AN ABSTRACT OF THE THESIS OF

William C. Clark for the degree of Master of Science in Geography presented on September 1, 2011.

Title: Road Networks, Timber Harvest, and the Spread of Phytophthora Root Rot Infestations of Port-Orford-cedar in Southwest Oregon.

Abstract approved:

Julia A. Jones

Phytophthora lateralis is the causal agent of cedar root rot, a fatal forest pathogen whose principal host is *Chamaecyparis lawsoniana* (Port-Orford-cedar), a predominantly riparian-restricted endemic tree species of ecological, economical, and cultural importance to coastal Oregon and California. Local scale distribution of *P. lateralis* is thought to be associated with timber harvest and road-building disturbances. However, knowledge of the landscape-scale factors that contribute to successful invasions of *P. lateralis* is also important for effective land management of Port-Orford-cedar. *P. lateralis* is able to infest in wet conditions via stream networks (zoospore) and dry conditions via road networks (resting spore). This study tested the hypothesis that vehicles spread *P. lateralis* by relating its distribution to traffic intensive, anthropogenic disturbances (i.e. a road network, timber harvest) over a 31-yr period in a 3,910-km^2 portion of the Rogue River-Siskiyou National Forest in the Siskiyou Mountains of Oregon. Indices of road disturbance (presence/absence, configuration, length, density, road-stream network connectivity) and timber harvest (presence/absence, area, density, frequency) were related to locations of infested cedar populations from a USFS survey dataset using a geographic information system (GIS). About 40% of 934 7^{th}-field catchments were infested with the pathogen. Total road length of the study site was 5,070 km; maximum road density was 8.2 km/km^2 and averaged 1.6 km/km^2 in roaded catchments (n = 766). Timber activities extracted 17,370 ha (2,338 cutting units) of forest across 509 catchments; 345 catchments were cut ≥ twice. Maximum harvest density was 0.92 km^2/km^2 ($\bar{x}$ = 0.04). Both road networks and timber harvest patchworks were significantly

related to cedar root rot heterogeneity. Chi-squared contingency tables showed that infestation rates were 2.2 times higher in catchments with roads compared to roadless catchments and 1.4 times higher in catchments with road-stream intersections compared to those that were unconnected. Infestation was twice as likely in catchments with both harvest and road presence than road presence alone. Single-variable logistic regression showed that a one percent increase in harvest density increased infestation odds 25% and a one-unit (km/km^2) increase in road density increased infestation odds 80%. Road and stream network configuration was also important to pathogen distribution: 1) uninfested catchments are most likely to be spatially removed from infested, roaded catchments, 2) only 11% of 287 roaded catchments downstream of infested, roaded catchments were uninfested, and 3) only 12% of 319 catchments downstream of infested catchments were uninfested. Road networks and timber harvest patchworks appear to reduce landscape heterogeneity by providing up-catchment and down-catchment access to host populations by linking pathogenic materials to the stream network. Timber harvest data suggest that while infestation risk to Port-Orford-cedar populations remains high, management policies may have curbed infestation risk in timber-harvested catchments; if this is a result of specific *P. lateralis* mitigation policies adopted in the late 1980's or broader, region-wide conservation policies (i.e. the Northwest Forest Plan) is yet unclear.

ROAD NETWORKS, TIMBER HARVEST, AND THE SPREAD OF PHYTOPHTHORA ROOT ROT INFESTATIONS OF PORT-ORFORD-CEDAR IN SOUTHWEST OREGON

by
William C. Clark

A THESIS

Submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented September 1, 2011
Commencement June 2012

Master of Science thesis of William C. Clark presented on September 1, 2011.

APPROVED:

Major Professor, representing Geography

Chair of the Department of Geosciences

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

William C. Clark, Author

ACKNOWLEDGEMENTS

Nothing is isolated from its environment, including this thesis – I am indebted to my whole community. Thank you to Dr. Julia A. Jones, a patient and pragmatic mentor. Thank you, also, to friends, family, and cohort but especially:

Autumn A. Carlsen
Elizabeth A. Clark.

TABLE OF CONTENTS

Page

1 INTRODUCTION 1

2 METHODS 4
2.1 STUDY SITE 4
2.2 DATA 5
2.3 HYPOTHESES 6
2.4 SPATIAL DATA ANALYSIS 7
2.5 DISTURBANCE METRICS 11

3 RESULTS 16
3.1 NETWORK DISTURBANCE 16
3.2 PATCHWORK DISTURBANCE 16
3.3 LANDSCAPE AND NETWORK PATTERN 17
3.3.1 Road network configuration 17
3.3.2 Stream network configuration 18
3.3.3 Road/stream network connectivity 19
3.4 LOGISTIC REGRESSION 19

4 DISCUSSION 42
4.1 ERRORS AND BIAS IN ANALYSIS 42
4.2 EFFECTS OF NETWORKS AND NETWORK CONFIGURATION 43
4.4 EFFECTS OF PATCHWORKS 46

5 CONCLUSIONS 53

BIBLIOGRAPHY 54

APPENDICES 58
APPENDIX A. CHI-SQUARED LOOK-UP TABLE. 59
APPENDIX B. HISTOGRAMS FOR CONTINUOUS VARIABLES. 60
APPENDIX C. CORRELATION REGRESSIONS FOR CONTINUOUS VARIABLES. 64
APPENDIX D. SPATIAL AUTOCORRELATION TEST OF CATCHMENT ROAD STATUS. 72
APPENDIX E. RR-SNF BIAS ASSESSMENT. 73

LIST OF FIGURES

Figure | Page
FIGURE 1. STUDY SITE. 13
FIGURE 2. SOUTHWEST OREGON LAND OWNERSHIP. 14
FIGURE 3. SOUTHWEST OREGON ROAD NETWORK. 15
FIGURE 4. CATCHMENTS IN THE RR-SNF. 32
FIGURE 5. ROGUE RIVER-SISKIYOU NF SURVEY. 33
FIGURE 6. CATCHMENT ROAD STATUS. 34
FIGURE 7. CATCHMENT CEDAR ROOT ROT STATUS. 35
FIGURE 8. CATCHMENT ROAD DENSITY. 36
FIGURE 9. TIMBER HARVEST DATA. 37
FIGURE 10. TIMBER HARVEST DENSITY MAP. 38
FIGURE 11. TIMBER HARVEST FREQUENCY FOR THE RR-SNF. 39
FIGURE 12. STREAM NETWORK CONFIGURATION. 40
FIGURE 13. ROAD-STREAM INTERSECTIONS. 41
FIGURE 14. SCHEMATIC OF A BRANCHING HEIRARCHY-TYPE ROAD NETWORK. 51
FIGURE 15. ROAD PRISM SCHEMATIC. 52

LIST OF TABLES

Table | Page

TABLE 2.1. EXAMPLE CONTINGENCY TABLE. 8

TABLE 2.2. TABLE NOTATION 8

TABLE 2.3. CATCHMENT CODE LOOK-UP TABLE. 11

TABLE 3.1. THE SPATIAL RELATIONSHIP BETWEEN THE ROAD NETWORK AND THE RR-SNF 21

TABLE 3.2. EFFECT OF CATCHMENT ROAD STATUS ON INFESTATION STATUS. 21

TABLE 3.3. TIMBER HARVEST SUMMARY. 22

TABLE 3.4. EFFECT OF TIMBER HARVEST FREQUENCY ON CATCHMENTS INFESTATIONS. 23

TABLE 3.5. EFFECT OF TIMBER HARVEST ON THE NUMBER OF CATCHMENTS WITH INFESTATIONS. 24

TABLE 3.6. EFFECT OF TIMBER HARVEST AND ROADS ON CATCHMENTS INFESTATIONS. 24

TABLE 3.7. TEMPORAL ANALYSIS OF INFESTATION RATES BASED ON HARVEST PERIOD. 25

TABLE 3.8. EFFECT OF ROAD CONFIGURATION ON CATCHMENT INFESTATION STATUS. 25

TABLE 3.9. EFFECT OF ADJACENCY TO UNINFESTED/ROADED CATCHMENTS. 26

TABLE 3.10. EFFECT OF ADJACENCY TO INFESTED/ROADLESS CATCHMENTS. 26

TABLE 3.11. EFFECT OF ADJACENCY TO UNINFESTED/ROADLESS CATCHMENTS. 27

TABLE 3.12. EFFECT OF ADJACENCY TO INFESTED/ROADED CATCHMENTS. 27

TABLE 3.13. EFFECT OF THE STREAM NETWORK ON DOWNSTREAM CATCHMENT INFESTATIONS. 28

TABLE 3.14. SPATIAL RELATIONSHIP BETWEEN THE ROAD AND STREAM NETWORKS. 29

TABLE 3.15. EFFECT OF ROAD-STREAM INTERSECTIONS ON THE NUMBER OF INFESTED CATCHMENTS. 29

TABLE 3.16. SUMMARY DATA OF SINGLE-VARIABLE ALTERNATIVE MODELS 30

TABLE 3.17. SUMMARY DATA OF MULTIVARIATE ALTERNATIVE MODELS 31

LIST OF APPENDIX FIGURES

Figure	Page
Figure 16. Catchment area and drainage density histograms.	60
Figure 17. Road length and density histograms.	61
Figure 18. Timber harvest area and density histograms.	62
Figure 19. Road-stream intersection density histograms.	63
Figure 20. Collinearity analysis of ln-transformed catchment area.	64
Figure 21. Collinearity analysis of ln-transformed drainage density.	65
Figure 22. Collinearity analysis of ln-transformed road length.	66
Figure 23. Collinearity analysis of ln-transformed road density.	67
Figure 24. Collinearity analysis of ln-transformed harvest area.	68
Figure 25. Collinearity analysis of ln-transformed harvest density.	69
Figure 26. Collinearity analysis of ln-transformed road-stream intersection density.	70
Figure 28. Moran's I test output from ArcGIS.	72

LIST OF APPENDIX TABLES

Table Page

TABLE 1C. SUMMARY DATA OF COLLINEARITY. 71

TABLE 1E. CONTINGENCY TABLE COMPARING ROAD STATUS AND SURVEY STATUS. 73

TABLE 2E. CONDITIONAL PROBABILITY RESULTS FOR THE RR-SNF. 73

TABLE 3E. SUMMARY OF POWER ANALYSIS FROM SELECTED STATISTICAL TESTS. 74

TABLE 4E. ANALYSIS OF COINCIDENCE BETWEEN PORT-ORFORD-CEDAR AND ROADS ON A CATCHMENT BASIS. 74

Road Networks, Timber Harvest, and the Spread of Phytophthora Root Rot Infestations of Port-Orford-cedar in Southwest Oregon

1 Introduction

Landscape heterogeneity is the result of processes operating at many spatial and temporal scales and is closely linked to landscape function (Forman & Godron 1986). In the Pacific Northwest, much of the forested ecosystem exists in varying states of disturbance and recovery from timber harvest. Timber harvest is a complex disturbance producing both patches of harvested land and a road network to access the resource. Most timber harvest patches on public forest lands in the Pacific Northwest are small, high-severity, disturbances semi-regularly distributed in the landscape in both space and time. The associated road system in contrast, is a larger-scale, linearly branching, permanent network that fragments the landscape into a mosaic of forest patches. Together, timber harvest patchworks and road networks alter the heterogeneity of forest structure and may alter functions within it. In particular, timber harvest patchworks and road networks may influence the relationship between *Phytophthora lateralis* and its host, *Chamaecyparis lawsoniana* (Port-Orford-cedar), in forests of the Siskiyou Mountains, Oregon.

Port-Orford-cedar is the largest tree species of the *Cupressaceae* (Cypress) family and is endemic to the Coast Range, Siskiyou and Klamath Mountains of Oregon and northern California (Zobel et al. 1982, Imper 1981; Zobel & Hawk 1980). Port-Orford-cedar is often limited to stream margins, areas with near-surface groundwater, or moist soils (Imper 1981; Farjon 2005). Port-Orford-cedar does not commonly form pure stands, but occurs in mixed coniferous forests dominated by Douglas fir (*Pseudotsuga menziesii*) with components of western redcedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), Pacific madrone (*Arbutus menziesii*), and Sitka spruce (*Picea sitchensis*) (Farjon 2005). Wood from Port-Orford-cedar has been in commercial demand since Europeans "discovered" it in the early 19th-century and is among the world's most commercially valuable conifers (Port Orford Cedar Products Company 1929; Hansen et al. 2000).

Phytophthora lateralis is a non-native, soil-borne, forest pathogen and the causal agent of cedar root rot disease, which was first reported as a pathogen of Port-Orford-cedar in the Coast Range of Oregon in 1952 (Trione 1957). The origin of cedar root rot is unconfirmed, but it is believed the pathogen was introduced from Asia or Europe on ornamental nursery stock (Zobel et al. 1982). Although it has been observed as a pathogen on other species, Port-Orford-cedar is its principal host (DeNitto 1991; Betlejewski et al. 2003; Murray & Hansen 1997). There is no known cure, and immunity has not yet been discovered in Port-Orford-cedar, supporting the hypothesis that cedar root rot is non-native (Oh 2005; Hansen 2008). Port-Orford-cedar trees usually survive less than four years after infection by *P. lateralis* (Jules et al. 2002; Hansen et al. 2000).

P. lateralis is an Oomycete, a water mold more closely related to algae than fungus, whose life cycle takes place in a wetted soil matrix environment. Depending on its life stage, cedar root rot is able to spread in water or survive dry conditions. Two stages of the cedar root rot life cycle are important to its functional distribution among Port-Orford-cedar populations: the motile zoospore and the immobile resting spore (chlamydospore) (Hansen 2008). The zoospore is biflagellate and can only infest downstream Port-Orford-cedar populations and those within the wetted soil matrix (Hansen et al. 2000). Conversely, the resting spore is resistant to dry conditions, giving the pathogen the ability to survive throughout a heterogeneous landscape. In favorable conditions, resting spores can germinate into zoospores or mycelium; a relatively small amount of inoculum is needed to infect a new host tree (Betlejewski et al. 2003).

Previous studies of spatial patterns of cedar root rot have suggested that it is inadvertently transported in infested soil or plant material by traffic along forest roads and from roads to streams (Roth et al. 1987; Jules et al. 2002; Betlejewski et al. 2003; Kauffman & Jules 2006). An extensive road network was constructed to support accelerated timber harvest in the Pacific Northwest in the mid-20th-century. The US Forest Service has monitored the spatial patterns of spread of cedar root rot in southwestern Oregon since 1964 (Betlejewski et al. 2003). However, no studies have related the spatial patterns of road networks and timber harvest to the spatial pattern of spread of cedar root rot over a landscape-scale in southwest Oregon.

The primary objective of this study is to examine how the heterogeneity of landscape elements affects the distribution pattern of a non-native forest pathogen as measured by infestation. To test the hypothesis that traffic spreads *Phytophthora lateralis*, this study examines the spatial configuration of traffic-intensive, anthropogenic disturbance (i.e. road networks, timber harvest) and its relationship to the distribution of cedar root rot and *Chamaecyparis lawsoniana* over the period of 1969 to 2000 (primarily 1986-1994) in a 3,910-km^2 portion of the Rogue River-Siskiyou National Forest (RR-Siskiyou NF) in the Siskiyou Mountains of Oregon. This study addressed the following questions:

1. How are spatial patterns of cedar root rot infestations of Port-Orford-cedar related to road networks and timber harvest?
2. How are spatial patterns of cedar root rot infestations of Port-Orford-cedar related to stream networks?
3. How are spatial patterns of cedar root rot infestations of Port-Orford-cedar related to connectivity of road networks with stream networks?

2 Methods

2.1 Study site

The study site is a 391,100-ha (3,910-km^2) area comprising the Gold Beach, Powers, and Wild Rivers Ranger Districts of the RR-Siskiyou NF at the center of Port-Orford-cedar's natural range (Figure 1). Federally managed forests (USDA Forest Service [USFS] and Bureau of Land Management [BLM]) constitute a large proportion of Port-Orford-cedar's range; the study site is nearly entirely public land (Figure 2). There are approximately 5,070 km of roads in the study site (Figure 3). Elevation across the study site ranges from 3 to 2,146 m above sea level.

Port-Orford-cedar is a key component of the local ecology. Over much of its range, parent materials are ultramafic (Imper 1981). Ultramafic soils are uncommon and have a distinct geochemistry to which few plants have adapted (Alexander 2007). Port-Orford-cedar is the defining (sometimes sole) overstory species of 43 plant associations in Oregon and California. Thirty rare, threatened and otherwise protected plant species are found within these communities and 11 are known to only occur with Port-Orford-cedar (Betlejewski et al. 2003). Port-Orford-cedar is also culturally significant. The Karuk and Hupa of California used Port-Orford-cedar as the main building material for their "living homes" and sweathouses (Roth et al. 1987). Before its own decline, Port-Orford-cedar was a common substitute for the declining hinoki (*C. obtusa*), revered by the Japanese for its spiritual importance.

In the 20th-century, timber production was a principal economic driver for economies of southwestern Oregon. Although Douglas fir was the primary species of harvest by volume, Port-Orford-cedar was a very high-value timber ($5,400-12,000/ thousand board feet), at times reaching ≤10x the commercial value of Douglas fir (Zobel et al. 1982; Betlejewski et al. 2003). Port-Orford-cedar harvest peaked in the 1940's at 60 million board feet annually (Zobel et al. 1982). During the early 19th-century, Port-Orford-cedar was used for a wide array of products, from specialty to ordinary: aircraft bodies, venetian blinds, battery separators, cabinetry, phone poles, bridge and ferry decking, ornamental veneers, and turpentine (Port Orford Cedar Products Company 1929). Harvest of Port-Orford-cedar declined starting in the 1960's as availability declined (Zobel et al. 1982). General timber harvest was further curtailed when the Northwest Forest Plan (1994) established forest reserve areas in federally managed forest lands.

2.2 Data

Data on Port-Orford-cedar infestation were obtained from the USFS (Dorena Genetic Resource Center, USDA Forest Service, Cottage Grove, Oregon, USA). Surveys of Port-Orford-cedar populations in the Gold Beach, Powers, and Wild Rivers Ranger Districts of the RR-Siskiyou NF have been ongoing since 1964 (Betlejewski et al. 2003). Presence and absence of cedar root rot infections (pathogen effects on individual hosts) have been recorded and entered into a GIS in the vector data model (polygons) by the USFS to record the extent of infestation (pathogen invasion of a host population); point data are not available. The survey was not exhaustive: areas within the study site lacking Port-Orford-cedar were not surveyed. This study uses a subset of the RR-Siskiyou NF data extending from 1969 to 2000 (primarily 1986-1994) consisting of 3,910 polygons of ≥3,910 observations (hereafter referred to as RR-SNF). Most of the observations took place in catchments with roads; sampling bias is addressed in Section 4.1. The RR-SNF is housed in an ArcInfo (version 9.3.0.1770, Environmental Systems Research Institute [ESRI], Redlands, California, USA) file geodatabase at the USDA Dorena Genetic Resource Center in Cottage Grove, Oregon. Several survey methods are included in the RR-SNF: roadside surveys, timber cruise data, stand exams, and aerial photography interpretation; aerial photographic methods were only used in the Powers Ranger District (Denton 2004). Detailed metadata about the number of observations used by the USFS to create each polygon and data collection methods have not been found.

Cedar root rot infection can be visually detected during most stages allowing for effective field-based surveys. Early detection relies on diagnosing loss of foliar turgidity. Inspecting the inner bark for brown, rotted cambium further corroborates cedar root rot presence. Once girdled, foliar discoloration begins. Early foliar discoloration may be a difficult diagnostic because Port-Orford-cedar has a naturally broad range of coloration, but late discoloration becomes more obvious as needles begin to brown; within two years of death defoliation occurs (Trione 1957). In many cases, opportunistic insect infestations, facilitated by the pathogen, are the proximal cause of tree death (Hansen 2008).

Regional catchment and stream network data were obtained from the Environmental Protection Agency-US Geological Survey joint data project, the National Hydrography Dataset Plus (NHDPlus; http://www.horizon-systems.com/nhdplus/). The RR-SNF data were examined at the 7^{th}-field level (Hydrologic Unit Code 14) since that is the management unit used for Port-Orford-cedar (Denton 2004). Road network data were obtained from a BLM dataset (1:24,000 scale). Timber harvest data were extracted from a Landsat change detection dataset created by the Laboratory for Applications of Remote Sensing in Ecology (LARSE, Corvallis, Oregon, USA; http://www.fsl.orst.edu/larse/). The harvest data extend from 1972 to 2005; the data were truncated to 2000 to coincide with the RR-SNF. The LARSE harvest data are parsed into six time periods: 1972-1977; 1977-1984; 1984-1988; 1988-1992; 1992-1996; 1996-2000. This dataset will not be able to capture the true harvest frequency within a catchment. Rather, it will capture the number of periods that harvest events took place between 1972-2000; this is a limitation of the source data. The LARSE dataset and analyses of relationships with timber harvest are restricted to Oregon.

2.3 Hypotheses

Several spatially explicit tests were conducted to examine the hypothesis that vehicles spread *P. lateralis* infestations:

H1. If traffic is a pathogen vector, then there will be a positive relationship between roads and infestation.

H2. If traffic is a pathogen vector, then there will be positive relationships between road length and density and infestation because they measure increased disturbance and infestation opportunity.

H3. If infestation spreads via road network (resting spore), then it will be rare to observe uninfested/roaded catchments adjacent to infested/roaded catchments and rare to observe infested/roadless catchments adjacent to uninfested/roadless catchments but common to observe infested/roaded catchments adjacent to other infested/roaded catchments.

H4. If infestation spreads via stream network (zoospore), then catchments downstream to infested catchments are likely to be infested.

H5. If the pathogen can travel both the road and stream networks, then there will be a positive relationship between road-stream connections and infestation.

H6. If traffic is a pathogen vector, then there will be a positive relationship between timber harvest and infestation because harvest activities are vehicle intensive.

H7. If traffic is a pathogen vector, then there will be positive relationships between harvest area, density, and frequency and infestation because they present increased disturbance and infestation opportunity.

2.4 Spatial data analysis

Geographic data analysis was conducted using ArcInfo version 10.1.0.3200 (ESRI, Redlands, California, USA). Statistical analysis utilized Excel for Mac version 12.2.9 (Microsoft, Redmond, Washington, USA) and R statistical software version 1.40 GUI for Mac OS X (The R Foundation for Statistical Computing). Statistical power was analyzed with G*Power version 3.0.0 (Faul et al. 2007).

