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Toward Geodesign for Watershed Restoration on the Fremont-Winema National Forest, Pacific Northwest, USA

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Abstract: Spatial decision support systems for forest management have steadily evolved over the past 20+ years in order to better address the complexities of contemporary forest management issues such as the sustainability and resilience of ecosystems on forested landscapes. In this paper, we describe and illustrate new features of the Ecosystem Management Decision Support (EMDS) system that extend the system's traditional support for landscape analysis and strategic planning to include a simple approach to feature-based tactical planning priorities. The study area for this work was the Chewaucan watershed of the Fremont-Winema National Forest, located in south-central Oregon, USA. The analysis of strategic priorities recommended five subwatersheds as being of high priority for restoration activities, based primarily on decision criteria related to the stream accessibility to headwaters and upland condition. Among high priority subwatersheds, the most common tactical action recommended was the removal of artificial barriers to fish passages. Other high priority tactical actions recommended in high priority subwatersheds to improve fish habitats were reducing the road density and restoring riparian vegetation. In the discussion, we conclude by describing how the simple tactical planning methods illustrated in this paper can be extended in EMDS to provide a more sophisticated hybrid approach to strategic and tactical planning that can evaluate alternative portfolios of designed management actions applied across landscapes. The latter planned improvement to decision support capabilities in EMDS encapsulates Carl Steinitz's concept of geodesign.

Keywords: decision support; landscape analysis; logic modeling; strategic planning; tactical planning; multi-criteria decision analysis; forest management; geodesign

1. Introduction

Spatial decision support systems for forest management have steadily evolved over the past 20+ years in order to better address the complexities of contemporary forest management issues such as the sustainability [1] and resilience [2,3] of ecosystems of forested landscapes, drawing on principles of ecosystem management [4] and processes for implementing adaptive management [5,6]. Broad reviews covering the recent developments in contemporary systems have been provided by Reynolds et al. [7], Borges et al. [8], and Vacik et al. [9].

Decision support systems (DSS) for environmental analysis and planning began appearing in the literature in significant numbers from about the mid-1980s. These earlier systems were mostly nonspatial in nature, but this class of system remains common today. Some recent examples of aspatial

DSS in the forest sector include a reforestation system that supports operational planning for tree species selection [10]; a web-based information service that supports the forecasting, diagnosis, and prevention and control of forest pests in cultivated forests [11,12]; a web-based system that supports the application of basic principles for the sustainable management of rural forests [13]; a system promoting management to reduce wildfire damage in lowland pine forests [14]; and a system that uses multi-criteria decision analysis to select the best use of forest resources to promote sustainable forest management [15]. Spatial decision support systems (SDSS) began to emerge in the mid-1990s, with the delay in their debut largely being a function of the need for advances in geographic information systems. One of the earliest SDSS was GEODES (GEOgraphic Decision Expert System), in which geographic data were used to identify favorable (versus less favorable) sites for the establishment of forest in a region [16]. More recent examples of SDSS include an agent-based system for integrating a suite of decision support tools to support multiple forest management objectives [17]; a system to determine cutting intensities and cutting cycles on a landscape scale [18,19]; a system targeted to private forestland owners to guide forest management decisions [20]; a system to estimate ecological security and related issues of environmental protection in land-use decisions [21]; and a land-use planning system with a particular focus on promoting forest carbon sequestration [22].

Among the portfolio of contemporary systems providing spatial decision support for environmental analysis and planning, the Ecosystem Management Decision Support (EMDS) system is one of the oldest [23,24], but it has steadily evolved to provide more comprehensive decision support for forest management [25]. For example, the earliest versions (1997 to 2001) provided spatial decision support for environmental assessment, using a logic-based modeling technology to interpret and synthesize environmental information [26]. However, with version 3 (2002), new functionality was introduced to support strategic planning for forest management (and environmental management more generally), based on multi-criteria decision models (MCDMs) [27]. Moreover, the latest EMDS release (version 5.1, released in August 2016) now provides spatial decision support for tactical planning. The present study illustrates the application of this newest EMDS feature in the context of watershed restoration in the Chewaucan watershed of the Fremont-Winema National Forest in south-central Oregon (Pacific Northwest, USA).

The original assessment of the Chewaucan watershed was conducted by Peets and Friedrichsen [28], and Reynolds and Peets [29] presented an EMDS application for the protection and restoration of the Chewaucan based on the original assessment. The present study extends the original work of Reynolds and Peets with the new tactical analysis feature available in EMDS 5.1. In particular, the overall goal of this work is to demonstrate an integrated, multi-step approach to delivering spatial decision support for forest management in which:

(1) Logic-based assessment is used to first characterize the present state of a forest ecosystem;
(2) Strategic decision models identify high-priority landscape units in need of restoration, considering the assessed state of the system and, optionally, practical logistical issues important to managers in restoration decisions; and
(3) Tactical decision models identify high-priority management activities in high-priority landscape units, given their evaluated state and the modeled efficacy of potential management actions.

In the discussion, we conclude by considering how new decision models that implement designed management actions (geodesign, Steinitz [30]) can build upon the basic tactical decision models by facilitating the design of landscape-scale prescriptions as portfolios of management actions that can be compared and contrasted in terms of their overall effects on improving the landscape condition.

2. Materials and Methods

2.1. Study Area

The Chewaucan watershed is a 10-digit hydrologic unit (HUC) in the national hydrologic hierarchy of the Unites States Geological Survey [31], and is located at the Fremont-Winema National Forest in south-central Oregon (Figure 1). The study area indicated in the figure includes the forested portion of the watershed on National Forest land, and includes nine 12-digit HUCs (subwatersheds), covering an area of about 69,000 ha.

