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Integrating fuel treatment into ecosystem management: a proposed project planning process

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Abstract. Concern over increased wildland fire threats on public lands throughout the western United States makes fuel reduction activities the primary driver of many management projects. This single-issue focus recalls a management planning process practiced frequently in recent decades – a least-harm approach where the primary objective is first addressed and then plans are modified to mitigate adverse effects to other resources. In contrast, we propose a multiple-criteria process for planning fuel-treatment projects in the context of ecosystem management. This approach is consistent with policies that require land management activities be designed to meet multiple-use and environmental objectives, while addressing administrative and budget constraints, and reconciling performance measures from multiple policy directives. We present the process borrowing from the Trapper Bunkhouse Land Stewardship Project example to show the logic for conducting an integrated assessment of ecological and natural resource issues related to multiple management scenarios. The effects and trade-offs of the no-action scenario and proposed action alternatives are evaluated relative to silviculture, disturbance processes (including fire behaviour), wildlife habitat, noxious weeds, water quality, recreation and aesthetics, and economic contributions. Advantages and challenges of this project planning approach are also discussed.

Introduction

The United States has had several long and expensive fires seasons since 2000 (Westerling *et al.* 2006). These dramatic increases in the number of large and damaging wildland fires triggered the commitment of substantial federal and state resources to reduce hazardous fuels on public lands. The Government Accountability Office (GAO) called for federal land management agencies to develop 'consistent criteria to identify and prioritize' areas requiring fuel reduction treatments and requested 'clearly defined outcome-oriented goals and objectives' (GAO 2002, p. 3). In response to this and other GAO reports (GAO 2002, 2005), an interagency policy statement from the US Department of Interior (DOI) and USDA Forest Service (USFS) now proposes fuel reduction activities on 'over four million acres (1.62 million hectares) of land each year'. This policy calls for coordination of all vegetation-related land management activities to 'maximise their combined benefit toward overall fuels management objectives' (US DOI and USDA Forest Service 2006, p. 3).

Legislation and policy directs the USFS to manage lands for a variety of uses and benefits, not just fuel treatments. For example, the Multiple-Use Sustained-Yield Act of 1960 (16 USC 528–531) (US Congress 1960) directed the Agency to manage National Forests for multiple uses, including 'outdoor recreation, range, timber, watershed, and wildlife and fish purposes'. The USFS Chief Robertson asked the agency to embrace ecosystem management and 'implement a new management philosophy for the national forests and grasslands' (F. D. Robertson, pers. comm., 1992). More than a decade later, the Healthy Forest Restoration Act (HFRA) of 2003 (16 USC 6501–6591) (US Congress 2003) established multiple goals for conducting hazardous fuels reduction projects on federal forested lands: (1) protect key ecosystem components; (2) reduce risk to communities and municipal water supplies; (3) improve critical habitat for threatened or endangered species; (4) restore vegetation structure to reflect historic variability; (5) improve commercial value of forest biomass; and (6) address insect infestation.

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Federal US fuel reduction policies have been criticised for failing to provide specific procedures and guidelines for managers to locate and prioritise fuels treatments (Franklin and Agee 2003; Nazzaro 2006). Existing policies do not clearly describe how managers should effectively integrate fuel treatment with the complexities of managing ecosystems for a variety of resource objectives into practical planning strategies (Franklin and Agee 2003). The urgency to reduce forest fuels, given the existing expectations that forest management will address competing resource objectives while applying the best available ecosystem science creates tension and confusion. Methods are needed that effectively integrate fuel treatments into the complexities of ecosystem science and multiple resource objectives to promote practical project planning that can benefit struggling land-management agencies.

One recent USFS approach to strategically locate fuel treatments, called FIRESHED (Ager *et al.* 2006), served as the basis for the Strategic Placement of Treatments (SPOTS) pilot program (Gercke and Stewart 2006). The process starts by defining the worst-case scenario ‘problem fire’ against which the predicted success of fuel reduction activities is to be measured. Yet impacts to other resources are considered only after fuel treatments are proposed. Treatments are then modified to limit negative impacts, constituting a least-harm planning approach essentially representing a constrained single-variable (hazardous fuel treatment effectiveness) optimal land-management approach. This approach is most applicable in areas where fuel treatment is the only driving force motivating vegetation treatment projects. However, for much of the nation’s public land, the public may be better served by projects designed explicitly to achieve multiple objectives.

In this paper, we present a multi-objective process for planning fuel-treatment projects. First, we provide background on existing multiple-objective planning frameworks, including their steps and the types of planning problems to which they have been applied. Then, we introduce the Trapper Bunkhouse Land Stewardship Project where an earlier iteration of our proposed process was applied. Next, we present the conceptual process for analysing and documenting environmental effects of alternative management decisions to facilitate integrated planning in areas where fuel reduction treatment is one of multiple important land-management objectives. The process we propose, which is a hybrid of integrated assessment modelling and trade-off analysis frameworks, is then presented in depth using the Trapper Bunkhouse Land Stewardship Project as an example. We use this example to show how this process could support a fully integrated National Forest Management Act (NFMA) (US Congress 1976) and National Environmental Policy Act (NEPA) (US Congress 1969) compliant[A] project planning process, incorporating metrics of success for fuel treatment and other management objectives. We discuss several opportunities to improve achievement tracking and collaborative relationships as well as challenges to this methodology given the realities of limited time, personnel, or financial resources.

