A COLLECTION OF SPROUTING PARAMETERS FOR SIMULATING REGENERATION ESTABLISHMENT IN THE MISSOURI OZARKS

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Abstract—Predicting the effects of silvicultural choices on tree regeneration has traditionally been difficult with the tools currently available to foresters. In an effort to improve this, we have developed a simulation framework based on hypotheses of stand dynamics for several species found in the Missouri Ozarks. This framework includes separate modules for establishment, growth, and mortality. Within the establishment module, empirical parameters are used to stochastically simulate regeneration establishment following a variety of harvest-based silvicultural manipulations. A pre-disturbance inventory is used to account for existing conditions and previously published sprouting parameters define the potential contributions of stump-sprouts to regeneration. The collection of previously published sprouting parameters selected for use and their role in simulating regeneration establishment in the Missouri Ozarks are discussed.

INTRODUCTION

Forest regeneration is a dynamic process involving the establishment, growth, and mortality of trees. Complex interactions between these three components continually shape the regeneration process, yet their outcomes may not manifest until years or decades have passed (Quero and others 2011). Given this timeframe and the crucial role of regeneration to sustainable forestry (Dey 2014), the need for computer simulated projections of regeneration to expedite silvicultural diagnoses and improve the likelihood of achieving desired outcomes at the end of regeneration is clear.

Many existing strategies for regeneration simulation were designed for specific silvicultural systems in specific regions. Recently, there have been dramatic shifts in management objectives in favor of more structurally and compositionally diverse forests with continuous canopy cover (Puetmann and others 2008). Accordingly, many of the previous strategies for simulating regeneration are not readily adaptable to the more structurally diverse forest conditions embodied by current management objectives. Moreover, many existing strategies combine the outcomes of regeneration and recruitment into a single point estimate of certain attributes (density, composition, structure). Combining regeneration and recruitment is biologically sound and likely has little impact for most applied objectives. However, non-process base modeling approaches may incur an opportunity cost of limited ability to simulate novel floristic and management scenarios. In addition, non-process based models are typically incapable of generating output in incremental time steps throughout the regeneration period. Consequently, they lack the ability to support adaptive management.

In an effort to improve upon the current capacity of foresters to simulate regeneration in more structurally diverse conditions, a research project was initiated to develop a simulation framework to examine the impact of overstory density on the establishment, growth, and mortality of reproduction in the Missouri Ozarks (Vickers 2015). This framework allows for output in incremental time steps, which contrasts to models that produce point estimates of structure, stocking and composition only at the end of the regeneration period. In addition, this framework permits evaluating the impact of varying residual overstory density resulting from differing silvicultural regeneration methods on regeneration and thus, is a more robust modeling approach. Under this approach, various silvicultural methods are viewed simply as manipulations that result in varying overstory density that is retained long enough to effect regeneration, and whose affect can vary spatially throughout the stand. The increased generalization offered by this approach greatly increases the breadth of harvest and natural gap based disturbance scenarios that can be examined for their impact on regeneration.

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Forest regeneration is a defining example of secondary succession (Horn 1974). A fundamental concept of secondary succession is the development of and reliance upon regeneration sources disseminated prior to or immediately following disturbance. Therefore, the composition of future forests is largely a function of the composition of previous forests (Egler 1954), though the ultimate identity of the regenerating stand will be influenced by the magnitude and timing of disturbances and their biological impacts on stand development along with other stochastic influences (Gleason 1917). Accordingly, a commonality among many regeneration models is the requirement of some metric of advance reproduction as input data. Weiskittel and others (2011, p157) described this as the "established seedling" approach to regeneration modeling. Our simulation framework largely follows this approach and requires an inventory of certain attributes of advance reproduction and potential sprouting sources prior to a disturbance event. The reliance on disturbance to initiate the regeneration process is consistent with leading hypotheses of forest stand development (Oliver and Larson 1996).

Sprouting is often critical to regeneration success in the oak-hickory dominated forests of the Missouri Ozarks (Johnson and others 2009), and is an important component of regeneration establishment for many species in other regions as well (Bond and Midgley 2003). Thus, several probabilistic models of stump sprouting have been developed to quantify possible contributions of this regeneration source to forest composition following disturbance. The objective of this manuscript is to describe a collection of existing empirical models of stump sprouting and stump clumping (number of sprouts per stump) that were identified for use in the establishment module of a regeneration simulator for the Missouri Ozarks. Establishment is defined herein as reproduction (trees ≤ 5cm d.b.h.) present three years following disturbance.

