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National fuel-treatment budgeting in US federal agencies: Capturing opportunities for transparent decision-making

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ABSTRACT

The Ecosystem Management Decision Support (EMDS) system has been used by the US Department of Agriculture, Forest Service and Bureaus of the Department of the Interior since 2006 to evaluate wildfire potential across all administrative units in the continental US, and to establish priorities for allocating fuel-treatment budgets. This article discusses an EMDS fuels-treatment decision-support application, agency experiences with the application, and the extent to which it addressed concerns in Congress, and those of the General Accountability Office. EMDS aids the budget allocation process by providing a rational, transparent, and reproducible process that can be clearly communicated to Congressional staff and oversight personnel. However, practical application of this decision-support process was not without challenges, which included missing or suboptimal data, clearly articulated fuels management objectives, and improved understanding (via re-assessing decision logic from prior years) of trade-offs in decision-making.

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1. Introduction

Over the past 70–100 years, wildland fuels have accumulated in large quantity in some forests of the western United States (US) due to 20th century management activities (Agee, 1998; Hessburg and Agee, 2003), and a warming climate (Burkett et al., 2005; Schoennagel et al., 2004). Historically, wildfires of varying size, frequency, and intensity, along with insect outbreaks, endemic disease, climate, and intentional aboriginal burning, created a range of patterns in forest vegetation that varied semi-predictably over space and time (Agee, 2003; Hessburg and Agee, 2003; Hessburg et al., 2005; Schoennagel et al., 2004; Turner, 1989; Whitlock and Knox, 2002). These patterns of forest vegetation were directly linked with the processes that created and maintained them (Pickett and White, 1985; Turner et al., 2001).

Circumstances are different today; patterns and processes are still tightly linked, but the interactions are much different. Human influences have created anomalous vegetation and fuel patterns, and these patterns support fire, insect, and disease processes that display uncharacteristically high duration, large spatial extent, and greater intensity than before (Ferry et al., 1995; Hessburg et al., 2005; Kolb et al., 1998). For example, 20th century fire-suppression and -prevention programs, roads, livestock grazing, and conversion of grasslands to agricultural production significantly reduced fire occurrence in many dry mixed coniferous forests. Limiting the size and number of fires led to increased functional homogeneity and these landscapes are now prone to larger and more intense wildfires than in the 20th century (Agee, 1998, 2003; Ferry et al., 1995; Hessburg et al., 2005). Consequently, valuable property and natural resources have been destroyed, costs of fire management have escalated, fire-dependent forest ecosystems have deteriorated, and risks to human life and property continue to rise (GAO, 2002, 2003, 2004).

Responding to the alarming increase in large and severe wildfires, especially in the western US, Congress passed the Healthy Forests Restoration Act in 2003 (U.S. Government 2003), a major focus of which is the restoration of forest-fuel conditions to a state more consistent with the fire ecology of natural systems. More or less contemporaneously, program reviews of natural resource agencies in the US Departments of Agriculture (USDA) and Interior (USDI) by the Government Accountability Office (GAO) reported substantial room for improvement with implementation of fuel-reduction programs nationally by federal agencies (GAO, 2002, 2003, 2007). Major criticisms by GAO included (1) lack of a consistent process coordinated across agencies, and (2) lack of a rational, transparent, and repeatable decision process for allocating fuel-treatment budgets both across and within agencies. In this paper, we describe the utility of the Ecosystem Management Decision Support (EMDS) system for supporting natural resource agencies' decisions to allocate fuel-treatment budgets within

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USDA and USDI from 2007 to 2009. We also discuss the extent to which the decision-support process addressed major criticisms of GAO and others concerning the budget allocation process.

2. Methods

2.1. The EMDS system

EMDS is a framework within which developers can design logic and decision models to address many different kinds of questions related to natural resource management, and at whatever spatial scale(s) may be relevant to their questions (Reynolds et al., 2003). Because of its implementation as a general framework, EMDS has been used in various natural resource applications around the world since 1997 (a few examples include Bleier et al., 2003; Hessburg et al., 2004; Hessburg et al., 2007; Reeves et al., 2003; Reynolds and Hessburg, 2005; White et al., 2005).

EMDS is a system for integrated environmental analysis and planning that provides decision support for landscape-level analyses through logic and decision engines integrated with the ArcGIS® 9.2 and 9.3 geographic information system (GIS, Environmental Systems Research Institute, Redlands, CA).[1,2] The NetWeaver logic engine evaluates landscape data against a logic model designed in the NetWeaver Developer system (Rules of Thumb, Inc., North East, PA),[3] to derive logic-based interpretations of complex ecosystem conditions such as wildfire potential. A decision engine evaluates outcomes from the logic model, and other feasibility and efficacy data related to fuel-treatment actions, against a decision model for prioritizing landscape treatments, built with its development system, Criterium DecisionPlus® (CDP, InfoHarvest, Seattle, WA).[3] CDP models implement the Analytical Hierarchy Process (AHP; Saaty, 1994), the Simple Multi-Attribute Rating Technique (SMART; Kamenetzky, 1982), or their combination.

The logic and decision models in EMDS are complementary to one another. The logic model focuses on the question, "What is the state of the system?", and the decision model focuses on the question, "Given the state of the system, what can be done about it?" Logistical issues are not pertinent to the first question, but they are very important to the second. One consequence of separating the overall modeling problem into two complementary models is that each model is rendered conceptually simpler. The logic model evaluates the status of the topics under evaluation; in our case, the components of wildfire potential (Fig. 1.). The decision model considers the status of wildfire potential of each landscape feature and places it in a social context that further informs decision-making (Fig. 2.). The decisions are only partially based on wildfire potential; they can also be based on social context and human values, such as the protection of people and their infrastructure in the wildland–urban interface, reduced wildfire smoke emissions, and protection of water supplies. After priorities have been derived by the decision model, decision-makers can review the results and observe the relative contributions of ecological states and social contexts to the overall decision.