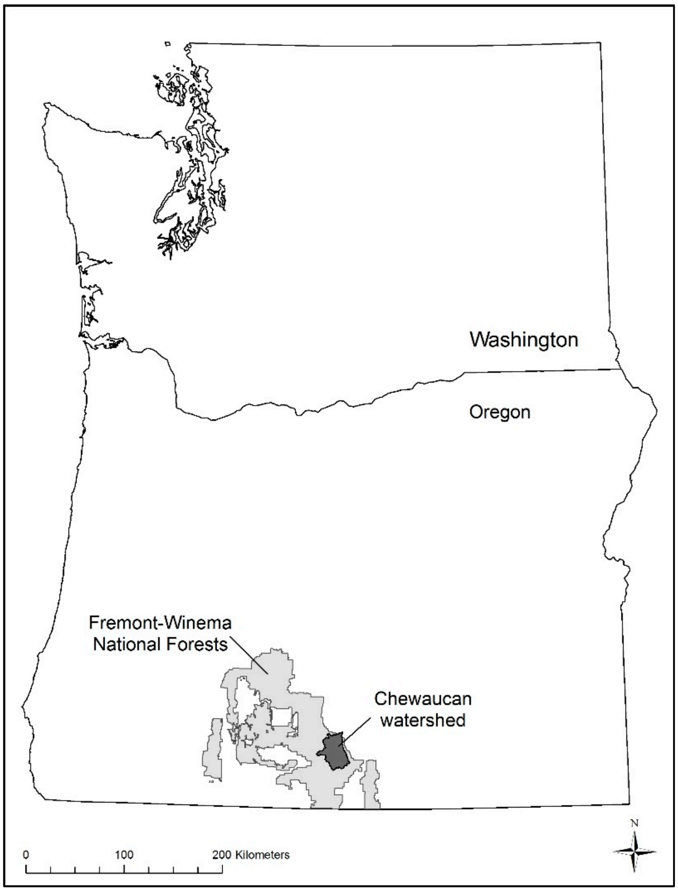

Figure 1. Location of the Chewaucan watershed in south-central Oregon, USA.

The western peaks of the Chewaucan lie to the east of the Cascade Range, which lifts the maritime air masses that move eastward from the Pacific Ocean. The watershed stands in the rain shadow of the Cascades, receiving about 40–90 cm of precipitation annually, depending on the elevation. Most precipitation falls as snow, with the highest elevations receiving the greatest depths [28]. Temperatures across the watershed range from −20 °C at higher elevations in winter to 38 °C at lower elevations in summer. Ponderosa pine is the dominant forest cover type across the watershed, but with juniper and sagebrush along the dry slopes to the east of the Chewaucan River, and with white fir and lodgepole pine forests occurring in the upper elevations.

Lying to the east of the Cascade Range, our study area belongs to the larger geographic region of the interior western U.S. To provide some context for the analyses presented subsequently, here we discuss the ecological transformation of the interior west that followed Euro-American settlement, beginning in the mid-19th century. Although these observations are broadly applicable to the larger region, they are also very relevant to our particular study area. With settlement, came land clearing and the expansion of agriculture, timber harvesting, and early attempts at wildfire suppression, which were highly effective after the 10 a.m. rule was enacted as federal policy between 1934 and 1935 [32,33]. This policy of suppression significantly altered the role of wildfire, especially as it applied to primeval landscapes of the region. The rule was formally removed in the early 1970s, but aggressive wildfire suppression is still practiced.

Natural variability in wildfire frequency, duration, severity, seasonality, and extent were subsequently transformed by decades of fire exclusion and wildfire suppression. Wildfire exclusion by cattle grazing, road construction, wildfire prevention, and suppression policies, and industrial-strength selective logging, beginning in the 1930s and continuing for more than 50 years, contributed not only to the extensive alteration of natural wildfire regimes, but also to forest insect and pathogen disturbance regimes, causing them to shift significantly from historical analogues. For example, the duration, severity, and extent of conifer defoliator and bark beetle outbreaks increased substantially [34], becoming more chronic and devastating to timber and habitat resources [35].

Selective logging steadily accelerated during and after the Second World War. Fire exclusion and selective logging advanced the seral status and reduced the fire tolerance of affected forests with the removal of large, thick-barked, old trees of the most fire-tolerant species [36]. It increased the density and layering of the forests that remained because selection cutting favored the regeneration and release of shade-tolerant and fire-intolerant tree species [37]. Recent warming and drying of the regional climate has exacerbated these changes [38–40]. Changes from the pre-settlement era variability of structural and compositional conditions also affected regional landscapes. Prior to the era of settlement, regional landscape resilience to wildfires naturally derived from mosaics of previously burned and recovering vegetation patches from prior wildfire events, and a predictable distribution of prior fire-event sizes [41]. This resilience yielded a finite and semi-predictable array of pattern conditions [42–45].

In summary, the ecological transformations accompanying the Euro-American settlement of the region substantially altered its ecological resilience [2,3], creating risks to ecosystem sustainability [1].

2.2. Data Sources

All data used in the present study were originally assembled by Peets and Friedrichsen [28]. Descriptions of the specific data elements from the original assessment, and used in the present study, are included in Table 1.

Table 1. Topic outline [1] of the NetWeaver logic model for evaluating the watershed condition of the Chewaucan watershed.

Topic Name	Datum Evaluated or Logic Operation
Watershed condition	Fuzzy AND
Upland condition	UNION
Upland cover	Fuzzy AND
Canopy density	Percent area of forest communities with canopy densities within historic range of variation.
Seral openings	Percent area of forest cover in young seral stage.
Road density	Kilometers of road per square kilometer of subwatershed area.
Stream crossings	Road crossings per kilometer of stream length in a subwatershed.
Stream access	Percent of total stream length in the watershed that is accessible to fish.
Stream condition	Fuzzy AND
Reach condition	Length-weighted average of reach condition indices from logic model that evaluates stream reaches.
Spawning fines	Percent spawning habitat composed of sand or silt.
Water temperature	Maximum 7-day running average water temperature over the summer (degrees F).

[1] The outline form of the logic model is a simplified view of the full logic specification. Complete HTML documentation of the logic is noted in the supplementary materials.

2.3. Overview of the EMDS System

EMDS version 5.1 is a spatially enabled decision support system for integrated landscape evaluation and planning. The system provides decision support for landscape-level analyses through logic and decision engines integrated with the ArcGIS1 10.x geographic information system (GIS, Environmental Systems Research Institute, Redlands, CA, USA). (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.) The NetWeaver logic engine (Rules of Thumb, Inc., North East, PA, USA) evaluates landscape data against a formal logic specification (e.g., a knowledge base in the strict sense) designed in the NetWeaver Developer System, to derive logic-based interpretations of ecosystem conditions such as landscape integrity or landscape resilience. The decision engine evaluates the NetWeaver outcomes, as well as data related to the feasibility and efficacy of land management actions, against a decision model for prioritizing landscape features built with its development system, Criterium DecisionPlus (CDP, InfoHarvest, Seattle, WA, USA). CDP models implement the analytical hierarchy process (AHP) [46], the simple multi-attribute rating technique (SMART) [47], or a combination of the AHP and SMART methods.

The NetWeaver engine, used in the evaluation phase of an EMDS project, interprets data and synthesizes information, given the formal specification of a logic model. A logic model can be thought of as a network of networks (i.e., it is structurally recursive). Each network evaluates a proposition relevant to some topic of interest (e.g., landscape integrity). The formal specification of a network is represented by (1) a set of premises, and (2) one or more logic operators that specify how the premises logically combine to contribute evidence to the proposition associated with the network (Table 1). The recursive nature of a logic model stems from the fact that the premises in a network specification are themselves networks. Terminal networks in the recursive structure can be thought of as elementary networks that interpret data, typically by means of fuzzy membership functions [26] that translate the observed value of a data input into a measure that expresses the strength of the evidence for the proposition being evaluated (Table 1). When a logic model is processed by the logic engine, the strength of evidence values that originate in the elementary networks propagate upward through the network architecture, so the strength of evidence is the key metric associated with all networks in a logic model.

