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REVIEW

Irregular Shelterwood Methods for Achieving Ecological and Climate Adaptation Objectives in the Central Hardwood Forest Region

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Abstract
Developing interest in using silviculture to achieve a broad array of objectives such as maintaining or restoring ecological function, increasing adaptive capacity, and providing timber products in the same forest stand has increased the appeal of irregular shelterwood methods. Despite growing application in Canada, Europe, and other regions of the United States, use of irregular shelterwood is limited across the Central Hardwood Forest Region, USA. Obstacles to broader implementation include a need for intermediate treatments to address existing challenges to oak regeneration, unfamiliarity with terminology, limited local guidance and insufficient access to demonstration sites, and greater demand for careful planning. To address some of these challenges and generally increase the accessibility of the methods, we present three case studies that illustrate how variants of irregular shelterwoods have been tailored to specific sites and objectives on the Cumberland Plateau (Kentucky, USA), in the Driftless Area (Iowa, Minnesota, and Wisconsin, USA), and in the Blue Ridge Mountains (North Carolina, USA). Each case study details the specific objectives each irregular shelterwood was designed to achieve and quantifies harvest outcomes. Irregular shelterwood methods are not appropriate for all situations, but with these examples we demonstrate potential ways they can be used to achieve ecological and adaptation objectives in the Central Hardwood Forest Region.

Keywords Irregular shelterwood · Femelschlag · Oak-hickory · Ecological silviculture · Adaptation silviculture · Central Hardwood Forest Region

Introduction

Changing conditions and unprecedented uncertainty have simultaneously increased the difficulty and urgency of sustainably managing forest ecosystems (Achim et al. 2022; Puettmann et al. 2025). Accordingly, great effort has been invested in

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developing frameworks to assist forest practitioners as they strive to balance increasingly complex objectives (Messier et al. 2015). This includes rapid development of strategies and tools associated with ecological and adaptation silviculture (D'Amato and Palik 2020). Ecological silviculture contrasts with conventional silviculture by prioritizing objectives related to ecosystem function, biodiversity, and health over commodity production while still maintaining economic viability and supporting forestry markets, infrastructure, and industry more broadly (Palik et al. 2020). Application of ecological silviculture involves adherence to four guiding principles (continuity, complexity and diversity, context, and timing (Palik et al. 2020)) informed by the prevailing natural disturbance regime relevant to a given forest (Spurr and Cline 1942; Seymour et al. 2002; Burton et al. 2006). While adaptation silviculture differs from ecological silviculture in many respects (e.g. by placing greater emphasis on maintaining forest function than historical species composition), it also incorporates elements of these four principles because of the potential they have for increasing the adaptive capacity of forest ecosystems in light of uncertainty, emerging threats, and ongoing change (D'Amato and Palik 2020).

Conventional silvicultural systems (e.g. clearcutting, shelterwood, seed tree, single-tree and group selection), as broadly applied across the United States and Canada, typically prioritize production of efficient, predictable yield and simplify forest structure and composition (Burton et al. 1999; Schuler 2004; Bauhus et al. 2009; Puettmann et al. 2009). These priorities and impacts are most obvious with even-aged systems, but even though typical, uneven-aged selection systems maintain multiple cohorts and generally create or maintain more complexity by comparison, they, too, prioritize sustained yield principles (Meyer 1952; Nyland et al. 2016; Kern et al. 2017; Ashton and Kelty 2018). Uneven-aged selection systems also lead to simpler species composition, lower functional diversity, lower structural complexity, and fewer large, old trees than exist in stands driven by disturbance more akin to the historical regime (Bauhus et al. 2009; Curzon et al. 2017; Palik et al. 2020). This tendency toward simplification in forest stands managed with standard single-tree or group selection silvicultural systems has been observed widely, as reported by studies in hardwood forests of the northeastern USA and Canada (e.g. Kenefic and Nyland 2007), the midwestern USA (e.g. Goodburn and Lorimer 1999), and the central Appalachians (Schuler 2004; Keyser and Loftis 2013). While originally developed to ensure successful regeneration (Hawley 1921), the continued appeal of the basic, conventional silvicultural systems could be said to lie primarily in their simplicity and in economics. These approaches are usually more profitable so long as environmental conditions are stable and predictable (see Knoke et al. 2008), but that profit comes at an ecological cost, particularly when forests are simplified across landscapes. As conditions become less certain and extreme events occur more frequently, even profit may ultimately be greater if "risk-averse" approaches that place more emphasis on complexity and diversity gain prominence in silviculture (Knoke et al. 2008; Puettmann 2021; Dickinson et al. 2025). Early contributors to the development of continuous cover forestry (CCF), a framework guiding forest management in parts of Europe, New Zealand and elsewhere, recognized both ecological and economic benefits of managing more complex, multi-cohort forests (Bauhus et al. 2013). While many applications have prioritized economic value and production, even relying on exotic species (Bauhus et al. 2013), CCF can be applied in a way that is analogous to ecological silviculture (Bauhus et al. 2013; Dickinson et al. 2025).

The shift to designing silvicultural treatments so that they more closely model natural disturbance requires regeneration methods that emphasize partial harvests (Seymour 2005; Raymond et al. 2009; O'Hara 2014; Knapp et al. 2017; York et al. 2025). Recognition of this need and of the importance of diversity and complexity in managed forests has led to greater adoption of less conventional management regimes over the last 40 years (Puettmann et al. 2015). This includes a global increase in modifications to even-aged silvicultural systems to include live tree retention (Gustafsson et al. 2012), the development and implementation of variable density thinning in the Pacific Northwest, USA and elsewhere (Carey 2003; Brodie and Harrington 2020; Donoso et al. 2020), and application of CCF in Europe, Australia, and New Zealand (e.g. Dickinson et al. 2025). Irregular shelterwood systems have also received greater attention (Raymond et al. 2009; O'Hara 2014; Ashton and Kelty 2018). As in conventional shelterwood, irregular shelterwood involves management of overwood, overstory trees that provide seed and an appropriate understory environment for facilitating advance regeneration (Deal 2018), but the harvest intensity typically lies between conventional shelterwood and group selection (Kern et al. 2017). Agreement over exactly what makes an irregular shelterwood method "irregular" may not be universal (see Trentanovi et al. 2023; Trerise et al. 2025), but it is generally accepted to indicate a multi-cohort age structure (Raymond et al. 2009; Ashton and Kelty 2018) as well as an irregular diameter distribution (Raymond et al. 2009; Kern et al. 2017) rather than balanced, as with selection (Nyland 1987). This lack of balance is at least partly related to a less tightly regulated age class distribution than might be expected with single-tree or group selection. The staged implementation of preparatory treatments, establishment cuttings, and site preparation that are typically applied uniformly across a stand with conventional shelterwood may be applied simultaneously, but in different parts of a stand with irregular shelterwood. Lastly, removal cuttings may not be complete if there are plans for legacy retention.

