Ecological Indicators xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Using a tree seedling mortality budget as an indicator of landscape-scale forest regeneration security

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ARTICLE INFO

Keywords:
Forest regeneration
Native forest
Young forest
Quercus/Carya
Acer/Fagus/Betula
Biodiversity

ABSTRACT

Securing desirable forest regeneration outcomes is an essential component of sustainable forest management. When natural reproduction is preferred over planting, achieving desirable outcomes may be the principal challenge for forest managers, as reports of struggles and even failures are common across many regions and forest ecosystems. Informing managers and policymakers of the prospects of regeneration success before practices and policies are implemented promotes long-term sustainability because rehabilitating undesirable regeneration outcomes is often lengthy, expensive, and uncertain. In 2012, the USDA Forest Service, Northern Research Station, Forest Inventory and Analysis program implemented Regeneration Indicator (RI) protocols that added detailed seedling measurements and browse impact assessments to a subsample of inventory plots across 24 states in the northern United States. The goal of this expanded sampling effort is to improve the ability to monitor broad scale regeneration trends and better inform forest management planning and policy. Modeling probable regeneration outcomes is difficult and the rarity of vetted models that can fully utilize RI inventory data highlights an immediate need for flexible methods to evaluate regeneration of different taxa at large scales. This manuscript is premised on estimation of a tree seedling mortality budget for inventoried reproduction. The method offers a transparent structure for leveraging existing literature and expert knowledge to gain provisional insight into plausible regeneration outcomes. The resulting tool provides flexibility for users to examine regeneration for multiple species, site conditions, and user-defined quantitative regeneration objectives. The approach is demonstrated by applying a suite of multispecies regeneration objectives to RI data for two case studies with different forest composition and geographic scales, the Ozark Highland Ecological Section (OHES) and the Monongahela National Forest (MNF). Within the *Quercus/Carya* dominated OHES, analyses indicate that desirable regeneration outcomes are more likely than not based on current plot conditions. Regeneration events were projected to produce new fully stocked forests on 76% of OHES plots, produce a sizable component of characteristic overstory species on 57%, and produce a sizable component of commercially important species on 59%. Within the *Acer/Fagus/Betula* and *Quercus/Carya* forests of the MNF, analyses indicated that difficulties in achieving desirable regeneration outcomes were likely. Only 36% of MNF plots were projected to produce new fully stocked forests following a regeneration event and only 29% were projected to regenerate a sizable component of either characteristic overstory species or commercially important species.

Abbreviations: NRS, USDA Forest Service, Northern Research Station; FIA, Forest Inventory and Analysis program; RI, Regeneration Indicator; OHES, Ozark Highland Ecological Section; MNF, Monongahela National Forest; AM, annual Allowable Mortality; EM, annual Expected Mortality; QRO, quantitative regeneration objective; DBH, diameter at breast height; QMD, quadratic mean diameter

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https://doi.org/10.1016/j.ecolind.2018.06.028
Received 10 January 2018; Received in revised form 24 April 2018; Accepted 13 June 2018

Please cite this article as: Vickers, L.A., Ecological Indicators (2018), https://doi.org/10.1016/j.ecolind.2018.06.028

1. Introduction

Successful forest regeneration is an essential component of sustainable forest management, yet achieving desirable regeneration outcomes can be difficult, unpredictable, and expensive (Kabrick et al., 2007; Loftis and McGee, 1993). Forest managers and policymakers need information on the likelihood of regeneration success before implementing regeneration treatments and policies to ensure long-term sustainability of forest ecosystems (Ferguson, 1984). Models that approximate the dynamics of the regeneration process are well-suited to provide such information but are scarce due to the expense and effort required for tracking individual seedlings through time at large spatial scales, as well as the difficulty of modeling complex regeneration dynamics (Beckage et al., 2005; Weiskittel et al., 2011). Models that provide short-term estimates of regeneration outcomes, e.g., up to 3 years, have high uncertainty because of the inherent variability of the regeneration process (Vickers et al., 2017). The degree of uncertainty increases with longer regeneration periods, and while some simulation models offer opportunities to incorporate that uncertainty into estimates, such tools are not fully developed in the eastern United States.

Despite these challenges, extensive research has been devoted to the complex dynamics of tree regeneration across many forest types and ecoregions, often with applications for development of silvicultural prescriptions for specific regeneration outcomes (Johnson et al., 2009; Smith et al., 1997; Tappeiner et al., 2015). This research has identified various factors that influence regeneration outcomes among species (Grubb, 1977). For naturally regenerating forests, the density, composition, and size of seedlings and small trees present in the forest understory before a releasing disturbance event (advance reproduction) strongly influence regeneration outcomes (Egler, 1954; Horn, 1974). For example, the relationship between stem size and survival is especially strong for several species and regions. The relationship has been described as a “U-shaped” distribution where mortality is more likely for seedlings and very large trees (Buchman et al., 1983; Fraver et al., 2008; Goff and West, 1975; Lorimer et al., 2001; Monserud and Sterba, 1999). The decrease in mortality risk with increasing size is steep for small trees, particularly in the first few years after germination because small seedlings are more vulnerable than adults to unfavorable conditions (Beckage et al., 2005; Franklin et al., 1987; Harcombe, 1987; Peet and Christensen, 1987).

The composition, structure, and abundance of advance reproduction are the product of complex histories and many antecedent influences prior to stand-initiation events. Prior to release, overstory density influences the density, composition, and structure of advance reproduction (Carvell and Tryon, 1961; Larsen et al., 1997; Schuler, 2004). Following release, residual overstory density influences growth and survival of advance reproduction (Oliver and Larson, 1996; Vickers et al., 2014). The influence of site productivity on advance reproduction attributes can also be strong (Bigelow and Canham, 2002; Kabrick et al., 2014; Latham, 1992) and persistent (Dey et al., 2009; Loftis, 1990a; Morrissey et al., 2008). Among other influential factors, the negative effects of over-browsing by *Odocoileus virginianus* (white-tailed deer) on reproduction density and composition has long been acknowledged (Leopold et al., 1947; Marquis, 1981). Waller and Alverson (1997) labeled *Odocoileus virginianus* a “keystone” herbivore due to their ability to affect the distribution and abundance of many species and modify community structure at multiple trophic levels. The impacts of continual over-browsing has long-term negative consequences for the establishment, growth, and survival of native forests (Côté et al., 2004; McShea et al., 1997; Nuttle et al., 2014; Rooney and Waller, 2003).