2.2. Overview of analyses from 2006 to 2009

Work on EMDS applications for prioritizing fuel-treatment budgets began with USDA in 2006 to support Forest Service funding allocation decisions for 2007. The authors worked with a team of Forest Service fire scientists to design the logic for evaluating wildfire potential (Fig. 1). Similarly, we worked with senior managers from the USDA Forest Service National Forest System (NFS) to design the decision models for fuel-treatment priority (Fig. 2). Data (see Section 2.4) were summarized first to National Forests, and the forest-level data were then summarized to Forest Service Regions. This approach was designed to support allocation decisions at both national and Regional scales. Comments from national fuels managers were used to make modifications to the logic and decision models in 2008 and 2009 and to establish a more inclusive and continuous process for refining models in the future.

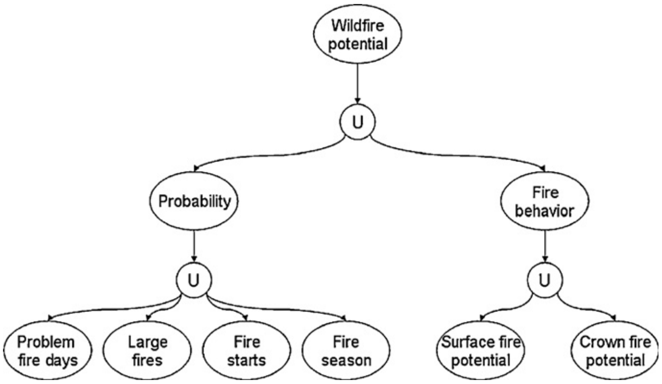

Fig. 1. Logic for evaluating *wildfire potential* on National Forests in 2009 for the USDA Forest Service decision process. Similar models were used in the 2008 and 2009 USDI analyses. Ovals represent logic topics that evaluate strength of evidence for a proposition. Circles indicate logic operators. In this example, the U operator performs a simple weighted average on its antecedents. The highest level topic, *wildfire potential*, evaluates evidence for a conclusion of low potential. Subordinate topics similarly test for evidence of conditions not conducive to wildfire. For example, the *probability* topic assesses evidence for low likelihood of wildfire. Definitions of data inputs to the model are given in Table 1.

Beginning in 2007, the project's scope was expanded to include USDI Fish and Wildlife Service, Bureau of Indian Affairs, National Park Service, and Bureau of Land Management. Fuels managers representing each of the four Bureaus were assembled to review and adapt the 2007 USDA models. Some adaptation of the models was viewed as necessary by USDI managers, partly because of the different missions of USDA and USDI, but also because a unified logic model and unified decision model for the four Bureaus (Figs. 1 and 2, respectively, are for the 2008 USDA process) must account for the differing missions. Similar to the USDA approach, the models were designed to support a two-step allocation process in the 2008 USDI analysis, in which allocation was first made to Bureaus, and then to Regions within Bureaus. However, a new analysis based on geographic areas (GAs) as defined by the National Interagency Coordination Center (NICC) [http://gacc.nifc.gov/]) was added in the 2009 analysis, in which data from each Bureau were summarized to a common spatial reporting unit, thus facilitating comparisons across Bureaus.

2.3. Example models

As described in the last section, the logic and decision models used for USDA and USDI differed slightly in their details in any given year, and models for both agencies evolved over the study period. A comprehensive description of all models is beyond the scope of this paper, so the following two subsections present USDA models used in 2009 as examples.

2.3.1. USDA logic model for wildfire potential

The logic for evaluating wildfire potential (Fig. 1) was designed with NetWeaver Developer (Miller and Saunders, 2002), whose

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[1] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

[2] EMDS 4.0 for Microsoft® Windows XP Pro™ and ArcGIS™ 9.2 or 9.3 can be downloaded from www.institute.redlands.edu/emds.

[3] Model development tools needed to build the logic and decision models used in EMDS can be obtained from, respectively, www.rules-of-thumb.com and www.infoharvest.com.

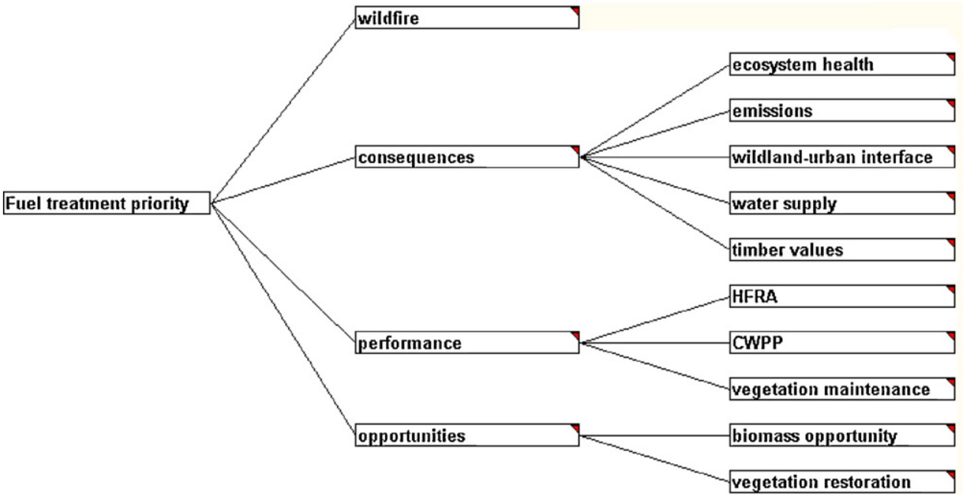

Fig. 2. Decision model for to prioritize fuel-treatment budget allocations to National Forests within a NFS Region, 2009 USDA analysis. The model used by the Forest Service in 2009 was considerably simplified from the 2007 version upon review of the 2007 process by Regional fuels managers. A similar, but simpler, model was used in the 2008 USDI analysis, and a more complex model was used in the 2009 USDI analysis. Each box represents a criterion or subcriterion of the overall decision model. Criteria at the lowest level (e.g., right-most in the figure) also represent the attributes of a Forest or, in the case of USDI analyses, a Region of a Bureau. Weights on decision criteria were determined by staff, using the standard AHP pair-wise comparison process (Saaty, 1994). Attribute values were interpreted with SMART utility functions (Kamenetzky, 1982). Definitions of data inputs to the model are given in Table 2.

engine is a component of EMDS. The overall architecture of a NetWeaver model is represented as a network of topics (Fig. 1), each of which evaluates a proposition (e.g., there is low wildfire potential) in terms of the strength of evidence provided by analysis of its subordinate propositions (secondary topics). The wildfire potential topic represents the top level (primary topic) of our model. Propositions for all other topics (Fig. 1) similarly take the null form; i.e., the test for all topics is always for a low condition.

