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Development and application of a geospatial wildfire exposure and risk calculation tool

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ABSTRACT

Applying wildfire risk assessment models can inform investments in loss mitigation and landscape restoration, and can be used to monitor spatiotemporal trends in risk. Assessing wildfire risk entails the integration of fire modeling outputs, maps of highly valued resources and assets (HVRAs), characterization of fire effects, and articulation of relative importance across HVRAs. Quantifying and geoprocessing wildfire risk can be a complex and time-intensive task, often requiring expertise in geospatial analysis. Researchers and land managers alike would benefit from a standardized and streamlined ability to estimate wildfire risk. In this paper we present the development and application of a geospatial wildfire risk calculation tool, FireNVC. We describe the major components of the tool and how they align with a geospatial wildfire risk assessment framework, detail a recent application of the tool to inform federal wildfire management and planning, and offer suggestions for future improvements and uses of the tool.

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1. Introduction

Wildfires, though under many circumstances desirable from an ecological perspective, can threaten human lives and property, degrade air and water quality, and damage natural and cultural resources. Prospectively assessing wildfire risk can help land managers better understand where fires are more likely to occur and with what impacts to highly valued resources and assets (HVRAs). Fundamentally assessing wildfire risk is built upon modeling the likelihood and intensity of wildfire interactions with HVRAs, as well as the magnitude of potential HVRA response to fire, which can be positive or negative (Finney, 2005; Miller and Ager, 2013; Scott et al., 2013). This information is useful for informing investments in loss mitigation and landscape restoration, in particular for pre-fire decisions relating to reduction of hazardous fuels and location-allocation of suppression resources. Assessment results can also be used to monitor trends in risk across space and time.

Assessing wildfire risk in a quantitative, spatial framework is essential for landscape planning (Thompson and Calkin, 2011). A quantitative framework for wildfire risk is consistent with actuarial principles and standard economic notions of risk, and further enables cost-effectiveness analysis as a basis for evaluating risk mitigation options. A spatial framework recognizes that wildfire is a spatial process with significant spatial variation in environmental factors driving wildfire likelihood and intensity, as well as resource and asset vulnerability.

Quantitative, spatial wildfire risk assessment frameworks are increasingly being applied, with growing sophistication, to inform wildfire management in the U.S. and elsewhere (Fiorucci et al., 2008; Bar Massada et al., 2009, Atkinson et al., 2010; Chuvieco et al., 2010; Thompson et al., 2011; Román et al., 2012). Applications vary, although many share the premise of coupling spatial information on fire likelihood with resource or asset vulnerability, and integrate multiple disciplinary perspectives including fire and fuels modeling, fire ecology, and resource economics. In particular the use of advanced spatial burn probability modeling techniques is gaining popularity (Carmel et al., 2009; Scott et al., 2012a; Parisien et al., 2013). The basic framework for exposure and risk assessment is flexible and scalable, applicable at national

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(Thompson et al., 2011), regional (Ager et al., 2013), landscape (Thompson et al., 2013a), and project-level (Ager et al., 2010) planning scales.

In recent years the application of risk analysis and use of risk-based decision support tools has greatly expanded for federal wildfire management in the United States (Miller and Ager, 2013). A particularly salient example is the Wildland Fire Decision Support System, which provides functionality for burn probability modeling and exposure analysis to support risk-informed incident decision making (Calkin et al., 2011a). There is great opportunity to expand efforts beyond the incident decision support realm to provide risk-based information for hazardous fuels and preparedness decisions. Along those lines, in recent years the list of "early adopters" has continued to grow, with risk-based assessments performed on federally managed lands throughout the western United States including the Beaverhead-Deerlodge National Forest, the Black Hills National Forest, the Bridger-Teton National Forest, the Deschutes National Forest, the Inyo National Forest, the Lewis and Clark National Forest, the Pike-San Isabel National Forest and the Cimarron and Comanche National Grasslands, the Sequoia National Forest, the Sierra National Forest, the Stanislaus National Forest, and the Grand Teton National Park.

In performing these geospatial risk assessments a number of significant process limitations became apparent. One key lesson learned from our experience is the need for a standardized and streamlined geospatial risk calculation tool. A potential bottleneck of calculating integrated risk scores is the large number of geoprocessing steps required, in particular the intersections of fire modeling outputs with HVRA maps and calculations of HVRA responses to fire. In practice these steps are repeated many times dependent on the total number of HVRAs, and are therefore quite time intensive and introduce the potential for human error. The computational time required for a landscape-level assessment using standard GIS software packages can take days to complete, making it difficult to use assessment results in a real-time workshop setting, or to quickly regenerate results if changes are warranted.

In order to address the limitations associated with the process, we developed a software toolbox, FireNVC, designed to perform risk calculations in a computationally efficient timeframe suitable for rapid analysis. We created FireNVC to provide a flexible research tool capable of landscape-scale exposure and risk assessment, and ultimately to provide decision support for land managers seeking to mitigate wildfire risk. Here we discuss the development of the FireNVC toolbox as well as the subsequent improvements in computational efficiency. As a demonstration of the tool's utility we detail a recent application of FireNVC for the U.S. Forest Service's Rocky Mountain Region.

In the subsequent sections we first describe in more detail the framework for wildfire risk assessment, as well as a geospatial modeling process to implement the framework. We then describe the development of the FireNVC tool itself, and next illustrate its application for the Rocky Mountain Region. Lastly we discuss strengths and limitations of both the framework and tool, and offer recommended directions for future work.

2. A wildfire risk assessment framework

A generalized framework for wildfire risk assessment entails four primary stages: problem formulation, exposure analysis, effects analysis, and risk characterization (Fairbrother and Turnley, 2005; Thompson and Calkin, 2011). In practice the process required to implement this framework entails multiple steps, and is based on an integrated, interdisciplinary perspective (Scott et al., 2013). In the sub-sections that follow we briefly review the wildfire risk assessment framework and process, informed by our experiences performing this process multiple times at varying planning scales.

2.1. Problem formulation

It is critical to begin by articulating the objectives of the assessment, the spatiotemporal scope of analysis, and the assessment endpoints. Assessment objectives relate to how assessment results are to be used and will fit into broader structured decision processes for wildfire management, ranging from project-level fuel treatment planning to strategic prioritization and budgeting. A critical step is the identification, characterization, and mapping of HVRAs that are likely to be impacted by fire and that are salient to wildfire management goals.

2.2. Exposure analysis

Exposure analysis explores the degree to which HVRAs are likely to interact with wildfire, and entails the coupling of fire modeling outputs with HVRA maps. Intersecting fire modeling outputs with rasterized HVRA maps allows for a fine-scale quantification of the likelihood of any given HVRA pixel burning, and further provides critical information in terms of the intensity with which fire will burn at that location. Pixel-based exposure can thus be quantified in terms of multiple metrics including expected HVRA area burned, expected HVRA area burned by flame length category, mean burn probability, mean fireline intensity, and conditional flame length (Salis et al., 2012).

2.3. Effects analysis

Effects analysis explores the potential consequences of varying levels of HVRA exposure, as a function of fire behavior – typically flame length – as well as other environmental characteristics that could influence HVRA susceptibility. There are at least two key reasons for contemplating fire effects. First, because wildfire can result in both negative and positive consequences, effects analysis can lead to the identification of areas on the landscape where resource protection or ecological restoration objectives are most appropriate. Second, fire effects are not necessarily directly proportional to probability and intensity, and thus areas of highest expected loss (or benefit) may not coincide with the areas of highest exposure; see Thompson et al. (2013a) for an illustration of this point.

