Western Root Disease Model Simulation Versus Plot Remeasurement: 11 Years of Change in Stand Structure and Density Induced by Armillaria Root Disease in Central Oregon

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Abstract—The purpose of this analysis was to use long term permanent plots to evaluate the short-term predictive capability of the Western Root Disease Model extension (WRDM) of the Forest Vegetation Simulator (FVS) in central Oregon mixed-conifer forests in project planning situations. Measured (1991–2002) structure and density changes on a 100-acre unmanaged area in south-central Oregon were compared to those predicted by the Southern-Oregon Northern-California variant (SORNEC) of FVS and the WRDM. Within the study area there were 149 variable-radius plots within 12 stands. Predictions were assessed using five variables that were collectively chosen to represent changes in stand density, stand structure, and are commonly used in project planning. For each indicator variable, projections were made using SORNEC alone and then with the WRDM. Projections were made at both the stand and plot level.

Where Armillaria root disease was present, the WRDM better predicted root disease impact than projections using SORNEC alone. Plot projections with the WRDM reduced the unexplained variation an average of 35% over projections made with SORNEC alone. Root disease impacts were generally overestimated using the WRDM as compared to measured changes. The correlations between the predictions and what was measured were much higher and always significant ($p \leq .0.05$) using plots and usually not significant using stands. The level of effort needed to parameterize and troubleshoot the WRDM creates significant barriers to its use as a project planning tool. Improvements that could reduce these barriers and thus, make the WRDM more attractive to project planners would be to provide users with a set of key parameters that are calibrated, offer full automation of the post-run data summaries, and make the root disease distribution and spread more transparent.

Introduction

Armillaria root disease, caused by the pathogen *Armillaria ostoyae*, is common in the mixed-conifer forests throughout western North America and central Oregon. Inventory plot data indicates that it occurs on approximately 25% of the overall acres of mixed-conifer forests in central Oregon (Simpson 2007). Mortality from this disease creates significant gaps in the forest and can change forest successional pathways in affected areas (Fields 2004; Filip and others, in preparation; Shaw and Kile 1991). Additionally, this disease may limit the effectiveness of proposed treatments, reduce productivity, increase susceptibility to bark beetles and other pests, and limit the number of suitable management options (Williams and others 1986).

The Western Root Disease Model (WRDM) extension of the Forest Vegetation Simulator (FVS) was designed to simulate the impact of Armillaria root disease and other root diseases at the stand- or inventory plot-level over time (Frankel and others 1998). The WRDM has been used in several environmental assessments and project planning efforts in central Oregon where root disease is an important disturbance agent. FVS and the WRDM were used to calibrate yield predictions in the mixed-conifer forests for the Deschutes National Forest Land and Resource Management Plan (USDA Forest Service 1990). FVS and the WRDM were also used to analyze how the presence of root disease would affect hazardous fuel accumulation and the development and retention of key structural elements of the Northern Spotted Owl (*Strix occidentalis* var. *caurina*) habitat under

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various proposed management scenarios in a late successional reserve on Sisters Ranger District, Deschutes National Forest (Maffei and Tandy 2002). Results from this analysis played an important role in the successful outcome of a legal challenge of the project.

Few analyses have been conducted that evaluate the accuracy of the WRDM predictions using long-term permanent plots and none of these have been located in central Oregon. The most comprehensive comparison has been conducted by Frankel and others (1998) in the mixed-conifer forests of the Stanislaus and Eldorado National Forests in California. They compared predicted changes in stand density (trees per acre and basal area per acre) and mortality (trees per acre and volume per acre) over 13 years to actual measured changes for 26 permanent 0.1-acre fixed-area plots. Comparisons were made using the base FVS model alone and the base FVS model plus the S-type annosus-model subroutines in the WRDM. Frankel and others (1998) found that predictions using the root disease model, on average, corresponded well to the measured values while the base model significantly underestimated the impacts of annosus. Further, initializing root disease from the damage codes resulted in better predictions than initializing using the keyword RRINT. However, correlation coefficients between the measured and predicted plot values were significant but not strongly correlated. They found the Pearson product-moment correlation (r) between the predicted change in basal area and what was measured was r = 0.59 when the root disease model was initialized with the RRTREIN keyword and a correlation of r = 0.14 when the base model was used alone (calculated from results table in Frankel and others 1998). Frankel and others (1998) speculate that this difference could be explained by "the small plot size [which] made the model simulations more variable; one tree killed or not killed on a plot is a high percentage of the volume of a very small plot."