The CDP engine, used in the planning phase of an EMDS project, supports both the strategic and tactical planning of EMDS 5.1. Whereas strategic planning is used to identify *which landscape units* are a priority for a management activity such as restoration, tactical planning is used to select *which management actions* are a priority in any particular landscape unit. Above, we mentioned that decision models for selecting among alternatives typically include logistical considerations, by which we mean additional information that is important to managers when selecting among alternatives. Logistical considerations are relevant to both strategic and tactical decisions. For example, when selecting land units for management activities in the strategic context, the land-type designation can be highly relevant because not all units are necessarily appropriate to consider for management (e.g., wilderness areas). Similarly, when selecting among alternative management actions to apply in the tactical context, cost may be an important consideration.

Finally, in the specific context of spatial decision support for landscape restoration, tactical decision models have the specific role of recommending management actions that are intended to improve the conditions in individual landscape units. Although there is no a priori structure for this type of model, a general architecture designed to evaluate the efficacy of management actions in response to the presence of stressors and associated threats is suggested below in Section 2.4.3. Restoration actions in this context can be understood as improving ecosystem resilience, and thus promoting ecosystem sustainability.

2.4. Analysis Process in EMDS

In the introduction, we described the decision support process for restoration planning in the Chewaucan watershed (Fremont National Forest) as a three-step process. In each of the following four subsections, we:

(1) present some conceptual background on the analytical step in the EMDS context,
(2) describe the design of the model(s) used in the analytical step, and
(3) discuss how the products of the analytical step provide a foundation or context for the subsequent step in order to produce an integrated decision support application for landscape analysis and planning.

Step 3, in particular, is addressed in the following subsections in order to make the reasoning behind the architecture of our decision support application as explicit as possible.

2.4.1. Logic-Based Landscape Assessment

In the first step of the decision support process, we begin with an assessment of the landscape condition, using NetWeaver Developer [26] to provide a logic-based interpretation and synthesis of landscape data. NetWeaver solutions have been an integral part of EMDS applications from the origins of the system because contemporary problems in spatial decision support for environmental analysis and planning are typically high dimensional, complex, and abstract. Logic-based solutions are particularly useful in this context because, to put it simply, with logic, if one can reason about the state of the system under study, one can model it [48].

The logic used for the assessment of the watershed condition is presented in outline form (Table 1). Each topic in the outline is represented by a network in NetWeaver that evaluates the strength of evidence for the logical proposition being tested by the network. Generically, the proposition associated with each topic in the table is testing that the conditions associated with a specific topic contribute to a suitable habitat for anadromous fish. For example, the topic, watershed condition, tests the proposition that the overall watershed condition provides a suitable habitat. In the table, the outline indicates that the immediate logical premises of the watershed condition are the upland condition, stream access, and stream condition. Given the fuzzy logic AND operator in the logic specification for the watershed condition, we can say that the watershed condition is suitable for fish habitats to the degree that the upland condition, stream access, and stream condition are suitable. Similarly, the immediate logical premises supporting the upland condition are the upland cover and road density.

The logic operators, AND and UNION, provide the specifications for how evidence from the premises (child networks) is synthesized by the parent network. Specifically, AND indicates that the premises are limiting factors, in which the factor contributing the least evidence strongly conditions the resulting evidence of the parent network. In contrast, UNION treats the premises as incrementally contributing evidence to the parent network, with the effect that the premises may compensate for one another. The lowest level topics in the outline (Table 1) are elementary networks in the sense that they read and interpret data based on fuzzy membership functions (Table 2).

Table 2. Parameters defining fuzzy membership functions for interpreting data inputs in Table 1.

Data Input	Parameter Value Indicating No Evidence [1]	Parameter Value Indicating Full Evidence
Canopy density	50	100
Seral openings	15	30
Road density	4.7	1.6
Reach condition [2]	−1	1
Stream crossings	0.5	0.1
Spawning fines [3]	25th percentile	75th percentile
Water temperature	23.89	17.78

Notes: [1] Units for parameters are defined in Table 1. Together, the two parameters for a data input define the shape of the fuzzy membership function as a ramp. Values ≤ the no-evidence parameter provide no evidence. Values ≥ the full-evidence value provide full evidence. Intermediate values provide partial evidence. [2] Reach condition is a NetWeaver metric from a finer scale analysis of stream reaches. [3] Percentiles are calculated as a function of stream channel morphology.

Summary information from a NetWeaver analysis is commonly used in strategic decision models because ecosystem states are usually important decision criteria for restoration decisions. In providing information to the strategic decision modeling step, NetWeaver is basically functioning as a preprocessor. Two compelling reasons for preprocessing landscape data are (1) to distill down high-dimensional landscape data which allows the design of a smaller and simpler decision model, and (2) to handle any complex or nonlinear relations between data inputs which cannot be adequately modeled in decision models that are intrinsically linear.

2.4.2. Strategic Priorities for Restoration

In the EMDS context of spatial decision support for landscape restoration, and given the evaluated state of the study system, strategic decision models answer the question, *where* are the high priority landscape units in the study area? As discussed in the previous section, the state of the system is an important consideration, but many other logistical considerations may also be important to resource managers in making optimal choices about where to target restoration work. For example, issues related to time, cost, feasibility, efficacy, efficiency, social acceptability, performance, etc., may all be factors that are important to managers, and influence the priorities, but these logistical considerations are not relevant to inferences concerning the current state of the system. In EMDS versions 3 to 5, these types of logistical considerations were addressed in strategic decision models. However, with the introduction of decision models for designed management actions (DMAs) into the decision support workflow presented here, there are advantages to deferring a consideration of the logistical issues until step 4 in the workflow. In particular, logistical issues in a strategic decision model often need to be modeled rather abstractly, whereas the explicit modeling of actions in the model for DMAs means that logistical considerations can be explicitly tied to specific actions. For example, specific actions may have well-defined costs.

EMDS uses the MCDM decision engine of Criterium DecisionPlus (CDP, InfoHarvest, Inc., Seattle, WA, USA) to evaluate strategic priorities [27]. Deferring the consideration of logistics, the strategic decision model for the Chewaucan becomes very simple (Figure 2). The overall goal of the model is to prioritize the subwatersheds of the Chewaucan watershed. The primary criteria represent the summary information summarized from the logic model (Table 1). Weights on the criteria at the goal level represent the importance of each criterion with respect to system function from a resource manager's perspective. For the purposes of this study, all criteria weights were set to 1 (e.g., equally weighted), but in practice, these would be determined by resource managers. In the context of strategic models in EMDS, the landscape features (subwatersheds in our case) represent the spatial alternatives to be prioritized.