In the framework described here, fire effects are quantified in terms of net value change (NVC), thereby explicitly recognizing the potential for both beneficial and detrimental effects. HVRA-specific tabular "response functions" determine NVC as a function of flame length, where NVC is expressed in relative terms as percentage loss or gain (e.g., complete loss = −100%). The response function approach provides a flexible, yet consistent, platform for evaluating potential fire effects across HVRAs. Multivariate response function definitions can be readily incorporated, for instance differentiating likely post-fire watershed response according to erosion potential. Geospatial calculations combining burn probabilities with response functions result in an HVRA-specific estimate of expected NVC, or E(NVC).

2.4. Risk characterization

Characterizing wildfire risk is the process of synthesizing results of the prior analyses to provide information useful for decision making. Identifying the risk attitude of the decision maker and how to balance non-commensurate risks to various HVRAs are two key questions. With respect to the former, a risk neutral approach is typically taken as the approach that can best maximize social welfare. In terms of the latter, an ideal assessment could monetize all HVRAs and their corresponding value changes from fire; however the applicability of such an approach across all possible HVRAs in all possible locations is limited, especially when considering the range of environmental goods and services stemming from ecosystems. Instead, fire managers articulate relative importance weights based upon existing wildfire management priorities and other relevant policies.

Using these HVRA-specific relative importance weights leads to a weighted E(NVC), or E(wNVC) score. This approach provides for an integrated, composite measure of risk useful for comparing risks and analyzing tradeoffs with a common metric. Further, importance weights can be apportioned according to the relative areal extent of each HVRA. This serves to distribute importance weights across HVRAs with a large mapped area and to concentrate importance for geographically rare HVRAs, and can help alleviate discrepancies in different HVRA spatial mapping techniques. Relative importance weights as articulated by fire managers relate to landscape priorities, although actual risk calculations apportion weights on a per-pixel basis (see §3.1).

2.5. Risk modeling considerations

Model-based evaluations of wildfire risk necessitate a number of considerations to ensure results are credible and effective for supporting decisions. Most importantly, the context must be clearly framed so that the aim and scope of the modeling effort align with that of the decision process (Marcot et al., 2012; Bennett et al., 2013). As described earlier, landscape planning and prioritization efforts require information that is spatial and quantitative, so model efforts must be designed to meet these requirements. Ensuring sufficiency of input data is important as well, in particular that HVRA datasets are complete over the extent of the study area and mapped using similar methods. Further, when introducing a new modeling tool, as we do here, it is imperative to demonstrate that the model has advantages over the prior art (see §3) and can provide utility for environmental assessment (see §4) (Alexandrov et al., 2011).

Comprehensive, integrated wildfire risk assessment requires the simultaneous consideration of three primary sources of uncertainty: (a) the inherent variability surrounding the occurrence, extent, and intensity of wildfires; (b) knowledge gaps regarding potential fire-induced benefits and losses to HVRAs; and (c) decision uncertainty regarding how to balance fire-related impacts across market and non-market HVRAs (Thompson and Calkin, 2011). Better understanding the type and magnitude of these sources of uncertainty allows for an improved ability to systematically address uncertainties in the assessment process, and to identify best practice modeling procedures (Robson, 2014). The primary modeling and analytical steps we have used to implement this framework are stochastic wildfire simulation, expert judgment elicitation, and multi-criteria decision analysis. Respectively these components provide flame length probability distributions, expert-defined characterization of fire effects via tabular response functions, and articulation of relative importance across HVRAs with weights that range from 0 to 100 (see §3.1). Selection of these specific modeling approaches reflects best practice efforts that specifically target the type of information being generated along with corresponding uncertainties (Ananda and Herath, 2009; Kuhnert et al., 2010; Thompson and Calkin, 2011; Krueger et al., 2012).

3. FireNVC: a wildfire exposure and risk calculation tool

3.1. FireNVC risk calculations

This section describes the specific model formulation for the pixel-based calculations of wildfire risk within FireNVC, based upon the framework introduced in the previous sections. Objectives for development of FireNVC include generating a flexible, streamlined tool that can perform quantitative, geospatial risk calculations across large landscapes. Additionally, FireNVC can be used through time to monitor spatiotemporal trends in HVRA exposure and risk. Relative to earlier assessment processes and wildfire decision support tools used by federal land management agencies, FireNVC's integration of effects analysis with exposure analysis is a key improvement, enabling explicit quantification of the potential consequences of wildfire. Relative to earlier work implementing this risk framework, the computational efficiencies and relative ease of use afforded by FireNVC greatly expand opportunities for application across potential users and planning contexts.

The actual generation of fire modeling outputs, geospatial mapping of HVRAs, definition of response functions, and articulation of relative importance weights are all processes external to the tool. Of course, it is only when these components are integrated that actual risks can be quantified, mapped, and evaluated. FireNVC takes in these inputs, geo-processes them, and produces tabular and geospatial exposure and risk outputs. The location of HVRAs with respect to wildfire activity, their susceptibility to wildfire, and their relative importance and extent are key factors driving assessment results.

Prior to presenting the risk equations we introduce key model nomenclature. Let:

$i \in I$ Elements in the set I of HVRAs
$j \in J$ Elements in the set J of flame length categories
$k \in K$ Elements in the set K of landscape pixels
BP_{jk} Burn probability of flame length j on landscape pixel k
RF_{ijk} Response function for HVRA i at flame length j on landscape pixel k
RI_i Relative importance weight for HVRA i
RE_i Relative areal extent of HVRA i
$E(NVC_i)$ Expected net value change for HVRA i
$E(wNVC)$ Weighted expected net value change integrating all HVRAs

$$E(NVC_i) = \sum_j \sum_k BP_{jk} RF_{ijk} \tag{1}$$

$$E(wNVC) = \sum_i E(NVC)_i RI_i / RE_i \tag{2}$$

Equation (1) provides the formula for calculating *E(NVC)*, the individual HVRA risk score, as a function of flame length burn probabilities and HVRA-specific response functions, summarized over all pixels in the assessment landscape. Equation (2) provides the formula for calculating *E(wNVC)*, the importance-weighted expected net value change across all HVRAs on the assessment landscape. In the next section we review the development of FireNVC to perform wildfire exposure and risk calculations in a geospatial environment.

3.2. FireNVC tool development & overview

FireNVC is a software tool which researchers and analysts with geographic information system (GIS) expertise can use to quantify wildfire risk to HVRAs using the framework outlined above. We implemented FireNVC within the ESRI ArcGIS Toolbox module, a GIS commonly used by land management agencies that will likely be familiar to many end users. Seamlessly integrating FireNVC into the ArcGIS environment minimizes the effort and time needed to run the tool.

We developed FireNVC using all open source software, specifically through the Python programming environment (Python Software Foundation). Python is an object oriented programming language which has been integrated into ArcGIS, and comes standard with ArcGIS. In particular we relied heavily on Python's scientific computing packages, numpy and scipy, which rapidly perform high level matrix and linear algebra computations. The resulting Python scripts are easily integrated into ArcGIS through the ArcToolbox window. This GUI produces a familiar platform to provide all necessary inputs to the FireNVC tool.

Fig. 1 displays the primary data inputs, scripted processes, stored data, and outputs of FireNVC. User inputs include fire modeling outputs, HVRA maps, HVRA response functions and relative importance weights, and optional summary masks (discussed below). The main functionality of the tool is based around three modules (scripted processes) that: (1) import pixel-based burn probability raster data layers, (2) import HVRA geospatial layers, and (3) perform the NVC calculations (see §3.1).