The evaluation of *wildfire potential* depends on its two secondary topics, fire occurrence *probability* and expected *fire behavior*, each of which incrementally contribute to the evaluation of wildfire potential. We use the U(nion) logical operator to jointly consider the evaluations of secondary topics under wildfire potential (Fig. 1). Conceptually, the U operator is used when developers wish to specify that low strength of evidence for one topic can be compensated by strong evidence from another (e.g., *probability* and *fire behavior* each make an incremental contribution to evidence for low wildfire potential). Arithmetically, the U operator computes the weighted average of its arguments, although in our models the default weight of 1 is always used, so U is computing a simple average of its arguments in this model. Similarly, each secondary topic under wildfire potential has its own subordinate topics (elementary topics), within which data are evaluated. Evidence from elementary topics is similarly synthesized to their respective secondary topics with the U operator. The full logic structure is given in Fig. 1.

Evaluations of data were performed within the elementary topics using membership functions (Zadeh, 1968), which map observed values into a measure of strength of evidence for each elementary topic. In the model for wildfire potential, the membership function for each elementary topic was specified by two pairs of x,y parameters that defined a simple ramp, with one pair specifying the condition for no evidence ($y = -1$), and the other the condition for complete evidence ($y = 1$). All x parameters were empirically derived as the 10th and 90th percentiles of the observed data distribution over all US National Forests. Using the observed data distribution as the basis for specifying the x parameters had the advantage of making parameter specification relatively objective. On the other hand, this approach tended to relativize the evaluation of wildfire potential, so, the model evaluated relative wildfire potential. However, due to the very broad geographic extent of the analysis and the wide range of data values within this extent, relativizing the analysis was not considered a liability that would compromise utility of the analysis.

2.3.2. USDA decision model for fuel-treatment priorities

The decision model for characterizing fuel-treatment priority (Fig. 2) was designed with Criterium DecisionPlus (CDP, InfoHarvest Inc., Seattle, WA), whose engine is a component of EMDS. The same model structure was used to set priorities for Forest Service Regions and National Forests within Regions. In the initial design phase, senior Forest Service staff in Washington, DC, representing a broad array of disciplines, participated in a workshop in which they defined the model structure in terms of criteria and subcriteria considered relevant to managers for purposes of allocating the fuels budget.

The overall goal of the CDP model was to establish priorities for fuel-treatment across Regions at the national level, and across National Forests within Regions at the Regional level. Primary criteria for assessing priorities were *wildfire potential*, *consequences* associated with wildfires if they occurred, *performance* measures of the administrative unit, and *opportunities* that could be realized with fuels management (Fig. 2). Each primary criterion, with the exception of *wildfire potential*, was further decomposed into subcriteria (Fig. 2 and Table 2). Note that the data input to *wildfire potential* in the CDP model is the evidence score for wildfire potential generated by NetWeaver, thus linking the two models. Analogous to elementary topics in NetWeaver, lowest level criteria in this application of CDP use SMART utility functions to interpret data inputs to the decision model (Kamenetzky, 1982). Staff who participated in the model design used Saaty's (1994) method of pair-wise comparisons to derive weights on primary criteria and subcriteria in a facilitated process (Table 3). The overall priority score for any alternative (in this case, Regions or Forests) was then computed as a weighted average of utilities. Because groups participating in the CDP model design (both in the initial design phase and in subsequent iterations) were always sufficiently small and because participants were colleagues accustomed to collaborating with each other, the weighting process was always routinely by consensus. In the consensus process, each participant was first polled to obtain their input on the relative importance of each

Table 1
Data sources for evaluating wildfire potential on National Forests in 2008 USDA analysis.

Datum	Definition	Source
Crown fire potential	Proportion of area with crown fire potential rated moderate or greater.	MFSL[a]
Fire season	Mean number of days energy release component exceeds 95th percentile.	MFSL
Fire starts	Number of wildfires started between 1980 and 2003.	BLM
Large fires	Number of fire starts that progress to large fires (>500 acres) between 1980 and 2003.	BLM[b]
Problem fire days	Number of problem fire days per fire season.	MFSL
Surface fire potential	Proportion of area with surface fire potential rated moderate or greater.	MFSL

[a] Missoula Fire Sciences Laboratory.

[b] Bureau of Land Management, Boise.

criterion in a criterion pair. This was typically followed by a round of discussion in which arguments were presented for and against contrasting evaluations.

Evaluations of data were performed with SMART functions (Kamenetzky, 1982), which map observed values into a measure of utility for each attribute (lowest level criterion) of an alternative. Similar to the methods used to define membership functions in the logic model, in the decision models for fuel-treatment priority, the utility function for each attribute was specified by two pairs of x,y parameters that defined a simple ramp, with one pair specifying the condition for no utility ($y = 0$), and the other the condition for complete utility ($y = 1$). All x parameters were empirically derived as the minimum and maximum of the observed data distribution over all Regions, in the case of the national model, and over all National Forests within a Region, as in the case of Regional models. Minimum and maximum values of the observed data range were used instead of the 10th and 90th percentiles of the distribution due to the limited number of observations (e.g., eight Regions and roughly 10–20 National Forests per Region). Whereas the membership functions for the logic model were defined globally based on the distribution of data values across all National Forests, parameters defining utility functions were specific to Regions in the Regional decision models.

2.4. EMDS analysis

Data for the logic model (Table 1) and the decision models (Table 2) used in the USDA analysis were introduced in previous sections. This section gives a more detailed account of data processing steps in the context of the overall EMDS analysis process for the USDA models. Steps for USDI analyses were analogous but differed in terms of spatial analysis units (e.g., Regions of Bureaus, and Bureaus in the USDI, and National Forests, and NFS Regions in the USDA).

2.4.1. Fuel-treatment priorities for national forests

All data were obtained as 1-km-resolution raster grids, or were converted from vector to 1-km rasters when necessary (Tables 1 and 2), and summarized to each National Forest using the zonal statistics tool in ArcMap. The result was a vector map of National Forests attributed with the data from Tables 1 and 2, which was input to EMDS. The NetWeaver component of EMDS evaluated the data for each National Forest (Table 1) against the logic for wildfire potential (Fig. 1). The CDP component was then used to assess fuel-treatment priority, evaluating the data for each National Forest within a Region (Table 2) against the decision model for that Region (recall that parameters defining utility functions were specific to each NFS Region).

