Black Hills National Forest

Noxious Weeds Ecological Risk Assessment Report

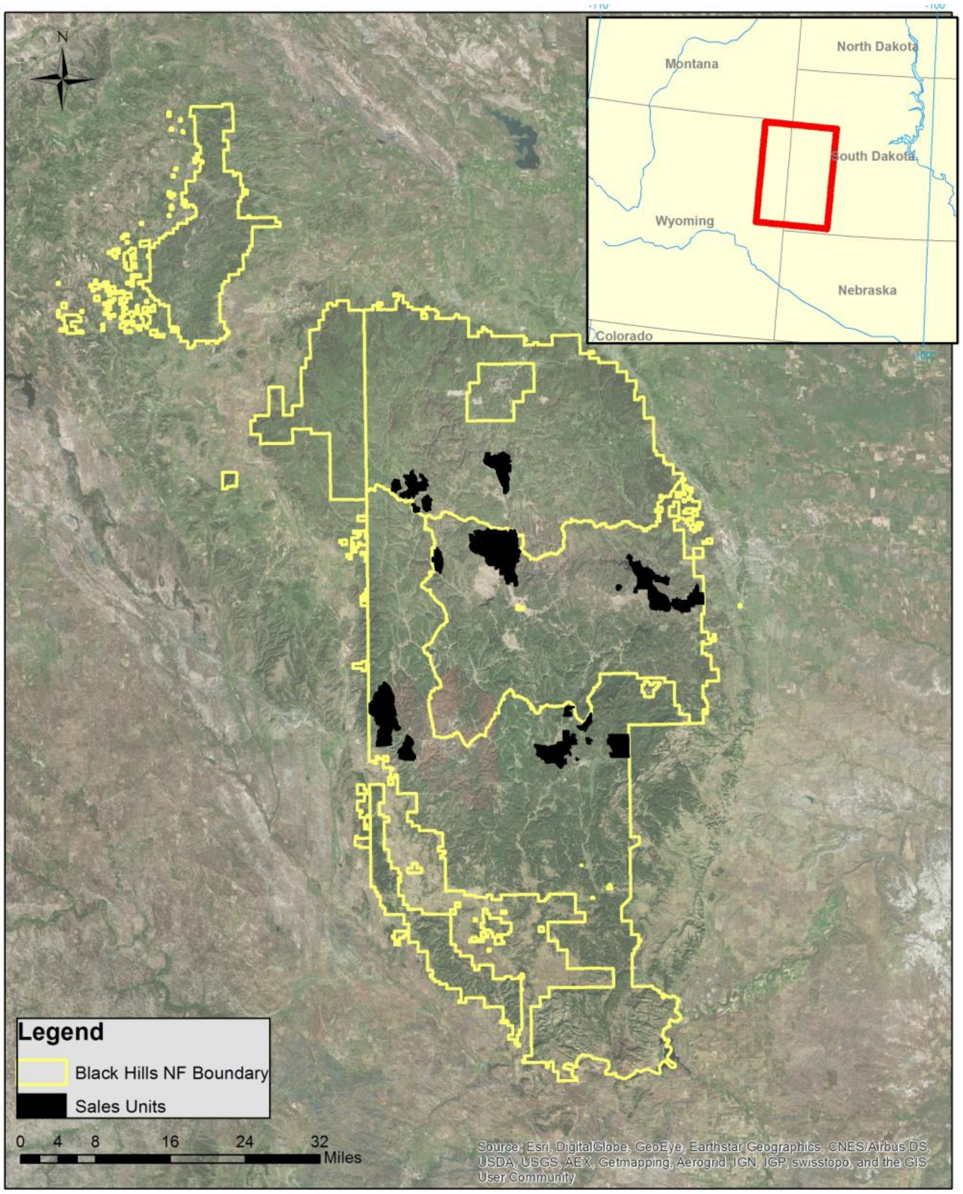

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

Appendix A.	Draft Conceptual Models for the BHNF Ecological Risk Assessment.
Appendix B.	Bayesian Networks for All Regions and Years.
Appendix C.	Input Frequencies for All Input Variables, Regions, and Years.
Appendix D.	CPTs and Supporting Materials; Including List of References.
Appendix E.	Complete Sensitivity Analysis and Influence Analysis Results.

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Special thanks to Jack Butler for providing us with timber sale area monitoring data, spatial data in the form of GIS shapefiles, and aerial images in the Black Hills National Forest region. The modeling and risk analyses would not have been possible without these data. We also greatly appreciate both Jack Butler and Stephanie Wacker working with us to develop the conceptual model for the invasive species ecological risk assessment and answering many questions over the course of our conducting this research project. They were knowledgeable and extremely responsive to us, which greatly facilitated our ability to complete this risk assessment in a timely manner.

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NOTE ON NETICA SOFTWARE

This research used the computer software program Netica^{TM} (Norsys Software Corp. 2014) to construct the Bayesian Networks, calculate relative risks, and evaluate the risk results. A free, limited version of this software is available at https://www.norsys.com/netica.html and can be used to read the models presented in the Appendices. We recommend taking the introductory tutorial at https://www.norsys.com/tutorials/netica/nt_toc_A.htm prior to examining the models.

LIST OF ACRONYMS AND ABBREVIATIONS

BHNF	Black hills National Forest
BN	Bayesian Networks or Bayes Nets
BN-RRM	Bayesian Network Relative Risk Model
CPT	Conditional Probability Table
EPA	Environmental Protection Agency (US EPA)
ERA	Ecological Risk Assessment
GIS	Geographic Information Systems
HPDP	Hierarchical Patch Dynamics Paradigm
NIS	Non-Indigenous Species
PPD	Posterior Probability Distribution
RRM	Relative Risk Model
USFS	U.S. Forest Service

RISK TERMINOLOGY

The risk assessment terminology used in this report is consistent with the U.S. EPA's framework for ecological risk assessment (U.S. EPA, 1992) and the work of Suter (1993). Additional terminology was derived from peer-review scientific literature, with citations provided at the end of the definitions.

Assessment Endpoint: An aspect of the natural system that is of value to society or the local community, as well as important to the ecology of the system.

Bayesian Networks: Bayesian networks (Bayes Nets or BNs) are directed acyclic graphs that links sources of stressors, habitats and endpoints through a web of nodes using conditional probability to estimate the likely outcome (McCann et al. 2006).

Bayesian network relative risk model (BN-RRM): A relative risk model where the linkages between the conceptual models are described by using a Bayesian network (also called a Bayes Net). (See Ayre and Landis 2012).

Conceptual Model: Diagrammatic description of the interactions stressors have with ecological components and their associated endpoints.

Effect: A change in the state or dynamics of an organism or other components of the ecological system resulting from exposure to a stressor. An indirect effect occurs when the initial effect results in additional stressors or effects to any component of the system.

Exposure: In the formulation of the relative risk model it is the colocation of a stressor with a receptor in a geographic area or habitat.

Habitat: The type of environment in which the receptors are found. Receptors may live exclusively within a single habitat or may move between and use several habitats.

Measurement Endpoint: An effect that is measured (e.g., toxicity test or field survey) and can be used to link the effects of a stressor to the assessment endpoints.

Stressor: Anything that is physical, chemical, or biological in nature which causes an effect to an organism or system. Initial stressors may result in secondary stressors, as in the case of excess nutrient input (initial stressor) causing mortality due to microbial activity and a decrease in oxygen (secondary stressor).

Receptor: The organism or group of organisms that have the potential to be affected by a stressor.

Relative Risk Model: A cause and effect modeling approach used to calculate risk to endpoints due to multiple stressors entering a number of habitats and having an effect on the endpoint(s) (See Landis and Wiegers 1997 and 2005).

Response: The effect on the receptor as a result of exposure to a stressor.

Risk: The probability, actual or relative, of an unwanted effect on a receptor judged by society to be important (Hines and Landis 2014).

Source: An anthropogenic input or activity that releases or creates a stressor in the environment. The characteristics of a stressor may be influenced by the type of source.

Uncertainty: There are two types of uncertainty we can address in ecological studies: epistemic and linguistic uncertainty (Regan et al. 2002). Uncertainty addressed in this risk assessment is mainly epistemic uncertainty.

> *Epistemic uncertainty* – This includes uncertainty of the knowledge of the state of a system. This could be limitations from measurement devices or uncertainty due to scarce data, extrapolation, and variability in spatial and temporal scales.

Linguistic uncertainty – This is the uncertainty due to the language and vocabulary used in scientific writing. This vocabulary can be very technical and context dependent. At times it can also be ambiguous and vague.

EXECUTIVE SUMMARY

We conducted a regional-scale ecological risk assessment (ERA) using the Bayesian Network Relative Risk Model (BN-RRM) to characterize the risk of *Cirsium arvense* (Canada thistle) invasion related to forestry activities in the Black Hills National Forest (BHNF). This project was conducted in collaboration with and support from the United States Forest Service (USFS). The goal of this project was to identify the spatial and temporal patterns of risk from Canada thistle introduction and establishment in the study area to support the USFS's forest management goals and decision-making needs.

The Black Hills National Forest is located in Western South Dakota and Northwestern Wyoming and encompasses an area of approximately 8000 sq. miles. The USFS manages the BHNF for species conservation, including timber sales, recreational activities, and the control of noxious weeds (Keely, 2006, Wacker and Butler, 2012). One noxious weed of management concern in the BHNF is Canada thistle, a non-indigenous plant that is highly invasive and is widespread throughout the BHNF.

Risk of invasion is influenced directly and indirectly by forestry activities in the BHNF, which include road building, tree and understory vegetation removal, slash pile burning, and soil compaction and disturbance. This risk assessment focused on the risk of Canada thistle invasion in four timber sale areas within the BHNF: Dark Canyon, Thrall, Mercedes, and Powerpole. The assessment encompassed a three year timeframe: time of timber harvest (Year 0), one year after harvest (Year 1), and three years after harvest (Year 3).

There were four specific findings from this invasive species ecological risk assessment:

- First, risk of Canada thistle invasion changes over time, with greatest risk occurring in either the first or third year after logging, depending on the harvest practices used in the timber sale area. Risk is present even before logging activities occur (Year 0) due primarily to historical logging impacts, roads, and proximity to other cutting areas.
- Secondly, risk differs between sale areas and is influenced by both logging management practices and location. Risk is higher in whole-tree harvest areas: Dark Canyon, Powerpole and Thrall sales and lower in the Mercedes conventional harvest timber sale area. Forestry activities will directly and indirectly alter the native understory and overstory vegetation, which increases the risk of Canada thistle establishment. The location of a timber sale area relative to other disturbed areas will contribute to the risk of invasive species establishment.
- Third, the availability of extensive spatial data reduced the uncertainty in this regional scale risk assessment. Geographic information systems (GIS) shapefiles and aerial images were used to develop the conceptual models, inform the BN-RRM and calculate risk. Risk communication benefitted from the spatially explicit nature of the data analysis and BN-RRM framework.
- Finally, the BN-RRM framework can be applied to assess risk of invasion by other species of management concern in the BHNF and at other USFS sites. The models developed as part of this ERA could be modified to assess risk of invasion by other noxious weeds or non-indigenous species in the BHNF.

INTRODUCTION

Background

The U.S Forest Service Rocky Mountain Region is comprised of 17 national forest and 7 national grasslands. The Black Hills National Forest (BHNF) is located in Western South Dakota and Northwestern Wyoming. It encompasses an area that is approximately 125 miles long and 65 miles wide (200 km by 105 km).

The U.S. Forest Service (USFS) manages the BHNF for species conservation, including timber sales, recreational activities, and the control of noxious weeds. Some of these activities, specifically logging practices and associated road-building, coupled with natural disturbances such as wildfires, have made the Black Hills region susceptible to the establishment and proliferation of non-indigenous species (NIS) (Keely 2006, Wacker and Butler 2012).

Those NIS identified as noxious weeds are a management priority for USFS managers and other stakeholders. They grow aggressively, reproduce quickly without natural controls on their proliferation, and cause adverse effects on other species and changes to the physical and chemical environment. As such, they pose significant threats to forests and rangelands managed by the USFS. To address these threats and mitigate their effects in the Black Hills National Forest, the USFS has recognized the need to identify the risks posed by permitted anthropogenic disturbances in the region that may be potentially increasing the introduction and spread of noxious weeds.

For this ecological risk assessment (ERA), we selected *Cirsium arvense* (Canada thistle) as the indicator species to focus on due to its classification as both a NIS and noxious weed in the BHNF. It is a perennial broadleaf weed that originated in Europe and has since spread throughout the United States and Canada (Moore 1975, Zouhar 2001, Becker et al. 2008). Canada thistle is known for its resilience to eradication once it becomes established in an area, as well as its ability to grow almost anywhere.

It is usually introduced to areas that have recently been disturbed and are adjacent to other established patches of Canada thistle (Heimann and Cussans 1996, Zouhar 2001, Becker et al. 2008). Its propagating root system allows for its rapid spread from established patches (Donald 1994, Zouhar 2001). Canada thistle also produce seeds that can be dispersed by the wind, as well as through human and animal transport to uncolonized areas (Heimann and Cussans 1996, Zouhar 2001, Becker et al. 2008). Once established, it has been shown to significantly decrease native plant cover and plant species diversity within an area (Zouhar 2001).

Canada thistle is managed as a noxious weed in the BHNF and is a specific management priority in areas that have been harvested for timber (USFS 2010a). Recently logged areas are susceptible to noxious weed establishment and are often in close proximity to other disturbed areas or sources patches of established Canada thistle. The results of this ecological risk assessment will allow BHNF managers to better understand, and thereby mitigate, risks associated with the introduction and spread of Canada thistle.

In 2014, Jack Butler, Research Ecologist for the USFS Rocky Mountain Research Station and Grassland Research Laboratory initiated communications with our research team regarding the need for an ecological risk assessment (ERA). In collaboration with Nancy Grulke, Director of the Western Wildland Environmental Threat Assessment Center, our project officer with the USFS, we communicated with Dr. Butler to identify the objectives and purpose of this proposed study.

BHNF ERA Research Objectives

The overall objectives of this research project that were identified in early fall of 2014 are as follows:

- Evaluate the effects of timber harvest on trends in 1) invasive plant populations within harvested units and 2) the spread of invasive plants from those harvested units

- Provide USFS managers the information they need to manage noxious weeds in the timber harvest areas, as well as along roads and boundary areas between the harvest plots and adjacent non-harvest areas.

From those overall objectives, we identified the following study question that could be addressed within the scope of this assessment using the data that were available to us.

Study Question: How do timber harvest practices (and associated disturbance factors) alter the risk of Canada thistle spread and establishment in the BHNF?