Feature 1 in the model is simply a placeholder. The actual set of subwatersheds evaluated by the model are "wired" into the model at runtime. In this very simple model, the decision criteria also represent the attributes of the subwatersheds (Figure 2). The attribute values are the evidence metrics computed by NetWeaver. At the attribute level of the model, each attribute applies a utility function to its attribute value to normalize the input to a [0, 1] scale [27]. Each of the attribute inputs to the model initially has a NetWeaver's [−1, 1] evidence metric, so the utility function maps the evidence metric into a CDP's utility metric. In the mapping process, the scale is inverted so that the evidence value of −1 maps to a utility of 1. In other words, in the context of a restoration problem, the lowest value of the NetWeaver outcome has the highest utility for restoration.

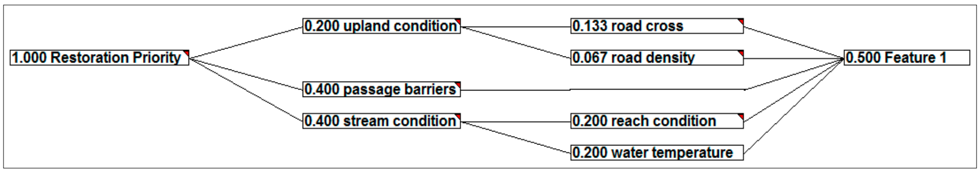

Figure 2. Strategic decision model for prioritizing subwatersheds for restoration.

The analysis of strategic priorities is useful as a precursor to analyses of tactical priorities or DMAs, especially when the study area contains a large number of landscape elements. Typically, restoration actions are time consuming and expensive, so the number of units that might realistically be treated in, say, the next 5 to 10 years might be only 10 percent of the total units. Given this reality, a strategic focus on high priority units provides an efficient path for implementing a long term restoration program. In the present study, the Chewaucan only contains nine subwatershed polygons, so the strategic prioritization step is not particularly important with respect to determining tactical priorities. However, as we show in Section 2.4.3, the strategic decision model is also a foundation for the decision model for DMAs, so the strategic model is presented here for completeness.

2.4.3. Tactical Priorities for Restoration Actions

Returning to the EMDS context of spatial decision support for landscape restoration, tactical decision support addresses the question, *which* types of potential management actions are the highest priority in a particular landscape unit, given the state of the unit, and the managers' knowledge of the efficacy of specific management actions in responding to specific ecosystem stressors and threats?

The decision model for computing the effectiveness of tactical actions is a CDP model formulated in terms of restoration actions, stressors, and threats (Figure 3). At the goal level, the weights assigned to the restoration actions would normally be used to reflect the relative importance of the threat-stressor pair that the action works on to improve the overall impairment in the study area (e.g., the "fish habitat" in this example). In the general case, at the level of restoration actions, weights reflect the effectiveness of an action in addressing a stressor, while at the stressor level of the model, weights on threats express the relative contribution of a threat to a stressor. For the model structure below, these lower weights are normalized to 1. Weights in our tactical model (Figure 3) were developed by the senior author, based on 19 years of experience with designing decision support systems for watershed assessment, but ideally, in practice, these weights would be collaboratively developed by a team of scientists and managers involved in watershed restoration. Finally, the utility values of each threat express the strength of evidence of the observed threat in each landscape unit (sub watershed) based on either direct observations or as interpreted by the NW model.

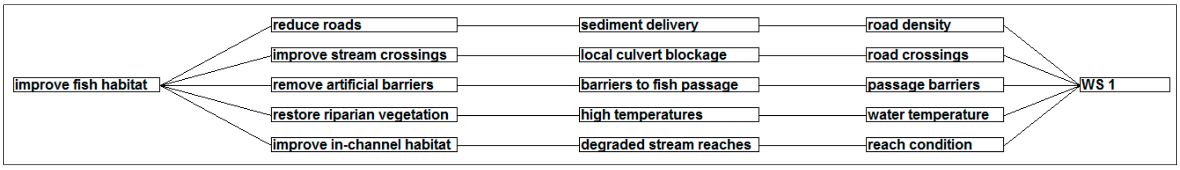

Figure 3. CDP tactical decision model for computing the effectiveness of tactical actions. Weights on stressors at the level of restoration action express the percent efficacy of the action on the stressor. Weights on threats at the stressor level express the relative contribution of a threat on a stressor. Each threat has a utility function that expresses the strength of the threat.

Unlike the previous two subsections in which the logic-processing phase sets the context for, and provides information to, the strategic planning step, the relation between tactical decisions, as described in this section, and decision support for DMAs, as described later in the discussion, is less direct and more informal. Indeed, when proceeding through the decision support process beyond strategic planning, users of the application might choose to implement tactical planning, or DMAs, or both. We return to this topic in the later discussion of DMAs.

Our model for evaluating tactical actions in the Chewaucan case (Figure 3) is unusually simple in that there is always a one-to-way relation between the management actions and stressors, and similarly, there is always a one-to-one relation between the stressors and threats for this particular example. However, in the more general case, a specific action might be relevant to multiple stressors, and multiple threats might contribute to a single stressor. A further simplification in our example is that the importance of the management actions is assumed to be equal with respect to their contribution to improving the fish habitat. Considering the many-to-one relations and the differential contributions of management actions addresses some, but not necessarily all, of the concerns related to the intrinsic linearity of MCDMs. Ultimately, the priorities for management actions therefore need to be regarded as a first approximation. The more surgical approach of DMAs, described in the discussion, further overcomes some of the problems of a nonlinear system response related to the interaction effects among management actions.

3. Results

3.1. Logic-Based Landscape Assessment

EMDS can produce maps for the evaluated state of all logic topics in an assessment area (Table 1), but here we present just a subset of the major map products (Figure 4). In the following discussion, we translate the NetWeaver's evidence metric into a more direct expression of the condition. Seven of the nine subwatersheds of the Chewaucan watershed were evaluated as being in very poor condition, while two were evaluated as poor (Figure 4A). With respect to the upland condition (Figure 4B), three of the four northern subwatersheds were evaluated as being in poor condition (low), whereas three of the five most southerly subwatersheds were evaluated as being in very poor condition. Stream accessibility for fish was very good in the lower portion of the stream network, but nearly uniformly very poor in the upper portion of the stream network (Figure 4C). The most variability among subwatersheds occurred in the context of the stream reach condition, which varied from very poor to good (Figure 4D).