The first two modules are preprocessing steps which are used for increased numerical efficiency in module three. Specifically, raster data are stored as numpy arrays, providing for efficiency gains through the use of linear algebra calculations to derive risk scores. The current version of FireNVC is coded to accept text files output from the FSim (Finney et al., 2011) or FlamMap v5 (Finney, 2006) fire modeling systems (see §4 for an example), as well as generic burn probabilities with or without conditional flame length raster data. In the second module, user generated HVRA raster datasets are similarly read into numpy arrays, and if need be, are projected, resampled and clipped to match the spatial reference, spatial extent, and resolution of the fire modeling inputs. The third module performs the fire effects (net value change) calculations for all HVRAs. The tool outputs cumulative risk as raster data and summary tables containing risk scores and expected area burned by flame length class (i.e., exposure metrics). The option to output individual HVRA risk scores as well as cumulative risk scores across all HVRAs is provided. Further, the option to summarize exposure and risk calculations according to a user-defined mask, or zone, allows users to geographically delineate and quantify risks, for instance, by watershed, forest, or ownership boundaries, or within areas identified as suitable for mitigation activities.

The implementation environment and computational efficiencies afforded by the FireNVC tool readily allow for real-time use and experimentation. The exposure and risk calculations occur within an acceptable time frame, typically minutes in our experience, although this will vary with computer specifications, landscape size, the quantity of HVRAs, and the number of response function variants. Two strengths of FireNVC are, therefore, greatly enhanced opportunities for both sensitivity and scenario analysis. With respect to the former, users can adjust the response functions or relative importance values, and then rapidly re-run the tool to see impacts to final risk results. With respect to the latter, users can input different burn probability raster data to examine alternative fuel treatment strategies or other fire management scenarios. Users can also import alternative HVRA raster data, to expand or limit the amount of HVRAs included in the assessment. Further, importing alternative HVRA raster data could be used to examine how risks change with future land use changes, such as expansion of

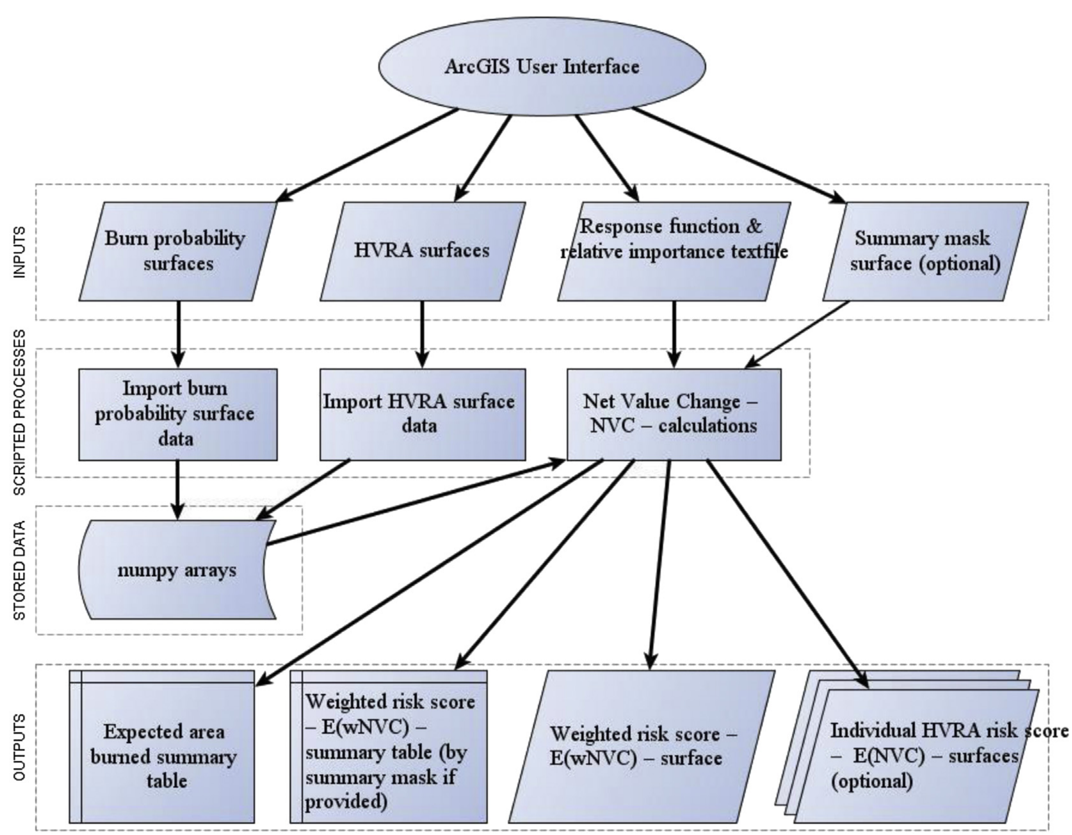

Fig. 1. Workflow diagram for the FireNVC tool with the primary inputs, scripted processes, stored data, and outputs displayed.

residential development or construction of new energy or telecommunication infrastructure.

4. Application of FireNVC

4.1. Risk assessment and mitigation planning in the Rocky Mountain Region

Here we review a recent application of FireNVC for wildfire exposure and risk analysis on National Forest System lands in the U.S. Forest Service's Rocky Mountain Region. The Rocky Mountain Region includes National Forest and Grasslands (NFG) in Colorado, Kansas, Nebraska, South Dakota, and Wyoming (Fig. 2). Our case study stems from a collaborative effort with the Region in which we summarized pixel-based wildfire exposure and risk assessment results at the NFG level. Notably, the Region used these results to inform budgetary allocation decisions relating to hazardous fuels and suppression preparedness investments, on the scale of tens of millions of dollars.

Burn probabilities are highest in the northern and northeastern portions of the Region, which in part is influenced by a greater proportion of grass and shrub fuel types with higher rates of spread, and which could also reflect geographic variation in suppression response capacity for initial attack operations to prevent escaped large wildfires (Fig. 3). These burn probability outputs were generated at 270 m × 270 m pixel resolution, for all the Fire Planning Units spanning the Rocky Mountain Region (Karen Short, Research Ecologist, personal communication). Specifically we used outputs from the FSim fire modeling system (Finney et al., 2011), which simulates thousands of artificial fire seasons based on historical fire weather to account for the range of fire weather and fuel moisture conditions driving wildfire occurrence and behavior. FSim does not model every single ignition, instead focusing on only those rare fires that grow large and account for the vast majority of area burned. Internally FSim combines models for fire occurrence, growth and behavior, and containment, typically for tens of thousands of large wildfires, over landscapes that can reach millions of hectares. Calibration efforts focus on historical fire size and annual area burned distributions, and analyses demonstrate a high degree of agreement between modeled and historical results (Mark Finney, Research Forester, personal communication). For additional validation we presented maps of modeled large fire burn probability and historical large fire occurrence to regional experts, and similar spatial patterns in areas of high/low likelihood helped solidify confidence in the risk modeling process. Readers interested in additional details on FSim model structure, calibration, and application are referred to (Scott et al., 2012a, 2012b; Thompson et al., 2013a, Thompson et al. 2013b).

Table 1 enumerates the HVRAs, sub-HVRAs, and relative importance scores identified by regional leadership, along with the tabular response functions as defined by the regional resource specialists. The Region ultimately identified a set of three HVRAs to be included in the assessment (listed in order of importance): water supply, the wildland–urban interface (WUI), and infrastructure. In some cases, HVRA information is broken down to capture differences in relative importance (e.g., population density within the wildland–urban interface), whereas others are broken down to capture differences in both relative importance and response functions (e.g., infrastructure).

