THE EXPOSURE INDEX: DEVELOPING FIREFIGHTER SAFETY PERFORMANCE MEASURES

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A cornerstone of effective institutional learning and accountability is the development, tracking, and analysis of informative performance measures. In a previous issue of *Fire Management Today* ("A New Look at Risk Management," Winter 2011), a series of articles highlighted the importance of organizational safety and risk management and the challenges of balancing safety, efficiency, and effectiveness in the wildfire management environment. Assessing risks to firefighter safety can be difficult, especially in the complex, uncertain, and dynamic environment of active incident management. Programmatic evaluation of firefighter safety is likewise difficult. Additional concerns regarding efficiency and escalating wildfire management costs pose challenges for the Forest Service.

In this report, we briefly review ongoing work to establish a performance measure that directly relates to firefighter safety, efficiency, and effectiveness. The measure is termed "Exposure Index," recognizing that firefighting is a

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dangerous endeavor and that the more time firefighters are exposed to the inherent danger of the fireline, the higher the likelihood of an injury or fatality. The research underway is part of a broader body of work undertaken by the National Fire Decision Support Center fire economics team to inform decisionmaking and ideally to improve wildfire risk management.

> "Reduced firefighter exposure to unnecessary risk during fire incidents continues to guide fire management decisions and anchors our actions."
>
> - Jim Hubbard, March 30, 2011

What Is the Exposure Index?

Exposure Index (EI) is a quantitative measure comparing the contained fire perimeter (CFP) to the total productive capacity (TPC) of the assigned firefighting resources. CFP is equal to the overall length of the final fire perimeter, while TPC represents the cumulative capacity of assigned resources for the duration of the fire event calculated as the sum of total daily productive capacity. EI is calculated as

the ratio of CFP to TPC, as shown below.

$$EI = \frac{CFP}{TPC}$$

EI is an integrated measure of both the relative productivity of resources in building fireline and the relative effectiveness of fireline in containing the fire. For instance, fireline may be burned over or the built contingency line may not intersect with a final fire perimeter. Thus, resources could work at full productive capacity yet have an EI less than 1.0. Alternatively, if a wildfire is allowed to burn itself out on a portion of the fireline, the portion of the contained perimeter that did not have built fireline will still contribute to EI, and thus EI could potentially exceed 1.0.

How the Exposure Index Works

We obtained data to estimate exposure levels for individual fires by identifying daily levels of all ground-based resources identified in incident status (ICS-209) reports for fiscal years (FYs) 2003 to 2010, which describe the incident location, weather, projected spread, firefighting resources, and other critical incident information. Many of the fire events were missing daily entries, and we excluded a number of fire events because too many dates were missing. However, if there appeared to be sufficient

information with a small number of missing days, we interpolated daily resource use based on use information from neighboring days. Suppression resources likely conducting mop-up operations and fireline rehabilitation assigned after the event was declared 100 percent contained were not counted towards TPC. In total, we identified 483 Forest Service large wildfires (fires larger than 300 acres [120 ha]) with data quality suitable for calculating EI.

To compute resource productive capacity, we used production rates provided by George Broyles of the San Dimas Technology Development Center. Production rates vary by fuel model. To identify the dominant fuel type (brush, grass, timber), we cross-walked ICS-209 reports with the fuel model recorded within the National Fire Occurrence Database.

Final fire perimeters were not available for all fires within the sample, so we estimated final perimeter length statistically. Fire perimeters are not smooth and, in many cases, are quite rough or convoluted. In a related study, we developed a statistical regression model that links final fire perimeter to final fire area, and the parameters of the model provide estimates of the fractal dimension, or roughness, of fire perimeters. For the EI study reported here, we ran this model using 461 large Federal fires between the years 2005 and 2009. Because we had data on final fire area for all fire events, we were able to use the parameter estimates from the regression model to estimate final fire perimeters (CFP) for the 483 wildfires in this dataset.

