Atmospheric Turbulence in Wildland Fire Environments: Implications for Fire Behavior and Smoke Dispersion

Warren E. Heilman

The atmospheric environment surrounding wildland fires is often extremely turbulent, characterized by varying wind speeds and directions (that is, wind gusts and vortices) associated with the ambient atmosphere or with fire-induced perturbations of the atmosphere. These turbulent circulations can have direct and indirect impacts on how wildland fires spread across landscapes and how fire emissions are transported and dispersed away from combustion zones (Forthofer and Goodrick 2011; Heilman and others 2019).

Connections between fire behavior, smoke plume dynamics, and atmospheric turbulence have been established through numerous past observations of wildland fire events and through idealized and case study numerical model simulations of fire/atmosphere interactions (such as Clements and others 2008; Sun and others 2009; and Ward and Hardy 1991). However, gaps in our understanding of the typical characteristics of turbulence regimes surrounding wildland fires and the mechanisms by which they can influence fire behavior and smoke dispersion still exist.

Scientists are working to fill these gaps in understanding through new observational research, with the ultimate goal of providing the foundational science for developing new and improved operational predictive tools for fire behavior and smoke dispersion. This paper summarizes some of these research efforts and their key findings.

PRESCRIBED FIRE AND WILDFIRE TURBULENCE OBSERVATIONS

Over the past 10 to 15 years or so, many wildland fire experiments have been conducted in a variety of settings, with a special emphasis on measuring turbulent circulations within and near the fire environment. In February 2006, one of the first comprehensive studies of fire-induced turbulence regimes during a prescribed high-intensity heading (generally spreading in the direction of the ambient wind) grass fire was carried out at the Houston Coastal Center in Texas; it was known as the FireFlux I experiment (Clements and others 2007).

Then, in January 2013, a second prescribed heading grass fire experiment (FireFlux II) with enhanced atmospheric measurements was carried out at the same location, with the same emphasis on measuring fire-induced turbulence regimes (Clements and others 2019). Using onsite tower-based high-frequency (10- or 20-hertz) sonic anemometer and thermocouple measurements for both experiments, the spatial and temporal

Warren Heilman is a research meteorologist for the Forest Service, Northern Research Station, Lansing, MI.

Figure 1—*Instrumented 30-meter (98-foot) mobile tower set up in the interior of a burn block in the New Jersey Pinelands National Reserve in 2011 to measure atmospheric turbulent circulations at multiple heights in the vicinity of a spreading prescribed fire beneath forest overstory vegetation. Photo: Nicholas Skowronski, USDA Forest Service.*

variations in the three-dimensional wind field and temperature field were examined as the grass fires spread through the monitoring networks. From these high-frequency measurements, new insight was gained into how heading grass fires can change the general properties of turbulent circulations typically found under no-fire conditions. For example, the measurements indicated that strong turbulent downdrafts (consistent with horizontal roll vortices; see Haines and others 1982) behind, just ahead, and downwind of advancing fire fronts can reach the surface and potentially contribute to the deposition of soot and embers.

Followup analyses of the FireFlux I data revealed that the energy of turbulent circulations (also known as turbulent kinetic energy) generated by and in the vicinity of heading grass fires can greatly exceed the typical energy of ambient (no-fire) near-surface atmospheric turbulent circulations over grasslands (Clements and others 2008). Furthermore, the energy of the horizontal versus vertical wind gusts/lulls within convective plumes above grassland fire fronts was found to be similar, in contrast to what is observed near the surface under no-fire conditions, where energy differences are typically much larger (that is, anisotropic turbulence).

The higher intensity FireFlux I grass fire experiment set the stage for a series of new lower intensity prescribed fire experiments conducted in forested (longleaf pine (*Pinus palustris* Mill.)) and nonforested (grass and shrub) ecosystems in Florida and Georgia during the autumn and winter seasons of 2008, 2011, and 2012. Collectively, this suite of experimental burns comprised the well-known Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE), which is fully described by Ottmar and others (2016). As in the FireFlux I and II experiments, a substantial component of the RxCADRE program was devoted to assessments of the atmospheric environment surrounding advancing fire fronts, including ambient and fire-induced turbulent circulations (Clements and others 2016). The RxCADRE onsite tower-based turbulence measurements revealed that even low-intensity surface fires beneath forest overstory vegetation can lead to fire/atmosphere interactions that generate turbulent circulations capable of perturbing fire fronts.