Whether the panoply of influential factors ultimately produce a ‘successful’ regeneration outcome or not depends directly on the forest manager’s regeneration management objectives (Stein, 1992). Forest managers have a variety of ecological, social, and economic factors to consider during the decision-making process (Messier et al., 2014; Puettman et al., 2008; Shifley et al., 2014; Wear and Greis, 2012). Consequently, quantitative definitions and explicit assumptions are essential to avoid misinterpreted, subjective, or inconsistent evaluations of regeneration success (Dey and Schweitzer, 2014; Stein, 1992).

Stocking charts and density management diagrams are essential silvicultural tools for quantifying available growing space and are useful for defining quantitative, scientifically supported targets and endpoints for regeneration success (Nyland et al., 2016; Smith et al., 1997; Weiskittel et al., 2011). For example, achieving a target of 30% stocking (989 trees·ha^{-1}) when quadratic mean diameter (QMD) is 7.6 cm will lead to full stocking within 10 years in upland hardwood (*Quercus/Carya*) forests based on Gingrich’s (1967) stocking chart. Consequently, many upland hardwood regeneration metrics adopt a 7.6 cm QMD endpoint, reached approximately 20 years following overstory removal because it is the earliest developmental point shown on the stocking chart (Dey et al., 1996, 1998; Sander et al., 1976, 1984; Weigel and Peng, 2002). Given local and regional differences in stand development patterns, these tools are usually developed independently for different forest types or site conditions.

Pre-harvest inventories of reproduction are important because advance reproduction is a primary regeneration source in many forest ecosystems. Several inventory-based evaluations have been developed to gauge the potential for advance reproduction to meet regeneration objectives (see Vickers et al., 2017; Weiskittel et al., 2011 for limited reviews). Such evaluations help foresters schedule harvests and triage silvicultural interventions to foster regeneration success by addressing whether there is enough competitive reproduction to meet a given regeneration objective. For example, McWilliams et al. (1995, 2015) specified a minimum reproduction count needed to ensure replacement of overstory trees following harvest or other stand-initiating disturbance. Reproduction counts were weighted to account for stem size, browse intensity, and site productivity based on a consensus of experts and recommendations from two regional silviculture guides (Brose et al., 2008; Marquis, 1994). Some evaluations explicitly consider spatial distribution within stands. Generally, existing inventory-based regeneration evaluation methods were developed for relatively small areas, a limited number of species, and specific regeneration objectives, and have not been used to address large forest landscapes.

The first objective of this manuscript is to describe an inventory-based method for evaluating the prospects of securing forest regeneration that can be applied across large regions ranging in size from thousands to millions of hectares of diverse forest ecosystems. The method facilitates the use of success criteria expressed as meaningful targets and endpoints for specific regeneration goals and objectives. This means that the inventory of tree seedlings and small saplings must at least meet the target number of stems desired for the future stand at the assumed endpoint in time. Otherwise, the likelihood of regeneration failure is immediately evident, assuming advance reproduction is the only reproduction source considered. If the density of advance reproduction exceeds the target, it may be unrealistic to assume all will survive to the endpoint because mortality is pervasive during the regeneration process and early stand development (Drew and Flewelling, 1977; Gingrich, 1967; Oliver and Larson, 1996). Building a flexible budget for reproduction mortality provides an indication of regeneration security. The annual Allowable Mortality (AM) approach estimates the amount of tree seedling mortality that can be afforded and still meet regeneration objectives. The second objective is to demonstrate the method for a range of quantitative regeneration objectives (QROs) for two different study areas.

2. Methods

2.1. Case study areas

The Ozark Highland Ecological Section (OHES) is located in the Central Interior Broadleaf Forest Province that spans 36–39° (N) latitude and 90–95° (W) longitude or nearly 12 million hectares of forestland across five states (Miles, 2017), the majority of which is in Missouri (Cleland et al., 2007). The remaining forestland is found in Arkansas (17%) and Oklahoma (4%), with trace amounts (< 1%) in both Illinois and Kansas. The region is an unglaciated, predominately limestone dissected plateau with a hot continental climate with average annual temperatures ranging from 12 to 15 °C, frost-free periods of 140–230 days, and average precipitation from 96 to 124 cm (McNab et al., 2007; Wiken et al., 2011). Elevations range from 80 to 560 m with considerable relief up to 460 m. Ultisols and Alfisols with mesic or thermic soil temperature regimes and udic soil moisture regimes are most common.

Forest composition in the OHES is dominated by the *Quercus/Carya* forest-type group, which accounts for 82% of the forestland (Miles, 2017). *Quercus/Pinus* (7%) and *Ulmus/Fraxinus/Populus* (4%) are other relatively minor forest-type groups. Nine additional miscellaneous deciduous, coniferous, and mixed forest-type groups combine to occupy about 7% of the forestland in the region.

The Monongahela National Forest (MNF) occupies about 372,000 ha at approximately 38.5° (N) latitude and 80° (W) longitude and accounts for about 8% of the forestland in West Virginia. The MNF is located in the Central Appalachian Broadleaf Forest-Coniferous Forest-Meadow Province. The Northern Ridge and Valley and Allegheny Mountains are the two predominant Ecological Sections within the forest boundaries. The climate in the region is humid continental with average annual temperatures ranging from 7 to 16° C, frost-free periods of 125–235 days, and average precipitation ranging from 90 to 150 cm (McNab et al., 2007; Wiken et al., 2011). The climate in the Allegheny Mountains Ecological Section tends to be somewhat cooler and wetter than the Northern Ridge and Valley due, in part, to a rain-shadow effect. Elevations range from 90 to 1500 m with occasional high relief (900 m). The Allegheny Mountains are an unglaciated, maturely dissected plateau with bedrock consisting of shales, siltstones, carbonates, and sandstones. The Ridge and Valley is a diverse, unglaciated region of somewhat parallel valleys and ridges with sandstone cap rocks that resulted from extreme folding and faulting. Limestone, dolomite, shale, siltstone, and sandstone are among the common geologic materials in the Ridge and Valley. In both Ecological Sections, Inceptisols and Ultisols with mesic soil temperatures (or thermic in the Ridge and Valley) and udic soil moisture regimes are typical.