Resource specialists identified two landscape variables influencing HVRA susceptibility to be included in response function definitions: erosion potential category and bark beetle impacts. The

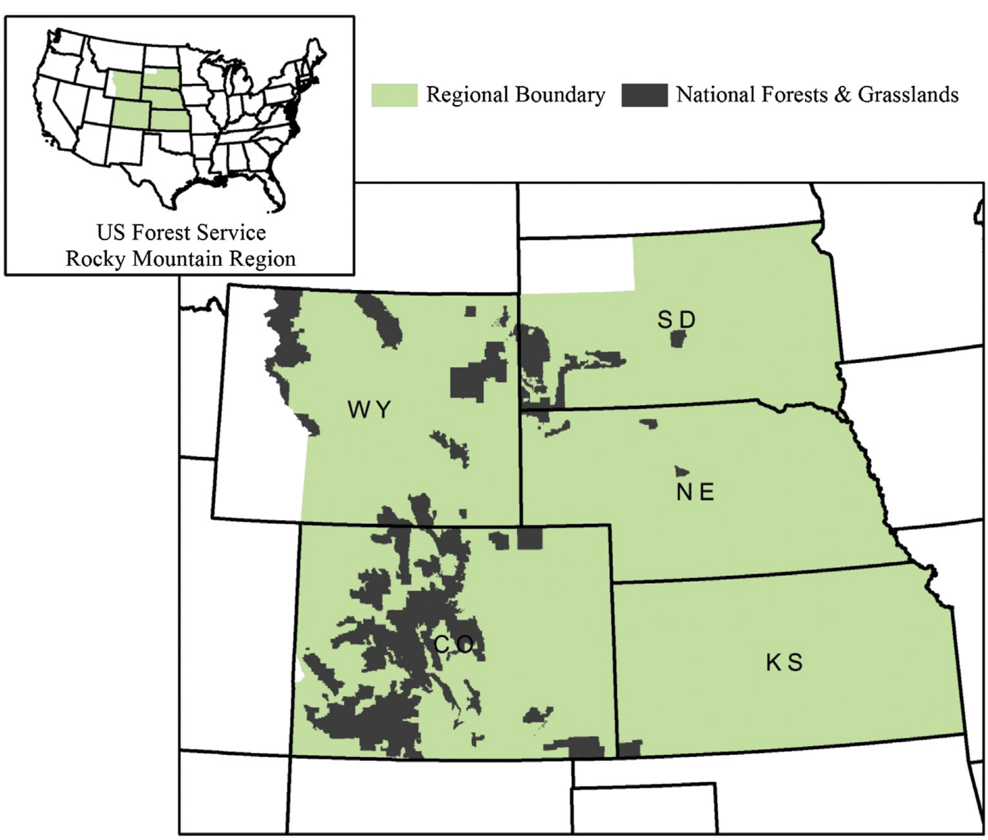

Fig. 2. National forests and grasslands in the forest Service's Rocky Mountain Region (CO = Colorado; KS = Kansas; NE = Nebraska; SD = South Dakota; WY = Wyoming).

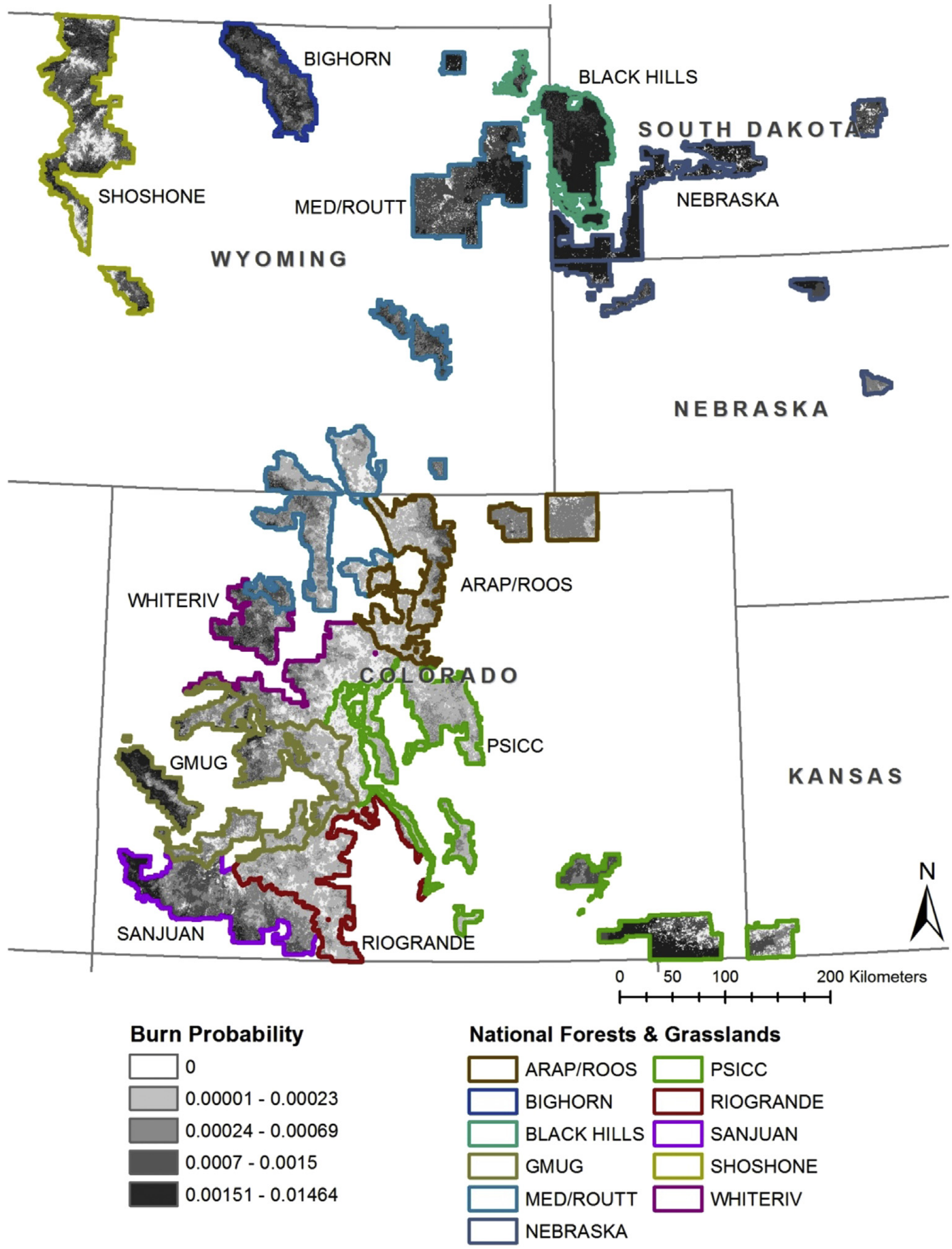

Fig. 3. Annual burn probabilities clipped to a 10-km buffer surrounding National Forest and Grassland boundaries in the Rocky Mountain Region.

erosion potential is based on soil type and slope steepness, and the bark beetle impacts layer is based on analysis of aerial survey data and relative levels of cumulative mortality. In both cases we used regionally developed datasets and reclassified the data categorically. Looking across the response functions, losses generally are expected to increase as erosion potential, bark beetle impacts, and flame length increase. All HVRAs in this assessment are considered fire-susceptible, with modest losses expected at low to moderate flame lengths. The wildland–urban interface HVRA and certain infrastructure sub-HVRAs are most susceptible to fire-related losses.