METHODS

Sprouting parameters were obtained from a review of existing literature and analyses. Existing parameters for both stump sprouting probability and stems per sprouted stump (clumping) were sought for the following species (or species groups) that are commonly found in Missouri Ozark forests: 1) ashes (*Fraxinus americana* L., *F. pennsylvanica* Marsh.), 2) blackgum (*Nyssa sylvatica* Marsh.), 3) black cherry (*Prunus serotina* Ehrh.), 4) dogwood (*Cornus florida* L.), 5) elms (*Ulmus alata* Michx., *U. rubra* Muhl., *U. americana* L.), 6) hickories (*Carya tomentosa* Sarg., *C. glabra* Mill., *C. ovata* (Mill.) K. Koch., *C. texana* Buckley, *C. cordiformis* (Wangenh.) K. Koch.), 7) red maple (*Acer rubrum* L.), 8) red oaks (*Q. rubra* L., *Q. velutina* Lam., *Q. coccinea* Münchh, *Q. marilandica* Münchh.), 9) sassafras (*Sassafras albidum* J. Presl.), 10) shortleaf pine (*Pinus echinata* Mill.), 11) sugar maple (*Acer saccharum* Marsh.), and 12) white oaks (*Q. alba* L., *Q. stellata* Wangenh, *Q. muehlenbergii* Engelm).

Species specific parameters were preferred when available. In cases where species specific parameters were not found, parameters for closely related species were accepted. Otherwise, parameters for a species may have been obtained from publications that reported parameters for a collection of species grouped according to the various publication specific criteria. When multiple publications were available for an individual species, those developed in forest communities that most closely resembled the Missouri Ozarks were preferred. Additionally, attributes such as the strength and range of data, as well as model form and complexity were considered when multiple publications were found for a single species. The potential impact of differences in sprouting parameters due to varying stand ages reported among the respective publication studies was ignored.

In order for these equations to be utilized, individual stems with the potential to sprout must first be identified from a provided inventory. For the purposes of the establishment module, the parent stem (all stems for multi-stemmed parents) must be identified as a tree to be removed in the pre-disturbance inventory. For multi-stemmed parents, attributes of the largest stem are used to apply the probabilistic sprouting parameters. These probabilities are used in a binomial random number generator to stochastically determine the sprouting outcome (success or failure) of each inventoried stem that has the potential to sprout. Although some species produce basal sprouts under an intact parent stem, this regeneration source along with root sprouts (suckers) were not directly considered. However, it is assumed that root sprouts are indirectly accounted for in the establishment estimates for reproduction that is not from obvious sprout origin (Vickers 2015). The clumping parameters are used in a Poisson random number generator to stochastically determine the number of new stems to be established per sprouted stump.

RESULTS AND DISCUSSION

Existing models for estimating the probability of establishment via stump sprouting were utilized for the species groups included in the establishment module. The models used for estimating stump-sprouting, along with their origin, are provided in table 1. Petrice and Haack (2011) reported approximately 96 percent sprouting for ash (*F. americana*, *F. pennsylvanica*, *F. nigra* Marsh.) stumps 1 year after midspring harvest in Michigan. Keyser and Zarnoch (2014) reported that breast height diameter influenced sprouting of blackgum one year following harvest in the Southern Appalachians. Wendel (1975) reported that 100 percent

Table 1—Existing stump sprouting parameters identified for use in the establishment module of a regeneration simulator for the Missouri Ozarks