Forest composition of the MNF is dominated by two forest-type groups, *Acer/Fagus/Betula* and *Quercus/Carya,* which comprise 50% and 41% of the forestland, respectively (Miles, 2017). *Picea/Abies* (3%) and six additional miscellaneous deciduous, coniferous, and mixed forest-type groups contribute the remaining forestland in the MNF.

2.2. Source data

The data used for evaluating forest regeneration security came from the USDA Forest Service, Northern Research Station (NRS), Forest Inventory and Analysis (FIA) program, which is the only seamless and consistent forest inventory operating at scales from thousands to millions of hectares. The NRS-FIA inventory covers 24 states in the northern United States (Fig. 1). The core FIA inventory is collected on sample plots located randomly within cells of a systematic national grid of hexagons roughly 2428 ha in size (Bechtold and Patterson, 2005). The inventory of trees > 2.5 cm diameter at breast height (DBH) is collected on FIA's standard "Phase 2" sample plots using a cluster of four 7.3 m fixed-radius subplots. Each subplot also contains a 2.1 m fixed-radius microplot offset from the subplot center used for inventory of seedlings and saplings.

In 2012, NRS-FIA included new Regeneration Indicator (RI) measurements of tree seedlings and an assessment of local browse impacts (USDA Forest Service 2012). The measurements are nested within the core Phase 2 sample grid using a randomly selected 12.5% subsample, referred to as "Phase 2+" (McWilliams et al., 2015). RI protocols tally most reproduction at least 0.05 m in height by species and the following six size classes: 0.05–0.14 m (code 1), 0.15–0.29 m (2), 0.30–0.90 m (3), 0.91–1.49 m (4), 1.50–3.04 m (5), and ≥ 3.05 m (6). Heavy-seeded genera, i.e., *Carya*, *Juglans*, and *Quercus*, are not tallied until their root-collar diameter (RCD) is ≥0.63 cm.

The OHES and the MNF case study regions were selected to represent two different forest biomes and spatial scales (Fig. 1). FIA Phase 2 and Phase 2+ RI inventories were used to assemble a dataset to examine the likelihood of successful forest regeneration. The data were obtained from the online database (https://apps.fs.usda.gov/fia/datamart/) and included all inventory years publicly available from 2012 to 2016 at the time of download (April 7, 2017) The OHES dataset was comprised of 158 sample plots in Missouri and 6 in Illinois (RI are collected by only NRS-FIA, which excludes the Arkansas and Oklahoma portions of the OHES). The MNF dataset was made up of 14 plots in West Virginia.

Small saplings (DBH 2.5–5.1 cm) sampled as part of NRS-FIA core Phase 2 protocols located within Phase 2+ microplot boundaries were included as advance reproduction in the RI tally as additional stems in size class 6. Analyses were limited to "regeneration-eligible" microplots with no physical site restrictions or land use/management limitations that prevent the establishment of advance reproduction. An example of a physical restriction on a microplot is a rocky surface with little or no soil. Land use/management limitations where regeneration from advance reproduction is not a reasonable expectation include microplots that were recently regenerated, i.e., small size-classes and young age-classes or microplots containing at least one adult tree large enough to completely occupy the growing space based on Chisman and Schumacher's (1940) tree-area equation as parameterized by Gingrich (1967) for the Central States, i.e., 20 cm DBH.

2.3. Allowable mortality

The AM approach uses large-scale inventory data to examine forest regeneration security using a three-step process: (1) establish QROs that include measurable targets and endpoints; (2) estimate an AM rate for tree seedlings and small saplings, i.e., the amount of mortality that can be afforded and still meet the QROs; and (3) compare the AM rate to an Expected Mortality (EM) rate based on available literature for a similar period.

2.4. Establishing QROs

Regeneration management decisions are multi-faceted because objectives range from maximizing economic returns to sustaining native forest biodiversity. To address this, a hierarchical approach was used to represent increasingly specific requirements for the new stand. The particular objectives, targets, and endpoints are based on the best available science but are intended to serve only as representative examples. Establishing QROs requires: (1) a quantitative expression of a future targeted/desired stand condition, such as stem density, percent stocking, and species composition, and (2) an identifiable endpoint, i.e., a point in stand development/age for the future target stand condition. Targets should represent minimum thresholds supported by available science. Stocking charts, normal yield tables, growth models, management guides, and relevant literature are often available for many of the major forest-type groups and can help establish feasible objectives with science-based targets and endpoints that reasonably estimate the length of time required to meet various stand development thresholds.

2.5. Estimating AM

The approach for building a mortality budget for forest reproduction comes from classic economic theory for expressing the future value of a commodity (Fisher, 1930). Put simply, future value is expressed as initial value compounded annually at a rate of interest. Similarly, AM is an approximation of the maximum annual rate of mortality that can be