It is important to note that the temporal scope of the response functions as defined here are short-term, because the assessment effort does not model post-fire regeneration, landscape succession, or future disturbances through time. Of course, landscape conditions can be reassessed at points in the future, and with updated fuel and fire modeling outputs, FireNVC can be utilized to reassess risks. As described earlier, monitoring and evaluating spatiotemporal exposure and risk trends are in fact key design objectives of both the risk framework and the FireNVC tool.

Key components of risk assessment results are summarized in Fig. 4. This figure shows in effect the risk profile of each NFG by plotting mean conditional wNVC versus mean burn probability (mean values are summarized across all pixels containing at least one HVRA). Conditional wNVC values quantify the HVRA loss for every pixel, given the pixel does burn. These values are calculated incorporating the flame length distribution, response function(s), and relative importance weight(s) for all HVRAs in a given pixel, but

Table 1
Listing of HVRAs and sub-HVRAs, including HVRA Relative Importance (RI) weights, variables included in response functions, and tabular response function definitions. Note that in some cases HVRA are broken down for the purposes of assigning different RI weights, for defining difference response functions, or both.

HVRA	RI	Sub-HVRA	Sub-RI	Variable 1	Variable 2	Variable 3					
				Erosion class	Bark beetle impacts	Flame length Category (ft)					
						0–2	2–4	4–6	6–8	8–12	12+
Water Supply	100	Importance to drinking water	High: 100 Moderate: 75	none – low	None – low	0	0	−10	−20	−30	−30
					Mod	0	0	−10	−20	−30	−30
					High	0	−10	−20	−25	−30	−30
				mod	None – low	0	−10	−20	−30	−40	−50
					Mod	0	−10	−30	−40	−50	−60
					High	−10	−20	−40	−60	−70	−80
				high	None – low	0	−20	−40	−60	−80	−80
					Mod	−10	−30	−70	−80	−90	−90
					High	−20	−40	−80	−90	−100	−100
WUI	80	Population density	High: 100 Moderate: 80 Low: 60	–	None – low	−10	−20	−40	−80	−100	−100
					Mod	−20	−40	−80	−100	−100	−100
					High	−20	−40	−80	−100	−100	−100
Infrastructure	60	Transmission lines	100	–	None – low	0	0	0	−30	−40	−50
					Mod	0	0	−30	−40	−50	−50
					High	0	0	−30	−40	−50	−50
		Communication facilities	70	–	None – low	0	0	0	−30	−40	−50
					Mod	0	0	−30	−40	−50	−50
					High	0	0	−30	−40	−50	−50
		Ski areas	50	–	None – low	0	−10	−10	−20	−50	−70
					Mod	−10	−20	−30	−40	−60	−70
					High	−20	−30	−40	−50	−70	−80
		Campgrounds, trailheads, etc.	25	–	None – low	0	−10	−10	−20	−50	−70
					Mod	−10	−10	−10	−10	−10	−10
					High	−10	−10	−10	−10	−10	−10
		Rec. residences/admin. sites	25	–	None – low	−10	−20	−40	−80	−100	−100
					Mod	−20	−40	−80	−100	−100	−100
					High	−20	−40	−80	−100	−100	−100

are exclusive of burn probability. The product of mean conditional wNVC and mean burn probability yields the expected overall NFG-level weighted risk score, or E(wNVC) (see Fig. 5).

Fig. 4 also includes isolines of equal expected loss (E(wNVC)) that can provide a reference for comparing how NFGs of similar expected loss vary in terms of their underlying risk factors. Clearly, for some NFGs wildfire risk is driven more by burn probability, whereas for other NFGs the high potential for loss drives results. This differentiation can be critical not only for understanding the nature of wildfire risk, but additionally for identifying cost-effective mitigation options. Fig. 5 further displays the E(wNVC) raster output by FireNVC, illustrating spatial variation in expected losses both within and across NFGs in the Region. Similar to the differentiation of probability and consequences in Fig. 3, this spatial differentiation of areas of high and low risk can be very informative for mitigation planning.

The efficiency of FireNVC greatly facilitated exploration and sensitivity analysis, particularly in three key areas. First, we were able to incorporate a burn probability adjustment factor to account for the ease of suppressing grassland fires relative to timber fuel types, consistent with how the Forest Service currently assesses wildfire potential for national-scale hazardous fuels prioritization (Jim Menakis, Fire Ecologist, personal communication). Second, regional leadership explored various relative importance scores for water supply and WUI, as well as identifying which highly valued watersheds across the Region were to be included in the HVRA. Third, the Region was able to incorporate additional HVRA layers (wildlife habitat and timber resources) and we summarized NFG risk scores inclusive and exclusive of these HVRAs (ultimately these HVRAs were excluded from the final prioritization model).

The Rocky Mountain Region used risk assessment results as a key component informing their budgetary allocation decisions across NFGs. The Region tiered NFG risk scores and integrated these results along with additional information on total fire load and fire management complexity indices in order to determine final allocations. These allocation decisions then led to investment levels for hazardous fuels and suppression preparedness in fiscal years 2013 and 2014, with continued use of risk assessment results planned in coming fiscal years.

4.2. Sensitivity analysis of NFG risk rankings

To explore and evaluate the performance of FireNVC as a prioritization tool, we analyzed the sensitivity of NFG risk rankings to changes in model inputs (see Equations (1) and (2)). Although regional leadership did explore various weighting schemes in the initial prioritization efforts, here our aim is to much more systematically explore the sensitivity of FireNVC results. To do so we varied response functions and relative importance weights, in order to explore changes in mean conditional weighted net value change (wNVC), and further varied mean burn probability, in order to explore changes in E(wNVC). For response functions we explored 4 scenarios where each HVRA's conditional response was changed by ± 25% and 50%, in addition to the baseline scenario. For relative importance weights we explored three alternative policies in addition to the baseline of 100/80/60 for Water Supply/WUI/Infrastructure: 100/60/20 (a larger gradation across existing priorities), 80/100/60 (Water Supply and WUI swap priorities), and 60/100/20 (Water Supply and WUI swap priorities, with a larger gradation across new priorities). For simplicity this sensitivity analysis did not consider variation in sub-HVRA weighting schemes. Collectively these changes led to 500 alternative NFG rankings for mean conditional wNVC. For each of these 500 ranking scenarios, we further explored changes in fire likelihood, where each NFG's mean burn probability was changed by ± 25% and 50%, in addition to the baseline scenario. Therefore we analyzed a total of 2500 alternative NFG rankings for E(wNVC).