2.4.2. Fuel-treatment priorities for NFS Regions

Data representing the forest-level attributes were summarized to the NFS Regions. Data representing actual counts (e.g., biomass opportunity and ecosystem health in Table 2) were simply summed over all Forests within a Region. Data representing proportions, as well as the NetWeaver score for *wildfire potential*, were summarized to the Region as area-weighted averages of National Forest values. The CDP component was then used to assess fuel-treatment priority, evaluating the data for each Region against the national-level decision model. As with the Regional level of the decision model, minimum and maximum values of the data distribution over the NFS Region data were used to parameterize the SMART utility functions.

Table 2
Data sources for decision models to prioritize fuel budgets for National Forests in 2008 USDA analysis.

Datum	Definition	Source
Biomass opportunity	Area (km^2) classified as moderate or high biomass opportunity.	RSAC[a]
Ecosystem health	Area (km^2) in classes 2 and 3 of fire-regime condition class (FRCC), LANDFIRE Rapid Assessment.	FSL[b]
Emissions	Area (km^2) in land classified as moderate or high emission sources.	FSL
HFRA authority	Proportion of Forest area treated under projects that use stewardship contracts or authorities under the Healthy Forests Initiative or Healthy Forests Restoration Act.	WO[c]
CWPP	Proportion of Forest area treated under the Community Wildfire Protection Program.	WO
Timber values	Area with commercial timber at risk (ha).	WO
Vegetation maintenance	Area (km^2) in fire-regime condition class 1 that is also in historic fire-regime classes 1 and 2.	MFSL
Vegetation restoration	Area of Forest (km^2) in fire-regime condition class 2 that is also in historic fire-regime classes 1, 2, and 3.	MFSL
Water supply	Population served (1000s of people) by municipal water intakes that are influenced by streams originating on Forest.	EPA[d]
Wildland–urban interface	Sum of low, moderate, and high housing density classes within a 2-km buffer around the WUI boundary that intersected the Forest boundary.	UW[e]

[a] Remote Sensing Applications Center (USDA Forest Service).

[b] Missoula Fire Sciences Laboratory.

[c] USDA Forest Service, Washington Office.

[d] Environmental Protection Agency.

[e] University of Wisconsin, Silvis Lab.

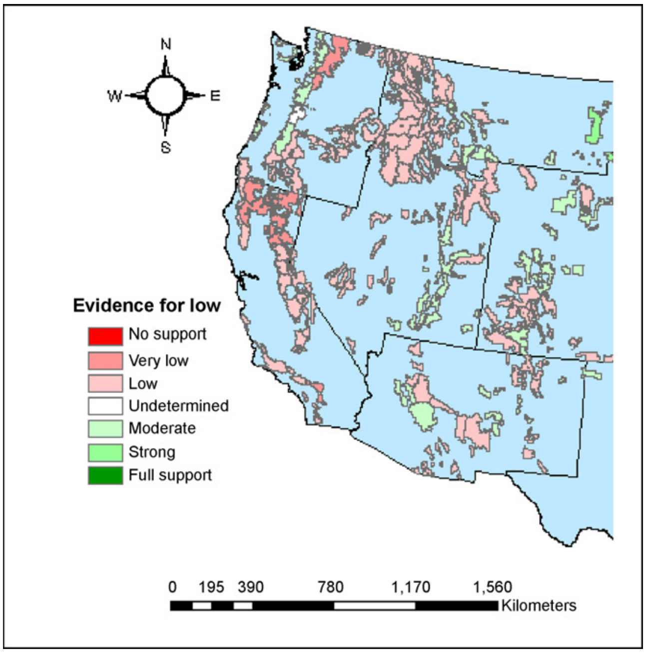

Fig. 3. Scores for *wildfire potential* in National Forests of the western US (2009 analysis). Scores for wildfire potential express the strength of evidence that the area has low wildfire potential. Evidence scores are calculated on a scale of −1 to 1, and evidence classes are defined as follows: no support = −1, −1 < very low ≤ −0.5, −05 < low < 0, undetermined = 0, 0 < moderate ≤ 0.5, 0.5 < strong < 1, and full support = 1.

3. Results

The primary products of an EMDS analysis are maps which display results of the logic and decision models. Logic models alone can generate many maps because each evaluated topic in a logic model can be displayed as a map. Consequently, in the space of this paper, it is only possible to present representative results from the three years of the USDA/USDI analyses. However, the narrative addresses additional implications associated with the complete set of map products and other EMDS outputs.

3.1. Wildfire potential

The first example illustrates the overall evaluation of *wildfire potential* in National Forests of the western US (Fig. 3). The full analysis encompassed the entire continental US, but the map is focused on a portion of the country to better display the details. Note that the map is symbolized in terms of strength of evidence for a conclusion of low wildfire potential. Across the west, evidence values ranged from very low to strong, with the preponderance of National Forests showing low evidence. The map symbology can be simply interpreted as red indicating very high wildfire potential and green indicating very low wildfire potential.

One of the products of the USDI analysis was an evaluation of *wildfire potential* on all USDI lands within GAs (Fig. 4). Although results were symbolized to entire regions for presentation purposes, data supporting the evaluation were specifically derived from the USDI parcels within each GA. In addition to the overall wildfire potential result, all topics were mapped to display how they contributed to the overall result (Fig. 4). Moreover, within the EMDS application, there is an interactive tool with which a user can trace all the details of the derivation of any conclusion for any selected map feature. Both of the latter capabilities facilitate understanding and communicating results. In addition to this aggregate analysis of USDI lands based on GAs, which one may think of as an agency-level view of wildfire potential, separate analyses and maps were generated for each Bureau.