Exposure Index Trends, 2005 to 2010

Figure 1 provides average EI by fiscal year. The annual EI is calculated as the sum of CFP for all fires divided by the sum of TPC on all fires for the identified year. EI was highest in FY 2005 (approximately 18 percent) and then trended downward to a low point in FY 2009, at 6 percent, with a modest recovery in FY 2010. Total EI over the 8-year period was computed to be 10.6 percent and indicates that the total productive capacity of ground-based firefighting resources was roughly 10 times the amount of fireline constructed along the final fire perimeter.

Figure 2 presents EI for individual fires, plotted against final fire perimeter size (in chains). This figure demonstrates that large fire events are typically characterized by relatively low EI values, whereas EI values on smaller fire events appear to be highly variable. Across all fires and across all years, EI for individual fires had a minimum value of 0.02 (2 percent), a maximum value of 14.77 (1,477 percent), a mean value of 0.49 (49 per-

cent), and a median value of 0.21 (21 percent). We note that mean and median values are higher than annual averages due to lower EI values for large fires, which carry more weight in the annual average computations due to larger CFP and TCP values. A total of 54 fires (11 percent of fires in our sample) had EI values greater than 1.0.

Related Studies and Future Work

In 2010, we conducted a research study to estimate daily productivity for individual firefighting resources using ICS-209 data for 46 fires that burned during FY 2008. In particular, we estimated the parameters of a well-known economic production function (known as the Cobb-Douglas production function), and then used the parameter estimates to compute the productivity of ground-based firefighting resources. Although these estimates differ from the EI estimates in that they allocate overall productivity to specific resources, the results are generally consistent with the EI analysis. In particular, resource productivity estimates from the Cobb-Douglas model suggest that
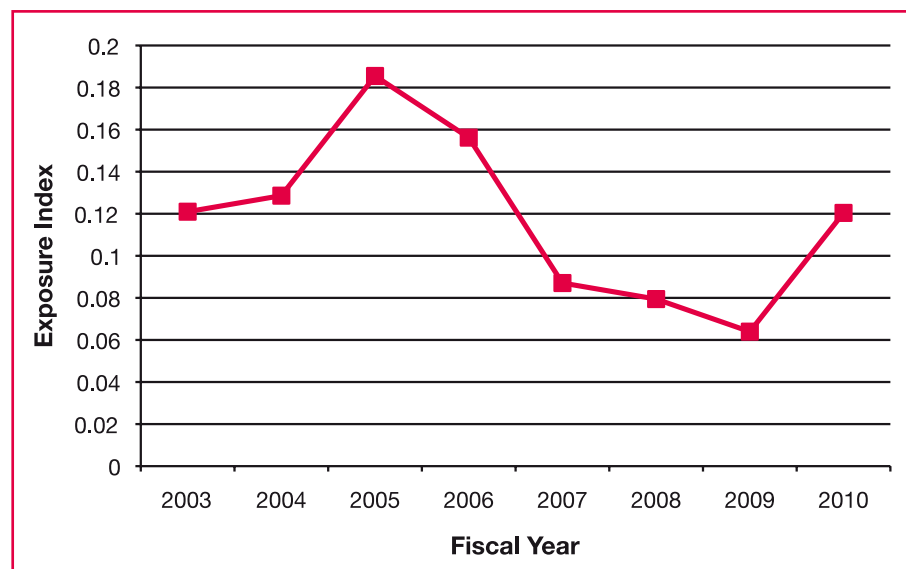

Figure 1—*Average exposure index (EI) by fiscal year.*

the productivity of suppression resources ranged from 8 percent (engines) to 51 percent (helicopters) of the San Dimas production estimates (fig. 3). Handcrew productivity in the Cobb-Douglas model was about 19 percent of the San Dimas production estimates, and dozer productivity was about 13 percent of the San Dimas estimates. Results from this study are currently being prepared for publication in a peer-reviewed journal (preliminary results are available from the authors).