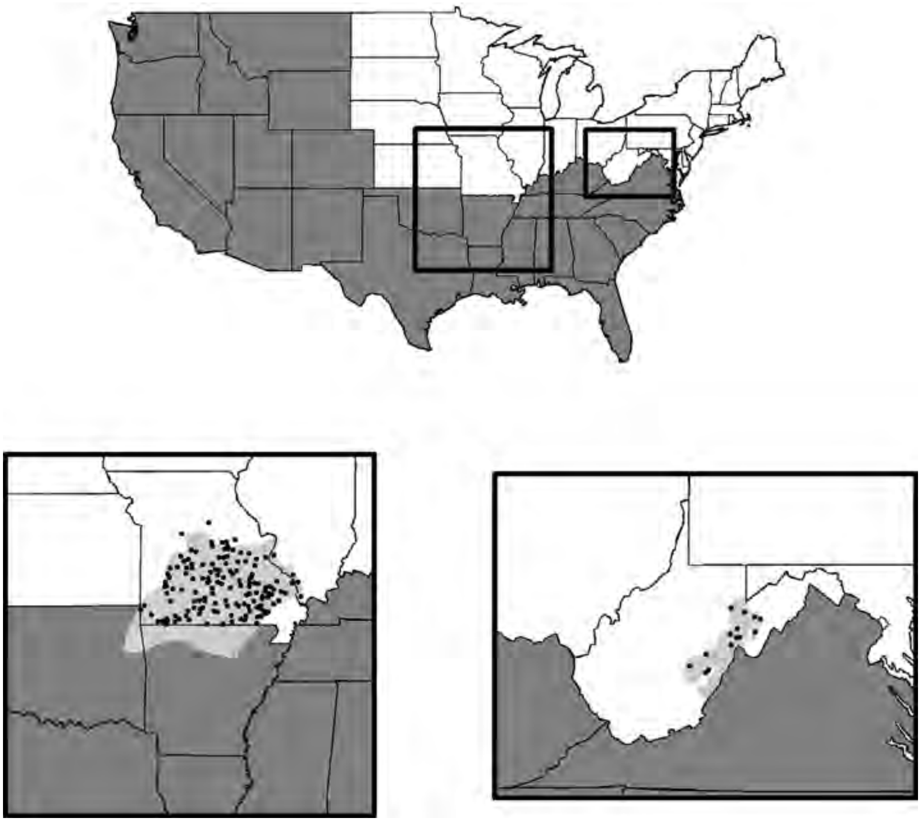

Fig. 1. Location of Midwest and Northeast NRS-FIA region (top, white) and approximate locations of RI inventory sample plots in the Ozark Highlands Ecological Section (n = 164) and Monongahela National Forest (n = 14) study areas. Boundaries (light grey) for the Ozark Highlands Ecological Section and Monongahela National Forest were obtained from the USDA Forest Service online at https://www.fs.fed.us/rm/ecoregions/products/map-ecoregions-united-states/# and https://www.fs.usda.gov/detail/mnf/landmanagement/gis/?cid=stelprdb5108081.

afforded among reproduction to meet the QRO target and endpoint. AM can be estimated using an algebraic re-arrangement of the future value formula as follows:

$$Survival \quad rate = \left(\frac{Target}{Inventory}\right)^{1/Endpoint} \tag{1}$$

$$Allowable \quad Mortality = 1 - Survival \quad rate \tag{2}$$

where *Survival rate* is the minimum annual survival rate required for the inventory to meet the target condition by the endpoint; *Target* is the number of desired future trees (future value); *Inventory* is the tally of advance reproduction (present value); *Endpoint* is the number of years (or n compounding periods) for the target to be met; and *AM* is the maximum annual mortality rate that can be afforded for the inventory to meet the target by the endpoint. If inventoried reproduction is less than the QRO target, *AM* is set to zero to reflect imminent failure to meet the regeneration objective.

2.6. Determining EM

The final step is to compare the AM rate to an EM rate for the same period described in the literature as ambient, background, inherent, intrinsic, marginal, or random mortality. The rates are commonly density-independent and have been published for many major forest types. Sources include scientific articles, management guides, normal yield tables, and growth models. Sander et al. (1976, 1984) reported an annual mortality rate of 1% during the first 12 years of stand development following clearcutting for the *Quercus/Carya* forest-type group. Fan et al. (2006) reported rates for various species groups in intermediate and suppressed canopy positions ranging from about 1% to 5%. Also notable is the Central States variant of the Forest Vegetation Simulator that generally predicts low annual rates of AM (< 1%) for individual small trees without competition mortality, though the final mortality rate used for simulation is a summation of all individual tree rates dispersed across all tree records based on other factors such as species and competitive position (Dixon and Keyser, 2008). In some cases, EM rates are not available for specific forest-type groups, but more general estimates may serve as useful substitutes. Keane et al. (2001) summarized that many existing models of forest dynamics (see Pacala et al., 1993), typically use a value of 1 to 2% to represent this source of random annual mortality. Where possible, it is preferable to consult EM rates applicable to small trees in young regenerating stands to maintain consistency with the regeneration period defined by the QRO endpoint.

Comparing the inventory-based AM estimate to the EM rate provides a qualitative indicator of regeneration security for the taxa under consideration. Three categories are suggested: “failure,” “insecure,” and “secure.” Failure is a special case that is assigned when reproduction inventory is < QRO target and is indicative of imminent failure to meet the regeneration objective. Insecure is defined as AM < EM and indicates that existing advance reproduction will likely fall short of the objective under normal conditions based on the evaluation assumptions that include ambient forest health. Secure is defined as AM ≥ EM indicating that there is enough advance reproduction to eventually meet the regeneration objective.

2.7. Reliability index: a mortality modifier

It is well known that many factors influence reproduction mortality (Franklin et al., 1987; Holzwarth et al., 2013; Waring, 1987). The AM budget provides a framework that can be applied across large, varied regions and adjusted to approximate trends that are known to influence mortality rates during the regeneration period, e.g., tree size (Buchman et al., 1983; Goff and West, 1975; Fraver et al., 2008; Lorimer et al., 2001; Monserud and Sterba, 1999). Most size-mortality relationships are parameterized using DBH and are not sensitive to size changes for stems < 1.37 m in height, which encompasses most reproduction. The size-mortality relationship for reproduction appears to be generalizable as height has been used as a proxy for diameter for naturally or

Table 1
Reliability indices by size of reproduction with large reproduction weighted more heavily based on the aggregate height hypothesis (Fei et al., 2006).

Size class	Size of reproduction		
Code	Height (m)	DBH (cm)	Reliability index
1	0.05–0.14	–	0.033
2	0.15–0.29	–	0.075
3	0.30–0.90	–	0.195
4	0.91–1.49	–	0.395
5	1.50–3.04	–	0.745
6	> 3.04	2.50–5.08	1.000

artificially established seedlings and is the most common size attribute for measuring reproduction (Brose et al., 2008; Marquis, 1994; Sander, 1972). The RI measurements include a tally of tree seedlings by six size classes, making it possible to incorporate a height-based mortality relationship into the AM calculation by weighting the *Inventory* component of Eq. (1).

