This paper is part of the Proceedings of the 3rd International Conference
on Environmental and Economic Impact on Sustainable Development (EID 2016)
www.witconferences.com

Incorporating landscape connectivity and uncertainty into ecosystem restoration scaling of environmental damage

D. A. Hanson[1], A. W. Wolfson[2], M. C. Buckley[3] & D. R. Reimer[4]
[1]*Hanson Resource Management, USA*
[2]*Biomass Options, USA*
[3]*ECONorthwest, USA*
[4]*D. R. Systems, Canada*

Abstract

The dramatic loss of wildlife habitat and ecosystem functions has been well documented, and much of the remaining habitat and services are highly stressed and/or fragmented. Valued biological and natural systems are threatened by rapid, non-stationary changes in environmental conditions associated with climate change, high severity wildfires, and other major perturbations. In response to these threats, resource management plans and climate adaptation strategies commonly call for the need to restore landscape connectivity in order to increase the resistance and resilience of natural systems. Although preservation and restoration of connectivity is well accepted as a desired management objective, few of the existing resource management tools explicitly or effectively address this need, especially when determining mitigation and compensatory restoration requirements to offset loss of ecosystem services due to releases of hazardous substances, human-caused high severity wildfires, and infrastructure development projects. When resources are valued and managed by enhancing the total amount of a desirable habitat or ecosystem function without metrics available to determine the effects of landscape connectivity, the restoration benefits cannot be reliably and defensibly estimated. This presentation explores the importance of incorporating the geospatial and temporal dynamics associated with landscape connectivity and non-stationarity in establishing compensatory restoration requirements at complex environmental settings. Furthermore, we present the

WIT Transactions on Ecology and The Environment, Vol 203, © 2016 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/EID160191

conceptual framework for integrating connectivity and uncertainty into restoration scaling of lost environmental services.

Keywords: habitat connectivity, non-stationarity, natural resources damage assessment, NRDA, habitat equivalency analysis, HEA, ecological restoration, geospatial modelling, non-stationarity, climate change, restoration scaling.

1 Introduction

Anthropogenic development and land use practices have frequently resulted in dramatic reduction in the amount of fish and wildlife habitat, much of which has been extensively fragmented in its structure and ecological function. Continued human population growth, urban and agricultural development, and climate change are expected to put additional future stresses on the structure and function of ecosystems. Recommended conservation strategies in response to these stresses call for increasing landscape connectivity and biodiversity in order to increase the resistance and resilience of ecological systems.

Landscape connectivity is often characterized in two categories: structural connectivity which refers to the physical relationship between landscape elements, and functional connectivity which refers to the degree which landscapes facilitate or impede the movement of organisms and ecosystem processes within and among habitats. The majority of the published papers regarding landscape connectivity are focused on the identification, preservation, or restoration of wildlife habitat corridors in response to urban development, transportation planning, or climate change adaptation. These efforts are typically based upon best professional judgment (BPJ) and GIS-based connectivity tools (e.g., Linkage Mapper or HCA Toolkit) (CA DFW [1] and WA WHCWG [2]).

Consideration of landscape connectivity and dynamic linkages of ecosystem services has not routinely been included as an explicit analytical component in restoration scaling of lost ecosystem services from hazardous waste releases, oil spills, and other sources of environmental injury that have required offsets of interim lost environmental services with compensatory services that provide an equivalent level of service. Habitat Equivalency Analysis (HEA) is a method for scaling the present value of natural resource service loss from an anthropogenic perturbation with the present value of compensatory restoration service gains required to offset the associated service loss when required by law, regulations, or a permit condition. HEA has been used to define applicable compensatory restoration requirements as part of Natural Resource Damage Assessment (NRDA) under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), the Oil Pollution Act (OPA), the Marine Sanctuaries Act, and the Clean Water Act (CWA), as well as to settle disputes for offsetting environmental losses from infrastructure development projects and human-caused severe wildfires in the United States. HEA has also been adopted for use in the European Union under The Environmental Liability Directive, Habitats and Wild Birds Directive, Water Framework Directives, Environmental Impact Assessment and Strategic Environmental Assessment Directives. Unsworth and Bishop [5], NOAA [6], and Dunford *et al.* [7] provide an overview of the elements, underlying assumptions, and methods for HEA. The objective of this paper is to build upon the work of Hanson *et al.* [3, 4] addressing how to adapt restoration scaling using HEA to accommodate environmental uncertainty and landscape connectivity for restoration scaling at ecologically or socially complex sites.