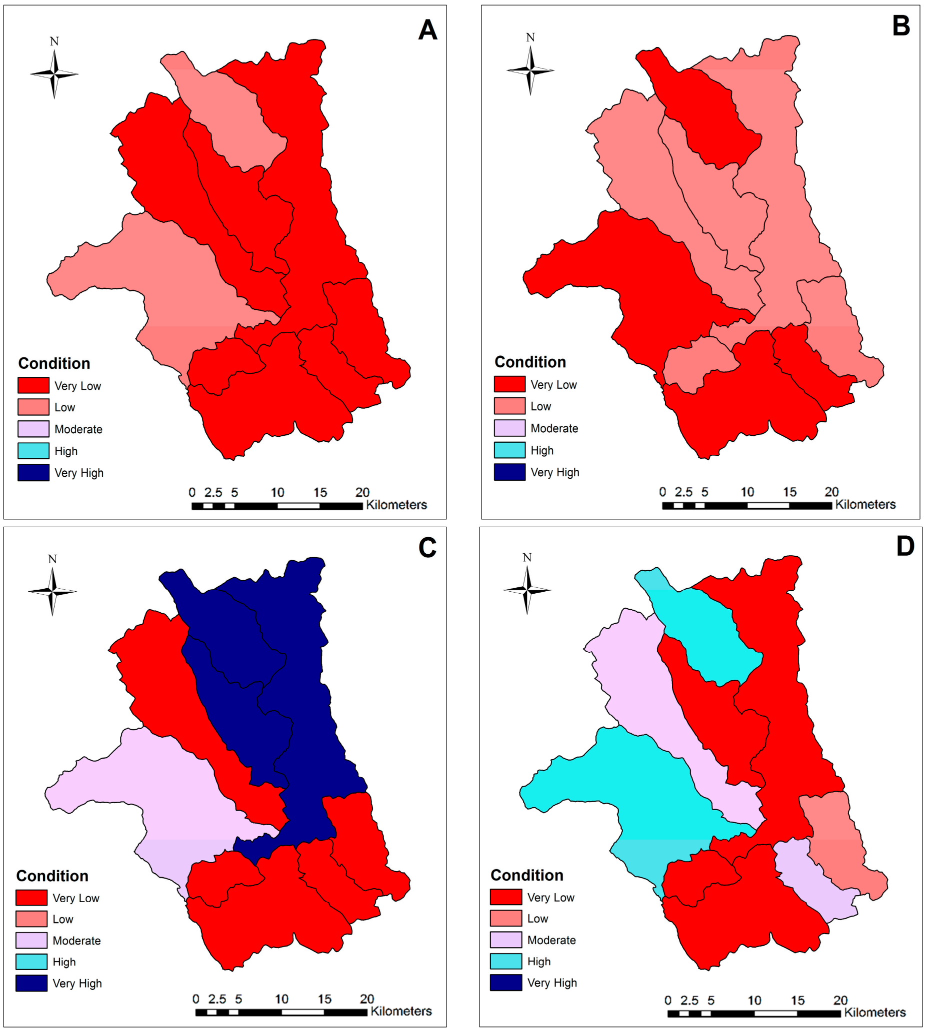

Figure 4. Selected results from the assessment of the watershed condition in the Chewaucan watershed. (**A**) overall watershed condition; (**B**) upland condition; (**C**) stream accessibility for fish; (**D**) stream reach condition. NetWeaver evidence metrics have been translated into a more direct expression of condition. The native NetWeaver scale for evidence is defined on the interval $[-1, 1]$. The condition class symbology represents five equal intervals (about 0.4) on the NetWeaver scale.

3.2. Strategic Priorities for Restoration

Based on the strategic decision model for watershed restoration (Figure 2), five of the nine subwatersheds were evaluated as high priority for possible restoration activities (Figure 5). Subwatersheds in the high priority category were Ben Young Creek, Elder Creek, Morgan Creek, South Creek, and Swamp Creek. Among these five high priority subwatersheds, stream accessibility, followed by upland condition, were the primary factors determining the priority for restoration of the subwatersheds (Figure 6).

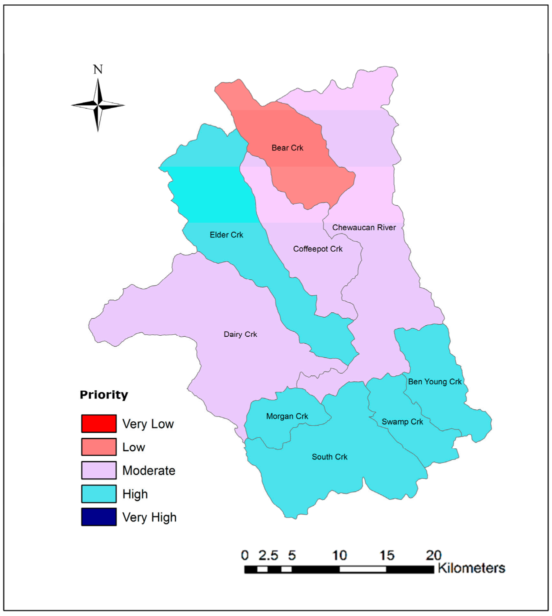

Figure 5. Strategic restoration priorities for the subwatersheds based on the model in Figure 2.

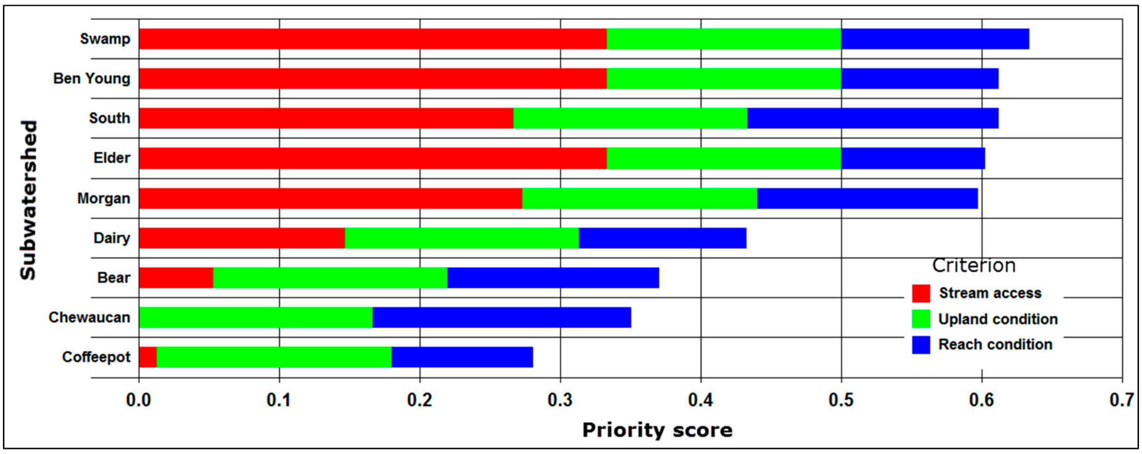

Figure 6. Contributions to the overall strategic priority from primary decision criteria (Figure 2). The total bar height for a subwatershed is the overall priority score for restoration. Contributions of the three primary criteria to the overall score are shown as stacked bars for each subwatershed.