Concurrent with the RxCADRE program, the U.S. Joint Fire Science Program sponsored a series of low-intensity wildland fire experiments conducted in forested environments in New Jersey (pitch pine (*Pinus rigida* Mill.) and mixed oak (*Quercus* spp.)) and North Carolina (longleaf pine) to assess how forest overstory vegetation can affect turbulent circulations in the vicinity of fire fronts and local smoke dispersion (Strand and others 2013; Heilman and others 2013). Onsite tower-based measurements (see, for example, figure 1) of turbulent circulations and thermal conditions within and above forest overstory vegetation layers during the experiments provided a wealth of information about (1) the energetics of fire-induced turbulent circulations (such as updrafts, downdrafts, and inflow into the combustion zone) when forest overstory vegetation is present; (2) the potential effects that fire fronts underneath overstory vegetation can have on the skewness of horizontal and vertical turbulent velocity distributions (that is, the creation of non-Gaussian turbulence); and (3) the relative contributions that horizontal and vertical turbulent fluxes of heat and momentum can make to the total heat and momentum flux fields in the vicinity of fire fronts in forested environments.

Key findings from fire experiments suggest the following:

- Downdrafts associated with fire-induced turbulent eddies in the vicinity of fire fronts can bring cooler air from aloft deep into forest overstory layers and potentially affect fire spread and local smoke dispersion (Seto and others 2014; Heilman and others 2015).
- The energy of fire-induced turbulent eddies (turbulent kinetic energy) is likely to be at a maximum at or near the top of forest canopies instead of near the surface combustion zones, which implies more turbulent mixing of smoke as it exits the top of the canopy than near the surface (Heilman and others 2015).
- The horizontal turbulent mixing of smoke during low-intensity fires in forested environments tends to exceed vertical turbulent mixing, especially near the surface and near the canopy top (Heilman and others 2015, 2017).
- Both vertical wind shear and buoyancy contribute substantially to the production of turbulent eddies and the increase in turbulent kinetic energy during the passage of fire fronts in forested environments, whereas the diffusion of turbulent kinetic energy during periods of fire front passage tends to reduce energy levels above fire fronts (Heilman and others 2017).
- The presence of wildland fires in forested environments can result in highly skewed horizontal and vertical velocity distributions (that is, non-Gaussian turbulence regimes), which calls into question the use of smoke dispersion predictive tools that assume Gaussian turbulence fields (Heilman and others 2017).