Species Group		Sprouting Probability	Source	Source Locale
ashes		0.96	Petrice & Haack 2011	MI
blackgum		$\{1+e^{-(5.5798-0.2011\cdot X_1)}\}^{-1}$	Keyser & Zarnoch 2014	S. Appalachians
black cherry		0.98	Wendel 1975	WV
dogwood		0.88	Keyser & Zarnoch 2014	S. Appalachians
elms		$\{1+e^{-(1.6323-0.0608\cdot X_1)}\}^{-1}$	Olson, M.G. unpublished	MO
hickories		0.77	Keyser & Zarnoch 2014	S. Appalachans
red maple		0.95	Keyser & Zarnoch 2014	S. Appalachians
red oaks	black oak	$\{1+e^{-(-0.7523-0.2691[1.2703(0.3937\cdot X_1)^{1.0105}]+0.0615[3.2808\cdot X_2])}\}^{-1}$	Dey 1991	MO Ozarks
	blackjack oak	$\{1+e^{-(2.6481-0.3005[1.3322(0.3937\cdot X_1)^{0.9955}])}\}^{-1}$	Dey 1991	MO Ozarks
	n red oak	$\{1+e^{-(-7.4793-0.0005[(0.3937\cdot X_1)X_3]+3.1679\cdot \ln X_2)}\}^{-1}$	Weigel & Peng 2002	IN
	scarlet oak	$\{1+e^{-(5.7710-0.3513[1.2154(0.3937\cdot X_1)^{0.9798}])}\}^{-1}$	Dey 1991	MO Ozarks
sassafras		0.91	Keyser & Zarnoch 2014	S. Appalachians
shortleaf pine		0.67	Clabo 2014	TN
sugar maple		0.81	MacDonald & Powell 1983	NB, Canada
white oaks	post oak	$\{1+e^{-(2.6481-0.3005[1.3322(0.3937\cdot X_1)^{0.9955}])}\}^{-1}$	Dey 1991	MO Ozarks
	white oak	$\{1+e^{-(1.7378-0.5476[1.5443(0.3937\cdot X_1)^{0.9532}]-0.0546\cdot X_3+0.0033[X_3(1.5443(0.3937\cdot X_1)^{0.9532})]+0.0705[3.2808\cdot X_2])}\}^{-1}$	Dey 1991	MO Ozarks
other species		0.89	Keyser & Zarnoch 2014	S. Appalachians

Where: X_1 = diameter at breast height (cm), X_2 = site index (m), X_3 = tree age (yrs). Values for black cherry were modified slightly from those reported (100%, Wendel 1975). The sprouting equations developed by Dey (1991) were originally fit using stump diameter rather than diameter at breast height. Because stump diameter is not commonly inventoried, these equations were modified to include a diameter at breast height to stump diameter conversion (Dey 1991). The parameters designated for the other species group were used for any sprouting species not included in the previous groups.

of black cherry harvested in a study in West Virginia produced a sprout within 1 year of harvesting. This value was modified slightly to ninety-eight percent to foster stochastic establishment in the regeneration simulator. Eighty-eight percent of dogwood stumps sprouted 1 year following harvest in the Southern Appalachians (Keyser and Zarnoch 2014). The sprouting probability of elm (*U. americana*) was influenced by breast height diameter one year post harvest in Missouri (unpublished data: Olson, M.G., Resource Scientist-Silviculturist, Missouri Department of Conservation). Seventy-seven percent of hickories sprouted 1 year following harvest in a Southern Appalachian study (Keyser and Zarnoch 2014). Ninety-five percent of red maple sprouted in the same study (Keyser and Zarnoch 2014).

Dey (1991) reported that the sprouting probabilities for black, blackjack, scarlet, post, and white oaks in the Missouri Ozarks were influenced by size (table 1). The sprouting equations developed by Dey (1991) were originally fit using stump diameter rather than breast height diameter. Because stump diameter is not commonly inventoried, these equations were modified to include the breast height to stump height conversions that were also developed by Dey (1991). Dey (1991) reported that the sprouting probability of black oak and white oak were also influenced by site index. The sprouting probability of white oak was also influenced by tree age (Dey 1991). Weigel and Peng (2002) reported that the sprouting probability of red oaks (*Q. rubra*, *Q. coccinea*) were influenced by breast height diameter, site index, and tree age.

Keyser and Zarnoch (2014) reported the sprouting probability of sassafras (ninety-one percent) one year post harvest as part of a species group that included shade tolerant species (table 1). Sixty-seven percent of clipped shortleaf pine seedlings sprouted in a study in Tennessee reported by Clabo (2014). The reported sprouting probabilities for shortleaf pine seedlings (Clabo 2014) were not used within the simulator for trees with a breast height diameter > 5cm. MacDonald and Powell (1983) reported sprouting probabilities for sugar maple one year following harvest in New Brunswick. The probability used for sugar maple (eighty-one percent) was an average calculated from the results reported by MacDonald and Powell (1983, table 1 column 3, rows 1-4). The sprouting probability (eighty-nine percent) designated for the other species group were used for any sprouting species not included in the previous groups and was the average of the tolerant and intolerant species group probabilities reported by Keyser and Zarnoch one year post harvest (2014).