3.2. Priorities for fuel treatment

Results of the decision model for prioritizing NFS Regions for fuel treatment in the USDA analysis are displayed in Fig. 5. The map is displayed using a natural breaks algorithm in ArcMap (the default symbology for priorities in EMDS) to deliberately accentuate differences among priority-scores of map features. If one carefully compares the priority map (Fig. 5) with the map of *wildfire potential* on National Forests (Fig. 3), it is apparent that there is no simple and direct relationship between *wildfire potential* and *fuel-treatment priority*. Although the difference in map symbology may account for a small part of the discrepancy, most of the difference is attributable to the contributions of the other primary criteria in the decision model (Fig. 2). Region 5 (California), for example, received the highest priority because there is a high potential for wildfire and its consequences, particularly with respect to water supply. In Region 8 (southeast US), wildfire potential was lower by comparison, but potential consequences were greater due to potential impacts to the wildland–urban interface, which is often closely associated with National Forests. More generally, Fig. 6 illustrates how primary criteria in the CDP model for USFS Regions contribute to the overall priority score for each Region. *Consequences* and *wildfire potential* are not only the largest contributing criteria (Fig. 6, and consistent with Table 3), but also generally account for the greatest differentiation among Regions. In addition to the national map of NFS regional priorities (Fig. 5), separate priority analyses were performed for each Region to support funding decisions to National Forests.

The final example illustrates priorities for fuel treatment across USDI Bureaus (Fig. 7) in the USDI EMDS analysis. At this national scale, the analysis is effectively aspatial, and this analysis was done directly in CDP as opposed to being performed with the CDP component of EMDS. Results indicate a clear priority ordering, from BLM (highest priority) to NPS (lowest). Moreover, Fig. 6 provides a partial explanation of the derivation of priority-scores, in terms of the relative contributions of primary criteria to each priority score. The same graphic presentation of priority-scores is implemented in EMDS as well, and it provided the basis for comments on priorities within NFS Regions in the USDA analysis. Analogous to NetWeaver's capacity to display results from all levels of a logic model, decomposition of priority-scores can be viewed at any level of a decision model.

Two additional features of the CDP component in EMDS are worth mentioning. They include a sensitivity analysis that provides diagnostics concerning the robustness of a decision model, and a trade-off analysis that describes how changes in attribute values trade with one another in terms of improving a priority score. In CDP, the sensitivity analysis reports, for each goal-criterion and criterion-subcriterion pair, the percent change in weight required to produce a reordering of priority-scores such that the highest ranked alternative is superseded by another alternative. A long standing heuristic for AHP-related sensitivity analyses is that a model can be considered adequately robust (in the sense that priority score ordering does not readily change) if the most sensitive weight in the model must be changed by at least 10% (Saaty, 1994). All models developed in this study for USDA and USDI over the period 2006–2009 satisfied this basic sensitivity test. We did not make use of the trade-off analysis function in the priority setting process for fuel-treatment budget allocation primarily because the analysis was intended for broader strategic purposes. However, it is worth mentioning that results of trade-off analyses in the CDP component provide a useful starting point for cost-benefit analyses when unit costs required to produce changes in attribute values of alternatives are known or can be estimated.

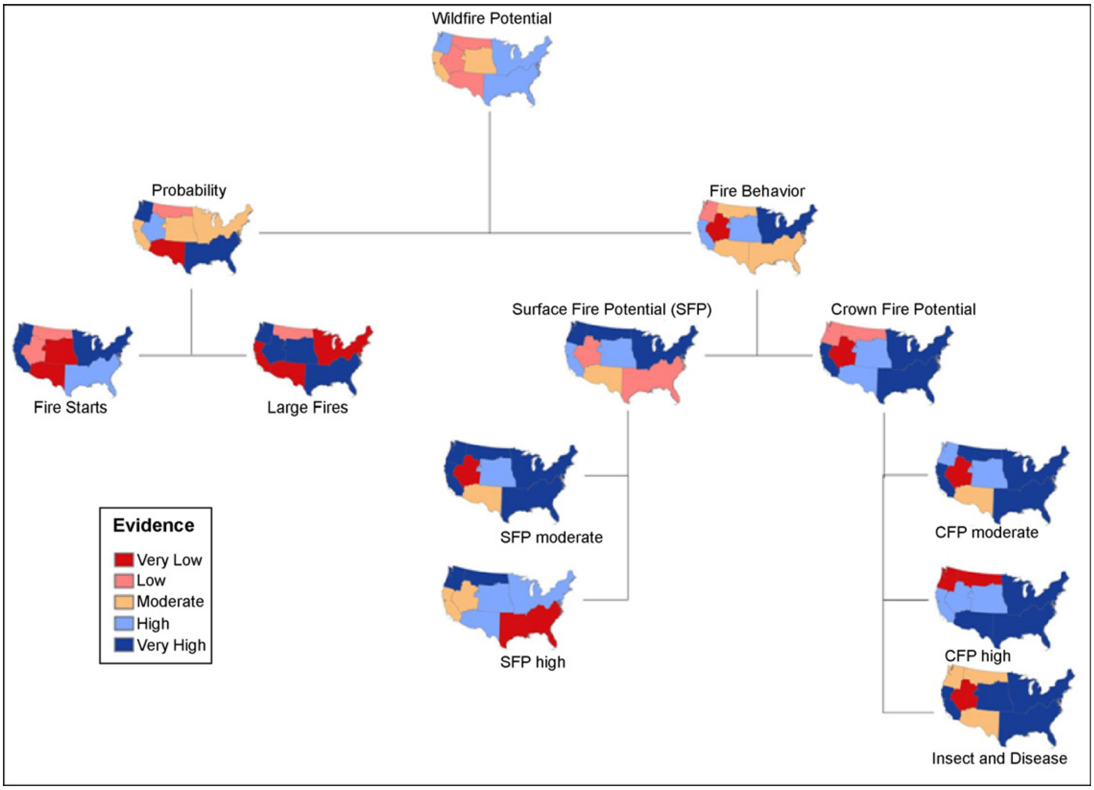

Fig. 4. Scores for *wildfire potential* by geographic areas (GAs, defined by the National Interagency Coordination Center (NICC), http://gacc.nifc.gov/) for all USDI lands (2009 analysis). Scores for *wildfire potential* express the strength of evidence for a conclusion of low wildfire potential. Similar maps, reporting *wildfire potential* by GA, also were produced for each Bureau. In addition to the overall evaluation of *wildfire potential*, the figure also illustrates how the evaluations of all antecedent logic topics are synthesized to derive the map for *wildfire potential*. The logic for this analysis differed from that illustrated in Fig. 1: *problem fire days* and *fire season* were dropped from the model due to concerns with the reliability of the modeled values, and; the USDI model elaborated on the logic specifications for *crown fire potential* and *surface fire potential* by assessing area extent of moderate versus high values, and including presence of *insects and disease* as a further consideration in *crown fire potential*. Evidence scores are calculated on a scale of -1 to 1, and evidence classes are defined as follows: very low ≤ -0.6, $-0.6 <$ low ≤ -0.2, $-0.2 <$ moderate ≤ 0.2, $0.2 <$ high ≤ 0.6, and very high > 0.6.