WRDM Overview

The WRDM provides a dynamic representation of the spatial epidemiology of three types of root diseases: laminated root rot caused by *Phellinus weirii,* annosus root disease caused by *Heterobasidion annosum*, and Armillaria root disease. It is a conceptual spatial model based on a simplified characterization of root disease epidemiology including: the geometry of its spread, root colonization, and impact on susceptible trees. The root disease center is assumed to expand or contract at its perimeter. Root disease spread is modeled based on the assumption that the distribution of root disease in a stand can be characterized as a number of circular root disease centers, each containing both infected and uninfected trees. Host trees become infected within a center when their roots contact the infected portion of the roots of live- or dead-infected trees. Infection spreads at a constant rate throughout the tree's root system until enough of the root system is infected to kill the tree (assumed default 10%). The root system is also represented as circular. After tree death the model tracks and decays the inoculum level of the dead root system. Everything else being equal, the larger the root system, the longer the inoculum remains.

Critical information when running the root disease model includes:

1. The type of root disease. Only one type may be selected since the WRDM does not simulate multiple root diseases at the same time.
2. The proportion of the plot/stand area in acres to be modeled as being inside the root disease center(s). This must be specified by the user as the model does not infer it.
3. The density of infected trees if the area is to be modeled as one center. This can be either be parameterized by the user or read from damage codes in the tree list file.

Unless damage codes from the tree list file are processed, the model randomly assigns infection to trees within the root disease center. The model also defaults to 25% of the stand area in root disease centers, unless the user defines the proportion of area infected. Stump and dead tree information can be provided to further define the disease simulation environment. However, this additional information is not collected as part of the standard stand exam inventory procedures.

Predicted impacts vary depending on how initial conditions are defined in the model. Sensitivity analysis of the WRDM by a number of investigators (Goheen and Thompson 1998; Marsden 1992a,b; Smith and Zhang 1997) provides the following guidance on critical sensitive variables during model initialization and calibration:

- The model is most sensitive to the type of root disease simulated.
- The size or proportion of the area inside root disease centers has a very significant effect on model results. In general, the greater the area inside the root disease centers, the greater the impact the root disease will have.
- In the WRDM, root disease centers are randomly placed within a stand unless coordinates are provided.
- When root disease occurs in numerous small centers or when the edges of centers are not readily discernible on the ground, the stand should be modeled as one disease center.
- Accuracy of the model run will be further improved if individual tree information regarding root disease infection and severity are obtained in the field and included (via keyword RRTREIN) in the run.
- At least 20 runs with 20 different random seeds (keyword RSEED) should be used for each projection to achieve +/– 4% of the "true" average. Changing some keywords can change the random variates throughout the model, so some variation exists when using the same seed, but different keywords.

The purpose of this analysis was to use local permanent plots in order to evaluate the short-term predictive capability of the WRDM in project planning situations. We evaluated this question by addressing the following questions:

- How accurately does the WRDM predict 11-year changes in stand structure and density compared to measured data when data normally available to project managers are used?
- Does the WRDM allow for better comparisons of alternatives compared to using SORNEC alone?
- How easy is the WRDM to use?
- How easy is managing and interpreting WRDM output?

Methods

Study Area

The data used for this analysis came from a 100-acre unmanaged administrative study area. This area was part of a larger (200-acre) administrative study designed to evaluate and compare silvicultural treatment systems with no management (Filip and others 1995, in preparation). In the portion of the study area being modeled in this analysis, planned treatments were not implemented due to wildlife and recreation restrictions. The study area is about 25 miles NW of Klamath Falls, OR, USA and encompasses some of the most productive sites for white fir (*Abies concolor*), Shasta red fir (*A. magnifica* var. *shastensis*), Douglas-fir (*Pseudotsuga menziesii* var *menziesii*), and ponderosa pine (*Pinus ponderosa*) in south-central Oregon. Elevation ranges from 4,900 to 5,300 ft with an E aspect and 15 to 35% slope. Site index at 50 yr ranges from 65 to 90 for white fir and 59 to 93 for Douglas-fir (Cochran 1979). The plant association is white fir/chinquapin (*Castanopsis chrysophylla*)-boxwood (*Pachistma myrsinites*)-prince's pine (*Chimaphila umbellata*) at the lower slopes and Shasta red fir-white fir/chinquapin-prince's pine/long-stolon sedge (*Carex pensylvanica*) at the upper elevation (Hopkins 1979).