Overview of ecosystem management, integrated assessment and trade-off analyses

Ecosystem management

Following the slow development of ecosystem management (EM) foundations for roughly half a century, EM emerged as a new paradigm in federal land management during the 1990s (Grumbine 1994). Although broad support existed for a shift to a new management paradigm, it is clear that interpretation of the meaning of EM varied sufficiently enough that various stakeholders lacked full agreement about the best path forward for US federal land management. Both Skroch (2005) and Yaffee (1999) concisely summarised the various definitions of EM, placing them on a large spectrum from environmentally sensitive multiple-use management (human needs are the focus, and damage from human actions are minimised while meeting those needs) to ecoregional management (where human activity is viewed as part of nature). Holling and Meffe (1996) described that at its most basic level, an ecosystem approach to management strives for diversity as a means to build or maintain resilience against catastrophic disruptions in biological, economic, organisational, and or political systems. Following 3 years of experimentation with EM, USFS Chief Dale Robertson circulated a heavily cited memo that pushed the USFS to embrace the basic tenets of EM: sustainability, measurable goals, scientifically sound ecological models and understanding, complexity and connectedness, the dynamic character of ecosystems, appropriate context and scale, humans as part of ecosystems, and adaptability and accountability (Skroch 2005).

Since 1992, through policy statements, training programs and other devices, the USFS and DOI land-management agencies committed themselves to EM (Congressional Research Service 1994); the agencies have broadened both their watershed assessments and NEPA project planning documents to holistically reveal ecological and human interactions and anticipated consequences of land-management actions. Even though EM was embraced and has been maintained as the guiding philosophy of most US land-management agencies, and it has held up to challenges in the judicial arena, the US Congress had yet to formally adopt this term in any legislation by the late 1990s (Keiter 1996). Yaffee (1999, p. 720) pointed out that, ‘Even federal agencies such as the USFS that have an ecosystem approach grafted onto an environmentally sensitive, multiple-use mandate have units that vary considerably in management style’. This decentralised style of development grew from frustration with earlier management paradigms (Yaffee 1999). Despite the nuances of the various efforts to achieve EM in practice, the general tenets of more comprehensive management approaches are a common thread that is expected to persist well into the future.

This development of a more comprehensive EM approach is not unique to the USFS or even forest management, but is common in most environmental management fields. Many environmental problems extend over large areas, across many

[A]The National Environmental Policy Act of 1969 specifies that compliant planning documents consider both a no-action alternative and a reasonable range of action alternatives to analyse environmental consequences of potential actions (42 USC 4321–4347). The National Forest Management Act of 1976 mandated extensive planning to promote effective and efficient conservation of forest resources and to resolve forest management controversies (16 USC 1600).

ownerships, and generate a wide variety of ecologic, economic and social concerns. Planning solutions for these complex problems require integration of science across a host of disciplines and participation of land managers and stakeholders within and beyond the primary planning area. Computer-based models used for many decades by managers and scientists provide a means to study an array of system components from wildlife habitat to economic impacts.

Integrated assessment modelling

Integrated Assessment Modelling (IAM) was developed to address complex environment management problems across large areas and over long periods of time. It evolved from regional air quality and global climate change analyses conducted in Europe starting in the 1980s (Schneider and Lane 2005; Oxley and ApSimon 2007) and IAM enabled the transition from multidisciplinary to integrated, interdisciplinary assessments and trade-off analyses. The IAM concept represents 'a method of analysis that combines modeling from the physical, biological, economic, and social sciences, and the interactions between these components, in a consistent framework to evaluate the status and the consequences of environmental change and the policy responses to it' (IPCC 2001, p. 715).

Integrated assessments are spatially explicit, accounting for interactions within and among specific land areas. Successful, sustainable land management requires careful consideration of the spatial arrangement and interactions of proposed activities relative to antecedent landscape conditions. Many unintended negative consequences of local land-use and land-management decisions are in large part due to failure to adequately consider consequences over large land areas and across long periods of time (Forman 1995). Put simply, 'Spatial arrangement matters' (Forman 1995, p. xvi). Sessions *et al.* (1997) described the key role that the development of geographic information systems (GIS) played in facilitating understanding of landscape-scale dynamics. Computer software representing important systems throughout a planning area now allows planning teams (including managers, citizens and scientists) to more effectively design and evaluate different scenarios and 'assess the ensuing trade-offs among indicators of environmental, economic and social outcomes' (Jakeman and Letcher 2003, pp. 492–493).

The IAM method has been used to evaluate trade-offs among economic and environmental outcomes. An application in northern Thailand evaluated trade-offs among soil erosion, forest cover, water quality and quantity, food supply and farm income, under variable climates and a range of commodity prices, technology, government regulation and investment levels (Letcher *et al.* 2006). Chinese analysts implemented IAM (Liu *et al.* 2007) to address environmental and economic problems resulting from conflicting land uses in lake districts at the urban fringe. They used multicriteria analysis and system dynamics techniques to inform planning efforts to balance urban expansion and ecological conservation.

Refsgaard *et al.* (2007) provided a European Union IAM framework focussing on the various uncertainty accounting approaches when modelling water management. These authors and Ascough *et al.* (2008) provide overviews of uncertainty issues and typologies geared towards the modelling community that are relevant to the IAM and trade-off process proposed below. In uncertainty discussions, both publications reference Walker *et al.* (2003), who pointed out that the definitions and relationships of uncertainty, error, variability and risk vary among different disciplines. The value of IAM is demonstrated by the increasing number of nations using it to assess and resolve inherently 'wicked problems' (Rittel and Webber 1973, p. 160) in environmental management.

Trade-off analyses

Integrated assessment modelling is functionally similar to multiple attribute decision making, a method of decision-support analysis rooted in general management science literature (Ohlson *et al.* 2006). Applied to EM, the goals of multiple-attribute decision making are fundamentally the same, to account for compound ecological, social and economic impacts of human activities (Prato 1999). Prato (1999, p. 207) introduced a process to implement multiple-attribute analysis for a watershed-based approach to 'multidimensional, community-based' natural resource planning. He argued that a well-designed, clearly defined and integrated planning framework offers improved trade-off analysis for non-market resources. Iteration is expected in this process to identify activity levels that collectively lead to economically beneficial conditions and ecologically sustainable land uses.