4. Discussion

If a decision-support process for fuel-budget allocation is going to be successful, then it needs to be understood and accepted by fuel managers at various organizational levels including, at a minimum, at Department, Bureau, and Regional levels (Hann and Bunnell, 2001). Understanding and acceptance tend to go hand in hand. In this respect, the EMDS experience with fuel-budget allocation has been relatively successful. In various meetings with new participants to the process over the past three years, one- to two-hour presentations have been sufficient to provide an in-depth orientation to the technology such that participants to the process could effectively engage in evolutionary improvements to the logic and decision models. Also, sharing and explaining results to interested groups has aided significantly in obtaining acceptance of these models.

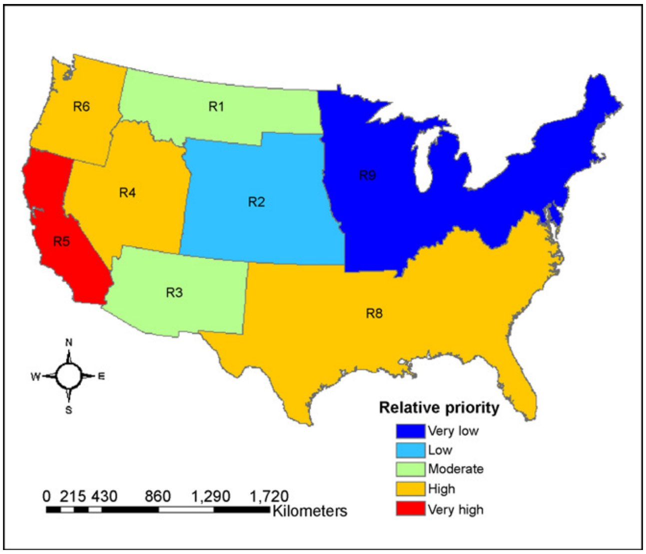

Fig. 5. Preliminary estimates of national priorities for fuel-budget allocation to Regions of the USFS (2009 analysis). Raw scores in this map have been symbolized with a natural breaks algorithm that accentuates differences in scores among Regions.

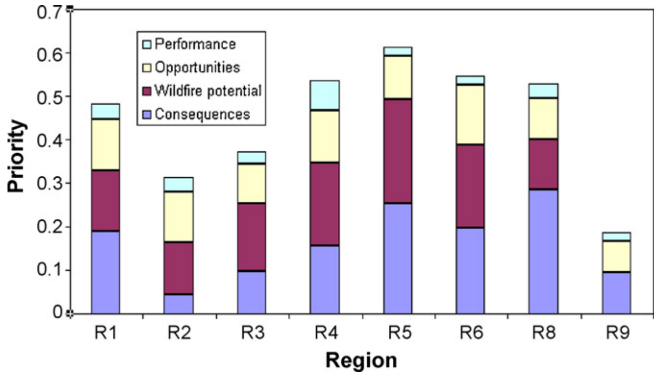

Fig. 6. Contributions of primary criteria to overall priority of USFS Regions (2009 analysis). Total bar height represents the overall priority score for each Region, and corresponds to Regions mapped in Fig. 5.

Table 3
Final weights assigned to decision criteria in 2008 USDA decision model.[a]

Criterion[b]	Weight[c]
Wildfire potential	0.238
Consequences	0.476
Ecosystem health	0.139
Emissions	0.035
wildland–urban interface	0.139
Water supply	0.139
Timber values	0.023
Performance	0.09
HFRA	0.005
CWPP	0.018
Vegetation maintenance	0.073
Opportunities	0.190
Biomass opportunity	0.063
Vegetation restoration	0.127

[a] Multiple weighting scenarios were developed and evaluated by senior managers. Each scenario reflected a different set of emphases among criteria. For example, one scenario emphasized the contribution of wildfire potential over other criteria. Weights within scenarios were developed by the Saaty (1994) pair-wise comparison process. After reviewing effects of different weighting scenarios, Managers agreed on a final recommended set of weights, again based on the pair-wise comparison process.

[b] Criteria are listed in outline form. For example, criteria indented under consequences are its subcriteria (see Fig. 2 for comparison). See Table 2 for definitions of criteria.

[c] Weights of primary criteria sum to 1. Weights of secondary criteria sum to the weight of their respective primary criterion.

Initial criticisms of the funding process from GAO (2002, 2003, 2004) and the USDA/USDI agencies' desires to improve fuel-budget allocation provided the impetus in 2006 for the modeling work presented in this study. Although the modeling process was not without shortcomings (see below), early EMDS products were acknowledged by GAO (2007) and Congressional committees as positive steps forward to improved consistency, transparency, and repeatability (Richard Lasko, personal communication).

GAO has also consistently called for an analysis process that would allow performance assessment of fuel-treatment effectiveness over time (GAO, 2007). This ability is intrinsic to the EMDS analysis and planning process, which can be clearly demonstrated over time as the base resource data that drive the analysis of *wildfire potential* are updated. A reasonable interval on which to assess treatment effectiveness is on the order of five to ten years, depending upon predominant fuel type. The approach is relatively simple because the logic for assessing *wildfire potential* is in effect, analyzing outcomes. Taking the National Forests as an example, distributions of outcomes can be compared over time by using standard nonparametric statistical tests such as the Kolmogorov–Smirnoff test (Khamis, 2000), or a multivariate analog.