2 Summary of Habitat Equivalency Analysis (HEA)

Figure 1 illustrates the basic elements of HEA. In Panel 1A, the red line depicts the level of ecosystem services as they are reduced by an impact and then return to the baseline condition (restored). The interim service lost (area A between the red and green lines) depicts the amount of lost ecosystem services that must be compensated due to the injury. HEA guidance acknowledges that baseline conditions may vary over time [6] but has historically assumed they were stationary. Stationarity, from an ecological systems perspective, refers to the expectation that future baseline conditions operate within a predictable window of variability.

Area B in Panel 1B shows the service gains from a compensatory restoration project that must be completed in addition to restoring the injured area to its baseline in order to make the public whole for the lost use of the service before full recovery. Area B (i.e., the amount of restored services) must equal the area A (the amount of interim lost services) when both service loss and restoration gains are adjusted for net present value in order to achieve parity. Although compensatory benefits (area B) appear to go on indefinitely, the discounting of future benefits essentially bounds the time scale for receiving compensatory benefits with a primary contribution within the next generation and effectively reaching zero at a point in the future determined by the discount rate being used. For example, if a habitat provided a steady state of annual service flow of 100 service acre years (SAYs), using a three percent discount rate (the rate typically used by the U.S. government under its NRDA program) the present value of the service for year 50 is only 21.5 SAYs, and declines to 10.3 and 4.6 SAYs for the 75th and 100th year, respectively.

HEA routinely is applied as a deterministic, spreadsheet model where differences in habitat conditions and environmental services are addressed by identification of multiple habitat or ecosystem service categories. Within a given

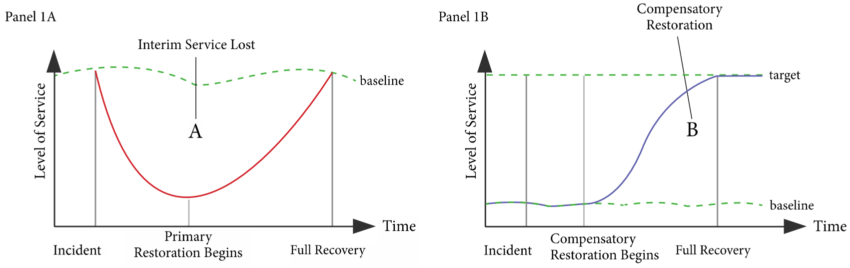


Figure 1: HEA depiction of ecosystem service losses (Panel 1A) and compensatory restoration gains (Panel 1B).

habitat or service category, all stands are assumed to be functionally equivalent and thus replaceable. The challenges in applying HEA are highly variable depending on the duration, magnitude, and complexity of the environmental perturbation and environmental loss. HEA can be applied with varying levels of scientific rigor based upon site complexity and the value of information to interested stakeholders in order to support settlement negotiations. In the U.S., the duration of natural resource damage settlements using HEA have ranged from weeks to multiple decades. The insufficiency of HEA as presently used to objectively address concerns associated with non-stationarity of environmental conditions and both the risks and benefits of landscape connectivity, can be contributing factors to the long duration of settlement negotiations.

