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Spatial modeling and inventories for prioritizing investment into oak-hickory restoration

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ABSTRACT

Oak (*Quercus* spp.) and hickory (*Carya* spp.) forests in the eastern United States provide a host of ecosystem services as their mast are prized by wildlife, the timber is a valued commodity, and they are generally more tolerant of extreme weather events under a changing climate. They are, however, undergoing a severe decline in prominence throughout the region, yielding to more mesic and shade-tolerant species, largely red maple (*Acer rubrum*). Two decades of research in Ohio have shown that silviculture and/or natural disturbances that reduce understory shade during seedling establishment and early growth, followed by canopy opening and competition management through prescribed fire and partial cutting, can encourage oak and hickory regeneration, most successfully on drier ridges and south- and southwest-facing slopes. We employed an ecological classification and mapping approach to prioritize areas across a 17-county region (~22,000 km^2) that may be more receptive, and thus more cost effective, to successful oak regeneration following silvicultural treatment. The ecomapping effort was comprised of two parts; a GIS model of the terrain, and a stand inventory of current vegetation condition coupled with the SILVAH decision-support system to recommend needed silvicultural treatments. The GIS model is based primarily on topography as vegetation patterns in the project area are largely driven by landscape position and soil moisture regimes. It uses transformed aspect, slope angle, topographic position index, and slope position as inputs to define six classes of landtype phases: ridge, southwest upper slopes, southwest lower slopes, northeast upper slopes, northeast lower slopes, and bottomland. The first three and following two classes, respectively, were hierarchically nested to form Dry Oak Forest and Dry-mesic Mixed Oak Hardwood Forest classes at the landtype level. Dry Oak Forests require the least silvicultural intervention to sustain or restore oak, while the other two landtypes normally require serious intervention to sustain oak into the future. To determine whether sufficient stocking is present for adequate regeneration, we use forest inventory data to represent current vegetation conditions including both overstory and understory stocking. Overall, these tools allow managers to identify 'zones of investment', i.e., those stands with the bulk of the area in the Dry Oak Forest landtype and with some level of advance oak regeneration, which will have a greater likelihood of growing into oak-dominated stands with minimal investment of scarce funding resources.

1. Introduction

1.1. Background

Oaks (genus *Quercus* L.) of eastern North America are a foundational species in our forests (Hanberry and Nowacki, 2016). Forests dominated by oaks are important ecosystems for many faunal assemblages, from birds and small mammals, to species such as white-tailed deer (*Odocoileus virginianus*) and black bear (*Ursus americanus*) (McShea and Healy, 2002; Dey et al., 2010). The importance of oaks goes much beyond acorn production, as numerous organisms directly or indirectly use other live and dead materials of the tree. For example, birds have been found to be more abundant and diverse in oak-dominated stands than in maple-dominated stands, most likely as a result of the presence of mast and differences in the arthropod prey, growth form, and leaf architecture that facilitates the way in which birds perceive, maneuver,

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and obtain food in forest habitats (Rodewald and Abrams, 2002; Wood et al., 2012). Tallamy and Shropshire (2009) found that oaks supported the greatest Lepidopteran richness (more than 500 species in the mid-Atlantic region of USA), an important food source for birds (Robinson and Holmes, 1982). Oak litter decays slowly and may provide more cover and increased prey availability, which is important for ground-foraging species (Fox et al., 2010) such as birds and amphibians. Oaks also provide vital economic resources via the timber industry, and is the species most removed from eastern US forests. For example in one typical hardwood state, Ohio's timber industry creates thousands of jobs, and in 2012 contributed $287 million in products (Coronado et al., 2014), with much of the value coming from oak-hickory forests (Coronado et al., 2014; Duval et al., 2014).

Because oak-hickory forests have been shown to be ecologically and economically important, the "oak regeneration problem" is one of the most important issues in the Eastern Deciduous Forest (Sutherland and Hutchinson, 2003; Johnson et al., 2009; Dey, 2014). Failure of oaks to regenerate after a canopy disturbance is primarily caused by a lack of larger and thus more competitive oak seedlings and saplings relative to other species in the understory, or failure to provide timely release of competitive seedlings when they exist (Loftis, 2004). This condition of oak (and hickory) being overstory dominants but poorly represented in the understory is evident in current Forest Inventory and Analysis (FIA) plot data for a 17-county region in southeastern Ohio (Fig. 1). Currently oak-hickory comprises 33.6% of stems > 15" DBH, but only 7.5% of stems 1' tall to < 3" DBH, the latter a classic signature of the sapling bottleneck incurred by oak in shaded conditions (Nowacki and Abrams, 2008). Under competition for light, many small saplings and especially seedlings < 1' tall linger and eventually die. Further, FIA data for Ohio between 1968 and 2011 show a decline of the oak proportion of the timber resource from 38 to 22 percent (Widmann et al., 2014). Maples and other shade-tolerant species currently dominate the smaller size classes (Fig. 1), and are increasing at a rate that is nearly four times their harvest rate, while white oak (*Quercus alba*) is being harvested at a rate exceeding growth (Widmann et al. 2014).

Silvicultural interventions are often needed to increase the competitiveness of existing oak seedlings, or create conditions in which new seedlings can establish strong root systems without being overwhelmed by aboveground growth of competitors (Brose et al., 1999). There is now a robust body of research that identifies effective silvicultural treatments to increase the probability of successful oak regeneration. Two decades of research in Ohio have shown that silviculture treatments that reduce understory shade during seedling establishment and early growth, followed by canopy opening and competition management through prescribed fire and partial cutting, can encourage oak and hickory regeneration, most successfully on drier ridges and south- and southwest-facing slopes (Iverson et al., 1997, 2008, 2017a; Hutchinson et al., 2005b, 2012). Prescribed fire, partial harvesting, herbicide application, and herbivore exclusion can all improve oak regeneration, if applied at the right time, at the right place and at the right frequency and/or intensity (Brose et al., 2008; Johnson et al., 2009; Iverson et al., 2017a). When appropriate conditions are met (e.g., drier positions with advance oak regeneration), these 'zones of investment' for prioritizing silvicultural treatments have been shown to increase the regeneration capacity for oaks. In contrast, areas not meeting criteria for the 'zones of investment' (e.g., mesic sites with little or no oak advance regeneration) are ill suited for silvicultural treatments aimed at oak regeneration based on limited available resources.

Meanwhile, prospects for oak regeneration may be changing as the climate warms (Wuebbles et al., 2017), and fire and drought frequency and intensity increase (Clark et al., 2016; Wehner et al., 2017). The climate is changing in a way that could be more favorable for oak-hickory forests and less so for mesic species, and therefore it is important to maintain oak-hickory stands to take advantage of those changes when they come. Even though many of the climate models show an increase in precipitation over the next decades in the eastern US, the additional precipitation trends so far, and expected in the future, are primarily expressed through more intense events and more concentrated in later winter and spring (Wuebbles et al., 2017). Simultaneously, the dramatic increase in heat (see Heat Index, Matthews et al., 2018), with its influence on the monthly Palmer Drought Severity Index (PDSI), creates a very large increase in the Cumulative Drought Severity Index (CDSI, based on 30 years of monthly PDSI) by century's end, especially under a scenario of continued high emissions (see CDSI, Matthews et al., 2018). For example, much of Ohio could have 80–100 *additional* days of maximum temperature exceeding 30 °C by 2100 under the high emissions scenario. These conditions would substantially increase the frequency and intensity of droughts according to