The entire study area is infected with *Armillaria ostoyae* with mortality patches abundant and varying in size from a few scattered trees to several acres (fig. 1). Healthy-appearing groups of trees occur among the mortality patches. The species of *Armillaria* causing mortality has been identified as *A. ostoyae* (NABS I) as determined by genetic testing (Reaves and McWilliams 1991).

The study area encompassed 12 stands (average = 13.8 ac., range = 9-20 ac.) and 147 variable-radius plots. The variable-radius plots were established in 1991 using a 40 BAF and remeasured in 2002. Individual tree measurements included dbh, live crown ratio, and tree condition and were collected according to Pacific Northwest Region stand exam procedures (USDA Forest Service 1991). Trees under 5.0 in. dbh were recorded on a fixed 1/100th acre plot. Plots were remeasured in 2002 for tree dbh and condition. Each plot was also given a root disease severity rating (RDSR) in 1991 (Hagle 1985), which was based on a visual above-ground estimation of the level of canopy reduction caused by root disease. The higher the RDSR, the more severe the impacts of root disease on the

Figure 1—Typical Armillaria root disease center in the study area.

canopy cover of a plot. Thirty-two of the plots had no detectable root disease (RDSR = 0) while the remaining 115 plots had light to severe root disease (RDSR = 1–9) (table1). The percentage of stand area with visible root disease ranged from 14 to 100%, as determined based on the number of plots with RDSR >0. The average plot root disease severity rating was 3.

WRDM Calibration

We were interested in testing the predictive capability of the WRDM when it was parameterized using only data likely to be available to project planners. The WRDM was, therefore, initialized using the standard stand examination data (as described above) we collected in the study, and where necessary, developing initialization logic that could

Table 1—Initial distribution of Armillaria root disease incidence and severity for 147 variable radius plots and 12 stand.

Stand	Root Disease Severity Rating[a]				
	0	**2**	**3-4**	**5-6**	**7-9**
816	6	7	0	0	0
817	3	7	2	0	1
818	0	2	2	7	2
819	1	2	0	2	2
820	0	3	5	0	1
821	1	4	4	1	0
822	5	6	2	1	2
823	3	10	0	4	2
824	5	8	0	0	0
825	6	8	2	0	0
826	1	5	2	1	0
827	2	2	3	0	2
Total	**33**	**64**	**22**	**16**	**12**

[a]Root Disease Severity Rating (Hagle 1985); higher numbers denote more impact of root disease on the plot.

be fully deduced from the stand exams. No additional stem maps or root disease center maps were provided for the simulations. Using these inferences we parameterized individual plots and stands only when we thought the process could be automated. This was because it is highly unlikely project planners are going to perform hand calibration on the large numbers of stands and plots that are typically modeled in project planning. The keywords and settings we used to initialize and calibrate the WRDM are as follows (Marsden 1992a,b; Smith and Zhang 1997):

- *Armillaria* root disease was identified as the root disease type (keyword RRTYPE = 3)
- The root disease in the stand or plot was assumed to occur as one center since the edges of the centers in the study area were not readily discernible on the ground (typical of root disease centers in mixed-conifer forests in central Oregon).
- For individual variable-radius plot projections, the total size of the area to be modeled was approximated as 1 acre (keyword SAREA).
- For stand projections, the total size of the area to be modeled was approximated as a constant 15 acres (keyword SAREA = 15) to more adequately describe the study units compared to the default of 100 acres.
- For projections, the acres in root disease (keyword RRINT) were assumed to be the stand size (15 acres) multiplied by the proportion of variable-radius plots in the stand where *Armillaria* root disease occurred (RDSR >1). Thus, if half of the plots had a RDSR >1, the area in root disease was set at 7.5 acres compared to the WRDM default of 25%. Thus, the stand acres in root disease were, on average, 7.5 acres in size with a range from 2–15 acres. Since projections are sensitive to the acres in root disease in a stand and there was variation in the incidence of root disease between stands, this adjustment to the default was preferable to setting it to a constant for all stands (e.g., 15 acres).
- For plot level projections, variable-radius plot were assumed to be a single root disease center (keyword RRINT) except when there was no measured root disease on the plot (RDSR = 0 or 1). On plots with RDSR = 0 or 1, some root disease was assumed to occur within the modeled area because root disease was widespread throughout the rest of the stand. Since there was no electronically accessible information (the usual situation for vegetation management projects) with respect to the relative location of infected plots to uninfected plots, the default value of 25% was used.
- The density of infected trees was estimated from the damage codes on individual measured trees (keyword RRTREIN).
- The model was run with default values for bark beetles since preferential bark beetle activity was observed inside the root disease centers.

