of growth, mortality, and decomposition to recalibrate fuel-load data.

C.9. Ecosystem-Disturbance Data Needs

Representing the range of disturbances affecting ecosystem carbon stocks and greenhouse-gas fluxes depends largely on the availability of input data needed to parameterize and execute the various disturbance components. Fires and fuel treatments have the most complete existing datasets; however, even these datasets have limitations. Many fires are not mapped by the MTBS project, especially small fires and unreported fires occurring on public and private lands (Eidenshink and others, 2007). The NFPORS fuel-treatment database lacks the spatial detail and treatment-effects information needed for more sophisticated modeling. Other disturbance types, especially insect outbreaks and storms, lack data documenting the extent and effects of these disturbances with enough detail to use for the modeling efforts. Even though the capability to use remote-sensing data or aerial surveys to track storm and insect damage has been demonstrated, nationally consistent datasets currently (2010) are lacking. Consequently, these data gaps will limit the ability to account for the effects of all disturbances on ecosystem carbon storage and greenhouse-gas fluxes. Future research is needed to identify the most suitable algorithms and approach to generate a comprehensive land-disturbance and severity inventory for the Nation for use in carbon and greenhouse-gas assessments, and to develop models sensitive to climate and land change to project future disturbance-occurrence patterns.

C.10. References Cited

[Reports that are only available online may require a subscription for access.]

Ahren, F.J., 1988, The effects of bark beetle stress on the foliar spectral reflectance of lodgepole pine: International Journal of Remote Sensing, v. 9, p. 1451–1468.

Aukema, B.H., Carroll, A.L., Zheng, Yanbing, Zhu, Jun, Raffa, K.F., Moore, R.D., Stahl, Kerstin, and Taylor, S.W., 2008, Movement of outbreak populations of mountain pine beetle—Influences of spatiotemporal patterns and climate: Ecography, v. 31, no. 3, p. 348–358.

Bessie, W.C., and Johnson, E.A., 1995, The relative importance of fuels and weather on fire behavior in sub-alpine forests: Ecology, v. 76, no. 3, p. 747–762, doi:10.2307/1939341.

Boose, E.R., Chamberlin, K.E., and Foster, D.R., 2001, Landscape and regional impacts of hurricanes in New England: Ecological Monographs, v. 71, no. 1, p. 27–48, doi:10.1890/0012-9615(2001)071[0027:LARIOH]2.0.CO;2.

Boose, E.R., Foster, D.R., and Fluet, Marcheterre, 1994, Hurricane impacts to tropical and temperate forest landscapes: Ecological Monographs, v. 64, no. 4, p. 369–400, doi:10.2307/2937142.

Cardille, J.A., Ventura, S.J., and Turner, M.G., 2001, Environmental and social factors influencing wildfires in the upper Midwest, United States: Ecological Applications, v. 11, no. 1, p. 111–127, doi:10.1890/1051-0761(2001)011[0111:EASFIW]2.0.CO;2.

Dodds, K.J., Garman, S.L., and Ross, D.W., 2006, Landscape analyses of Douglas-fir beetle populations in northern Idaho: Forest Ecology and Management, v. 231, no. 1–3, p. 119–130, doi:10.1016/j.foreco.2006.05.023.

Eidenshink, Jeff, Schwind, Brian, Brewer, Ken, Zhu, Z.L., Quayle, Brad, and Howard, Stephen, 2007, A project for monitoring trends in burn severity: Fire Ecology, v. 3, no. 1, p. 3–21.

Elith, Jane, Graham, C.H., Anderson, R.P., Dudik, Miroslav, Ferrier, Simon, Guisan, Antoine, Hijmans, R.J., Huettmann, Falk, Leathwick, J.R., Lehmann, Anthony, Li, Jin, Lohmann, L.G., Loiselle, B.A., Manion, Glenn, Moritz, Craig, Nakamura, Miguel, Nakazawa, Yoshinori, Overton, J.M., Peterson, A.T., Phillips, S.J., Richardson, Karen, Scachetti-Pereira, Ricardo, Schapire, R.E., Soberon, Jorge, Williams, Stephen, Wisz, M.S., and Zimmermann, N.E., 2006, Novel methods improve prediction of species' distributions from occurrence data: Ecography, v. 29, no. 2, p. 129–151, doi:10.1111/j.2006.0906-7590.04596.x.