Statistical analyses tested how the presence of cedar root rot (response variable; based on the RR-SNF) was related to the presence and density of road networks, stream networks, and timber harvest. Statistical methods included contingency tables (cross tabulation) with the Pearson chi-squared statistic (X^2), conditional probability, and logistic (logit) regression analysis.

Contingency tables (e.g. Table 2.1) were used to test relationships between binary response variables and a dependent variable. The null hypothesis (H_0) of a contingency table is that the response variable (e.g. infestation status) is independent of the condition variable (e.g. road status). Since the data tested in this study are spatially explicit, rejection of H_0 indicates a spatial pattern other than random between the response and condition variables. The contingency table uses the X^2 test to compare observed to expected counts. Expected counts are 1) calculated under the assumption that H_0 is true using Equation 1 and 2) compared to observed counts using Equation 2 (Christensen 1997). This analysis follows the notations used by Christensen (1997) outlined in Table 2.2: for a table with I rows and J columns, observed values have notation n_{ij}, $I = 1, 2 \ldots i$ and $J = 1, 2 \ldots j$. Larger tables incorporate expected values (m_{ij}) into the same table and use the same subscript notations as Table 2.2.

Table 2.1. Example contingency table.
This contingency table has two binary variables, infestation status and road status, and tests for independence between them.

Observed				Expected			
	Road status				Road status		
Infestation status	roadless	roaded	∑	Infestation status	roadless	roaded	∑
uninfested	135	434	*569*	uninfested	102	467	*569*
infested	33	332	*365*	infested	66	299	*365*
∑	*168*	*766*	*934*		*168*	*766*	*934*

Table 2.2. Table notation.
The notation becomes important when identifying specific contributions to the X^2: e.g. in Table 2.1 n_{11} = 135 and m_{11} = 102.

		Columns		
		1	2	∑
Rows	1	n_{11}	n_{12}	$n_{1:}$
	2	n_{21}	n_{22}	$n_{2:}$
∑		$n_{:1}$	$n_{:2}$	$n_{::}$

Expected counts (m) were determined using Equation 1. This example calculates m for position n_{11} of Table 2.2:

$$m_{11} = n_{:1}\,(n_{1:} / n_{::}); \qquad \text{(Equation 1)}$$

and X^2 was computed using:

$$X^2 = \sum^{I} i = 1 \sum^{J} j = 1 \quad \frac{(n_{ij} - m_{ij})^2}{m_{ij}}; \qquad \text{(Equation 2)}$$

Where:
n_{ij} = the observed value of the cell
m_{ij} = the expected value of the cell.

The calculated X^2 was compared to the critical chi-squared value table (χ^2, *df*, *p-value*; Appendix A). Degrees of freedom (*df*) were calculated using (Ramsey & Schafer 1997):

$$(r - 1) * (c - 1). \qquad \text{(Equation 3)}$$

Where:
r = the number of rows in the observation table
c = the number of columns in the observation table.

The H_0 was rejected if, and only if, the calculated X^2 exceeded the critical χ^2. H_0 was rejected at the following significance levels: very strong ($p \leq 0.001$), strong ($p = 0.010$), moderate ($p = 0.025$), slight ($p = 0.050$), very slight ($p = 0.100$), and not significant ($p > 0.100$). Contingency tables were constructed to test the relationships between: roads and infestation, harvest and infestation, harvest frequency and infestation, road and stream network configuration and infestation, and road-stream intersections and infestation.

Logit regressions were run using R software. Logit regression (π) is a model for response variables of binomial distribution that results in the log odds probability that a particular response or event (e.g. that pathogen infestation) will occur based on the value of the independent variable (e.g. road density):

$$\pi = \beta_0 + \beta_1 x_1 + \ldots + \beta_p x_p + \varepsilon \qquad \text{(Equation 4)}$$

Where:
β = parameter value
x = regression parameter (e.g. road density)
ε = model residual.

Log odds were then exponentiated for interpretation:

$$\text{Odds that } \pi = 1: \omega = \exp(\beta_0 + \beta_1 x_1 + \ldots + \beta_p x_p + \varepsilon) \qquad \text{(Equation 5)}$$

Where:
π = 1 = positive infestation status
β = parameter value
x = regression parameter (e.g. road density)
ε = model residual.

Pathogen infestation (response variable) was related to 11 explanatory variables at the catchment scale using single-variable logistic regression: 1) catchment area, 2) road presence, 3) road length, 4) road density, 5) harvest presence, 6) harvest area, 7) harvest density, 8) harvest frequency, 9) drainage density, 10) road/stream intersections, and 11) road-stream intersection density (count per km^2). A histogram was created for each of the continuous variables using R (Appendix B). Catchment area, road length and density, harvest area and density, drainage density, and road-stream intersection density were transformed using the natural logarithm (base *e*); the common logarithm (base 10) was also tested, but the natural logarithm resulted in more normal distributions (Appendix B). A dummy value of 0.0001 was added to transformed variables before transformation to preserve zero values. The 11 variables were assessed for collinearity using simple linear regression (Appendix C). Variables were also examined using multivariate logistic regressions. Alternative multivariate logistic model assessment started using a "rich model" of all statistically significant variables regardless of collinearity (the presence/absence metrics were not addressed in multivariate logistic regression). The Akaike information criterion (AIC), a metric that incorporates log-likelihood to measure relative goodness of model fit, and delta (Δ) deviance, a metric that evaluates the fitness of the model with a covariate to the fitness of the model without the covariate, were used to evaluate model fit as step-wise dropterm functions were used to eliminate variables. Variable removal ceased when further removals resulted in increased AIC or decreased Δ deviance. Collinearity results were then used to inform model selection and prevent over-fitting of the data. Adjustments were made while maintaining the best (lowest) AIC, greatest significance of variables, and greatest model simplicity.

2.5 Disturbance metrics

The NHDPlus dataset was used in a spatial query (overlay) to identify the 7th-field catchments included in the USFS pathogen survey (RR-SNF). Surveyed catchments were overlayed with the BLM road layer to determine road status. Catchments were coded based on pathogen absence (0) and presence (1) and road absence (0) and presence (1). The codes were concatenated to assign each catchment a compound binary code (Table 2.3). To test how road presence was related to cedar root rot infestation, catchment codes were tallied and tested in a contingency table.

Table 2.3. Catchment code look-up table.
Look-up table defining the compound binary codes used to describe the status of the surveyed catchments of the RR-Siskiyou NF.

Code	Key
00	uninfested, roadless
01	uninfested, roaded
10	infested, roadless
11	infested, roaded

To test whether road length and density were related to cedar root rot infestation, each was calculated for the 7th-field catchments in the study site. The BLM road layer was intersected with the NHDPlus catchment data. Road lengths (km) were then joined to the catchment data using Spatial Join in ArcGIS. Dividing by catchment area (km^2) yielded road density (km/km^2).

To test how cedar root rot infestation was related to timber harvest, timber harvest data were extracted from the LARSE dataset. The spatial data coincident to each time period were exported to separate datasets for pre-analysis. Timber harvest was measured using four metrics: 1) absence/presence, 2) harvest area (km^2), 3) harvest density (km^2/km^2), and 3) harvest frequency. A second binary code was appended to the catchment data table to specify absence (0) and presence (1) of harvest.

Harvest area, density, and frequency were determined for each catchment in the study site using the Zonal Statistics as Table tool in ArcGIS.

To test how road status and cedar root rot infestation status of one catchment was related to road and infestation status of adjacent catchments, all possible pairs of adjacent catchments were identified and their infestation and road status were queried in GIS. Tallies were input to Excel and analyzed in contingency tables. A test of independence was conducted for each of five contingency tables: one of overall adjacency and one each for the statuses in Table 2.3.

To test the hypothesis that within hydrologically adjacent catchments (i.e. upstream/downstream pairs) infestation of the downstream catchment is more likely if the upstream catchment is also infested all pairs of hydrologically adjacent catchments were spatially queried in GIS. Tallies were input to Excel and analyzed in contingency tables.

To test how road-stream connections were related to cedar root rot infestation, points where roads crossed streams were identified using GIS. A culvert inventory does not exist for the RR-Siskiyou NF. Instead, a spatial overlay of geometric intersections between the road and stream networks was computed in GIS. The analysis resulted in net-net nodes, an indication of the road-stream network connectivity of each catchment sub-network. A third binary code was appended to roaded catchments (codes: 01 and 11) indicating absence (0) and presence (1) of road-stream intersections.

FIGURE 1. STUDY SITE.

Shown are the extents of the USFS pathogen survey (1969-2000), the Rogue River-Siskiyou NF, and Port-Orford-cedar's natural range. The range is approximate and delineated using Port-Orford-cedar breeding data created by the USFS.

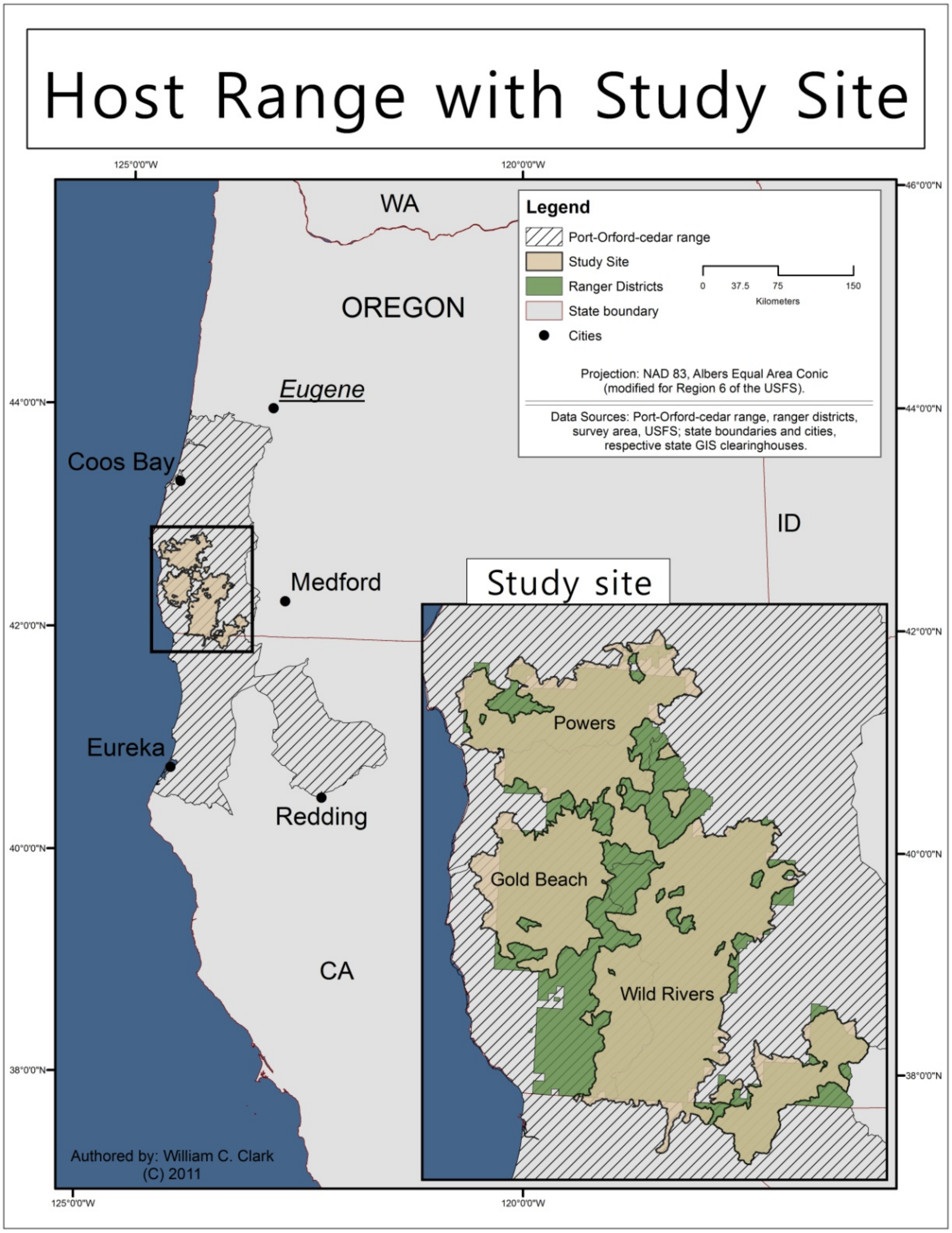


FIGURE 2. SOUTHWEST OREGON LAND OWNERSHIP.
The study site is contained within the Rogue River-Siskiyou NF, specifically the Gold Beach, Powers, and Wild Rivers Ranger Districts. The study site is approximately 391,000 ha (3,100 km^2). Port-Orford-cedar's range is 50% federally managed.

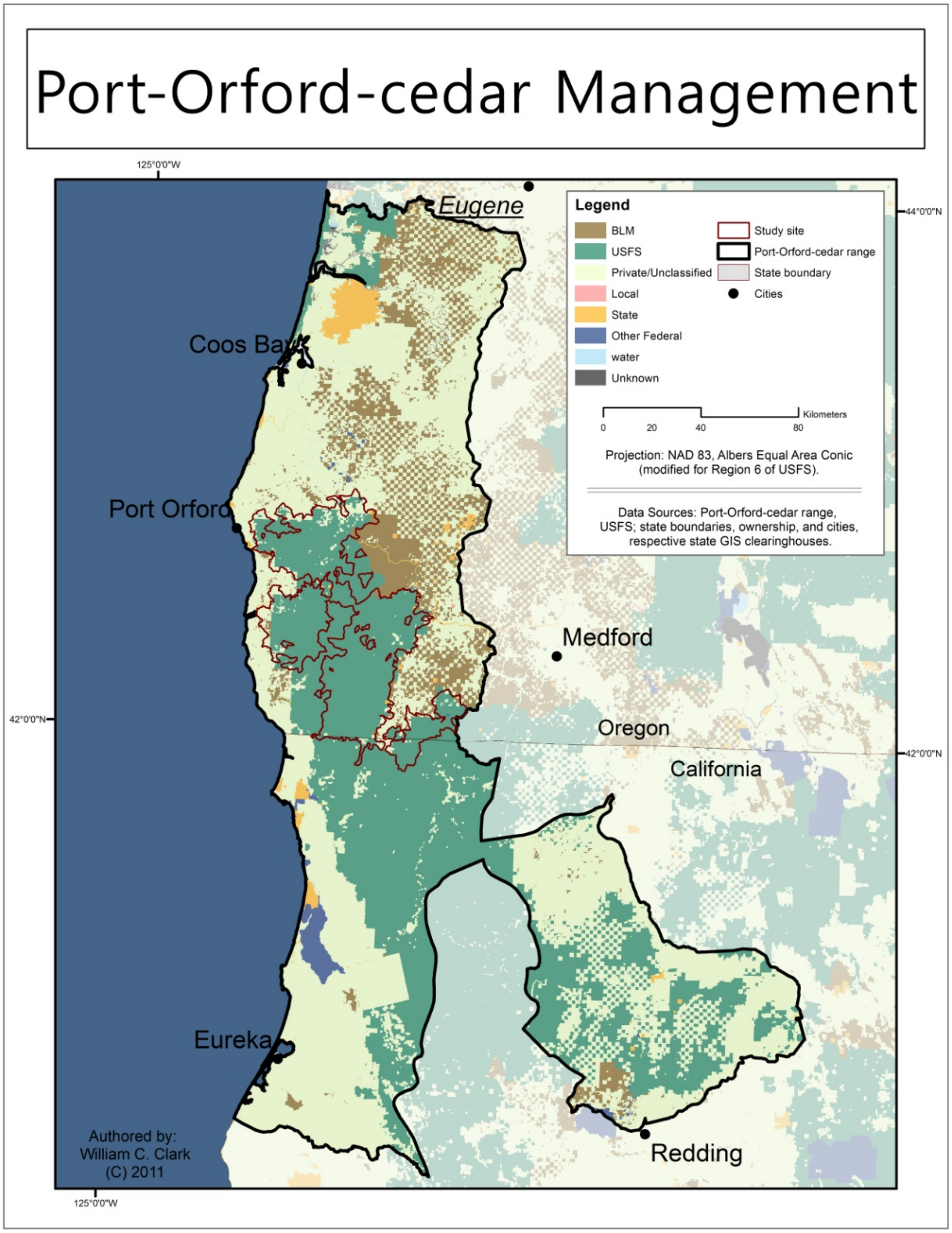
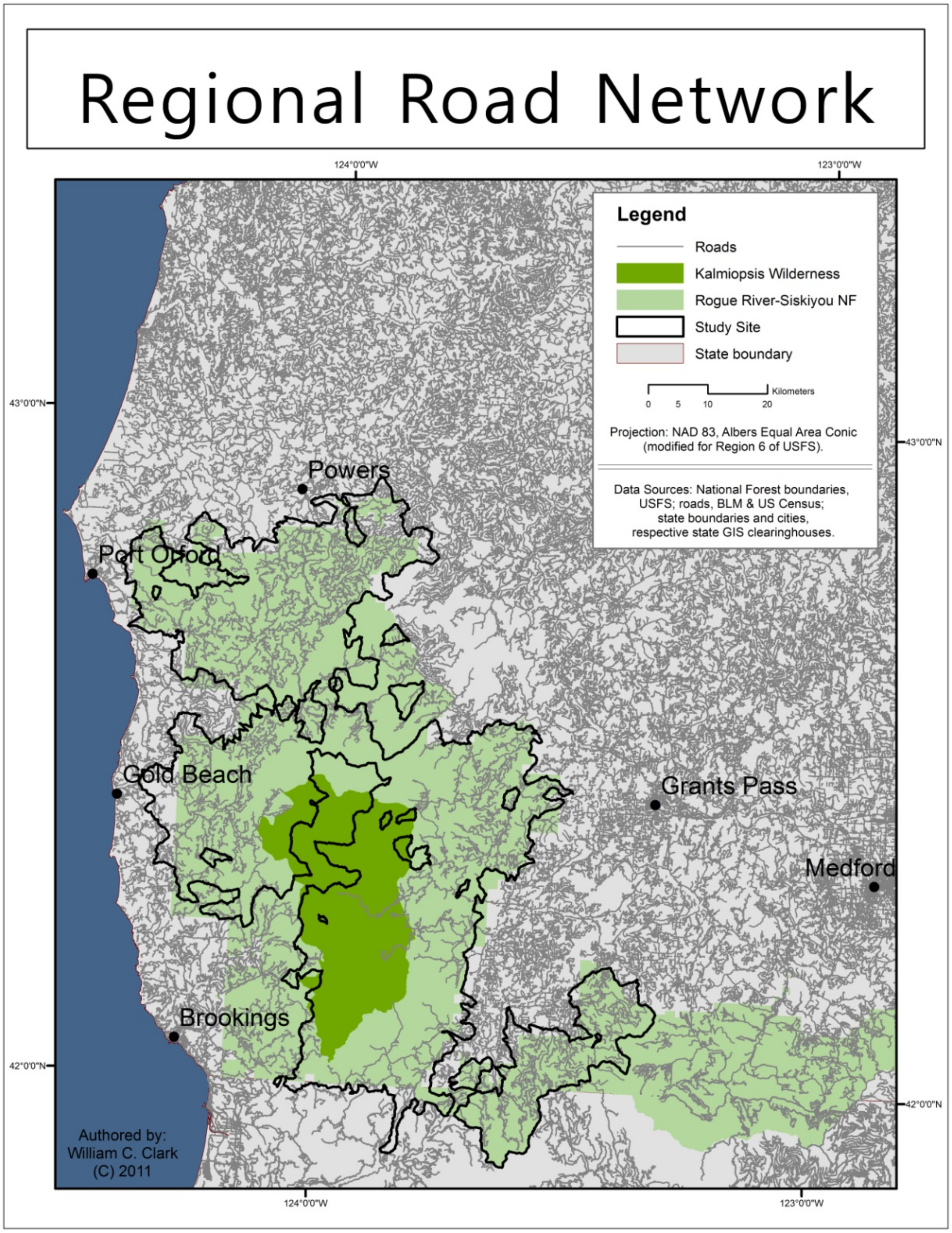


FIGURE 3. SOUTHWEST OREGON ROAD NETWORK.

There are 5,070 km of roads in the study site. The Kalmiopsis Wilderness Area is a 72,800 ha (728 km^2) largely roadless area in the southwest portion of the study site.



3 Results

3.1 Network disturbance

The cedar root rot survey (RR-SNF) spans 934 7^{th}-field catchments (Figure 4) representing ~3,910 km^2 of the RR-Siskiyou NF (Figure 5). Mean catchment area was 4.2 km^2 (max = 33.7; $\sigma = 3.6$). Pathogen presence was recorded in 647 (17%) observations. Of the 934 catchments, 766 (82%) have roads (Table 3.1; Figure 6) and 365 (39%) were infested with cedar root rot as of 2000 (Figure 7). Infestation at the catchment scale was strongly positively associated with the presence of roads ($p < 0.001$, $X^2 = 32.5$, $df = 1$; Table 3.2). Overall, 43% (332/766) of catchments with roads but only 20% (33/168) of catchments without roads had infestations. Catchments with roads were 2.2 times more likely to be infested than catchments without roads.

For the study site ($n = 934$), mean catchment road length was 5.4 km (range: 0-44.8; $\sigma = 6.9$) and mean road density was 1.3 km/km^2 (range: 0-8.2 km/km^2; $\sigma = 1.2$; Figure 8). For roaded catchments ($n = 766$), mean road length was 6.6 km ($\sigma = 7.1$) and mean road density was 1.6 km/km^2 ($\sigma = 1.0$).

3.2 Patchwork disturbance

From 1972-2000, 17,370 ha (173.7 km^2; 4%) of the study site were harvested; 2,338 harvest units were cut over 509 (54%) catchments (Figure 9; Table 3.3). For the study site ($n = 934$), mean timber harvest area was 18.6 ha per catchment (range: 0-367; $\sigma = 40.5$) and mean harvest density was 0.04 km^2/km^2 (range: 0-0.92; $\sigma = 0.08$). Mean harvest area in harvested catchments ($n = 509$) was 34.1 ha ($\sigma = 43.4$) and mean harvest density was 0.07 km^2/km^2 ($\sigma = 0.08$; Figure 10). Catchments on average experienced 2.1 harvest events; 345 catchments were harvested ≥ twice and 62 were harvested ≥ four times (Figure 11; Table 3.4). Only 109 of 425 (26%) catchments with no timber harvest were infested with cedar root rot, but 256 of 509

(50%) catchments with timber harvest were infested (Table 3.5). Infestation was positively associated with timber harvest within a catchment (p < 0.001, X^2 = 86.7, df = 1); catchments with harvest were twice as likely to be infested. Harvest frequency was strongly positively related to infestation (p < 0.001, X^2 = 64.4, df = 4). However, the X^2 was dominated by the individual statistic for zero harvest frequency; when zero harvest frequency is excluded from analysis, there is no statistically significant relationship between harvest frequency and infestation status (X^2 = 2.3, df = 3).