While notably increasing in popularity in recent decades, irregular shelterwood methods have long been recognized in European and North American silviculture (e.g. Troup 1928). Historically, irregular shelterwood methods were developed to address local conditions and constraints in a way that facilitated natural regeneration of multiple species (Puettmann et al. 2009). Two primary versions of femelshlag, the Bavarian (Bayerischer) femelshlag and the Baden (Badische) femelshlag, named after their respective region of application, were recognized and applied in Germany (Spurr 1956; Puettmann et al. 2009; Raymond et al. 2009). Despite widespread belief that German silviculture was a "highly systematic artificial system", Stephen Spurr notes that it was strongly based on a well-researched understanding of forest ecology (1956). The Bavarian femelschlag (a version of the expanding gap irregular shelterwood (Raymond et al. 2009)) developed from a need to balance high light requirements of desired oak species with the shade necessary to reduce understory competition while still allowing beech regeneration. The method involved creating relatively large initial openings to encourage regeneration of oak species. Then, additional harvests were used to expand openings and release regeneration that had developed along forest edges after the initial entry (Puettmann et al. 2009). The Baden Femelschlag (a form of continuous cover irregular shelterwood (Raymond et al. 2009)) involved smaller initial openings distributed across a stand. Additional openings of similar size were then regenerated in future entries in a way that facilitated the development of younger cohorts beneath the oldest cohort (Spurr 1956; Puettmann et al. 2009; Raymond et al. 2009), eventually resulting in a relatively open multi-cohort structure that has been compared to selection systems applied in the western United States (Spurr 1956). Variants of irregular shelterwood are still applied in Germany and have been recommended for stands where objectives include regenerating oak species and when canopy openings must be large enough to favor oak over more competitive and shade tolerant beech (Lüpke 2007).

The flexibility of irregular shelterwood methods has contributed to recent, increased appeal among those seeking to model the severity and frequency of disturbance associated with natural regimes that create partial canopy openings (Seymour 1995; Raymond et al. 2009; O'Hara 2014; Kern et al. 2017) and to achieve other objectives related to biodiversity conservation and forest ecosystem health (Seymour 1992, 1995; Brang et al. 2014; Sedmáková et al. 2017). Following the prohibition of clearcutting in Slovenia in the 1940s and widespread dissatisfaction with uneven-aged selection methods, irregular shelterwood emerged as the method of choice in beech-dominated forests (Diaci 2006). Variants of the irregular shelterwood method continue to be used to regenerate beech-dominated forests in Central Europe, and benefits include enhanced growth and survival of yew (*Taxus baccata* L.), an important species with projected declines related to climate change (Sedmáková et al. 2017). Extended irregular shelterwood has been recognized in the USA for at least 30 years (Seymour 1995). This form of irregular shelterwood can be used to manage two-cohort stands. In these systems, evenly distributed overwood is retained for a period exceeding 20% of the stand rotation age with or without reserves, and a younger cohort establishes beneath the older (Raymond et al. 2009). Relative to selection, extended irregular shelterwood creates structural conditions more analogous to the natural disturbance regime in Acadian mixedwoods and was originally proposed as an option for reversing declines in red spruce (*Picea rubens,* Sarg.*)* abundance with the added benefit of encouraging production of self-pruned, high value sawlogs (Seymour 1995). Likewise, the Acadian femelshlag, a variant of the expanding gap irregular shelterwood (or Bavarian Femeschlag), was developed in the 1990s for mixedwood forests of the northeastern USA (Seymour 2005, 2024). As an alternative to clearcutting in the Acadian mixedwood forest type, the method increases structural and compositional diversity while continuing to meet commodity objectives (Seymour et al. 2006) as well as emerging adaptation objectives (Seymour 2024). Evidence suggests irregular shelterwood methods also have potential application in efforts to rehabilitate degraded mixedwood forest stands in Quebec (Raymond et al. 2020), and continuous cover irregular shelterwoods have been used successfully to increase the abundance of desired tree species with intermediate shade tolerance where regeneration has proved difficult with other methods (Raymond and Bédard 2017). Nova Scotia, Canada provides another notable example of adoption, also building on the framework proposed by Raymond et al. (2009);

silvicultural guidelines for the province recommend irregular shelterwood variants for application across the ecological matrix on Crown lands, an area that includes nearly one million ha of boreal forest (McGrath et al. 2021), Seymour 2024). Yet another example, implemented in mixed conifer forests of the Sierra Nevada Mountains in California, USA, demonstrates application in very different forests. There, irregular shelterwood methods that involve creating gaps of varying sizes and eventually expanding them (a form of expanding gap irregular shelterwood, Raymond et al. 2009) have been used successfully in combination with prescribed fire to achieve restoration objectives (York et al. 2025).

As illustrated above, applications of irregular shelterwood methods vary across biomes, forest types, and individual stands. Despite this variability, all of the methods described above (including the two primary German femelschlags) arguably fit within a widely referenced framework for classifying irregular shelterwood methods proposed by Raymond et al. (2009) that we strive to adhere to throughout this paper. The inherent flexibility of these silvicultural systems allows them to be tailored to meet the regeneration objectives specific to a given site in balance with other objectives related to ecological function and adaptation. Likely for these reasons, irregular shelterwood systems were the most common approach proposed in a recent collection of ecological silvicultural systems developed for 19 different forest ecosystems (Palik and D'Amato 2024). Irregular shelterwoods were featured 12 times in this collection, in each case modified to achieve conditions associated with three of four prevailing natural disturbance regimes that characterize forests (infrequent severe, mixed-severity, and frequent gap-scale) (D'Amato and Palik 2024). Variable density thinning also featured prominently as an effective regeneration method for ecological silvicultural systems, and while the primary objective of this method is to increase structural complexity across a stand, it could be argued that variable density thinning is a variation of irregular shelterwood (D'Amato and Palik 2024).