3 Demonstrating the importance of connectivity in restoration planning

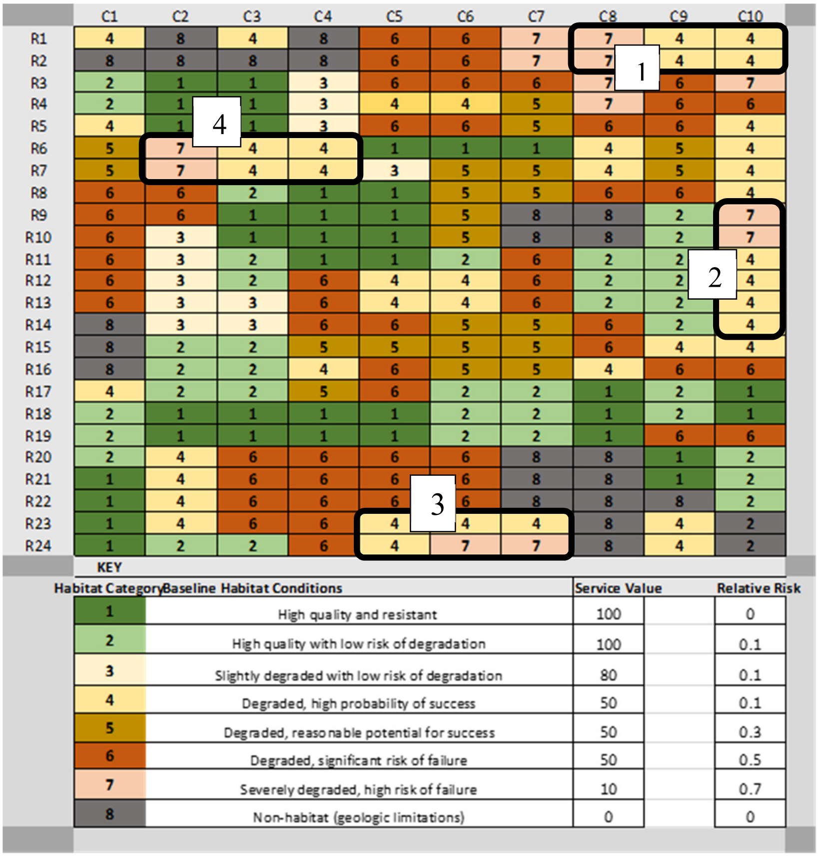
This section provides a demonstration of how landscape connectivity can impact the restoration scaling process for NRDA. Figure 2 depicts a hypothetical shrub-step landscape that consists of 260 equal size parcels with each parcel representing one of eight habitat categories. The habitat categories are based on quality of rangeland habitat and either the risk of habitat degradation (for existing high quality habitats) or successful restoration into a high quality resistant habitat (for existing degraded habitats) based upon risks of invasive species and wildfire. For illustrative purposes, assume initially: (1) the type and cost of restoration and resistance/resilience building (where appropriate) is the same for each parcel within a given category, and (2) the level of current and future ecosystem services and the risk of degradation is dependant only on the conditions of each individual parcel (i.e., existing and potential benefits, as well as risks, for each parcel are independent and do not vary based on ecosystem connectivity with other parcels). Furthermore, assume the amount of liability for the injury being compensated is equivalent to improving four parcels of Category 4 and two parcels of Category 7 to Category 1 conditions and the temporal aspects of the compensatory restoration alternatives are equivalent or are being ignored. These are simplistic initial assumptions for illustrative purposes due to space limitations for this paper.

Are the four restoration alternatives depicted in Figure 2 equal?

- Scenario 1: The necessary restoration and its cost is the same for all parcels within the same habitat category and connectivity is not considered in the valuation of ecosystem services. Then the ecological lift from restoration Alternatives 1–4 in Figure 2 is all the same, and we would expect responsible parties to be indifferent to the four alternatives. In contrast, in the absence of an ecosystem service metric that includes detailed information on site conditions and connectivity, we believe that natural resource managers would prefer Alternative 4 based upon best professional judgment (BPJ).
- Scenario 2: Costs for restoration are a function of site conditions (as assumed above) and differences in site access, and (1) Alternatives 1 and 3 have good access, equal costs, and lowest costs of the four alternatives

due to road access, (2) Alternative 2 has 50 percent higher costs than Alternatives 1 and 3 due to no road access but does has seasonal water access, and (3) Alternative 4 has only foot access resulting in 400 percent higher cost than Alternatives 1 and 3. Under these assumptions, we would expect responsible parties to seek Alternatives 1 or 3 based on a more favourable cost/unit ecological lift while the natural resource managers would still prefer Alternative 4 but might be willing to settle for Alternative 2 in negotiations based on a cost effectiveness argument by the responsible parties.