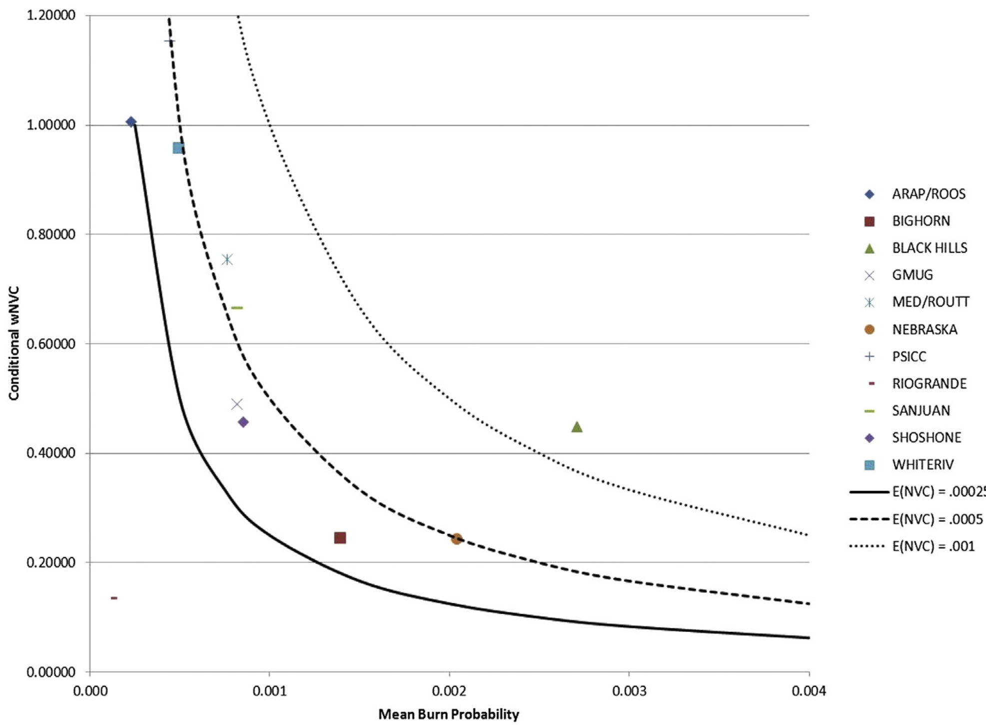

Fig. 4. Scatterplot diagram of mean conditional weighted net value change (wNVC) scores (y-axis) and mean burn probability (x-axis), for all National Forests and Grasslands in the Rocky Mountain Region. The three lines in black represent contours of equal expected net value change.

To quantify the sensitivity of NFG risk rankings we kept track of the number of times each of the eleven NFGs was assigned to each rank. Table 2 summarizes these results by identifying the highest, lowest, and most common rank (mode) for each NFG (which can be the same), along with the proportion of total scenarios analyzed where the NFG was assigned to these respective ranks. Consistent with Fig. 4, there is significant variation in the potential for loss that drives conditional wNVC rankings. Similarly, significant variation in the probability of experiencing large wildfire drives E(wNVC) rankings. Results indicate that risk rankings are quite robust, with an average difference of only 2.73 between the highest/lowest conditional wNVC rankings, and an average difference of only 3.55 between the highest/lowest E(wNVC) rankings. The larger difference between E(wNVC) rankings is expected due to the added variability from a wider range of mean burn probabilities. Even in cases where a given NFG exhibits a wider range of possible ranks, often the relative proportion of scenarios corresponding to a high/low ranking is quite low. Across NFGs the average proportion of the most common rank was 65% and 58% for the mean conditional wNVC and E(wNVC) rankings, respectively, with ranges of 35–93% and 30–100%. These results indicate that for NFG risk rankings to dramatically shift would require major changes in response function definitions, a major reordering of priorities, and/or significant and widespread changes in modeled burn probabilities, none of which is likely.

5. Discussion

5.1. *Implications & applications*

FireNVC proved to be a useful and computationally efficient tool for a real-world application of wildfire exposure and risk assessment and mitigation planning on National Forest System lands in the Rocky Mountain Region. The collaborative assessment process was iterative in nature, and reemphasized needs to clearly identify how assessment results are to be used, to invest in upfront geospatial data management, and to carefully evaluate and critique fire modeling outputs. Satisfaction with the process and the FireNVC tool has led to subsequent downscaling within the Region for assessments at smaller planning scales, including the Black Hills National Forest and the Upper Monument Creek Collaborative Landscape Restoration Initiative on the Pike-San Isabel National Forest. This downscaling enables use of refined HVRA and fire modeling data, and increased local stakeholder involvement, illustrating the flexibility and utility of the decision support tool across planning scales.

At present FireNVC is primarily a research tool, although we have shared the tool with a select set of National Forest System partners. While the time and resources necessary to provide comprehensive documentation and user support are still being weighed, a clear future direction for FireNVC includes additional research-management partnerships with the objectives of advancing wildfire risk science and the application of that science. We anticipate that FireNVC could have broad application to assess wildfire risk on fire-prone landscapes across a variety of geographic areas and ownerships. We have shared the fundamentals of this process and the key lessons learned with other Forest Service Regions, as well as broader audiences, with the aim of expanding the user base and facilitating adoption of a consistent risk assessment framework.

There are a number of potential benefits to be realized from expanded use of FireNVC. First and foremost, the tool is premised on application a structured and systematic process for assessing risk in a quantitative and spatial manner. Adoption of risk-based decision support tools is consistent with broader recommendations for wildfire management, particularly in the context of federal land management in the United States (Calkin et al., 2011b, 2011c). A risk assessment perspective can lead to an improved characterization of the potential socioeconomic and ecological impacts of fire, through the spatial overlays of fire modeling outputs with