Multiple Attribute Trade-off Analysis (MATA) is a GIS-based variant of multiple-attribute decision making used recently in Canada to support development and evaluation of fuel management strategies (Ohlson *et al.* 2006, p. 826). Application of a generalised MATA framework involves: (1) defining the management context and problem; (2) establishing multiple objectives and measurable attributes; (3) identifying a range of management alternatives; (4) assessing consequences, including the explicit examination of risk and uncertainty; and (5) evaluating and making trade-offs. The goal of this Canadian work was to select the best fuel management alternatives relative to: treatment costs, potential property damage, the area of wildland–urban interface that could burn, and the consequences of alternatives relative to biodiversity, air quality and greenhouse gas emissions. The modelling components used in the Canadian MATA example included spatial and temporal simulations of wildland fire, prescribed burns, mechanical activities, fire emissions, changes in habitat and biodiversity, activity costs, and future timber supply.

The US-based Ecosystem Management Decision Support (EMDS) system is an IAM variant built on 'knowledge-based' logic (Reynolds 2001) with trade-off analysis capabilities. A collaborative analysis and planning group defines logical rules, which are used to test the relative validity of assessment statements. The EMDS software was developed as an extension to *ArcGIS* software, so inputs and outputs are spatially explicit. Logic operators and subjective weighting factors allow the users to make broad assessments of integrated resources. Optional decision software includes many of the desirable features of other multicriteria decision support systems, such as documentation and transparency for decision logic and the ability to estimate the value of missing data. The EMDS has been successfully demonstrated for watershed restoration analysis (Reynolds and Hessburg 2005) and in fuel-reduction budget planning through generalised treatment prioritisation (Hessburg *et al.* 2007).

Although many of these integrated multiple criteria analysis tools, like EMDS, have proved to be useful for national-, regional- or national forest-level allocation, their use at the project-level planning scale is not well documented. The small-scale project approach to land management in the US is being replaced with larger landscape planning, which may make the use of these tools more attractive. This paper demonstrates how integrated logic can be applied with some simple adjustments to current planning processes or with sophisticated decision-support tools such as EMDS to design projects that include fuel treatment as one of numerous concurrent land-management goals.

Trapper Bunkhouse Project Area, Bitterroot National Forest, USA

The study area covers 23 139 acres (9364 ha) on the Bitterroot National Forest in south-western Montana, USA (Fig. 1). The climate of this terrain is predominately montane with a tempering Pacific maritime influence. Snowfall dominates precipitation, but intense, short-duration thunderstorms occur intermittently throughout the warm, dry summers. The area is bounded to the west by steep, rocky terrain managed as the Selway–Bitterroot Wilderness Area and to the east by developed, rural wildland–urban interface (WUI), which rolls down to the West Fork and main stem of the Bitterroot River. Coniferous species dominate the nearly continuous low-elevation forest cover, with a 1–30-year fire return interval (Arno 2000). The habitat of the sensitive and endangered fish species that populate the streams within this roaded area is degraded by road crossings that break stream continuity and increase sedimentation, and by irrigation canals that may reduce in-streams flows to levels that compromise fish health. Local residents and visitors use the area for hiking, camping, hunting, motorsports and other recreation activities. We borrow some, but not all, of the process history and analysis results conducted in support of this land-management project to illustrate our proposed methodology. For more information about this project, see USDA Forest Service (2008).

Fig. 1. Location of Trapper Bunkhouse Land Stewardship Project Area in south-western Montana, USA.

Proposed planning methods

An integrated modelling process for fuel-treatment project planning

Here, we present a conceptual framework for integrating fuel-treatment project planning into an EM context that simultaneously develops and evaluates alternative strategic fuel-treatment placements and opportunities for multiple resource enhancements as interdependent impacts and trade-offs. This process is designed to plan for SPOTS objectives within the broader context of EM in a NEPA-compliant integrated resource assessment and project planning process. The IAM–MATA design is sufficiently flexible to accommodate evolving metrics for measuring fuel treatment effectiveness and climate change. As debate continues to develop and refine useful metrics for fuels and emissions management, these can easily be embedded into this evolving IAM–MATA design.

The following steps outline the integrated assessment process. Although presented in a stepwise format, the proposed integrated assessment process is expected to be iterative to adjust to relevant new information and assessment results:

- Step 1. Convert resource assessments and observations into a preliminary set of management issues, leading to a 'purpose and need' statement with clearly stated management objectives.
- Step 2. Develop an IAM framework by translating management objectives into quantitative and qualitative metrics.
- Step 3. Define the basis for the MATA of alternative management scenarios.
- Step 4. Build and run component models for the baseline (no-action) scenario.
- Step 5. Build alternative management scenarios and conduct the analysis to evaluate resource trade-offs across management alternatives with iterative refinement of a preferred alternative.

Despite the typical discomfort that managers exhibit towards reporting uncertainty in planning documents, the best way to navigate these steps successfully is to openly identify knowledge limitations and sources and magnitude of modelling uncertainty. Nearly every step creates opportunities to use this discovery process to convey the depth and quality of our understanding. As Schluter and Ruger (2007) pointed out, natural system complexity can be addressed with modelling tools that combine information from the research, management and stakeholder communities to facilitate decisions. The better informed the assessment team and audience are about modelling capabilities, and associated measures of uncertainty, the more appropriate will be the application of these modelling results in decision-making.