- <u>Scenario 3:</u> If site risks (e.g., wildfire and invasive species) are a function of both site-specific conditions and the associated conditions and risks of adjacent sites are recognized in the responsible party's restoration requirements but landscape connectivity of ecosystem benefits is still not explicitly incorporated into the metric representing ecosystem service value, then responsible parties will seek alternatives where the expected value of their restoration requirement's success is high based on a function of both risk and costs. This might encourage responsible parties to pursue Alternative 2 given the lower risks for the parcels for this alternative. Better yet, responsible parties might prefer a safer new alternative (call it Alternative 5, not depicted in Figure 2) that includes the following discrete parcels: (R1, C1), (R1, C3), (R23, C9), (R24, C9), (R24, C6), and (R24, C7). The parcels under Scenario 5 would have lower risks and lower access related costs related to any of the other alternatives previously presented. Natural resource managers, on the other hand, would recognise Alternative 5 provides marginal benefits of additional fragmented high quality habitat but provides neither significant risk reduction benefits for existing high quality sites nor synergistic benefits of connecting with existing high quality parcels and would likely oppose this alternative. Furthermore, the resource managers would likely prefer Alternative 2 or a new Alternative 6 that is explicitly designed to reduce risks to existing high quality habitat. The difference in perspectives among parties under this scenario is that while natural resource managers intuitively recognise differences between connected and fragmented habitat, there is no tangible benefit for the responsible parties to consider this factor in the settlement of compensatory restoration requirements.
- <u>Scenario 4</u>: If both risks and benefits associated with landscape connectivity were explicitly included in the metric defining the level of service, the complexity of potential restoration alternatives increases as all parties consider how to decide between restoring ecosystem services on distressed lands, improving ecosystem connectivity among existing fragmented parcels of high quality habitat, and reducing the risk of lost ecosystem services for parcels with moderate or low resistance and resilience. Presently, each of the stakeholders rely heavily on BPJ to the extent they consider such decisions as the implications of landscape connectivity and potential non-stationarity of baseline conditions are not effectively incorporated in HEA.



	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
R1	4	8	4	8	6	6	7	7	4	4
R2	8	8	8	8	6	6	7	7	4	4
R3	2	1	1	3	6	6	6	7	6	7
R4	2	1	1	3	4	4	5	7	6	6
R5	4	1	1	3	6	6	5	6	6	4
R6	5	7	4	4	1	1	1	4	5	4
R7	5	7	4	4	3	5	5	4	5	4
R8	6	6	2	1	1	5	5	6	6	4
R9	6	6	1	1	1	5	8	8	2	7
R10	6	3	1	1	1	5	8	8	2	7
R11	6	3	2	1	1	2	6	2	2	4
R12	6	3	2	6	4	4	6	2	2	4
R13	6	3	3	6	4	4	6	2	2	4
R14	8	3	3	6	6	5	5	6	2	4
R15	8	2	2	5	5	5	5	6	4	4
R16	8	2	2	4	6	5	5	4	6	6
R17	4	2	2	5	6	2	2	1	2	1
R18	2	1	1	1	1	2	2	1	2	1
R19	2	1	1	1	1	2	2	1	6	6
R20	2	4	6	6	6	6	8	8	1	2
R21	1	4	6	6	6	6	8	8	1	2
R22	1	4	6	6	6	6	8	8	8	2
R23	1	4	6	6	4	4	4	8	4	2
R24	1	2	2	6	4	7	7	8	4	2

KEY

Habitat Category	Baseline Habitat Conditions	Service Value	Relative Risk
1	High quality and resistant	100	0
2	High quality with low risk of degradation	100	0.1
3	Slightly degraded with low risk of degradation	80	0.1
4	Degraded, high probability of success	50	0.1
5	Degraded, reasonable potential for success	50	0.3
6	Degraded, significant risk of failure	50	0.5
7	Severely degraded, high risk of failure	10	0.7
8	Non-habitat (geologic limitations)	0	0

Figure 2: Hypothetical example of importance in geospatial relationships in the selection of restoration alternatives (labelled 1–4) in restoration scaling.

Given considerations such as those demonstrated in the four scenarios about, a traditional, non-spatial HEA evaluation becomes very complicated, and subsequent negotiations can become very contentious, with the following conditions:

- The size of the study area and restoration requirements increases from a few hundred acres to thousands or millions of acres;
- The complexity of the geology, hydrology, and geography increases;
- The number, type, and stages of habitat stands increases;
- The risks and uncertainty associated with non-stationary conditions increases due to climate change, disease, invasive species, or severe wildfire;

- The number of endangered or highly valued species which utilize the study area but prefer different habitat categories increases;
- The extent and severity of residual contamination increases;
- The presence of significant cultural resource areas that must be protected and preserved exist in the study area;
- Differences exist in society preferences and opportunity costs among parcels;
- The temporal implications of restoration alternatives are incorporated in the analysis, and/or
- The overall cost of restoration increases.