Because a stump that successfully sprouts often produces more than one new stem per stump, existing models of stems per sprouted stump were used to account for multi-stemmed stump-clumps. The models used for estimating the number of stems per sprouted stump, along with their origin, are provided in table 2. Kays and Canham (1991) reported a mean of 5.2 stems per sprouted ash stump 3 years following harvesting in New York. Atwood and others (2009) reported a mean of 4.3 stems per sprouted stump 9 years following harvesting in the Southern Appalachians for a group of predominately midstory species that included dogwood and sassafras among others. This value was applied to the blackgum and other species group as well. An average of 4.3 stems per sprouted stump was also reported for black cherry 3 years following harvesting in New York (Kays and Canham 1991). In Missouri, 7.3 new stems per sprouted stump were reported for elm (*U. americana*) 3 years following harvest (unpublished data: Olson, M.G., Resource Scientist-Silviculturist, Missouri Department of Conservation). Atwood and others (2009) reported a mean of 3.2 stems per sprouted stump 9 years post harvest in the Southern Appalachians for a species group that included hickories and white oak. This value was used only for hickories. Three years following harvest in New York, red maple averaged 6.2 stems per sprouted stump (Kays and Canham 1991). Clabo (2014) reported an average of 2.1 stems per sprouted stump for clipped shortleaf pine seedlings in Tennessee. An average of 10 sugar maple stems per sprouted stump was reported 1 year following harvest in a study in New Brunswick (MacDonald and Powell 1983).

Dey and Jensen (2002) reported that the number of stems per sprouted stump one year following harvest was influenced by stump diameter and tree age for black, scarlet, and white oaks in the Missouri Ozarks (table 2). The parameters identified for blackjack oak and post oak were taken from the equations reported by Dey and Jensen (2002) for black oak and white oak respectively. Johnson (1975) reported that the number of northern red oak stems per sprouted stump in Wisconsin, Michigan, and Iowa was influenced by breast height diameter and stand age.

Ecological classification systems have been suggested for regeneration research (Dey and others 2009, Kabrick and others 2008). Accordingly, an ecological classification system was used to delineate site differences in the regeneration simulator framework (Vickers 2015). Consequently, it was assumed that site index will often be unknown. For sprouting equations that required site index (black oak, northern red oak, white oak), empirical mean and standard deviation site index values for each site class (exposed backslopes: 21.0 ± 1.3m, protected backslopes: 22.0 ± 1.1m; black oak, base age 50) are used in a Gaussian random number generator to stochastically assign a site index value for a plot (Vickers 2015).

Table 2—Existing stump-clump parameters identified for use in the establishment module of a regeneration simulator for the Missouri Ozarks

Species Group		Sprouts per stump	Source	Source Locale
ashes		5.2	Kays & Canham 1991	NY
blackgum		4.3	Atwood et al. 2009	S. Appalachians
black cherry		4.3	Kays & Canham 1991	NY
dogwood		4.3	Atwood et al. 2009	S. Appalachians
elms		7.3	Olson, M.G. unpublished	MO
hickories		3.2	Atwood et al. 2009	S. Appalachians
red maple		6.2	Kays & Canham 1991	NY
red oaks	black oak	$21.028+(-0.0310[1.2703(0.3937 \cdot X_1)^{1.0105}])+(-0.1537 \cdot X_2)$	Dey & Jensen 2002	MO Ozarks
	scarlet oak	$20.9773+(-0.0310[1.2154(0.3937 \cdot X_1)^{0.9798}])+(-0.1537 \cdot X_2)$	Dey & Jensen 2002	MO Ozarks
	blackjack oak	$21.028+(-0.0310[1.3322(0.3937 \cdot X_1)^{0.9955}])+(-0.1537 \cdot X_2)$	Dey & Jensen 2002	MO Ozarks
	n red oak	$3.7+8.82([0.3937 \cdot X_1]/X_3^2)$	Johnson 1975	WI,MI,IA
sassafras		4.3	Atwood et al. 2009	S. Appalachians
shortleaf pine		2.1	Clabo 2014	TN
sugar maple		10	MacDonald & Powell 1983	NB, Canada
white oaks	white oak	$17.0967+(-0.0310[1.5443(0.3937 \cdot X_1)^{0.9532}])+(-0.1537 \cdot X_2)$	Dey & Jensen 2002	MO Ozarks
	post oak	$17.0967+(-0.0310[1.3322(0.3937 \cdot X_1)^{0.9955}])+(-0.1537 \cdot X_2)$	Dey & Jensen 2002	MO Ozarks
other species		4.3	Atwood et al. 2009	S. Appalachians

Where: X_1 = diameter at breast height (cm), X_2 = tree age (yrs), and X_3 = post disturbance stand age (yrs). A post disturbance stand age of 3 is used for stem establishment in the simulator. The equations developed by Dey and Jensen (2002) were originally fit using stump diameter rather than diameter at breast height. Because stump diameter is not commonly inventoried, these equations were modified to include a diameter at breast height to stump diameter conversion (Dey 1991). The parameters designated for the other species group were used for any sprouting species not included in the previous groups.