Nearly all catchments with timber harvest also had roads; only 21 catchments with harvest had no roads. The association of timber harvest with cedar root rot was examined for roaded catchments only (n = 766) (Table 3.6). Only 79 of 278 (28%) roaded catchments with no harvest activities were infested, whereas 253 of 488 (52%) catchments with harvest were infested; infestations were twice as frequent in catchments with both roads and harvest compared to those with roads only (p < 0.001, X^2 = 39.6, df = 1).

Infestation rates for timber harvest periods were similar prior to 1992 and ranged from 47% (78 of 166) to 56% (196 of 351; Table 3.7). After 1992, infestation rate dropped to 0% (of 27) between 1992-1996 and 6% (2 of 33) between 1996-2000: catchments that were harvested prior to 1992 were significantly more likely to be infested in 2000 than those that were harvested after 1992. The majority (76% [141 of 186]) of catchments that were harvested twice were done so by 1988, whereas only 41% (40 of 97) of catchments harvested thrice were done so by 1988.

3.3 Landscape and network pattern

3.3.1 Road network configuration

A total of 4,736 catchment neighbor pairs were coded into Excel ($\bar{x}$ = 5.0 adjacencies per catchment; σ = 1.8); 2,368 pairs were unique. The infestation and road status of a catchment was highly associated with those of its neighbors (p < 0.001, X^2 = 1,714, df = 9; Table 3.8). Like-status neighbors (i.e. 00-00, 01-01, 10-10, and 11-11 pairs) comprised 85% of the X^2 indicating strong spatial clumpiness within the data. This is corroborated by a Moran's *I* spatial autocorrelation test (Appendix D); roaded/infested and unroaded/uninfested catchments were highly spatially autocorrelated. Uninfested catchments adjacent to infested/roaded catchments were observed more rarely than expected if their distribution had been random (361 observed instances versus 749 expected; Table 3.8). There was a very strong relationship between the status of uninfested/roaded ($p < 0.001$, $X^2 = 36.9$, $df = 1$) and infested/roadless catchments ($p < 0.001$, $X^2 = 14.7$, $df = 1$) and the status of their adjacent catchments (Tables 3.9 and 3.10). There were far fewer infested/roadless catchments adjacent to uninfested/roaded catchments than expected ($X^2 = 23.1$ of 36.9 [63%]; Table 3.9). Uninfested/roadless catchments were adjacent to infested/roadless catchments more frequently than expected ($X^2 = 6.1$ of 14.7 [41%]; Table 3.10). Infestation status of uninfested/roadless catchments ($p < 0.05$, $X^2 = 1.6$, $df = 1$) and infested/roaded catchments ($p < 0.05$; $X^2 = 0.8$, $df = 1$) was less strongly related to the road and infestation status of their neighbors (Tables 3.11 and 3.12).

3.3.2 Stream network configuration

Of the 934 catchments in the study site, 485 (52%) were headwater catchments with only downstream neighbors; 184 (38%) headwater catchments were infested. A total of 792 pairs of catchments were hydrologically connected in the sense that one was a tributary of the other (Figure 12; Table 3.13). Infested catchments tend to be downstream of other infested catchments: 281 of 319 (88%) catchments downstream of infested catchments were infested, whereas only 61 of 473 (13%) catchments downstream of uninfested catchments were infested. Catchments downstream of roaded catchments were more commonly infested (304 of 645; 47%) than catchments downstream of roadless catchments (38 of 147; 26%). Notably, uninfested/roaded catchments were never observed downstream of infested/roadless catchments.

3.3.3 Road/stream network connectivity

Mean drainage density of the NHDPlus data layers was 0.85 km/km^2 (range: 0.04 – 7.9; σ = 0.64). A total of 758 road-stream intersections occur in the study site (Figure 13). Infested catchments had 33% more road-stream intersections per catchment on average than uninfested catchments (Table 3.14). The road network did not intersect the stream network in 409 (53%) of the 766 roaded catchments (Table 3.15), and these catchments were less likely to be infested (149/409; 36%) than catchments with road-stream intersections (183/357; 51%). The presence of road-stream intersections in a roaded catchment increases the relative risk of infestation by 1.4 times compared to roaded catchments without intersections and 2.6 times compared to roadless catchments.

3.4 Logistic regression

Collinearity was observed between some of the 11 variables tested; r^2 reached 0.71 (Appendix C). In simple logistic regression roads, road length, road density, road-stream intersections, harvest, and harvest frequency were very strongly related to infestation ($p < 0.001$) and drainage density, harvest area, and harvest density were strongly related to infestations ($p < 0.01$); catchment area and road-stream intersection density were not statistically significantly related to infestations (Table 3.16). The strength of the relationship between road and harvest density can be seen when graphically displayed (Figure 15). Density metrics were given more attention since inferences from density metrics can be most easily applied to other case studies.

The multivariate rich model began using six explanatory variables and yielded an AIC = 353.9 (Table 3.17). It was the intent to use recursive dropterms procedures to remove variables. However, only one application of the dropterm function was necessary before subsequent applications increased AIC. The dropterm procedure removed harvest frequency and resulted in a five-variable model: drainage density, harvest area, and harvest frequency, which reduced AIC to 353.7. Based on their greater model output *p*-values, harvest density (instead of harvest area) and road length (instead of road density) were removed from the model to prevent over-fitting caused by collinearity. The AIC of this model rose to 356.3. The interaction between drainage density and road density reduced AIC while increasing Δ deviance. The final model (Model no. 4) for the log odds of an infestation (π):

$$\pi = -12.4 + 5.6D + 1.1H + 0.4R - 0.5D*H \qquad \text{(Equation 6)}$$

Where:

D = drainage density (km/km^2);
H = harvest area (km^2);
R = road density (km/km^2).

Table 3.1. The spatial relationship between the road network and the RR-SNF.
Most catchments (82% of 934) have a road within them and of those, 332 (43%) are infested with cedar root rot.

Code	Key	Count	∑
00	uninfested/roadless	135	165
10	infested/roadless	33	
01	uninfested/roaded	434	766
11	infested/roaded	332	

Table 3.2. Effect of catchment road status on infestation status.
The X^2 indicates that the null hypothesis should be rejected: infestation and roads are dependent.

Road status					
Infection status	roadless		roaded		∑
	observed	expected	observed	expected	
uninfested	135	102	434	467	*569*
infested	33	66	332	299	*365*
∑	*168*	*168*	*766*	*766*	*934*

Table position	$(o_b - e_b)^2 / e_b$
n_{11}	10.4
n_{21}	16.2
n_{12}	2.3
n_{22}	3.6
X^2	32.5 ***

*** $p < 0.001$, $df = 1$

Table 3.3. Timber harvest summary.

Summary data of harvest disturbance in the RR-Siskiyou NF study site during the period of the survey. Catchments were subject to a mean of 2.1 harvest events and 4.5 units between 1972 and 2000.

Harvest	No. of Units	No. of Catchments	Harvest Area (ha)
1972-1977	539	261	3245
1977-1984	842	351	7401
1984-1988	504	246	3624
1988-1992	331	166	2543
1992-1996	59*	27	262
1996-2000	63*	33	296
∑	*2338*	*1084* ^	*17371*

* - some harvest units cross multiple 7th-field catchments.

^ - Of this only 509 unique catchments were harvested.

Table 3.4. Effect of timber harvest frequency on catchments infestations.

The X^2 indicates that the null hypothesis should be rejected. Thus, the infestation status of roaded catchments depends on the number of harvest events that occurred within that catchment. Catchments with 2 harvest events had significantly higher proportions of infestations compared to those with 1, 3, or 4+ harvest events.

Catchment by harvest frequency

Catchment status	Number of harvest events in a catchment										
	0		1		2		3		4-6		∑
	o	e	o	e	o	e	o	e	o	e	
uninfested	316	259	85	100	84	113	53	59	31	38	*569*
infested	109	166	79	64	102	73	44	38	31	24	*365*
∑	*425*		*164*		*186*		*97*		*62*		*934*

o = observed
e = expected

Table position	$(o_b - e_b)^2 / e_b$
n_{11}	12.6
n_{21}	19.6
n_{12}	2.2
n_{22}	3.5
n_{13}	7.6
n_{23}	11.8
n_{14}	0.6
n_{24}	1.0
n_{15}	1.2
n_{25}	1.9
X^2	62.0 ***

*** $p < 0.001$, $df = 4$

Table 3.5. Effect of timber harvest on the number of catchments with infestations.
The X^2 statistic indicates a strong relationship between infection status and presence of harvest units.

Infestation status	Harvest Status: no harvest		harvest		
	observed	expected	observed	expected	∑
uninfested	316	253	253	255	*569*
infested	109	163	256	163	*365*
∑	*425*		*509*		*934*

Table position	$(o_b - e_b)^2 / e_b$
n_{11}	15.7
n_{21}	0.0
n_{12}	17.9
n_{22}	53.1
X^2	86.7***

*** $p < 0.001$, $df = 1$

Table 3.6. Effect of timber harvest and roads on catchments infestations.
The X^2 statistic indicates a strong relationship between infection status and presence of harvest units.

Roaded catchment by harvest presence

Catchment status	Harvest status: no harvest		harvest		∑
	observed	expected	observed	expected	
Uninfested/roaded	199	158	235	276	*434*
Infested/roaded	79	120	253	212	*332*
∑	*278*		*488*		*766*

Table position	$(o_b - e_b)^2 / e_b$
cell aa	10.9
cell ba	14.3
cell ac	6.2
cell bc	8.1
X^2	39.6 ***

*** $p = 0.001$, $df = 1$

Table 3.7. Temporal analysis of infestation rates based on harvest period.
Infestation rates dropped in the early 1990's; sample sizes are, however, 85-93% fewer than those of the 1970's and 1980's .

	Period					
	1972-1977	1977-1984	1984-1988	1988-1992	1992-1996	1996-2000
No. of harvested catchments	261	351	246	166	27	33
No. of harvested catchments infested	146	196	117	78	0	2
Proportion	56%	56%	48%	47%	0%	6%

Table 3.8. Effect of road configuration on catchment infestation status.
The X^2 indicates that the null hypothesis should be rejected. Thus, a catchment's infection-road status is dependent on that of its neighbor.

	Neighbor catchment								
Base catchment	uninfested/ roadless		uninfested/ roaded		infested/ roadless		infested/ roaded		Σ
	o	e	o	e	o	e	o	e	
uninfested/roadless	193	37	196	193	29	14	41	215	*459*
uninfested/roaded	--	--	802	483	19	36	320	534	*1141*
infested/roadless	--	--	--	--	27	3	71	46	*98*
infested/roaded	--	--	--	--	--	--	670	313	*670*
Σ	*193*		*998*		*75*		*1102*		*2368*

o = observed
e = expected

Table position	$(o_b - e_b)^2 / e_b$
n_{11}	647.1
n_{12}	0.0
n_{22}	214.4
n_{13}	14.4
n_{23}	8.1
n_{33}	184.0
n_{14}	140.6
n_{24}	85.7
n_{34}	13.8
n_{44}	405.4
X^2	1713.5 ***

*** $p < 0.001$, $df = 9$

Table 3.9. Effect of adjacency to uninfested/roaded catchments.
The χ^2 indicates that the null hypothesis should be rejected. Thus, the status of uninfested, roaded catchments is dependent on the status of their neighbors.

Neighbor catchment	**Base Catchment** Uninfested/roaded Road status				
Infection status	roadless		roaded		∑
	observed	expected	observed	expected	
uninfested	196	160	802	838	*998*
infested	19	55	320	284	*339*
∑	*215*		*1122*		*1337*

Table position	$(o_b - e_b)^2 / e_b$
n_{11}	7.9
n_{21}	23.1
n_{12}	1.5
n_{22}	4.4
X^2	36.9 ***

*** $p < 0.001$, $df = 1$

Table 3.10. Effect of adjacency to infested/roadless catchments.
The X^2 indicates the null hypothesis should be rejected. Thus, the status of infested, roadless catchments is dependent on the status of their neighbors.

Neighbor catchment	**Base Catchment** Infested/roadless Road status				
Infection status	roadless		roaded		∑
	observed	expected	observed	expected	
uninfested	29	18	19	30	*48*
infested	27	38	71	60	*98*
∑	*56*		*90*		*146*

Table position	$(o_b - e_b)^2 / e_b$
n_{11}	6.1
n_{21}	3.0
n_{12}	3.8
n_{22}	1.9
X^2	14.7 ***

*** $p < 0.001$, $df = 1$

Table 3.11. Effect of adjacency to uninfested/roadless catchments.
The null hypothesis is not rejected: the status of uninfested/roadless catchments is independent of the status of their neighbors.

Neighbor catchment	**Base Catchment**				
	Uninfested/roadless				
	Road status				
Infection status	roadless		roaded		∑
	observed	expected	observed	expected	
uninfested	193	188	196	201	*389*
infested	29	34	41	36	*70*
∑	*222*		*237*		*459*

Table position	$(o_b - e_b)^2 / e_b$
n_{11}	0.1
n_{21}	0.7
n_{12}	0.1
n_{22}	0.7
X^2	1.6†

† $p = 0.26$, $df = 1$

Table 3.12. Effect of adjacency to infested/roaded catchments.
The null hypothesis is not rejected: the status of infested/roadless catchments is independent of the status of their neighbors.

Neighbor catchment	**Base Catchment**				
	Infested/roaded				
	Road status				
Infection status	roadless		roaded		∑
	observed	expected	observed	expected	
uninfested	41	37	320	324	*361*
infested	71	75	670	666	*741*
∑	*112*		*990*		*1102*

Table position	$(o_b - e_b)^2 / e_b$
n_{11}	0.5
n_{21}	0.2
n_{12}	0.1
n_{22}	0.0
X^2	0.8†

† $p = 0.42$, $df = 1$

Table 3.13. Effect of the stream network on downstream catchment infestations.
Uninfested areas are rarely downstream of infested catchments, but often downstream of other uninfested catchments. Uninfested/roaded catchments are never observed downstream of infested/roaded catchments.

Downstream Catchment Status	**Upstream Catchment Status**: uninfested/ roadless		uninfested/ roaded		infested/ roadless		infested/ roaded		Σ
	o	e	o	e	o	e	o	e	
uninfested/roadless	72	18	45	56	2	5	4	45	*123*
uninfested/roaded	35	47	260	148	0	13	32	118	*327*
infested/roadless	3	6	6	17	12	2	17	14	*38*
infested/roaded	5	44	47	137	18	12	234	110	*304*
Σ	*115*		*358*		*32*		*287*		*792*

o = observed
e = expected

Table position	$(o_b - e_b)^2 / e_b$
n_{11}	164
n_{21}	3
n_{31}	1
n_{41}	35
n_{12}	2
n_{22}	85
n_{32}	7
n_{42}	59
n_{13}	2
n_{23}	13
n_{33}	71
n_{43}	3
n_{14}	37
n_{24}	63
n_{34}	1
n_{44}	139
X^2	686 ***

*** $p < 0.001$, $df = 9$

Table 3.14. Spatial relationship between the road and stream networks.

Catchment status	*n*	Intersections *n*	Per catchment	Per catchment area (km^2)
uninfected, roaded	434	367	0.85	81.6
infected, roaded	332	391	1.18	79.8
∑	*766*	*758*		

Table 3.15. Effect of road-stream intersections on the number of infested catchments. Contingency table and X^2 for the road-stream intersection analysis. The X^2 indicates that the null hypothesis should be rejected. Thus, the infection status of roaded catchments depends on the road-stream intersection status of that catchment.

	Intersection status					Table position	$(o_b - e_b)^2 / e_b$
Infection status	no intersections		intersections			n_{11}	3.4
	observed	expected	observed	expected	∑	n_{21}	4.5
uninfested	260	232	174	202	*434*	n_{12}	4.0
infested	149	177	183	155	*332*	n_{22}	5.2
∑	*409*		*357*		*766*	X^2	17.1 ***

*** $p < 0.001$, $df = 1$

Table 3.16. Summary data of single-variable alternative models.
Most explanatory variables were statistically significantly related to infestation status at $p < 0.001$.

Model	Model Variable	Units	Log odds	Odds	Std. Error	z-value	Significance	AIC	Δ Deviance	*n*
1	catchment area	km^2	0.07	1.07	0.06	1.06		1253	1.2	934
2	drainage density	km/km^2	-0.35	0.70	0.13	-2.65	**	1247	7.2**	934
3	roads	(0/1)	1.14	3.13	0.21	5.50	***	1219	35.2***	934
4	road length	km	0.34	1.41	0.06	5.61	***	1017	34.5***	766
5	road density	km/km^2	0.59	1.80	0.09	6.30	***	1002	50.4***	766
6	intersections	(0/1)	0.83	2.28	0.14	5.95	***	1218	35.8***	934
7	intersection density	per km^2	0.04	1.04	0.06	0.64		498	0.4	357
8	harvest	(0/1)	1.08	2.93	0.14	7.57	***	1194	60.4***	934
9	harvest area	km^2	0.18	1.20	0.06	3.00	**	700	9.3**	509
10	harvest density	km^2/km^2	0.22	1.25	0.07	3.26	**	699	11.0**	509
11†	harvest variety 1		0.99	2.69	0.19	5.17	***	1197	63.1***	934
	harvest variety 2		1.26	3.52	0.18	6.82	***			
	harvest variety 3		0.88	2.41	0.23	3.78	***			
	harvest variety 4		1.06	2.90	0.28	3.84	***			

*** $p < 0.001$
** $p < 0.01$
† as a categorical variable, harvest frequency outputs one AIC and Δ deviance.

Table 3.17. Summary data of multivariate alternative models.

The chosen model (model no. 5) has the lowest AIC while retaining a high Δ deviance. The interaction between drainage density and harvest area was only slightly statistically significant ($p < 0.05$).

Model no.	Interacting Variables	Variables	No. variables	AIC	Δ Deviation	Notes
1		dd, ha, hd, hf, rl, rd	6	353.9	18.4	rich model
2		dd, ha, hd, rl, rd	5	353.7	12.6	dropterm selected
3		dd, ha, hd, rd	4	355.2	9.1	adjusted for over-fitting
4		dd, ha, rd	3	356.3	6.0	adjusted for over-fitting
5	dd * ha	dd, ha, rd	3	352.6	11.6	chosen model
6	dd * rd	dd, ha, rd	3	357.1	7.2	

Variables: dd = ln of drainage density; ha = ln of harvest area; hd = ln of harvest density; hf = harvest frequency (factor variable); rl = ln of road length; rd = ln of road density.

FIGURE 4. CATCHMENTS IN THE RR-SNF.

The RR-SNF consists of at 3,910 polygon observations that span 934 7th-field catchments, an area ~3,910 km^2.

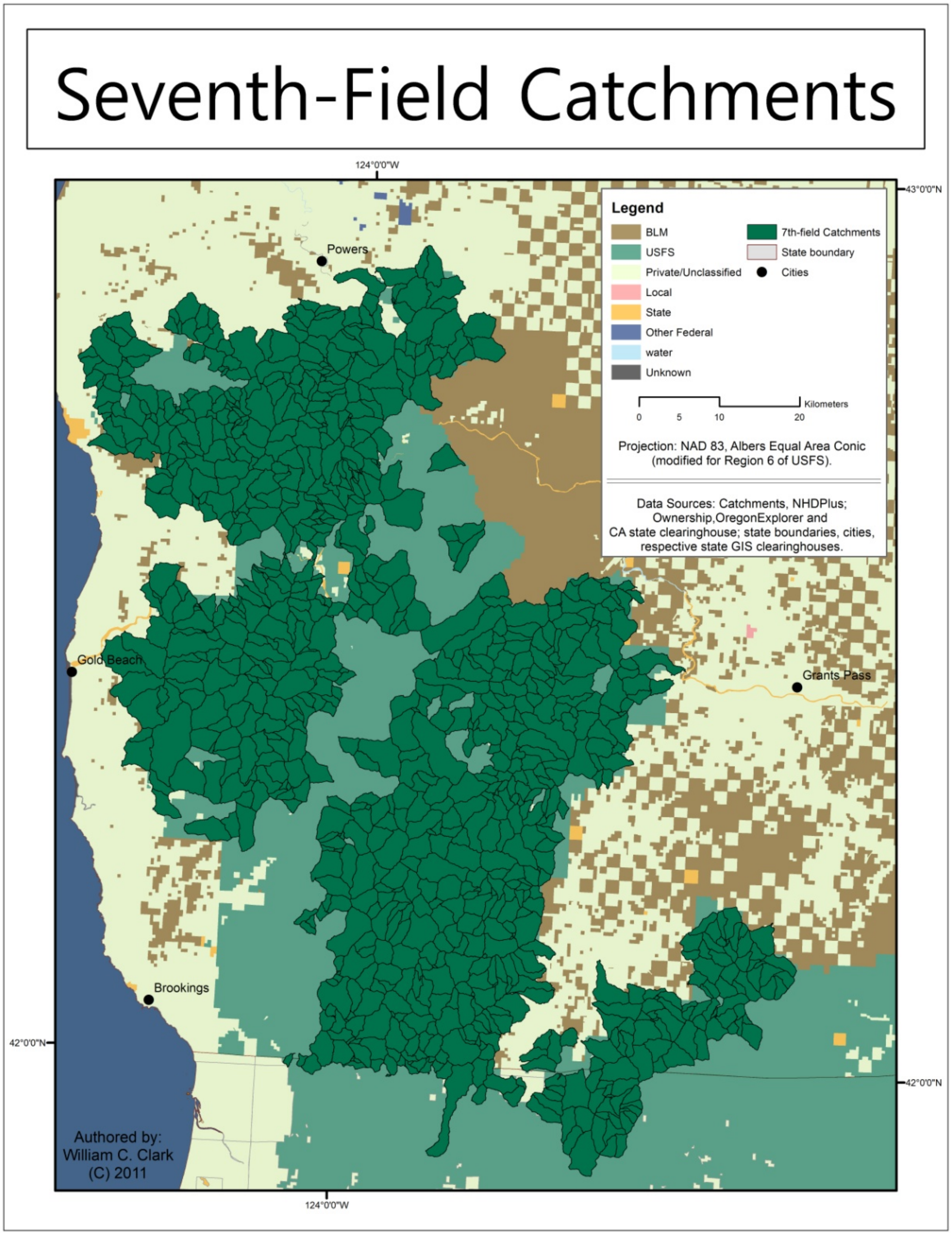


FIGURE 5. ROGUE RIVER-SISKIYOU NF SURVEY.
RR-SNF observations from 1969 – 2000; conservatively there are 3,910 polygons in the dataset that correspond to at least that many observations.