In each of the above hypothetical scenarios, both the natural resource managers and responsible parties would be responding in good faith based upon their perspectives and the capabilities and limitations of the compensatory restoration analysis. Although the process of defining environmental service loss is separate from the selection of the compensatory restoration alternative, the importance of explicitly incorporating landscape connectivity and uncertainty associated with non-stationarity increases as the complexity of the site and injury increases.

4 Desired attributes of landscape level decision support system

Section 3 demonstrates that properly incorporating ecosystem linkages and landscape connectivity in restoration scaling for complex sites can significantly improve decision-making across compensatory restoration alternatives. The objective of this section is to discuss the desired attributes from existing and/or future landscape models that could be incorporated into the restoration process to provide more cost-effective settlements at NRDA sites.

There are an extensive number of landscape level resource modelling tools for predicting habitat stand conditions under alternative resource management scenarios. Although such tools may be extremely useful for the on-going management of natural resources, they are difficult to apply directly into restoration scaling efforts. The majority of resource management models are similar to HEA in that they are deterministic models of predicted conditions based on average or some other statistical representation of habitat class. Many, if not most, of these models have the ability to: (1) define and model geospatially-explicit polygons or habitat categories for habitat and ecosystem services using data describing individual polygon conditions based upon field surveys, aerial photographs, or a variety of other existing sources, and (2) model ecological dynamics which are controlled by geospatial and temporal specific production functions. However, the vast majority of these models do not address geospatially-explicit landscape connectivity or the synergistic implications of uncertainty and input parameter variability. Although incorporating GIS tools provides some level of geospatial understanding, most GIS results are simply an overlay of independently modelled variables to a common point of time and do not fully reflect the ongoing interactions between ecosystem services and the individual habitat polygons.

Incorporation of landscape connectivity into restoration scaling can be addressed by integrating the concepts of HEA with a geospatially explicit landscape model with the following additional capabilities and attributes.

- Ability to assign and model linkages and interactions between environmental, social, and economic parameters for individual user-defined geospatial polygons over the entire geospatial area and temporal period of interest.
- Inclusion of user-defined spatial adjacency algorithms (moving windows) to run possible combinations of habitat corridors and adjacency traits which can be related back to each individual polygon. This enables valuation of adjacency and connectivity at the individual polygon level.
- Scenario based analyses which can cover a range and scale of likely occurrence (which may be linked directly to selected outcomes of Monte Carlo or Bayesian Network simulations).

The authors are aware of one modelling program (D.R. Systems' OPTIONS Model) that has the attributes and capabilities identified above. OPTIONS is a PC-based, land management spatial simulation model used for a wide range of resource management planning applications involving ecological, economic, and social considerations of ecosystem goods and services (D.R. Systems 8). The software was developed initially for the forest industry but has been applied on a range of landscape systems, including: wetlands and riparian systems, urban/forest interface, rangeland management, and both wilderness and commercial forests. OPTIONS is a rules-based, spatial simulation model which attempts to maximize management objectives, subject to meeting all scenario rules and regulations first. It forecasts future scenarios by paying attention to the detail of the biological dynamics of the resources present, the spatial relationships of all resources and regulations and by directly linking the modelling rules for the scenario definition with the detailed biological and spatial dynamics of the resources present. This analytical approach provides transparency of biotic and abiotic interactions in complex settings to support a greater understanding of the dynamics, as well as the limitations and capabilities, of the resource base.

It is not the intent of this paper to endorse a single geospatially-explicit modelling platform. If further review of the literature identifies additional models with the attributes and capabilities defined above, they should also be considered in the development of a new approach to incorporate landscape connectivity for restoration scaling at complex sites.

5 Accommodating landscape connectivity and uncertainty into restoration scaling

Section 4 discusses the desired attributes from resource management modelling tools that can be used to incorporate connectivity risks and benefits in restoration scaling for complex sites. The challenges associated with landscape connectivity are further complicated if the potential impacts associated with non-stationarity of baseline conditions due to climate change, severe wildfire and other potential sources is a concern. Rohr et al (9) discuss the potential impacts of climate change on the definition of baseline conditions and both the extent and recovery of environmental service loss. Hanson *et al.* [3, 4] describes how the use of Monte Carlo (MC) and/or Bayesian Network (BN) simulation can be used to evaluate the potential impacts of environmental uncertainty into restoration scaling. The purpose of this section is to discuss how recommendations in Section 4 can be incorporated into the recommendations from Hanson *et al.* to address connectivity and non-stationarity concerns at complex NRDA sites.