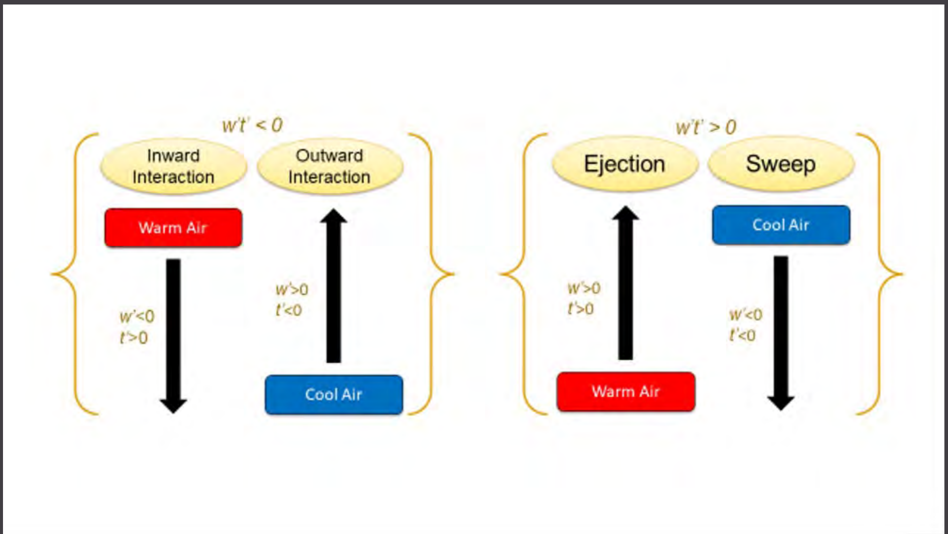

Figure 2—*Schematic of the contributions of sweep, ejection, outward interaction, and inward interaction events to vertical turbulent heat fluxes (w't'), where w' is a perturbation vertical velocity and t' is a perturbation temperature. Inward and outward interactions (left side of figure) result in negative heat fluxes (w't' < 0) caused by the downward transport (w' < 0) of warm air (t' > 0) from above (inward interaction) or the upward transport (w' > 0) of cool air (t' < 0) from below (outward interaction). Ejections and sweeps (right side of figure) result in positive heat fluxes (w't' > 0) caused by the upward transport (w' > 0) of warm air (t' > 0) from below (ejection) or the downward transport (w' < 0) of cool air (t' < 0) from above (sweep).*

Scientists are working to fill these gaps in understanding through new observational research.

- On average, horizontal turbulent heat fluxes tend to exceed vertical turbulent heat fluxes above and in the vicinity of surface fire fronts in forested environments, whereas vertical turbulent momentum fluxes tend to exceed horizontal turbulent momentum fluxes (Heilman and others 2019).

Forest Service scientists and external collaborators are conducting research to assess the mechanisms by which heat and momentum are vertically transported away from and into wildland fire fronts in forested and grassland environments by atmospheric turbulence. The vertical transport of warm/cool air and high/low-horizontal-momentum air away from and into combustion zones by turbulent eddies is accomplished through events called sweeps, ejections, outward interactions, and inward interactions (figs. 2, 3):

- ***Sweeps:***
  - Heat—Downward flux of cool air from above.
  - Momentum—Downward flux of high-horizontal-momentum air from above.
- ***Ejections:***
  - Heat—Upward flux of warm air from below.
  - Momentum—Upward flux of low-horizontal-momentum air from below.
- ***Outward Interactions:***
  - Heat—Upward flux of cool air from below.
  - Momentum—Upward flux of high-horizontal-momentum air from below.

- ***Inward Interactions:***
  - Heat—Downward flux of warm air from above.
  - Momentum—Downward flux of low-horizontal-momentum air from above.

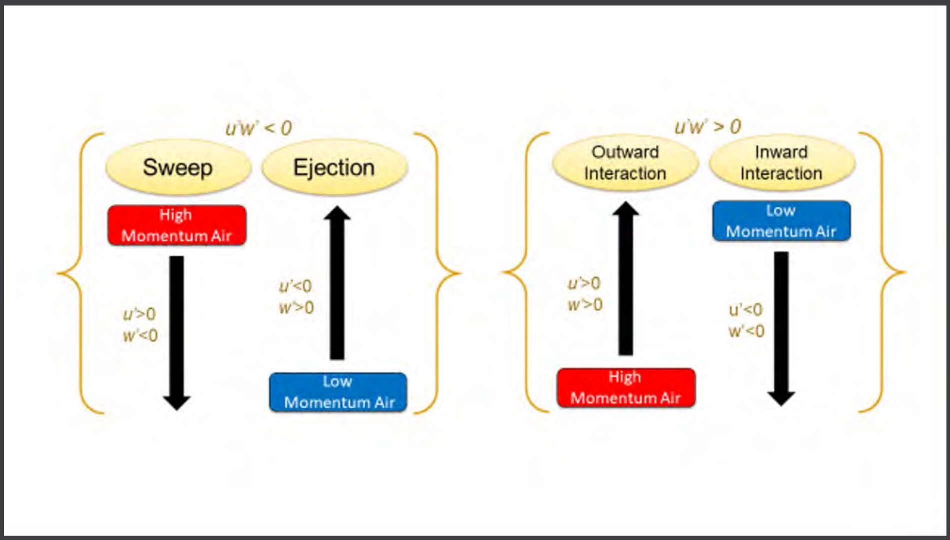

Figure 3—*Schematic of the contributions of sweep, ejection, outward interaction, and inward interaction events to vertical turbulent momentum fluxes (u'w'), where u' is a perturbation streamwise horizontal velocity and w' is a perturbation vertical velocity. Sweeps and ejections (left side of figure) result in negative momentum fluxes (u'w' < 0) caused by the downward transport (w' < 0) of high horizontal momentum air (u' > 0) from above (sweep) or the upward transport (w' > 0) of low horizontal momentum air (u' < 0) from below (ejection). Outward and inward interactions (right side of figure) result in positive momentum fluxes (u'w' > 0) caused by the upward transport (w' > 0) of high horizontal momentum air (u' > 0) from below (outward interaction) or the downward transport (w' < 0) of low horizontal momentum air (u' < 0) from above (inward interaction).*