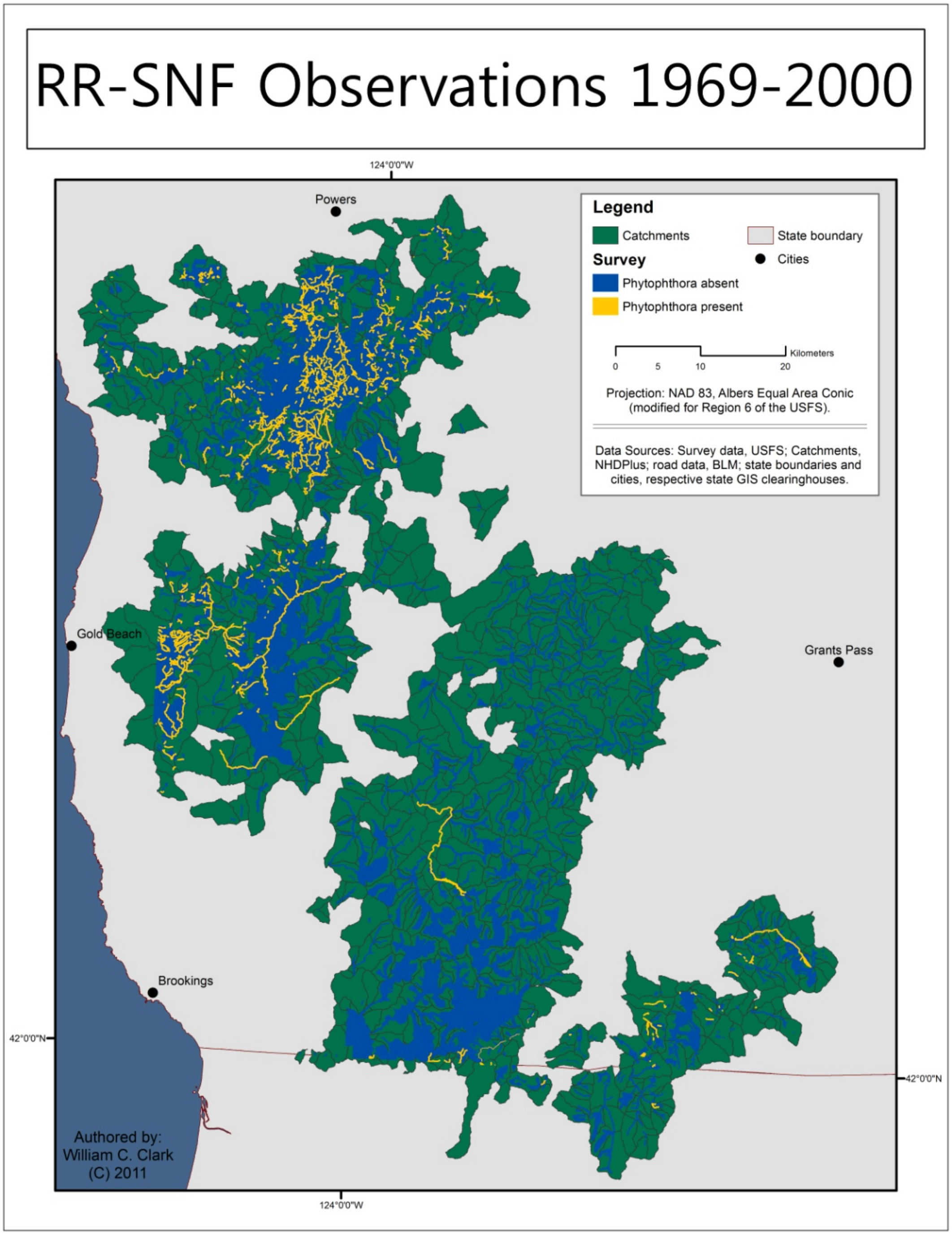


FIGURE 6. CATCHMENT ROAD STATUS.

A road network covers some of the RR-SNF area, but not all. Each catchment was coded for the presence of roads. Most of the roadless areas border or are part of the Kalmiopsis Wilderness Area, but there are some roadless areas scattered throughout the RR-SNF.

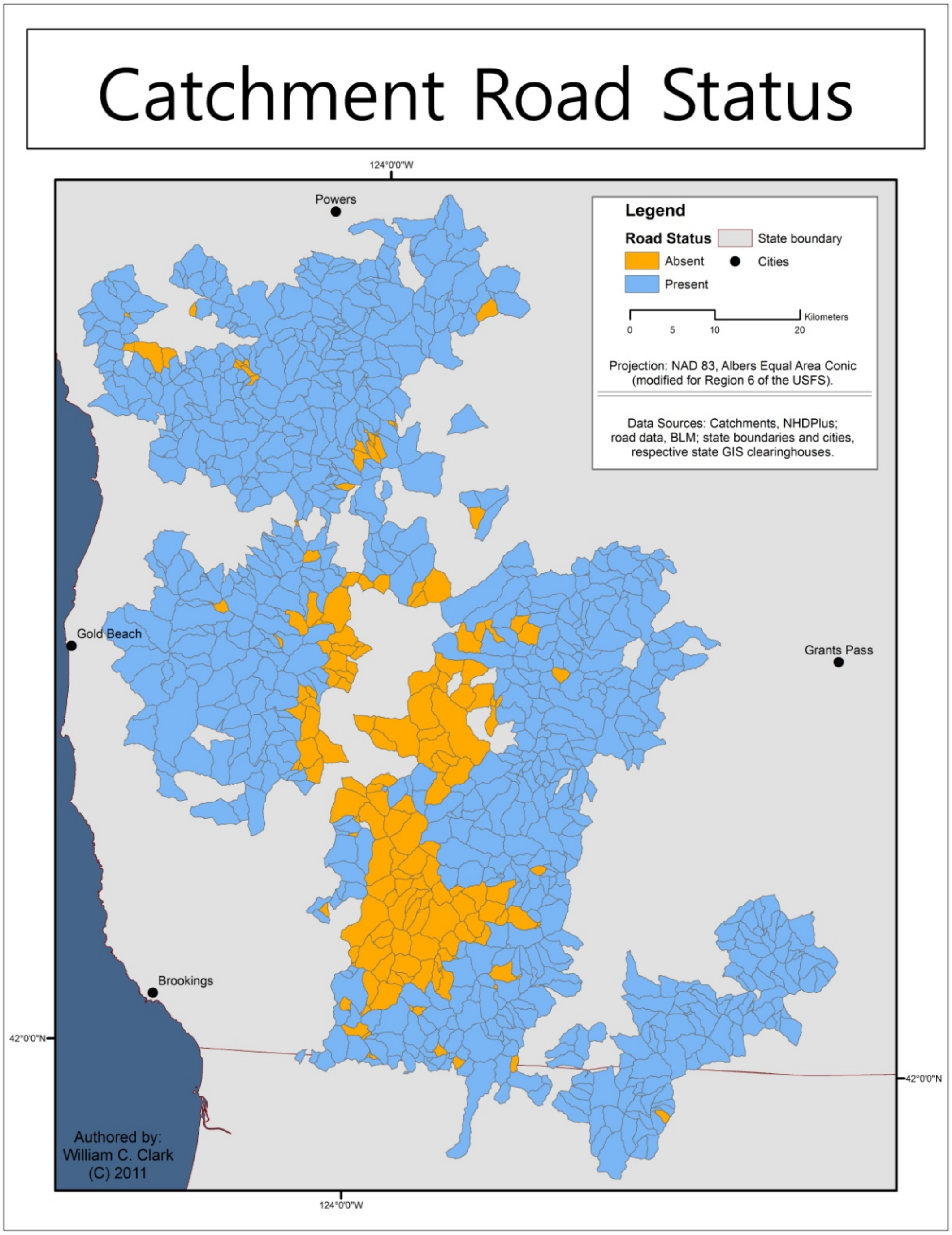


FIGURE 7. CATCHMENT CEDAR ROOT ROT STATUS.

The RR-SNF survey was overlayed with the catchment and road data to assign compound binary codes to each catchment based on presence/absence of 1) infestation and 2) part of a road network.

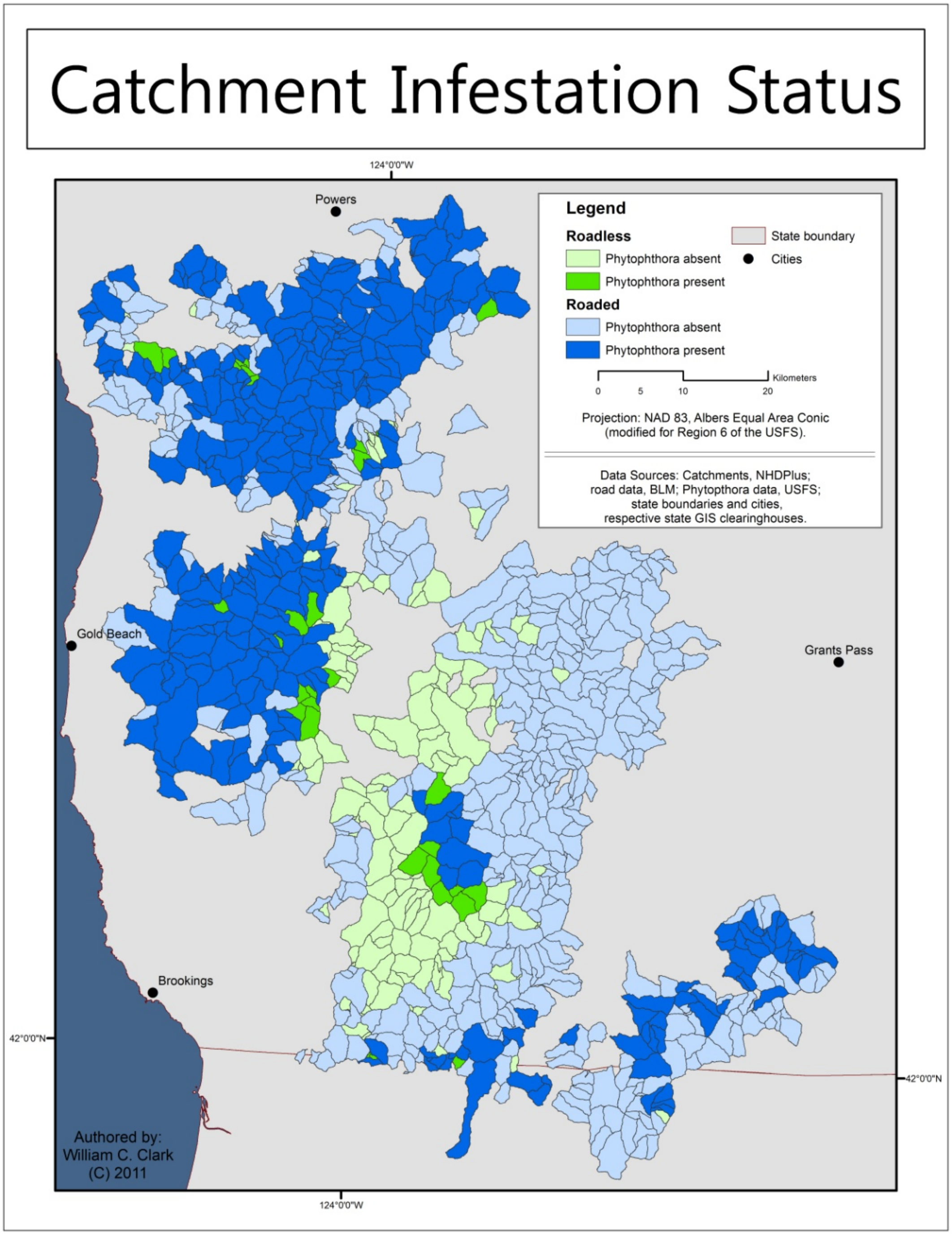


FIGURE 8. CATCHMENT ROAD DENSITY.

Road density ranged from 0 – 8.2 km/km^2.

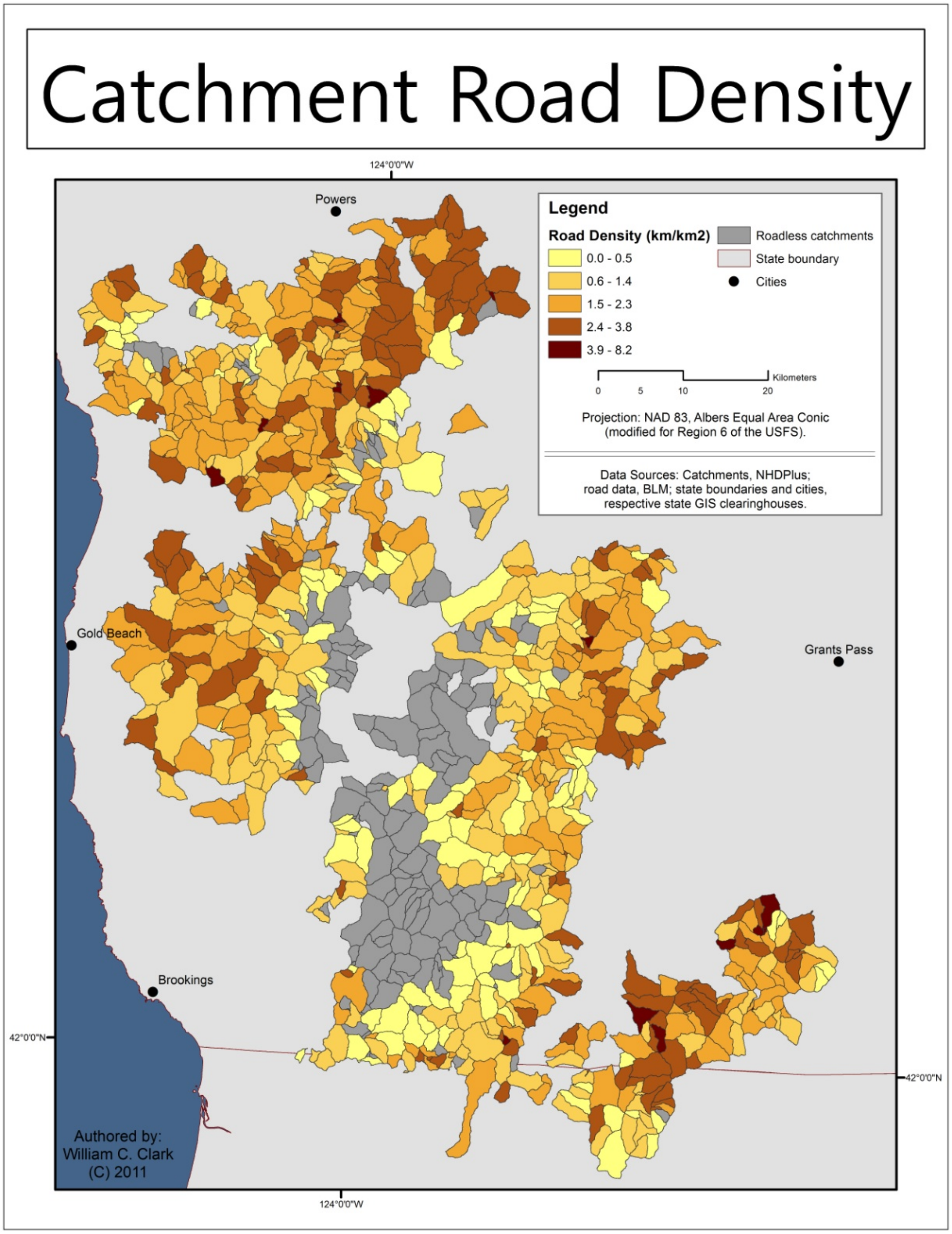


FIGURE 9. TIMBER HARVEST DATA.

Harvest data was extracted from the LARSE stand replacement dataset and truncated to 2000, the last year of survey in the RR-SNF. Note: the LARSE dataset does not extend into California.

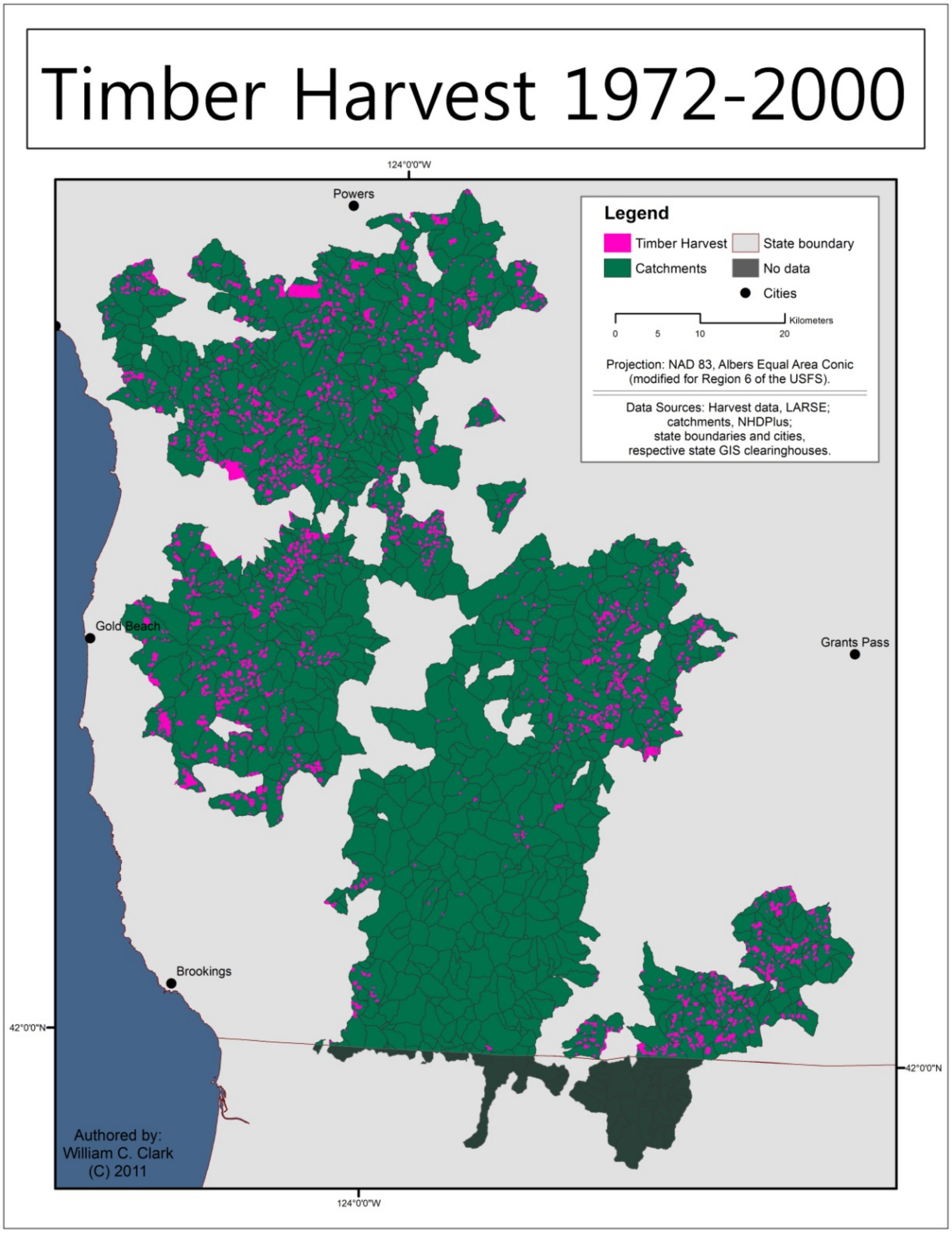


FIGURE 10. TIMBER HARVEST DENSITY MAP.

Harvest density reached a maximum of 0.92 km^2/km^2; mean harvest density was 0.04 km^2/km^2 for all catchments and 0.07 km^2/km^2 for harvested catchments.

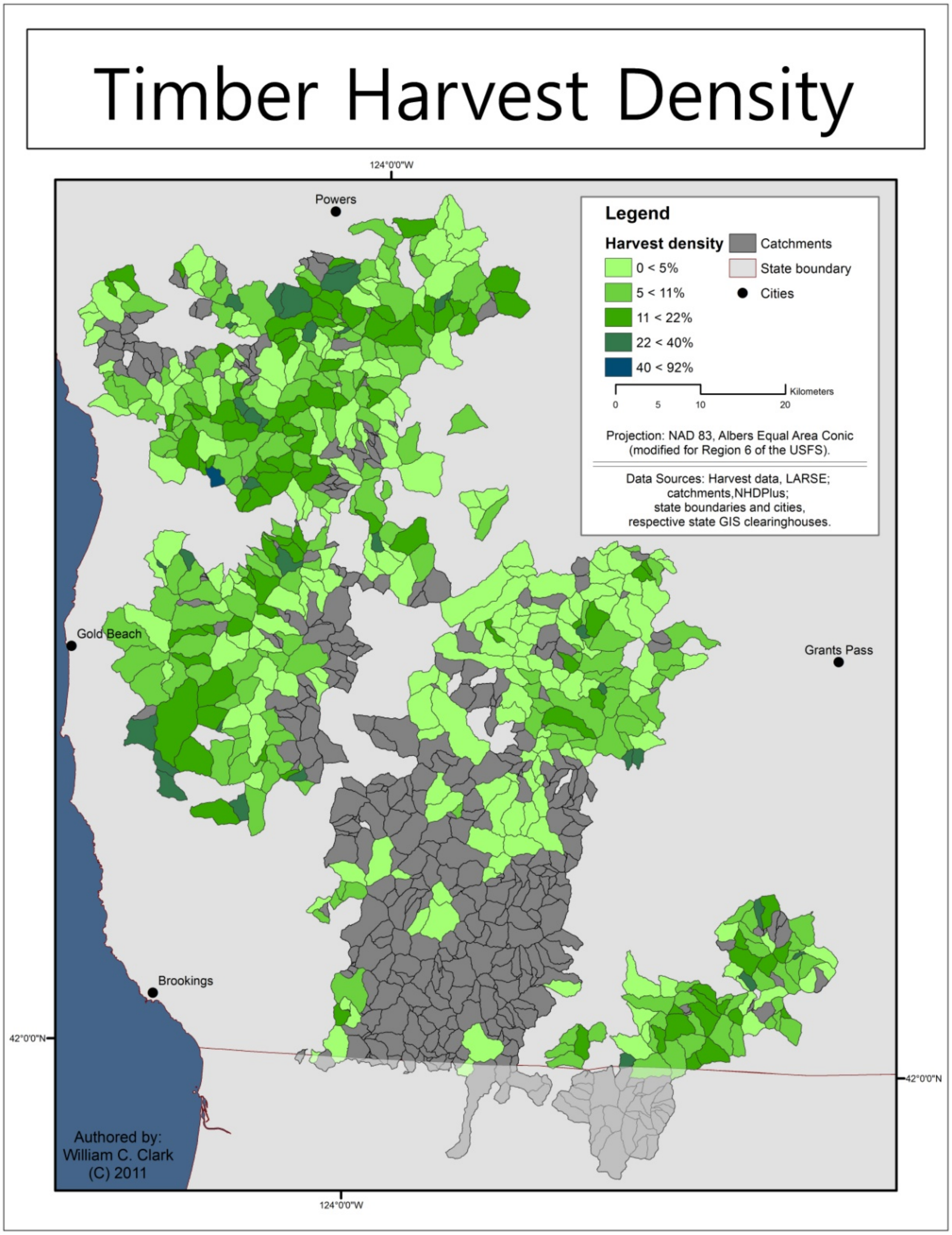


FIGURE 11. TIMBER HARVEST FREQUENCY FOR THE RR-SNF.
Harvest frequency ranged from 0-6 events over the six periods assessed between 1972 and 2000. On average, catchments experienced 2.1 harvests during the 28-yr period.