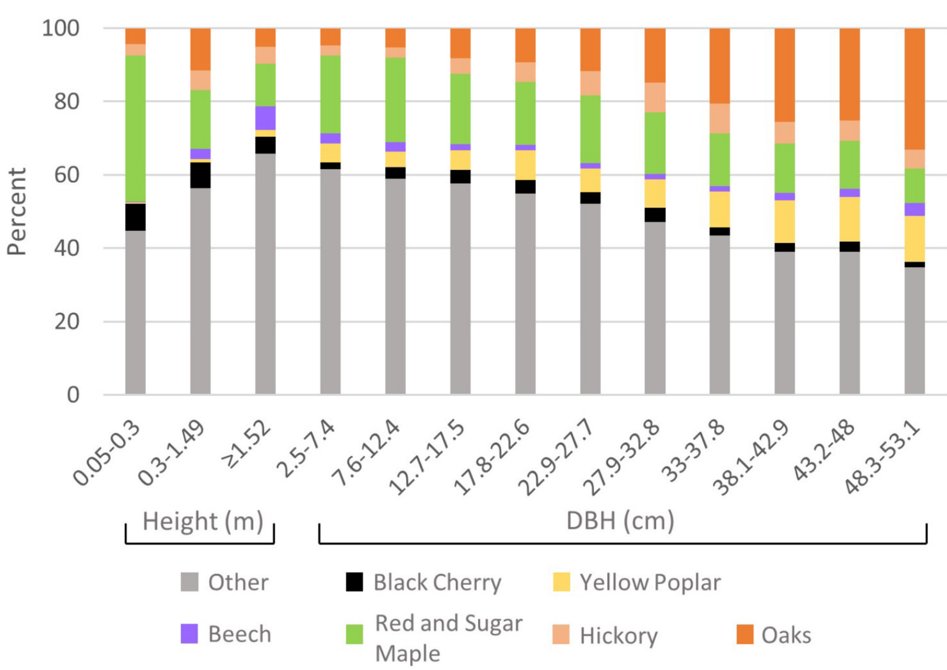

Fig. 1. Species prominence by size class.. Percent of total number of seedlings, live saplings, and dominant/codominant growing-stock trees (adults) for select taxa in the 17-county region of southeast Ohio, 2007–2016. The first three bars represent heights and remaining bars are dbh in cm. Seedling estimates are based on forested Phase 2-plus sample plots for 2012–2016. Sapling and tree estimates are based on forested Phase 2 plots for 2007–2011. Select taxa are those with the most above-ground biomass for all trees. Sampling errors are high because of relatively small numbers of samples. Besides oaks (*Quercus* spp.), yellow poplar (*Liriodendron tulipifera*), black cherry (*Prunus serotina*), red maple (*Acer rubrum*), sugar maple (*A. saccharum*), beech (*Fagus americana*), and hickory (*Carya* spp.), and 'other' species are graphed. The 'other' class is made up of 63 species including, in decreasing importance of basal area: white ash (*Fraxinus americana*), American elm (*Ulmus americana*), sassafras (*Sassafras albidum*), bigtooth aspen (*Populus grandidentata*), eastern white pine (*Pinus strobus*), Virginia pine (*P. virginiana*), American sycamore (*Platanus occidentalis*), black locust (*Robinia pseudoacacia*), slippery elm (*U. rubra*), and black walnut (*Juglans nigra*). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the CDSI, and is a continuation of a trend already documented for the period 1960–1986 vs. 1987–2013 (Peters et al., 2014, 2015; Matthews et al., 2018). These conditions are expected to favor most oaks and hickories because they are physiologically more competitive under such conditions (Brose et al., 2014; Butler et al., 2015; Iverson et al., 2017b). It is therefore incumbent upon society and forest managers to work to sustain oaks and hickories so that adequate supplies of propagules, safe sites, and migration corridors are available into the future.

Landownership patterns in the region pose another challenge for landscape-scale oak restoration. The area of focus in this study, southeastern Ohio, contains 67% of the forest resource in the state, including 17 state forests and the state's only national forest. Federal and state lands make up only 23% of the land base in the study area. Seventy-seven percent of the forest resource resides in family-owned woodlands with an average parcel size of 17.3 acres (Ohio_Division_of_Forestry, 2010b) and fewer than 12% of private forest ownerships in Ohio are covered by a written management plan. Thus, there is a substantial mismatch between the sophisticated silvicultural actions required to ensure oak regeneration and the actual level of management planning (Butler et al., 2016). In addition, spatially discontinuous ownership patterns decrease management efficiencies for willing landowners.

When public land ownership is limited and fragmented, landscape-level outcomes require the collective effort of land management actions across a spectrum of land ownerships, including federal, state, non-governmental organizations, and private land holders. Each of the major public land management agencies in Ohio has identified sustaining the oak resource as a principal objective, including the Wayne National Forest (USDA_Forest_Service, 2006), Ohio Division of Forestry (Ohio_Division_of_Forestry, 2010a), and the Ohio Division of Wildlife (Ohio_Division_of_Wildlife, 2015), and recognized the southeastern portion of the State as a high-priority landscape. Each entity understands the downward trends of oak on the landscape, the factors influencing those trends, and the complexity of management interventions that are required to reverse them. Thus, in 2008, the Ohio Interagency Forestry Team was established by the US Department of Agriculture (USDA) Forest Service, USDA Natural Resources Conservation Service, and the Ohio Department of Natural Resources Division of Forestry to increase the efficiency and effectiveness of public interventions to sustain the oak resource in southeast Ohio. This paper, in part, reports on work to help achieve that objective.

In 2015–2017, the team received support through a national restoration initiative sponsored by the Chiefs of the Forest Service and Natural Resources Conservation Service for collaborative oak management in southeastern Ohio. This restoration effort focuses on 17 counties in the Southern Unglaciated Allegheny Plateau Section of Ohio (Cleland et al., 2007) and is designed to coordinate the inventory, monitoring, silviculture, and management of oak-hickory forests. The team is working to increase the impact of government programs by pooling efforts toward the problem. In doing so, the team hopes to foster both natural resource managers and family woodland owners to understand the barriers and see their own connections to the larger landscape.

The SILVAH decision support system (https://www.nrs.fs.fed.us/tools/silvah/) uses a strategic inventory to identify the abundance and spatial distribution of various desirable seedlings of known competitive status and the barriers to their success. At the heart of SILVAH are silvicultural guidelines for reducing barriers to regeneration and fostering growth or release of desirable oak seedlings. SILVAH organizes these potential silvicultural interventions and links them to inventoried conditions in the forest overstory and understory at the forest stand level. These interventions may be costly, as they require advance inventory of overstory and understory conditions and careful timing of treatments to stages of oak forest and seedling development. The SILVAH system specifically recognizes that the probability of successful oak regeneration increases on xeric, low-fertility sites and decreases on mesic high-fertility sites where oak reproduction is recalcitrant (Brose et al. 2008, Johnson et al. 2009). For example, research in southern Ohio shows that partial cutting or other canopy opening disturbances and repeated prescribed fires greatly reduced midstory competition from shade-tolerant saplings and increased the abundance and competitive position of oak-hickory advance reproduction on dry and intermediate sites, but to a much lesser degree on mesic sites, as classified by the Integrated Moisture Index (IMI); IMI maps long-term moisture regimes based on derivations from digital elevation models and soil water holding capacity (Iverson et al., 1997, 2008, 2017a). SILVAH provides decision charts at the stand level for management, predicts success in perpetuating oak forests (Brose et al., 2008), and has been adopted by state and federal agencies in the Central Appalachian region to assist oak management, including the recommendations of silvicultural treatments based on levels of oak regeneration stocking and the abundance of interfering vegetation. However, it was apparent that the individual stand approach utilized by SILVAH needed to be coordinated at the landscape scale (an aim of this project) to truly make an impact on the overall downward trends for oak.

1.2. Objectives

Our overall objective was to provide a spatially informed planning tool that would help identify and prioritize silvicultural treatments at the landscape scale and ultimately inform zones of management investment which target silvicultural interventions in the areas most likely to yield positive results toward the maintenance or restoration of mixed oak forests. Prior research has shown these areas to be located on the driest portions of these landscapes.

The variables that drive competitive relationships between oak seedlings, and other, usually more shade-tolerant but less drought-tolerant species, are strongly associated with landscape position, i.e., landtypes and landtype phases. Accordingly, silvicultural strategies aimed to increase the competitiveness of oak advance reproduction will likely differ, and require more severe intervention with increasing moisture, among landscape positions to achieve the desired outcomes. Thus, the objectives of this project were:

- To develop a methodology to map landtypes and landtype phases using an ecosystem classification approach across a 17-county region of southern Ohio.
- To test the association of mapped landtypes and landtype phases with current oak composition.
- To link oak regeneration potential and silvicultural recommendations via the SILVAH system with mapped landtypes and landtype phases to facilitate cross-boundary, landscape-scale strategies for sustaining oak forests.