Model Runs and Post Run Processing

Simulations were made using the Southern Oregon Northern California (SORNEC) version of base FVS along with version 3.1 of the WRDM. Twenty runs were made for each projection (including those that were made using the base model only). In each of these projections only the random seed was changed (keyword RSEED). Outputs from the 20 projections were then averaged in a spreadsheet. Measured data were also summarized in SORNEC so that the algorithms used to compute canopy cover for the measured data would be identical to those computed by the projections. The average 11-year change (measured and predicted) was then calculated for each indicator variable and exported to the SPSS statistical software program for further analysis.

Analysis

Wildlife habitat is a crucial management concern in mixed-conifer forest types on the eastern slopes of the Cascades. Usually, mixed-conifer forests east of the Cascade crest are under the jurisdiction of the Northwest Forest Plan (Thomas and others 1990). Therefore, we evaluated the predictive capability of the model with variables that are useful for demonstrating the effect of root disease in late successional habitat, as well as displaying changes in risk of this habitat to insects, diseases, and wildfire. Because the stands are primarily white fir, variables that collectively represent stand structure and density were chosen as most important and designated as evaluation variables. The indicator variables are calculated as FVS event monitor custom variables from the plot measurements (year 1991 and 2002) and 11-year projections of the 1991 measurements. Indicator variables are as follows:

1. Total canopy cover[2] (TOT) (dbh ≥ 5.0 in.; proportion of total % cc, x = 55, min = 38, max = 81).
2. Canopy cover of pole-size trees (PT) (dbh 5.0–8.9 in.; proportion of total % cc, x = 14 min =0, max = 30).
3. Canopy cover of medium-size trees (MT) (dbh 9.0–20.9 in. proportion of total % cc, x = 49, min = 31, max = 64).
4. Canopy cover of large-size trees (LT) (dbh 21.0 ≥ in.; proportion of total % cc, x = 31 min = 11 max = 52).
5. Stand basal area (ba/acre).
6. Total trees per acre (tpa) ≥5.0 in. dbh.

These diameter class groupings and a fifth grouping consisting of small trees <5.0 in. dbh, are routinely used to describe forest structure and density. Combined with species composition, site productivity, and other factors, they form the building blocks of the assessment process. The process has been adopted and is currently being used to evaluate forest ecosystem health, viable wildlife habitat, and to identify hazardous conditions caused by various disturbance agents. Changes in these variables also indirectly represent changes in other variables of interest including: stand basal area, wood fiber volume, and fuel loads.

For each of the size class groups, 11-year projections (with SORNEC and SORNEC + WRDM) were compared with the measured results and performed in the following formats:

1. Individual inventory plots as the primary modeling unit.
2. Stands as the primary modeling unit.
3. Plots grouped by RDSR measured in 1991

The performance of the model as a predictor of the impact of Armillaria root disease on forest structure and density was based on assessment of both the accuracy and the precision of the WRDM projections of the predictor variables and was based on the following analyses:

1. *The accuracy of the WRDM was assessed in terms of the significance and strength of the positive correlation between the predicted- and the measured-changes for the indicator variables*. The model was considered to have performed well if these correlations were significant, positive, and at least moderate in strength (r > 0.40). Pearson's product-moment correlation (r) was used to designate the simple correlation between the measured and predicted variables. The significance of the correlation was tested at the 0.05 level. Correlations would not be expected to be much higher than SORNEC projections for structural components less affected by root disease.
2. *The accuracy of WRDM predictions was based on whether the average value of the predictions is significantly different from the measured value ($p < 0.05$).* As with the correlation coefficients analysis, accuracy would be expected to increase when the WRDM is used, especially for structural components most severely impacted by root disease. A paired sample t-test was used to compare the mean projected value of the indicator variables using the WRDM with the measured values and with projections using SORNEC alone.
3 *The WRDM correctly predicts the impact on structure*. Weighting the strength of the correlation of all the indicator variables equally may not be an appropriate assessment of model performance. Alternatively, it is desirable that WRDM predictions are assigned relative to the amount of potential root disease impact that each structural element within the stand is likely to incur. The greatest positive impact on the correlation coefficient (r) (between the projected and measured

[2] Canopy cover was calculated from algorithms in FVS (SORNEC) for both measured and projected plots.

data), when the WRMD is used over SORNEC alone, is expected to occur in the pole- and mid-sized class structural groups because they are assumed to be more severely impacted by root disease than larger trees (Fields 2004). The assumption that different structural groups will experience different levels of impacts from Armillaria root disease in our study is further supported by the negative significant (at the 0.05 level) correlation between RDSR in the pole and medium sized tree and RDSR together with the lack of a significant correlation for the large tree structure class (fig. 2) in the 1991 data.