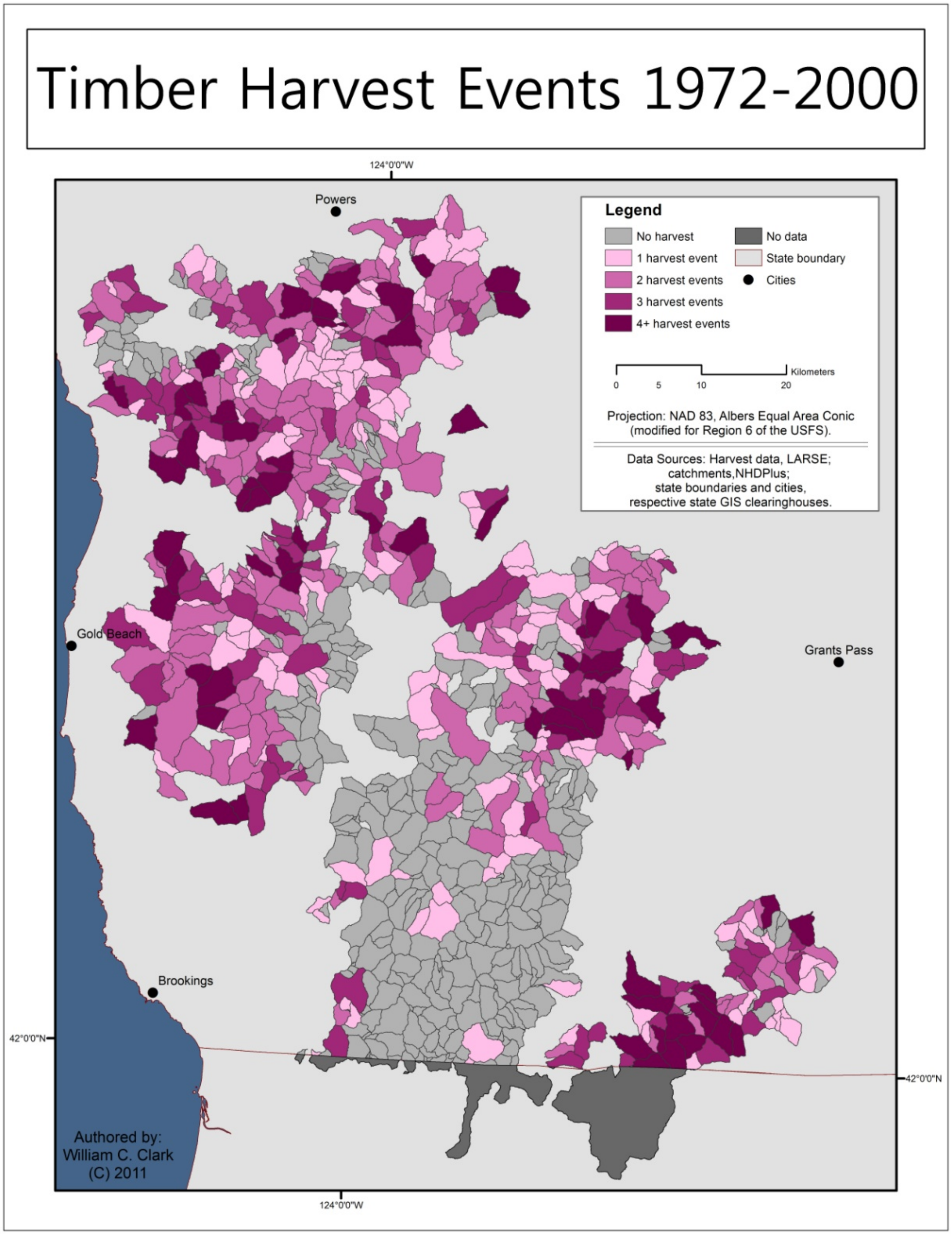


FIGURE 12. STREAM NETWORK CONFIGURATION.
Of the 934 surveyed catchments, 485 were headwater catchments with no upstream neighbor.

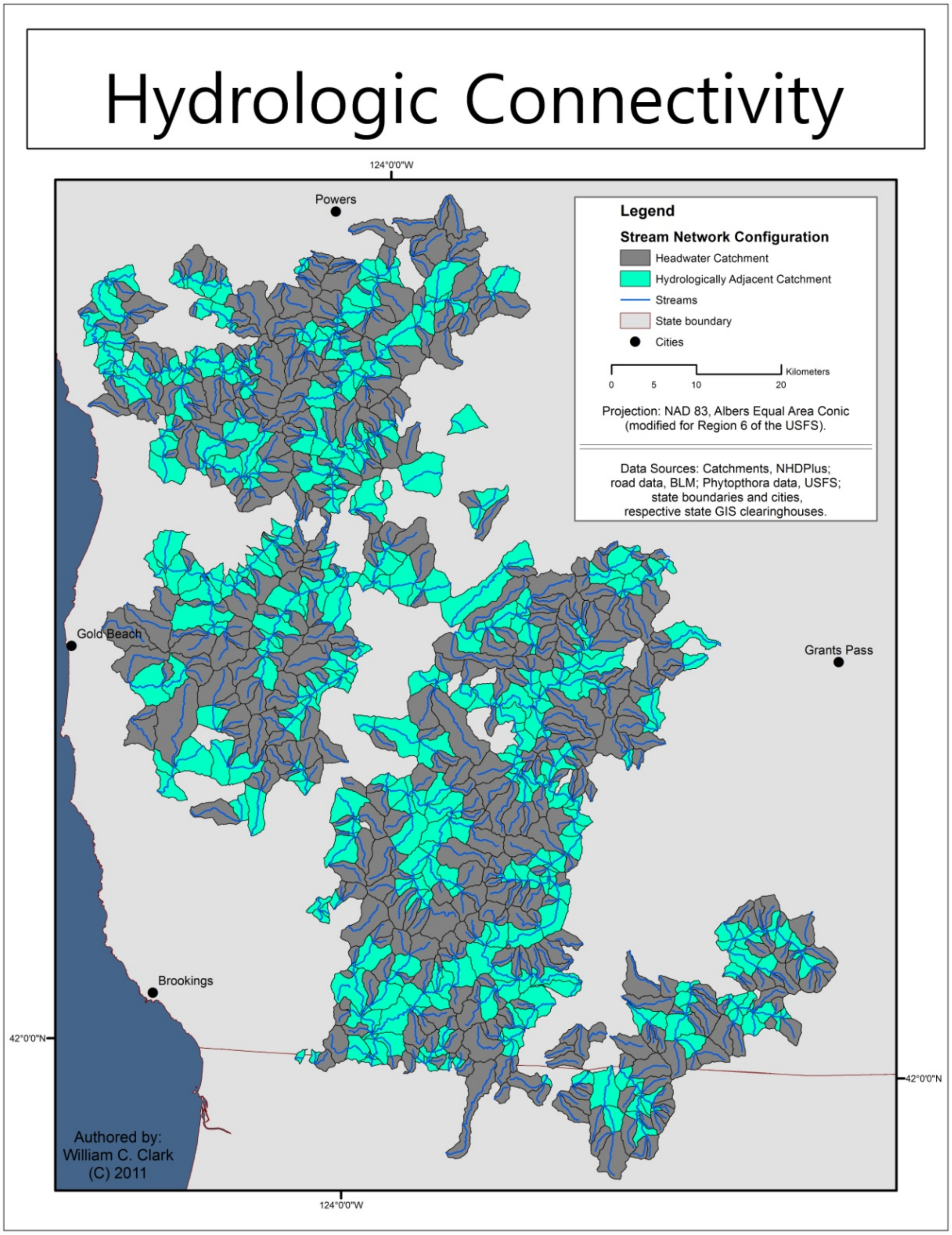
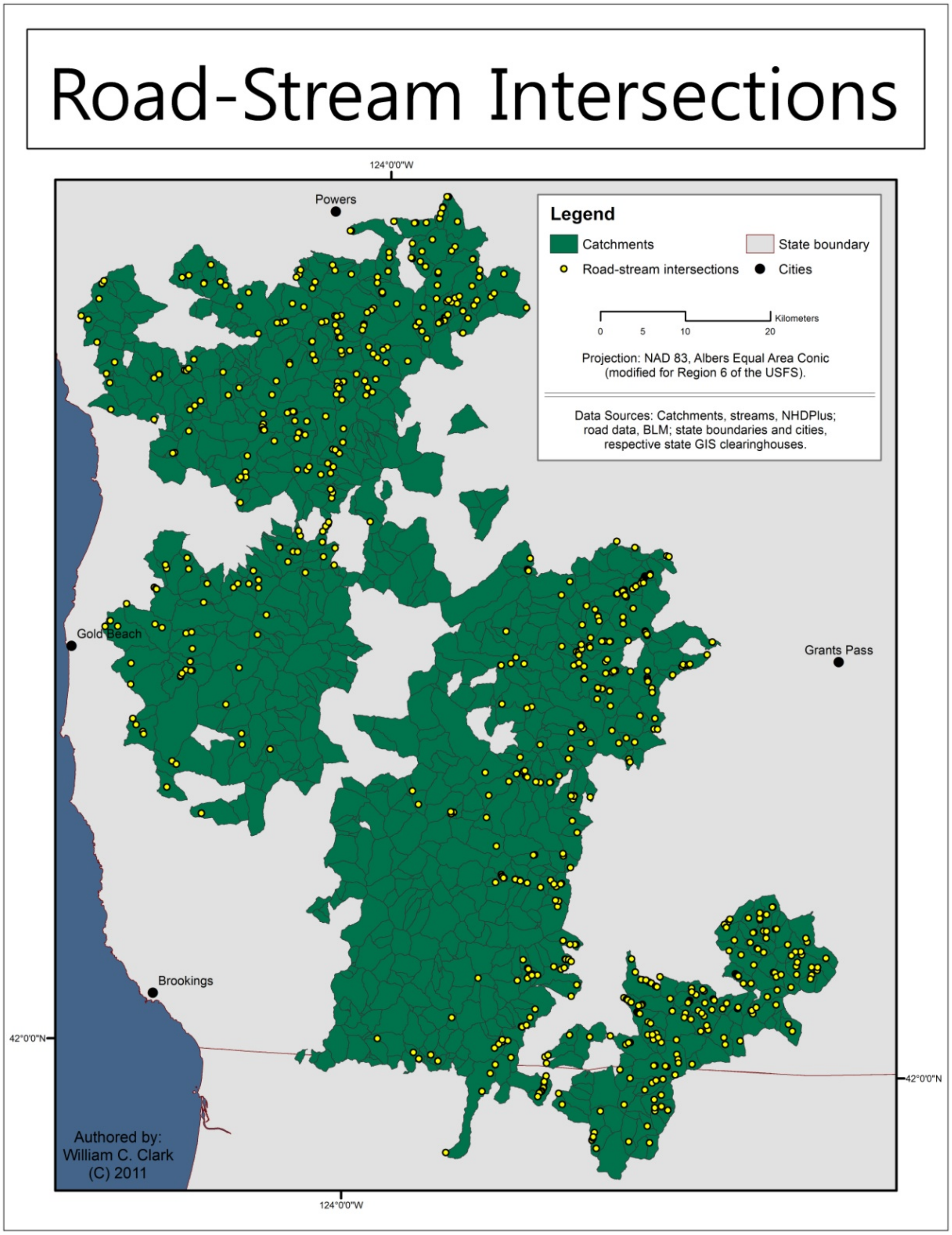


FIGURE 13. ROAD-STREAM INTERSECTIONS.

Road-stream intersections mark the direct linkage between the road network and the stream network. There are 758 linkage nodes in the study site.



4 Discussion

This study showed that *Phytophthora lateralis* infestations in *Chamaecyparis lawsoniana* populations in southwest Oregon were strongly positively associated with forest roads and timber harvest. In Oregon and California, *P. lateralis* has infested Port-Orford-cedar populations within federally managed commercial forest lands. The association of *P. lateralis* with roads and timber harvest has been noted by previous studies (Jules et al. 2002; Roth et al. 1987). However, this is the first study to use broad-scale survey data in conjunction with geographic information on roads, timber harvest, and streams to test hypotheses about landscape-scale factors influencing the spread of *P. lateralis* within the natural range of its host.

The association of *P. lateralis* with timber harvest and roads indicates that forestry operations have imposed significant negative consequences for Port-Orford-cedar and associated forest ecosystems in southwestern Oregon. Damage from cedar root rot is estimated at $27-54 million annually based on mid-1980s harvest rates and peak infestation rates (Zobel et al. 1982). Since commercial forests are heavily managed, they tend to be vulnerable to non-native pathogen and pest outbreaks (Pimental 1986; Chornesky et al. 2005); Port-Orford-cedar forests of southwestern Oregon appear to be vulnerable to non-native pathogen and pest outbreaks due to large scale, repeated, high magnitude disturbance (i.e. road building, timber harvest).

4.1 Errors and bias in analysis

The sampling design of the RR-SNF, which relied on road access, was tested for sampling bias. The Gradient Nearest Neighbor vegetation model (GNN; LEMMA Laboratory, Corvallis, Oregon USA, http://www.fsl.orst.edu/lemma/splash.php) was used to identify 7th-field catchments containing Port-Orford-cedar that could have been sampled in the RR-Siskiyou NF. The GNN identifies areas (30m x 30m) where Port-Orford-cedar is dominant (≥80%) or subdominant (≥20%) in the canopy. Conditional probability analysis and Pearson chi-squared contingency table suggest roadless areas of Port-Orford-cedar were under sampled and that catchment road status lent some inference to sample status (Appendix E; Tables 1E and 2E). However, the statistical analyses used in this study, do not assume exhaustive survey. In fact, the null hypotheses of the statistical methods examine the marginal proportions of the observed phenomena given a certain sample size. This analysis would be biased if there were evidence of systematic Type II error (false negatives) in roadless areas that did not occur in roaded areas. Power analyses of the statistics indicate that the likelihood of Type II error (β) is exceptionally small (Appendix E, Table 3E).

Another potential source of bias is the coincidence between Port-Orford-cedar and roads (Appendix E, Table 4E). As a highly valuable commodity, Port-Orford-cedar may be inherently associated with roads as they were the means to extract market value from the landscape. Port-Orford-cedar is only weakly associated with roads (p = 0.14, X^2 = 2.4, df = 1) and does not detract from the power of the statistics or the relationships herein described.

Lastly, this analysis could have benefited from a study site-wide debris slope/debris flow survey to directly test hypotheses of the influence of road networks and timber harvest patchworks on the mass movement of the pathogen. Such surveys are uncommon but do exist in the western Cascades of Oregon (Swanson & Dyrness 1975; Wemple et al. 2001).

4.2 Effects of networks and network configuration

Roads appear to increase risk of cedar root rot infestation by increasing opportunities for: 1) network dispersion via movement within road networks, 2) net-net dispersion via ditch and culvert systems, and 3) increased soil erosion within a catchment. These processes may facilitate the increased dispersion of resting spores. Road networks serve as a sink for and source of materials (e.g. propagules) and an agent by which they can flow through the landscape (Wemple et al. 1996; Forman 2003; Yupiana et al. 2010). Roadbeds store propagules that can be transported throughout the road network (network dispersion), to the stream channel via ditch and culvert systems (net-net dispersion), or to adjacent forest patches via cut- and fill-slope failures (net-patch dispersion) (Parendes & Jones 2000; Watterson & Jones 2006). Natural propagule dispersion along roads occurs chronically via water and sediment load movement and episodically when entrained in soils during mass movement events. In the Pacific Northwest, forest road networks on steep slopes appear to contribute to increased peak flows, which may persist for decades (Jones 2000) and are positively correlated to mass movement events and increased erosion rates (Wemple et al. 2001; Jones et al. 2000; Swanson & Dyrness 1975). Human movement also distributes propagules. Vehicle traffic is the primary mechanism of human-aided propagule dispersion. Vehicles carry propagules long distances on tires (Clifford 1959) and entrained in mud on vehicle bodies (Wace 1977; Schmidt 1989; Von der Lippe & Kowarik 2007).

This study found a strong positive relationship between roads and catchment infestation (H1); road networks provided a corridor for pathogenic materials to distribute through the RR-Siskiyou NF. In addition to road presence, road length and density were very strongly positively related to catchment infestation (H2). Of the road metrics, road density was most strongly related to infestation in single-variable regression models. This may be because pathogenic material transport by vehicles to the road network is subject to predictability, but successful delivery of pathogenic materials to the road network is more stochastic. Successful delivery of pathogenic materials seems to increase with increased catchment road density because of positive relationships between road density and 1) exposure potential between the vector and the environment and 2) potential traffic rate, which is positively related to sediment loads of forested roads (MacDonald et al. 2001; Baird 2011). Traffic rate, which was not measured in this study, is also likely to be a good predictor of infestation. This study presents evidence that supports the hypothesis that as traffic rate increases, the delivery of infested sediment increases.

This study showed that the spatial configuration of the road network in southwest Oregon was strongly autocorrelated. Spatial autocorrelation is apparently caused by network topology that creates hierarchically branched road patterns (Figure 14) and patterns of land ownership blocks and management philosophies. The spatial arrangement of road networks influenced the transmission of pathogenic materials, and thus, infestation patterns among Port-Orford-cedar populations. In this study, uninfested catchments were most likely to be spatially removed from infested/roaded catchments and infested/roaded catchments tend to be adjacent to other infested catchments (H3). However, when roadless catchments were adjacent to infested/roaded catchments they were often infested (71/112); a catchment's lack of roads was not enough to prevent infestation if that catchment was adjacent to an infested/roaded catchment. It has been asserted that these roadless areas are infested by ungulate and other foot traffic (Jules et al. 2002). However, it has yet been studied how far, and at what rate, an infestation can traverse a roadless area. However, configuration data suggest that to prevent infestation of a large roadless area, a one 7^{th}-field catchment buffer is needed between roaded and roadless areas. For management considering Port-Orford-cedar reserves, this implies that the shape and interior (core) patch size of a preserve would be more important to its effectiveness than raw size.

Additionally, road networks appear to promote the movement of the resting spore from roads to the stream network. Catchments directly downstream of infested catchments were predominantly infested (H4). These data suggest: 1) upstream/infested-downstream/uninfested arrangements do not often naturally occur, 2) infestation of the study site has progressed to a homogeneous stage at the 7^{th}-field catchment level so these arrangements are no longer observed, or 3) a combination of 1) and 2).

In-board ditches and culverts directly link road surface flows to stream flows and many of the road and stream sub-networks of roaded catchments in the study site were connected. In-board ditches have been observed to effectively deliver propagules from the road surface to the stream network, which dissects adjacent forest patches (Parendes & Jones 2000). This study used a conservative count of road-stream intersections because of: 1) limitations in source data and 2) the cut-and-fill roads that are typically angled in-slope and have an in-board ditch to divert and collect road surface flow (Figure 15). This engineering technique significantly increases the level of connection between the road and stream networks and increases the effective drainage density of roaded catchments (Wemple et al. 1996). However, the method used to measure road-stream connections will capture the streams with the larger, most consistent flow. This study found strong evidence that supports the hypothesis that resting spores effectively move from the road surface to inner-patch host populations via the in-board ditch system (H5). This net-net dispersal pathway has many implications. First, because resting spores survive at least 7 yrs of drying while maintaining infectiousness (Hansen 1996), net-net *P. lateralis* dispersal remains viable for a period of nearly a decade beyond the last date of its introduction. Second, previous studies have found that forest roads 1) increase peak flows of existing stream reaches (Jones 2000) 2) reduce channel initiation thresholds (Wemple & Jones 2003), which further increases catchment drainage density (Jones et al. 2000), and 3) alter erosional processes by changing the spatial distribution of water, sediment load, and energy on a catchment-wide scale (Wemple et al. 2001). If road-stream connections increase infestation risk, forest roads are poised not only to facilitate resting spore distribution to adjacent forest patches, but also to enhance zoospore distribution by increasing the effective reach of zoospores at both the landscape and local scales.

4.4 Effects of patchworks

Timber harvest appears to increase cedar root rot dispersal by increasing opportunities for: 1) net-patch dispersion via off-road traffic, 2) repeated, high magnitude disturbance, and 3) increased peak stream flows. These processes may facilitate the increased dispersion of both resting spores and zoospores.

Timber harvest patchworks alter the type and quality of available habitat (Reed et al. 1996; Tinker et al. 1998) and perforate much of the Pacific Northwest landscape. Timber harvested landscapes have decreased slope stability and increased risk of debris slides and debris flows (Anderson 1983). Additionally, timber harvest combines with road networks to initiate disturbance cascades throughout forested catchments (Wemple et al. 2001). Swanson et al. (1975) found that in the western Oregon Cascades harvest increased slope failures nearly three-fold. Similar post-harvest dynamics (i.e. reduced rooting strength, reduced topsoil structure, and increased snowmelt runoff) presumably occur in the Siskiyou Mountains

This study found that in the RR-Siskiyou NF, timber harvest patchworks significantly affected the spatial heterogeneity of cedar root rot distribution (H6). In the RR-Siskiyou NF, harvest area and density were strongly positively associated with cedar root rot infestations (H7). Granted, without the road network pathogenic materials are unlikely to infiltrate deeply into the landscape. However, the data suggest that catchments with harvest are more susceptible to infestations than those with roads alone. The data suggest that traffic intensity, of which harvest density may be a proxy, and traffic rate, of which harvest frequency may be a proxy, are the two best measures for predicting infestation. Traffic intensity associated with harvest units is much greater than traffic intensity on connecting roads within the road network. Timber landings and harvest patches are areas of high-intensity, localized disturbance from heavy machinery associated with basic travel but also are areas of log preparation and extraction. Conversely, most road segments of the network are conduits of ephemeral, low-intensity traffic. Driving conditions within the road network compared to within and near harvest units may also be a contributing factor to increased infestation risk. Forest roads are graded and armored, whereas driving conditions in harvest units are ungraded and the exposed earth is easily scarred. There is greater opportunity for successful delivery of resting spores from vehicles and vehicle-induced surface erosion in the harvest patchwork than the road network. Additionally, traffic rate is positively related to harvest frequency: as a catchment is revisited for additional resource extraction, total traffic intensity, harvest density, and level of disturbance will increase. Thus, the repeated, high magnitude nature of timber harvest seems to increase its predictive value for infestation.