2. Methods

2.1. Study location

The study location comprises 17 counties (146,600 sq km) in southeast Ohio, USA (Fig. 2). It forms a large portion of the Southern Unglaciated Allegheny Plateau Section of the Eastern Broadleaf Forest Province (Section 221E of the Ecoregions of the United States (Bailey, 1980)), a highly dissected (but with total relief only 278 m within the region), unglaciated region immediately south of the maximum extent of past glaciations. The highly weathered soils are derived from sandstones and shales of Pennsylvanian age. It is ~64% forested, a species rich region, a home to 75 species of trees (Prasad et al., 2007), and primarily classified as oak-hickory forest type (https://www.fia.fs.fed.us/library/maps/docs/USForest_fullview.gif). The climate of the region is influenced by its highly dissected topography, where micro- and mesoclimate variation are greater than macroclimate variation within this region. Mean annual temperature for the region is 11.4 °C (range: 10.2–12.8) and mean annual precipitation is 87 cm (range: 81–96),

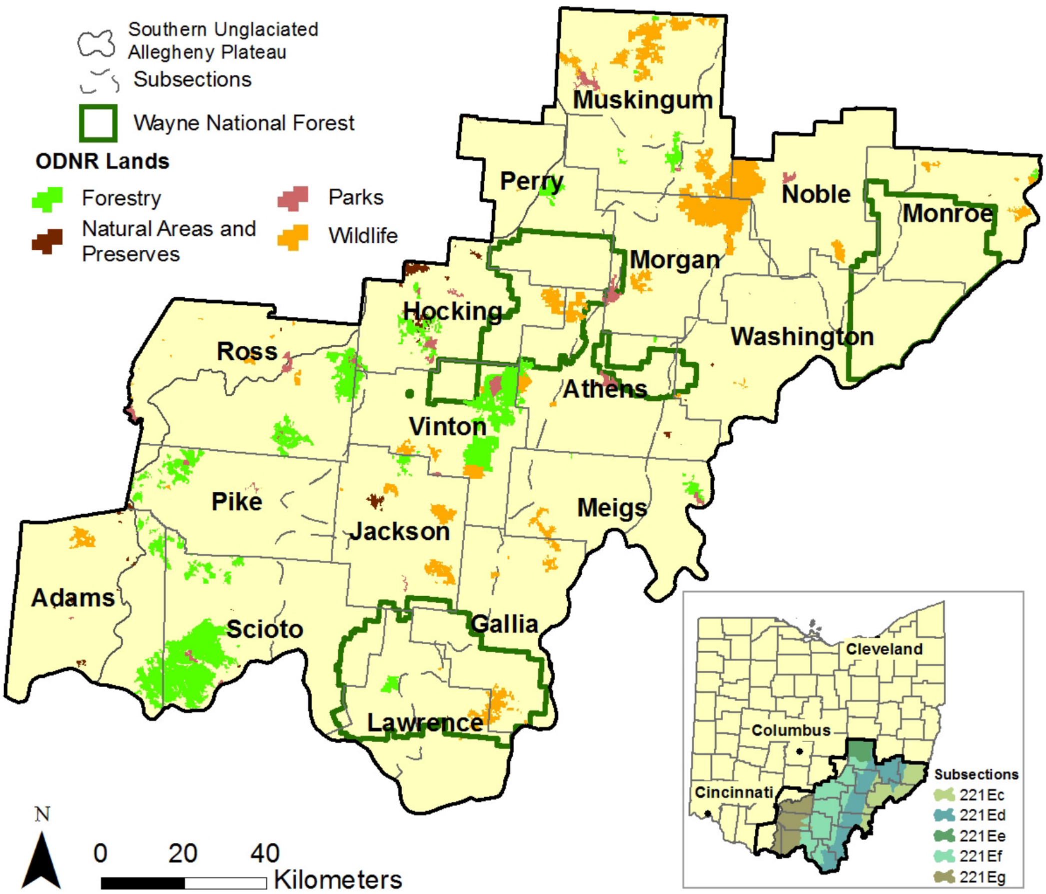

Fig. 2. State of Ohio and the 17-county region of study in southeastern Ohio. Also presented are the locations of federal US Forest Service land and State of Ohio land. Northern Athens County hosts the location of the Bailey's Project Area, represented at high resolution for Figs. 3,4 and Online Supplement Figs S1–S8. The inset map shows the study area within Ohio and the ecological subsections for 221E (221Ec, d, e, f, g) within the 17-county study region.

according to PRISM climate data (Daly et al., 2008).

Prior to Euro-American settlement (ca. 1800), land surveys indicated that the region was almost entirely forested and oaks and hickories were dominant (Gordon, 1969). White oak (*Quercus alba*) was particularly abundant, comprising more than 30% of survey "witness" trees (Dyer, 2001). During European settlement, most forests were cut and converted to agricultural fields or pasturelands. Forests were retained on topographically rugged areas, being repeatedly cut-over for industrial uses, especially for charcoal iron production and railroad and mine timbers (Stout, 1933; Williams, 1987). Surface and underground mining for coal has affected over 230,000 ha in Ohio (Lorenz and Lal, 2007), and much of that land remains unreclaimed (e.g., 135,650 unreclaimed abandoned mines remain; (Mishra et al., 2012), or was excessively compacted during reclamation, preventing adequate tree root penetration and ensuring a poorly forested future. The rate of forest loss was especially rapid from 1850 to 1880, when most of the counties in the study area went from being > 60% to < 35% forested (Leue, 1886; Trautman, 1977). Fires were frequent (< 10 year return interval) in regenerating forests from ca. 1870 until fire control became effective in the 1930s (McEwan et al., 2007; Hutchinson et al., 2008). With agricultural abandonment, the decline of industrial exploitation, and wildfire suppression (and ensuing mesophication) over the first half of the Twentieth Century, forest cover has returned to or exceeded ca. 1850 levels in most of the counties (Leue, 1886; Ohio_Division_of_Forestry, 2010b). Unlike some other areas in the central Appalachians, deer browsing pressure in southeastern Ohio is generally low and does not have a major impact on tree regeneration outcomes (Apsley and McCarthy, 2004).

2.2. Ecological classification and mapping (ECOMAP)

The National Hierarchical Framework of Ecological Units forms the basis of terrestrial ecological unit inventory for the U.S. Forest Service (Cleland et al., 1997; Winthers et al., 2005). It is a nested, 8-tier, hierarchical system that allows the classification, mapping, and description of ecosystems from global (millions of square miles) to site level (< 100 acres). In the 1990's a large field effort was conducted to develop an ecological classification system for the Wayne National Forest (Hix and Pearcy, 1997; Pearcy et al., 1999); the project did not, however, include mapping of the landtypes and landtype phases. This mapping need formed the impetus of this project. The creation of landtype and landtype phase maps allowed the opportunity to identify and define zones of optimal (or marginal) oak investment. The primary data needed for this effort to model oak investment zones was a digital elevation model (DEM) at 10 m resolution, obtained from the Ohio Environmental Protection Agency Division of Emergency and Remedial Response. Derivatives of the DEM used for modeling were all generated within ArcGIS, and each of the derivatives, or intermediate products necessary for the final products and described below, are represented in a flowchart (Fig. 3), and displayed for one portion of the study area in online supplement Figs S1–S8.

Aspect was transformed to a 0–2 scale according to Beers et al. (1966), where 2 are cool, NE slopes and 0 are warm, SW slopes. Slope angle was used to designate flat areas (< 15% slope, e.g., valley bottoms and ridge tops).