Elith, Jane, and Leathwick, J.R., 2009, Species distribution models—Ecological explanation and prediction across space and time: Annual Review of Ecology, Evolution, and Systematics, v. 40, p. 677–697, doi:10.1146/annurev.ecolsys.110308.120159.

Falk, D.A., Miller, Carol, McKenzie, Donald, and Black, A.E., 2007, Cross-scale analysis of fire regimes: Ecosystems, v. 10, p. 809–823.

Finney, M.A., 2002, Fire growth using minimum travel time methods: Canadian Journal of Forest Research, v. 32, no. 8, p. 1420–1424.

Finney, M.A., 2004, FARSITE—Fire Area Simulator—Model development and evaluation (revised edition in 2004 of 1998 report): U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Research Paper RMRS–RP–4 (revised), 47 p., available at http://www.fs.fed.us/rm/pubs/rmrs_rp004.html.

Finney, M.A., 2006, An overview of FlamMap fire modeling capabilities, *in* Andrews, P.L., and Butler, B.W., comps., Fuels management—How to measure success—Conference proceedings, 28–30 March 2006, Portland, Oreg.: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Proceedings RMRS–P–41, p. 213–220, accessed June 22, 2010, at http://www.fs.fed.us/rm/pubs/rmrs_p041.html.

Finney, Mark, Grenfell, I.C., and McHugh, C.W., 2009, Modeling containment of large wildfires using generalized linear mixed-model analysis: Forest Science, v. 55, no. 3, p. 249–255.

Franklin, S.E., Wulder, M.A., Skakun, R.S., and Carroll, A.L., 2003, Mountain pine beetle red-attack forest damage classification using stratified Landsat TM data in British Columbia, Canada: Photogrammetric Engineering and Remote Sensing, v. 69, no. 3, p. 283–288.

Gan, Jianbang, 2004, Risk and damage of southern pine beetle outbreaks under global climate change: Forest Ecology and Management, v. 191, no. 1–3, p. 61–71.

Huang, Chengquan, Goward, S.N., Masek, J.G., Gao, Feng, Vermote, E.F., Thomas, Nancy, Schleeweis, Karen, Kennedy, R.E., Zhu, Zhiliang, Eidenshink, J.C., and Townshend, J.R.G., 2009, Development of time series stacks of Landsat images for reconstructing forest disturbance history: International Journal of Digital Earth, v. 2, no. 3, p. 195–218, doi:10.1080/17538940902801614.

Huang, Chengquan, Goward, S.N., Masek, J.G., Thomas, Nancy, Zhu, Zhiliang, and Vogelmann, J.E., 2010, An automated approach for reconstructing recent forest disturbance history using dense Landsat time series stacks: Remote Sensing of Environment, v. 114, no. 1, p. 183–198, doi:10.1016/j.rse.2009.08.017.

Keane, R.E., Burgan, Robert, and van Wagtendonk, Jan, 2001, Mapping wildland fuels for fire management across multiple scales—Integrating remote sensing, GIS, and biophysical modeling: International Journal of Wildland Fire, v. 10, no. 3–4, p. 301–319, doi:10.1071/WF01028.

Kennedy, R.E., Cohen, W.B., and Schroeder, T.A., 2007, Trajectory-based change detection for automated characterization of forest disturbance dynamics: Remote Sensing of Environment, v. 110, no. 3, p. 370–386, doi:10.1016/j.rse.2007.03.010.

Kramer, M.G., Hansen, A.J., Taper, M.L., and Kissinger, E.J., 2001, Abiotic controls on long-term windthrow disturbance and temperate rain forest dynamics in southeast Alaska: Ecology, v. 82, no. 10, p. 2749–2768.

Krist, F.J., Jr., Sapio, F.J., and Tkacz, B.M., 2007, Mapping risk from forest insects and diseases: U.S. Department of Agriculture, Forest Service, Forest Health Technology Enterprise Team, FHTET 2007–06, 115 p., accessed June 22, 2010, at http://www.fs.fed.us/foresthealth/technology/pdfs/FHTET2007-06_RiskMap.pdf.

Omernik, J.M., 1987, Ecoregions of the conterminous United States: Annals of the Association of American Geographers, v. 77, no. 1, p. 118–125.

Phillips, S.J., Anderson, R.P., and Schapire, R.E., 2006, Maximum entropy modeling of species geographic distributions: Ecological Modelling, v. 190, no. 3–4, p. 231–259.