Using monitoring data from BHNF vegetation surveys and spatial data documenting the location and cover of logging activities within the forest, we assessed the risk of Canada thistle spread and establishment over both space (by timber sale) and time (by year). Findings from this study can be applied to the management of Canada thistle, as well as other noxious weed species within the BHNF.

Regional Risk Assessment and the Relative Risk Model

The ecological risk assessment of the fjord of Port Valdez that was conducted by our research group led to the development of the relative risk model (RRM) (Wiegers et al. 1998, Landis and Wiegers 2005). The impetus for the development of the method was the necessity to incorporate multiple sources with multiple stressors within multiple, diverse habitats in the landscape that were potentially affecting multiple assessment endpoints within the fjord, as well as in the surrounding watershed. At that time there was not a suitable framework to use on such a complex site at a landscape scale.

The basis of the RRM is a conceptual model that identifies (from left to right) sources of stressors, the individual stressors, linkages of the stressors to ecological receptors, and the resulting impacts on receptors (endpoints) within large spatial scales. Due to the spatially explicit nature of the relative risk model, risk gradients are revealed across the study area. The RRM method has been applied to assess a variety of stressors and combinations of stressors including contaminants, disease, environmental parameters, and non-indigenous species in a number of studies since its development (Hayes and Landis 2004, Colnar and Landis 2007, Ayre and Landis 2012, Hines and Landis 2014, Ayre et al. 2014).

Colnar and Landis (2007) introduced the most current version of the RRM framework. This version described how the hierarchical patch dynamics paradigm (HPDP), as formulated by Wu and David (2002), could be used to conceptualize how spatial scales, dynamic ecological processes, and habitats interact. The HPDP considers both site-specific and regional-scale stressors that may act upon the endpoint or endpoints (Wu and David 2002, Colnar and Landis 2007, Landis et al. 2010). The HPDP and the RRM were integrated by Colnar and Landis (2007) to create the hierarchical invasive risk model (HIRM) (Colnar and Landis 2007). It was used to assess risk to local ecological endpoints from two invasive species at Cherry Point, WA: 1) the European green crab (Hayes and Landis 2004, Landis 2004, Landis et al. 2005, Colnar and Landis 2007) and 2) *Sargassum muticum* (Seebach et al. 2010). More recently, Anderson and Landis (2012) provided an extensive demonstration of how this method could be applied with the inclusion of management options for a USFS managed forest system.

Bayesian Network Relative Risk Model (BN-RRM)

In order to describe the probabilistic nature of risk, Bayesian networks (BNs) have recently been applied to the calculation of risk in the RRM (Ayre and Landis 2012, Hines and Landis 2014, Ayre et al. 2014). The BNs link cause and effects through a web of nodes using conditional probability to estimate the likely outcome (McCann et al. 2006). Bayesian networks are now used increasingly in risk assessment (Uusitalo et al. 2007, Hart and Pollino 2008) because this tool inherently deals with cause-effect relationships, as well as incorporates uncertainty and enables the use of combinations of available data and expert knowledge (Uusaitalo et al. 2007). Bayesian belief and decision networks also work well as modeling tools for adaptive management (Nyberg et al. 2006). The causal structure of the RRM can be directly translated into the tiered node structure of a BN (Ayre and Landis 2012, Hines and Landis 2014).

Bayesian networks are comprised of nodes and linkages, which are adapted to reflect the components and causal pathways of the RRM. In the BN, nodes represent variable or parameters, and links represent the relationships between two or more nodes. Tighe et al. (2013) provides definitions for the basic components of a BN. In this study, the BN is structured (from left to right) of input nodes (i.e., parent nodes) based on site-specific data, intermediate nodes that include summary nodes reflecting combinations of intermediate nodes, and an endpoint node with the risk calculation (score) for that endpoint.

Invasive Species Risk Assessment and Modeling

Ecological risk assessment can be used to support invasive species research and management (Andersen et al. 2004, Landis 2004, Bossenbroek et al. 2005, Kerns and Ager 2007, Linder and Little 2010). An invasive species risk assessment requires a spatially explicit, probabilistic approach (Andersen et al. 2004, Landis 2004, Landis et al. 2010, Linder and Little 2010, Stohlgren et al. 2010). As such, certain characteristics of invasive species risk assessment diverge from the traditional US EPA risk assessment approach. Though the US EPA framework can be modified for conducting an invasive species risk assessment, other risk frameworks (Landis and Wiegers 2005, Venette et al. 2010) are more compatible for addressing biological stressors in a probabilistic large scale landscape relevant to an invasive species risk assessment. Landis et al (2010) summarized the traits of invasive species risk assessment using the RRM that are comparable to the more traditional contaminant-based ecological risk assessments.

There are three specific characteristics of an invasive species risk assessment. First, the study of invasive species is inherently on a landscape-scale, requiring spatial analysis tools and spatially explicit data. An invasive species risk assessment therefore requires a spatially explicit approach and applicable environmental data for the region to reduce uncertainty and increase robustness in the risk estimates (Andersen et al. 2004, Landis 2004, Linder and Little 2010, Stohlgren et al. 2010). Habitat mapping supports the data needs of an invasive species risk assessment by overlaying multiple variables (or data layers) for visualization and data analysis (Stohlgren et al. 2010). Similarly, spatially explicit modelling may enhance the predictive capabilities of an invasive species risk assessment (Deines et al. 2005, Sikder et al 2006).

Second, the spread of invasive species across the landscape is inherently probabilistic (Landis 2004, Sikder et al 2006, Kerns and Ager 2007, Linder and Little 2010, Landis et al. 2010, Seebach et al. 2010). Heterogeneous landscapes and stochastic processes are not easily or accurately accommodated by contaminant-based deterministic risk assessment frameworks. As such, predicting the spread of invasive species requires a probabilistic approach like the RRM method that considers sources of uncertainty, as well as variability in environmental responses to biological and contaminant stressors (Linder and Little 2010, Landis et al. 2010, Seebach et al. 2010).

Third, an invasive species risk assessment requires a multiple stressor approach (Andersen et al. 2004, Landis 2004, Linder and Little 2010, Landis et al. 2010, Seebach et al. 2010). The introduction, establishment and spread of an invasive species is influenced by many factors that are both directly and indirectly related to the species in question. Characteristics such as dispersal mechanisms, propagation/transport distance, habitat requirements, competitive advantages, and specialist/generalist tendencies alter the species' ability to spread and become established in new patches (Andersen et al. 2004, Landis 2004, Deines et al. 2005, Kerns and Ager 2007, Landis et al. 2010, Seebach et al. 2010). Additionally, characteristics of the receiving landscape will determine whether the invasive species is successful. These characteristics may include community structure of native and non-native organisms, disturbance regimes, connectivity and patchiness in the landscape, habitat type, and environmental conditions, such as elevation and precipitation (Andersen 2004, Landis 2004, Deines et al. 2005, Sikder et al 2006, Linder and Little 2010, Landis et al. 2010, Seebach et al. 2010, Stohlgren et al. 2010).

The RRM has been used previously to assess the risk of non-indigenous or invasive species (Landis 2004, Colnar and Landis 2007, Landis et al. 2010, Seebach et al. 2010, Ayre et al. 2014, Herring 2015). Specifically, Landis (2004) provided the foundation for the RRM as a tool for invasive species risk assessment in two case studies: 1) bacterial genetics using the patch-dynamics framework and 2) population dynamics of the invasive European green crab (*Carcinus maenas*) at Cherry Point, WA, that was developed further by Colnar and Landis (2007). Landis et al. (2010) continued work in nonindigenous species risk assessment with two case studies that evaluated 1) the potential risk to indigenous species from Asian oysters inadvertently released from aquaculture facilities in Chesapeake Bay, MD, and 2) the potential risk to five indigenous species should the Nun moth, *Lymantria monacha*, inadvertently be introduced in the Mid-Atlantic region, USA.

Other modifications to the invasive species risk assessment model were implemented in subsequent research studies by our research team. Seebach et al (2010) evaluated the ecological risks of the spread of the invasive seaweed *Sargassum muticum* at Cherry Point, WA. Ayre et al. (2014) adapted the RRM for use with Bayesian networks to assess the risk of whirling disease, caused by the parasite *Myxobolus cerebralis*, in wild trout populations of the western USA. Herring et al. (2015) applied the BN-RRM to evaluate the risk of non-indigenous species in the Padilla Bay National Estuarine Research Reserve.

The current BN-RRM model we used to conduct the Black Hills National Forest ecological risk assessment is therefore the culmination of years developing, applying, and improving our RRM models and spatial analysis tools.

BHNF ERA Results - Summary

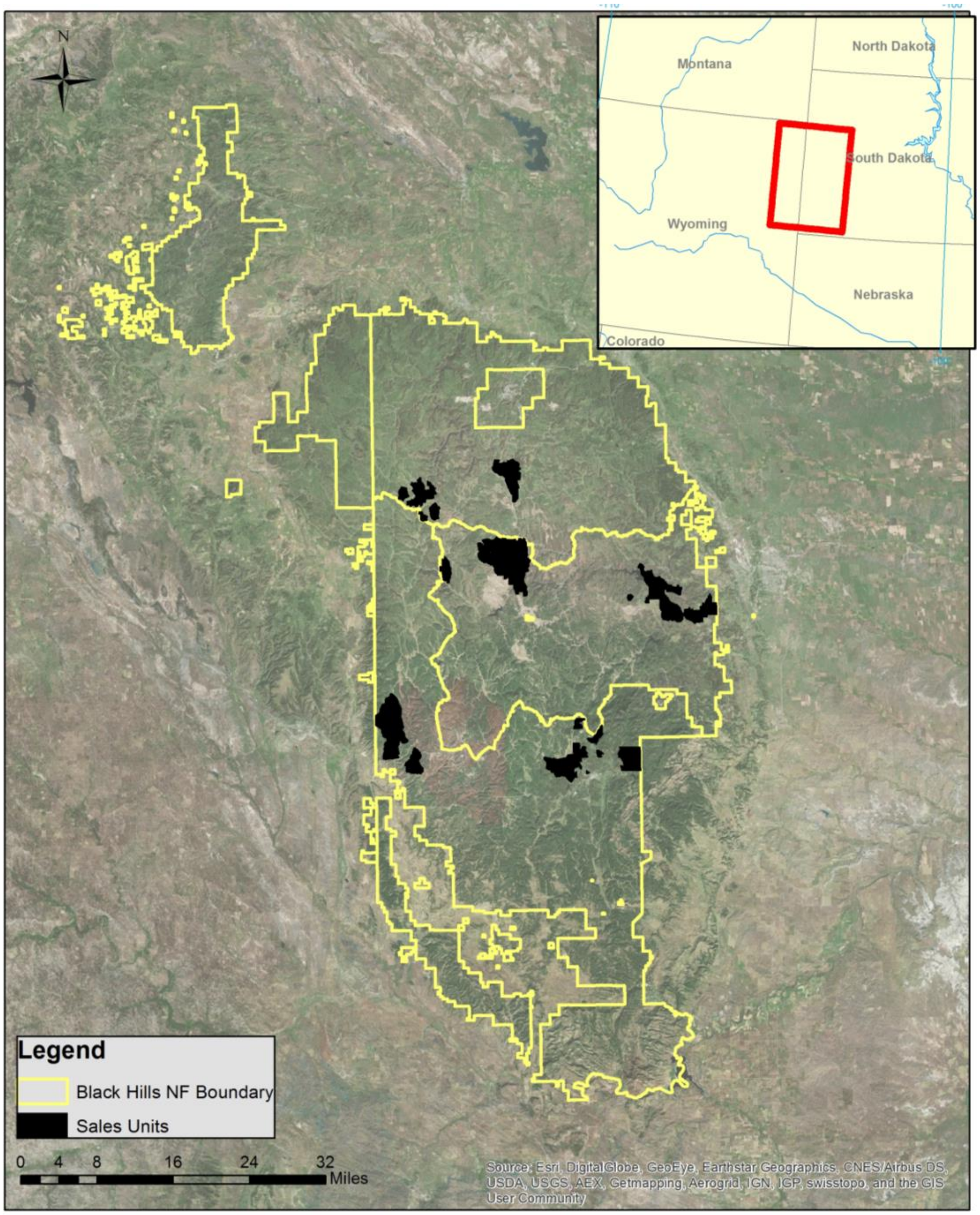
This risk assessment focuses on the risk of *Cirsium arvense* (Canada thistle) invasion in four timber sale areas within the BHNF: Dark Canyon, Thrall, Mercedes, and Powerpole. Risk of invasion is influenced by forestry activities in the BHNF, which including road building, tree and understory vegetation removal, slash pile burning, and soil compaction and disturbance. We assessed risk for four timber sales over three years (time of timber harvest, one year after harvest, and three years after harvest. In summary, the results of the BHNF ERA are as follows:

1. Risk of Canada thistle establishment differs over time, with greatest risk occurring in either the first or third year after logging, depending on the timber sale. Risk is present even before logging activities occur (Year 0).
2. Risk differs between sale areas and is influenced by both management and location. Regrowth of the native understory and overstory vegetative species decreases risk of Canada thistle establishment over time. Timber sales in close proximity to other disturbed areas will be at higher risk of establishment than areas that are isolated.
3. Spatial data (i.e. monitoring data, geographic information system shapefiles, and aerial images) reduced the uncertainty of the regional scale risk assessment.
4. The BN-RRM framework can be applied to assess risk due to the introduction, spread, and establishment of other species that are management priorities for the BHNF and other USFS sites.

METHODS

Study Area

This study focused on four timber sales plots (Dark Canyon, Mercedes, Powerpole, and Thrall) that are a subset of the thirteen sale plots located in the BHNF (Figure 1). Each timber sale represents a risk region, as defined by Landis and Wiegers (2005).



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 1. Map of the Black Hills National Forest with the four timber sales: Dark Canyon, Thrall, Mercedes, and Powerpole.

Dark Canyon, Thrall, and Mercedes are located in the Mystic Ranger District, whereas Powerpole is located further northwest in the Northern Hills Ranger District. The Dark Canyon and Thrall sale areas are located on the eastern border of the BHNF and share a sale boundary. The Mercedes sale is located approximately 12 miles (21 km) west of Thrall. Powerpole is approximately 5 miles (8.5 km) northwest of Mercedes (Jack Butler *pers. comm.*, 2015). Powerpole is comprised of four smaller sale units, in close proximity (less than one mile) to each other. Thrall is the largest of the four sales (11.49 sq. miles). Powerpole and Mercedes are slightly smaller (7.83 and 7.62 sq. miles, respectively), and Dark Canyon is the smallest (4.85 sq. miles) (Jack Butler *pers. comm.*, 2015).