Also related to these efforts, we conducted a field study in 2010 with additional data collection scheduled for 2011 to estimate daily resource productivity at the division level for large wildland fires. This study is unique because it allows us to estimate the amount of fireline constructed relative to the productive capability as well as the proportion of built fireline that actually engages the final fire perimeter. The analysis will include spatial and temporal measures of how different types of firefighting resources are deployed on a large wildland fire in terms of the terrain, fuels, weather, and fire progression. By matching resource assignments from the daily shift reports with the fire perimeter and developed firelines, the productivity and effectiveness of resources can be measured. Beyond measuring productivity and efficiency, geospatial analyses allow for enhanced evaluation of exposure of firefighters to fireline dangers. Figure 4 demonstrates how we estimated wildfire efficiency for the Tecolote Fire on the Santa Fe National Forest in New Mexico.
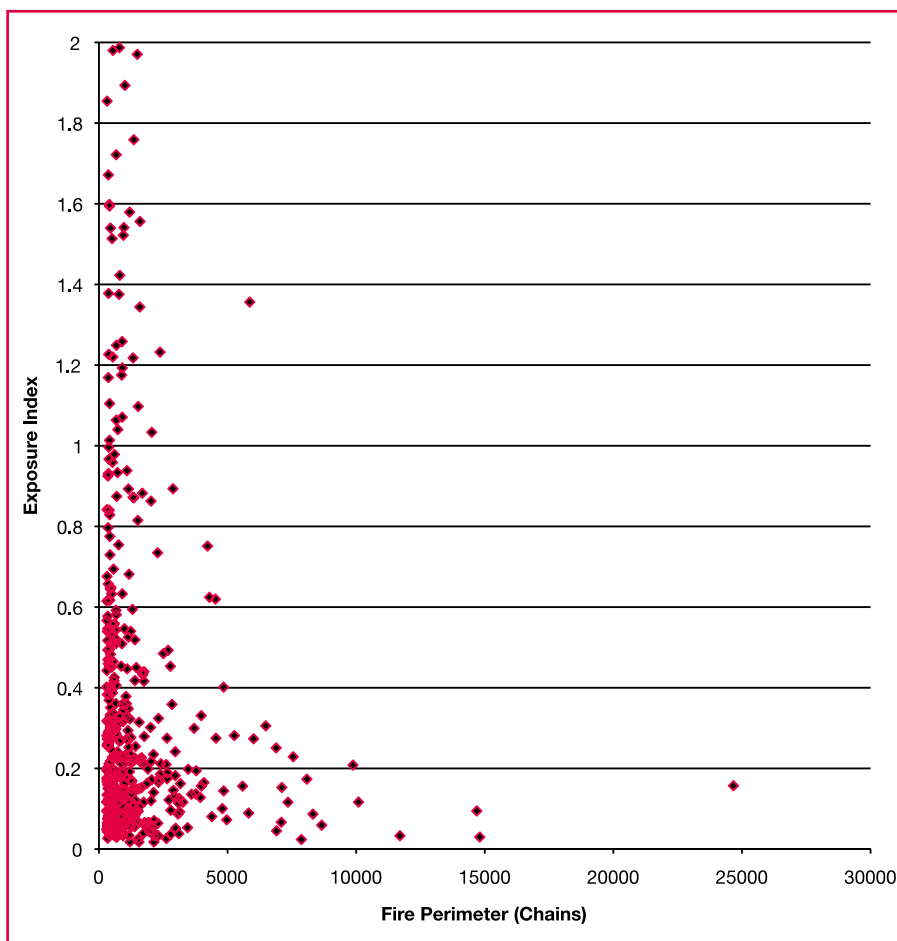