Available empirical research on the height-mortality relationship for reproduction is limited. Generalized approximations can be substituted to improve projections when empirical mortality data are lacking. A simple generalized weighting scheme adopted from Fei et al.'s (2006) aggregate height hypothesis approximates the size-related differences in mortality rates among advance reproduction. The hypothesis postulates an equivalence in regeneration capacity across various structural permutations that yield the same aggregate (summed) height, e.g., 10 stems, each 0.1 m tall ≈ 1 stem, 1 m tall. Following this, standardizing stems across each size class based on size-class midpoints with a single stem in the largest size class (6) weighted as 1, yields a weighting factor, or "Reliability Index" for each size class (Table 1). This weighting scheme approximates a general trend where large reproduction has a higher survival rate than smaller reproduction. To clarify, the Reliability Index weights signify that it takes about 30 stems in the smallest size class (1) to have the same odds of surviving as a single stem in the largest size class (6). Similar size-based weighting schemes have been used to examine regeneration success and other factors can be incorporated if desired (see McWilliams et al., 1995, 2015).

2.8. Establishing QROs for the case studies

Three QROs representing common regeneration management needs were chosen to demonstrate the AM budget. The QROs range from broad to specific and typify real world objectives quantified by target stand conditions at desired endpoints. QRO1 stipulates that existing advance reproduction must have the capacity to produce a new, fully stocked stand regardless of species composition following release. QRO2 stipulates that existing advance reproduction of species commonly found in the overstory must have the capacity to become a sizable component of the new, fully stocked stand. QRO3 stipulates that existing advance reproduction for a single species or groups of species must have the capacity to meet taxa-specific goals.

The responsibility for choosing feasible regeneration objectives and meaningful criteria to benchmark those objectives is ultimately incumbent on managers (Dey and Schweitzer, 2014; Stein, 1992). The objectives, targets, and endpoints used were founded on available science and expertise, but they are intended to serve only as examples and were developed independently of the AM budget. Existing stocking charts, management guides, and relevant literature were used to define specific targets, endpoints, and EM rates for three forest-type groups of the case study areas: *Quercus/Carya*, *Querus/Pinus*, and *Acer/Fagus/Betula* (Table 2).

For *Quercus/Carya*, the target for QRO1 was 30% stocking, or 'C-line', at the earliest endpoint provided by Gingrich's (1967) stocking chart (QMD of 7.6 cm). Young stands at this stocking level should become fully stocked within 10 years (Gingrich, 1967). From the Gingrich (1967) stocking equation, the target equates to 989 trees·ha^{-1}. The 7.6 cm QMD endpoint generally occurs about 20 years following overstory removal (Dey et al., 1998; Sander et al., 1976) and is a common developmental endpoint for regeneration metrics and models in deciduous forests of the eastern United States (Dey et al., 1996; Sander et al., 1984; Weigel and Peng, 2002). An EM rate of 1.5% per year was chosen from a range of similar reported values (Sander et al., 1984; Shifley and Smith, 1982; Fan et al., 2006; Dixon and Keyser, 2008).

For *Quercus/Pinus*, the QRO1 target was also 30% stocking at a QMD of 7.6 cm, although a stocking chart specific to this forest-type group was not found. As a substitute, a weighted average of stocking chart values (1146 trees·ha^{-1}) was calculated from *Quercus/Carya* (989 trees·ha^{-1}, Gingrich, 1967) and *Pinus echinata* (1236 trees·ha^{-1}, Rogers, 1983) using reported maximum stand density index values for upland oak (570 trees·ha^{-1}, Schnur, 1937) and *Pinus echinata* (990 trees·ha^{-1}, Reineke, 1933) as the weights. To calculate endpoints and EM rates for *Quercus/Pinus*, the same weighted average procedure was used with values from *Quercus/Carya* above and other sources for *Pinus echinata* (Mattoon, 1915; Keyser, 2008; Shifley and Smith, 1982; Smalley and Bailey, 1974).

For *Acer/Fagus/Betula*, the target was 30% stocking at a quadratic mean diameter of 10 cm, or 162 trees·ha^{-1} (Leak et al., 2014; Solomon and Leak, 1969). This target condition typically occurs about 35 years following overstory removal (Solomon and Leak, 1969). An EM rate of 2% annually was used for *Acer/Fagus/Betula* (Spaeth, 1920).

QRO2 focuses only on overstory species and the targets are 33% of the total stand target from QRO1 for each forest-type group. Depending on the forest-type group, some species seldom reach the dominant canopy in mature stands. Furthermore, dominant and co-dominant overstory trees in naturally regenerated multi-species stands usually comprise only a fraction of the total number of trees in a stand. Kabrick et al. (2002) reported that only about one-third of all trees in several undisturbed mature stands in the OHES occupied overstory canopy positions. In a similar analysis of 213 NRS-FIA plots on the MNF, almost identical proportions were found for *Acer/Fagus/Betula* (31%, 95% CI: ± 4%) and *Quercus/Carya* (27%, 95% CI: ± 3%).

For *Quercus/Carya* and *Quercus/Pinus* of the OHES, reproduction of three genera were evaluated in QRO2 (*Quercus, Carya*, and *Pinus*) because these dominants have been found to comprise 95% of stand basal area (Kabrick et al., 2002). For *Quercus/Carya* of the MNF, *Quercus* and *Carya* along with nine associate species were evaluated for QRO2 because they were found to be the dominant overstory species on 213 plots and comprised 95% of overstory basal area. The associates were *Liriodendron tulipifera*, *Acer rubrum*, *Betula lenta*, *Tilia americana*, *Acer saccharum*, *Robinia pseudoacacia*, *Prunus serotina*, *Pinus strobus*, and *Fraxinus americana*. For the MNF *Acer/Fagus/Betula* group, reproduction from 14 species were evaluated for QRO2 as they were found to be the dominant overstory species, comprising 95% of overstory basal area and overstory trees: *Acer rubrum*, *Prunus serotina*, *Acer saccharum*, *Betula alleghaniensis*, *Picea rubens*, *Fagus grandifolia*, *Tsuga canadensis*, *Tilia americana*, *Betula lenta*, *Fraxinus americana*, *Liriodendron tulipifera*, *Quercus rubra*, *Magnolia acuminata*, and *Magnolia fraseri*. The same endpoints and EM rates from QRO1 were used for each forest-type group and location in QRO2.