Despite the growing use of irregular shelterwood and other partial harvest methods across the Pacific Northwest, northern hardwood and boreal forests across northeastern North America, and the forests of Central Europe, adoption in the Central Hardwood Forest Region (CHFR) of the USA has lagged. The CHFR includes five ecoregion provinces (Fralish 2003; Hanberry et al. 2012) (Fig. 1). Forests and woodlands in the region are largely in private ownership (> 75% in most states) (Johnson et al. 2019), and ongoing fragmentation continues to diminish the size of already small forest properties (Butler et al. 2021). Across its broad geography, the CHFR hosts an abundance of species. This includes over 70 native tree species in the CHFR west of the Appalachians alone, and trees in the oak (*Quercus*) and hickory (*Carya*) genera are the most common, especially in the overstory (Parker and Merritt 1995). This diversity of tree species varies widely in shade tolerance, and recruitment to the canopy for many (particularly oak and hickory) depends on the presence of advance regeneration.

Historically, frequent to moderately frequent low-severity surface fires dominated the disturbance regime for forests and woodlands across most of the CHFR (Hart 2016; Stambaugh et al. 2021). This was sometimes punctuated by intermediate-severity (gap-scale) disturbance (e.g. Hart 2016). Such a dynamic regime, consisting of a combination of fire, wind events, insect and disease outbreaks, ice damage, and

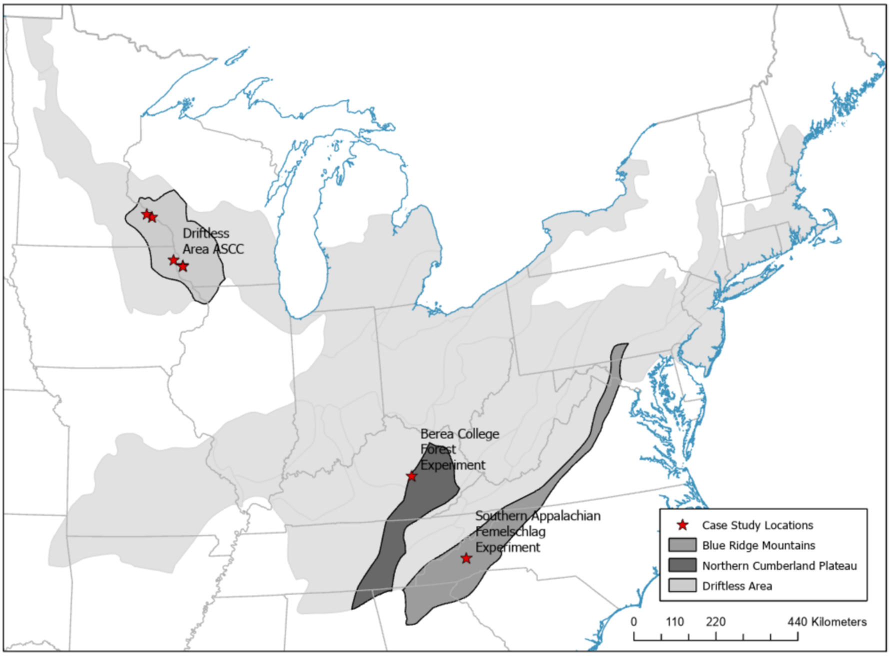

Fig. 1 Central Hardwood Forest Region of the eastern United States (light gray), defined based on ecosystem provinces (Bailey 1995), Hanberry et al. 2017). Gray shading indicates the ecoregional section (Bailey 1995) where each case study occurs

other disturbance agents led to a mosaic of forests and woodlands with greater age and structural diversity than maintained by most management today (Abrams 1992; Hart and Cox 2017; Johnson et al. 2019; Goode et al. 2022). Even-aged regeneration methods prevail where silviculture is applied in the CHFR. Even more commonly, forests are managed passively or are high-graded, and in the absence of fire, this also leads to different species composition and structure than would be expected with the natural disturbance regime. High-grading, specifically, degrades timber quality over time and can lead to the local loss of species with high economic value like black walnut (*Juglans nigra* L.). Evidence also suggests that high-graded mixed oak stands store less aboveground biomass, accumulate lower densities of advance regeneration, and more frequently exhibit characteristics associated with poorer health (e.g. epicormic branching) (Curtze et al. 2022).

Oak and hickory species provide many ecosystem services, including valuable timber products and mast for wildlife (Dey et al. 2017; Pile Knapp et al. 2021, Adams et al. in press). Compared with other common tree species, many in these two genera also exhibit stress and disturbance responses that suggest valuable potential for maintaining or increasing adaptive capacity in forest ecosystems negatively impacted by changing conditions and emerging stressors (Dey et al. 2017; Curzon and Kabrick 2024, Adams et al. in press). They are well adapted to frequent disturbance and flourish in the type of edge environments that may have occurred more frequently in the past considering the historical disturbance regime (a regime driven by both natural and anthropogenic disturbance with varying intensity and frequency across the landscape). Irregular shelterwood methods can be designed to model the moderate-severity disturbance events that historically increased recruitment of oak and hickory species (Hart 2016), particularly when additional treatments like prescribed fire (Brose et al. 1999; Arthur et al. 2012; Brose 2014; Greenler and Saunders 2019) and midstory removal (e.g. Hackworth et al. 2020) are incorporated as needed into the larger silvicultural system. Depending on the design, irregular shelterwood systems can produce more edge environments than conventional shelterwood systems, demonstrated to encourage better establishment and growth of oak regeneration (Lhotka and Stringer 2013). To this end, recent silvicultural experiments have demonstrated the potential efficacy of irregular shelterwood methods for regenerating oak species, given their intermediate shade tolerance and reliance on advance regeneration (Greenler and Saunders 2019; Patterson et al. 2022; Clark et al. 2024c, 2024b).