Prasad, A.M., Iverson, L.R., Peters, M.P., Bossenbroek, J.M., Matthews, S.N., Sydnor, T.D., and Schwartz, M.W., 2010, Modeling the invasive emerald ash borer risk of spread using a spatially explicit cellular model: Landscape Ecology, v. 25, no. 3, p. 353–369, doi:10.1007/s10980-009-9434-9.

Prichard, S.J., Ottmar, R.D., and Anderson, G.K., 2006, Consume 3.0 user's guide: Seattle, Wash., U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 234 p., accessed June 22, 2010, at http://www.fs.fed.us/pnw/fera/research/smoke/consume/consume30_users_guide.pdf.

Ramsey, E.W., Hodgson, M.E., Sapkota, S.K., and Nelson, G.A., 2001, Forest impact estimated with NOAA AVHRR and Landsat TM data related to an empirical hurricane wind-field distribution: Remote Sensing of Environment, v. 77, no. 3, p. 279–292.

Reinhardt, E.D., Keane, R.E., and Brown, J.K., 1997, First Order Fire Effects Model—FOFEM 4.0 user's guide: U.S. Department of Agriculture, Forest Service, Intermountain Research Station, General Technical Report INT–GTR–344, 65 p., accessed June 22, 2010, at http://www.fs.fed.us/rm/pubs_int/int_gtr344.html.

Rollins, M.G., 2009, LANDFIRE—A nationally consistent vegetation, wildland fire, and fuel assessment: International Journal of Wildland Fire, v. 18, no. 3, p. 235–249, doi:10.1071/WF08088.

Rollins, M.G., and Frame, C.K., eds., 2006, The LANDFIRE prototype project—Nationally consistent and locally relevant geospatial data for wildland fire management: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, General Technical Report RMRS–GTR–175, 416 p., accessed June 22, 2010, at http://www.fs.fed.us/rm/pubs/rmrs_gtr175.html.

Santos, M.J., and Whitham, T.G., 2010, Predictors of *Ips confusus* outbreaks during a record drought in Southwestern USA—Implications for monitoring and management: Environmental Management, v. 45, no. 2, p. 239–249, doi:10.1007/s00267-009-9413-6.

Schulte, L.A., Mladenoff, D.J., Burrows, S.N., Sickley, T.A., and Nordheim, E.V., 2005, Spatial controls of pre-euro-american wind and fire disturbance in northern Wisconsin (USA) forest landscapes: Landscape Ecology, v. 8, no. 1, p. 73–94, doi:10.1007/s10021-004-0052-8.

Skakun, R.S., Wulder, M.A., and Franklin, S.E., 2003, Sensitivity of the Thematic Mapper enhanced wetness difference index to detect mountain pine beetle red-attack damage: Remote Sensing of Environment, v. 86, no. 4, p. 433–443, doi:10.1016/S0034-4257(03)00112-3.

Swetnam, T.W., and Betancourt, J.L., 1990, Fire-southern oscillation relations in the Southwestern United States: Science, v. 249, no. 4972, p. 1017–1020.

Syphard, A.D., Radeloff, V.C., Keeley, J.E., Hawbaker, T.J., Clayton, M.K., Stewart, S.I., and Hammer, R.B., 2007, Human influence on California fire regimes: Ecological Applications, v. 17, no. 5, p. 1388–1402, doi:10.1890/06-1128.1.

Syphard, A.D., Radeloff, V.C., Keuler, N.S., Taylor, R.S., Hawbaker, T.J., Stewart, S.I., and Clayton, M.K., 2008, Predicting spatial patterns of fire on a southern California landscape: International Journal of Wildland Fire, v. 17, no. 5, p. 602–613, doi:10.1071/WF07087.

U.S. Congress, 2007, Energy Independence and Security Act—Public Law 110–140: U.S. Congress, 311 p., available at http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=110_cong_public_laws&docid=f:publ140.110.pdf

Vickery, P.J., Skerlj, P.F., and Twisdale, L.A., 2000, Simulation of hurricane risk in the U.S. using empirical track model: Journal of Structural Engineering, v. 126, no. 10, p. 1222–1237.

Vogelmann, J.E., Tolk, Brian, and Zhu, Zhiliang, 2009, Monitoring forest changes in the Southwestern United States using multitemporal Landsat data: Remote Sensing of Environment, v. 113, no. 8, p. 1739–1748.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., and Swetnam, T.W., 2006, Warming and earlier spring increase Western U.S. forest wildfire activity: Science, v. 313, no. 5789, p. 940–943, doi:10.1126/science.1128834.

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