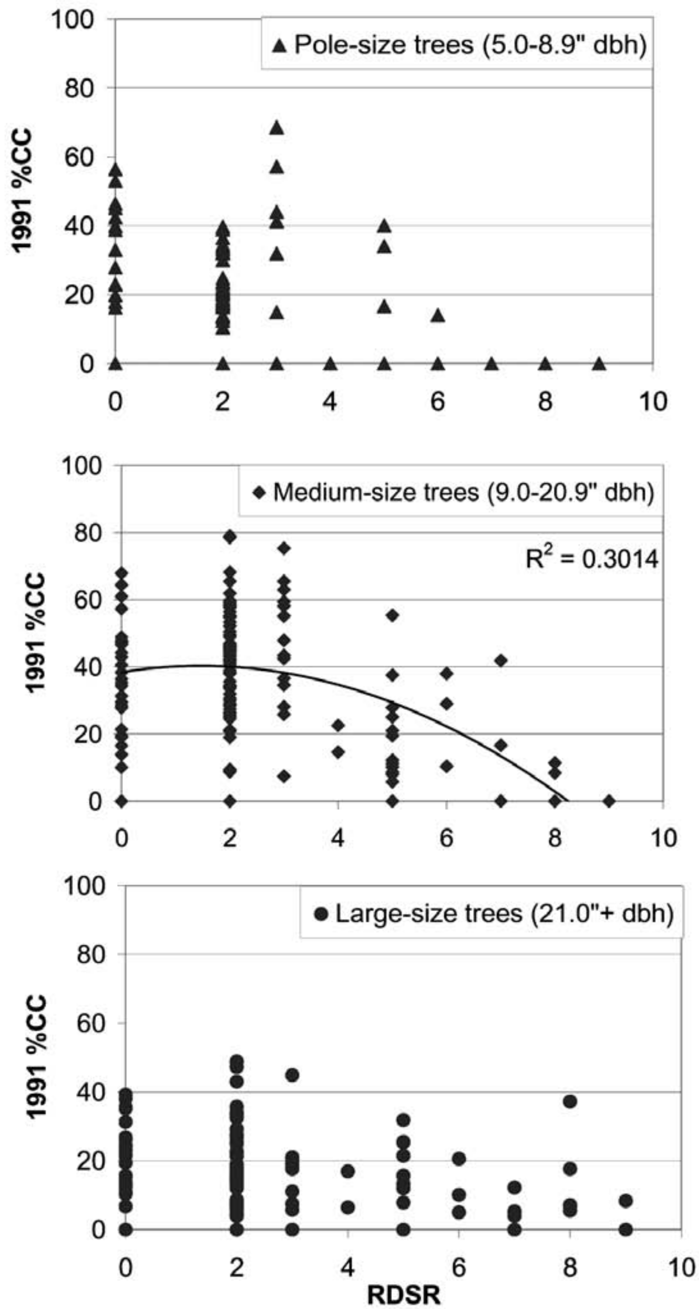

Figure 2—Measured relationship between percent canopy cover and plot root disease severity ratings (RDSR) for the pole sized tree structural class (5.0–8.9" dbh), the medium-sized tree structural class (9.0–20.9" dbh), and the large tree structural class (≥21.0 dbh) in 1991.

Table 2—Averaged 11-year measured changes in % canopy cover and basal area compared with predicted changes (using both variable radius plots and stands as the projection unit) SORNEC alone, and then with the addition of the WRDM. (n = 147 for plot level data; n = 12 for stand level data; TOT = all trees; LT = large trees; MT = medium-size trees; PT = pole-size trees; and BA = basal area ft^2/ac. * indicates that the projection is significantly different from the measured value.)