Figure 2—*Exposure index (EI) versus fire perimeter, in chains, for individual fires in fiscal years 2003 to 2010. Eighteen fires with EI exceeding 2.0 were removed to allow for improved resolution for the majority of the data. One chain equals 66 feet or 20 meters.*
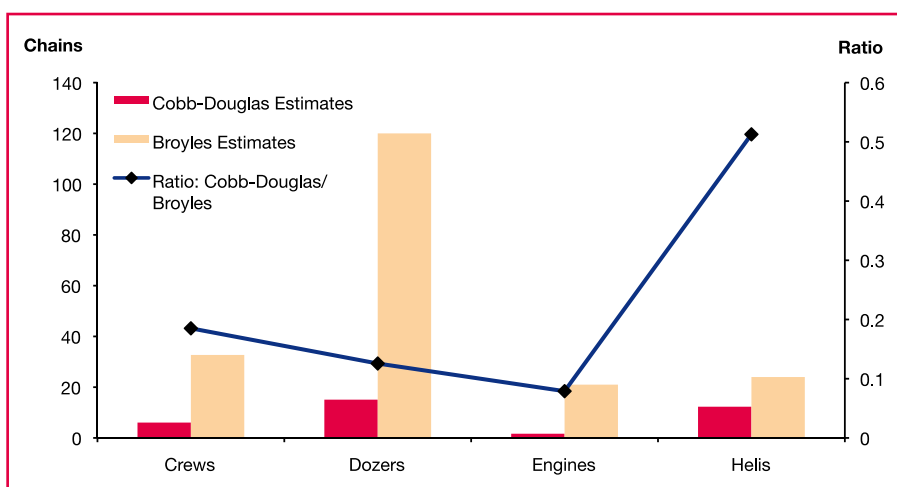

Figure 3—*Resource efficiency estimates from the Cobb-Douglas production model as compared to production rates estimated by Broyles (San Dimas Technology and Development Center). Note: all rates are for a single resource. Broyles' estimates for crews and helicopters are for type II resources. In the Cobb-Douglas production model, all crew and helicopter types were aggregated. One chain equals 66 feet or 20 meters.*
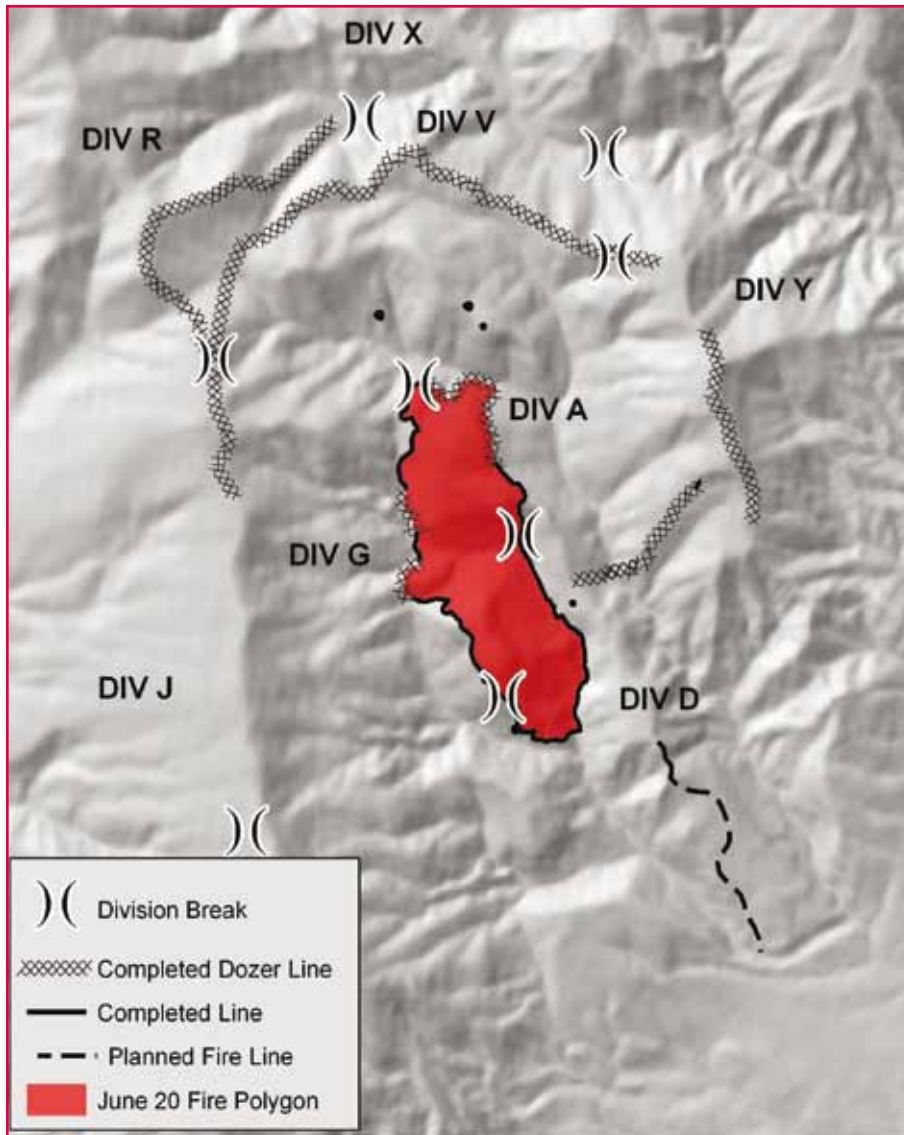
Figure 4—*Mapped fireline and perimeter for the Tecolote Fire on the Santa Fe National Forest in New Mexico. Productive efficiency of resources in producing fireline was estimated at 17 percent. Total fireline built was approximately 2.4 times the total fire perimeter, resulting in an overall efficiency rating of 6.9 percent.*