Topographic position index, or TPI (Jenness et al., 2011), was used to identify slope positions. It is simply the difference between the elevation value of a focal cell and the average elevation of the

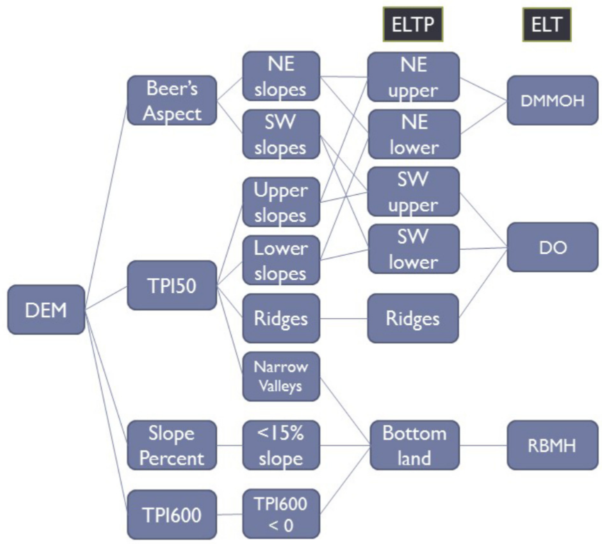

Fig. 3. Flowchart showing flow of ArcGIS processing to produce the ecological landtype phases (ELTP) and ecological landtypes (ELT). Final ELTs are Dry-mesic mixed oak hardwood forests (DMMOH), Dry oak forests (DO), and rolling bottomland mixed hardwood forests (RBMH). See explanations in text.

neighborhood radius around that cell. Positive values mean the cell is of higher elevation than its neighborhood, while negative values mean it is lower. Highest positive values will occur on ridges, while lowest negative values occur in valley bottoms. TPI therefore can be used to classify slope position by changing the thresholds within the TPI (Land Facet Corridor Designer, Jenness et al. 2011). In this effort, we used a radius of 50 m and adjusted TPI cutoffs within the software to classify various slope positions in this tightly dissected region. We used cutoffs of -7 to -0.01 for lower slopes and 0.01–7 for upper slopes, with values > 7 as ridges, and < -7 as valleys. TPI with a radius of 600 m was used for determining the broad, flat valley bottoms.

By combining the Beer's aspect map (northeast (NE) vs southwest (SW) slopes) with the TPI-defined upper vs. lower slopes, we generated four basic components important for ecological unit mapping in this highly dissected sector of Ohio: SW upper, SW lower, NE upper, and NE lower slopes. The combination of ridges and valleys from the 50 m radius slope position with the 4 slopes classes yielded a 6-class landtype phases map, except that the broad, flat valleys needed to be "burned in", or overlaid with priority as a last step, to accommodate these prominent features that we chose to eliminate from consideration for intentional oak regeneration management. This final combination produced a 6-class map of landtype phases, ranging from the dry ridges to dry SW slopes to moist NW slopes and rolling bottomlands ('rolling' in that the broad bottomland class did contain some toeslopes from all aspects, but hereafter referred just as bottomland forest).

Finally, based on empirically derived relationships from previous work on oak regeneration success (e.g., Iverson et al. 2017a) and soil moisture characteristics from IMI modeling (Iverson et al., 1997), the six landtype phases were reduced to three landtype classes. The ridge, SW upper, and SW lower slopes were collapsed into the Dry Oak (abbreviated DO) forest landtype, the NE upper and NE lower phases were combined into the Dry-Mesic Mixed Oak Hardwood (DMMOH) forest landtype, and the rolling bottomland class remained as the Rolling Bottomland Mixed Hardwood (RBMH) forest landtype. A thinning and smoothing algorithm was also used to smooth the data to a version that removes or merges many small patches (0.8 ha resolution), more practical for managers.

The agencies owning most of the public land in the study area also provided detailed GIS layers of their ownership and stand boundaries. Ohio Department of Natural Resources' (ODNR) Divisions of Forestry and Wildlife and the Wayne National Forest (WNF) use stand boundaries for management, even though the boundaries are dynamic. In the current study, ownership boundaries were used to summarize landtypes as well as report out plot level data (Fig. 2).

Five subsections of the Southern Unglaciated Allegheny Plateau Section are represented in the study area (Cleland et al., 2007), indicating variation in parent material across the region (Fig. 2). These five subsections are used in conjunction with the three forest landtypes (DO, DMMOH, RBMH) to yield 15 mapped landtypes across the 17-county area, each with a unique concatenated name. Our example study site, the Bailey's Project Area, is within the Subsection 221f, Western Hocking Plateau Subsection of the Southern Unglaciated Allegheny Plateau Section.

2.3. Plot data used to assess current vegetation condition and oak regeneration potential

Forest inventory data were used both to assess current vegetation condition and validate landtypes. Understory and overstory inventory data came from a regional dataset of SILVAH inventory plots collected by public agencies across southeast Ohio. The ODNR Divisions of Forestry and Wildlife have both adopted SILVAH and created data sets from their respective State Forests (1673 plots) and State Wildlife Management Units (1133 plots). Additionally the WNF provided data from 104 plots for a combined total of 2910 georeferenced plots. Overstory and understory data collection protocols for SILVAH plots are described in Brose et al. (2008). All plot data were placed into a GIS to assess spatial relationships between oak composition and the proposed landtypes.

Overstory data are collected using SILVAH methodology, by using a 10-factor prism for all trees more than 2.54 cm (1 in.) diameter breast height (dbh) (Brose et al. 2008). Diameters were measured and placed into size classes that allowed an estimation of basal area (BA) which was summed for all species, and then calculated as the percent of total BA that is oak. Overstory plot data were used to assess each of the landtypes for the amount of larger oak (> 2.54 cm dbh) they support now, even though conditions present now may or may not support the regeneration of oak. SILVAH and forest management agencies define an oak stand as having 50% or greater stocking in oak, while a mixed oak-hardwood stand is defined as having roughly 25–49% stocking in oak (Brose et al. 2008). These overstory and understory metrics were used to assign and map both overstory and understory conditions of oak dominance for selected areas that have had SILVAH inventories completed.

Total BA on all plots ranged from 0 to 75 $m^2 ha^{-1}$ (mostly very low numbers), reflecting the differences in age and management. In our evaluation of the landtypes with SILVAH plot data, we restricted our sample plots to total BA between 16 and 27.5 $m^2 ha^{-1}$ (70–120 $ft^2 ac^{-1}$), representing the more mature and less degraded (e.g., high graded) stands on each landtype. This subset consisted of 1183 plots. We developed a contingency table of the percent oak in the overstory from the SILVAH plots by the six landtype phases and the three landtypes, with the expectation that as oak overstory increases, there should be a greater proportion of the plots on the DO landtype, the ridge and SW slopes. To evaluate the performance of the DO landtype to predict oak in the overstory, we calculated AUC statistic (area under the Recursive Operator Curve, (Jiménez-Valverde, 2012) between the binary presence or absence of the DO landtype by the percent of oak BA in the overstory.

Understory sampling utilizes 1.83-m radius plots to assess oak regeneration potential. Regeneration stocking criteria vary by seedling size, or developmental state of a seedling cohort. Within each plot, if any of the following criteria are met, the plot's understory is considered stocked for oak under low deer pressure (Brose et al. 2008): (a) stocked with competitive oak: at least 1 oak > 1 m height, or > 1.9 cm diameter root collar; (b) stocked with established oak: at least 12 oaks 15–100 cm in height, or 0.64–1.9 cm root collar diameter; or (c) stocked with new oak: at least 25 oaks < 15 cm in height. For purposes of planning silvicultural interventions at the landscape scale, we developed an Oak Stocking Index (OSI) that emphasized whether or not plots were stocked with oak seedlings rather than their specific stage of development. Based on Brose et al. (2008), we used the following formula to assign a score for each GPS-located SILVAH plot, with a minimum score of 25 needed to assign the plot as stocked for oak:

Oak Stocking Index = (25 * competitive oak) + (2 * established oak) + (1 * new oak).

As with the overstory data, the OSI was tallied for the subset of 1183 SILVAH plots, for both landtypes and landtype phases, to further validate the models. The percent of plots with OSI above and below 25 revealed those with a stocking level of advance regeneration (or not) likely to provide oak into the next forest. By ratioing the percentage stocked to unstocked, one can determine a probability that a plot will be stocked, in a particular landtype or landtype phase.