Using data collected during some of the previously described wildland fire experiments (FireFlux I and II and the Joint Fire Science Program New Jersey burn experiments), scientists are investigating the typical frequencies of occurrence for the different types of events and their typical overall contributions to average heat and momentum fluxes near fire fronts in grassland and forested environments. Initial findings from this research suggest that, for turbulent heat fluxes, ejection events (upward fluxes of warm air from below) may be the most common type of event within near-surface atmospheric layers above grassland fire fronts, whereas sweep events (downward fluxes of cool air from above) may be the most frequent type of event above surface fire fronts in forested environments. For turbulent momentum fluxes, the initial analyses suggest that both sweeps (downward fluxes of high-horizontal-momentum air from above) and ejections (upward fluxes of low-horizontal-momentum air from below) are likely the most prevalent types of events above grassland fire fronts. Above surface fire fronts in forested environments, initial results suggest a very different momentum flux picture, with sweeps and outward interactions (upward fluxes of high-horizontal-momentum air from below) potentially being the most prevalent types of events. New wildland fire experiments currently underway, such as experiments funded by the U.S. Department of Defense's Strategic Environmental Research and Development Program in the New Jersey Pine Barrens (*https://www.serdp-estcp.org/Program-Areas/Resource-Conservation-and-Resiliency/Air-Quality/RC-2641*), are providing critical observational datasets for further evaluating how sweeps, ejections, outward interactions, and inward interactions contribute to turbulent heat and momentum fluxes under different environmental and fire-intensity conditions.

In addition to wildland fire experiments in relatively flat terrain (discussed above), other recent experiments have assessed fire-induced turbulence regimes in areas of complex terrain. These experiments have expanded our understanding, based on earlier studies (as summarized in Werth and others (2011)), of potential fire/turbulence interactions in complex-terrain settings.

For example, Seto and Clements (2011) conducted a prescribed (heading) grass fire experiment in 2008 in complex terrain east of San José, CA. They used tower-based sonic anemometer and thermocouple instrumentation to measure terrain- and fire-induced turbulent circulations and temperature fluctuations as the fire spread through the burn block. The study was instrumental in showing how sea-breeze fronts, upvalley flows, and fires can interact to create near-surface turbulence regimes favorable for firewhirl formation.

Clements and Seto (2015) conducted another prescribed grass fire experiment (known as the Grass Fires on Slopes Experiment) in 2010, with a heading fire on a simple slope near Dublin, CA, under ambient cross-slope winds. Using monitoring technology similar to that used in their 2008 experiment, they found that fire-induced turbulent circulations can enhance the upslope spread of fires, even in the presence of moderate ambient cross-slope winds. They also found that the energy associated with fluctuations in horizontal velocities tended to exceed the energy associated with vertical velocity fluctuations just above fire fronts (that is, anisotropic turbulence), although the degree of anisotropy was less than what is typically observed under no-fire conditions. The anisotropy was most pronounced for low-frequency velocity fluctuations associated with large

Gaps in our understanding of the connections between atmospheric turbulence and wildland fires still exist.

turbulent eddies (Seto and others 2013). These findings are consistent with other observations of turbulence anisotropy above fire fronts in forested environments, also described in Seto and others (2013) and in Heilman and others (2015, 2017).

A year later in 2011, Charland and Clements (2013) conducted a prescribed downslope surface backing fire experiment in an oak woodland located in a complex-terrain area east of San José, CA. Utilizing ground-based scanning Doppler lidar technology, they were able to identify windflow convergence zones associated with turbulent vortices/eddies within and downwind of the convective smoke plume generated by the fire. These types of vortices/eddies can affect the entrainment of ambient air into convective smoke plumes and the dispersion of fire emissions.