Much of the proposed analysis can be accomplished within a GIS. This permits spatially explicit analysis and visualisation of possible consequences and trade-offs of NEPA alternatives that may help estimate and confirm anticipated costs, benefits and conflicts. Results of the modelling used in this process may also reveal unanticipated opportunities and pitfalls. Generalised steps are now described in detail.

Step 1

Convert resource assessments and observations into a preliminary set of management issues, leading to a purpose and need statement with clearly stated management objectives.

In the first step, public land resource issues are identified and translated into management objectives, which form the basis for scoping. Some of these issues arise from observations and large-scale assessments. Planning areas frequently have multiple resource issues, and therefore multiple project objectives. For example, the purpose and need for action for the Trapper Bunkhouse Project is to:

- *Reduce risk from stand-replacing and uncontrollable fires.* Reduce the size of areas where stand-replacing crown fires and uncontrollable fire intensities in the suitable timber base and WUI are likely to occur. This will reduce the risk from fires harming human life (firefighters and the public), private property and natural resources in the Trapper Bunkhouse area.
- *Improve resiliency and provide forest products.* Provide economic value to the community and funding opportunities for the activities related to reducing sediment contributions and forest fuels through timber harvest by capturing the economic value of insect- or disease-killed or infested trees and fire-killed trees. Provide for green-tree thinning in plantations, and at-risk areas outside plantations, to improve resiliency to insects and disease.
- *Fuel reduction research.* Conduct research to evaluate our ability to influence fire spread rates and severity using vegetation management, and to analyse the effects on ecosystem components such as soil productivity and weed invasion.
- *Watershed improvement.* Reduce sediment contribution in South Fork Chaffin and Little Trapper Creeks, from the identified high-priority road segments and crossings. Improve aquatic connectivity in South Fork Chaffin Creek.

Explicitly identifying all the relevant objectives that address the important management issues present in an area in Step 1 sets the stage for multiple-attribute trade-off analysis. In this step of the Trapper Bunkhouse Project planning process, the items listed in the purpose and need were translated into 13 independent objectives (Table 1, A–M).

The reactions of colleagues and the public to scoping documents during the public comment phases of NEPA assessments help bolster issue comprehension and articulation of project objectives. Although we recognise that a unique set of issues will be present in each project proposal, the variety of objectives listed in Table 1 may be typical for planning areas in the US interior west. In the future, we expect that carbon management will become one of these multiple objectives in public land management, and useful metrics representing impacts to the carbon cycle will likely emerge.

This integrated process contrasts with single-objective planning, which focusses only on one objective of concern at this initial stage in planning. In that single-objective framework, all other resource issues are either ignored or enter the planning

Table 1. Integrated resource objectives for the Bitterroot National Forest Trapper Bunkhouse Land Stewardship Project, the results of Step 1

Objective code	Objective description	Affected environment
A	Reduce size of area where stand-replacing and uncontrollable fires are likely to occur	Fire and fuels
B	Improve the resiliency of vegetation to insects and disease in areas with moderately high to high risk of loss	Vegetation
C	Improve channel conditions and connectivity specifically within South Fork Chaffin and Little Trapper Creeks, and within all area watersheds in general	Watershed
D	Reduce sediment contribution in South Fork Chaffin and Little Trapper Creeks, from the identified high-priority road segments and crossings. Improve aquatic connectivity in South Fork Chaffin Creek	Fisheries
E	Maintain soil productivity while meeting fuel reduction purpose and needs	Soils
F	Reduce habitat impacted by proposed treatments on federally listed, proposed, threatened, and endangered species, Forest Service sensitive species, or Forest Plan management indicator species	Wildlife
G	Evaluate impacts to population, numbers, habitat, population, and viability of sensitive plant species	Threatened, endangered and sensitive plants
H	Control noxious weeds to protect resource values and minimise adverse effects on adjacent private land	Noxious weeds
I	Avoid adverse effects on historic properties; prevent loss or damage of cultural resources	Heritage
J	Assess the existing condition and potential effects to existing recreation opportunities and changes to those opportunities	Recreation, roadless areas and wilderness
K	Analyse impacts of the alternatives on scenic quality	Visual resource
L	Provide funding opportunities for activities to reduce sediment contributions and for fuel reduction by capturing economic value of insect- or disease-killed or infested trees as well as selected thinning to improve resiliency to insects and disease	Economics and social contributions
M	Avoid adverse impacts of smoke emissions from understorey and pile burning on Darby area residents and the Selway–Bitterroot Wilderness Class 1 Airshed	Air quality

process at a later stage only when addressing unacceptable impacts. These other planning issues and objectives are addressed in a reactive mode, as opposed to the proactive mode of the IAM–MATA attempted during the Trapper Bunkhouse project and proposed here.

Step 2

Develop an IAM framework by translating management objectives into quantitative and qualitative metrics.

Metrics that measure achievement of objectives are selected by the interdisciplinary team members and stakeholders. The selection of metrics is done with consideration of the appropriate conceptual or numeric models for evaluating or computing progress towards objectives. Selected metrics may be the result of very simple rules developed from research and expert opinion or they can be computed by sophisticated computer programs. Several criteria important to model selection include data availability, modelling expertise availability, and the professional and social acceptance of selected models.

Model choice can be done by asking important questions and comparing options. The following are important questions to ask during the design of each IAM. Is the model appropriate for the intended application? Does it answer the questions asked or represent the phenomenon relevant to an objective? Is it applicable in the given environment? Are there sufficient data available for model application? What are the assumptions and limitations of the modelling systems and data choices? Can critical epistemic uncertainties be reduced in the short term through further research or data collection? How significant will consequences be if either the assumptions or the limitations are exceeded? Does variability significantly compromise confidence in the trade-off analysis of outcomes for the proposed alternatives? In other words, does the uncertainty regarding representation of the current or no-action scenario overwhelm the variability in model predictions associated with alternatives such that model predictions are not enlightening? These questions should be asked during the design of each IAM to ensure adequate yet parsimonious model selection.