The timber harvest practices in each sale area influences the degree of soil disturbance and may impact the regeneration of timber species, as well as increase the risk of NIS establishment. Dark Canyon, Thall, and Powerpole are whole-tree harvest sites, whereas Mercedes is a conventional harvest site (Jack Butler *pers. comm.*, 2015). Conventional harvest methods leave limbs and branches as slash on the forest floor to decompose, whereas whole-tree harvest removes the entire tree and limbs from the harvest site, leaving behind large swaths of bare soil. Slash from the delimbing process is usually stacked in large slash piles near timber landings and roadways where they may be burned on-site or sold as wood residue for energy production (Roxby et al. (2015). Slash piles are therefore more numerous in whole-tree harvest areas compared to conventional harvest areas. This is true in the study area where there are 9 to 21 slash piles associated with the Dark Canyon, Thall, and Powerpole study plots compared to a single slash pile in the Mercedes plot (Jack Butler *pers. comm.*, 2015).

The effects of these harvest methods on soil, biota, and forest productivity are still not well known (Roxby et al. 2015). A number of studies of whole-tree harvest methods have shown reductions in soil nutrients (Vanguelova et al. 2010), changes in seed bank composition, and declines in local songbird populations compared to nearby conventional harvest sites (Lohr et al. 2002). Other studies have found decreased forest productivity and timber regeneration rates in whole-tree sites as well, compared to conventionally harvested sites, however other studies have not detected this effect (Roxby et al. 2015).

Assessment Endpoint Selection

Through communications with the BHNF managers, we identified a list of potential endpoints for this assessment and selected a single endpoint: Canada Thistle Establishment[1]. Canada thistle was selected as the endpoint for this assessment due to the abundance of data on the species and management priority as a noxious weed within the BHNF. It was also agreed that Canada thistle

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[1] When referred to in the text as the endpoint, Canada Thistle Establishment, it is capitalized. Other variables in the BNs are capitalized when referring to the specific title of the BN node. These variables are not capitalized when they are discussed more generally.

represents an appropriate surrogate for other noxious weed species in the BHNF, given its natural history, dispersal patterns, and current distribution within the BHNF.

Invasive species ecology defines four distinct stages of biological invasion: 1) entry, 2) establishment, 3) spread, and 4) impact(s) to the receiving environment (Andersen 2004). Canada thistle has already entered the BHNF and has spread throughout much of the landscape (USFS 2010a, Wacker and Butler 2012). For the purposes of this assessment, we focused on the other three stages of biological invasion.

Establishment and spread of an invasive species like Canada thistle follows classic metapopulation and patch dynamic models where newly established patches become sources from which nearby patches are formed (Andersen et al. 2004, Landis 2004, Deines et al. 2005, Lenda et al. 2010). At times these two processes can co-occur and have been modeled in a number of contexts (Deines et al. 2005, Gallien et al. 2010, Lenda et al. 2010). Impacts to the receiving environment will depend on the rate of biological invasion, the total vegetative cover of the invasive species, the competitiveness of it relative to native and non-native plant communities, and site-specific environmental conditions (Andersen et al. 2004, Landis 2004, Deines et al. 2005, Sikder et al 2006, Kerns and Ager 2007, Stohlgren et al. 2010).

Though the risk of Canada Thistle Establishment and total Canada thistle cover are certainly related, they are not synonymous variables. Figure 2 provides a generic example of their relationship in which risk decreases over time while the patch of Canada thistle continues to grow (total cover increases). The rate at which the Canada thistle patch is expanding, however, decreases over time with reduced risk of further introduction and establishment.

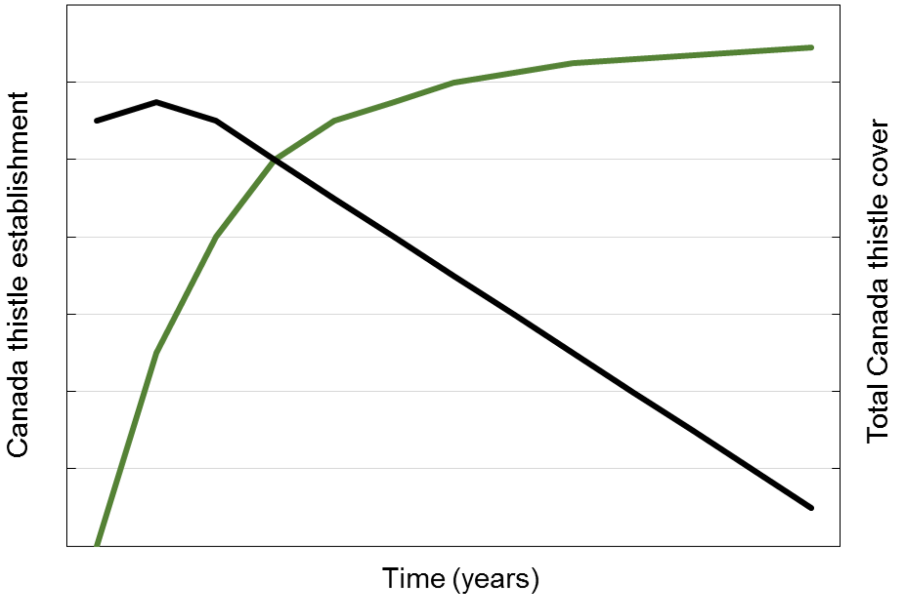

Figure 2. Canada Thistle Establishment (black line) compared to Canada thistle percent cover (green line).

Temporal Scale

The risk of Canada Thistle Establishment is likely to change over time, from the disturbance event (logging) through the process of regrowth and secondary succession (Zouhar 2001). USFS managers are interested in both the short- and long-term risk of Canada Thistle Establishment after sale areas are harvested for timber (USFS 2010a). Understanding the current and future relative risk will allow managers to prioritize management actions and track changes in risk as actions are implemented.

Working with BHNF managers and based on the data provided to us, we selected three datasets to use in the risk assessment based on time of timber harvest: actual time of timber harvest (Year 0), one year after harvest (Year 1), and three years after harvest (Year 3). Complete datasets existed for each of these years, thereby reducing uncertainty in the risk calculations. When additional data are collected for Years 5 and 7 post-logging, BNs could be created for these times as well.

Conceptual Model

We worked directly with USFS managers and scientists Jack Bulter (BHNF), Nancy Grulke (USFS), and Stephanie Wacker (currently at Yellowstone National Park) to develop a conceptual model for assessing risk of Canada Thistle Establishment in the BHNF (Figure 3). This conceptual model was subjected to multiple revisions to ensure that it 1) incorporated relevant factors affecting Canada Thistle Establishment in the BHNF, 2) represented known causal relationships and 3) captured the relevant interactions and relationships in such a way that the end results would meet the needs of the risk managers. Additional documentation of the model construction process can be found in Appendix A.

Evaluation of potential stressors in the four BHNF sale's plots began with a comprehensive literature search for information and data regarding site-specific stressors, Canada thistle biology, logging practices, and forest ecology. After identifying stressors (and sources of those stressors) in the study area, we linked them to site specific habitats and pathways of exposure to create the conceptual model. This methodology follows that of the RRM (Landis and Wiegers 2005).

The sources of stressors in the conceptual model were categorized into three separate modules (boxes): (1) logging (direct effects) (creation of roads, slash piles, increased percent-disturbed area), (2) logging (indirect effects) (decrease/elimination of native and exotic understory vegetation, overstory vegetation) and (3) locational factors (proximity to other disturbed areas). A review of scientific literature and governmental reports was conducted to ensure that each source of stressor could be linked causally to the risk of Canada Thistle Establishment. Intermediate boxes in the conceptual model were used to summarize the individual pathways and link the stressors to the endpoint.

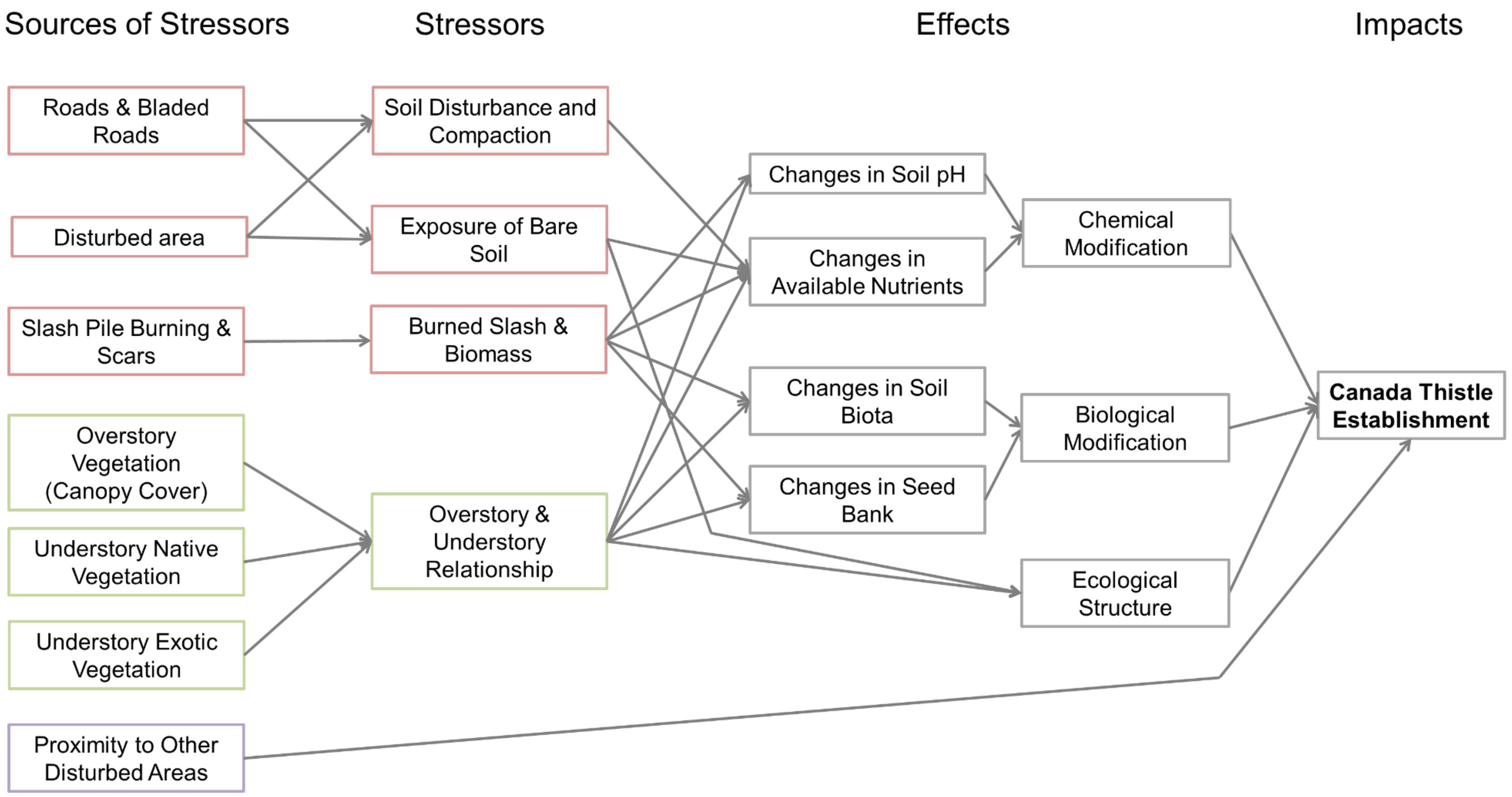

Figure 3. Conceptual model for the risk of *Cirsium arvense* (Canada thistle) establishment with forestry activities in the BHNF. There are three pathways from sources and stressors: (1) the pink nodes represent direct effects of timber harvest, (2) the green nodes represent indirect effects of harvest through vegetation cover and species, and (3) the purple node represents locational factors that affects the dispersal and distribution of Canada thistle.

Bayesian Network- Relative Risk Model

The structure of the BN-RRM was derived directly form the conceptual model (Figure 4). The BNs maintain the tiered nature and linear flow of the conceptual models. Each box in the conceptual model became a node in the BN, an input (parent node), an intermediate variable (child node), or endpoint (final child node). Arrows in the conceptual model, which represent cause and effect relationships, were translated into the BN as linkages. In creating the BNs, we followed the guidelines outlined by Hosack et al. (2008) and Marcot et al. (2006), using the metrics of model complexity to test the structure, performance, and parsimony of the BNs (Marcot 2012). Bayesian networks were created for each of the four timber sale areas for Year 0, Year 1, and Year 3, resulting in a total of 12 BNs.

For this research, we use the software Netica™ (Norsys Software Corp. 2014) to construct the BNs, calculate relative risk, and evaluate the risk results. A limited mode version of this software is available for free download (https://www.norsys.com/netica.html). It can be used to open the models that are presented in Appendix B, as well as the probability distributions for each input variable used in the BNs that are listed in Appendix C.

Data to Inform the Model

The BN-RRM framework uses data to parameritize the variables in the model and the relationships between variables. This process can be divided into three steps, which are described in further detail in the following paragraphs. First, a ranking scheme is set for all input (parent) nodes. Then, site-specific data are used to set the probability distributions of states in each input node. Finally, the relationships between input nodes are defined, and these relationships are quantified in conditional probability tables (CPTs). The sources of data used in this model are documented in Tables 1 through 3 and in Appendix D. (Additional information is available on request.) Site-specific monitoring data and USFS spatial files were obtained from Jack Butler at USFS.

1. Set a ranking scheme for each node (parent and child nodes).

Each variable (node) in the model was discretized into states, or ranks. In most cases, we followed the zero, low, medium, high ranking scheme, which has been used in previous risk assessments by Hayes and Landis (2004), Colnar and Landis (2007), Hines and Landis (2014), and Herring and Landis (2015). Using this scheme, states were assigned a numeric ranking value (Zero=0, Low=2, Medium=4, High=6). For some nodes, three states were preferable to four states to more accurately reflect natural breaks in the data or management decisions.