3.3. Tactical Priorities for Restoration Actions

The tactical analysis focused on the five high priority subwatersheds from the strategic analysis (Figure 5). Based on the tactical decision model (Figure 3), EMDS identified removing artificial barriers as the most effective management action in four of the five subwatersheds from the strategic analysis (Figure 7). In the case of ties, the map symbology identifies more than one action, so the top priority actions for Swamp Creek include both removing barriers and reducing roads. In the case of South Creek, however, restoration of riparian vegetation was identified as the most effective management action. Although the map displaying the results of a tactical decision analysis only generally displays the most effective management action in each landscape unit, standard map query tools in the GIS interface can be used to review the effectiveness of all potential management actions in a selected landscape unit (Figure 8).

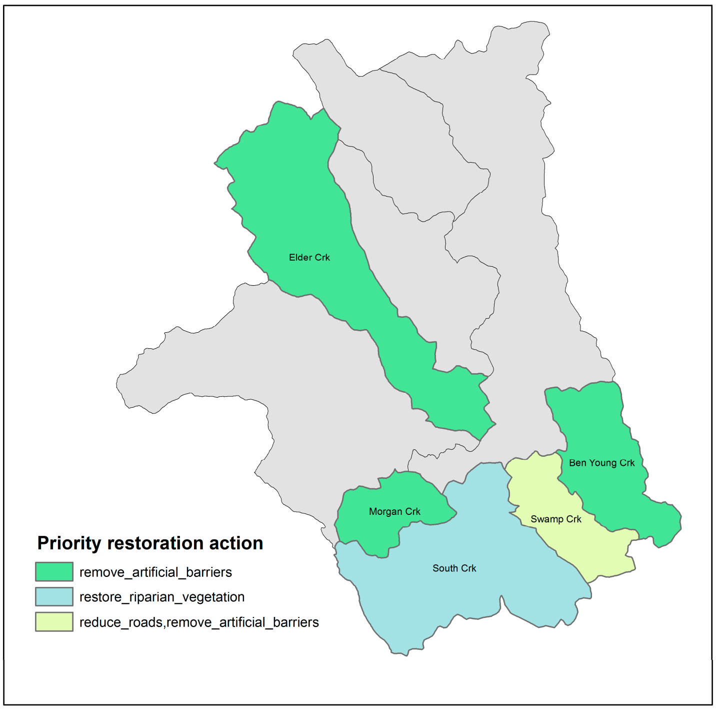

Figure 7. Tactical restoration priorities for the top five subwatersheds with a high strategic priority (Figure 5).

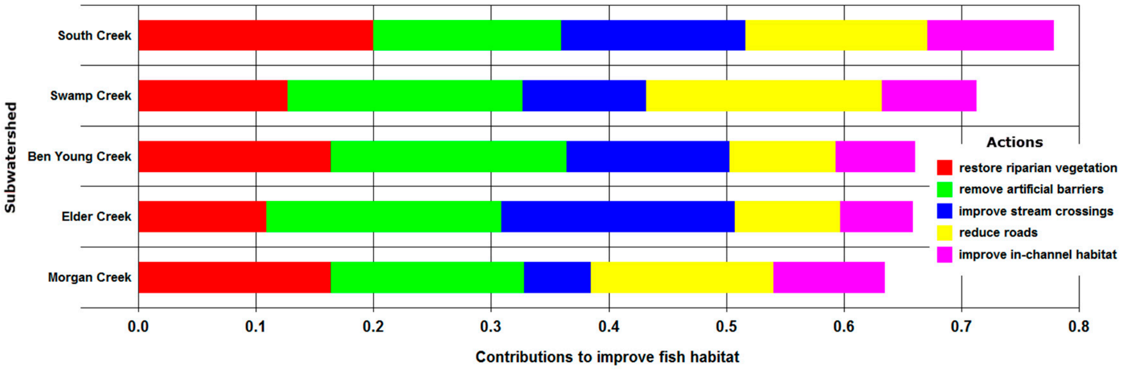

Figure 8. Effectiveness of management actions for addressing restoration needs in the top five subwatersheds considering their strategic priority. For each subwatershed, the cumulative effects of implementing two or more actions can be calculated as the sum of their contributions.

4. Discussion

In this section, we discuss the strengths and weaknesses of the EMDS system, flexible workflows as a special case of a strength, and extending the current system to include designed management actions.

4.1. Strengths and Weaknesses of EMDS

EMDS is not a decision support system in the conventional sense of Waterman [49]. Instead, the system is a *general framework for building* decision support systems, in which application developers are free to design analytical models for a very wide range of topics requiring decision support, and at whatever spatial scales are appropriate to the modeling topics covered. Thus, the system has a potentially very broad application to natural resource management problems. The present study illustrates a very simple example, in which the entire project involves only a single spatial scale of analysis, but, more generally, a project can span as many spatial scales as the problem requires. Our example also illustrates a very simple application of integrated assessment, proceeding from assessment to strategic planning to tactical planning. In the following section, we also explain how a project can flexibly support multiple alternative analytical pathways, depending on the complexity of the overall decision support problem. As we mentioned earlier, a notable feature of logic-based models is that, in effect, if one can reason about an analytical problem, then one can model it in logic. Thus, logic-based models are well-suited to tackling the kinds of large, complex, abstract problems that are typical of contemporary decision support in natural resource management. Finally, on the strength side, the model design tools used in EMDS for logic and decision models both employ graphical model design, which not only provides an intuitive interface within which domain experts from multiple disciplines can effectively collaborate, but which also provides stakeholders with intuitive graphical explanations of how the models derive their conclusions. These latter communication features of EMDS are perhaps the most important to the success of the system for the past 20 years, as evidenced by the wide range of case studies listed in [24].