For all forest-type groups and locations the target associated with QRO3 is the presence of at least 149 commercially valuable trees·ha^{-1}, as studies have shown 98–99% of the commercial value of a stand can be attributed to just 149–173 trees·ha^{-1} (Brose et al., 2008; Miller et al., 2007; Ward, 2009). For the OHES, only *Quercus* reproduction was evaluated for QRO3 because it dominates sawtimber markets in the region (Missouri Department of Conservation, 2016). For the MNF, reproduction from *Prunus serotina*, *Liriodendron tulipifera*, *Acer saccharum*, *Acer rubrum*, *Fraxinus americana*, and all *Quercus* species were

Table 2
Targets, endpoints, and Expected Mortality rates by quantitative regeneration objective (QRO) and forest-type group, Ozark Highlands Ecological Section and Monongahela National Forest.

Quantitative regeneration objective	Forest-type group	Target (trees·ha^{-1})	Endpoint (# of years)	Expected mortality (% per year)
QRO1	*Quercus/Carya*	989	20	1.5
	Quercus/Pinus	1146	20	1.2
	Acer/Fagus/Betula	989	35	2.0
QRO2	*Quercus/Carya*	327	20	1.5
	Quercus/Pinus	379	20	1.2
	Acer/Fagus/Betula	327	35	2.0
QRO3	*Quercus/Carya*	149	20	1.5
	Quercus/Pinus	149	20	1.2
	Acer/Fagus/Betula	149	35	2.0

evaluated in QRO3 as they are the most common and economically important taxa in the region (Appalachian Hardwood Center, 2017). The same endpoints and EM rates from QRO1 and QRO2 were used for each forest-type group and location in QRO3.

2.9. Building the AM budget

All of the calculations used to build the AM budget were done on a per hectare basis. First, a tally of advance reproduction from the RI data (including small saplings) for each microplot was computed using the Reliability Index weighting scheme. An average weighted tally was then computed across all microplots in the plot-cluster (up to 4). If a plot straddled multiple conditions, e.g., forest type or stand size, microplot averages were computed for each forested condition. Next, the average weighted tally for the plot was used to compute AM per hectare (Eqs. (1) and (2)) using the appropriate *Target* and *Endpoint* by forest-type group and QRO. AM was then compared to EM and the prospect of meeting the regeneration objective was categorized as failure, insecure, or secure under the assumption of immediate release. All analyses were conducted using R statistical software (R Core Team, 2017, version 3.3.3).

3. Results

The analysis of OHES samples for QRO1 resulted in an average AM of almost 5% (SE: 0.26%) for advance reproduction meeting the basic regeneration objective of stand replacement (Fig. 2, Table 3). The results for QRO2 using the same plots resulted in an AM of 3% (SE: 0.29%) indicating the ability to regenerate a sizable component of overstory species. The results for QRO3 show that the plots can afford about 4% annual mortality (SE: 0.36%) and still regenerate *Quercus*.

Seventy-six percent of the OHES plots for QRO1 were classified as secure, 17% as failure, and 7% classified as insecure. Fifty-seven percent of the plots analyzed for QRO2 were considered secure, leaving 43% as insecure or failure. For QRO3, 41% of the plots were classified as either failure or insecure compared to 59% classified as secure.

On average, the MNF sample plots analyzed for QRO1 were found to afford just over 1% (SE: 0.57%) annual mortality to meet the basic regeneration objective of stand replacement. The same plots can afford about 2% annual mortality (SE: 0.87%) and still regenerate a sizable component of overstory species (QRO2). When analyzed for QRO3, the plots can afford AM slightly over 1% (SE: 0.60%) and still regenerate commercially important species.

For MNF plots evaluated for QRO1, stand replacement was secure on 36%. The remaining 64% of the plots were categorized as failure indicating advance reproduction was insufficient for stand replacement. The results for QRO2 indicated 71% of the plots were either insecure or failure, leaving 29% secure to replace canopy species. Results for QRO3 were identical to QRO2 because the commercially important species are also the most common canopy dominants.

4. Discussion

Examining regeneration success and the adequacy of advance reproduction inherently depend on objectives and assumptions (Stein, 1992). Dey and Schweitzer (2014) highlight the importance of developing meaningful metrics to evaluate the status of restoration (or regeneration) activities and the potential difficulties in developing them. The first objective of this manuscript was to describe a flexible method for evaluating advance reproduction for large landscapes using available forest inventory data. As shown for the cases studies, this is achieved primarily by adjusting *Targets* and *Endpoints* (Eq. (1)). The ability to consider various regeneration objectives and the transparency required of QROs are strengths of the AM budget. While the example QRO structures used in the case studies may be broadly applicable, targets and endpoints chosen by end-users should consider more specific needs and objectives, as needed.

The opportunity to consider both single and multi-species objectives is another strength of the AM budget. As shown for the case studies, this is primarily achieved by filtering the *Inventory* component (Eq. (1)). Many existing regeneration evaluation methods were designed for application to a limited suite of species for relatively small geographic areas (e.g., Brose et al., 2008; Sander et al., 1984; Steiner et al., 2008). When evaluation needs meet the application criteria for existing peer-reviewed evaluation methods, their use is recommended. The specificity and scale of the underlying FIA data align well with the AM budget approach; however, as regeneration objectives increasingly include broader species assemblages and larger geographic areas, the limitations of existing methods become more constraining (Messier et al., 2014; Puettmann et al., 2008; Wear and Greis, 2012).

An additional strength of the AM budget is the ability to utilize multiple sources including existing literature, expert knowledge, and silvicultural guidelines to establish EM rates and weighting factors for inventories. When empirical mortality models are lacking, generalized approximations of mortality trends can be substituted. The Reliability Index used for the case studies is simply a generalized approximation of a size-mortality relationship where large reproduction is more reliable than small reproduction based on the aggregate height hypothesis (Fei et al., 2006). The accuracy of the specific weights is unknown. Such substitutions are at the user's discretion and should be carefully considered and acknowledged when reporting results.

Information for seedling and small tree mortality rates have been published but are relatively rare in the literature (Smith and Shifley, 1984; Shifley and Smith, 1982). Quantitative data may be available as components of larger investigations, but few published reports were found that featured these data or quantitative results. Many studies have found recent diameter increment is the best predictor of tree mortality (Buchman et al., 1983; Collet and Le Moguedec, 2007; Kneeshaw et al., 2006; Kobe et al., 1995). Woodall et al. (2005) used diameter and diameter increment to apply survival analysis to trees with DBH > 13.0 cm in Minnesota using FIA data.