2.4. GIS extraction tool

A GIS tool for extracting information for any particular stand, set of stands, or other area was developed to summarize information for particular areas of interest, to assist in the prioritization of where and which silvicultural practices are needed, in concert with SILVAH inventories, to maintain or restore oak-hickory stands. The tool generates areal summaries for one or more defined areas of interest, reporting the percentage of each landtype, the OSI and percent of oak BA for each plot contained within the area, and if specified, the percent of land cover or land use classes.

3. Results

3.1. Landtypes and landtype phases

The map of landtype phases, the initial 6-class product, reveals a complex, dissected landscape with many ridgelines and drainages in a portion of the Athens District of the Wayne National Forest called the Bailey Project Area (Fig. 4). The map is simply derived from derivatives of the digital elevation model (10 m) so that the outcomes can be logically deduced from a 3D map (Fig. S9), or from a compass and eyesight from the field. This map has a resolution of only 10 × 10 m so that many small patches are revealed when zoomed to high resolution (Fig. S10a), too fine-grained for operational-scale management; the smoothed and thinned map with a resolution of 0.8 ha may be more practical for field use and land management application (Fig. S10b). Nonetheless, the full resolution map was used for all statistical summaries to avoid distorting the role of some of the smaller side slopes or ridge patches.

Similarly, the 3-class landtype map, as collapsed from the landtype phase map, shows again the complex nature of the landscape but at a scale that correlates better with forest types and stand mapping. The DO landtype, by definition, is prominently featured on ridges and SW-facing slopes (Fig. 5). Among the stands from the Bailey's project area on the WNF (delineated with black lines), the DO landtype ranges from 16 to 70% of stand area, and 10 of the 17 stands have at least 50% mapped as DO landtype (Fig. 5). These stands have a potential site productivity conducive to regenerating oak. Again, zooming in on the maps of landtypes shows the impact of generalizing by filtering and smoothing to a resolution of 0.8 ha, with the advantage for general planning and disadvantage for specific understanding of subtle topographic influences on the current and future vegetation (Fig. S11a vs. b).

Over the entire 17-county area, 77% of the land is privately owned with most of the remaining divided between state (18.5%) and federal (4.5%) ownerships (Table 1). The model places about 40% of the

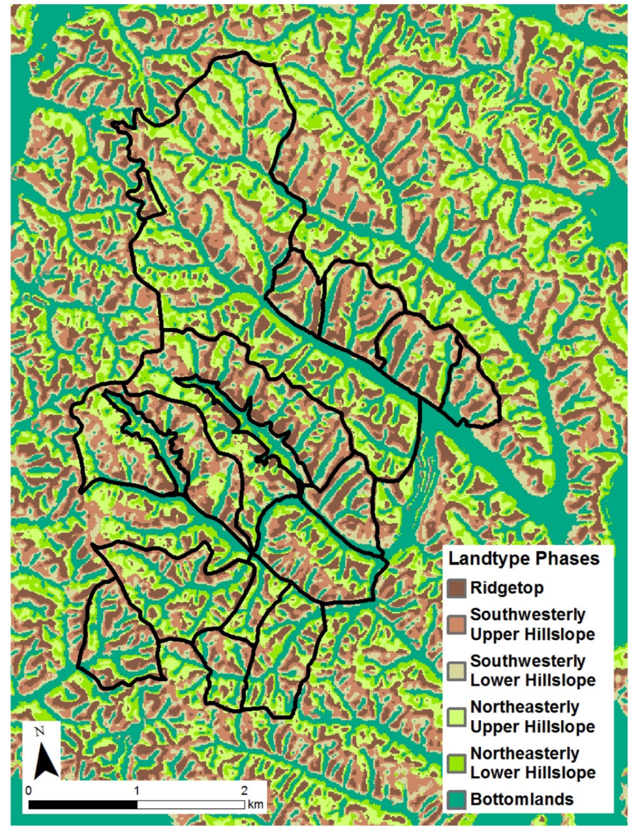

Fig. 4. Subsection 221 Ed East Hocking Plateau landtype phases in the Bailey's Project Area on the Wayne National Forest in Athens County, Ohio.

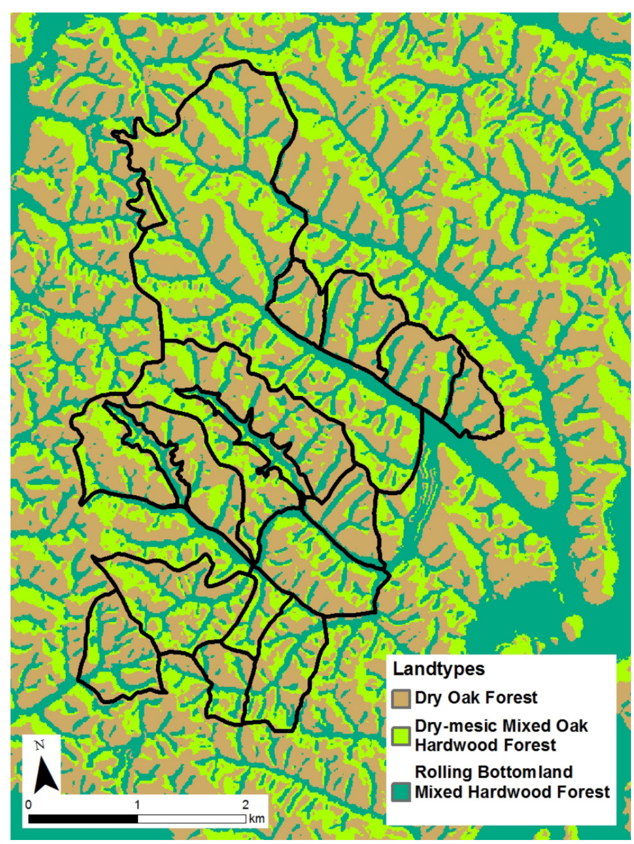

Fig. 5. Subsection 221 Ed East Hocking Plateau Landtypes in the Bailey's Project Area on the Wayne National Forest in Athens County, Ohio.

Table 1
Area and percentage land in each of three landtypes by ownership classes, and by ecological subsections. DO = dry oak; DMMOH = dry-mesic mixed oak hardwood; RBMH = rolling bottomland mixed hardwood.

Name	Hectares	Percent of area	DO landtype	DMMOH landtype	RBMH landtype
17-County project area	2,195,558	–	39.7	29.3	31.1
Privately owned land	1,690,985	77.0	38.8	29.4	31.8
State land					
Forestry	186,599	8.5	49.1	28.0	22.9
Natural areas and preserves	13,369	0.6	43.9	31.0	25.1
Parks	30,599	1.4	37.4	23.1	39.5
Wildlife	175,339	8.0	42.5	29.0	28.5
total/average	405,906	18.5	43.2	27.8	29.0
Wayne National Forest					
Athens District	29,316	1.3	46.2	28.5	25.4
Ironton District	43,193	2.0	48.3	27.1	24.6
Marietta District	26,158	1.2	48.8	30.9	20.4
total/average	98,667	4.5	47.8	28.8	23.4
Federal and State Owned land	504,573	23.0	48.3	29.8	21.9
Ecological subsections					
Ohio Valley Lowland (221Ec)	330,914	16.9	44.3	30.0	25.7
East Hocking Plateau (221Ed)	548,256	28.0	42.2	29.6	28.2
Unglaciated Muskingum Plains (221Ee)	107,005	5.5	34.7	29.9	35.4
Western Hocking Plateau (221Ef)	640,622	32.8	41.5	27.4	31.1
Lower Scioto River Plateau (221Eg)	328,005	16.8	37.4	30.7	32.0

landscape, or about 8,700 out of 22,000 km^2, into the DO landtype. For stands being managed by the WNF, 48% were classified as DO, or about 441 of the 923 km^2; and for the Ohio Division of Forestry, 49% is in the DO category (Table 1). The other state ownerships, Wildlife, Natural Areas and Preserves, and Parks, each have a more evenly distributed area in the three landtypes with less than 44% in the DO landtype, while the private land has only 39% in this class (Table 1). Within the agencies with objectives extending beyond forest management (ODNR Wildlife, Natural Areas and Preserves, and Parks), and over the entire 17-county area dominated by private lands, there are many broad river valleys which diminish the overall proportion of DO (to ~40% or less) as compared to the agencies managing the forest (~50%). Within the private landholdings, much of the flat, broad valleys (mostly classed as RBMH landtype) are in agriculture.