Of course, EMDS also has its weaknesses. Perhaps the most fundamental weakness is that the logic and decision engines only operate on the attributes associated with individual spatial features or rasters. In other words, there is no native support for neighborhood analysis. However, because EMDS is implemented in GIS, standard geoprocessing tools are available to application developers so that spatial considerations such as neighborhood influence can be modeled, but providing this capability is left to the developer. A similar weakness occurs in the context of multi-scale analyses. Projects can support as many spatial scales of analysis as are appropriate to the overall project, but it is likewise left to the application developer to prescribe the geoprocessing steps needed to pass data between scales. Finally, we have discussed the interpretation and synthesis in the assessment step in Section 2.3. There are both strengths and weaknesses associated with synthesis. On the one hand, MCDMs like the AHP are intrinsically linear models. Thus, if the data inputs to an MCDM have strong nonlinear dependencies, the resulting decision scores will at least be of questionable value. On the other hand, nonlinear dependencies are easily handled in logic processing, where two or more synergistic or antagonistic landscape conditions can be combined into a suitable input for the MCDM model. In addition, if the SMART mode is used rather than AHP in the MCDM, nonlinear (though still monotonic) value functions can been used. Together, these methods can largely, if not completely, eliminate the nonlinearity problem in MCDMs. An additional virtue of logical synthesis as a preprocessing step is that it reduces the dimensionality of the decision model, making the latter smaller and easier to understand. Conversely, synthesis as a preprocessing step can unnecessarily obscure important details generated in logic processing, but useful in the decision stage, so there is, almost inevitably, some tension between preserving the details and synthesis.

4.2. Flexible Workflows

In Section 2, we described the architecture of our decision support application for restoration planning in the Chewaucan watershed in terms of a three-step process. These steps can be thought of as a decision support workflow [50]. However, EMDS applications are not limited to the specific workflow described in this work. The current EMDS user interface supports a variety of decision support workflows, the choice of which depends on the size and complexity of the decision support context (Figure 9).

Table 3. Characteristics of typical EMDS workflows as illustrated in Figure 9.

Workflow [1]	Landscape Features	Need for Synthesis and Interpretation
1	Few (e.g., 10)	No
2	Many (e.g., >100)	No
3a	Few	Yes
3b	Many	Yes
3c	Few or many	Yes [2]

[1] Numbers correspond to pathways in Figure 9. [2] Workflow 3c is a special case when data or logic require editing. In EMDS, this is called a scenario.

The number of workflow pathways illustrated (Figure 9) is not exhaustive, but represents those which are most typical. Workflows in EMDS are supported by the Windows Workflow Foundation from Microsoft Research [50]. Later versions of EMDS will expose a custom workflow interface within which application developers will be able to design their own customized, special-purpose workflows in order to extend the decision support functionality of the EMDS framework. We introduce the term framework here in order to draw a useful distinction between EMDS and classical decision support systems. The classical notion of a decision support system is an application engineered to address a very specific problem [49]. In contrast, EMDS is a collection of decision support components (e.g., Figure 9) with which application developers design a wide variety of decision support applications. Thus, EMDS is a decision support framework in the sense that it is actually an application generator.

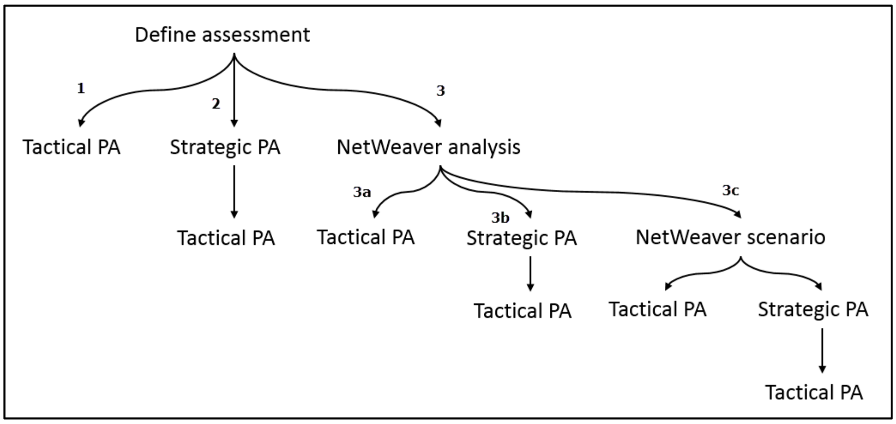

Figure 9. EMDS version 5.1 supports multiple alternative decision support workflows within assessments, depending on the size and complexity of the problem. PA = Priority Analyst, which is the EMDS decision engine. In this diagram, tactical PA can represent either a simple tactical decision model (Section 2.4.3) or a decision model that implements designed management actions, or both. Problem characteristics associated with each numbered pathway are described in Table 3 and discussed further in the text. The present study follows workflow 3b.

Referring to Figure 9 and Table 3, we summarize the rationale behind each workflow as follows:

- Workflow 1 is relevant when (1) there are only a small number of data inputs that do not have any complex nonlinear dependencies that would suggest the need for preprocessing with logic as discussed in the Section 4.1, and (2) there are only a few landscape features to be evaluated in the study area.
- Workflow 2 applies when the first condition for workflow 1 is met, but there are many landscape features to be considered. In this case, the strategic decision model can usefully first be used to reduce the number of landscape units to a smaller subset that is feasible to treat within a short-term planning horizon.

- Workflow 3 applies when there are at least a moderate number of data inputs, and there are complex nonlinear dependencies among them that suggest the need for preprocessing the data in a logic model that performs some interpretation and synthesis before passing analysis results along to more decision models.
- Given the need for preprocessing in logic, the choice between workflows 3a and 3b depends upon the considerations already discussed for workflows 1 and 2, respectively.
- Workflow 3c is a somewhat special case in which, for a variety of reasons, the analyst may want to modify the input data or the structure of the logic model. In Figure 9, the first NetWeaver analysis shown at the top of workflow 3 is *required* to be run in EMDS *with no alterations to either data or logic*. The latter requirement is a simple way to enforce data and model integrity in the system. If an analysis suggests the need for either type of alteration, these changes are allowed in NetWeaver scenarios.

4.3. Beyond Tactical Actions: Designed Management Actions for Landscape Restoration

The need for design capabilities in forest management has long been recognized [51]. However, the integration of design and science, particularly in the spatial realm, has long been a challenge [52]. A core aim of the current research and development work on the EMDS is to provide formal support for design in ecosystem management.

EMDS has used MCDMs to support strategic prioritization since 2002 by addressing the question, "Which landscapes are the highest priority for management actions?" With version 5.1, system functionality has been extended to support tactical planning, as demonstrated in this study in Section 3.3, answering the question, "Which possible management actions are the highest priority for implementing in any specific landscape unit, considering the effectiveness of the alternative actions, and given data about the state of a landscape unit?" However, the EMDS development team is currently working on further extending spatial decision support for environmental analysis and planning with what we refer to as DMAs—designed management actions. The aim of this work is to implement Steinitz's [30] concepts of geodesign through new workflows in EMDS. Geodesign as a methodology for changing the world has many characteristics suitable for sustainable design [53]. The remainder of this section sketches the concepts and methods of DMAs as planned for EMDS version 5.2.