Calibrating mortality models is both difficult and data-intensive

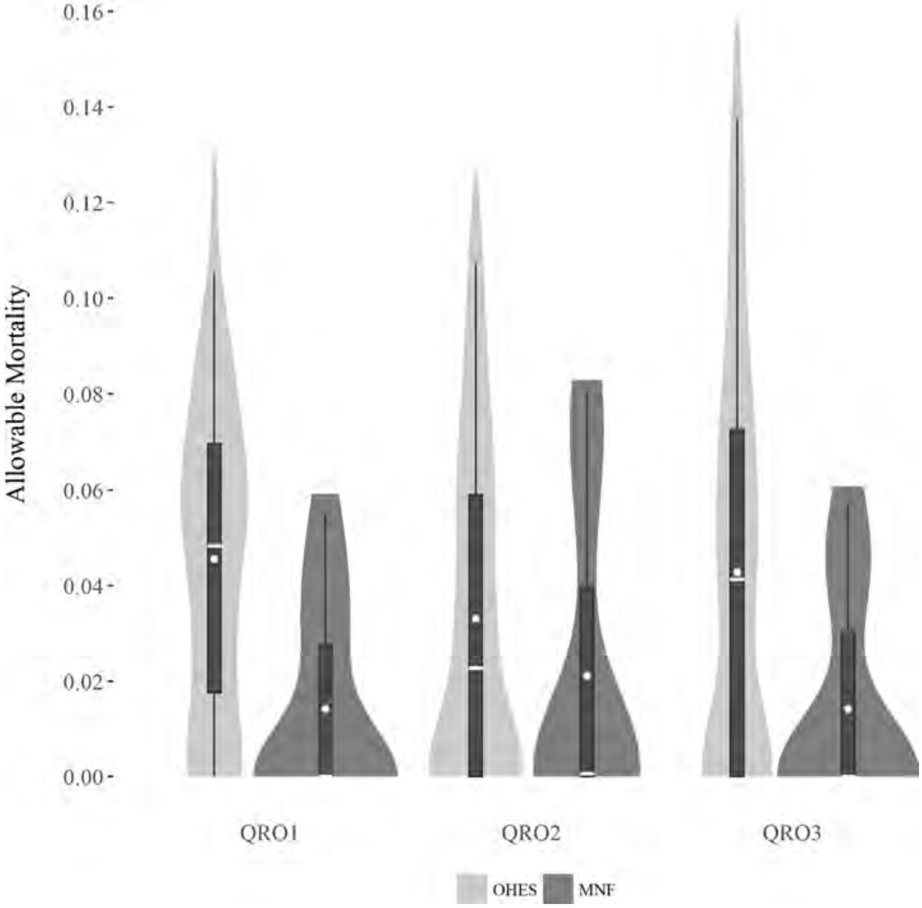

Fig. 2. Allowable Mortality (%) by quantitative regeneration objective (QRO), Ozark Highlands Ecological Section (light-grey fill) and Monongahela National Forest (dark-grey fill) study areas. Violin plots depict Allowable Mortality estimates with plot density (shaded areas), interquartile range (boxplots), 2.5th and 97.5th percentiles (whiskers), median (horizontal lines), and mean (points).

Table 3
Percent of samples by quantitative regeneration objective (QRO), study area, and regeneration security class, Ozark Highlands Ecological Section and Monongahela National Forest.

Quantitative regeneration objective	Study area	Regeneration security		
		Failure	Insecure	Secure
QRO1	OHES	17	7	76
	MNF	64	0	36
QRO2	OHES	36	7	57
	MNF	50	21	29
QRO3	OHES	38	3	59
	MNF	64	7	29

(Hawkes, 2000). Most depend on breast height diameter or growth trends derived from repeated measurement, but this limits their applicability for reproduction assessments of large landscapes (Beckage et al., 2005). The cost of the NRS-FIA RI data acquisition precludes permanently marking individual seedlings. This lack of re-measured data for seedlings in the NRS-FIA RI data limits opportunities for deriving new individual-tree statistical models of reproduction mortality. Increasing emphasis on monitoring forest regeneration indicators of changing climate and disturbance regimes will generate future datasets for improving mortality rate estimates (Cleavitt et al., 2014; Woodall et al., 2009).

Rather than develop an empirical model of regeneration dynamics, the AM budget leverages available science to gain insight into plausible regeneration outcomes for very large forested landscapes. The flexibility of the AM budget provides opportunities and advantages for robust broad-scale analyses, but tradeoffs must be considered due to the intricacies of species- and site-specific regeneration dynamics. Limitations to the AM budget largely result from promoting simplicity to limit the number of foundational assumptions required. One limitation is the inability to fully simulate the complex stand dynamics that occur in regenerating stands. Those dynamics result from both intra- and inter-specific differences in establishment, growth, mortality, growing space, disturbance type, and interactions with other influential factors. Though important, attempts to simulate those complexities fall into the realm of comprehensive regeneration simulation and are beyond the scope of this effort and the current state of available science.

As presented here, the AM budget examines advance reproduction but does not account for additional reproduction sources that may arise following disturbance, e.g., future germination from dispersed or stored seed and vegetative reproduction (stump sprouts) after future harvest. Depending on the regeneration strategies of local species, these additional sources of reproduction can be quite important. For example, in upland hardwood systems, stump sprouting is understood to be important for many species and estimates of sprouting probabilities have been published for several (Dixon and Keyser, 2008; Keyser and Loftis, 2015; Keyser and Zarnoch, 2014). For some species, stump sprouting will likely be the primary reproduction source following removal of adults. The AM budget can incorporate additional reproduction sources by adding expected contributions to the reproduction cohort into the *Inventory* component of Eq. (1). The Reliability Index accommodates additional weights or modifiers to reflect differences in the various sources of reproduction. Using additional sources requires explicit assumptions for proposed management activities as well as empirically derived quantitative models for sprouting probabilities and expected seed establishment (or their approximations). For example, when using FIA data this would require “digital stand marking” on the larger Phase 2 FIA plots to quantify the number and size of both cut stumps and expected residual stems to estimate potential stump sprouting and residual seed production via existing models or approximations along with the expected contributions of the seedbank to the regeneration cohort.