Within the study area, the five ecological subsections (Fig. 2) were also overlain to assess the proportion of landtypes within each. The more dissected subsections of Ohio Valley Lowland, East Hocking Plateau, and Western Hocking Plateau had the largest proportions of DO landtype (41.5–44.3%), and the relatively flatter Unglaciated Muskingum Plains and Lower Scioto River Plateau had the largest share of Bottomland Forest (32–35.4%, Table 1).

The relationship of the landtypes and landtype phases to the Integrated Moisture Index (Iverson et al. 1997) is apparent, especially for sloping lands (Table 2). IMI was much higher on northeast-facing slopes than ridges and especially southwest-facing slopes. The Bottomland Forest class (identical for both landtype and landtype phase) has a somewhat lower IMI (drier) than the northeast-facing slopes. This is expected because, by definition, the bottomlands are a broad class (using the TPI of 600 m) intended to include some lower slopes of all aspects and allow for riparian forests to remain mostly intact. The IMI is related to many ecological phenomena driven by moisture, including oak-hickory regeneration (Iverson et al. 2017a), but it is not very effective in two situations: when the landscape has broad valleys of flat land, and when there are very long slopes. The current ecological mapping effort addresses these shortcomings and models across broad expanses of southern Ohio.

3.2. SILVAH inventory assessments

The SILVAH inventory plots indicate the abundance of oak and other tree species at precise locations. The percentage of oak basal area in the overstory was higher on the DO landtype (Table 3) with 70.8% of this landtype dominated by oak. This was in contrast to the other two landtypes where 37.7–43.5% of the sites were oak-dominated. The ability to predict an oak-dominated overstory on the DO landtype was classed as 'good' (AUC = 0.70) and the optimal threshold to balance sensitivity and specificity was reached at 30% oak in the overstory. Similarly, within landtype phases, the percentages followed a predicted pattern with ridge and southwest upper slopes having over 71% of plots dominated by oak (> 50% oak), while only 34% of the northeast lower slopes were oak-dominated (Table 3). The RBMH landtype had slightly more oak than the mesic, northeast slopes but much less than the DO landtype.

The understory data revealed stocking for advance regeneration oak, as captured in the Oak Stocking Index, with a value of 25 necessary for the plot to be considered stocked. The ratio of stocked to unstocked plots was 0.25 for DO landtype, 0.10 for DMMOH landtype, and 0.14 for RBMH landtype (Table 4), meaning that 25% of the plots placed on the DO landtype are considered stocked with advance oak regeneration. By extension, assuming adequate representation of the plots within the

Table 2
Integrated Moisture Index (IMI) values (mean, median, standard deviation) for each landtype and landtype phase. Higher IMI values equates to higher long-term soil moisture. DO = dry oak; DMMOH = dry-mesic mixed oak hardwood; RBMH = rolling bottomland mixed hardwood.

Landtype	IMI mean	IMI median	IMI std	Landtype phase	IMI mean	IMI median	IMI Std
DO	20.4	19	9.4	Ridge	26.8	28	12.6
DMMOH	38.0	38	8.3	SW_up	18.4	19	6.9
RBMH	30.3	30	9.3	SW_low	18.1	17	6.8
				NE_up	35.8	36	9.4
				NE_low	39.4	40	8.6
				Bottomland	30.3	30	9.3

Table 3
Percent of SILVAH plots (n = 1183) within each landtype or landtype phase in each of 10 classes of oak percentage (by basal area) in the overstory, and by greater or less than 50% oak in overstory. DO = dry oak; DMMOH = dry-mesic mixed oak hardwood; RBMH = rolling bottomland mixed hardwood.

Proportion Oak	DO landtype	DMMOH landtype	RBMH landtype			
0	12.4	33.8	23.7			
0.1	4.2	13.1	10.3			
0.2	4.2	6.2	10.3			
0.3	3.7	4.7	6.5			
0.4	4.6	4.5	5.6			
0.5	6.4	5.0	6.5			
0.6	7.3	3.3	6.0			
0.7	8.3	5.0	8.2			
0.8	8.5	8.3	8.6			
0.9	7.0	1.8	6.0			
1	33.4	14.2	8.2			
Percent < 50	29.2	62.3	56.5			
Percent > 50	70.8	37.7	43.5			
Proportion Oak	Ridge	SW_up	SW_low	NE_up	NE_low	Bottomland
0	10.1	12.4	15.5	33.5	34.2	23.7
0.1	2.4	5.8	4.1	9.1	17.4	10.3
0.2	4.8	3.9	4.1	5.7	6.8	10.3
0.3	3.8	2.3	6.1	5.1	4.3	6.5
0.4	5.8	4.3	3.4	5.7	3.1	5.6
0.5	4.8	4.7	11.5	5.1	5.0	6.5
0.6	9.1	7.0	5.4	2.8	3.7	6.0
0.7	6.3	8.5	10.8	5.7	4.3	8.2
0.8	10.6	6.6	8.8	8.0	8.7	8.6
0.9	7.2	7.8	5.4	1.7	1.9	6.0
1	35.1	36.8	25.0	17.6	10.6	8.2
Percent < 50	26.9	28.7	33.1	59.1	65.8	56.5
Percent > 50	73.1	71.3	66.9	40.9	34.2	43.5

landtypes, 25% of the DO landtype should be stocked with advance oak regeneration. However, given that the SILVAH plots fall exclusively as yet on public lands, with at least some forest management encouraged, this figure is likely optimistic across private lands which are often not managed or mismanaged (high graded). In contrast, only 10% of DMMOH plots and 14% of RBMH plots were adequately stocked with oak. Among landtype phases, the highest stocking was found in southwest upper slopes, at 30%, followed by ridges at 26% (Table 4). Southwest lower slopes were stocked at much lower levels (17%), even approximating the levels of the northeast upper slopes and bottomland (14–15%). Thus, a more limited definition of the DO landtype, considering only the understory data, might include only the landtype phases of Ridge and SW upper slopes. However, given it is hard to distinguish SW lower and SW upper hillslopes during on-site inspection, and that IMI data support the distinction of SW lower from NE (both hillslopes), we chose to keep SW (both hillslopes) combined with ridges as the DO landtype. In contrast, the northeast lower slopes were only stocked with oak 5% of the time (Table 4).

A representative map detailing overstory and understory oak stocking by plot is provided for one Ohio State Wildlife Management Area (Fig. 6). In this example, only 16.3% of the plots (36 of 221 plots) are considered stocked according to the formula given above.

Table 4
Percent of SILVAH plots (n = 1183) within each landtype or landtype phase in each of 6 classes of oak understory (by Oak Stocking Index), by greater or less than Oak Stocking Index of 25 in understory, and by ratio of stocked (St) to Total plots (assuming 25 or higher is stocked). DO = dry oak; DMMOH = dry-mesic mixed oak hardwood; RBMH = rolling bottomland mixed hardwood.