Despite this potential, current silviculture guidelines published online by state agencies across the eastern USA rarely describe irregular shelterwood systems. Of 23 states that fall within the CHFR (Fig. 1), only 9 have silviculture guidance readily available online as of 2025 (Table 1). None of those states list irregular shelterwood as a primary regeneration method, but Connecticut, Wisconsin, and Minnesota describe irregular shelterwood as an appropriate choice for specific ecosystems or circumstances, and Virginia lists "periodic partial harvest" as an alternative option to clearcutting and shelterwood (Table 1). The limited availability of online, state-level information may not reflect the frequency of irregular shelterwood application, but it does give some indication of how little local guidance is easily accessible. With the three case studies that follow, we aim to illustrate how irregular shelterwood methods have been tailored to specific sites and objectives across the CHFR. This includes examples from the Cumberland Plateau (Kentucky, USA), the Driftless Area (Iowa, Minnesota, and Wisconsin, USA), and the Blue Ridge Mountains (North Carolina, USA). Each case study details the specific objectives each irregular shelterwood was designed to achieve, describes the irregular shelterwood methods prescribed following the framework proposed by Raymond et al. (2009), and quantifies harvest outcomes. Ultimately, we hope to increase the accessibility of irregular shelterwood methods by providing tangible examples and to demonstrate that variants of irregular shelterwood have immense potential for application in the CHFR as balancing economic, social, ecological, and adaptation objectives continues to increase in complexity and importance.

Case Studies

Cumberland Plateau (Kentucky, USA)

In 2012, an irregular shelterwood study focusing on regeneration of mixed oak forests in the Cumberland Plateau was established on Berea College Forest (Fig. 1). Oak regeneration in this ecological section can be problematic due to the diverse suite of competitors, including both shade intolerant and shade

Table 1 Summary of silviculture guidance for public and/or private land made available online by state agencies and the USDA Forest Service (through National Forest Land and Resource Management Plans) across the CHFR.

State/National Forest	Does a state agency provide state-specific silviculture guidance online?	Is irregular shelterwood listed as a primary regeneration method?	Do silviculture guidelines mention irregular shelterwood?	Notes	Source
Ozark-St. Francis National Forest (AR)	n/a	No	No	Shelterwood with reserves, a two-aged method, is listed among acceptable silvicultural systems	Ozark-St. Franics National Forest Land and Resource Management Plan, 2005
Connecticut	Yes	Yes	Yes	Irregular shelterwood is described as a method for achieving climate adaptation objectives	Connecticut Department of Energy & Environmental Protection 2024
Chattahoochee-Oconee National Forests (GA)	n/a	No	No	An Environmental Assessment finalized in October 2021 describes gap-based regeneration methods, including "expanding gaps" evaluated for the purpose of restoration and increasing structural complexity	Land and Resource Management Plan, Chattahoochee-Oconee National Forests, 2004; Foothills Landscape Project Environmental Assessment, 2021
Shawnee National Forest (IL)	n/a	No	No	Shelterwood with reserves, a two-aged method, is listed among acceptable silvicultural systems	Shawnee National Forest Land and Resource Management Plan, 2006
Indiana	Yes	No	No		Indiana Department of Natural Resources, 2022

Table 1 (continued)

State/National Forest	Does a state agency provide state-specific silviculture guidance online?	Is irregular shelterwood listed as a primary regeneration method?	Do silviculture guidelines mention irregular shelterwood?	Notes	Source
Hoosier National Forest (IN)	n/a	No	No		Hoosier National Forest Land and Resource Management Plan, 2006
Iowa	Yes	No	No		Iowa Department of Natural Resources 2023
Massachusetts	No	n/a	n/a	Some management plans for public land published online prescribe irregular shelterwood silvicultural systems. Silviculture resources from other agencies are referenced	Massachusetts Bureau of Forest Fire Control and Forestry 2025
Minnesota	Yes	No	Yes	Irregular shelterwood is described as a method relevant to white spruce management	Minnesota Department of Natural Resources 2012
Missouri	Yes	Yes	No	Two-aged shelterwood with reserves is listed as a primary regeneration method	Missouri Department of Conservation 2014
Mark Twain National Forest (MO)	n/a	No	No	Shelterwood with reserves, a two-aged method, is listed among acceptable silvicultural systems	Mark Twain National Forest Land and Resource Management Plan, 2005
New Jersey	Yes	No	No		New Jersey Forest Service, n.d

Table 1 (continued)

State/National Forest	Does a state agency provide state-specific silviculture guidance online?	Is irregular shelterwood listed as a primary regeneration method?	Do silviculture guidelines mention irregular shelterwood?	Notes	Source
Nantahala and Pisgah (NC)	n/a	Yes	Yes	Plan defines irregular shelterwood regeneration methods as "an expansion of two-aged structure representing a range of age structures bridging even-aged and balanced uneven-aged structures"	Nantahala and Pisgah National Forests Final Land Management Plan, 2023
Virginia	Yes	No	No	"Periodic partial harvest" is named as a regeneration practice	Virginia Department of Forestry 2025
Wisconsin	Yes	No	Yes	Irregular shelterwood is listed as a method relevant to northern hardwood and bottomland hardwood management	Wisconsin Department of Natural Resources 2020