Although onsite or nearby measurements of turbulence regimes during wildfires are much more difficult to carry out than experimental fires (which are typically lower in intensity), some recent wildfire behavior observations and analyses (such as alpine bushfires in Australia in 2003) strongly suggest that ambient and fire-induced turbulence can contribute to the spread of fires over complex terrain in directions transverse to ambient wind directions, the development of spot fires through ember transport by turbulent eddies, and the generation of firewhirls (see, for example, Sharples 2009; and Sharples and others 2010, 2012). The connections between ambient and fire-induced turbulence and convective smoke plume behavior during wildfire events in complex-terrain regions have also been measured recently through remote sensing technology (such as Doppler lidar) as part of the Rapid Deployments to Wildfires Experiment (Clements and others 2018). For example, Lareau and Clements (2017) used a scanning Doppler lidar system during the 2014 El Portal Fire in California to measure turbulent circulations within and in the vicinity of the fire's convective plume. The measurements clearly highlighted the important role that turbulent eddies play in entraining ambient air into smoke plumes and increasing the radii of smoke plumes with height as they move upward.

Fire-induced turbulent circulations can enhance the upslope spread of fires, even with the presence of moderate ambient cross-slope winds.

RESEARCH GAPS AND OPPORTUNITIES

The onsite and remotely sensed measurements of atmospheric turbulence characteristics during wildland fire events carried out over the last 10 to 15 years have led to a much-improved understanding of how fires can interact with the atmosphere. Nevertheless, gaps in our understanding of the connections between atmospheric turbulence and wildland fires still exist. In particular, we don't fully understand how backing and heading fires with different intensities in grassland and forested environments actually respond to turbulent circulations associated with different turbulent eddy sizes.

New wildland fire experiments that incorporate high-frequency measurements of fire front behavior and spread, coupled with onsite or remotely sensed measurements of atmospheric turbulence-related variables at and near the fire front, are needed to close the knowledge gap. The suite of ongoing and planned wildland fire experiments for the Fire and Smoke Model Evaluation Experiment (FASMEE) (Potter and Clements 2017; Prichard and others 2019) offers an excellent opportunity to assess the direct and indirect connections between wildland fire behavior and turbulence. The knowledge gained from FASMEE and similar wildland fire experiments will be critical for the development of atmospheric turbulence parameterizations that more fully capture the effects of fire-induced turbulent circulations on fire spread and smoke transport in operational fire behavior and smoke dispersion modeling systems.

LITERATURE CITED

Charland, A.M.; Clements, C.B. 2013. Kinematic structure of a wildland fire plume observed by Doppler lidar. Journal of Geophysical Research: Atmospheres. 118: 1–13.

Clements, C.B.; Zhong, S.; Goodrick, S. [and others]. 2007. Observing the dynamics of wildland grass fires. Bulletin of the American Meteorological Society. 88: 1369–1382.

Clements, C.B.; Zhong, S.; Bian, X. [and others]. 2008. First observations of turbulence generated by grass fires. Journal of Geophysical Research. 113: D22102. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2008JD010014. (21 January 2020).

Clements, C.B.; Seto, D. 2015. Observations of fire-atmosphere interactions and near-surface heat transport on a slope. Boundary-Layer Meteorology. 154: 409–426.

Clements, C.B.; Lareau, N. P.; Seto, D. [and others]. 2016. Fire weather conditions and fire–atmosphere interactions observed during low-intensity prescribed fires – RxCADRE 2012. International Journal of Wildland Fire. 25: 90–101.

Clements, C.B.; Lareau, N.P.; Kingsmill, D.E. [and others]. 2018. The Rapid Deployments to Wildfires Experiment (RaDFIRE). Bulletin of the American Meteorological Society. 99: 2539–2559.

Clements, C.B.; Kochanski, A.K.; Seto, D. [and others]. 2019. The FireFlux II experiment: a model-guided field experiment to improve understanding of fire–atmosphere interactions and fire spread. International Journal of Wildland Fire. 28: 308–326.

Forthofer, J.M.; Goodrick, S.L. 2011. Review of vortices in wildland fire. Journal of Combustion. 2011: 984363. https://doi.org/10.1155/2011/984363. (21 January 2020).

Haines, D.A. 1982. Horizontal roll vortices and crown fires. Journal of Applied Meteorology. 21: 751–763.

Heilman, W.E.; Zhong, S.; Hom, J.L. [and others]. 2013. Development of modeling tools for predicting smoke dispersion from low-intensity fires. Final Report; U.S. Joint Fire Science Program; project 09–1–04–1. 61 p. https://www.firescience.gov/projects/09-1-04-1/project/09-1-04-1_final_report.pdf. (21 January 2020).