There may be multiple ways of measuring achievement of any selected objective. Consider, as an example, an objective to reduce undesirable fire behaviour by implementing forest fuel treatments. A simple measure of achievement is area treated, but this metric provides little information about the effectiveness of those treatments. Another option is to select modelled expectations of fire behaviour modification for the area treated, such as the crowning or torching indices (Scott and Reinhardt 2001), which predict the effect of treatments on fire behaviour for the area on which treatments are proposed, but which provide little information regarding fire behaviour modification at the landscape scale. Another option is to use landscape-level fire behaviour modelling (e.g. the FlamMap suite of models: Minimum Travel Time, Treatment Optimisation Model (Finney 2006)), probability-based fire spread models (e.g. RANDIG (Ager *et al.* 2006)), or disturbance simulation models (e.g. SIMPPLLE (Chew *et al.* 2004)) to predict the frequency, intensity, and location of fire on both treated and untreated portions of the landscape. These modelled metrics incorporate the spatial location of treatment and the expected effects of those treatments on the spatial probabilities of fire and its effects on the landscape.

Multiple metrics may be necessary to adequately represent different aspects of fire and fuel objectives, as well as other integrated objectives. The metrics selected to reflect trade-offs for achievement of the objectives for the Trapper Bunkhouse Project are presented later in the first three columns of Table 2.

For example, expected improvement under the fire and hazardous fuel objective 'Reduce size of areas where stand-replacing and uncontrollable fires are likely to occur', was tracked using three metrics (net area of decreased fireline intensity (A_1), area of decreased fire severity (A_2), and hours for fire arrival (A_3)) based on FARSITE, Fire and Fuels Extension to the Forest Vegetation Simulator (FVS-FFE, available at http://www.fs.fed.us/fmsc/fvs/description/ffe-fvs.shtml, accessed 20 July 2010) and Minimum Travel Time modelling respectively. Similarly, expected improvements under the fisheries and wildlife objectives for the Trapper Bunkhouse Project (Table 1, D and F) were tracked using multiple metrics (eliminate or improve man-made barriers to allow aquatic species passage, counted for each alternative (D_1), maintain old growth (F_1), and maintain elk habitat (F_2)).

Some decision tools such as PROMENTHEE and GAIA (Brans and Mareschal 1994) require all metrics be numeric for optimisation computations. The non-market aspects of public lands management may make numeric rating impractical in some cases. Other decision-support systems use various logic functions to score metrics representing statements based on degrees of validity. When limited resources constrain options, simple quantitative or qualitative metrics are an option. Despite the fact that estimating ranges *v.* point estimates complicates the calculation of trade-offs at the margin, this may be superior when modelling outputs are ranges, adjusting key parameters leads to different results, or stochastic model output variance is high.

Agency-wide use of standard metrics might facilitate analysis at geographic levels greater than individual projects or land jurisdictions. However, while the addition of new or tailor-made metrics for projects might inhibit larger-scale analysis, the need to respond to specific concerns raised by stakeholders and partners may override this concern.

The selection of metrics will no doubt improve as interdisciplinary teams gain experience in this IAM–MATA process. The challenge of selecting appropriate metrics cannot, of course, be clearly separated from challenges of understanding the complex systems of interest or the assumptions and limitations of the modelling tools used. To the extent possible, metrics should be capable of detecting changes that result from management activities and free of confounding background trends that complicate interpretation.

Step 3

Define the basis for the MATA of alternative management scenarios.

To complete this step, the planning team must develop a format for displaying trade-offs among the metrics describing the no-action alternative and active management alternatives. This step has two main components: (1) deciding the platform for comparison between the no-action and the action alternatives, and (2) weighting the relative importance of the various objectives. This MATA platform is important because it provides a mechanism for evaluating and communicating the trade-offs among the planning team members, partners, stakeholders, decision-makers and the public. At a minimum, we suggest a performance report that compares the metrics selected in Step 2 as measures of achieving the project objectives across the management alternatives, including the no-action alternative. Table 2 presents the performance report for the Trapper Bunkhouse Project. This report directly reflects the project 'purpose and need' and can explicitly document the expected positive and negative resource effects, the financial feasibility, and any other social effects that have been analysed. If no-action and action alternatives vary with regards to temporal effectiveness, the expected duration of these effects may be highlighted by reporting metrics for multiple years. Supplemental charts, graphs or other visualisations can be used to isolate and illuminate key quantitative trade-offs. Categorical reporting in combination with interpretive narrative can be used in documents to compare differences between alternatives.

Weighting objectives can help decision-makers select alternatives when no alternative is clearly superior to other alternatives for all objectives. The interdisciplinary team may want to heavily weight the importance of meeting mandatory or desirable thresholds (e.g. 24-h maximum downwind smoke emission threshold) or avoiding highly undesirable outcomes. Discussions needed to support this step can help decision-makers, team members, partners and the public understand the legal, political and social merit each specialist feels drives the proper weighting of each resource objective and metric. It may be easier for the team and stakeholders to reach agreement regarding the merits of the various weighting options when weights are established before any modelling is completed. Although the metrics were not formally weighted in the Trapper Bunkhouse Project, in Table 2 we present example weights based on our interpretation of the decision rationale found in the Record of Decision document (USDA Forest Service 2008).

Weighting can be used to evaluate trade-offs and to communicate the relative emphasis of the multiple objectives to team members and stakeholders. However, if weighting proves excessively contentious, MATA can proceed in a less explicit manner without assigned weights or with multiple weighting schemes. Other options are to run sensitivity analyses as part of the MATA to see how sensitive alternative selection is to weights, or to assess uncertainty of decision scores by synthesising an uncertainty measure on the priority score over all attributes.