States in the CHFR that do not appear to have silviculture guidance provided online by the DNR or a comparable agency and do not direct viewers to another resource are excluded from table: Alabama, Arkansas, Georgia, Illinois, Kentucky, Maryland, Michigan, New York, North Carolina, Ohio, Pennsylvania, Rhode Island, South Carolina, Tennessee, and West Virginia. Note that many of these states do publish best management practices online and also encourage landowners to seek professional assistance with a forest management plan for their property tolerant species, that proliferate on sites across a wide productivity gradient (Schweitzer and Dey 2011, Hackworth et al. 2020). The most notable competitors in the region are red maple (*Acer rubrum* L.) and yellow-poplar (*Liriodendron tulipfera* L.) whose central core of their ranges overlap within the Cumberland Plateau. The goal of the study was to develop an expanding gap irregular shelterwood method with potential to address challenges to oak regeneration common in the region's mature oak-dominated stands while also promoting species diversity, structural complexity, and forest health. The study examined how oak and its major competitors interact within 60 m (200 ft) diameter gap harvests and in a 30 m wide area of the forest matrix surrounding each gap. This gap size (0.3 ha), with a diameter approximately twice the height of the overstory canopy, was chosen based on research from the region indicating that the highest relative density of oaks occurs in intermediate-sized gaps, approximately 45 to 70 m wide (Lhotka et al. 2018). A midstory removal treatment, applied as a preparatory cutting ahead of future gap expansion, was implemented in the area surrounding some gaps, informed by results suggesting that the influence of edge environments on oak regeneration and growth can extend up to 20 m into stands adjacent to large regeneration openings (Lhotka and Stringer 2013).

The experiment was implemented across twelve study sites on Berea College Forest (Patterson et al. 2022). All sites were situated on lower slopes with elevations ranging from 300 to 350 m, and they were of intermediate site quality (upland oak site index at base age 50: 22–24 m). At the time of study establishment, the mean ages of the overstory ranged from 95 to 110 years. White oak (*Quercus alba* L.) and hickories (*Carya* spp.) were the predominant species groups in the overstory, while chestnut oak (*Q. montana* Willd.), black oak (*Q. velutina* Lam.), and scarlet oak (*Q. coccinea* Muench.) were present as minor overstory components. Additionally, the sites featured a dense midstory canopy, primarily composed of shade tolerant species like red maple, sugar maple (*Acer saccharum* Marshall), and blackgum *(Nyssa sylvatica* Marshall).

Gaps harvests were completed in fall/winter 2012–2013 by logging contractors (Fig. 2). Within each gap, all trees > 30 cm DBH were directionally felled, and harvested stems were whole-tree skidded to outside the gap for delimbing and bucking. Following the removal of trees > 30 cm DBH, all remaining trees in the gaps > 1.4 m tall were chainsaw felled. Surrounding the gaps, complete midstory removal was applied as an experimental treatment to half of the twelve sites. The midstory removal treatment was applied so that all non-oak stems in intermediate and overtopped crown classes with height > 1.4 m were chainsaw felled. An herbicide concentrate with a 50% solution of glyphosate was applied to all non-oak cut stumps to preclude stump sprouting.

Analysis of pretreatment regeneration surveys provided strong evidence that oak regeneration height and density were similar across the spatial extent of the gaps and surrounding forest matrix areas. Prior to treatment, mean height of oak regeneration among sites was 20.7 ± 1.4 cm (mean ± SE), and mean oak density was 22,480 ± 4,359 trees ha^{-1}. White oak was the most prevalent oak species sampled prior to treatment and represented 48% of all oak regeneration. Chestnut

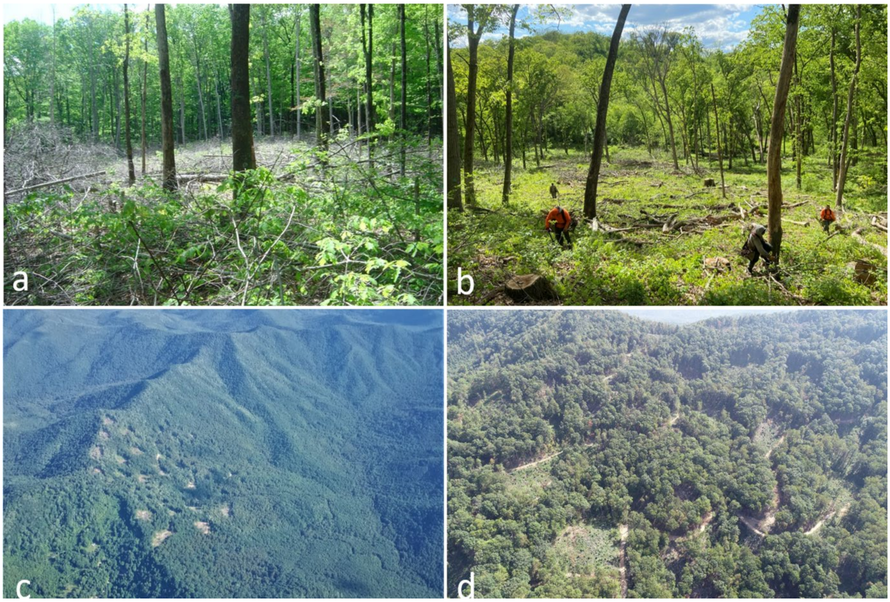

Fig. 2 Photographs of forest stands at Berea College Forest, KY, USA (**a**), Hallock Demonstration Forest, WI, USA (Driftless Area ASCC, **b**), and the Southern Appalachian Femelschlag Experiment, NC, USA (**c**, **d**) shortly following implementation of an irregular shelterwood as described in Table 2. Note that the effects of a midstory removal treatment are evident in the area surrounding gaps at Berea College Forest (a). The photo of the Driftless Femelschlag (b) illustrates both a stand-wide midstory removal and thinning of the matrix. Photo credits: John M. Lhotka (a), Bradley Hutnik (b), Kenny Frick (c), USDA Forest Service (d).

oak, scarlet oak, and black oak accounted for 25%, 16%, and 8% of observed oak regeneration, respectively.

Unlike the pretreatment data, a distinct spatial pattern in oak regeneration height was observed eight years following gap creation along sample transects that extended from each gap center to the outer margin of a 30 m wide midstory removal treatment area surrounding each gap. Oak regeneration was tallest in the gaps and spatial patterning in relation to gap center exhibited a sigmoidal shape with the most significant changes occurring within 10 m of gap edge. While the distance from the gap center was an important predictor of oak height, the midstory removal treatment had no effect on spatial patterning of oak regeneration heights.