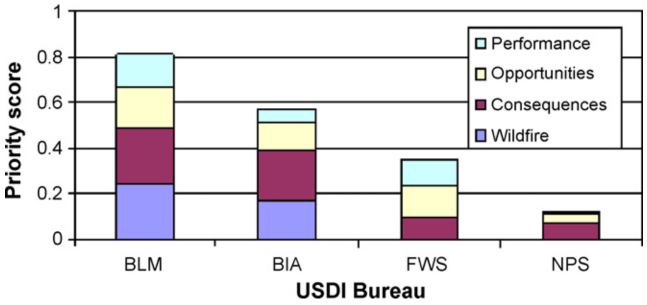

Fig. 7. Preliminary estimates of national priorities for fuel-budget allocation to USDI Bureaus (2009 analysis), showing contributions to overall priority-scores from primary decision criteria (Fig. 2). Results shown are for the recommended scenario, which was one of several scenarios representing different alternative weightings on decision criteria. Acronyms BIA, BLM, FWS, and NPS indicate Bureau of Indian Affairs, Bureau of Land Management, Fish and Wildlife Service, and National Park Service, respectively.

From the beginning, a key charge to the development teams was that logic and decision models be developed to make use of nationally available and nationally consistent data. Thus far, these two requirements have imposed a significant constraint on model development, and explain why the current logic for *wildfire potential* (Fig. 1) is relatively simple. In contrast, Hessburg et al. (2007) present a more comprehensive model for evaluating *wildfire potential* which considers a variety of factors influencing fire hazard, fire behavior, and ignition risk. Also, in a new model under development (Hessburg, personal communication), the previous logic is being expanded to include a fire-regime change topic, and the geographic scope expanded to a regional scale model that addresses *wildfire potential* in all subwatersheds (~10–20,000 ha) of Oregon and Washington. The Hessburg model (2007) was widely vetted among professionals of the fuel-management community, but much of the data required to support the more advanced logic in the Hessburg model is not yet available in a full national coverage; however, it should be available from the LANDFIRE program (Keane et al., 2007, Rollins and Frame, 2006) by the close of 2009. Likewise, the necessary fire-behavior data are not generally available, but must be simulated from surface- and crown-fuel data with simulation systems such as FIREHARM (Keane et al., in press). Executing such models at a national scale represents a formidable computational task.

Data limitations were not as constraining for the decision models (Fig. 2), but here also compromises had to be made. For example, early versions of the decision models envisioned use of performance metrics to gauge administrative-unit performance in terms of efficiency and effectiveness, of fuel treatments. However, because no such metrics are yet available in agency databases either nationally or regionally, they remain largely non-implemented in the decision model. However, evaluation of vegetation maintenance (percent of land area with minimal departure from historic conditions) is included in the model (Fig. 2) as a proxy for efficiency on the grounds that it is more economically efficient to maintain lands in good condition than to rehabilitate them.

It is difficult to give a detailed accounting of how model outputs were used in final budget allocation decisions, in part because the decision process spanned multiple years, and it was distributed across two US federal departments, five agencies, and many USDI and USDA Regions in aggregate. In addition, the authors did not directly participate in those decisions. However, based upon personal communications with key senior officials such as Richard Lasko (USDA) and Erik Christiansen (USDI, see Acknowledgments) as well as internal department reports, use of EMDS results can be summarized approximately as follows. National-level allocations to USFS Regions and USDI Bureaus were decided first, after decision makers agreed ahead of time on the proportion of the total fuels budget that would be subject to influence by decision scores provided by EMDS. Normalized decision scores (score of a unit divided by the sum of scores over all units) typically were used as a starting point for discussions among decision makers for setting Region and Bureau allocations, but the expertise of decision makers also was relied upon to make adjustments, based on their knowledge of external factors either not addressed by the decision model, or at least not adequately addressed. Because the EMDS process lends itself to proportional allocation, national and sub-national-level decisions on allocation could, in principle, be executed in parallel, but in practice allocations have consistently been performed in a top-down, stepwise manner. Within the USFS, application of models at the Regional level has been optional at least up to the present, and about half of USFS Regions have implemented the Regional priority analyses implemented by EMDS. USFS Regions also have had the flexibility to apply their own data sources, and to adapt the logic and decision models as deemed necessary, although there also has been emphasis from the national level to maintain as much consistency as practicable across administrative levels. In contrast, USDI Bureaus have been applying the models as given to their respective Regional allocation processes. The difference in approaches between USDA and USDI is understandable from the perspective that the individual Bureau analyses are still national in scope. On the other hand, decision makers at the Bureau level also have had the same flexibility to adjust preliminary decision scores based on Bureau-specific exigencies.

Lack of confidence in modeling results could have easily hampered model development and application, especially considering that over time, billions of dollars in agency funding were at stake, and as in any budgeting process there are inevitable winners and losers. Three factors have contributed to successful application: First, from the beginning, we strongly emphasized to senior managers that the role of decision support in the budgeting process was not to deliver "the answer," but to organize and present information in a way that facilitated deliberations among decision makers. Senior managers within USDA and USDI accepted the advice. Second, modeling results were used as a guide to incremental, rather than wholesale, changes to budgets, which would have been highly disruptive to operations within administrative units at all levels. Finally, and most importantly, there was a high level of involvement of senior managers, technical specialists, and scientists in formulating the models in current usage. In 2006, initial model development was done in small groups, which proved effective for rapid prototyping, but then senior managers very successfully engaged Regional, Forest, and Bureau managers to review and revise the models from 2006 to 2009.

5. Summary

The USFS and USDI have experimented with application of an integrated, multi-scale decision-support system for funding fuel treatments at agency, regional, and local levels. A distinct advantage of doing so is development of a nationally consistent approach that operates across spatial scales, thus bringing consistency to decision processes at multiple levels within each agency and potentially across agencies. Three years into an iterative process, there is room for improvement with respect to the extent of data coverage, data quality, and the sophistication of the available models; however, an approach, based on rational and transparent models and manager involvement during model formulation and revision, has proven to be successful without the disruptions that are common to process changes. Success to date, based on improved accountability and transparency in priority setting, is attributable to effective engagement of scientists, managers, and technical specialists at various levels of the agencies.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.foreco.2009.08.011.

References

Agee, J.K., 1998. The landscape ecology of western forest fire regimes. Northwest Sci. 72, 24–34.

Agee, J.K., 2003. Historical Range of Variability in Eastern Cascades Forests, 18. Landscape Ecol., Washington, USA, pp. 725–740.

Bleier, C., Downie, S., Cannata, S., Henley, R., Walker, R., Keithley, C., Scruggs, M., Custis, K., Clements, J., Klamt, R., 2003. North Coast Watershed Assessment Program Methods Manual. California Resources Agency and California Environmental Protection Agency, Sacramento, CA.