Size class	Average measured values		Average 11-year change	Projection models[a]	
Projected by plot	**1991**	**2002**	**MEASURED**	**SORNEC**	**WRDM**
Canopy cover by:					
TOT (dbh > 5")	53	40	–13	–4*	–28*
LT (dbh > 21")	14	14	0	3*	–6*
MT (9"< dbh <21")	37	24	–13	–6*	–22*
PT (5"< dbh <9")	13	8	–5	–2*	–7*
BA (dbh > 5")	270	200	–70	–18*	–153*
Projected by stand					
Canopy cover by:					
TOT (dbh > 5")	53	40	–14	–3*	–23*
LT (dbh > 21")	14	14	0	3*	–3
MT (9"< dbh <21")	37	24	–14	5*	–18
PT (5"< dbh <9")	13	8	–5	–3*	–8*
BA (dbh > 5")	270	200	–72	–10*	–122*

[a] 11-year projections are averages of the 20 runs where only the random seed was changed (keyword RSEED).

Results

On average, root disease caused a decline in stand density as well as caused significant changes in stand structure. Average decline in canopy cover at the plot-level over the 11 year measurement period were 13, 0, 13, and 5%, for TOT (≥5.0 in. dbh), LT (large-size trees ≥21.0 in. dbh), MT (medium-size trees 9.0–20.9 in. dbh), and PT (pole-size trees 5.0–8.9 in. dbh), respectively (table 2). Average decline in basal area was 70 ft^2/ac. The largest proportional decline in the total canopy cover (38%) occurred in MT and PT size classes while the least occurred in the LT size class (0%) (table 2). Irregardless of initial RDSR, the presence of root disease increased the variability in 11 year changes in the indicator variables over what would have been predicted by SORNEC alone. The WRDM projections appeared to reflect this variability (fig. 3).

Precision of WRDM

Projections using WRDM were generally more highly correlated with the measured changes than predictions using SORNEC alone (table 3) though none of the correlations could be considered strong. The strength of the correlation between WRDM predictions and measured changes depended on the primary modeling unit (stand or plot) as well as the size-class group. Plot-level predictions of 11-year changes of the 5 variables representing changes in stand density and structure tended to be more highly correlated with the measured data than the stand level predictions. For example, the average reduction in the unexplained variance was 0.49 and 0.34 for the plot and stand projections, respectively and the one to one correlations between WRDM predicted and measured 11-year change was significant (at the 0.05 level) for all predicted variables at the plot level but for only three variables at the stand level (table 3). On average, plot predictions with the WRDM reduced the unexplained variation by an additional 35% over predictions made with SORNEC alone (table 3). For the plot predictions using the WRDM, Pearson correlation coefficients ranged from r = 0.41 to r = 0.69 with significant, but not strong, one-to-one