When assessing the density of oak versus its competitors, results following eight growing seasons indicate that oak was disadvantaged by one or more species groups at all distances along the gap-edge-matrix extent surveyed. While a mean density of 6,400 trees ha^{-1} was found for white oak, the oaks were nearly universally outnumbered by red maple and other species groups. Very large densities (> 16,700 trees ha^{-1}) of red maple were present, and its densities were significantly higher in most portions of the forest matrix compared to gaps. A declining trend in yellow-poplar density was observed from the inner portion of gaps to the outer extent of the forest matrix. Results suggest that oaks had a density advantage over yellow-poplar in the forest matrix areas surrounding the gaps. Additionally, the density of white oak was similar to that of yellow-poplar within each gap and at gap edges.

Several important trends from this study are worth noting for broader implementation of expanding gap irregular shelterwood systems within the Cumberland Plateau. Across a small spatial footprint (1.13 ha), the study treatments successfully regenerated a diverse group of species, including shade intolerants like yellow-poplar, oaks possessing intermediate shade tolerance, and a suite of shade tolerant trees. Treatments were successful at promoting the development of oak advance regeneration. However, oaks were overtopped and outnumbered by other species across the gaps and forest matrix areas whether midstory removal was applied or not. Even within this overall pattern, there were two positive trends relative to the regeneration of oak. Results suggest that oaks were able to meet or exceed the height growth of red maple over the eight growing seasons after study implementation. Additionally, oaks located near the gap edge exhibited increased growth compared to those further into the matrix and demonstrated an improved height differential to the large suite of competitors when compared to inner gap locations.

The Driftless Area (Iowa, Minnesota, and Wisconsin, USA)

In 2024, a variant of continuous cover irregular shelterwood ("Driftless Femelschlag") was implemented across five replicate blocks in dry-mesic oak-hickory forests of the Driftless Area region through a collaborative effort involving the states of Iowa, Wisconsin, and Minnesota. Timber harvests are planned on an additional three blocks during the winter of 2025–2026. The Driftless Area (Fig. 1) escaped glaciation during the most recent two glacial advances and is distinguished from the surrounding region by unique geology, topography, and diversity of associated natural communities. Forests in the Driftless Area occupy over 2.3 million ha that has been characterized as a transition between species associated with the CHFR (e.g. white oak, shagbark hickory (*Carya ovata* (Mill.) K. Koch)) and northern hardwoods (e.g. sugar maple, yellow birch (*Betula alleghenіensis* Britt)). As is common across the eastern United States, oak-hickory forests in the Driftless Area have been impacted by land use change, fragmentation, altered disturbance regimes, and invasive species (Knoot et al. 2015). Regenerating oak is a common and challenging objective, in large part because of these impacts. Most Driftless Area forests are under private ownership (Knoot et al. 2015).

Prior to treatment, northern red oak (*Q. rubra* L.), white oak, sugar maple, and black walnut dominated the forest canopies study-wide. These forests are classified locally as MHs37, Southern Dry Mesic Oak Forest (Aaseng et al. 2011), and as the Southern Dry-Mesic Forest natural community in the Minnesota and Wisconsin native plant community systems, respectively. All sites are located on silt loam soils with mean stand ages ranging from 84 to 100 + years. Acceptable growing stock ranged from 38% – 75% of stand basal area.

The Driftless Femelschlag designed for this treatment addressed objectives related to *resilience* in the face of anticipated change as part of a larger, operational-scale Adaptive Silviculture for Climate Change (ASCC) (Nagel et al. 2025) study. This treatment essentially aimed to increase adaptive capacity of these forests by restoring historical woodland structure, species composition, and function. Other goals included increasing age diversity and horizontal structural complexity, encouraging fire-adapted and drought-tolerant species, maintaining mast-production for wildlife, and increasing the genetic diversity and response diversity of the tree community. The natural disturbance archetype (Palik et al. 2020) in these oak systems is best characterized by frequent low-severity fire disturbance, with low intensity surface fires every 1–20 years that created an open and spatially complex woodland with high-light conditions conducive to perpetuating intermediate shade tolerant species, such as oaks.

This disturbance regime and associated structure informed the development of the Driftless Femelschlag (Fig. 3) which creates three distinct structural conditions in each treated stand (Table 2, Fig. 3). The first harvest entry involved cutting 0.3 ha gaps (D:H = 2) with one legacy tree retained across approximately 20–25% of each

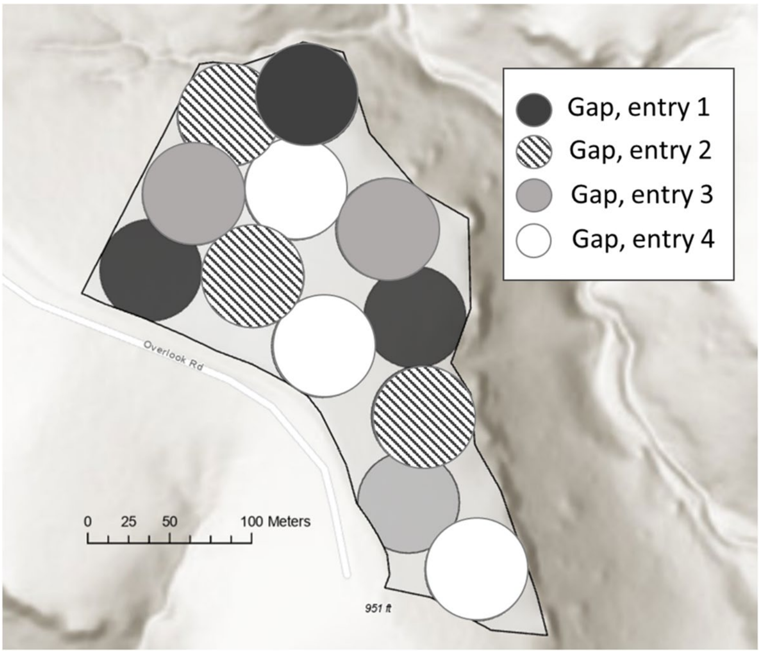

Fig. 3 Diagram illustrating the distribution of three different structural conditions created with the Driftless Femelschlag. The stand pictured is 4.6 ha in area, located at Yellow River State Forest, Harpers Ferry, IA. The 0.3 ha gaps labeled "entry 1" were harvested in 2025 with one dominant tree retained. The 0.3 ha gaps labeled "entry 2" were also harvested in 2025, but 50% cover was maintained as overwood. These gaps will be completely harvested (and become new gaps with 1 retained tree) in the second harvest entry. A similar sequence will follow with gaps marked for the third and fourth entries. The "matrix" (area outside of gaps marked for entry 1 or entry 2) was thinned in 2025.