Ranking schemes for each input node were set using peer-reviewed literature, governmental reports, USFS data, or a combination thereof. A review of the site-specific data ensured that each ranking scheme was comparable to the data for that variable. Table 1 presents the ranking

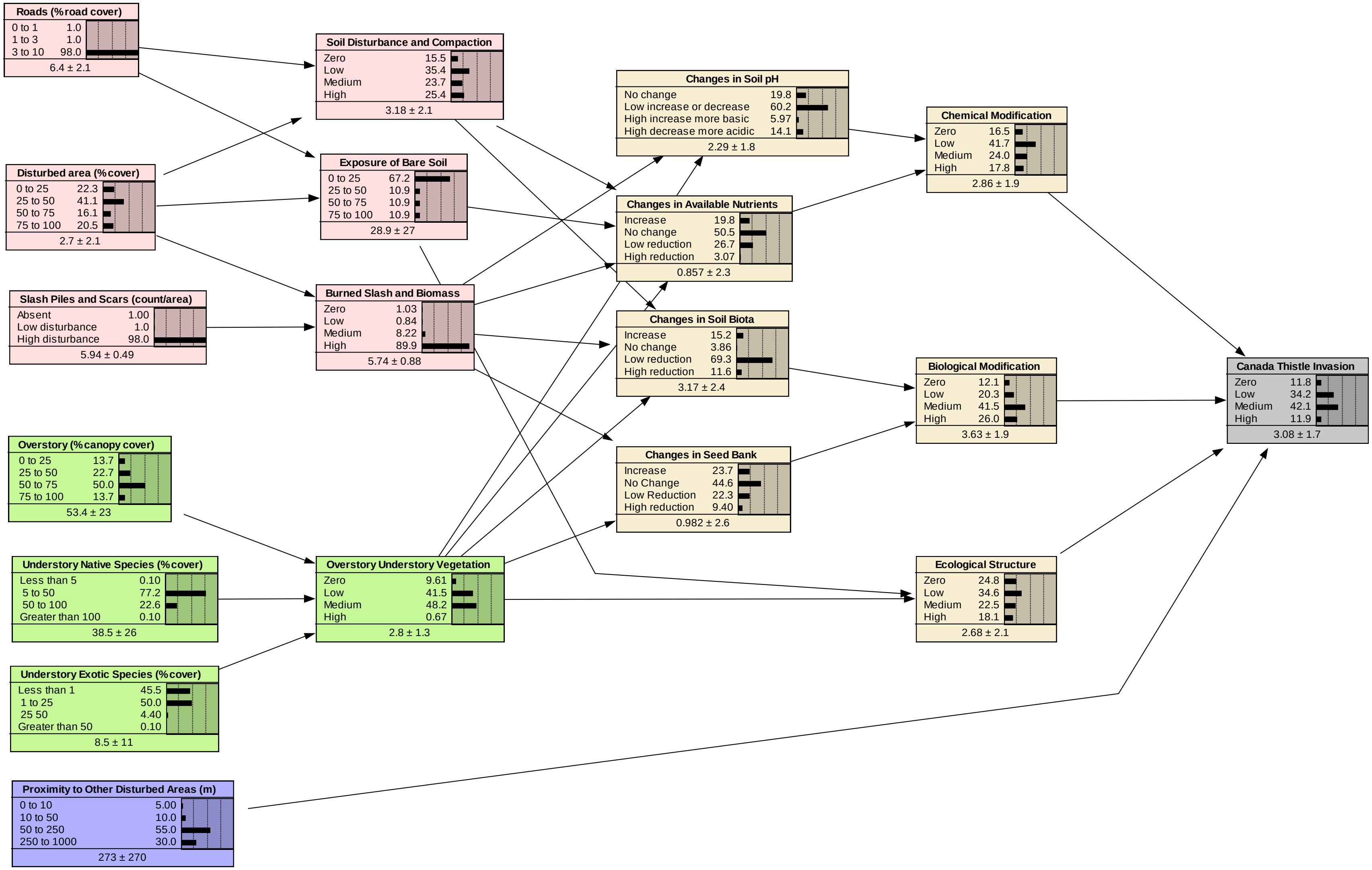

Figure 4. Example of Bayesian network for Dark Canyon Year 3. The BN maintains the structure of the conceptual model and the three colored pathways (pink, green, and purple) are consistent with the conceptual model (Figure 1).

schemes for each input variable along with a definition of the variable and a justification for each of the breakpoints between the variable states.

For example, the Proximity to Disturbed Area node is divided into four states: 0-10 meters, 10-50 meters, 50-250 meters, and 250-1000meters (Table 1). These distances are based on Canada thistle dispersal mechanisms and dispersal distances, as documented by Skarpaas and Shea (2007). The ranking schemes for the vegetation nodes (Overstory Vegetation, Understory Native Vegetation, Understory Exotic Vegetation) were based on ranges, corresponding to those of the monitoring data collected for that parameter (e.g., a 0-100% range for Overstory Vegetation as opposed to a 0-50% range for Understory Exotic Vegetation) (Table 1).

2. Set the probability distribution for each input (parent) node using site-specific data.

The BN for Canada Thistle Establishment has seven input variables (Table 1) that reflect site-specific sources of stressors. For each input variable, site-specific monitoring data (e.g. vegetation surveys) or spatial data (e.g. road and slash pile locations) were used to populate the ranks, i.e., states determined for that variable. The result was a unique distribution curve within each node defined by the pattern of the populated ranks (states) within that node. The distribution curve in a node is therefore different for each risk region and year, depending on the data for that site and time period (Appendix C). The data were provided by the USFS in three different formats: tabular monitoring table, GIS shapefiles, and aerial images (Table 2).

Tabular monitoring data from vegetation surveys were used to set the probability distributions for the vegetation nodes (Overstory Vegetation, Understory Native Vegetation, Understory Exotic Vegetation). Vegetation monitoring data were collected from sampling locations with each of the timber sale areas at three times (Year 0, Year 1 and Year 3).

Spatial data on the location and percent cover of roads, the location and size of slash piles, and proximity of sale areas to other disturbed areas were taken from GIS shapefiles provided by USFS. Metadata for the GIS shapefiles provided additional information on the source of the data and the years the data were collected.

Aerial images in GIS format were used to determine the probability distributions for the Disturbed Area node. Aerial images exist for the BHNF for each year from 2008 to 2013. These images were used to compare changes in percent cover of a disturbed area after logging activities as regrowth occurred over time. Aerial images were compared to the GIS shapefiles to confirm the location of roads, slash piles, and other anthropogenic or natural landmarks within the sale areas.

3. Complete a conditional probability table for each intermediate and endpoint node to describe and quantify the relationships between two or more variables.

Lines or arrows connecting nodes in the BN were based on known cause-effect pathways and were derived directly from the conceptual model. In the BN, each line connecting two or more input nodes to an intermediate node relied on a CPT to quantify the causal relationships and calculate the probability distributions in the intermediate node.

Table 1. Definitions of model inputs for all sources of stressors.

Input Variable	Definition	Ranking	Justification	References
Roads	Percent cover of roads in timber sale area (including 25 m road buffer)	0 - 1% 1 - 3% 3 - 10%	Roads and road buffers are vectors of exotic spp. transport; road buffers are susceptible to establishment by Canada thistle and other exotics. Ranking is based on Tinker et al 1998, McGarigal et al. 2001, and Wemple et al. 2001	Buckley et al. 2003 Fowler et al 2008 Forman and Alexander 1998
Disturbed Area	Percent of timber sale area disturbed through logging activities	0 - 25% 25 - 50% 50 - 75% 75 - 100%	Disturbance is a function of total area impacted by logging activities. Disturbance includes skid trails, logged areas, and landing/loading decks. Disturbance was estimated from aerial images. Ranking is set as equal intervals.	Williamson and Nielsen 2000 Buckley et al. 2003
Slash Piles and Scars	Ratio of Area of slash piles to Area of timber sale unit	0 - < 0.1% Low - < 1% High - > 1%	Area of slash piles relative to total are of the timber sale unit. Ranking is based on natural breaks in the data.	Haskins and Gehring 2004, Korb et al. 2004, Creech et al. 2012, Halpern et al 2014
Overstory Vegetation	Percent canopy cover, predominantly Ponderosa Pine (*Pinus ponderosa*)	0 - 25% 25 - 50% 50 - 75% 75 - 100%	Canopy Cover is inversely proportional to understory/overstory vegetation. Shading decreased the likelihood of establishment by Canada thistle and other exotics. Ranking is set as equal intervals.	Abella and Covington 2004
Understory Native Vegetation	Percent cover of native understory vegetation	0 - 5% 5 - 50% 50 - 100% > 100%	Greater percent cover of native species decreases likelihood of establishment by Canada thistle and other exotics. Ranking is based on ranges corresponding to those of the monitoring data collected for that parameter.	Abella and Covington 2004
Understory Exotic Vegetation	Percent cover of exotic understory vegetation	0 - 1 % 1 - 25% 25 - 50% > 50%	Greater percent cover of exotics increases likelihood of Canada thistle establishment throughout the remainder of the timber sale unit. Ranking is based on ranges corresponding to those of the monitoring data collected for that parameter.	Abella and Covington 2004
Proximity to Other Disturbed Areas	Proximity to nearest disturbance (road or sale unit) in meters	0 – 10 10 – 50 50 – 250 250 - 500	Proximity to a source patch will increase the likelihood of Canada thistle introduction and spread. Numerical ranges for the ranking scheme are based on Canada thistle dispersal mechanisms and distances.	Skarpaas and Shea 2007

Table 2. Data sources for input variables. Obtained from Jack Butler pers. comm., 2015.

Input variable	Definition	Description of Data	Years
Roads	Percent cover of roads in timber sale area	GIS shapefile: System Roads Confirmed with aerial images from USFS	Unknown
Disturbed Area	Percent of timber sale disturbed through logging activities	Aerial images from USFS	2008 - 2013
Slash Piles and Scars	Ratio of Area of slash piles to Area of timber sale unit	GIS: SlashPile_KVPlots Confirmed with aerial images from USFS	Unknown
Overstory Vegetation	Percent canopy cover	USFS data Treedata.xls	2008 - 2009
Understory Native Vegetation	Percent cover of native understory vegetation	USFS data Totalcover_origin.xls	2008 - 2010
Understory Exotic Vegetation	Percent cover of exotic understory vegetation	USFS data Totalcover_origin.xls	2008 - 2010
Proximity to Other Disturbed Areas	Proximity to nearest disturbance (road or other sale unit)	GIS: System Roads, All_sales, All_units, KVPlots	Unknown

Conditional probability tables can be completed using a variety of methods depending on the data available. These methods can be divided into four categories: expert judgment, empirical evidence, calculations and/or mathematical or biological equations, and case file learning (Marcot et al. 2006, Pollino et al. 2006, Chen and Pollino 2012). In a single BN model, CPTs for different nodes may be completed using different methods (Chen and Pollino 2012) or combination of methods within a single CPT (Pollino et al. 2006).

In this research, we used three different methods for creating the CPTs: empirical evidence, case file learning, and a combination of empirical evidence and mathematical calculations. These methods were determined to be the most appropriate given the data available to us. Table 3 provides the parameters and inputs used to derive each CPT in the model, including which method(s) for CPT development was/were used.

Table 3. Description of CPTs. (Color corresponds to those in the conceptual model (Figure 3) and BN (Figure 4)).

Parameter	Inputs	Node Type	CPT Derivation
Soil Disturbance and Compaction	Roads Disturbed area	Stressor Node	Mathematical calculations Empirical evidence
Exposure of Bare Soil	Roads Disturbed area	Stressor Node	Case file learning
Burned Slash and Biomass	Disturbed area Slashing Piles	Stressor Node	Empirical evidence
Overstory/ Understory Relationship	Understory Native Vegetation Understory Exotic Vegetation Overstory Vegetation	Stressor Node	Mathematical calculations Empirical evidence
Changes in Soil pH	Burned Slash and Biomass Overstory/Understory	Effect Node	Empirical evidence
Changes in Available Nutrients	Soil Disturbance and Compaction Burned Slash and Biomass Exposure of Bare Soil Overstory/Understory	Effect Node	Empirical evidence
Changes in Soil Biota	Overstory/Understory Burned Slash and Biomass Soil Disturbance and Compaction	Effect Node	Empirical evidence
Changes in Seed Bank	Overstory/Understory Burned Slash and Biomass	Effect Node	Empirical evidence
Chemical Modification	Changes in Soil pH Changes in Available Nutrients	Summary Node	Mathematical calculations Empirical evidence
Biological Modification	Changes in Soil Biota Changes in Seed Bank	Summary Node	Mathematical calculations Empirical evidence
Ecological Structure	Overstory/Understory Exposure of Bare Soil	Summary Node	Mathematical calculations Empirical evidence
Establishment of Canada Thistle	Chemical Modification Biological Modification Ecological Structure Proximity to Other Disturbed Areas	Endpoint Node	Empirical evidence

Empirical evidence.
The majority of the CPTs in these models were completed using data obtained from peer reviewed literature, government reports, and information from personal communications with Jack Butler and Stephanie Wacker. These sources (Appendix D) provided quantitative information on the relationships between the variables for each CPT.

Using the quantitative relationships defined in the literature, conditional probability distributions were defined for each row in the CPT. Marcot et al. (2006) described an approach for translating empirical evidence into conditional probability distributions. First, the extreme cases are set to 0% or 100%. Then the probabilities for either a known combination of states or the most moderate combination is set. The remaining combinations are interpolated between the known or moderate case and the extreme cases (Marcot et al. 2006). This method is particularly useful for the initial construction of BNs and when incorporating a breadth of information as in the case of the BHNF models for Canada thistle spread and establishment. A more specific example of this approach for the Changes in Seed Bank node can be found in Appendix D.3.

Case file learning
By importing data directly into Netica, the software can "learn" from a collection of "cases" or observations to develop the CPT. This method can be employed for any relationship in which there are data for both the parent and child nodes. For example, importing BHNF data for Roads, Disturbed Area, and Exposure of Bare Soil into Netica, the case file learning function was able to create a CPT that defined the quantitative relationship between these nodes (Appendix D, Table D.4A). This was the only CPT in the BHNF model that was derived using case learning. A more detailed explanation of this approach is included in Appendix D.4.

Mathematical calculations (with empirical evidence)
This method primarily entailed using calculations, as well as empirical evidence from the scientific literature to derive the summary nodes. Summary nodes represent combinations from the input nodes (i.e., parent nodes). Summary node ranks are summed results from the combination of input node ranks using the numerical ranking scheme (0, 2, 4, and 6). For example, a combination of low (2) and medium (4) for two input nodes resulted in a 6 (2+4) in the summary node. Then, this 6 was translated into a probability distribution using a set of rules established *a priori*. Using this approach, the empirical evidence obtained from the scientific literature was used to assign a weighting scheme for the instances in which one parent node was more likely to influence the distribution of the child node (Marcot et al. 2006). A more detailed explanation of this approach using the Ecological Structure node as an example is included in Appendix D.5.

Risk Calculations

Netica uses probabilistic inference to update all the intermediate nodes, including the summary nodes, and the final endpoint node based on the input probabilities and CPTs (Norsys Software

Corp. 2014). The final result is a risk distribution for each endpoint, which is also referred to as the posterior probability distribution (PPD). In addition to the PPD, Netica calculates a risk score for each intermediate node and endpoint, which is simply the mean of the distribution of ranks in that node. Risk scores range from 0 to 6 and may be similar to other risk scores in the BN, however, keep in mind that the scores reflect different rank distributions.