The integration of the principal components of existing modelling approaches can provide better estimates of the value of lost ecosystem services by incorporating ecosystem linkages, as well as addressing the implications and uncertainties associated with non-stationarity. Three types of modelling systems, and their relevant principal components, are identified in Table 1 and discussed further below. The first modelling platform is the use of Monte Carlo and/or Bayesian Networks to address non-stationarity of ecosystem conditions and services due to climate change, wildfire, insects, invasive species, and other major perturbations that can change baseline conditions and the recovery of ecosystem values. The specific model components for estimating uncertainty and non-stationarity would depend in part on the types of perturbations most likely to impact the assessment area. For example, the risk and impacts of wildfire would combine weather, climate and fire models to predict the probability, location, extent and severity of fire. The MC or BN analysis would be used to define the expected value for future conditions and risks as the primary scenario for the restoration scaling. Additional scenarios representing the range of uncertainty from the MC and/or BN analyses should be included in the scaling analysis.

The principle component of the second modelling system is the concept of restoration scaling as depicted using HEA where the difference between projections of ecosystem service values under baseline, ecosystem damage and recovery, and compensatory restoration alternatives are evaluated and compared over time given appropriate temporal preferences.

The principal components of the third modelling platform are the elements of a landscape planning model as discussed in Section 4 above that can simulate changes in ecosystem services and values based on a function of parcel specific conditions and its linkages with ecological, economic, and cultural factors occurring across the landscape. As presently configured, the OPTIONS model runs alternative management scenarios and comparisons are made of scenario results. Ideally, the model should be modified to incrementally scale the polygon-specific differences between environmental services and baseline within each year or applicable time increment based on the principal component of the HEA model.

Table 1: Principle components to incorporate landscape connectivity and uncertainty in restoration scaling.

UNCERTAINTY SIMULATION FOR NON-STATIONARITY

- Monte Carlo Analysis of uncertainty perturbations (e.g., wildfire, climate change, etc.) to incorporate risks in the prediction ecosystem service values for alternative baseline conditions
    - Determination of *expected value* of baseline conditions as primary estimate in restoration scaling
    - Selection of alternative baseline scenarios from Monte Carlo simulation for uncertainty analysis associated with baseline conditions
    - Use of Bayesian Network of uncertainty to define alternative scenarios of baseline conditions if Monte Carlo simulation not possible
    - Simulation of uncertainty to determine compensatory restoration projects

RESTORATION SCALING (e.g., HEA model)

- Restoration scaling comparing environmental service and recovery curve with baseline
- Restoration scaling comparing alternative compensatory restoration projects with baseline
- Selection of appropriate discount rates for damage and compensatory restoration

GEOSPATIAL LANDUSE MODELING WITH LANDSCAPE CONNECTIVITY (e.g., OPTIONS or comparable model)

- Operates at the individual GIS-polygon level and maintains built-in linkages to GIS so spatially-specific ecological dynamics, management rules, constraints, and results are generated
- Accurately relates spatial linkages and constraints with restoration and recovery
- Simulation of succession and recovery of habitat and ecosystem services on a polygon-specific basis
- Tracking and modelling ecosystem service values and costs for natural recovery and primary restoration
- Spatially explicit modelling and tracking of ecosystem service values, costs, and present values for baseline, damage recovery, and alternative restoration projects

6 Conclusions

This paper demonstrates how the lack of incorporating the effects of landscape connectivity for the determination of compensatory restoration can lead to conflicting positions for complex sites. We believe that these issues can be evaluated more objectively and lead to quicker and more appropriate settlements through the modification of existing restoration scaling methods based upon the incorporation of existing spatial and probabilistic methods and technologies. Restoration scaling methods should continue to be flexible in order to adjust the complexity and rigor of the scaling evaluation with the value of information to all stakeholders and its potential implications on the analysis and subsequent negotiations.