Our methodology for DMAs combines aspects of both strategic and tactical planning. Whereas tactical actions evaluate the efficacy of types of restoration actions in one subwatershed at a time (Section 3.3), DMAs are spatially delineated actions of a specified type, and the DMA approach evaluates the aggregate effect of each specific action (or combinations of actions) on one or more landscape units in terms of how each action (or combination) improves the overall condition of the entire landscape (e.g., the entire Chewaucan watershed).

The type of DMA action leverages conceptual models of action and threat such as Salafsky et al. [54] which are widely used in restoration projects worldwide through the Open Standards for Conservation Restoration [55]. In EMDS 5.2, each DMA type works on one or more input data fields that contribute to stressors. The efficacy of the action, were it to be implemented at a realistic level—the exemplar action—is declared by the analyst setting target levels for each data field (e.g., a reduced sediment level of 20 ppm). In addition to the desired effects of the DMA, the analyst can also introduce resource costs for the DMA type, typically as density costs (e.g., cost per acre or cost per linear mile).

Within the EMDS application, the analyst designs a spatially specific DMA by selecting which landscape units it acts on, either by using a table to list the landscape units or by sketching the footprint of the DMA on the map. They specify both the DMA type and the intensity of the action as a percentage of that of the exemplar DMA type level.

Within the EMDS framework, estimating the impact of a DMA is a three step process. In the first step, a new DMA scenario is generated based on the original assessment, and all input data fields in the landscape units affected by the DMA(s) are then updated. In the second step, the NetWeaver analysis model is run against the scenario to evaluate the effects on logic outcomes. And in the third, the impacts for each DMA are estimated by aggregating the changes in each logical outcome and each resource cost across all the landscape units in the study area.

The precise details of the workflow for the analysis of DMAs will vary, depending on the size and complexity of the problem (Figure 9, Table 3). However, as we mentioned in Section 2.4.3, a strategic decision often forms the foundation for the watershed-scale decision model for DMAs (compare Figures 2 and 10). If we assume that the workflow prior to the analysis of DMAs follows path 3b in Figure 9, then the weights on the subcriteria of watershed function (Figure 10) are conserved from the strategic decision model (Figure 2), and we have added a cost criterion as a simple example of introducing an efficacy criterion into the analysis. In this new CDP model (Figure 10), scenarios generated by specific DMAs now play their more traditional role of alternatives in a classical MCDM (compare this model structure with Figure 3). As with the strategic (Figure 2) and tactical (Figure 3) decision models, the single action scenario in the model for DMAs (Figure 10) is again simply a placeholder for all the scenario actions defined by the analyst at runtime. Model weights at the top of the model would reflect the study-area-wide logical outcomes traded off against aggregate logistical attributes.

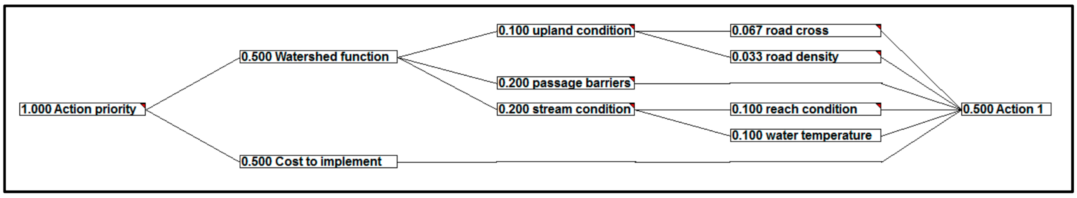

Figure 10. CDP decision model for scenarios generated by designed management actions. Weights on project area states are repeated from the strategic decision model (Figure 2). Weights on actions are calculated as part of the designed management actions methodology as explained in the text.

These new capabilities can be formally mapped to the geodesign framework of Steinitz [30]. Implementing the Assessment, NetWeaver analysis, and Strategic PA that begin the 3b workflow, corresponds to implementing the Representation, Process, and Evaluation models of geodesign. Generating specific DMAs corresponds to implementing the change model, rerunning the NetWeaver Analysis model corresponds to the impacts model, and the DMA MCDM model to the Decision model. Having a formal MCDM model for the geodesign decision model means that the sequential and optimization design techniques that Steinitz [30] identified as two of the eight distinct approaches to designing changes to the world, are readily executed manually or through automation. Indeed, for a specified overall management budget, the use of strategic and tactical models as the initial steps of the DMA workflow as described above jump starts the search for acceptable design solutions, and the iterative development is likely to efficiently approach a satisficing [52] solution.

For much larger problems, with 1000s of landscape units, we envision the workflow as supporting a guided iterative process. We start by taking advantage of the information gained from combining the strategic and tactical models—"Which types of possible management actions are the highest priority for implementing in any specific landscape unit, considering the effectiveness of the alternative types of actions, and given data about the state of a landscape unit?"—to select the highest ranking type of action for each landscape unit and declare it a DMA. This automatically yields a set of landscape specific actions very likely to be effective in significantly improving the condition of the study area—scenario 1. Next, we could build upon scenario 1 with the addition of the second-ranked tactical priorities to create scenario 2, add third-ranked tactical priorities in scenario 3, and so forth. In this way, a sequence of scenarios could examine the cumulative landscape effects, and resource costs, of progressively implementing tactical actions across a study area. For completeness, the original analysis of 3b (with no management actions taken) would be included for comparison. Placing all the scenarios in the DMA decision model helps the decision makers answer the key question of geodesign, "How should the study area be changed?" [30].

Finally, the team plans to implement a dashboard to record a) required targets related to logical outcomes (e.g., 60% of the subwatersheds must be in satisfactory condition) and b) multiple logistical constraints (e.g., total costs and human resource limits). The aggregate progress of each scenario against these targets and constraints is tracked and visually presented, and both sequential and combinatorial design methods [30] can be pursued to generate acceptable sets of DMAs—essentially forest plans. Moreover, the provenance engine supporting the EMDS workflows allows for the efficient rollback and branching of solutions being generated by either of these design methods.

5. Conclusions

Decision support for strategic planning was introduced into the Ecosystem Management Decision Support system of version 3.0 in 2002. In version 5.1, the system now supports integrated strategic and tactical planning. Support for geodesign, as implemented in designed management actions, opens significant new opportunities for strengthening spatial decision support for environmental analysis and planning in the context of the contemporary, complex challenges related to addressing ecosystem sustainability and resilience.

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Abbreviations

The following abbreviations are used in this manuscript:

AHP	Analytic Hierarchy Process
CDP	Criterium DecisionPlus
DMA	designed management action
EMDS	Ecosystem Management Decision Support (System)
HTML	hypertext markup language
MCDM	multi-criteria decision model

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