Burkett, V.R., Wilcox, D.A., Stottlemeyer, R., Barrow, W., Fagre, D., Baron, J., Price, J., Nielsen, J.L., Allen, C.D., Peterson, D.L., Ruggerone, G., Doyle, T., 2005. Nonlinear dynamics in ecosystem response to climatic change: Case studies and policy implications. Ecol. Complexity 2, 357–394.

Ferry, G.W., Clark, R.G., Montgomery, R.E., Mutch, R.W., Leenhouts, W.P., Zimmerman, G.T., 1995. Altered Fire Regimes within Fire-Adapted Ecosystems. United States Department of the Interior, National Biological Service, Washington, DC.

GAO, 2002. Severe wildland fires: leadership and accountability needed to reduce risks to communities and resources. Report to Congressional Requesters, GAO-02-259. United States General Accounting Office, Washington, DC.

GAO, 2003. Additional actions required to better identify and prioritize lands needing fuels reduction. Report to Congressional Requesters, GAO-03-805. United States General Accounting Office, Washington, DC.

GAO, 2004. Forest Service and BLM need better information and a systematic approach for assessing risks of environmental effects. GAO-04-705. United States General Accounting Office, Washington, DC.

GAO, 2007. Better information and a systematic process could improve agencies' approach to allocating fuel reduction funds and selecting projects. Report to Congressional Requesters, GAO-07-1168. United States General Accounting Office, Washington, DC.

Hann, W.J., Bunnell, D.L., 2001. Fire and land management planning and implementation across multiple scales. Int. J. Wildl. Fire 10, 389–403.

Hessburg, P.F., Agee, J.K., 2003. An environmental narrative of Inland Northwest US forests, 1800-2000. For. Ecol. Manag. 178, 23–59.

Hessburg, P.F., Agee, J.K., Franklin, J.F., 2005. Dry mixed conifer forests of the Inland Northwest, USA: contrasting the landscape ecology of the pre-settlement and modern eras. For. Ecol. Manag. 211, 117–139.

Hessburg, P.F., Reynolds, K.M., Salter, R.B., Richmond, M.B., 2004. Using a decision support system to estimate departures of present forest landscape patterns from historical conditions: an example from the Inland Northwest Region of the United States. In: Perera, A.H., Buse, L.J., Weber, M.G. (Eds.), Emulating Natural Forest Landscape Disturbances: Concepts and Applications. Columbia University Press, New York, pp. 158–175.

Hessburg, P.F., Reynolds, K.M., Keane, R.E., James, K.M., Salter, R.B., 2007. Evaluating wildland fire danger and prioritizing vegetation and fuels treatments. For. Ecol. Manag. 247, 1–17.

Kamenetzky, R., 1982. The relationship between the analytical hierarchy process and the additive value function. Decis. Sci. 13, 702–716.

Keane, R.E., Rollins, M.G., Zhu, Z., 2007. Using simulated historical time series to prioritize fuel treatments on landscapes across the United States: the LANDFIRE prototype project. Ecol. Modell. 204, 485–502.

Keane, R.E., Drury, S.A., Karau, E., Hessburg, P.F., Reynolds, K.M., in press. A method for mapping fire hazard and risk across multiple scales and its application in fire management. Ecol. Modell.

Khamis, H.J., 2000. The two-stage delta-corrected Kolmogorov–Smirnov test. J. Appl. Stat. 27, 439–450.

Kolb, P.F., Adams, D.L., McDonald, G.I., 1998. Impacts of fire exclusion on forest dynamics and processes in central Idaho. Tall Timbers Fire Ecol. Conference 20, 911–923.

Miller, B.J., Saunders, M.C., 2002. The NetWeaver Reference Manual. Pennsylvania State University, College Park, PA.

Pickett, S.T.A., White, P.S., 1985. The Ecology of Natural Disturbance and Patch Dynamics. Academic Press, San Diego, CA.

Reeves, G.H., Hohler, D.B., Larsen, D.P., Busch, D.E., Kratz, K., Reynolds, K., Stein, K.F., Atzet, T., Hays, P. Tehan, M., 2003. Aquatic and riparian effectiveness monitoring program for the Northwest Forest Plan. USDA For. Serv. Gen. Tech. Rep. PNW-GTR-577. United States Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portand, OR.

Reynolds, K.M., Rodriguez, S., Bevans, K., 2003. User guide for the Ecosystem Management Decision Support System, Version 3. 0. Environmental Systems Research Institute, Redlands, CA.

Reynolds, K.M., Hessburg, P.F., 2005. Decision support for integrated landscape evaluation and restoration planning. For. Ecol. Manag. 207, 263–278.

Rollins, M.G., Frame, C., 2006. The LANDFIRE Prototype Project: nationally consistent and locally relevant geospatial data for wildland fire management. General Technical Report RMRS-GTR-175. United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Saaty, T.L., 1994. Fundamentals of Decision Making and Priority Theory with the Analytical Hierarchy Process. RWS Publications, Pittsburgh, PA.

Schoennagel, T., Veblen, T.T., Romme, W.H., 2004. The interaction of fire, fuels, and climate across the Rocky Mountain forests. Bioscience 54, 661–676.

Turner, M.G., 1989. Landscape ecology: the effect of pattern on process. Ann. Rev. Ecol. Syst. 20, 171–197.

Turner, M.G., Gardner, R.H., O'Neill, R.V., 2001. Landscape Ecology in Theory and Practice. Springer-Verlag, New York.

U. S. Government, 2003. Healthy Forests Restoration Act of 2003. 108th Congress, 1st Session. House of Representatives Report 108–386, 1–48.

White, M.D., Heilman, G.E., Stallcup, J.E., 2005. Sierra Checkerboard Initiative. Conservation Biology Institute, San Diego, CA (irreg. pagination).

Whitlock, C., Knox, M.A., 2002. Prehistoric burning in the Pacific Northwest. In: Vale, T.R. (Ed.), Fire, Native Peoples, and the Natural Landscape. Island Press, Washington, DC, pp. 195–231.

Zadeh, L.A., 1968. Probability measures of fuzzy events. J. Math. Anal. Appl. 23, 421–427.