Risk scores facilitate the communication of general trends, whereas risk distributions are useful for conveying specific information about patterns of risk and comparing differences in risk by region or by year. There is no assumption of a normal distribution of the states within a node; rather, the distribution reflects the actual probability of those states to occur based on the model's calculations. Differences among the distributions provide information about the probability of risk and the associated uncertainty.

In total, we have calculated risk for 4 sale areas and 3 years (a total of 12 BNs). These risk results can be used to compare risk over space (by region) and time (by year). Additionally, risk scores were summed to compare total risk by region (all years) and by year (all regions). Complete risk results as risk distributions can be found in Table 4.

Model Evaluation

After completing the BNs and calculating risk, we evaluated the models using two approaches: sensitivity analysis and influence analysis. A brief description of each method follows. Additional information can be found in Pollino et al. (2006) and Marcot (2012). Complete sensitivity and influence analysis results can be found in Appendix E.

Sensitivity Analysis

Sensitivity analysis explains the extent to which the endpoint node is influenced by the values of the input nodes (Pollino et al. 2006, Marcot 2012, Hines and Landis 2014). The sensitivity analysis is used to understand which variables contribute risk to the endpoint (Pollino et al. 2006, Marcot 2012, Hines and Landis 2014). The sensitivity analysis results can be used to compare the relative influence of input nodes on the endpoint to evaluate the model structure, interpret the risk results, and provide further information to the risk managers as to the sources of risk to the endpoint. For example, Hines and Landis (2014) used sensitivity analysis to identify variables important for future monitoring efforts or risk management actions.

The sensitivity analysis also measures mutual information between each of the input nodes and the endpoint node (Norsys Software Corp. 2014, Pollino et al. 2006, Woodberry et al. 2004). Mutual information measures how much one random variable tells us about another, i.e., their mutual dependence. A high value of mutual information for an input indicates a greater degree of influence on the endpoint node (Hosack et al. 2008, Marcot 2012). Mutual information is a function of both the findings in the node (probability distributions) and the relationship described in the CPT (Marcot 2012, Norsys Software Corp. 2014).

Table 4. Risk distributions and overall risk score for all risk regions and years. The most likely risk distribution is denoted in pale-yellow shading for each result.

Timber Sale	Results	Year 0	Year 1	Year 3	Total Risk by Region
Dark Canyon	**Risk Score**	**2.61**	**3.03**	**3.04**	**8.68**
	Zero	18.9	13.4	12.5	
	Low	38.8	33.8	34.5	
	Med	35.4	40.8	41.6	
	High	6.9	11.9	11.3	
Mercedes	**Risk Score**	**2.48**	**2.88**	**2.79**	**8.15**
	Zero	18.2	13.7	14.5	
	Low	44.0	38.2	39.7	
	Med	33.2	38.7	37.8	
	High	4.6	9.5	8.1	
Powerpole	**Risk Score**	**2.57**	**2.76**	**3.21**	**8.54**
	Zero	18.1	15.6	10.1	
	Low	41.4	38.9	33.0	
	Med	34.4	37.1	43.1	
	High	6.2	8.3	13.8	
Thrall	**Risk Score**	**2.94**	**3.20**	**3.02**	**9.16**
	Zero	14.9	12.3	13.1	
	Low	34.8	31.4	34.5	
	Med	38.7	40.4	40.7	
	High	11.6	15.9	11.7	
Total Risk by Year		**10.6**	**11.87**	**12.06**	**34.53**

The *Sensitivity to Findings* tool within Netica was used to conduct this analysis on the 12 BNs that were constructed as part of this risk analysis. The tool enabled us to determine the effect of all nodes in a given model on its endpoint. We divided this analysis into two parts: 1) sensitivity to model inputs and 2) sensitivity to stressor exposure pathways (Chemical Modification, Biological Modification, Ecological Structure and Proximity to Disturbed Area). We found that this approach allows for clearer interpretation and discussion of model sensitivity.

In the first approach (sensitivity to model inputs), we focused the analysis on the input variables, many of which would change with the implementation of a management action. In the second approach, the sensitivity analysis provides information on the relative importance of the stressor-exposure pathways. This analysis was used to evaluate the structure of the model, as well as the CPTs and provide information about the way in which the stressors influenced the endpoint.

Influence Analysis

To further evaluate the models, we conducted an influence analysis on each of the models following the methods described by Marcot (2012). An influence analysis provides information on the possible range of risk. In this approach, input variables are set to their maximum or minimum states and changes in the distribution of risk are compared. Influence analysis can be used to understand minimum and maximum limits of risk relative to the risk results calculated in the model. It also can provide information about theoretical scenarios in which input values are higher or lower than measured values (Marcot 2012).

We performed the influence analysis of all the input nodes in the model. We set each of the input variables to 100% probability in the minimum[2] state and compared this risk distribution (minimum) to the expected risk result. Then, we set each of the input parameters to 100% probability in the maximum state and again compared this risk distribution (maximum) to the expected risk result. Any nodes that were not connected in the Year 0 and Year 1 models remained disconnected for the influence analysis.

RESULTS

Patterns of Risk

This section summarizes the risk estimates for Canada Thistle Establishment in the four timber sale areas. The results are presented in two ways. In the first section, we summarize the information using the numeric risk scores. The advantage to this type of presentation is that it gives an overview of the patterns in a user-friendly format for those not familiar with interpreting distributions. The second section presents information about the risk distributions, comparing the probability distributions for each region and year.

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[2] For nodes that were inversely correlated to the endpoint (e.g. native understory), the minimum state was actually the highest numeric value.

Risk scores

Risk of Canada Thistle Establishment was moderate for all regions and years, with risk scores ranging from 2.48 (Mercedes, Year 0) to 3.21 (Powerpole, Year 3) (Table 4, Figure 5). To put these scores in perspective, the scale is from zero to 6, with 6 being the maximum risk.

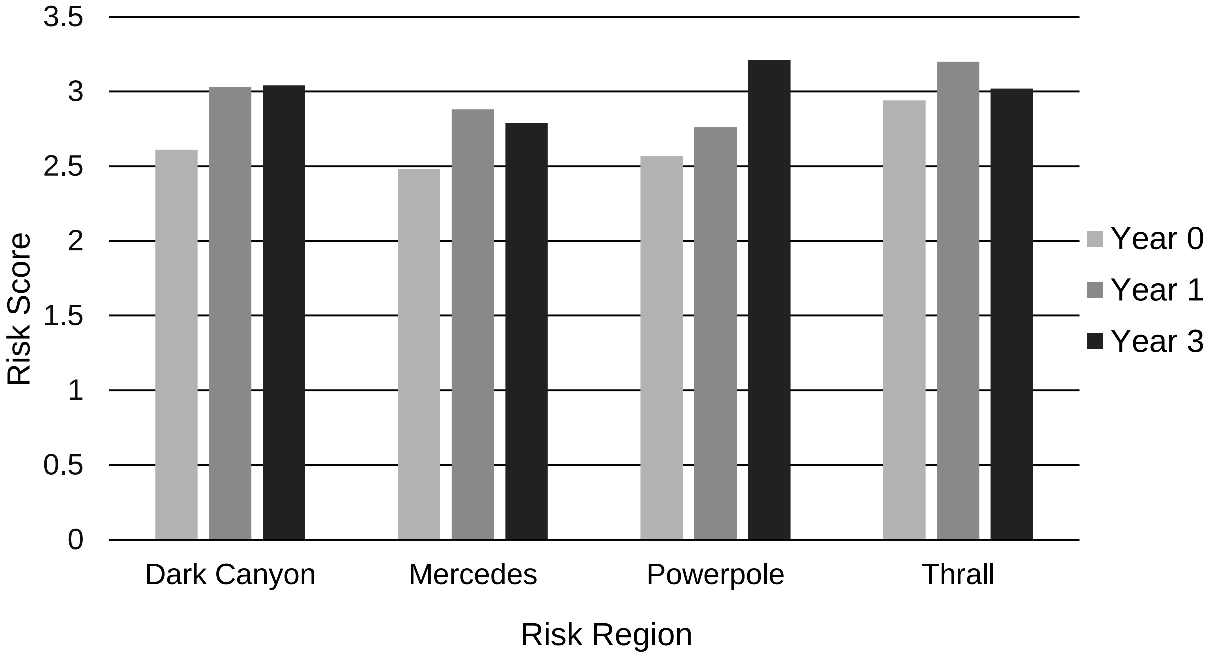

Figure 5. Risk scores by risk region and by year.

In all regions, Canada Thistle Establishment risk was lowest in Year 0 and increased after logging in both Years 1 and 3. The greatest risk occurred in either the first or third year after logging, depending on the timber sale. In Mercedes and Thrall, risk was higher in Year 1 (2.88 and 3.20, respectively) than in Year 3 (2.79 and 3.02) (Table 4). In Powerpole, risk increased from Year 1 to Year 3 (2.76 to 3.21). In Dark Canyon, risk increased slightly from Year 1 to Year 3 (3.03 to 3.04).

Total risk for each year was calculated as the sum of the risk scores for that year. Total risk for Year 0 (10.8) was lower than total risk for Years 1 and 3 (11.87 and 12.06, respectively). This is consistent with the Canada thistle risk patterns for each region independently.

Thrall had the highest risk of all four sales in Years 0 and 1 and the greatest total risk (9.16) when the risk from each year was combined (Table 4). Dark Canyon had the second highest total risk (8.68) through it is not the region at the highest risk for any of the years individually. Mercedes had the lowest total risk score (8.15) and the lowest risk in Years 0 and 3, though not in Year 1. Powerpole has the second lowest total risk (8.54) and the lowest risk in Year 1. By Year 3, risk is most similar in Dark Canyon and Thrall (3.04 and 3.02, respectively).

Risk probability distributions

The risk distribution is formed by the probability of risk in each of the four risk states (Zero, Low, Medium, and High). The shape of the distribution curve provides information about the most and the least likely risk states. The tails of the curve tell us the probability of risk in the more extreme states (Zero risk and High risk). Larger tails can reflect two conditions: 1) a greater probability of Zero or High risk or 2) greater uncertainty in the actual distribution of risk. Either way, they provide useful information to the risk manager. (Note: the influence analysis and other model evaluation tools can be used to understand which condition is more likely to be causing the larger tails of the risk distribution.)

The most likely risk state for each result is highlighted in Table 4. Risk is most likely to fall in the Low or Medium state for all regions and years (Figure 6A - 6D). For example, there is a 38.8% probability of Low risk in Dark Canyon Year 0 and a 40.8% probability of Medium risk by Year 1 (Table 4, Figure 6A). Low risk is the most probable state in Year 0 for all regions except Thrall (Figure 6B), where Medium risk is more probable. Medium risk is the most probable state in Year 1 for all regions except Powerpole (Figure 6C), where Low risk is more probable. Medium risk is the also the most probable state in Year 3 for all regions except Mercedes (Figure 6D), where Low risk is more probable. Overall these results indicate that risk will be Low or Medium in all regions and years with a 71.8- 77.5% probability of combined Low and Medium risk, depending on the region and year.

Though the probability of risk is skewed towards the central states (Low and Medium), the tails provide additional information about the probability of extreme events (Zero or High risk). For example, risk is Low to Medium in Thrall, however there is still an 11.6% to 15.9% probability of High risk in Year 0 and Year 1 (Table 4). During Year 1, there is an 8.3 to 15.9% probability of High risk depending on the region; similarly, in Year 3 there is an 8.1 to 13.8% probability of High risk.

Sensitivity Analysis

The sensitivity analysis used mutual information as a measure of which stressors (and sources of stressors) were driving risk to the endpoint. Sensitivity analysis results for each model are described below. These results are presented in two parts: 1) sensitivity to the input variables and 2) sensitivity to the stressor-exposure pathways. The mutual information values are most informative in context with one another, telling us more about the models and risk patterns in the BHNF than as standalone values (Figures 7 and 8).

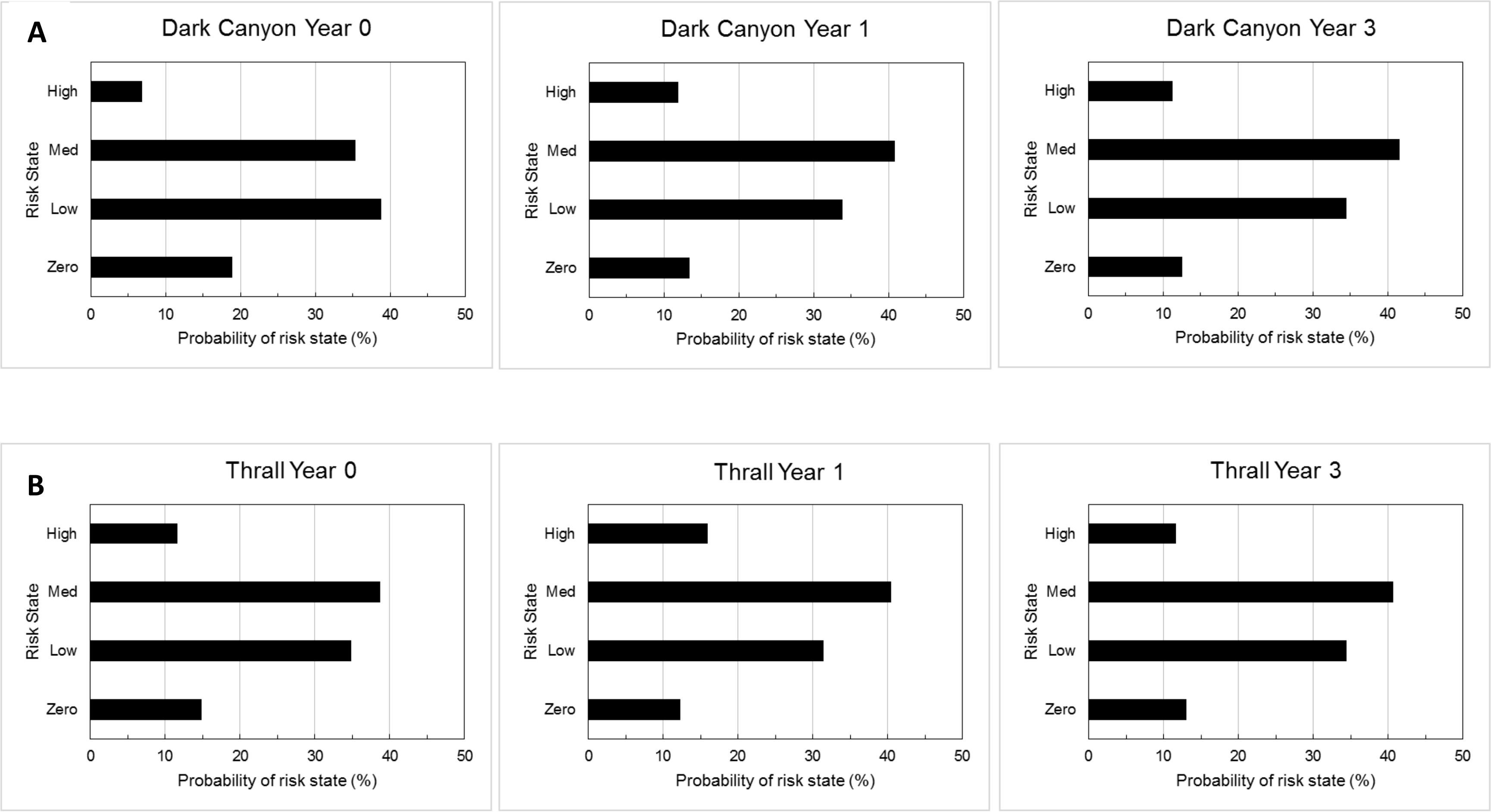

Figure 6A - 6B. Risk distributions for each risk region by year. **A.** Dark Canyon sale. **B.** Thrall sale.