Some previous evaluations of the potential importance of stand changing conditions (e.g., severe wildfire impacts on baseline conditions) approached the issue by applying the annual risk to each parcel on an independent basis over the entire recovery period and then comparing discounted level of service with a stationary estimate of discounted baseline services. This approach can result in inappropriate conclusions regarding the potential importance of landscape connectivity and non-stationarity for a couple of reasons. First, the risk of severe wildfire, drought, insect and/or invasive species infestation is not an independent event on a per acre basis in areas of high fire or other risks. Second, changing stand conditions involving the temporary loss of environmental service within a large forest or rangeland could actually result in a benefit from increasing biodiversity, rather than a system loss, if the risk and impact could be restrained to a small area and/or the extent of service loss is more moderate (e.g., maintaining or creating small habitat patches within a healthy landscape and using controlled fire or other management techniques to reduce risks to align more closely with management objectives). We believe the proposed alternative approach would provide much more meaningful information regarding the above issues for complex sites; however, how do we decide when and where to adopt a more rigorous approach has yet to be defined and needs further consideration.

This study has identified two additional policy issues worthy of further research and evaluation to support the proposed methodology, as well as existing approaches, at complex sites. These issues are briefly identified below.

1. *How should we define and equate value for environmental services between resilient and high-risk habitats prior to a significant stand-changing event?* Current approaches to restoration scaling do not adequately differentiate between the expected value of high risk vs. resilient habitats prior to a stand changing event. This also implies that a compensatory restoration project to reduce climate, wildfire, and other risks has no value unless resistance or resilience to a stand changing event occurs in that year. This seems inconsistent with typical management goals for building more resistant and resilient systems. To what extent should future methods consider to restore impaired environmental services based on changes in expected services rather than actual annual services is a topic worthy of further consideration. Furthermore, there is a need to determine how subsequent monitoring and adaptive management should be incorporated into settlement agreements if scaling requirements are defined by changes in expected value.
2. *How should we align the concept of discounting with resource management goals of building resilient, sustainable ecological systems?* If the ultimate goal when building resistance and/or resilience is to improve the likelihood of being able to maintain a consistent level of environmental service and the risk of climate change and other related perturbations is expected to increase significantly overtime, does it make

sense to use a discount factor based on short-term preferences for compensatory restoration? Similarly, how does the use of discounting impact goals to preserve valued cultural resources? Lastly, to what extent will such a policy discourage critical restoration on high risk forests and rangelands whose risks are, and will be, based largely on factors other than the specific perturbation causing the service loss being evaluated?

References

[1] CA Department of Fish and Wildlife (CA DFW). 2010 California Essential Habitat Connectivity Project. (Nov. 24, 2015). https://www.wildlife.ca.gov/Conservation/Planning/Connectivity/CEHC

[2] WA WHCWG. 2010 Washington Wildlife Habitat Connectivity Working Group. http://waconnected.org/habitat-connectivity-mapping-tools/ (Nov. 24, 2015)

[3] Hanson, D.A., E.M. Britney, C.J. Earle, and T.G. Stewart. Adapting Habitat Equivalency Analysis (HEA) to assess environmental loss and compensatory restoration following severe forest fires. Forest Ecology & Management 294 (2013): 166–177.

[4] Hanson, D.A., E.M. Britney, T.G. Stewart, A.W. Wolfson, and M. Baker. Restoration Scaling of Environmental Damages in the Face of a Changing Environment and Uncertainty. WIT Transactions on Ecology and Environment Vol. 181 (2014a): 491–502 (ISSN 1743-3451).

[5] Unsworth, R.E. and R.C. Bishop. Assessing natural resource damages using environmental annuities. Ecological Economics 11 (1994): 35–41.

[6] National Oceanic and Atmospheric Administration (NOAA). Habitat Equivalency Analysis: An Overview. Washington DC, 23 pp. March 21, 1995. October 4, 2000 (Revised) www.cbrestoration.noaa.gov/documents/cbhy-a.pdf

[7] Dunford, R.W., T.C. Ginn, and W.H. Desvousges. The use of habitat equivalency analysis in natural resource damage assessments. Ecological Economics 48 (2004): 49–70.

[8] D.R. Systems. OPTIONS Model (referenced December 8, 2015). http://www.drsystemsinc.com/software_products.php?SID=5

[9] Rohr, J.R. and five others. Implications of global climate change for natural resource damage assessment, restoration, and rehabilitation. Environmental Toxicology and Chemistry 32(1): 93–101, 2013.