The Value of Understanding EI

Although EI is a relatively simple value to calculate, interpretation can be more complicated. Low EI values could indicate relatively unproductive use of resources, ineffective fireline construction, or both. Such results could imply unnecessary expenditures and have budgetary implications for nonfire programs. Alternatively, a low EI could be driven by the complexity of the fire environment (e.g., values at risk requiring that extensive sup-

pression resources be deployed for point protection), or operational constraints, such as extreme fire weather or difficult terrain and access. However, we propose that EI is a useful aggregate measure of firefighting resource efficiency and exposure to hazard. Initial results suggest that ground-based firefighting resources currently operate at around 11 percent efficiency when considering the theoretical productive capacity of all assigned resources relative to the final contained fire perimeter. A working hypothesis driving our research is that an

increase in the efficiency of ground-based resources will translate into a lower level of exposure of these resources to fireline hazards as they will be engaging the fire for a lesser amount of time, thus reducing annual injury and fatality rates.

An important caveat to the EI measure is that production rates for aviation resources on large wildfires are not available. Thus, our initial results leave out two important factors: (1) aviation resources can be quite productive at building fireline relative to other resources, and (2) aviation is potentially the most dangerous component of the wildfire suppression enterprise. We maintained count data on aviation resources assigned to individual fires; however, incorporation into the existing EI model is currently not feasible and will require additional research.

Ensuring that firefighter exposure is justified by the values protected from suppression efforts remains a key objective for wildfire management. Our expectation is that higher EI values would indicate enhanced firefighter safety, in that fewer firefighters would be exposed to the harms of travelling or direct or indirect line building. It is reasonable to expect that there are different relationships between level of exposure and injury and fatality rates for the different categories of firefighting resources. We recognize that fire complexity and other concerns will limit our ability to increase EI significantly and that on a case-by-case basis, low EI values may be entirely defensible. Nevertheless, in general, reducing unnecessary exposure should result in higher EI and lower aggregated fatalities. Future work could expand this investigation into issues concerning aviation exposure. ■