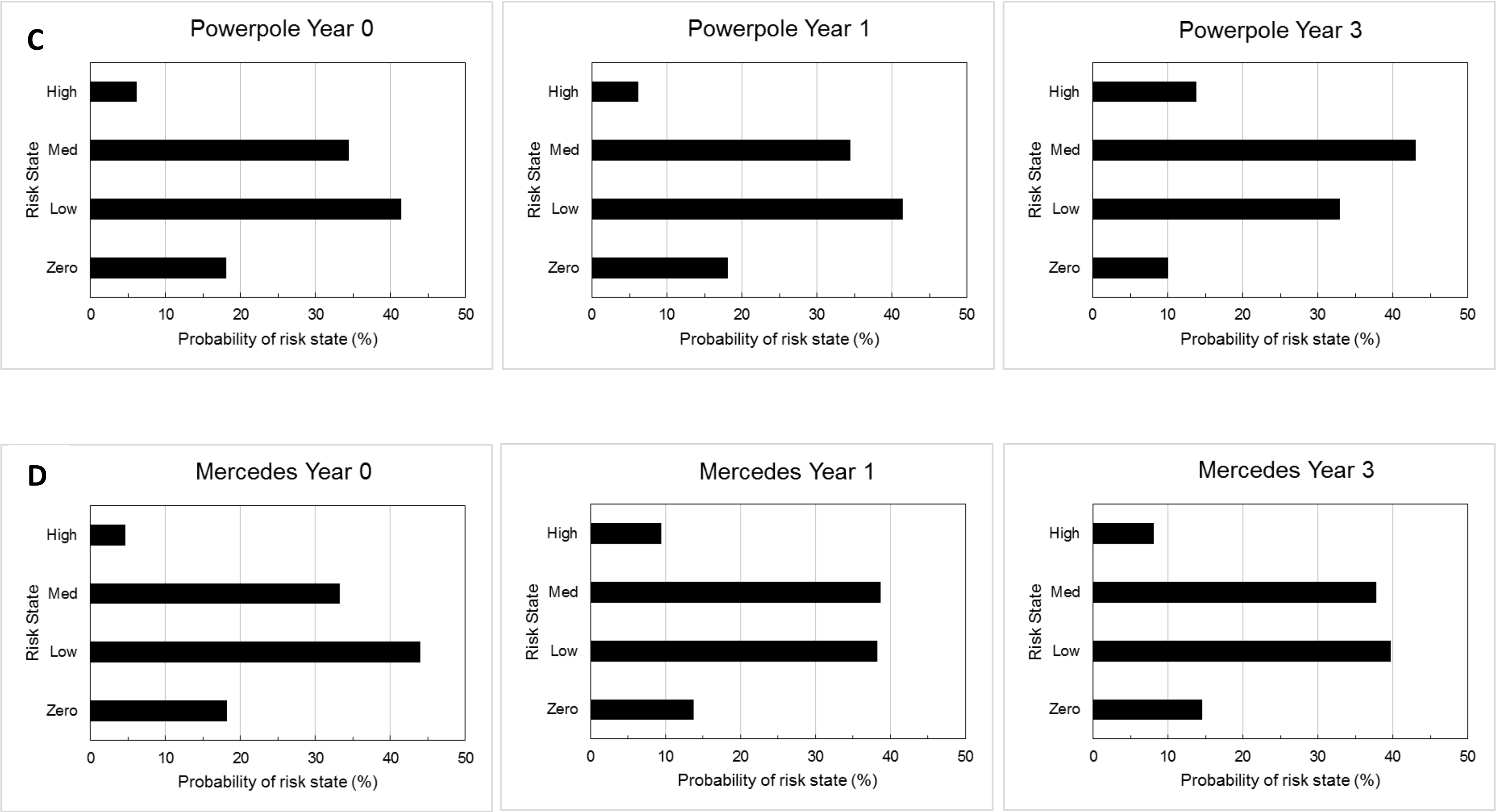

Figure 6C - 6D. Risk distributions for each risk region by year. **C.** Powerpole sale. **D.** Mercedes sale.

Sensitivity to Input Parameters

Understory Native Vegetation had the greatest influence on risk to the Canada Thistle Establishment endpoint in most regions and years (Figure 7). In Dark Canyon and Thrall, Overstory Vegetation also influenced risk to the endpoint. In Powerpole, Disturbed Area was the second most important factor influencing risk in Years 1 and 3. Slash Piles and Roads were not influential variables in any of the models, according to the sensitivity analysis.

In Dark Canyon, Overstory and Understory Native Vegetation have the first and second greatest effects on the endpoint in Year 0 (mutual information of 0.031 and 0.014, respectively). By Year 1, the influence of Understory Native Vegetation was greater (0.030), but Overstory Vegetation still influenced the endpoint (0.019). These two input nodes remained the primary drivers of risk in Year 3, however the mutual information values decreased and the Disturbed Area input node accounted for a greater proportion of the mutual information by Year 3 than in Years 0 and 1.

In Thrall, Understory Native Vegetation and Overstory Vegetation also played an important role in the risk to the endpoint. In Year 0, both had high mutual information values (0.029 and 0.044, respectively). The same pattern persists in Year 1, however Understory Exotic Vegetation became more important. By Year 3, the Canada thistle endpoint in Thrall was less sensitive to Understory Native Vegetation and the relative influence of Disturbed Area increased.

In Mercedes, Understory Native Vegetation was again the most influential input variable on the endpoint. In Years 0 and 1 it was the primary driver of risk with mutual information value of 0.011 and 0.037, respectively. By Year 3, Understory Native Vegetation remained the greatest driver of risk, but Overstory Vegetation was increasingly important as a factor determining risk.

In Powerpole, mutual information values were lower overall than for the other risk regions. The highest value was 0.017 for Understory Native Vegetation in Year 0. Understory Exotic Vegetation and Overstory Vegetation were other contributors of risk in Year 0. By Year 1, Understory Native Vegetation and Disturbed Area were the primary contributors of risk, and the relative influence of these variables was essentially the same (0.012 and 0.011). These variables remained important in Year 3, and Overstory Vegetation became the third most important variable for risk in this region.

While the Proximity to Disturbed Area is not included in Figure 7, it is by far the single input variable with the greatest effect on the endpoint. The mutual information values for this node were consistent with the values for the stressor-exposure pathways (Biological Modification, Chemical Modification, and Ecological Structure) (Figure 8).

Sensitivity to Stressor-Exposure Pathways.

The Canada thistle endpoint was most sensitive to the Ecological Structure node (Figure 8), which is an aggregate node describing the effects of Overstory/Understory Vegetation and Exposure of Bare Soil on the establishment of Canada thistle. The Canada thistle endpoint was

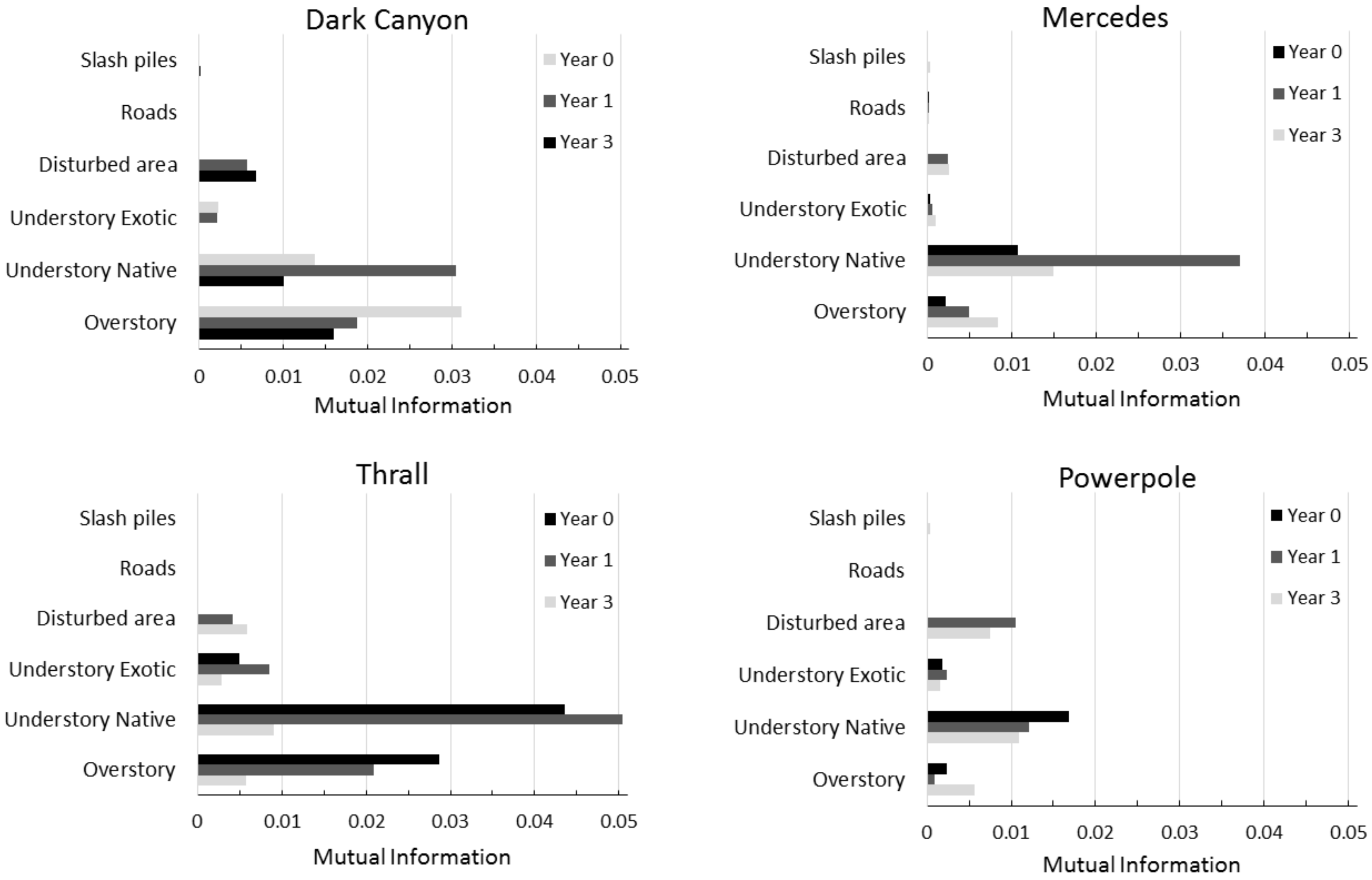

Figure 7. Results of the sensitivity analysis of the input (parent) nodes.

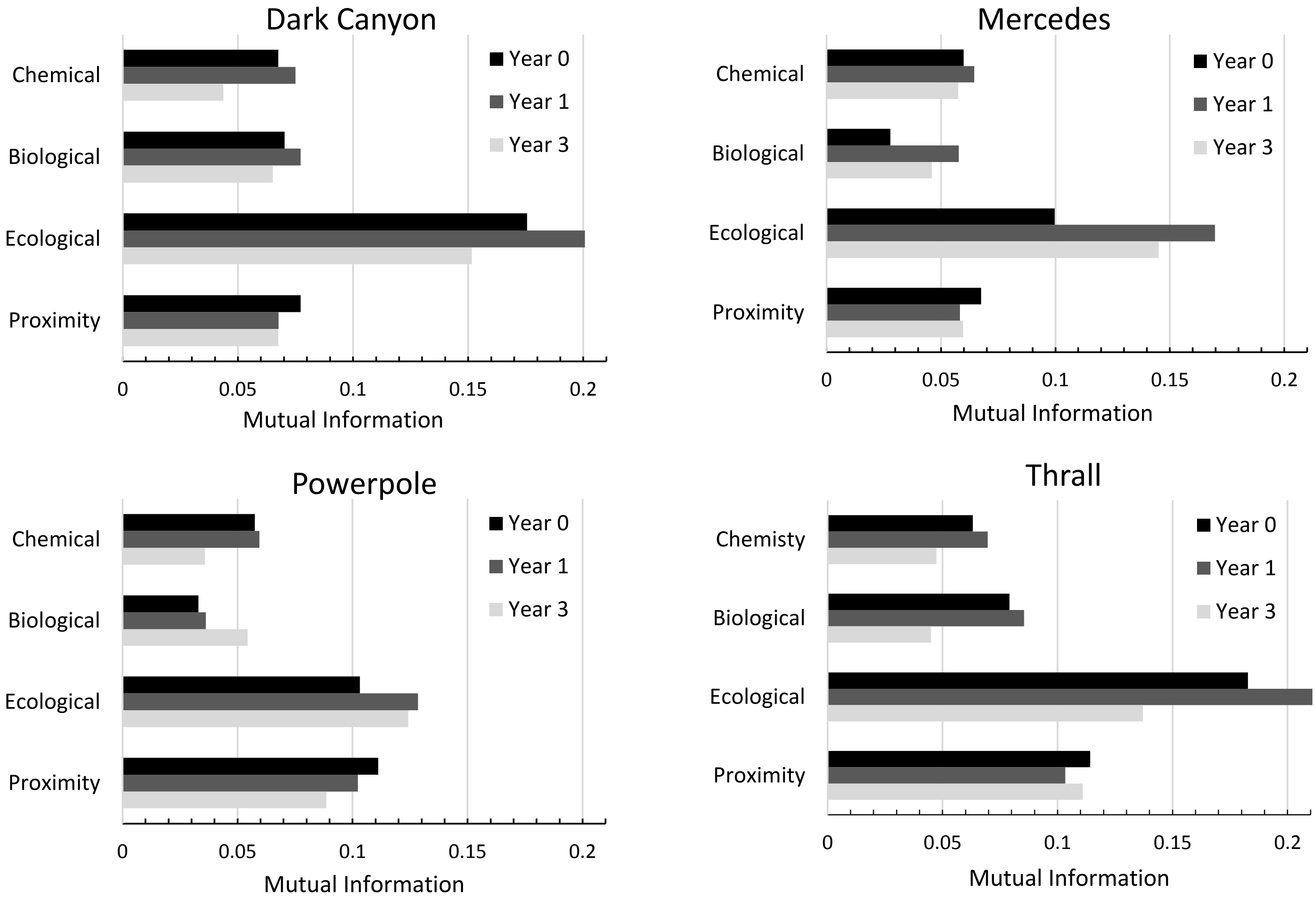

Figure 8. Results of the sensitivity analysis of the stressor-exposure pathways (intermediate nodes).

less sensitive to the Chemical Modification and Biological Modification nodes in all regions (Figure 8). In general, the endpoint was most sensitive to these two nodes in Year 1, due to the effects of logging disturbance and changes in vegetation post-logging. By Year 3 (when slash piles are usually burned) the endpoint was less sensitive to changes to the Chemical Modification and Biological Modification nodes. The exception to this trend was in Powerpole, where the greatest sensitivity to Biological Modification occurred in Year 3. Biological Modification in Year 3 in Powerpole was higher than in Mercedes and Thrall, but similar to Dark Canyon, where sensitivity in Year 3 was similar (mutual information of approximately 0.06) (Figure 8).