Step 4

Build and run component models for baseline (no-action) scenario.

The metric values computed for the no-action alternative document the current conditions and predict how these conditions are expected to change. These conditions underlie the management issues and resulting project objectives, providing a baseline for comparison between the treatment alternatives revealing the expected effectiveness of the proposed activities

Table 2. Trapper Bunkhouse Land Stewardship Project IAM–MATA (integrated assessment modelling–multiple attribute trade-off analysis) performance and trade-off report

CFF, 100 cubic feet (volume estimate); $PM_{2.5}$, particulate matter with an aerodynamic diameter up to 2.5 μm

Objective	Weight (%)	Metrics	Alternative 1	Alternative 2	Alternative 3	Alternative 4
A_1	5	Fireline intensity (net area of decreased fireline intensity) (ha)	0	414	988	818
A_2	5	Fire type (decrease of fire severity area) (ha)	0	104	190	149
A_3	4	Fire arrival time (hours from wilderness ignition with SW wind)	96	95	99	97
B_1	15	Area treated to improve resiliency (ha)	0	1421	1049	1789
C_1	5	Sediment delivery decrease over existing levels (%)	0%	19%	19%	19%
C_2	2	Upgrade high-priority roads with best management practice (km)	0	9.7	9.7	9.7
C_3	3	High-priority road decommissioned, relocated, stored, or seasonally closed (km)	0	11.9	11.9	11.9
C_4	4	High priority crossings eliminated or improved that reduce sediment (*n*)	0	14	14	14
D_1	4	Man-made barriers eliminated or improved to allow aquatic species passage (*n*)	0	5	5	5
E_1	4	Detrimental soil disturbance from ground-based harvesting (ha)	0	32	32	45
F_1	2	Maintain old growth (percentage decrease)	0	0	0	0
F_2	2	Maintain elk habitat (miles of seasonal and year-long elk habitat road closures)	0	23.2	23.2	23.2
G_1	1	Adverse effects on sensitive plants (count of species that may be impacted) (*n*)	0	7	7	7
H_1	2	Potential for spreading noxious weeds (Low, L; Moderate, M; High, H)	L–M	H	H	H^+
I_1	1	Potential for direct adverse effects on heritage sites (Yes, Y; No, N)	N	Y	Y	Y
J_1	1	Increase in cross-country travel (Yes, Y; No, N)	N	Y	Y	Y
J_2	1	Displace dispersed recreation (Yes, Y; No, N)	N	Y	Y	Y
J_3	1	Direct effects on wilderness characteristics (Yes, Y; No, N)	N	N	N	N
K_1	2	Meet visual quality objectives (Yes, Y; No, N)	Y	Y	Y	Y
L_1	5	Volume harvested (m^3)	0	23 786	24 256	32 176
L_2	20	Revenue available (advertised rate multiplied by volume, thousands of dollars)	0	261.1	271.4	356.7
L_3	10	Labour income (thousands of dollars)	0	3135.6	3069.7	4497.4
M_1	1	24-h maximum downwind smoke emissions from treatments measured in $PM_{2.5}$ ($\mu g\,m^{-3}$)	0	≤ 35	≤ 35	≤ 35

in achieving the stated objectives. Values for each of the metrics in Table 2 were estimated. Some of the results presented in the Final Environmental Impact Statement are also reported in Table 2 (which also reports metric values for action alternatives accomplished during Step 5). For example, using the Minimum Travel Time (Finney 2006) model, fire arrival times at specified locations were estimated for several wind scenarios under the no-action alternative. Fireline intensities and fire types were also predicted for the no-action alternative across the planning area. For many of the metrics, null values are reported for the no-action alternative owing to inactivity. These figures serve as the baseline for comparison of potential changes among all alternatives in Table 2.

Step 5

Build alternative management scenarios and conduct the analysis to evaluate resource trade-offs across management alternatives with iterative refinement of a preferred alternative.

Once Steps 1–4 are complete, it is then appropriate for planning teams to consider various treatments and activities suitable to meet objectives, and then package sets of locations and levels for these activities into several action alternatives. Table 3 describes activity levels for each of the Trapper Bunkhouse alternatives. Designing alternatives can be guided by team member knowledge and experience, research, and input from partners and the public. One strategy for building alternatives is to first look for treatments that achieve more than one objective simultaneously. Consider the following examples from the Trapper Bunkhouse Project:

- Removing ladder fuels to reduce the potential for extreme fire behaviour could also reduce moisture and nutrient competition for the larger trees, promoting stand health and resistance to insects. Road maintenance upgrades on timber haul routes can reduce sediment delivery to fish-bearing streams.
- Revenues from timber harvesting to reduce stand density within insect-infested areas could help fund stream restoration projects.

Conversely, activities designed to meet one or more objectives might directly conflict with other resource objectives. For example, mechanical activity to reduce hazardous forest fuels could increase soil disturbance, adversely affecting wildlife habitat and aesthetics through the spread of invasive weeds. Once the activities that meet multiple objectives are considered, then teams identify other treatments that are effective at addressing single goals, especially goals not addressed by the multiple-objective treatments. For example, fish passage improvements to otherwise adequate drainage structures may only serve to attain one objective. After the activity list of effective treatments is identified, then it is a matter of analysing where and how much to treat. The challenge of an integrated process is to define resource relationships sufficiently to illuminate benefits, costs, and trade-offs within the modelling environment before alternative selection and implementation.