Timber harvest patchworks also have implications for cedar root rot zoospore distribution. In forested catchments of the Pacific Northwest, streamflow is expected to increase post-harvest, the degree to which is dependent on the relative importance of evapotranspiration in the system (Jones 2000). Since local streamflow controls the dispersion of cedar root rot zoospores (Hansen et al. 2000), timber harvest could, depending on local geomorphology, enhance the lateral dispersion of zoospores outward from stream margins by increasing the zone of inundation for long periods. Downstream of harvest activities, populations of Port-Orford-cedars that once were out of the reach of consistent high water may become vulnerable to infestation post-harvest.

However, post-harvest streamflow increases are temporary (<10 yrs) (Jones 2000) since in commercial forests timber harvest is only an ephemeral process of land cover change. Conversely, the forest road network influence on cedar root rot dispersion is more permanent since road networks are a change in land use. Therefore, zoospore response to timber harvest disturbance is different than to road-building disturbance. Increased zoospore spread induced by timber harvest patchworks may be temporary; this is not the case for road network disturbance. Despite timber harvest's shorter durational effect on the dispersion of the zoospore compared to that of the road network, timber harvest is still the stronger predictor of infestations suggesting the difference in effect between the two disturbances may be greater than measured in this study.

Harvest data indicate that the odds of infestation increase as harvest frequency increases from one to two events (the majority of which were completed earlier in the survey period). This relationship is expected considering the findings with harvest density. However, the odds associated with ≥ three events (the majority of which occurred later in the survey period) declined significantly (-110 %) compared to two harvest events. One expects that as a process (i.e. pathogenic material transport) is repeated its total success rate (i.e. pathogenic material delivery) would increase, unless the behavior of the process has changed. Additionally, the harvest data indicate that infestation rates of harvested catchments are significantly different before 1992 (~50%) than after 1992 (~5%). Together, the harvest frequency and period data suggest that infestation risk is positively associated with harvest activities that occurred earlier. Research has shown no significant latency (<< 1 yr) between cedar root rot introduction to a host and symptom development (Hansen 1996). In fact, unless the pathogen is in the resting spore stage, the environmental storage of infectious material is unlikely: pathogen survival in a soil and host rootlet matrix is short (<20 days) and inoculum survival after host mortality is <2 yrs (Hansen 1996). Therefore, without re-introductions, some infestations may be observed given favorable conditions caused by old resting spore deposits, but a lagged "second wave" epidemic associated with an incubation or latency period appearing after 2000 (the temporal extent of this study) is unlikely. Therefore, the decrease in infestation odds observed after 1992 may be a signal from management practices. Cedar root rot mitigation policies were first adopted in 1989. However, in 1994 the Northwest Forest Plan was adopted. The timber harvest event data shows that the reduction of infestation odds coincide with the timing of new management policies and supports the hypothesis that these policies have mitigated some of the infestation risk associated with timber harvest practices. Whether the observed effect is due to cedar root rot specific policies or broader, region-wide conservation policies is yet unclear. While management efforts appear to have been effective at decreasing infestation risk associated with timber harvest, the data suggest that much of the effect is likely attributed to catchments that have been harvested once and after 1992, otherwise infestation risk remains very elevated.

This study does support some of the implications of roads and road-stream intersections on cedar root rot dispersion that Jules et al. (2002) put forth. However, the authors were limited to a far smaller geographic area (37 km^2) and unable to create models that combined road and stream metrics at the landscape scale, which prevented the assessment of their configuration. Consequently, some of this study's findings do not necessarily concur with those of Jules et al. (2002). For example, Jules et al. (2002) found a significant, positive relationship between catchment area (a proxy for stream flow) and infestations. However, this study presents evidence, based on 934 7^{th}-field catchments ($\bar{x} = 4.2$ km^2), of a slightly negative, but statistically insignificant relationship between catchment area and infestation risk and a moderately significant, positive relationship between drainage density and infestation risk. It is possible that catchment area and drainage density are scale dependent metrics, and that higher in the catchment hierarchy (i.e. 6^{th}-field catchment level) the relationship between catchment area or drainage density and infestation changes. However, Port-Orford-cedar is currently managed at the 7^{th}-field catchment level (Betlejewski et al. 2003) and at this level, it appears that metrics of harvest, roads, and road-stream network connectivity are more useful in their application to current management strategies; the usefulness of catchment area or drainage density as explanatory variables are yet unclear.

As far as the author is aware, this study is the first to present empirical, spatially explicit evidence linking forest roads and timber harvest activities to the spatial and temporal patterns of cedar root rot at the landscape scale within Port-Orford-cedar's natural range. Previous studies have not considered the effects of landscape disturbance configuration as it relates to the configuration of stream networks. This study found that the configurations of disturbance networks (roads) and patchworks (timber harvest) in combination with the configuration of stream networks appear to explain the observed pattern of infestation by providing physically and biologically plausible mechanisms for the movement of both the zoospore and resting spore of *P. lateralis*. This study is the first to test several road and timber harvest metrics for their utility in cedar root rot risk assessment and explanatory models. Finally, this study is the first to report an observed response in infestation data of timber-harvested catchments that indicates management policies have been effective at reducing infestation risk.

FIGURE 14. SCHEMATIC OF A BRANCHING HEIRARCHY-TYPE ROAD NETWORK.

A road network configuration is modeled with road lengths (solid lines), nodes (empty points), and a stream network (dashed lines) with a) low road-stream network connectivity and b) high road-stream network connectivity. [Partially adapted from Swanson and Jones unpublished.]

a) low road-stream network connectivity

b) high road-stream network connectivity

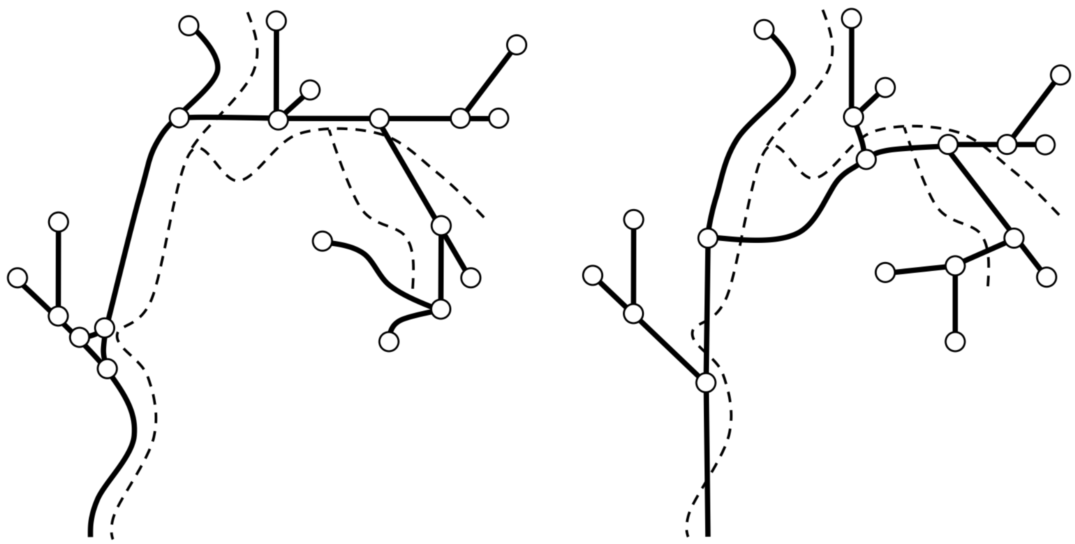
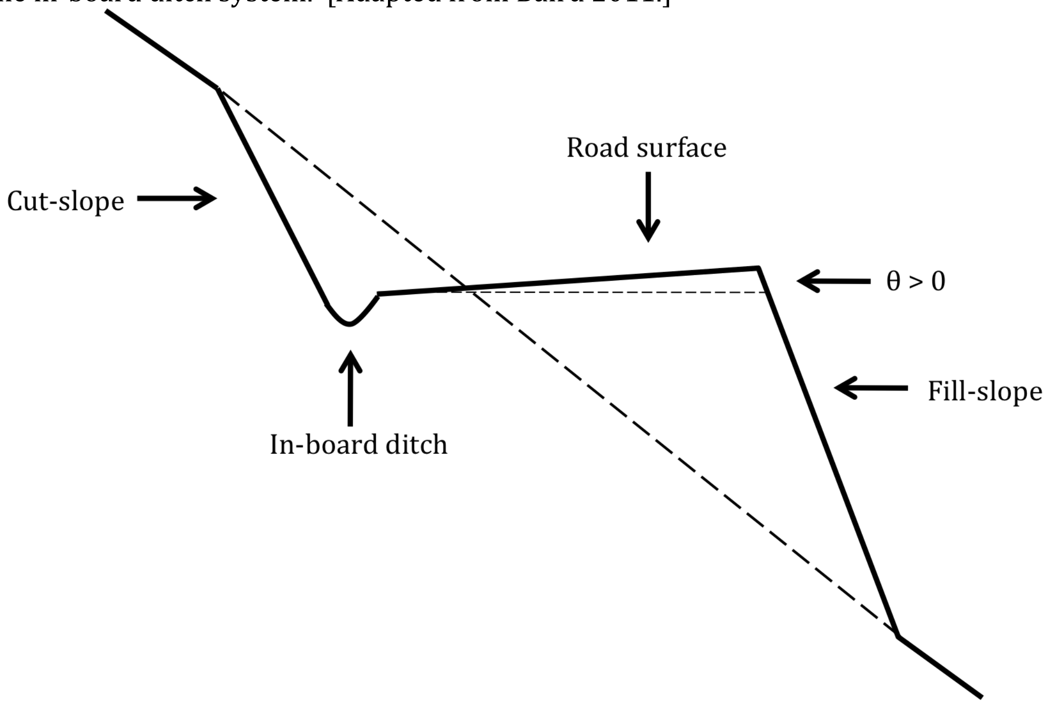


FIGURE 15. ROAD PRISM SCHEMATIC.

Schematic of the road-building technique used in the Pacific Northwest. The road surface is tilted toward the cut-slope to divert road-surface flow toward the in-board ditch system. [Adapted from Baird 2011.]



5 Conclusions

Road networks and timber harvest patchworks are significant disturbances that shape landscape heterogeneity in Pacific Northwest ecosystems and often present opportunities for non-native species dispersal. This study provides empirical evidence that strongly implicates the road network and timber harvest patchwork as vectors for pathogen spread. This means that cedar root rot is not topographically restricted. Roads provide a mechanism for *P. lateralis* to infest up-catchment and road-stream network connections provide a pathway to infest down-catchment via the stream network. Connections between the road and stream networks create one larger network that disperses pathogenic materials catchment-wide. With respect to *P. lateralis*, roads appear to decrease landscape heterogeneity by facilitating the distribution of pathogenic materials through the landscape.

Pathogen infestations persist until host population density declines or the immunity of the host population reaches a threshold (Haggett 2000). This model assumes no re-introduction of the pathogen to the system. With no innate immunity in Port-Orford-cedar populations, effective management becomes paramount. However, cedar root rot infestations are atypical; they do not follow a pattern of contagious diffusion outward from the primary host or vector. Kauffman et al. (2006) suggest that on a local scale cedar root rot infests Port-Orford-cedar hierarchically. This study suggests that on a landscape-scale management of the Port-Orford-cedar/cedar root rot dynamic could also be based on a hierarchical risk assessment framework structured on: 1) harvest density, 2) road density, and 3) harvest frequency.

If management pursued a series of Port-Orford-cedar reserves as a means to protect the species, the reserves should: 1) have a large core size relative to its total edge length, 2) be buffered from catchments with roads by catchments without roads, 3) be off limits to harvest activities, and 4) be very infrequently travelled by vehicles.

Bibliography

Alexander, E.B., 2007. *Serpentine geoecology of western North America*, Oxford University Press.

Anderson, M., 1983. Road-cut slope topography and stability relationships in St. Lucia, West Indies. *Applied Geography*, 3, pp.104-114.

Baird, E., 2011. *Controls on sediment generation from forest roads in a Pacific Maritime watershed*. MS Thesis. British Columbia, Canada: Simon Fraser University.

Betlejewski, F. et al., 2003. *A Range-wide Assessment of Port-Orford-Cedar (Chamaecyparis lawsoniana) on Federal Lands*, US Forest Service, Department of Agriculture.

Chornesky, E. et al., 2005. Science priorities for reducing the threat of invasive species to sustainable forestry. *BioScience*, 55(4), pp.335-348.

Christensen, R., 1997. *Log-Linear Models and Logistic Regression* 2nd ed., 175 Fifth Avenue, New York, NY 10010: Springer-Verlag.

Clifford, H.T., 1959. Seed Dispersal by Motor Vehicles. *Journal of Ecology*, 47(2), pp.311-315.

Cohen, J., 1992. Statistical Power Analysis. *Current Directions in Psychological Science*, 1(3), pp.98-101.

DeNitto, G., 1991. First report of Phytophthora lateralis on Pacific yew. *Plant Disease*, 75(9), pp.968-968.

Denton, K., 2004. *Final Supplemental Environmental Impact Statement: Management of Port-Orford-cedar in Southwest Oregon*, US Department of Agriculture and US Department of the Interior.

Farjon, A., 2005. *A Monograph of Cupressaceae and Sciadopitys*, Kew Publishing.

Faul, F. et al., 2007. G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, 39(2), pp.175-191.

Forman, R.T.T., 2003. *Road ecology*, Island Press.

Forman, R.T.T. & Godron, M., 1986. *Landscape ecology*, Wiley.

Haggett, P., 2000. *The geographical structure of epidemics*, Clarendon Press.

Hansen, E.M., 1996. Survival of Phytophthora lateralis in infected roots of Port Orford cedar. *Plant Disease*, 80(9), p.1075.

Hansen, E., 2008. Alien forest pathogens: Phytophthora species are changing world forests. *Boreal Environment Research*, 13, pp.33-41.

Hansen, E. et al., 2000. Managing Port-Orford-cedar and the introduced pathogen Phytophthora lateralis. *Plant Disease*, 84(1), pp.4-10.

Imper, D.K., 1981. *The Relation of Soil Characteristics to Growth and Distribution of Chamaecyparis lawsoniana and Thuja Plicata in Southwestern Oregon*. MS Thesis, Oregon State University.

Jones, J., 2000. Hydrologic processes and peak discharge response to forest removal, regrowth, and roads in 10 small experimental basins, western Cascades, Oregon. *Water Resources Research*, 36(9), pp.2621-2642.

Jones, J. et al., 2000. Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. *Conservation Biology*, 14(1), pp.76-85.

Jules, E. et al., 2002. Spread of an invasive pathogen over a variable landscape: A nonnative root rot on Port Orford cedar. *Ecology*, 83(11), pp.3167-3181.

Kauffman, M. & Jules, E., 2006. Heterogeneity shapes invasion: Host size and environment influence susceptibility to a nonnative pathogen. *Ecological Applications*, 16(1), pp.166-175.

MacDonald, L., Sampson, R. & Anderson, D., 2001. Runoff and road erosion at the plot and road segment scales, St John, US Virgin Islands. *Earth Surface Processes and Landforms*, 26(3), pp.251-272.

Murray, M. & Hansen, E., 1997. Susceptibility of Pacific yew to Phytophthora lateralis. *Plant Disease*, 81(12), pp.1400-1404.

Oh, E., 2005. *Resistance Mechanisms of Port-Orford-cedar to Phytophthora lateralis*. PhD Thesis. Corvallis, OR: Oregon State University.

Oregon Public Broadcasting, 1997. The Oregon Story: History of Logging in Oregon. Available at: www.opb.org/programs/oregonstory/logging/timline.html.

Parendes, L. & Jones, J., 2000. Role of light availability and dispersal in exotic plant invasion along roads and streams in the H. J. Andrews Experimental Forest, Oregon. *Conservation Biology*, 14(1), pp.64-75.

Pimental, D., 1986. Biological Invasions of Plants and Animals in Agriculture and Forestry. In *Ecology of Biological Invasions of North American and Hawaii*. New York: Springer-Verlag, pp. 149-162.

Port Orford Cedar Products Company, 1929. Port Orford cedar - Its Properties and Uses.

Ramsey, F.L. & Schafer, D.W., 1997. *The Statistical Sleuth: A course in methods of data analysis* 1st ed., Wadsworth Publishing Company.

Reed, R., JohnsonBarnard, J. & Baker, W., 1996. Contribution of roads to forest fragmentation in the Rocky Mountains. *Conservation Biology*, 10(4), pp.1098-1106.

Roth, L.F., Harvey Jr., R.D. & Kliejunas, J.T., 1987. *Port-Orford-Cedar Root Disease*, US Forest Service, US Department of Agriculture.

Schmidt, W., 1989. Plant dispersal by motor cars. *Vegetatio*, 80(2), pp.147-152.

Swanson, F. & Dyrness, C., 1975. Impact of clear-cutting and road construction on soil erosion by landslides in western Cascade Range, Oregon. *Geology*, 3(7), pp.393-396.

Tinker, D. et al., 1998. Watershed analysis of forest fragmentation by clearcuts and roads in a Wyoming forest. *Landscape Ecology*, 13(3), pp.149-165.

Trione, E.J., 1957. *The Physiology and Pathology of Phytophthora lateralis on native Chamaecyparis lawsoniana*. PhD Thesis. Corvallis, OR: Oregon State University.

Von der Lippe, M. & Kowarik, I., 2007. Long-distance dispersal of plants by vehicles as a driver of plant invasions. *Conservation Biology*, 21(4), pp.986-996.

Wace, N., 1977. Assessment of dispersal of plant species: the car-borne flora in Canberra. *Proceedings of the Ecological Society of Australia*, 10, pp.167-186.

Watterson, N.A. & Jones, J.A., 2006. Flood and debris flow interactions with roads promote the invasion of exotic plants along steep mountain streams, western Oregon. *Geomorphology*, 78(1-2), pp.107-123.

Wemple, B. & Jones, J., 2003. Runoff production on forest roads in a steep, mountain catchment. *Water Resources Research*, 39(8).

Wemple, B., Jones, J. & Grant, G., 1996. Channel network extension by logging roads in two basins, western Cascades, Oregon. *Water Resources Bulletin*, 32(6), pp.1195-1207.

Wemple, B., Swanson, F. & Jones, J., 2001. Forest roads and geomorphic process interactions, Cascade Range, Oregon. *Earth Surface Processes and Landforms*, 26(2), pp.191-204.

Yupiana, Y. et al., 2010. Risk factors of poultry outbreaks and human cases of H5N1 avian influenza virus infection in West Java Province, Indonesia. *International Journal of Infectious Diseases*, 14(9), p.E800-E805.

Zobel, D. & Hawk, G., 1980. The Enviornment of Chamaecyparis lawsoniana. *American Midland Naturalist*, 103(2), pp.280-297.

Zobel, D.B., Roth, L.F. & Hawk, G.M., 1982. *Ecology, Pathology, and Management of Port-Orford-Cedar (Chamaecyparis lawsoniana)*, Pacific Northwest Forest and Range Experiment Station: US Forest Service, Department of Agriculture.

APPENDICES

Appendix A. Chi-squared look-up table.
Distribution table of chi-squared critical values (χ^2).

degrees of freedom *(df)*	α = 0.900 *p* = 0.100	α = 0.950 *p* = 0.050	α = 0.975 *p* = 0.025	α = 0.990 *p* = 0.010	α = 0.999 *p* = 0.001
1	2.71	3.84	5.02	6.64	10.8
2	4.61	5.99	7.38	9.21	13.8
3	6.25	7.82	9.35	11.4	16.3
4	7.78	9.49	11.1	13.3	18.5
5	9.24	11.1	12.8	15.0	20.5
6	10.6	12.6	14.4	16.8	22.5
7	12.0	14.0	16.0	18.5	24.3
8	13.4	15.5	17.5	20.1	26.1
9	14.7	16.9	19.0	21.7	27.9
10	16.0	18.3	20.5	23.2	29.6
11	17.3	19.7	21.9	24.7	31.3
12	18.5	21.0	23.3	26.2	32.9
13	19.8	22.4	24.7	27.7	34.5
14	21.1	23.7	26.1	29.1	36.1
15	22.3	25.0	27.5	30.6	37.7
16	23.5	26.3	28.8	32.0	39.3
17	24.8	27.6	30.2	33.4	40.8
18	26.0	28.9	31.5	34.8	42.3
19	27.2	30.1	32.9	36.2	43.8
20	28.4	31.4	34.2	37.6	45.3
30	40.3	43.8	47.0	50.9	59.7
40	51.8	55.8	59.3	63.7	73.4
50	63.2	67.5	71.4	76.2	86.7
60	74.4	79.1	83.3	88.4	99.6
70	85.5	90.5	95.0	100	112
80	96.6	102	107	112	125
90	108	113	118	124	137
100	118	124	130	136	149

Appendix B. Histograms for continuous variables.

FIGURE 16. CATCHMENT AREA AND DRAINAGE DENSITY HISTOGRAMS.