The Proximity to Disturbed Area node had an equal or greater influence on the Canada thistle endpoint than the Biological Modification or Chemical Modification nodes in many regions (Figure 8). This is an important result of the sensitivity analysis because the Proximity node is a single input variable whereas the Biological and Chemical nodes summarized the effects of multiple input variables. As such, you would expect a far greater sensitivity to the Biological and Chemical nodes if all of the inputs have an equal effect on the endpoint. The Proximity node had mutual information values ranging from approximately 0.05 to 1.2, which were larger than the mutual information values for any single input node independently (Figure 7). The Canada Thistle Establishment endpoint is therefore highly sensitive to the location of the timber sale relative to other disturbed areas, e.g., other logged/harvested areas, roads.

Influence Analysis Results

The influence analysis compared the calculated risk results (Most Likely) to hypothetical scenarios for Minimum and Maximum risk based on changes to the input nodes. Figure 9A - 9D present the results of the influence analysis for the four timber sales. Regardless of the initial conditions, the Minimum and Maximum scenarios do not differ between risk regions. The minimum risk is skewed towards Zero risk and the Maximum scenario is skewed towards High risk (Figure 9). The scenarios differ slightly between Years 0, 1 and Year 3 because of differences in the CPTs.

Minimum Risk Scenario

In Years 0 and 1, the Minimum scenario had a 61% probability of Zero risk, 29.4% probability of Low risk, 9.5% probability of Medium risk, and < 1% probability of High risk. In Year 3, the Minimum scenario had a 58.5% probability of Zero risk, 31.3% probability of Low risk, 10.3% probability of Medium risk, and < 1% probability of High risk.

Maximum Risk scenario

In Year 0, the Maximum scenario had < 1% probability of Zero risk, 2.3% probability of Low risk, 24.8% probability of Medium risk, and 72.8% probability of High risk and. In Year 1, the Maximum scenario had < 1% probability of Zero risk, 1.4% probability of Low risk, 20.7% probability of Medium risk, and 77.8% probability of High risk. In Year 3, the Maximum

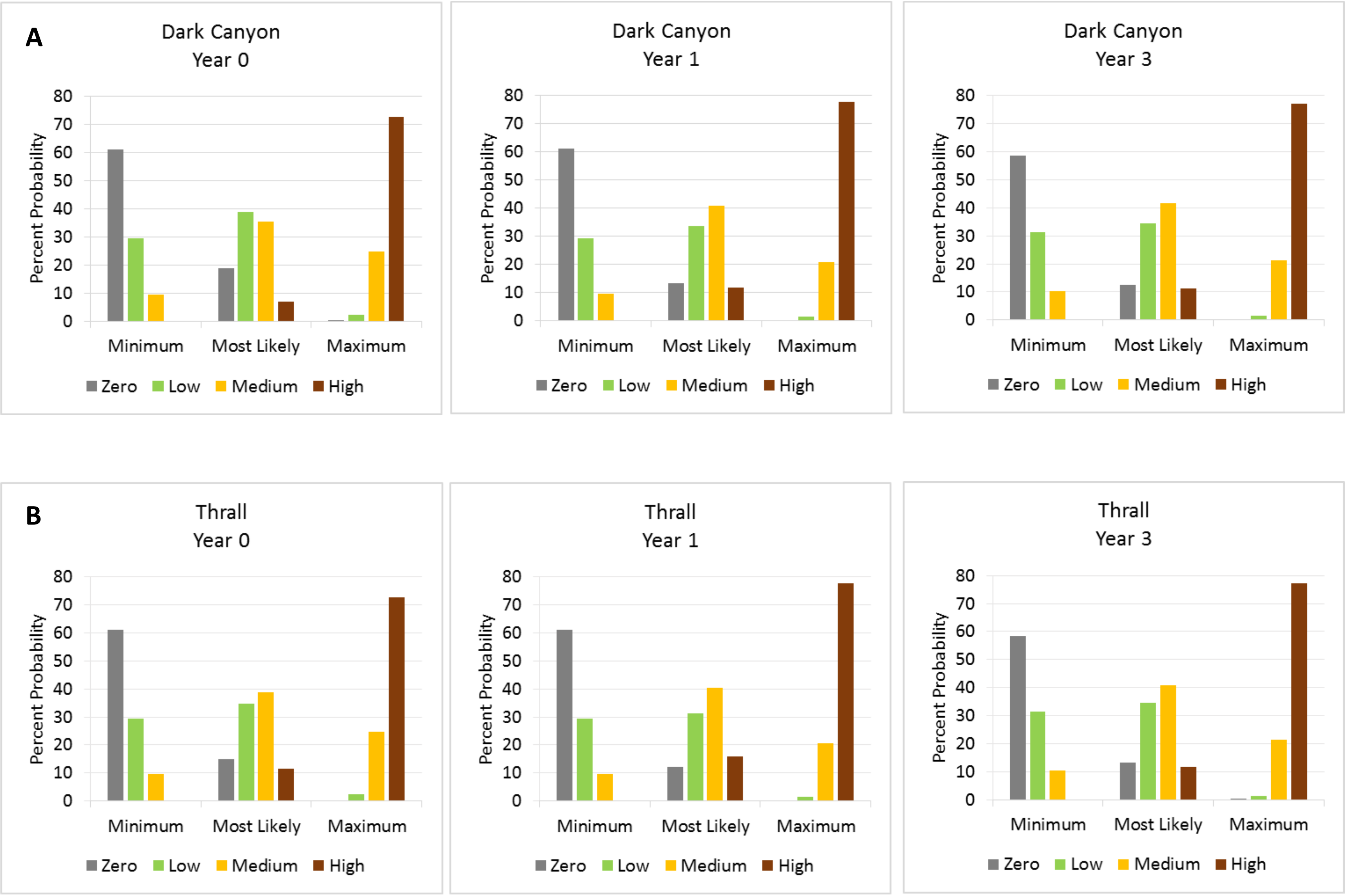

Figure 9A – 9B. Results of the influence analysis**. A.** Dark Canyon sale. **B.** Thrall sale.

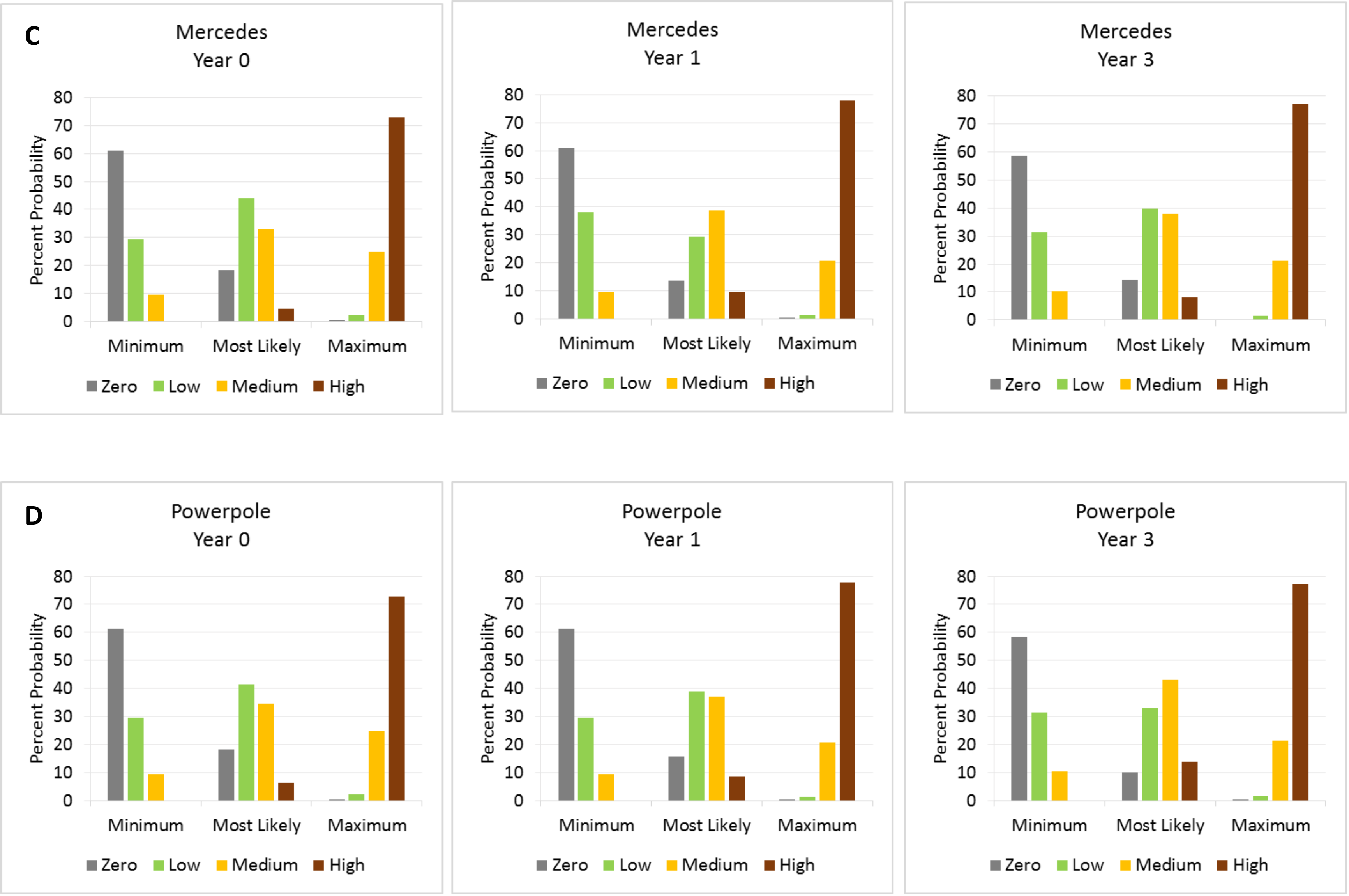

Figure 9C – 9D. Results of the influence analysis. **C.** Mercedes sale. **D.** Powerpole sale.

scenario had < 1% probability of Zero risk. 1.4% probability of Low risk, 21.3% probability of Medium risk, and 77.2% probability of High risk.

Generally, the calculated Most Likely results were approximately in the middle of the range set by the results from the Minimum and Maximum scenarios. Risk in Year 0 was closer to the Minimum scenario than to the Maximum scenario in every region except Thrall. Risk in Years 1 and 3 was closer to the Maximum scenario in most regions, the exceptions being Powerpole (Year 1) and Mercedes (Year 3).

DISCUSSION

Risk Estimates by Year

Risk of Canada Thistle Establishment differs over time, with greatest risk occurring in either the first or third year after logging. Risk is present even before logging activities occur (Year 0) but increased with logging in Year 1.

In Year 0, risk of Canada thistle establishment was dependent on three factors: Roads (and associated human activity), Understory/Overstory Vegetation, and Proximity to Disturbed Area. Roads exist across the BHNF landscape due to current and historical logging throughout the region. The roads have been maintained to some extent over time, resulting in periodic disturbances of the soil and surrounding vegetation to keep these corridors open (Jack Bulter, *pers. comm.*, 2015). The BHNF aerial images and road layers showed that the percent cover of roads changed very little in the 3-5 year timeframe evaluated in this study. These corridors and associated human activities provided opportunities for facilitated Canada thistle seed dispersal and root propagation.

Secondly, the presence or absence of Understory/Overstory Vegetation in Year 0 prior to or after logging inhibited or promoted, respectively the risk of Canada thistle invasion and establishment. Vegetation presence or absence was a function of a number of factors including previous logging history and site conditions (e.g. soil type, other natural disturbances).

Finally, the Proximity to Disturbed Area increased the risk of Canada thistle introduction and establishment through seed dispersal. This risk was present even before logging occurred in a timber sale area. Canada thistle seeds can be transported by wind, animals, and human activity (Heimann and Cussans 1996). Areas in closer proximity to established Canada thistle patches, therefore, will be at a higher risk for the introduction and spread of Canada thistle. These pre-harvest results indicated that to mitigate the risk of Canada thistle establishment, actions must be implemented even before harvest occurs.

In Year 1, the increased risk in all regions could be attributed to the direct and indirect effects of logging. Logging and harvest practices directly altered ecological structure by increasing the percent area of disturbed land and the removing percent cover of native and exotic understory vegetation. Reduced canopy cover as overstory trees are removed, as well as removal of understory vegetation, created large swaths of bare soil ideal for Canada thistle establishment. Canada thistle grows rapidly in bare soils and areas with little understory competition (Wilson Jr. 1979). The increase in sunlight also contributes to the success of Canada thistle in these disturbed areas (Zimdahl et al. 1991, Parendes and Jones 2000).

Indirect effects of logging included changes to the chemical and biological composition of the soil. Soil compaction from forestry equipment and log transport can lead to soil nitrogen losses and decreases in soil nitrification due to suppressed microbial activity (Neve and Hofman 2000, Gomez et al. 2002). Bare soils are prone to erosion, which can lead to losses in soil organic matter, as well as soil nitrogen and phosphorus (Munn 1973, Gyssels et al. 2005). In addition, risk from the Roads and Proximity to Disturbed Area variables persisted into Year 1.