Different combinations of desired outcomes become the basis for developing various alternatives emphasising a particular mix of resource objectives. Alternatives can be developed iteratively by posing options, computing the effects, and modifying alternatives to adjust proposed activities to derive effects

Table 3. Trapper Bunkhouse Land Stewardship Project comparison of activities

Activities	Alternative			
	1	2	3	4
Total number of treatment units	0	112	34	121
Acres of treatment in wildland–urban interface (percentage of total acres treated)	0	1739 (91%)	1450 (91%)	2182 (93%)
Proposed treatment in hectares (percentage of total area treated)				
Aspen treatments (ha)	0	10 (1%)	0 (0%)	10 (<1%)
Commercial thin (ha)	0	765 (40%)	880 (55%)	1048 (44%)
Fire salvage harvest (ha)	0	76 (4%)	0 (0%)	76 (3%)
Maintenance burn (ha)	0	236 (12%)	236 (15%)	227 (10%)
Prescribed burn (ha)	0	217 (11%)	287 (18%)	301 (13%)
Small tree thin (ha)	0	94 (5%)	84 (5%)	94 (4%)
Small tree thin plantation (ha)	0	485 (25%)	0 (0%)	485 (21%)
Slashing (ha)	0	6 (<1%)	85 (5%)	91 (3%)
Sanitation and salvage (ha)	0	17 (1%)	17 (1%)	17 (1%)
Research control (ha)	0	8 (<1%)	8 (1%)	8 (<1%)
Total area treated (ha)	0	1915	1598	2358
Total commercial treatments (ha)	0	858 (45%)	896 (56%)	1141 (48%)
Total non-commercial treatments (ha)	0	1057 (55%)	701 (44%)	1217 (52%)
Other restoration work				
Temporary road construction (km)	0	4.3	1.1	4.5
Road decommissioning (km)	0	11.9[A]	11.9[A]	11.9[A]
Watershed mitigation (km)	0	9.7[B]	9.7[B]	9.7[B]
All road closures, seasonal and year-long (km)	0	34.4	34.4	34.4
Future maintenance burns (km)	0	1004	1338	1448

[A]Roads will be decommissioned as funds become available.

[B]Tied to commercial timber harvests. If commercial timber treatments are implemented, this watershed work will be accomplished.

at the desired levels. This process can continue until the users believe they have reached a spatial and temporal schedule of fuel treatments and other management activities that most effectively meet multiple objectives. Modelling alternative configurations of treatments often strengthens the feasibility and quality of each management alternative identified. Analysts may consider easy-to-compute proxies in lieu of running time-consuming models in the iterative alternative phase, but analysts should consider running the resource models once an alternative has been finalised to compute the metric trade-offs among the alternatives. Existing decision-support systems can automate a coordinated process of modelling incremental changes to the various alternatives making changes to all the selected models, revealing the impacts on all metrics.

The evaluation platform selected in Step 4 is applied to evaluate the trade-offs across alternatives. Selected metric values for the Trapper Bunkhouse Project are shown for the no-action and three action alternatives in Table 2, under Alternatives 1, 2, 3, and 4. In the Trapper Bunkhouse case, there are substantial differences among alternatives in the total treatment area ranging from 3948 to 5827 acres (1598–2358 ha) (Table 3). Among alternatives, area of decreased fireline intensity, fire type, and fire arrival time (Table 2, A_1, A_2, A_3) are all improved the most following treatment under Alternative 3. Contrary to this, area treated to improve resiliency (B_1), available revenue to fund restoration activities (L_2), and projected labour income (L_3) are highest following treatment under Alternative 4. Although this increased treatment volume comes at a cost of increased detrimental soil disturbance (E_1) and higher potential to spread noxious weeds (H_1), there appears to be little difference among all three action alternatives for expected sediment delivery (C_1), adverse impacts to sensitive plants (G_1), wildlife habitat (F_1, F_2), visual (K_1) or recreation impacts (J_2). Although alternative selection appears to make little or no difference for many of the project objectives, it does make a substantial difference for the fire behaviour and economic contributions. Although the purpose and need for this project area emphasises desire to reduce risk from uncontrollable fires, the desire to improve resiliency to insects and disease and availability of revenue to fund restoration work override fire management objectives in the Record of Decision (USDA Forest Service 2008). Therefore, we have weighted these objectives accordingly, *ex post facto*, in Table 2.

Once the MATA is built, the decision-maker has good information on which to base a decision. The intent of integrating assessment across multiple resource areas is not to produce an automated decision selection process. In most cases, the decision-maker will need to expend time and effort evaluating the trade-offs of the various alternatives, using discretion and judgment to make a selection. The more agreement exists regarding the framework for the MATA, the easier the selection. Notice from Table 2 that there is no alternative superior with regard to all metrics. However, when weights reflecting the decision rationale in the Record of Decision are considered, Alternative 4 emerges as the preferred alternative, illustrating the value of the second portion of Step 5. When larger, more complex projects are planned, more complicated MATA techniques relying on decision-support tools (e.g. Analytic Hierarchy Process (AHP) or Multi-Criteria Decision Making (MCDM) approaches) may be appropriate.

Challenges to the proposed project planning process

Several common challenges that need to be addressed for successful project planning are described below. Although experience and lessons learned should improve the IAM–MATA process over time, some of these realities plague all planning approaches and are recognised simply to remind the reader that they must be handled.

Uncertainty

Integrated assessment modelling allows a planning team to test and consider multiple courses of action and associated consequences to best inform decisions. Complex systems cannot be perfectly modelled. By its nature, modelling simplifies reality to promote understanding of complex systems. Stochastic uncertainty is inherent in complex natural systems, and therefore, it is a non-reducible factor in scientific analysis and modelling efforts (Refsgaard *et al.* 2007).