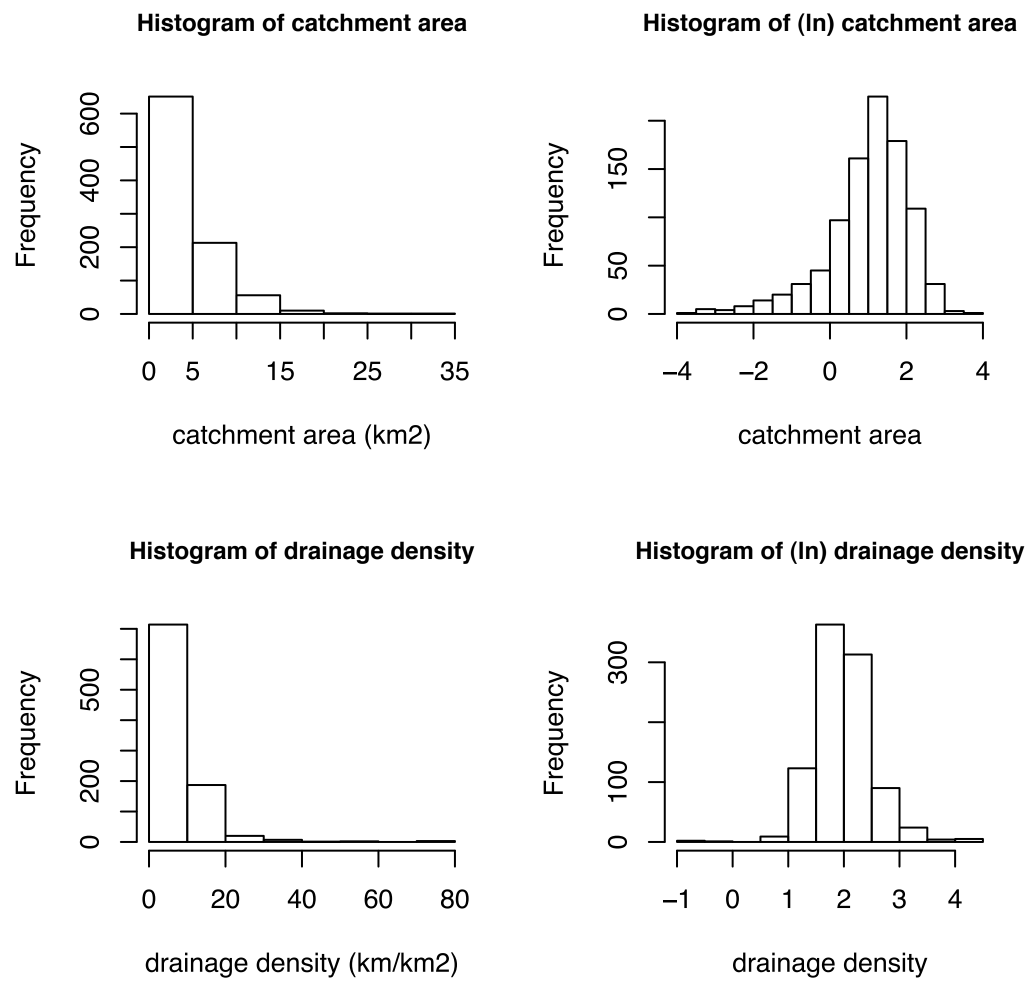


FIGURE 17. ROAD LENGTH AND DENSITY HISTOGRAMS.

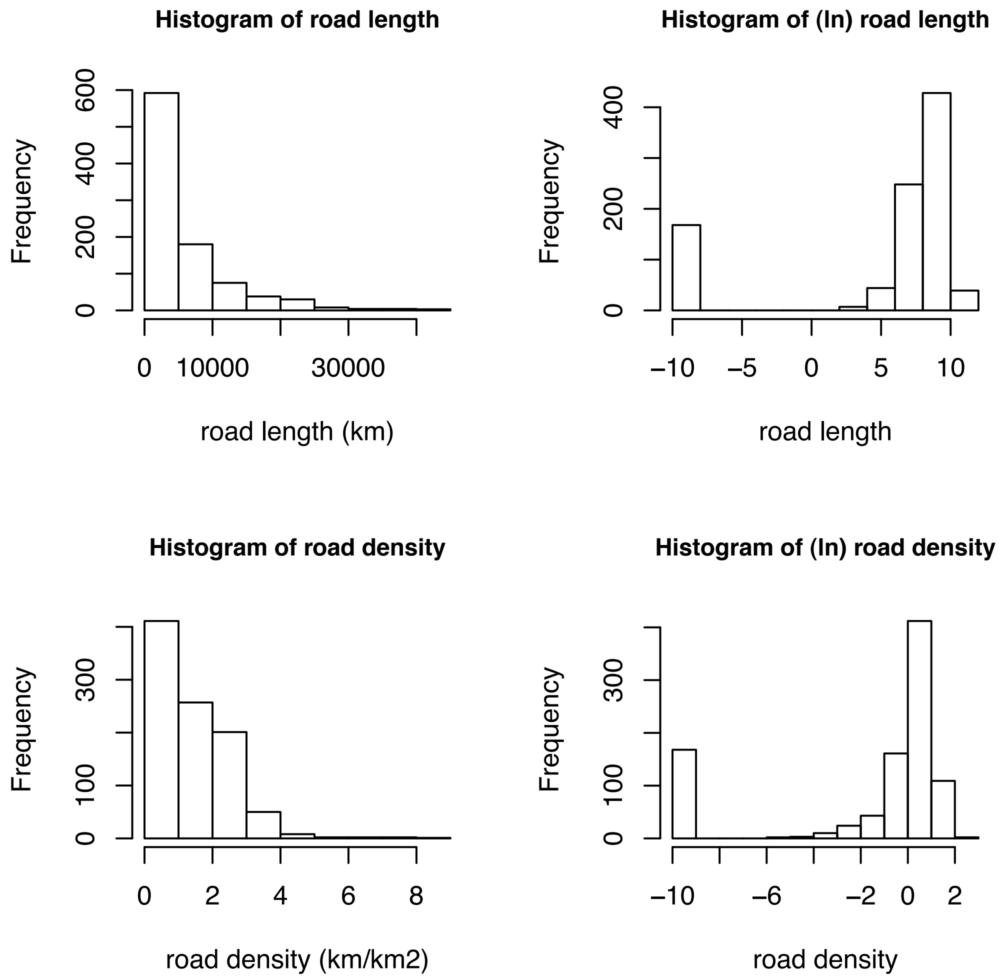


FIGURE 18. TIMBER HARVEST AREA AND DENSITY HISTOGRAMS.

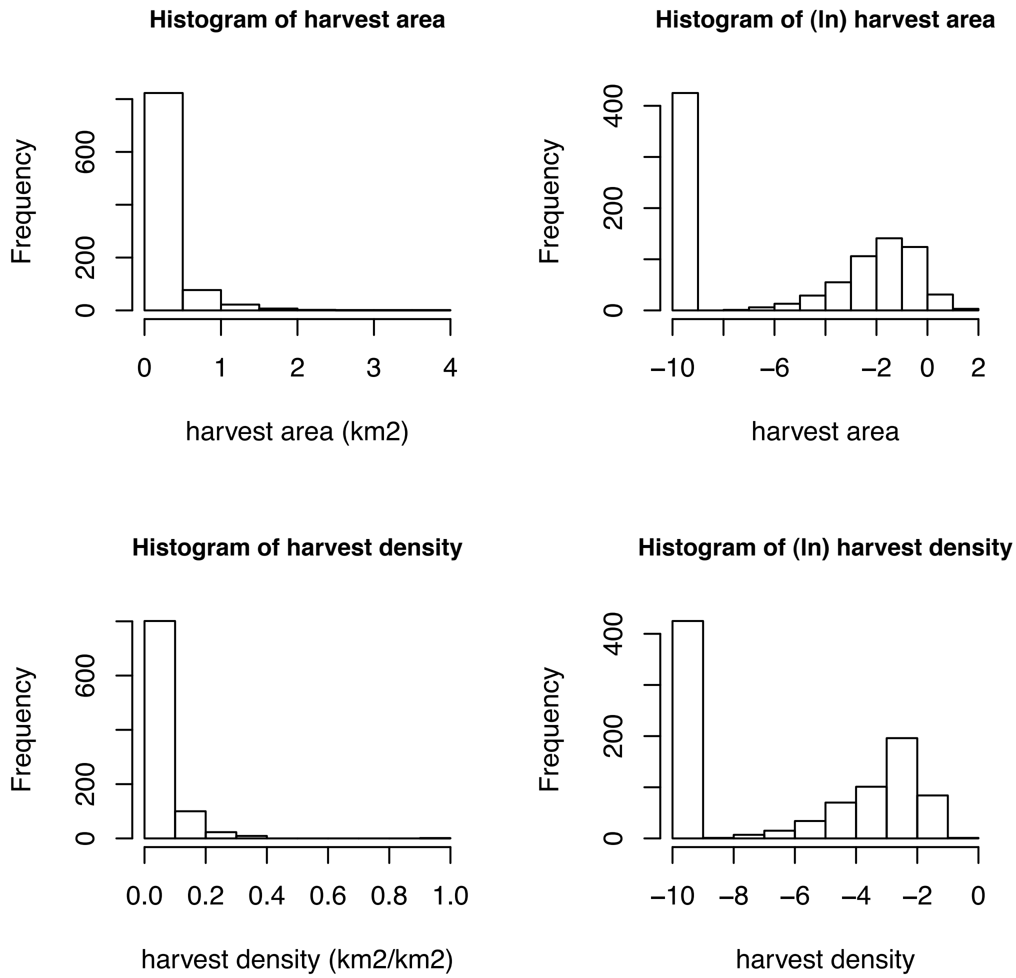
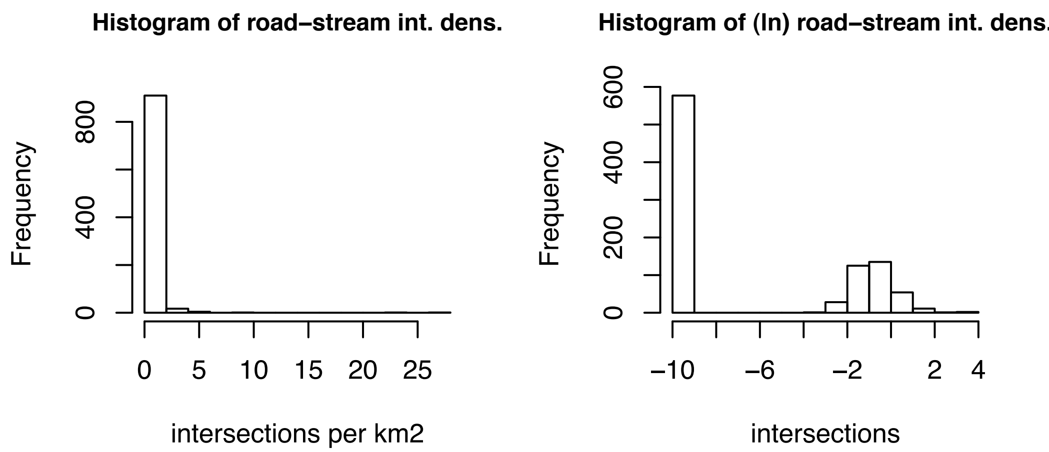


FIGURE 19. ROAD-STREAM INTERSECTION DENSITY HISTOGRAMS.



Appendix C. Correlation regressions for continuous variables.

FIGURE 20. COLLINEARITY ANALYSIS OF LN-TRANSFORMED CATCHMENT AREA.

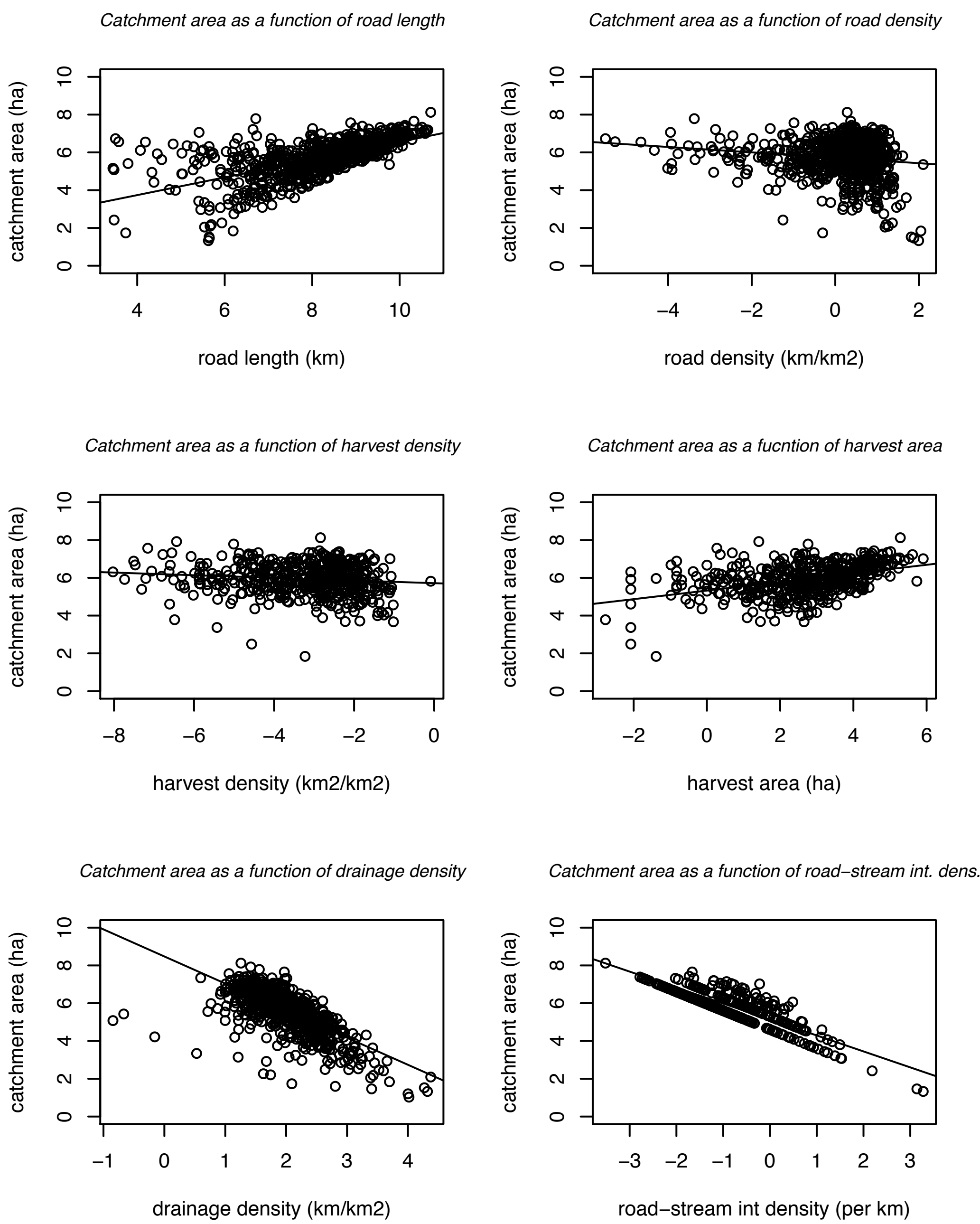


FIGURE 21. COLLINEARITY ANALYSIS OF LN-TRANSFORMED DRAINAGE DENSITY.

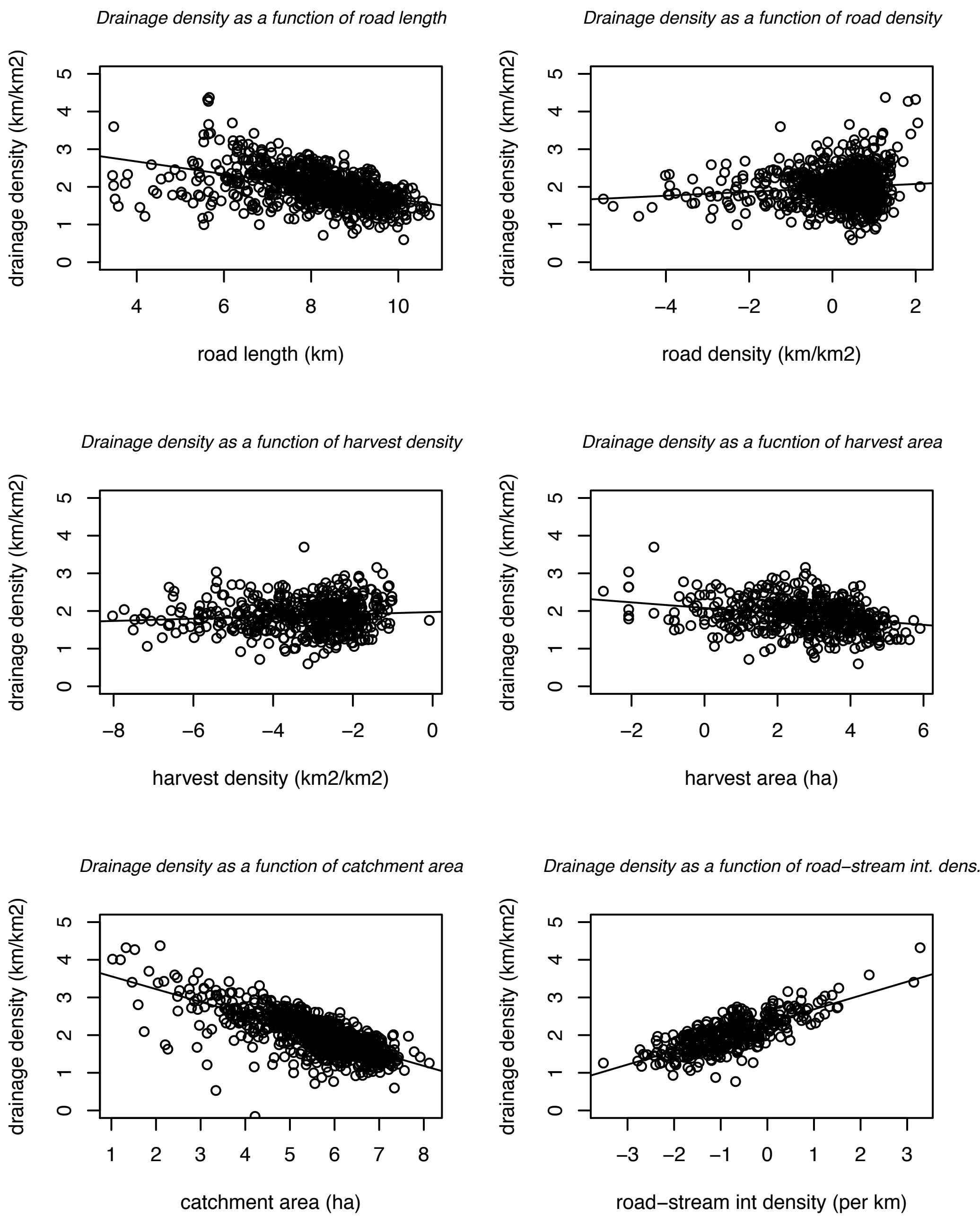


FIGURE 22. COLLINEARITY ANALYSIS OF LN-TRANSFORMED ROAD LENGTH.

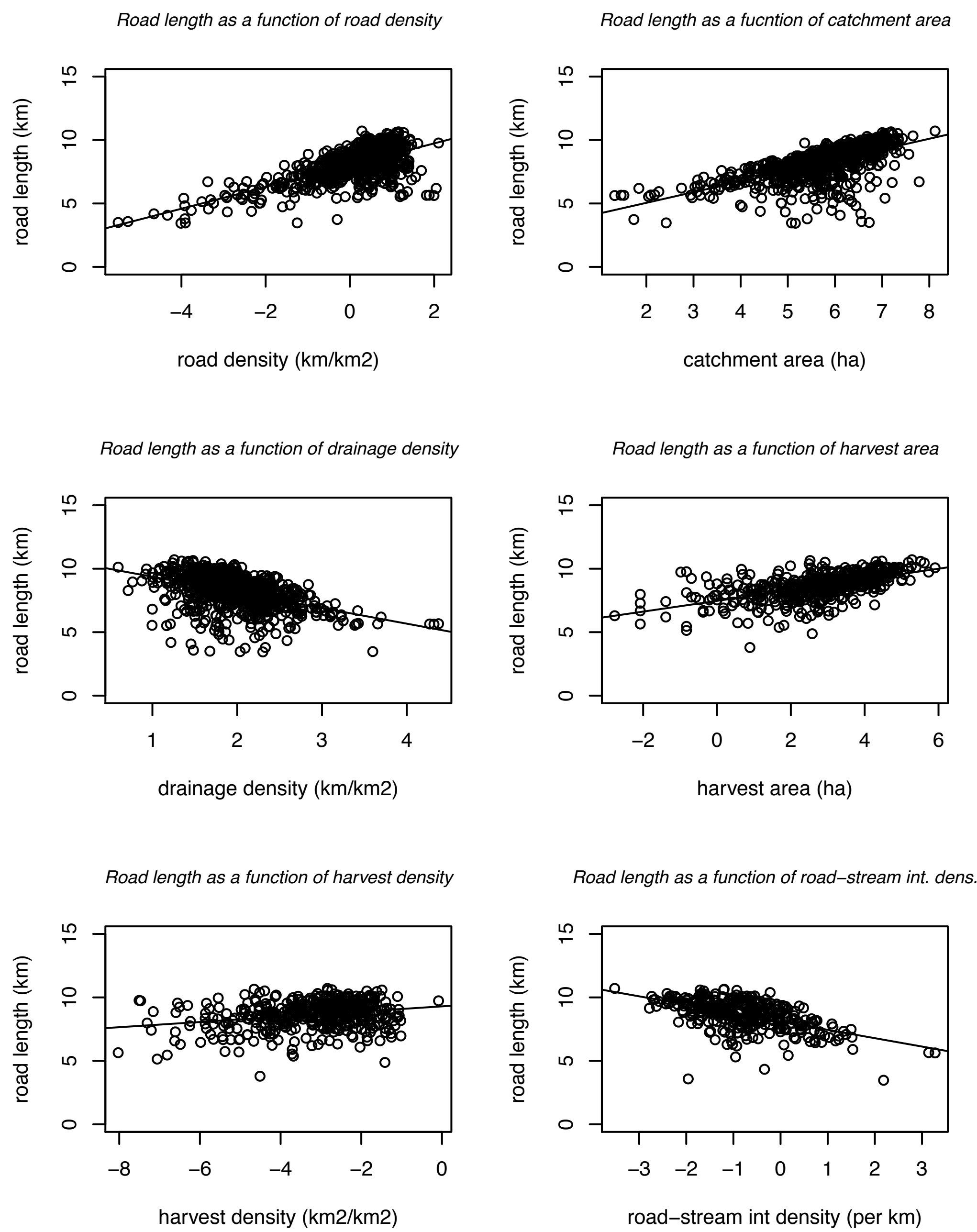


FIGURE 23. COLLINEARITY ANALYSIS OF LN-TRANSFORMED ROAD DENSITY.