Oak stocking index	DO landtype	DMMOH landtype	RBMH landtype			
0	13.3	16.1	9.4			
1:9	19.9	8.2	6.3			
10:24	5.7	1.3	1.2			
25:49	6.6	1.7	1.1			
50:99	3.8	0.8	1.0			
> 100	2.7	0.3	0.7			
Percent < 25	38.8	25.6	16.8			
Percent > =25	13.1	2.9	2.8			
Ratio Stocked:Total	0.25	0.10	0.14			
Oak stocking index	Ridge	SW_up	SW_low	NE_up	NE_low	Bottomland
0	4.1	4.1	5.0	7.9	8.2	9.4
1:9	6.7	9.0	4.2	3.7	4.5	6.3
10:24	2.3	2.2	1.2	1.0	0.3	1.2
25:49	2.2	3.1	1.3	1.0	0.7	1.1
50:99	1.4	1.8	0.6	0.8	0.0	1.0
> 100	0.8	1.6	0.3	0.3	0.0	0.7
Percent < 25	13.1	15.3	10.4	12.7	12.9	16.8
Percent ≥ 25	4.5	6.5	2.1	2.2	0.7	2.8
Ratio Stocked:Total	0.26	0.30	0.17	0.15	0.05	0.14

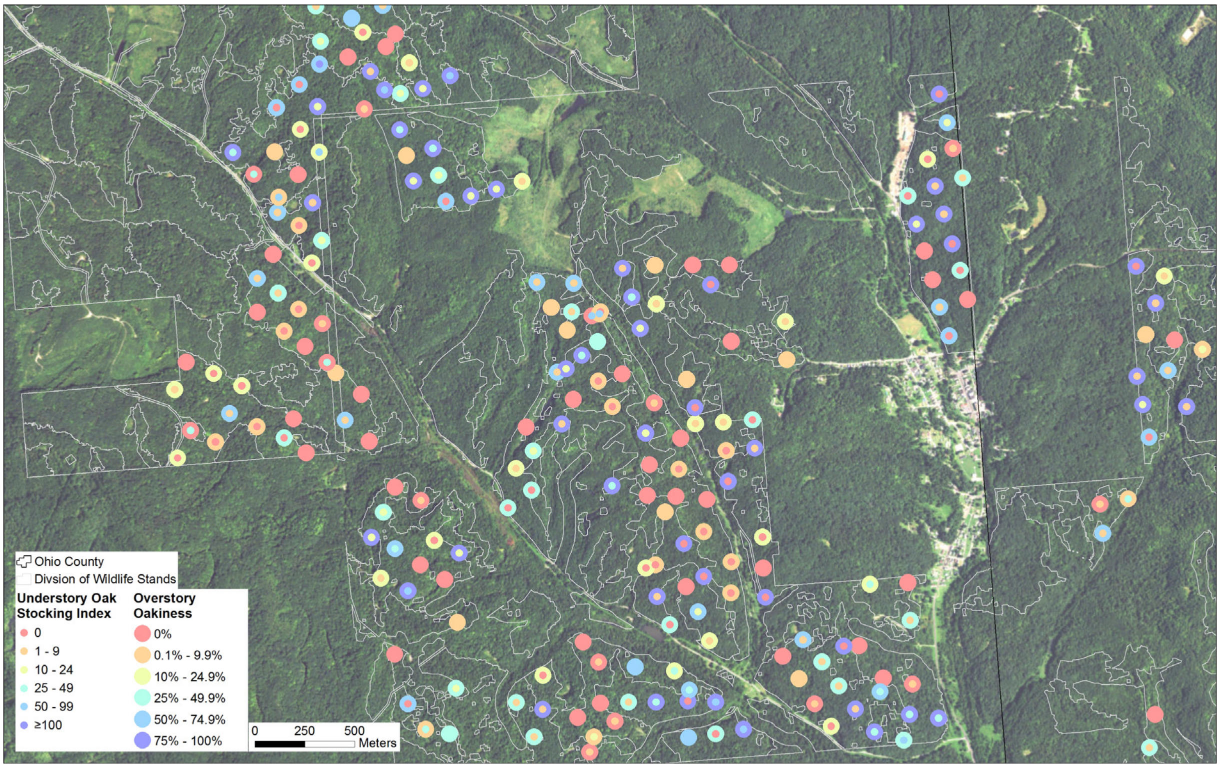

Fig. 6. SILVAH overstory (percent basal area (BA) in oak) and understory (Oak Stocking Index, OSI) plots mapped for the O'Dowd Wildlife Management Area in southern Ohio. For the 221 plots shown here for overstory: 88 had < 10%, 26 had 10–25%, 30 had 25–50%, 26 had > 50–75%, and 51 plots had 75–100% oak of the total basal area in the plot. For understory OSI: 185 were < 25% (= unstocked), while 36, or 16.3%, of plots were considered stocked. Gray lines indicate delineated stands inside the O'Dowd.

Additionally, over half (114) of the overstory plots have < 25% of the basal area in oak, meaning a relatively small acorn source for future oak regeneration. Nonetheless, given the potential for animal dispersal (e.g., Pesendorfer et al., 2016) and the number of plots with high oak basal area, this management zone could respond with adequate oak regeneration if targeted management were applied in a timely manner.

Similar to the example provided, we summarized the SILVAH plot information for other state forests and wildlife management areas, and found a preponderance of understory plots with poor stocking of oak regeneration (Table 5). Across all state lands, only about 31.7% of understory plots were considered stocked for oak, but they ranged from 12.1 to 50.7% stocked. As indicated with Fig. 1, the overstory was substantially higher in oak prominence, averaging about 45% of plots dominated by oak (with overstory oak > 50% of basal area), ranging from 14.1 to 74.4% oak by basal area (Table 1). Interestingly, the State Forests had higher oak overstory stocking as compared to the State Wildlife Management Areas (52.9% vs. 33.5%), but the percentage of stocked plots in the understory was nearly identical between the two agencies (31.9% vs. 31.3% for Forests and Wildlife Areas, respectively, Table 5).

3.3. GIS extraction tool

The custom GIS tool provides a spreadsheet of information summarizing the overstory and understory data from each SILVAH plot, and the area and percentages of each landtype within a GIS-selected area of interest (Fig. S12). Using information generated by this tool, managers can compare information among several areas of interest to determine which have: (1) a larger portion of DO landtype and thus be more likely to benefit from silvicultural treatments to promote oaks; (2) sufficient oak in the canopy with or without sufficient stocking of oak in the understory; and (3) land cover or land use that might be favorable to oak if inventory data are unavailable. While the GIS tool can provide information in the absence of inventory data, current conditions should be evaluated by field surveys to verify potential benefits of any management practices.

4. Discussion

4.1. Oak investment zones

The oak-hickory forest is generally on a declining trajectory in Ohio (Fig. 1) and elsewhere throughout the eastern United States (e.g. (Nowacki and Abrams, 2008; Hutchinson et al., 2012). Many factors likely contribute to poor oak regeneration but a lack of disturbance (e.g., fire) and appropriate management for oak, as well as the intense competition from competing vegetation (native and non-native), and excessive deer browsing in some areas are particularly important (McEwan et al., 2011; Dey, 2014). Moreover, even relatively small variations in topography can result in large variations in overall moisture regime (Iverson et al., 1997), which, in turn, affect the growing conditions for oak and hickory (Iverson et al., 2017a). Many studies have shown that greater oak-hickory regeneration occurs on relatively dry sites that have adequate light penetrating to the forest floor (e.g., (Arthur et al., 2012; Hutchinson et al., 2012; Brose et al., 2014; Dey, 2014; Waldrop et al., 2016; Iverson et al., 2017a). As such, it is clear that the DO landtype has the greatest potential to sustain oak in the future.

Prioritizing silvicultural activities that maximize oak and hickory regeneration can be challenging. However, informing management decisions with information about landtypes and recent inventory data can aid in selecting where management might help to achieve both short- and long-term objectives for oak restoration. The methods described here allow a narrowing of the potential locations to those with relatively drier conditions. In southern Ohio, the DO landtype, which occurs on ridges and southwest-facing slopes, occupies about half the

Table 5
Ohio state forests and wildlife management areas, their sizes and number of SILVAH plots, the percent of understory plots stocked with oak, the percent of overstory with > 20% and > 50% overstory basal area in oak, and the percentage of each landtype. DO = dry oak; DMMOH = dry-mesic mixed oak hardwood; RBMH = rolling bottomland mixed hardwood.