Heilman, W.E.; Clements, C.B.; Seto, D. [and others]. 2015. Observations of fire-induced turbulence regimes during low-intensity wildland fires in forested environments: implications for smoke dispersion. Atmospheric Science Letters. 16: 453–460.

Heilman, W.E.; Bian, X.; Clark, K.L. [and others]. 2017. Atmospheric turbulence observations in the vicinity of surface fires in forested environments. Journal of Applied Meteorology and Climatology. 56: 3133–3150.

Heilman, W.E.; Clements, C.B.; Zhong, S. [and others]. 2019. Atmospheric turbulence. In: Manzello, S., ed. Encyclopedia of wildfires and wildland-urban interface (WUI) fires. Basel, Switzerland: Springer Nature. https://doi.org/10.1007/978-3-319-51727-8. (21 January 2020).

Lareau, N.P.; Clements, C.B. 2017. The mean and turbulent properties of a wildfire convective plume. Journal of Applied Meteorology and Climatology. 56: 2289–2299.

Ottmar, R.D.; Hiers, J.K.; Butler, B.W. [and others]. 2016. Measurements, datasets and preliminary results from the RxCADRE project – 2008, 2011 and 2012. International Journal of Wildland Fire. 25: 1–9.

Potter, B.E.; Clements, C. 2017. Development of a comprehensive plume dynamics and meteorology study plan for FASMEE. Final report; U.S. Joint Fire Science Program; project 16–4–03–1. 9 p. https://www.firescience.gov/projects/16-4-03-1/project/16-4-03-1_final_report.pdf. (22 January 2020).

Prichard, S.; Larkin, N.; Ottmar, R. [and others]. 2019. The Fire and Smoke Model Evaluation Experiment—a plan for integrated, large fire–atmosphere field campaigns. Atmosphere. 10(2): 66. https://doi.org/10.3390/atmos10020066. (22 January 2020).

Seto, D.; Clements, C.B. 2011. Fire whirl evolution observed during a valley wind-sea breeze reversal. Journal of Combustion. Article ID 569475. DOI: 10.1155/2011/569475.

Seto, D.; Clements, C.B.; Heilman, W.E. 2013. Turbulence spectra measured during fire front passage. Agricultural and Forest Meteorology. 169: 195–210.

Seto, D.; Strand, T.M.; Clements, C.B. [and others]. 2014. Wind and plume thermodynamic structures during low-intensity subcanopy fires. Agricultural and Forest Meteorology. 198–199: 53–61.

Sharples, J.J. 2009. An overview of mountain meteorological effects relevant to fire behaviour and bushfire risk. International Journal of Wildland Fire. 18: 737–754.

Sharples, J.J.; McRae, R.H.D.; Weber, R.O. 2010. Wind characteristics over complex terrain with implications for bushfire risk management. Environmental Modelling and Software. 25: 1099–1120.

Sharples, J. J.; McRae, R.H.D.; Wilkes, S.R. 2012. Wind-terrain effects on the propagation of wildfires in rugged terrain: fire channeling. International Journal of Wildland Fire. 21: 282–296.

Strand, T.M.; Rorig, M.; Yedinak, K. [and others]. 2013. Sub-canopy transport and dispersion of smoke: a unique observation dataset and model evaluation. Final report; U.S. Joint Fire Science Program; project 09–1–04–2. 63 p. https://www.firescience.gov/projects/09-1-04-2/project/09-1-04-2_final_report.pdf. (21 January 2020).

Sun, R.; Krueger, S.K.; Jenkins, M.A. [and others]. 2009. The importance of fire–atmosphere coupling and boundary-layer turbulence to wildfire spread. International Journal of Wildland Fire. 18: 50–60.

Ward, D.E.; Hardy, C.C. 1991. Smoke emissions from wildland fires. Environment International. 17: 117–134.

Werth, P.A.; Potter, B.E.; Clements, C.B. [and others]. 2011. Synthesis of knowledge of extreme fire behavior: volume I for fire managers. Gen. Tech. Rep. PNW–GTR–854. Portland, OR: USDA Forest Service, Pacific Northwest Research Station. 144 p.