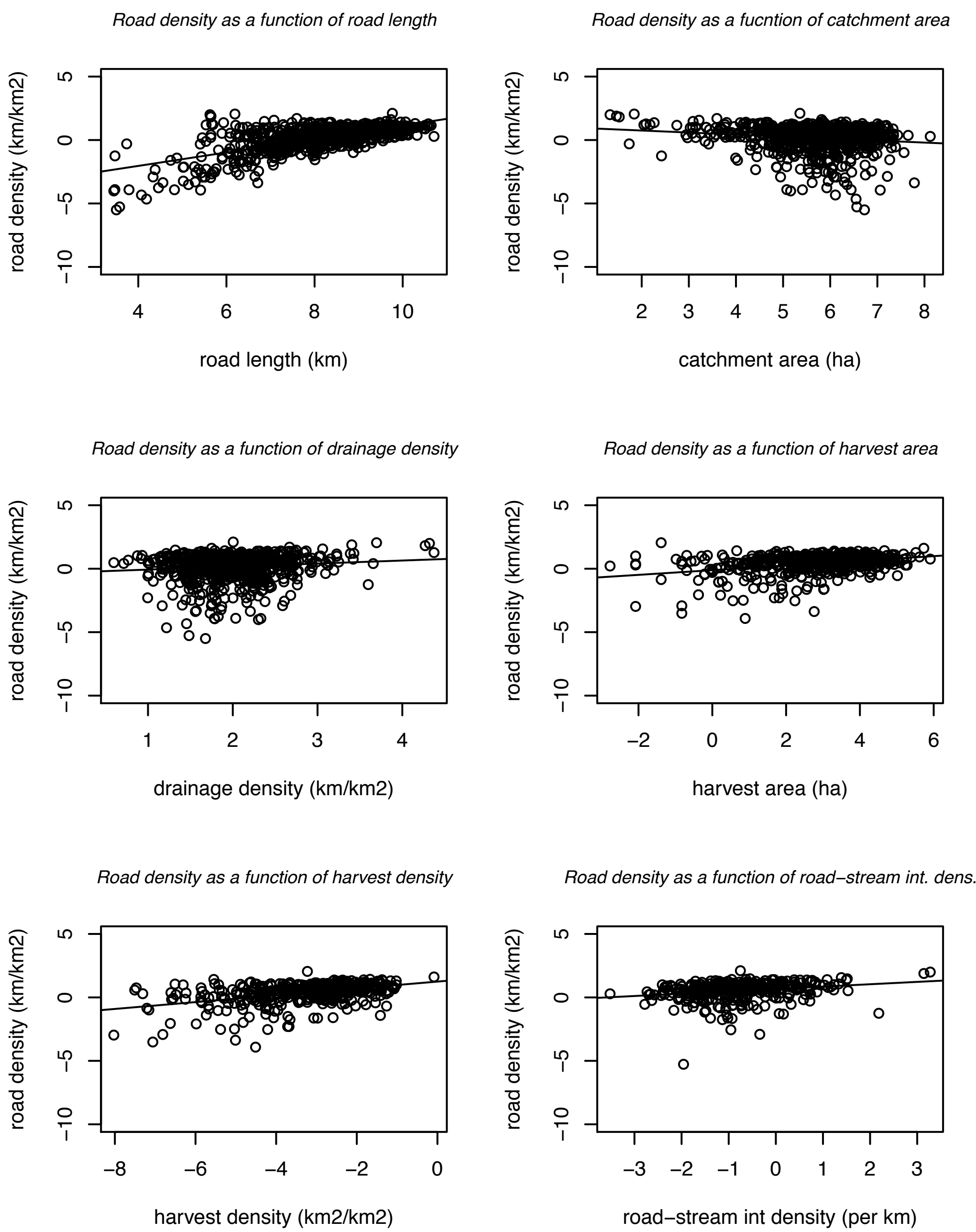


FIGURE 24. COLLINEARITY ANALYSIS OF LN-TRANSFORMED HARVEST AREA.

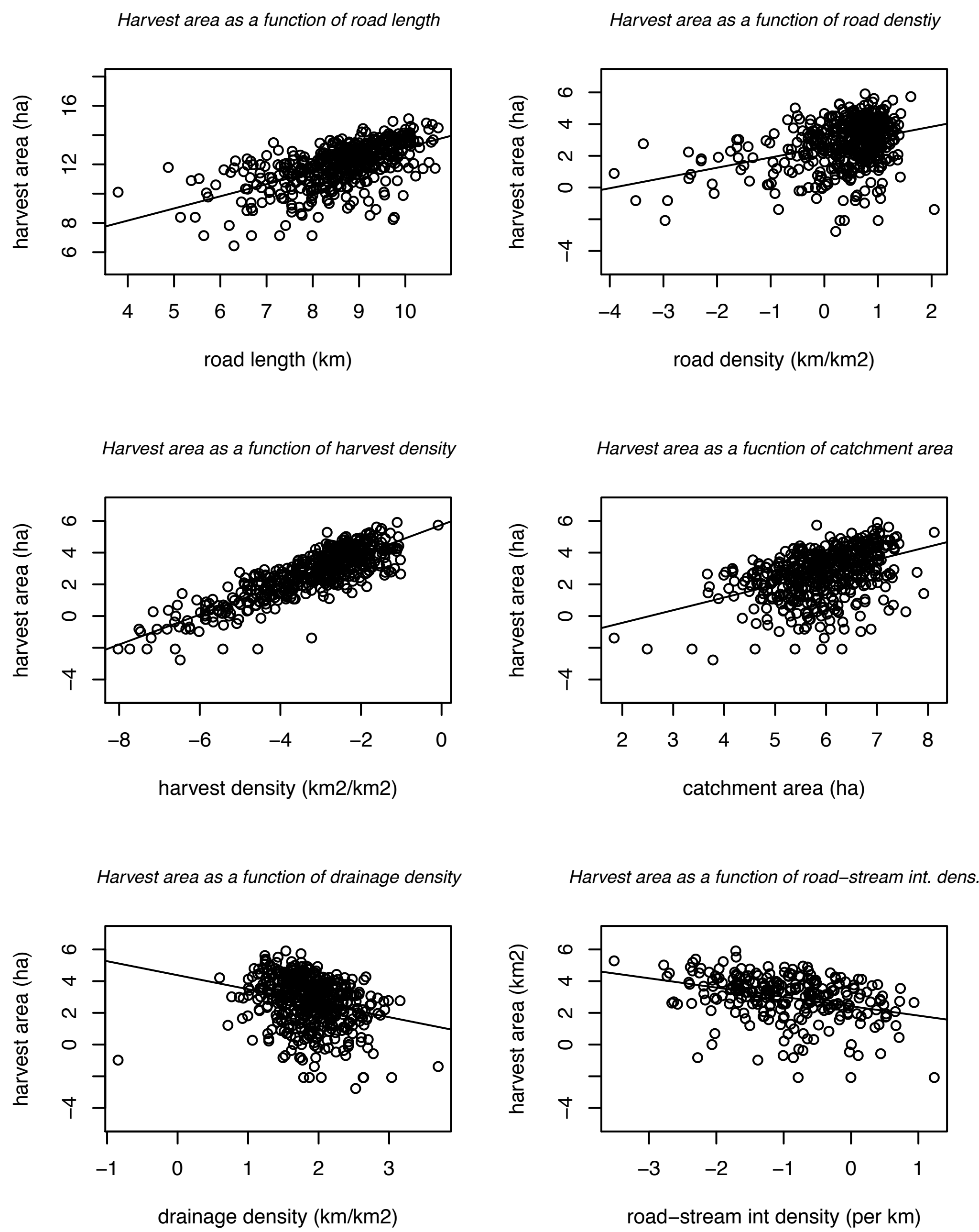


FIGURE 25. COLLINEARITY ANALYSIS OF LN-TRANSFORMED HARVEST DENSITY.

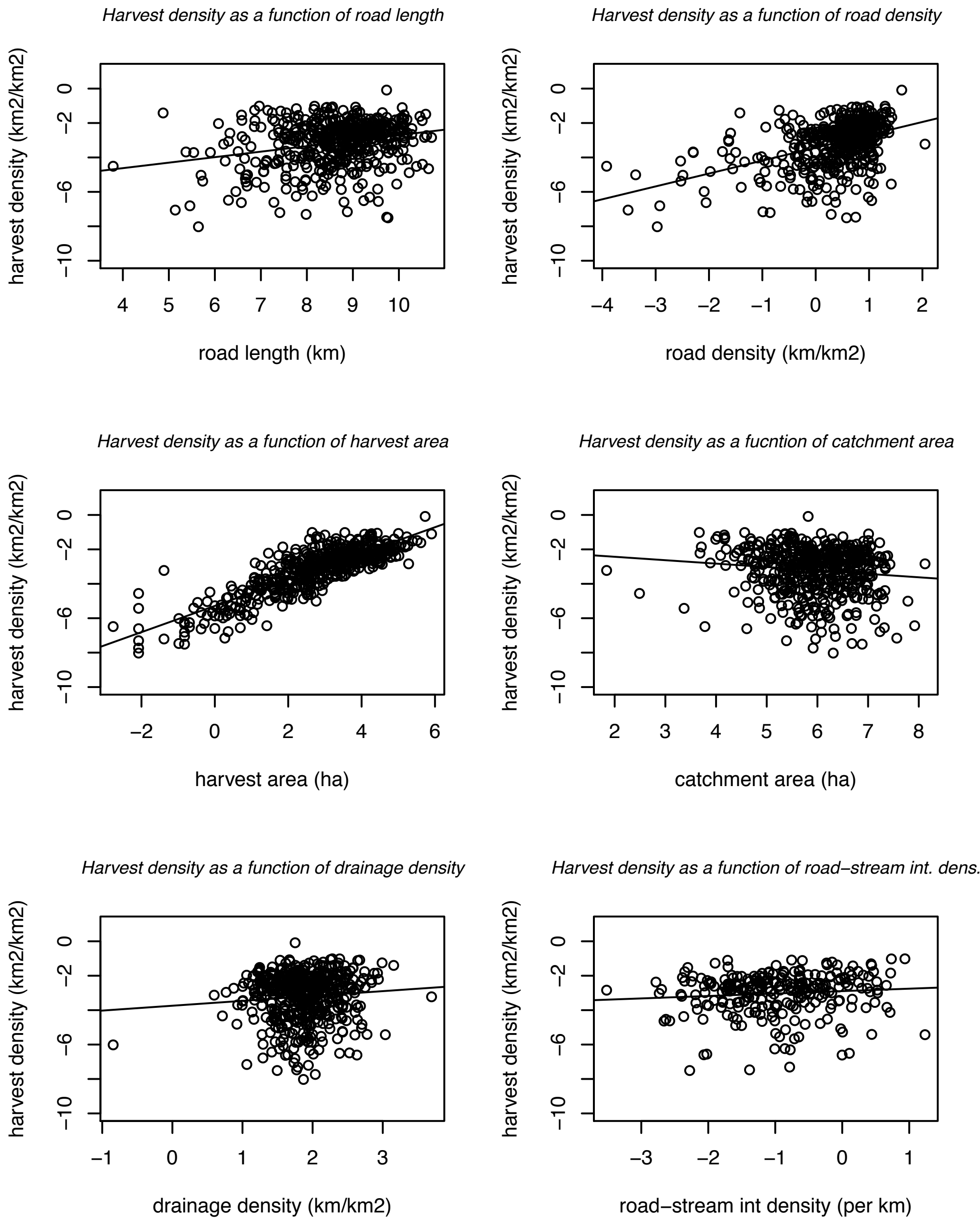


FIGURE 26. COLLINEARITY ANALYSIS OF LN-TRANSFORMED ROAD-STREAM INTERSECTION DENSITY.

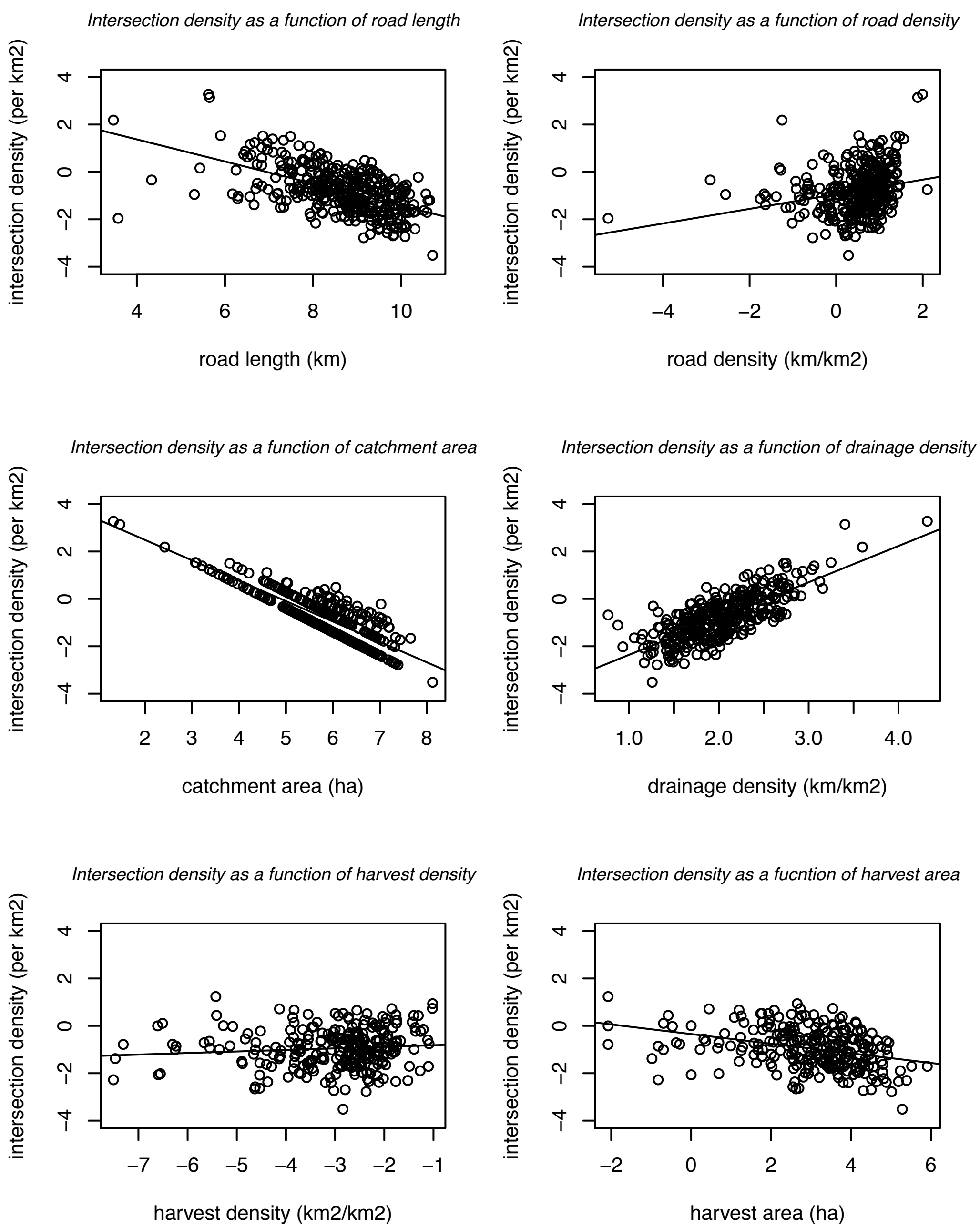
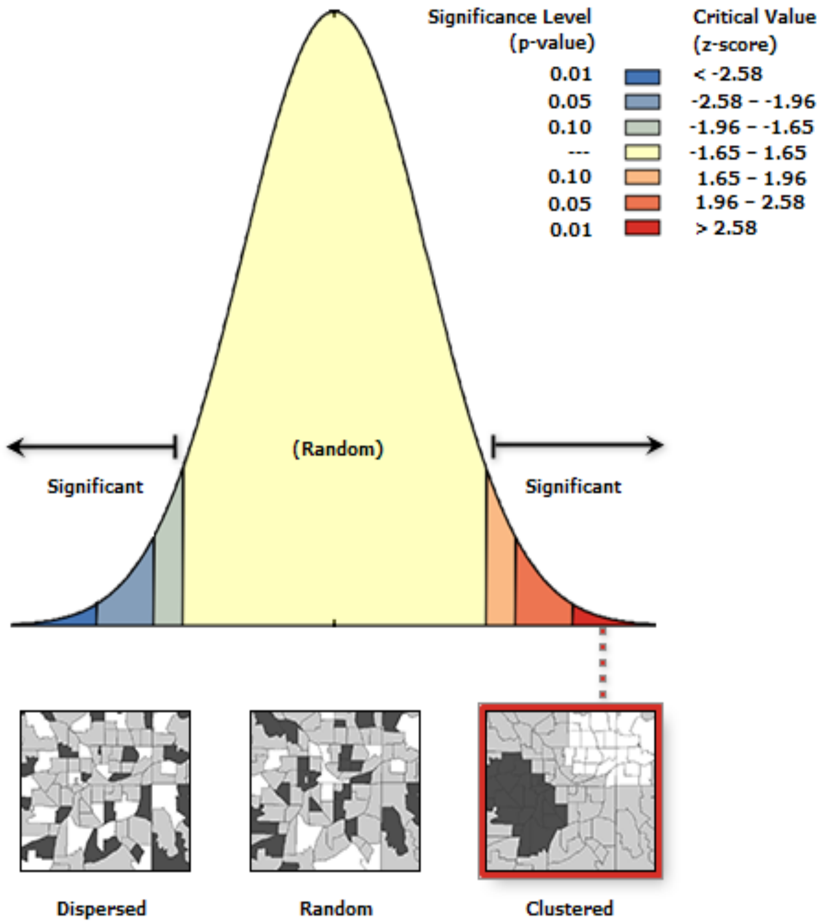


Table 1C. Summary data of collinearity.

Variable 1	Variable 2	r^2
Catchment area	Drainage density	0.49
Catchment area	Harvest	0.11
Catchment area	Harvest area	0.14
Catchment area	Harvest density	0.09
Catchment area	Harvest frequency	0.14
Catchment area	Road-stream intersections	0.07
Catchment area	Road-stream intersection density	0.38
Catchment area	Road density	0.02
Catchment area	Road length	0.39
Catchment area	Roads	0.02
Harvest	Drainage density	0.06
Harvest	Road-stream intersections	0.01
Harvest	Road-stream intersection density	0.05
Harvest	Roads	0.50
Harvest area	Drainage density	0.08
Harvest area	Harvest density	0.71
Harvest area	Harvest frequency	0.41
Harvest area	Road density	0.12
Harvest area	Road length	0.35
Harvest area	Road-stream intersections	0.02
Harvest area	Road-stream intersection density	0.06
Harvest density	Drainage density	0.04
Harvest density	Harvest frequency	0.26
Harvest density	Road density	0.20
Harvest density	Road length	0.06
Harvest density	Road-stream intersections	0.01
Harvest density	Road-stream intersection density	0.04
Harvest frequency	Drainage density	0.07
Harvest frequency	Road density	0.07
Harvest frequency	Road length	0.21
Harvest frequency	Road-stream intersections	0.07
Harvest frequency	Road-stream intersection density	0.01
Road density	Drainage density	~0.00
Road density	Road length	0.45
Road density	Road-stream intersections	0.08
Road density	Road-stream intersection density	0.07
Road length	Drainage density	0.01
Road length	Road-stream intersections	0.06
Road length	Road-stream intersection density	~0.00
Road-stream intersections	Drainage density	~0.00
Road-stream intersections	Road-stream intersection density	~0.00
Road-stream intersection density	Drainage density	0.28
Roads	Drainage density	~0.00

Appendix D. Spatial autocorrelation test of catchment road status.
Figure 28. Moran's I test output from ArcGIS.
Strong spatial autocorrelation is indicated by the Moran's I spatial statistic.



Appendix E. RR-SNF bias assessment.

Table 1E. Contingency table comparing road status and survey status. Catchments are based on Port-Orford-cedar presence from the GNN model.

Survey Status	Port-Orford-cedar catchments				
	roaded		roadless		
	observed	expected	observed	expected	∑
surveyed	724	687	153	190	*877*
not surveyed	213	250	106	69	*319*
∑	*937*		*259*		*1196*

X^2 = 34.3

Significant: (χ^2, *df*=1, *p*=0.001)

Table 2E. Conditional probability results for the RR-SNF.

Condition	Marginal Probability of being surveyed	Conditional Probability
Pr(Rd|S)	0.73	0.77
Pr(Rd|Ns)	0.27	0.23
Pr(Nrd|S)	0.73	0.59
Pr(Nrd|Ns)	0.27	0.41

Note: Pr(Rd|S) = Probability (Pr) of a catchment that is roaded (Rd) and surveyed (S). Nrd = No road; Ns = No survey. When the conditional probability equals the marginal probability, the events are independent. Disparate probabilities indicate dependence between the variables (i.e. bias). Also, conditional probabilities > marginal probabilities indicate an increased likelihood of that event and vice verse. Therefore, knowing a catchment is not surveyed indicates that it is more likely to be roadless (0.41 > 0.27).

Table 3E. Summary of power analysis from selected statistical tests.

Analysis	Observations (n)	Effect size (w)*	Error prob. (p)	*Df*	β	Power (1- β)
Road effect (catchment scale)	934	0.539	0.001	1	~0.00	~1.00
Neighbor analysis	2368	0.672	" "	9	~0.00	~1.00
Uninfested/roadless #	459	0.076	" "	1	0.95	0.05
Uninfested/roaded	1337	0.177	" "	1	0.01	0.99
Infested/roadless	146	0.467	" "	1	0.01	0.99
Infested/roaded #	1102	0.027	" "	1	~1.00	~0.00
Road-stream intersections	766	0.216	" "	1	0.01	0.99
Harvest effect	766	0.465	" "	1	~0.00	~1.00
Survey bias	1196	0.199	" "	1	0.01	0.99
Host/road coincidence ^	1436	0.052	0.001	1	0.90	0.10

* - 0.1, 0.3, 0.5 = small, medium, and large w in X^2 tests respectively (Cohen 1992). Smaller w requires more observations to increase power (1- β) and reduce the probability of Type II error (β).
# - Very small w may indicate no difference in the samples of the populations. Further analysis (Section 3.3.1) determined no significant difference in these sample populations; a suitable n to increase power is not possible.
^ - Only weak significance was determined ($p < 0.01$).

Table 4E. Analysis of coincidence between Port-Orford-cedar and roads on a catchment basis.

Port-Orford-cedar	Port-Orford-cedar and Roads				
	roaded		roadless		
	observed	expected	observed	expected	∑
present	937	928	259	268	*1196*
absent	177	186	63	54	*240*
∑	*1114*		*322*		*1436*

$X^2 = 2.4$
Not significant: $p < 0.5$; $df = 1$