Some sprouting and clumping equations required tree age, but tree age is often not included in forest inventories. Thus, it was assumed that tree age will often be unknown and published equations for converting diameter at breast height to tree age (Lowenstein and others 2000) were used when required for stump sprouting probabilities (northern red oak, white oak) and clumping (black oak, scarlet oak, blackjack oak, white oak, post oak). Due to a positive interaction between tree age and diameter in the equation used for the sprouting probability of white oak, increasing tree age substantially improved sprouting probability with increasing diameter once age exceeded certain thresholds. In contrast, Johnson and others (2009) suggest that it is unlikely that large diameter oaks will sprout if harvested. Thus, an algorithm was required to ensure that spurious sprouting probabilities were not produced as a result of age estimates that fell outside the range of the fitted dataset. Similarly, an algorithm was required to ensure that the clumping equations that required tree age did not produce spurious estimates when age estimates fell outside the range of the original dataset.

Most of the available models of stump sprouting probabilities were developed from data following clearcut harvesting. Foresters have long recognized differences in life history traits among species and the influence of overstory density and crown cover on regeneration dynamics. Despite this longstanding recognition, relatively little progress has been made toward simulating the impact of varied overstory conditions on the development of reproduction, particularly in naturally regenerated mixed species stands. Evidence of reductions in stump sprouting probabilities with increasing residual overstory density in oak-dominated forests has been reported 9-11 years after harvesting (Atwood and others 2009), but a separate study conducted 1-3 years after harvesting did not report reductions in stump sprouting probabilities with increasing residual overstory density (Keyser and Zarnoch 2014). Keyser and Zarnoch (2014) suggested that this discrepancy could be due to accumulated mortality in the older stands analyzed by Atwood and others (2009). This suggestion is supported by the report of Dey and others (2008), that increasing residual overstory density lowered survival and growth of oak stump-sprouts 10 years after harvesting, but the proportion of sprouting stumps in the first year after harvest was not significantly affected (Dey and Jensen 2002). Keyser and Zarnoch (2014) also found that the heights of sprouts were reduced with increasing residual overstory density. In light of these reports, it is apparent that residual overstory density influences stump sprouting dynamics in oak dominated forests. However, this influence appears to be primarily a reduction in growth rates which, in turn, reduces stump-sprout survival during stem exclusion. This hypothesis is followed in the regeneration simulator. Dey and Jensen (2002) also reported that the number of oak sprouts per stump was significantly affected by stump diameter, but not by residual overstory density. Consequently, models of stump sprouting and clumping probabilities following clearcutting may provide reasonable estimates of third-year regeneration establishment following a variety of harvest-based silvicultural manipulations. However, the prolonged influence of residual overstory density on sapling survival which, in turn, influences the abundance of potential sprouting sources should be considered. Additional research into the influence of residual overstory density on stump sprouting dynamics is warranted but beyond the scope of this effort.

Many studies suggest that the sprouting probability of small diameter trees is high after harvesting, but the minimum diameter included in sprouting models vary (e.g., Johnson and others 2009). The probability of advance reproduction being damaged or top-killed during a disturbance has not been well defined empirically. Additional research to provide empirical parameters for the probability of damage/topkill and subsequent sprouting probabilities of advance reproduction is warranted.

CONCLUSION

Regeneration is a dynamic process involving the establishment, growth, and mortality of individual trees and their neighbors. The capability to stochastically simulate reproduction establishment across a gradient of residual overstory density allows foresters to examine the potential outcomes of proposed regeneration treatments. The collection of sprouting parameters identified in this report provide an empirical foundation for estimating the potential contributions of this, often critical, source of reproduction to post disturbance composition in Missouri Ozark forests. Areas in need of additional work have been suggested. It is possible that alternative or, perhaps, more appropriate parameters than those included in this report currently exist or may be developed with future research. Periodic literature reviews are suggested to ensure the best available science is incorporated in future regeneration simulations.

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