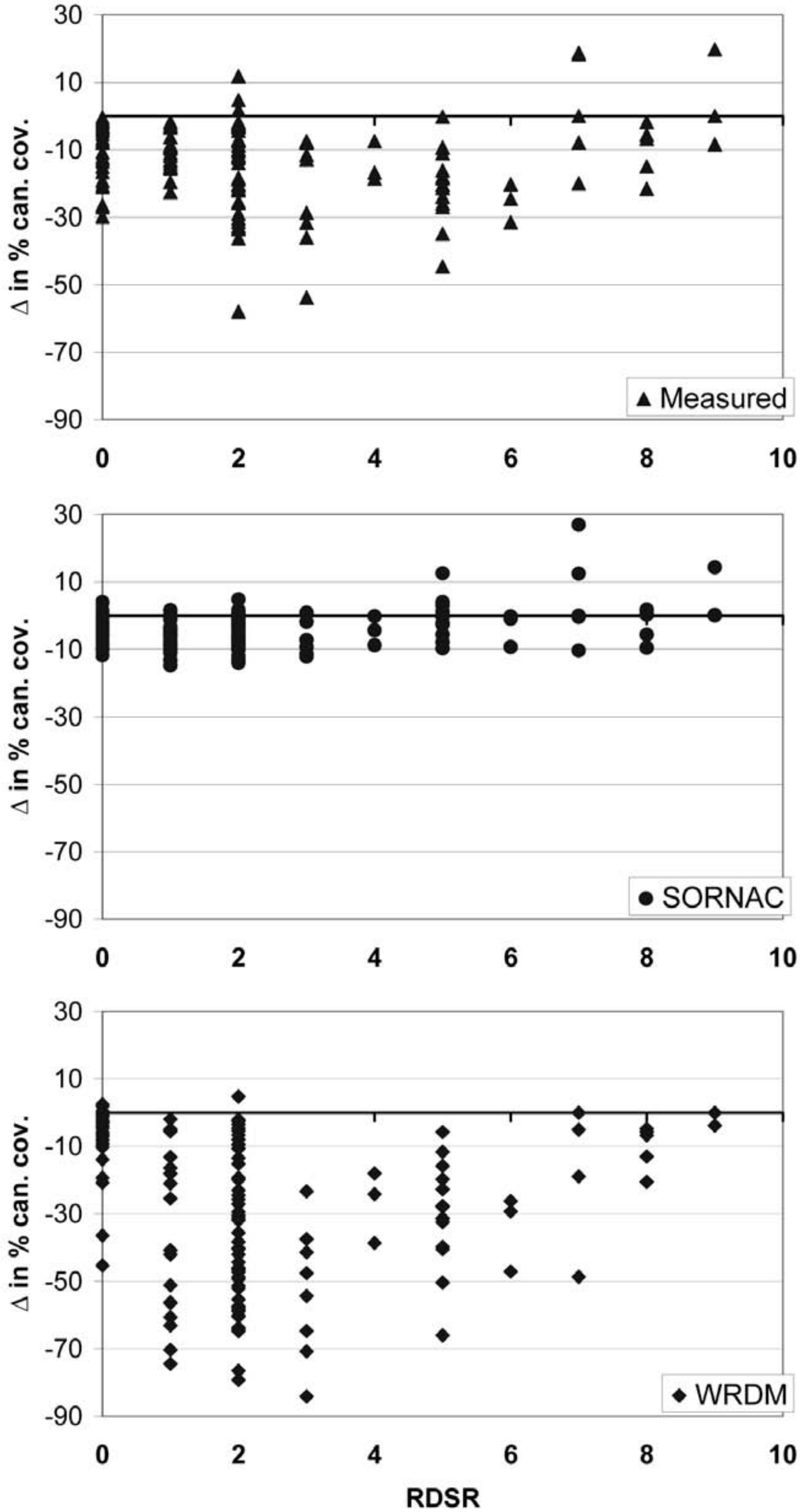

Figure 3—Comparisons of 11-year change in % canopy cover by root disease severity rating (RDSR) for 147 variable radius plots: (1) Measured, (2) SORNEC predictions, and (3) SORNEC + WRDM predictions.

Table 3—Comparison of the positive correlation[a] between 11-year measured and predicted[b] changes in variables representing stand structure and density using SORNEC (base FVS) only, and then adding Western Root Disease Model Extension (WRDM). Both variable-radius plots and stands were used as the projection unit. (Correlations that are significant are in bold. Correlations are significant at the 0.05 level. n = 116 for plot level data; n = 12 for stand level data; plot data are for RDSR > 0; TOT = all trees; LT = large trees; MT = medium-size trees; and PT = pole-size trees.

	Projection models	
Size-class group	**SORNEC**	**SORNEC + WRDM**
Projected by plot	**Pearson's correlations**	
Canopy cover by:		
TOT (> 5" dbh)	**0.27**	**0.41**
LT (> 21" dbh)	**0.55**	**0.51**
MT (9–21" dbh)	**0.27**	**0.42**
PT (5–9" dbh)	**0.50**	**0.69**
BA (basal area ft^2/ac)	NS	**0.43**
Projected by stand		
Canopy cover by:		
TOT (> 5" dbh)	0.00	0.21
LT (> 21" dbh)	0.30	**0.74**
MT (9–21" dbh)	–0.84	–0.04
PT (5–9" dbh)	–0.94	0.49
BA (basal area ft^2/ac)	–0.14	0.27

[a] Positive correlations represent the precision of the predictions.
[b] 11-year projections used for correlations are averages of the 20 runs where only the random seed was changed (keyword RSEED).

correspondence between what was predicted and what was measured on individual plots. For infected plots, the initial RDSR appeared to have little, if any, relationship to the correlation between the predicted and measured values indicating a lack of bias. There was no correlation (r = 0) between the predicted and measured change for plots with no initial root disease (RDSR = 0) (measured) for any of the indicator variables.

Accuracy of WRDM Projections

WRDM projections at both the stand and plot level did not meet our criteria as an accurate predictor of 11-year change except in the case of stand projections using the LT and PT structure class variables. Overall, the WRDM tended to over predict the impact of Armillaria root disease while SORNEC did not predict any impact. Paired t-test results were all significant (two-sided p-value <0.05) for comparisons at the plot-level across all size classes for both measured data vs. SORNEC projections and measured data vs. WRDM projections (table 2). At the stand level, paired t-test results were insignificant for the PT and MT (p = 0.123 and 0.159 respectively) size classes, indicating that the WRDM is accurately predicting canopy cover changes in these size classes at the stand level (table 3). Thus, for stands, WRDM projections were acceptably accurate, for the LT and MT size classes; i.e. those most severely impacted by root disease (table 2).