Essential modelling simplifications, based on necessary assumptions, can mask complexity and may amplify errors when models representing natural systems are combined into IAM systems. Despite the acknowledged limitations models have, their predictive ability can be a powerful tool for understanding and explaining complex environmental problems. Accounting for modelling uncertainty begins with careful documentation of selection criteria, assumptions and limitations for each model and how these affect the accuracy and uncertainty of predicted outcomes.

Selecting the appropriate planning time horizon

The selection of a planning horizon can strongly influence the comparison of alternatives. This is especially true with hazardous fuel treatments, where the duration of effectiveness varies depending on the vegetation community involved. When temporal variability is substantial across alternatives, efforts to display effectiveness for several intervals may be very useful as part of the MATA platform.

Multiple stakeholder preferences

The disagreement between influential parties when it comes to managing Federal lands is a very important reality in project planning. Although this IAM–MATA approach is by no means an all-encompassing resolution to convert persistent public-lands controversy into successful management, there are several features that can promote effective project planning. First, Step 1 provides an opportunity early in the planning process to incorporate the various concerns of multiple stakeholders. Steps 2 and 3, when done with stakeholder participation, can set up an agreeable decision framework before modelling outputs are revealed in later steps. Step 5, at which alternatives are constructed and refined, is another opportunity to include and test stakeholder ideas with a performance report that links clearly back to Step 1. These opportunities may help address this persistent challenge of managing for multiple preferences.

Institutional resources

Although integrated fuel-treatment planning enhances project design, it can extend the time required to conduct both planning and implementation. What we have proposed will indeed require a commitment of adequate financial and personnel support to carefully plan the future of public lands. Common practical logistics are barriers to implementation including: time, resources, skills, institutional commitment, and the ability of managers and the public with a wide variety of preferences to collaborate.

In some cases, the effort required to build an IAM may not be justifiable based on the scale and complexity of a project. In other cases, the pressure to keep projects simple and focussed (to elevate the probability of expedient implementation) may be stronger than the desire to address multiple management issues with a single project. However, investing resources in building an integrated assessment framework by compiling the data required for IAM operations likely makes sense for large land-management entities or in mixed-ownership landscapes that include private and public owners with different objectives and perspectives, and operating under different sets of agency policies and state and local regulation. When this is done, multiple long-term benefits are expected, including: consistent assessment procedures and documentation; shorter start-up times and lower costs for future projects; and enduring management of analytic models and supporting data. Effective IAM requires well-organised, well-documented data sources. This requirement drives a positive feedback loop through which data sources are developed and improved. Successful IAM approaches will require personnel trained and experienced in IAM implementation. A modelling cadre may be the most efficient and effective approach where dedicated, highly skilled analysts work with local project teams to customise and implement IAM for each project.

Discussion

The IAM–MATA project planning process we propose offers several tangible advantages over the single-objective fuel-treatment planning approaches. These advantages include: focus on multiple objectives from the project outset; appropriate selection of modelling tools with accompanying documentation of uncertainty and limitations; a more transparent and interactive process offering better understanding of ecosystem complexities, as well as stakeholder positions; and clearer articulation of expected decision trade-offs. Collectively, these advantages may improve the quality and support for integrated resource-management projects, potentially enhancing implementation success.

Fire and fuel management is one important driver when the USFS and DOI select project areas. Although the threat of wildland fire damage to life, houses, personal property, community infrastructure and ecological resources may be the focus at the outset of these projects, policy direction, broad-scale assessment and specialists' concerns guide land-management professionals to make numerous concurrent improvements with the same project. This leads to an ecosystem management planning design for many projects. Therefore, strong integration between fuel-treatment planning and public land-management policy throughout the NEPA process is needed for future land management to be successful.

There is policy direction to do fuel treatments, but other legislation and policy described earlier in the Introduction section directs US public lands management for other benefits and uses as well. Considering this broader policy, the opening assessment questions should not be, 'What is the problem fire and how can it be mitigated?' Instead, the user of this process would ask, 'What management actions are warranted to address overall ecosystem and society health, including the need to modify expected fire behaviour with additional consideration of ecological, social, and economic impacts?' The problem we address is how to plan treatments and activities that address multiple objectives. By using this process, justification for land-management actions is made holistically, beyond simply the reduction of hazardous fuel and potentially improved changes to fire behaviour for several years or decades. The IAM–MATA process and performance and trade-off report help generate balanced management alternatives and address a common concern, 'Given the range of possible fire scenarios for the planning horizon (including no fire occurrence), how do the expected benefits (market and non-market) of vegetation and land-management activities compare with the expected costs (market and non-market) for each alternative?'

Success of this holistic management approach basically boils down to land managers' relationships with the public and the best ways to make decisions under a cloud of uncertainty about what the future will bring. Having a realistic attitude about the value of IAM, that it can 'increase understanding of the directions and magnitudes of change under different options' (Jakeman and Letcher 2003, p. 493) is essential for this IAM–MATA process to work. Although IAM does not explain all the interactions of the ecosystem, it can be used as an important tool to provide the best assessment of future conditions and impacts under either no-action or various alternative sets of management activities.

What is considered by some to be the best available science might be considered untested and experimental by others, and is occasionally used as a justification for inaction. In situations where inaction could plausibly result in unacceptable outcomes, we simply cannot afford to defer decisions indefinitely until we possess more perfect knowledge (Beder *et al.* 2005). By clearly framing trade-offs to the best of our ability before decision-making, the decision-maker is providing valuable information showing how they are incorporating various stakeholder positions and values.

Application of the approach proposed here, especially when used within the collaborative working environment of future land management, may increase support for more balanced land-management decisions. This has the potential to improve implementation success rates and reduce time and resources spent in litigation. The informative MATA framework proposed here is flexible enough to be useful in most public land-management decision-making.

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