In Year 3, changes to the landscape both increased and decreased risk compared to Year 1. First, slash pile burning and the effects of pile burning on bare soil, soil pH, soil biota and soil nutrients increased the risk of Canada thistle establishment. Most slash piles in the BHNF are burned three years post-logging. Within a few meters of the slash pile, burning can sterilize soils, removing soil biota and producing unviable seed banks (Thompson 1996, Korb et al. 2004, Abella et al. 2007, Creech et al. 2012. Farther away from the slash pile, the effects of burning may include short-term releases of carbon and nitrogen into the soil, though these effects do not persist 3-5 years after the burn (Monleon et al. 1997, Esquilin et al. 2007).

Regrowth of the native understory and overstory species after the timber harvest alleviated the risk of Canada thistle establishment. As the understory regrew after harvest, Canada thistle competed against other plants for sunlight and nutrients, thereby controlling its spread. In fact, understory vegetation is often more dense after the canopy cover is removed due to the greater amount of sunlight reaching the forest floor, enabling it to effectively compete against potential invasion from Canada thistle (Zouhar 2001). Risk from Roads and Proximity to Disturbed Area variables persisted into Year 3, even as revegetation occurred in the logged areas.

Risk Estimates by Region

Risk of Canada thistle invasion and establishment differs between timber sale areas and is influenced by both location and logging management practices within the study area.

Risk is higher in the Dark Canyon, Powerpole and Thrall timber sale areas and lower in the Mercedes. The differences in risk cannot be attributed to location alone. Dark Canyon and Thrall are located near one another with Powerpole located approximately 22 miles (35 km) to the northwest and Mercedes located between Thrall and Powerpole. Whole-tree versus conventional harvest management practices and characteristics of the sites contributed to the differences in risk between regions. For example, Mercedes is the only area in which conventional harvest methods are used and as such has a low number of slash piles in the sale area. This method greatly reduces the probability of changes in soil biota and chemistry after slash pile burning compared to the other three sale areas in which whole-tree harvest methods create a much higher number of slash piles.

Understory Native Vegetation, Understory Exotic Vegetation, and Overstory Vegetation accounted for many of the differences in the model inputs for the four risk regions. These variables were influenced by a number of processes. First, logging removed understory and overstory vegetation in each of the sale areas. Moreover, the percent that was logged, as well as regrowth rates of the vegetation after logging activities differed between them. In most sales, the relative percent cover of Understory Exotic Vegetation increased after logging for Years 1 and 3, whereas the relative percent cover of Understory Native Vegetation increased only the first year after logging and decreased by Year 3. This decrease was likely due to competition with exotics, as well as shading effects from the regrowth of overstory vegetation by Year 3.

In the Dark Canyon timber sale area, the understory native vegetation cover decreased from Year 1 to Year 3 in most study plots. The exotic understory remained relatively constant at less than 30% cover (USFS vegetation data, Jack Butler, *pers. comm.* 2015). In both Powerpole and Thrall sale areas, the understory native vegetation percent cover varied greatly between study areas, but remained relatively the same at each study site between Years 1 and 3. The understory exotic vegetation increased in some plots by Year 3, with percent cover reaching nearly 60-80% in some. In Mercedes, the understory vegetation regrowth by Year 1 was less rapid with percent cover similar to, but did not in exceedance of the pre-harvest percent cover. By Year 3, however, percent cover of understory native species ranged from 0 to just over 100% cover[3]. Understory exotic species did increase some by Year 3, but did not exceed 50% cover in any study plot.

Without data for Overstory Vegetation in Year 3, it was challenging to discern the effect of increased canopy cover on the risk of Canada Thistle Establishment in any region. This data gap increased the uncertainty in the risk estimates for Year 3.

Proximity to Disturbed Area also accounted for differences in risk between risk regions. Though proximity did not change year-to-year, it did differ between timber sale areas. For example, Powerpole and Thrall had 17 and 15.5 % probability, respectively, of a sale unit being located within 10 m of a disturbed area (Appendix C). This proximity increased the likelihood in Canada thistle spread through root propagation between contiguous established patches (Heimann and Cussans 1996, Zouhar 2001, Becker et al. 2008). In contrast, Dark Canyon and Mercedes had 5 and 9 % probability of sale units being located within 10 m of a disturbed area, resulting in a lower probability of Canada thistle invasion. In these two sale areas, introduction

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[3] Percent cover understory exceeded 100% in some sites because the sampling considered overlapping vegetation (ground cover and shrub layer, for example) and then summed the total coverage. For some sites, percent cover was nearly 200%.

of Canada thistle would be more likely a result of seed dispersal by wind, animal, or human activity (Donald 1994, Zouhar 2001, Becker et al. 2008).

At distances greater than several hundred meters, wind dispersal of seeds was less likely to result in successful introduction of new Canada thistle plants. At those distances, transport by animals and humans was considered the primary mechanism of dispersal (Zouhar 2001). Dark Canyon had the greatest percentage of sale units (30%) located at least 250 m from a disturbed area (Appendix C). Interestingly, Mercedes had the lowest percentage of sale units (1%) located at least 250 m for a disturbed area. These results indicated that, although proximity is an important contributor of risk, a linear relationship between the distance to a disturbed area and the risk of Canada Thistle Establishment is unlikely. Seed dispersal mechanisms did, however, appear to influence the relationship between the Proximity to Disturbed Area node and risk of Canada Thistle Establishment node. Further analysis of the site-specific data or additional data collection to address this data gap could elucidate these differences in seed dispersal and patterns of risk.

Model Evaluation

Sensitivity analysis

Sensitivity analysis was used to evaluate the extent to which the Canada Thistle Establishment is influenced by forest management practices and environmental variables. The sensitivity analysis results explained which of these variables contributed to or alleviated the risk of Canada Thistle Establishment.

Sensitivity analysis indicated that a primary driver of Canada Thistle Establishment node risk was the Proximity to Disturbed Area node. As the distance between a timber sale and other disturbed areas decreased (greater proximity), the risk of Canada thistle introduction and establishment increased. Canada thistle is introduced to new areas by seed dispersal through wind, wildlife, and human activity (Heimann and Cussans 1996). Moreover, the mechanism of dispersal (wind, wildlife, humans) influences the dispersal distance (Heimann and Cussans 1996). The ability of Canada thistle to disperse viable seeds, however, decreases with distance from the source population, resulting in an inverse relationship between the likelihood of Canada thistle colonization and distance from the source patch.

Influence analysis

The results of this influence analysis were useful in bracketing the range of possible risk of Canada Thistle Establishment in the timber sale areas of the BHNF. More useful however, are the actual models that can be used to conduct other influence analyses depending on the specific questions of the resource managers. For example, the model could be used to determine whether risk would increase if an area near one of the timber sale areas is logged (changing the Proximity to Disturbed Area node) or whether the number and size of slash piles in a timber sale area would alter the risk. The model could also be used to determine whether risk decreased if planting of rapidly growing non-invasive species were implemented post-harvest to expedite understory/overstory vegetative regrowth rates.

Patterns of Risk over Time

In this study, the models were used to evaluate the effects of forestry management practices (i.e., logging) at different time scales to compare risk of Canada thistle introduction and establishment over time. This approach was made possible by the robust time series dataset obtained from the USFS. We found that the risk of Canada Thistle Establishment changed over time due to changes in the landscape such as growth of understory and overstory vegetation and changes in soil chemistry. Logging activities including road building and slash pile burning altered the risk of Canada Thistle Establishment in the different risk regions. These results are not unique. The risk of biological invasion is expected to change with time, however, the models we used allowed us to understand which variables were changing over time and how these variable influenced risk each year.

These same methods could be used in the adaptive management process to assess the changes in risk after the implementation of an adaptive management action (Nyberg et al. 2006). For example, data collected during the post-management monitoring phase could be used as inputs in the model to evaluate whether the management action reduced or increased risk.

Application of Geographic Information Systems and Spatial Data

The quality of the spatial data made available to us reduced the uncertainty of this regional-scale invasive species risk assessment. Geographic information systems (GIS) shapefiles and aerial images were used to develop the conceptual models, inform the BN-RRM and calculate risk. Risk communication benefitted from the spatially explicit nature of the data analysis and BN-RRM framework.

The robust dataset from USFS monitoring efforts (Jack Butler, *pers. comm.*, 2015) allowed us to derive probability distributions for each timber sale area and calculate risks to them over a three-year timeframe. For most input variables, we organized the tabular data by risk region and categorized the data using the ranking scheme for each node. The probability distributions for the Disturbed Area node were derived from the aerial images using expert judgement and spatial analysis tools within ArcGIS.

The same techniques that were used in conducting this regional-scale invasive species risk assessment, could be used on a finer spatial scale, though additional monitoring data and model development would likely be required to understand and incorporate processes that influence Canada Thistle Establishment at this scale. For example, soil matrices, microclimates, or soil conditions may be important factors in the establishment of Canada thistle across smaller spatial scales. Plot-level soil data would decrease the model uncertainty related to the Biological and Chemical Modification nodes, which would allow us to refine the models for use at the finer spatial scale.

Landscape Connectivity and Patch Dynamics

Landscape connectivity (as measured by proximity between timber sale units) was a driving factor for risk of Canada Thistle Establishment in the BHNF. Other studies and modeling efforts have shown that location relative to an established patch of the invasive species is a predictive factor in their spread (Kolar and Lodge 2001, Deines et al. 2005). Risk also depends on the degree of habitat fragmentation and the dispersal ability of the invasive species (Marvier et al. 2004).

Metapopulation models of patch dynamics can be used to understand the spatial factors that affect biological invasion (Wu et al. 1993, McLaughlin and Landis 2000, Marvier et al. 2004). In those models the relative location of patches and the distances between patches affected the probability of invasive species dispersal between patches and success within a patch (Marvier et al. 2004, Deines et al. 2005). Deines et al. (2005) used the patch dynamics approach to account for short-range and long-range dispersal mechanisms in invasive species modeling.

Next Steps

In the following section, we present a number of “next steps” or projects that would build on the techniques and findings of this risk assessment. The first two projects represent near-term activities and goals. The next four projects represent broader research topics that would draw upon this work (and other work by Landis and colleagues) for future risk assessment partnerships between the USFS and Western Washington University.

Near-Term

Reduce model uncertainties

Additional BHNF data from the USFS would reduce uncertainties in the model. For example, soil monitoring data could be used to revise or ground-truth the CPTs for the Changes in Soil pH, Changes in Available Nutrients, Changes in Soil Biota, and Changes in Seed Bank nodes. These CPTs were developed using empirical evidence from the scientific literature due to the lack of site-specific data, resulting in a higher degree of uncertainty in these models. Soil data from BHNF study plots would allow us to use other approaches to complete the CPTs, including case file learning. Similarly, monitoring data for Overstory Vegetation for Year 3 would reduce uncertainties in the risk estimates for that year.

Assess risk of Canada Thistle Establishment for additional timber sales and years
This assessment could be expanded to include other timber sale areas within the BNHF, as well as additional years post-harvest if additional monitoring data were available. Initially 12 timber sale areas were considered for inclusion in this invasive species risk assessment. Due to a number of factors (including paucity of data for other timber sale areas and later timber harvests), we worked with USFS managers to select four timber sales to be the focus of this research. By narrowing the scope of the project, we were able to focus our attention on developing and improving the BNs and defining the relationships between each of the nodes in the BNs. The four timber sales selected had the most complete datasets, thereby reducing the uncertainty in the risk estimates. With additional data for the other eight timber sales, we could derive probability distributions and calculate risk of Canada Thistle Establishment in those areas as well. We have constructed the BNs in such a way that they are user friendly and available to the USFS. As such, future modeling and/or refining this invasive species risk assessment could be conducted by us or the USFS.

Similarly, risk could be assessed beyond Year 3 for the four sales included in this assessment, as well as for the other timber sale areas within the BHNF. Currently, monitoring data are not available for all four sales beyond Year 3. As these data becomes available, they can be easily incorporated into the BNs. We have already developed the CPTs for Years 4-10, though they are not included in the Netica files, but will be made available to USFS to support future work on this project.

Long-Term

Assess risk of Canada Thistle Establishment on other national forest lands
The models created for this research project in the Black Hills National Forest could be used to conduct a risk assessment of potential Canada thistle establishment at other USFS managed sites. Many components of the BN models are transferrable, though the BNs would certainly need to be adapted to incorporate site-specific data for those sites. Chemical or biological stressors may be present at other sites that were not considered in the BHNF, such as precipitation, elevation, or grazing. For these models to be used at other sites, robust, site-specific data would be required.

Assess risk to other invasive species endpoints, either within the BHNF or for another site
Another step would be to apply the models developed in this risk assessment to other endpoints in the BHNF. There are two possible approaches: First, this risk assessment could be expanded to assess the risk of impacts to other biological endpoints *from* Canada thistle establishment in a timber sale area. Second, the BN-RRM framework could be applied to assess risk of establishment by other invasive plant species in the BHNF. In either approach, the models will require the selection of other invasive species endpoints for which the biology is reasonably understood, as well as site-specific monitoring data.

Climate Change and Invasive Species

Other possible risk assessment partnerships between USFS and WWU could include a risk assessment that included the effects of climate change on invasive species introduction and establishment. The USFS already has conducted extensive modeling and documented the predicted effects of climate change (USFS 2009, USFS 2010b). The BN-RRM models can incorporate these results to create new models that assess future climate change risk across a temporal and spatial scale.

With climate change accelerating, long-term management of sites will require managers to consider the local and landscape-scale of the effects of changing climate (Landis et al. 2013). The stresses associated with changing climate (e.g. altered temperature and precipitation regimes, climate induced organism sensitivity, creation of novel ecosystems) are likely to influence the distribution and establishment success of invasive species (Hellman et al. 2008). Hellman et al. (2008) presented hypotheses regarding the effects of climate change on biological invasion that could be tested using a quantitative ecological risk assessment. The BN-RRM framework provides a multiple-stressor, multiple endpoint approach to ERA that could incorporate the effects of climate change and invasive species at local or regional scales.

Wildfire and Invasive species

Similarly, wildfires have been shown to alter the distribution of invasive species across a landscape (Grace et al. 2002). In some cases, wildfires increase the spread of invasive species by creating areas of disturbance that are susceptible to biological invasions. In other cases, fire is used as a management tool to remove invasive species from a landscape. (Grace et al. 2002). Wildfires and invasive species may act as co-stressors in an environment, resulting in additive or synergistic adverse effects to the ecological community. Risk assessment is an increasingly common tool for wildfire management on USFS lands (Ager et al. 2015, Haas et al. 2015, Hand et al. 2015). The multiple-stressor, multiple endpoint approach of the BN-RRM is well suited to accommodate these complex ecological processes in a spatially explicit manner.

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