Resource limitation, primarily due to prolonged understory inhabitance, can be a considerable source of mortality for seedlings and saplings (Kobe et al., 1995; Loftis, 2004; Wycoff and Clark, 2002). By not explicitly accounting for the influence of management activities and inter-specific differences in stress tolerance on reproduction mortality, the AM budgets and EM values for the case studies assume that reproduction in the inventory will be immediately released. If evaluation needs include management activities that do not provide immediate release, incorporating inventory weights that reflect inter-specific differences or other modifications may improve projections. Dixon and Keyser (2008) provide species-specific mortality modifiers used to reflect species differences in shade tolerance. Several alternative shade tolerance delineations have also been proposed that could be adapted to include additional species (Niinemets and Valladares, 2006; Saunders and Arseneault, 2013).

The second objective of this manuscript was to demonstrate applications of the AM budget for a range of example QROs using NRS-FIA RI data for the study areas. As shown in the results, the AM budget can be used to examine a diverse suite of regeneration objectives that includes multiple and varying species across broad and varying scales. Projections showed that successful stand replacement (QRO1) seems likely in the OHES but tenuous for the MNF. The comparatively lower likelihood of successfully replacing common overstory species (QRO2) for both regions is consistent with several reports that shorter-statured species that do not achieve high-canopy position are often a large component of regenerating cohorts (Brashears et al., 2004; Vickers et al., 2017). *Quercus* is both the dominant overstory and commercial species in the OHES. Results for QRO3 suggest that regenerated stands are more likely than not to contain enough *Quercus* from advance reproduction alone to maintain their commercial potential. In general, difficulties regenerating *Quercus* tend to be less frequent in the OHES compared to many other upland broadleaf forest communities in the eastern United States (Johnson et al., 2009).

The ability to consider multiple objectives is not only important in providing flexibility for applications across large and varied regions but also for opportunities to assist stand-level management decisions. The approach used here should be useful for large-scale inventories that have compatible data. Use of multiple QROs with individual stand inventories can help identify where additional silvicultural interventions are required to ensure regeneration success. Silviculture directs the regeneration process, both in fostering the initial establishment of reproduction and its timely release to promote continued development (Dey, 2014; Loftis, 2004; Nyland et al., 2016; Smith et al., 1997). Where regeneration difficulties are expected, forest managers must consider treatments that foster the establishment of more abundant and reliable reproduction prior to overstory release (Brose et al., 1999; Loftis, 1990b; Sander, 1972), such as enrichment planting (Johnson et al., 2009). Site preparation treatments can also be used to improve seedbed conditions and/or reduce the influence of competing vegetation (Löf et al., 2012).

Within the OHES, reproduction density may be improved in dense, fully stocked mature stands by treatments that temporarily create openings in the canopy by reducing overstory stocking below approximately 60%, i.e., B-Line levels (Dey et al., 2017; Gingrich, 1967; Johnson et al., 2009). Treatments that promote desirable regeneration in one region may not necessarily work as well in others, as has been demonstrated by research on the MNF (Schuler and Miller, 1995). In some regions, overstory reductions may promote interfering vegetation and exacerbate regeneration difficulties (Brose et al., 2008; Leak et al., 2014; Royo and Carson, 2006). The beech bark disease (BBD) complex that has severely altered *Fagus*-inhabited forests in the northeastern United States by killing mature trees and triggering the formation of dense 'beech-brush' thickets from prolific root sprouting is a prime example (Houston and O'Brien, 1983; Mize and Lea, 1979; Ostrofsky and McCormack, 1986). *Fagus* reproduction may impede successful regeneration of associate species, becoming an undesirable regeneration component because of its continued disease susceptibility. *Fagus* is not common to the OHES but is found throughout the MNF. Removing *Fagus* from the QRO2 for the MNF reduced the odds of successfully replacing the overstory canopy composition by half (29–14%). It is unlikely that stands with dense interfering vegetation, high browse pressure, or those with inadequate advance reproduction after initial overstory reductions will be remedied by canopy release and alternative silvicultural treatments may be needed. In some cases, a reconsideration of regeneration objectives may be the only option.

Targets for the case study QROs were chosen as minimum thresholds that are consistent with each respective objective and should be used with caution. Periodic monitoring of all regenerating stands during the regeneration phase of development is recommended to ensure successful development trajectories are maintained. Establishing enough desirable reproduction to eventually fully occupy available growing space is a pre-requisite for successful canopy recruitment, but it is not necessarily sufficient given the complex growth dynamics in developing stands (Dey, 2014; Vickers et al., 2014). In some cases, silvicultural interventions may be needed to maintain desirable species composition in stands with notable competition from less desirable species and invasive plants (Dey et al., 2009; USDA Forest Service, 2017; Ward, 2009).

The method described fills a technological gap and makes it possible to utilize NRS-FIA RI data to gain valuable insight into regeneration outcomes for individual species and assemblages across large forested landscapes. This provides information for NRS-FIA forestland by addressing geographic areas that range from hundreds of thousands to millions of hectares. Because the method is based on inventory data, per hectare summary statistics based on plot sample sizes can be computed easily. This means that standard inventory expansion factors can be used to conduct analyses at the plot-, gap-, stand-, or landscape-scale using various plot groupings. This provides opportunities to examine and compare regeneration trends across diverse management regimes and ecological regions. The direction and strength of ecological relationships that may explain trends can be investigated using other FIA attributes, e.g., overstory density, site productivity, browse intensity, and ownership.

Efforts to examine regeneration trends across the entire 24-state region where RI data are collected are logical research extensions. This would synthesize available literature and the experiences of regional experts to develop meaningful regeneration objectives for forest biomes of interest. Additional research to investigate relationships between the probability of regeneration success and underlying causal factors would further inform regeneration management efforts.

Declarations of interest

None.

Acknowledgements

The authors appreciate the efforts of FIA field crews and staff. This work was supported by the USDA Forest Service Northern Research Station Forest Inventory and Analysis (Cooperative Agreement Grant Number 15-JV-11242311-090 [University of Missouri and USFS]).

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