Table 2 Examples of irregular shelterwood applications in the CHFR with associated terminology following Raymond et al. (2009). The canopy opening diameter (D): tree height (H) ratio is provided for area where possible following Hart (2016).

Silvicultural System and Description	Name used by authors and source	Objectives	Harvest details	Anticipated regeneration period	Location	Forest type and site characteristics	Associated treatments
Expanding Gap Irregular Shelterwood *Gap-sized openings are created by removal of one to a few trees with or without retention; Advance regeneration encouraged in gap edges is released with subsequent cuttings that expand the original gap openings; Intervals between harvests are long enough to create multi-cohort age structure with cohorts typically occupying concentric rings.*	Expanding gap irregular shelterwood (Patterson et al. 2022)	To encourage oak regeneration; to promote species diversity, structural complexity, and forest health	0.3 ha gaps (D:H = 2)	Indefinite; will depend on monitoring	Berea Forest, Cumberland Plateau (Kentucky, USA)	mixed oak forests	midstory removal

Table 2 (continued)

Silvicultural System and Description	Name used by authors and source	Objectives	Harvest details	Anticipated regeneration period	Location	Forest type and site characteristics	Associated treatments
	Southern Appalachian Femelshlag (Forrester et al. 2023)	To model natural disturbance; create within stand structural complexity; regenerate oak and hickory species	0.1 ha (small) and 0.4 ha (large) gaps created by harvesting merchantable stems > 30 cm DBH; gaps distributed across stand (small gaps post-harvest ranged from 0.14—0.44 ha) and large gaps ranged from 0.70 to 1.3 ha); expansions planned when competitive oak and hickory develop in the edge/matrix environment (~7—10 years). Expansions will be of irregular patterns around existing openings. Planned D:H = 1.0—2.1; Implemented D:H; 1.2—3.3	Regeneration harvests will be completed within the first 30 years, with a 'rest period' thereafter	Blue Ridge Mountains, North Carolina, USA	oak-hickory; SI = 26 m (upland oak, Olson 1959)	Site-prep included felling of all non-merchantable (stems 5–20.3 cm DBH) material left post-harvest within the gap except oak and hickory species; midstory removal of mesophytic, non- oak-hickory competitors (5–20.3 cm DBH) throughout the residual stand after gap creation; stump sprout control via basal bark application of herbicide of non-oak and hickory species sprouting in the gaps; artificial regeneration of white oak in a subset of gaps (see Clark et al. 2024b)
	Irregular shelterwood (Clark et al. 2024c)	To regenerate oak species	0.2 ha gaps	Unspecified	Tennessee, USA	oak-hickory; SI = 21 m (70 ft) (upland oak)	artificial regeneration; midstory removal of all non-oak and hickory stems 2.5–15.2 cm DBH (with herbicide injection); cleaning (release of saplings at 5 years)
	Expanding gap irregular shelterwood (Adams et al. in press)	To increase age diversity, structural complexity, species diversity, and environmental variability; to encourage oak and hickory regeneration	Eight 0.04 ha gaps, eight 0.1 ha gaps in each stand (20% of area harvested)	20–45 years	Vinton Furnace State Forest and Experimental Forest (Ohio, USA)	oak-hickory	Prescribed fire in spring immediately after harvest and repeated on 5-year interval; midstory removal; thinning from below; chemical site preparation
	Expanding gap irregular shelterwood (Adams et al. in press, https://adaptivesilviculture.org/ohio-hills/)	To increase age diversity, structural complexity, species diversity, and environmental variability; to encourage natural regeneration of oak and hickory; to increase adaptive capacity with enrichment planting of future-adapted species and genotypes	Five 0.2 ha gaps, three 0.4 ha gaps in each stand (20% of area harvested)	20–45 years	Vinton Furnace State Forest and Experimental Forest (Ohio, USA)	oak-hickory	Prescribed fire in spring immediately after harvest and repeated on 5-year interval; midstory removal; thinning from below; chemical site preparation

Table 2 (continued)

Silvicultural System and Description	Name used by authors and source	Objectives	Harvest details	Anticipated regeneration period	Location	Forest type and site characteristics	Associated treatments
Continuous cover irregular shelterwood *Gap-sized openings are created by removal of one to a few trees with or without retention; Size of gaps varies in order to encourage species of various shade tolerances but are never so large that regeneration is unaffected by mature canopy; Subsequent, periodic entries create new gaps and multi-cohort age structure.*	Driftless Femelschlag (https://adaptivesilviculture.org/driftless-area/)	To encourage oak and hickory regeneration, increase structural complexity and age diversity, restore historical woodland character	0.3 ha gaps with reserves; 0.3 ha gaps with 50% overwood; D:H = 2	Indefinite; regeneration harvests are planned for completion within 45–60 years with a subsequent rest period but exact timing will depend on monitoring	Driftless Area (Iowa, Minnesota, Wisconsin, USA)	oak-hickory	artificial regeneration, midstory removal of all non-oak and hickory stems 2.5—20.3 cm DBH; free thinning of matrix to 70% stocking; periodic prescribed fire (planned)

Table 2 (continued)