Impact on Stand Structure—WRDM projections were better predictors of the measured 11 year changes in stand structure than projections with SORNEC alone. For size classes (medium (MT) and Pole (PT)) most severely impacted by root disease, the addition of the WRDM decreased the unexplained variation by an average of 32% (table 3). In general, correlations with the measured data were much stronger with WRMD projections than projections with SORNEC alone. The exception to this was seen in the large Tree (LT) structural class where there was no improvement in the correlation (r) (table 3).

Discussion

The use of WRDM simulates changes in stand structure and density better when Armillaria is present, than the use of FVS alone. The WRDM is a more precise and more accurate predictor of the impacts of Armillaria root disease on stand structure and density, especially for variables that represent the structural classes most impacted by the disease. Even when correlations were not significant at the stand level, the addition of the WRDM resulted in trends in the right direction while use of SORNEC drove the projections in the wrong direction in many cases. Given the choice of using the WRDM or SORNEC without the WRDM, we therefore conclude that using the WRDM is preferable in projects where Armillaria root disease is an important management consideration.

While correlation coefficients were similar to the results by Frankel and others (1998), the precision of the projections, on average, is much lower. The lower accuracy in our study could potentially be caused by number of factors including: (1) different inventory methods (fixed plots vs. variable radius plots; plot center located in the middle of the root disease center vs. plot center located on a grid); (2) different root disease (annosus root disease vs. Armillaria root disease); and (3) random chance. The lower precision when projections were made at the stand level vs. projections at the plot level was puzzling since we would have expected the opposite. We hypothesize that the cause might be that the smaller plot sizes impose limitations on variability in the placement of root disease centers as well as the location of infected trees relative to susceptible non-infected trees. Limited variability in these spatial elements might limit potential variability in spread rates.

Although we believe it is preferable to use the WRDM in situations where root disease is an important factor, a number of characteristics are a significant deterrent to its use for routine project planning:

1. *The level of technical expertise required to properly initialize, run the model, and interpret the output is very high*. The WRDM models the process of spread and mortality by individually simulating the many sub-processes thought to be involved. These many processes are governed by numerous random variates and parameters, many of which the user (even those who are advanced) have no way to measure or validate. In addition to the complex parameterization requirements, a fairly extensive knowledge of how the model works is necessary (for example the importance of changing the random seed).
2. *The WRDM is difficult to troubleshoot*. Identifying areas where functions in the model could be better parameterized or improved is difficult because the user cannot see the distribution of centers, infected trees, and spread scenario for an individual run
3. *The predictive capability of the WRDM predictions is disappointing given the model's complexity, especially with respect to the level of precision attained with stand projections and the level of accuracy attained with plot projections*. While the WRDM generally did a better job than SORNEC alone, the performance of the model was not outstanding over the timeframe we evaluated. Whether it is even possible (given the high natural variation in the field and limited available spatial data) to modify the model to achieve consistently better performance remains a question.
4. *Data summarization outside of the model is required for the initialization process and the data output*. For example, we had to export and summarize the results of the 20 runs outside of FVS. While not an overwhelming task, it is another step where errors could occur.

The barriers to using the WRDM raise questions with regard to its routine use in project planning. Some of these include: Does the predictive capability of the WRDM justify the level of proficiency it takes to use it? If not, do we improve the existing model to the point at which it is both easier to run and achieves better predictions? Or, would a simpler model structure be preferable and better serve project planning needs? While providing answers, these questions are outside the scope of this paper, we suggest that mitigated by the following:

1. *Provide users with a set of key parameters calibrated to the mixed-conifer forest communities in central Oregon*. A sensitivity analysis (with this data set and others) may enable us to refine parameterization and better initialize the model for similar mixed-conifer forests in central Oregon. A set of keywords provided to

users specifically tailored to these forests would save time and reduce the amount of expertise required from the user to run the model.

2. *Fully automate post-run data summaries and key parts of the initialization process*. For example, since we know that multiple runs are required to achieve a good average prediction, the WRDM could be modified so that it automatically varies the random seed a set number of times and summarizes the average of all the projections so that the user does not have to perform these operations manually. The area in root disease could also be internally calculated based on the number of plots with root disease damage codes.
3. *Provide the user an option to make root disease distribution and spread transparent*. Perhaps a user-selected option could generate a simple map of the root disease centers and individual infected trees.

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