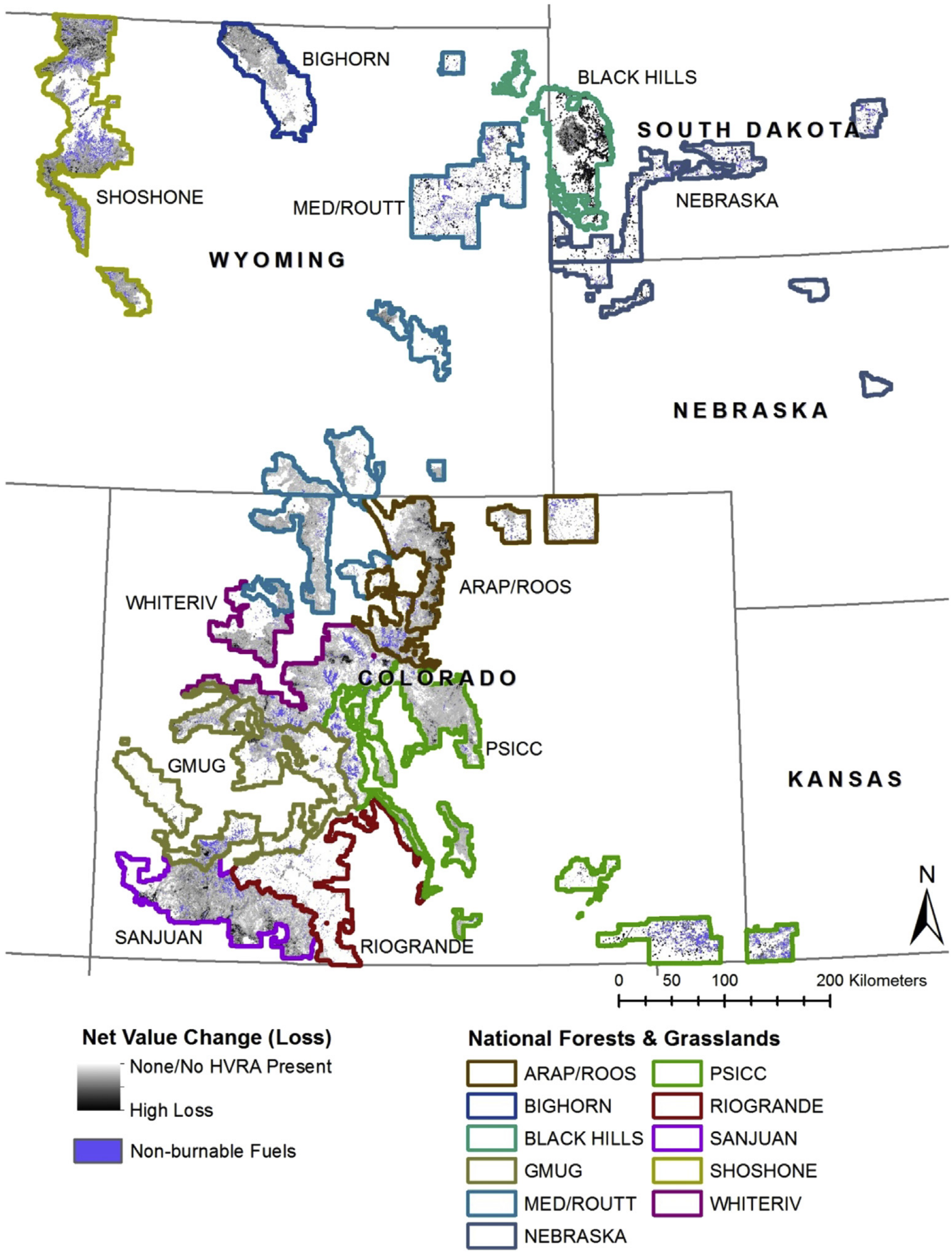

Fig. 5. Weighted risk score (E(wNVC)) raster output by FireNVC, mapped on National Forest and Grasslands in the Rocky Mountain Region. Areas mapped in white contain no HVRAs, and thus by definition present no risk to HVRAs.

HVRAs, as well as the structured incorporation of disciplinary expertise and local knowledge into fire effects analysis. The delineation of response functions and relative importance weights provides for a transparent integration of science-based and value-based information into a broader decision support process (Marcot et al., 2012; Thompson et al., 2013c). The FireNVC tool is premised on a flexible and scalable framework that can be applied at various planning scales and that can readily incorporate additional information to modify wildfire potential, to characterize fire effects, or to differentiate fire management priorities.

FireNVC's ability to rapidly generate risk calculations in a geospatial context will provide researchers and land managers with an accessible and familiar context with which to evaluate fire management threats and opportunities. Tabular outputs and summarization according to user-defined spatial layers can highlight areas of relatively high or low risk mitigation potential. The ability to perform both sensitivity and scenario analysis afforded by the tool greatly enhances opportunities for model evaluation as well as comparison of fire management alternatives and tradeoff analysis. The menu of exposure and risk modeling approaches provides users with flexibility to tailor the assessment to their specific context.

5.2. Extensions

A number of extensions to FireNVC are foreseeable and/or ongoing. Four opportunities in particular merit discussion. First, exposure analysis functionality within FireNVC could be expanded to include simulated fire perimeter polygons in addition to aggregated pixel-based probability outputs. Overlaying individual fire

Table 2
Sensitivity analysis results comparing variation in NFG risk rankings, identifying the high/mode/low ranks along with their respective proportion of all scenarios analyzed.

NFG ID	Mean Conditional wNVC Rankings			E(wNVC) Rankings		
	High	Mode	Low	High	Mode	Low
ARAP/ROOS	2	2	3	8	10	10
	82%	82%	18%	7%	66%	66%
BIGHORN	8	10	11	8	9	10
	1%	55%	10%	24%	41%	29%
BLACK HILLS	3	8	8	1	1	2
	2%	39%	39%	98%	98%	2%
GMUG	5	7	8	6	7	8
	3%	73%	9%	4%	68%	28%
MED/ROUTT	3	4	5	2	3	5
	1%	72%	27%	21%	46%	8%
NEBRASKA	7	9	10	2	2	10
	2%	48%	35%	43%	43%	2%
PSICC	1	1	2	3	4	7
	93%	93%	7%	29%	46%	1%
RIOGRANDE	10	11	11	11	11	11
	10%	90%	90%	100%	100%	100%
SANJUAN	3	5	7	2	2	8
	4%	54%	1%	35%	35%	3%
SHOSHONE	6	8	9	3	8	10
	33%	35%	18%	2%	30%	3%
WHITERIV	1	3	5	3	6	7
	7%	76%	2%	5%	63%	11%

perimeters with HVRA maps can yield useful information regarding the annual probability that a wildfire will reach any portion of an HVRA, as well as the expected annual HVRA area burned. Even more informative is the characterization of the conditional distribution of HVRA area burned, providing an estimate of how much of the HVRA could burn in any given fire season or any given fire event. This information can help differentiate across HVRA polygons with equal expected area burned, where a given HVRA may be more likely to experience fire but the fires may tend to burn less HVRA area when they do occur. Conditional distributions of HVRA area burned can be especially useful where the cumulative area burned is an important predictor of fire effects, for instance watershed response.

As an illustrative example, Fig. 6 displays polygon-based exposure analysis results for eight highly valued watersheds (labeled A-H) within the Pike-San Isabel National Forest in the Rocky Mountain Region. Because the watersheds vary in size, the bottom *x*-axis is displayed in terms of percentage of watershed burned, which is the metric we use here for comparative purposes. Exposure levels vary considerably across the watersheds assessed, which are presented in order of decreasing exposure levels. Variation in wildfire size and location, fuel structure and continuity, and other factors driving wildfire occurrence and spread all influence watershed exposure, but generating these polygon-based exposure results allows for a concise summary of areas where concern over post-fire watershed response and additional analysis may be warranted. Details on the fire simulation modeling for this example are available in Thompson et al. (2013d), which additionally provides further examples of polygon-based exposure for wildlife habitat and human communities. Integrating this polygon-based approach into FireNVC could allow for streamlined, complementary approaches to HVRA exposure analysis.

A second, related, extension could modify FireNVC's fire effects functionality to account for alternative spatiotemporal characterizations of response functions. One promising avenue is the characterization of fire effects on a per fire basis to account for distributions of HVRA area burned. FireNVC could be coupled with other models such as post-fire debris flow models (Cannon et al., 2010; Friedel, 2011) in an attempt to better capture fire effects. Longer-term models integrating vegetative succession and disturbance (Millington et al., 2009) as well as shifting climatic influences on fire likelihood (Carvalho et al., 2011) could also be integrated. FireNVC could also be modified to include suppression cost models in order to estimate likely fire management costs and to compare costs and risks in a comprehensive cost effectiveness framework (Thompson et al., 2013e).

Third, FireNVC could be integrated with broader landscape assessment and fuel treatment planning decision support systems (e.g., Ager et al., 2011; Vaillant et al., 2013). The consolidation of FireNVC's multivariate response function and relative importance functionality with fire behavior modeling and fuel treatment planning could provide a powerful tool for land and fire managers seeking to explore how alternative strategies could best mitigate wildfire risk. Additionally, because FireNVC's functionality is built on open source software, future applications could operate FireNVC within an open source GIS and thereby broaden the potential user base.

Fourth, FireNVC could be used not only to monitor exposure and risk trends, as described earlier, but also to measure improvements from risk mitigation investments. By maintaining consistency in response functions and relative importance weights, changes in risk can directly tie to changes in landscape condition (e.g., from fuel treatments) or the frequency/intensity of wildfire (e.g., from ignition prevention programs or altered suppression strategies). Pairing risk assessment with counterfactual fire simulation could explore differences in risk across landscapes had certain mitigation strategies not been implemented (e.g., Cochrane et al., 2012). Use of FireNVC would allow for performance measurement on the basis of risk rather than simpler measures like area treated or area burned. Of course, isolating the influence of risk mitigation investments against the backdrop of vegetation dynamics, expanding human development, and a changing climate would not be without challenges.