Name	Hectares	SILVAH Plots, #	Understory Stocked, %	Overstory oak > 20%, %	Overstory oak > 50%, %	DO landtype, %	DMMOH landtype, %	RBMH landtype, %
State Forests								
Pike	4663	173	12.1	37.6	23.1	48.7	37.3	14.0
Richland Furnace	1012	43	44.2	86.0	74.4	46.5	29.8	23.7
Scioto Trail	3786	167	36.5	80.8	69.5	46.7	32.2	21.0
Shawnee	26,463	731	39.5	78.2	61.0	52.0	24.8	23.2
Tar Hollow	6650	124	23.4	58.1	38.7	49.7	28.0	22.2
Vinton Furnace	6424	69	50.7	79.7	60.9	48.2	25.9	25.9
Zaleski	11,592	82	17.1	58.5	42.7	47.3	26.5	26.2
Total/average	60,590	1389	31.9	68.4	52.9	48.5	29.2	22.3
State Wildlife Management Areas								
Cooper Hollow	2343	334	45.8	55.1	40.1	43.2	27.5	29.3
Sunday Creek Coal	1349	96	27.1	37.5	22.9	49.0	26.6	24.4
Wallace H. O'dowd	2741	400	29.0	51.8	36.0	47.8	26.0	26.2
Waterloo	1077	118	42.4	72.0	54.2	49.6	24.6	25.7
Wolf Creek	1611	185	12.4	21.1	14.1	38.8	30.1	31.2
Total/average	9120	1133	31.3	47.5	33.5	45.7	27.0	27.4
Grand total/ average	69,710	2522	31.7	59.7	44.8	47.3	28.3	24.4

area currently under federal and state agency forest management. This disproportionally high DO acreage in public ownership is largely the legacy of past land use, whereby institutions such as the U.S. Forest Service effectively acquired "the lands nobody wanted" (Shands and Healy, 1977). Of course, this analysis provides only the first step on prioritizing lands for management under limited resources. Agency foresters and biologists will have many other sources of information to consider as they determine treatment locations, such as prior land-use history, accessibility, prior treatments, current stocking, and understory stocking. Many of these may be available through GIS map layers, but ground investigation will still be needed. This is where the SILVAH plots are invaluable.

The SILVAH plots complement the landtype outputs in that they provide a detailed view of the composition and potential future capacity of oak regeneration. Where sufficient SILVAH plot data have been collected, an immediate understanding of probable oak regeneration success may be possible. At present, however, only a small portion of the landscape has been inventoried via SILVAH methods so that the ecomapping tools presented here can be used to identify more "optimal" sites without the need for plots. Additional field work, modeling, and remote sensing could provide additional information sources to improve the extrapolation across non-inventoried areas. Across the 1183 mature forest SILVAH plots, the landtypes and landtype phases described here do capture the relative prevalence of oak in the overstory. While an AUC of 0.70 is on the lower end of representative model performance (Sobek-Swant et al., 2012), we reiterate that the landtype classes were developed to capture long-term conditions and utilize landform as the main derivative. Further, the use of AUC has been cautioned in its utilization of species distribution models (especially where absence data are not available (Jiménez-Valverde, 2012)) but our application here uses a complete independent data source of plot level tree data. The detailed plot data on tree species composition captures many different land use and management histories. The landtypes depicted here may also help in targeting locations for future SILVAH inventories, for example into stands that have a higher proportion of the DO forest landtype. The precise geo-location of the small SILVAH plots across the landscape allows for specific mapping and interpretation within the stands being inventoried. Most SILVAH applications to date average the SILVAH plots within a stand; this can be disadvantageous in highly heterogeneous landscapes such as those in southern Ohio. Individual SILVAH plots also allows for realignment of stand boundaries if desired.

4.2. Implications for management

The ecosystem model presented here takes an all-lands approach and connects to both national and regional science frameworks. The landtype modeling lies in the context of overall efforts to hierarchically map the nation into meaningful ecological units at coarse to fine scales (Winthers et al., 2005; Bailey, 2009). Analysis and management of ecosystems increasingly rely on ecomap products to help manage land holdings for biodiversity, timber resources, and the changing climate. Map units derived from the models here are presented as landtypes and landtype phases, and in this case, are mostly distinguished by variations in microclimate (Winthers et al. 2005). These landtypes and landtype phases, because they are geared to moisture regimes, not only are linked to oak-hickory distribution, but also many other overstory, understory, ground flora, and fauna distributions, similar to the Integrated Moisture Index (Iverson et al., 1997; Hutchinson et al., 2005a).

The assessment of current vegetation coupled with the SILVAH decision-support system is part of a regional community of practice with the common interest of sustainable forestry for the mixed oak forests of the mid-Atlantic region. Training sessions offered by scientists for managers from all land management organizations on a common method of inventory in turn linked to computer software for science-based silvicultural prescriptions has helped build a regional science framework and understanding for inventory, monitoring, and management in the states that have opted in to the program. This community of practice has a systematic framework with a common vocabulary and regular training sessions and interactions between scientists and managers. The point-level inventory data from SILVAH are tied to specific silvicultural prescriptions toward achieving desired future conditions. Though beyond the scope of this paper to outline various prescriptions, the SILVAH prescription outcomes can therefore often be mapped along with the landtypes and landtype phases.

This information can be used to assess public and private land opportunities to invest in oak management. Estimations can be made for the cost of oak treatment based on site productivity, the landtypes, and the condition of existing oak regeneration; it can thus help prioritize the investment of limited management dollars. Collaborative oak management in southeastern Ohio can only be possible if land managers and family woodland owners understand the need for management and can see their own connection to the larger landscape.

i. *Application on WNF.* On the WNF, the ecosystem model is being used to establish priorities for silvicultural treatments for oak-hickory stands to meet short-term objectives (e.g., to create early successional forest habitat for wildlife) as well as the longer-term goal to keep oak-hickory forests on the landscape. In using these tools, WNF personnel have saved considerable time in developing management projects and priorities.
ii. *Application across the 17-county area*. The Ohio Interagency Forestry Team plans to apply the ecosystem model across the 17-country project area as they align government incentive programs and authorities with family forest landowner communities of interest in managing for oak. Additionally, the SILVAH community of practice, convened in southeastern Ohio over the past eight years on public lands, has allowed for the creation of a regional inventory dataset that can now be combined with national Forest Inventory and Analysis (FIA) overstory and new understory plot data to extend SILVAH science to a greater landscape.
iii. *Possible application elsewhere.* Because one part of the methodology described is based almost entirely on a digital elevation model and its derivatives, it can be simply adopted anywhere where solar exposure, and its consequential effect on long-term soil moisture, is a driving influence on the success of oak regeneration. Surely this approach can be applied to similar non-glaciated, highly dissected landscapes of the eastern United States. Specifically, within the Eastern Region of the U.S. Forest Service, this ecomapping method could be easily transferred to the "southern tier" National Forests (Mark Twain, Shawnee, Hoosier, and Monongahela National Forests). The broad-scale, 600 m topographic position index provides a mechanism to capture the broad valleys, and eliminate them from consideration into the DO landtype, as would be the case with portions of the valleys if only fine-scale analyses were included. We do understand that oaks do not always occupy the driest portions of the landscape as presented here; in these cases, other environmental factors may need to be assessed. Lands with very little topographic relief also will require another process to identify lands most suitable for oak regeneration management. Perhaps soil texture, pH, or nutrition would be primary drivers for oak in those systems. Of course, land use history is also very important in understanding the factors associated with successful oak regeneration. Besides identifying locations to focus for oak regeneration, the identification of other, moister landtypes or landtype phases can provide information on habitats for particular species that specialize in those habitats.

5. Conclusions

In this study, we used GIS tools to map ecological units (LTs and LTPs) to locate the landscape positions (i.e., the Dry Oak Forest landtype) that previous research has shown to be optimal for supporting oak, and then overlaid these units with current vegetation condition. Forest inventory data were assessed according to stocking criteria from SILVAH to provide representation of where oak exists on the landscape in both the overstory and understory and in what condition. Inventory data further corroborated the relationship between ecological units and optimal positions for supporting oak. Individually, SILVAH inventories and our model provide important and useful information, however, when synthesized as done here, the wealth of spatial information creates a more complete picture to begin developing management strategies to slow the downward decline of oaks. Overall, these tools allow managers to identify 'zones of investment', i.e., those stands with the bulk of the area in the Dry Oak forest landtype and with at least some advance oak regeneration, which will have a greater likelihood of growing into oak-dominated stands with minimal investment of scarce funding resources.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.foreco.2018.05.018.

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