5.3. Limitations

There are a number of potential limitations to the assessment framework and its implementation within FireNVC. Broadly speaking these include potential errors and uncertainties associated with fire modeling inputs and outputs, HVRA response functions, and HVRA relative importance weights. With respect to fire modeling, research efforts could focus on establishing a firmer theoretical basis for fire spread modeling and developing a stronger empirical basis for evaluating model performance (Sullivan, 2009; Cruz and Alexander, 2010; Finney et al., 2012). In the case of the Rocky Mountain Region assessment, for example, there was an expectation of refined burn probability results from simulating fire at a finer spatial resolution to better capture variation in fuel conditions and fire weather patterns, and further from use of an updated and more comprehensive fire history database (Short, 2013) for calibration purposes.

Predicting fire effects is subject to multiple sources of uncertainty, including limited or inadequate empirical observations, and gaps in fire effects science (Hyde et al., 2012), highlighting a need for continued empirical research into post-fire impacts (Riley et al., 2013). A lack of HVRA-specific predictive models also limits the ability of fire managers to assess the potential consequences of wildfire, especially where non-market HVRAs are concerned (Reinhardt and Dickinson, 2010; Venn and Calkin, 2011). Validation of risk modeling results can therefore be difficult, particularly as multiple HVRAs are integrated and model complexity increases, and as metrics to measure impacts are not immediately evident (i.e., observed wildfire impacts may not be readily monetized or translated into NVC scores). Continued data collection on wildfire impacts and the integration of fire ecology with resource economics

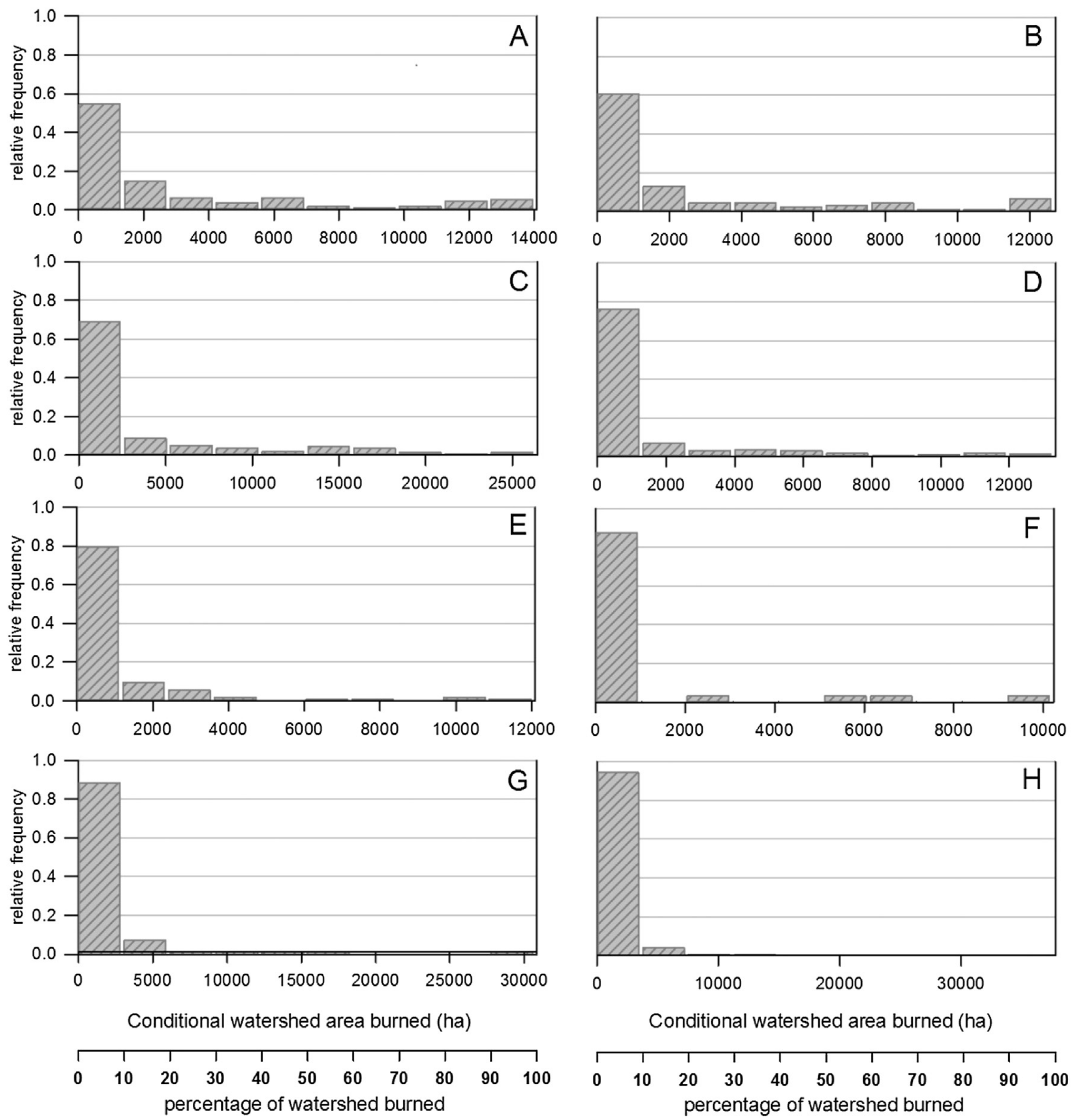

Fig. 6. Conditional distributions of watershed area burned (absolute area and as a percentage of watershed area) for highly valued watersheds (labeled A through H) located in the Pike-San Isabel National Forest.

are recommended, and the need for reliance on expert judgment to validate risk modeling results will likely remain for some time.

Nevertheless, effects analysis remains a critical component of quantitative risk assessment and wildfire management. With that said, the response function approach itself may be not appropriate in all circumstances, in particular for single HVRA assessments where other modeling approaches exist and can readily be integrated, such as post-fire erosion and impacts to water quality, although additional assumptions and inferences will likely be necessary to translate fire intensity outputs into burn severity metrics typically ingested by such models (Robichaud and Ashmun, 2013). Lastly, fire managers may have difficulty quantitatively articulating fire management priorities across HVRAs, although as we demonstrated approaches such multi-criteria decision analysis can help manage this source of uncertainty (Ananda and Herath, 2009; Thompson and Calkin, 2011).

While important, these aforementioned issues are largely external to the design and implementation of FireNVC itself, however. The tool is largely model-independent and amenable to a number of alternative characterizations of burn probabilities and response functions. The spatiotemporal scales of fire modeling outputs, fire effects analysis, and geospatial data layers across the assessment landscape must be consistent. Computational issues may arise for particularly large or complex analyses. With increasing spatial resolution, landscape size, number of HVRAs, and number of HVRA covariates, computational burdens will increase.

6. Conclusion

In summary, we reviewed the supporting framework and the development of FireNVC, a geospatial wildfire risk calculation tool. Our illustrative example application was not merely a proof of concept, but rather an instance of real-world decision support for budgetary decision processes on National Forest System lands in the Rocky Mountain Region of the United States. A great strength of this process was the implementation of a systematic and welltested assessment framework, for which FireNVC enabled streamlined calculations and provided geospatial and tabular risk summarizations. FireNVC is a flexible platform to integrate key pieces of information and to assess risks to multiple HVRAs. Future uses of the tool and refinements to the tool both will ideally support risk-informed and science-based decision making in the context of land and natural resource management.

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