Silvicultural System and Description	Name used by authors and source	Objectives	Harvest details	Anticipated regeneration period	Location	Forest type and site characteristics	Associated treatments
Extended Irregular Shelterwood *Overwood is maintained for > 20% of rotation length and removal is incomplete (reserves are maintained); Overwood distribution is commonly even, but different patterns can be applied; Cohorts are vertically integrated.*	Extended two- or three- stage shelterwood (https://adaptivesilviculture.org/robinson-forest/)	To create variable structure with lower stocking rates of 60%; to encourage a shift to pine-oak dominated ecosystem; to increase species and structural diversity	0.4–0.6 ha gaps across 30–40% of treatment; matrix density reduced to 50–55% stocking (Gingrich 1967); periodic harvest to maintain density levels; final removal while retaining some mature reserve trees to promote 3rd age class		Proposed for University of Kentucky Robinson Forest (Kentucky, USA)	oak-hickory	Periodic prescribed fire may be used before or after the initial shelterwood treatments once oak species are able to remain competitive

stand (Fig. 2). Additionally, 0.3 ha partial gaps with 50% overwood retained were also installed across 20–25% of each stand. These partial gaps will be harvested during the second entry (with one legacy tree retained), and new partial gaps will be created (Fig. 3). To simplify long-term implementation and monitoring, the location of future gaps has already been determined (Fig. 3), but this may be adapted over time in response to observations of inventory data. The remainder of the stand ("matrix"), including those areas designated as future gaps, was thinned. As prescribed, this thinning treatment involved targeted release of high quality, healthy, dominant white oak, northern red oak, and black walnut where they occurred combined with low thinning to reduce the stocking to 70%.

Additional treatments incorporated into the silvicultural system included a stand-wide midstory removal in which all non-oak or hickory hardwoods 2.5–20.3 cm in diameter at breast height (DBH) were cut and treated. Mechanical cutting and basal bark herbicide application were used to control non-native, invasive shrubs including Amur honeysuckle (*Lonicera maackii* Rupr.), common buckthorn (*Rhamnus cathartica* L.), multi-flora rose (*Rosa multiflora* Thunb.), and other species. During spring 2023, prior to the first harvest, native, fire-adapted, mast-producing species were underplanted at a density of 500 trees ha^{-1}. These species included white oak, northern red oak, bur oak (*Q. macrocarpa* Michx.), black oak, black walnut, shagbark hickory, and black cherry (*Prunus serotina* Ehrh.). Planting of most of the same species also occurred post-harvest in April and May, 2025 at the same density. Unfortunately, sufficient stock of shagbark hickory was not available in 2025, but chinkapin oak (*Q. muehlenbergii* Engelm.) seedlings (unavailable in 2023) were included in the 2025 planting mix.

Future management will include prescribed fire and a continuation of the harvest entry regime described above. Fire is an important component of the natural disturbance regime and, silviculturally, will prepare the seedbed in areas where regeneration is planned as well as release newly established regeneration from competing vegetation and generally enhance the competitive advantage of fire-adapted species (Brose et al. 1999; Brose 2014).

The Southern Appalachian Femelschlag Experiment (North Carolina, USA)

The complex topography of the southern Appalachian Mountains – characterized by steep slopes, varied elevations, and diverse landforms – creates strong environmental gradients in temperature, moisture, and edaphic conditions, all of which interact with complex disturbance regimes to support a high diversity of habitats and species. Although forests of the southern Appalachians are diverse, the oak-hickory cover type dominates the landscape (Keyser et al. 2014). Like many forests across the eastern USA, these oak-hickory forests regenerated in the early twentieth century after widespread exploitive logging and are predominantly mature (> 80 years) and even-aged with a closed canopy (Hutchinson et al. 2008; Grover et al. 2023). Oak species dominate the overstory, but contemporary land use practices, including fire exclusion, have facilitated the development of a dense midstory comprised by shade tolerant and mesophytic species (Woodbridge et al. 2022). Left unchecked, the successional trajectory away from oak and hickory towards mesophytic species will negatively impact the sustainability of myriad ecosystem services, including wildlife habitat and food resources (McShea et al. 2007), water supply (Caldwell et al. 2016), and carbon storage capacity (Brzostek et al. 2014).

Traditional forest management approaches, including even-aged, two-aged, and uneven-aged regeneration methods, have proven ineffective at regenerating oak and hickory forests in the southern Appalachians, particularly on productive sites. Intense, punctuated harvesting conducted as part of conventional even- and two-aged regeneration methods often accelerate forest mesophication by converting diverse oak-hickory forests to monocultures of yellow-poplar (Swaim et al. 2018; Beasley et al. 2022) or black birch (*Betula lenta* L) (Miller et al. 2006). An assessment of 0.05 ha gaps suggested that even openings this small may fail to regenerate oak and hickory and facilitate the establishment, growth, and recruitment of shade intolerant yellow-poplar (McNab and Oprean 2021), but later and more detailed spatial analyses of the same gaps revealed that patterns are more nuanced. Competitive (dominant, co-dominant, intermediate) oak and hickory regeneration were present and clustered in the western portion and periphery of the 13-year old harvest gaps (Schnake et al. 2025). In this context, the expanding gap irregular shelterwood system (Bavarian femelschlag) emerges as a promising strategy to restore and manage southern Appalachian oak forests. By retaining a mosaic of tree ages and sizes while periodically opening the canopy, this system can mimic natural disturbance regimes, promote regeneration of oak and hickory as well as other species intermediate in shade tolerance, and restore structural complexity.

In 2014, an irregular shelterwood study, modeled after the Bavarian Femelschlag variant, was established on a 60.7 ha stand in the Blue Ridge Mountains section of the Central Appalachian Broadleaf Forest Province (Cleland et al. 2007) of the Pisgah National Forest in western North Carolina (Fig. 1). Elevations of the study site ranged from 700–1070 m, with slopes between 10 and 90% (Arteman 2024; Grover et al. 2023). Goals were multifaceted but centered on regenerating oak and hickory species while creating high levels of within-stand structural complexity that creates diverse wildlife habitats across space and time. Initial stand conditions were typical of mature southern Appalachian mixed-oak forests. A mixture of oak (white oak, chestnut oak, northern red oak, scarlet oak, black oak) and yellow-poplar with ages ranging 95 to 150 years (Grover et al. 2023) dominated the overstory ($\geq$12.7 cm DBH) while the midstory ($\geq$1.5 cm and $<$12.7 cm DBH) was dominated by shade tolerant species, such as red maple, sourwood (*Oxydendrum arborea* L), and blackgum. The seedling layer ($<$1.5 cm DBH) was abundant and diverse. Although oak and hickory seedlings were numerous, stems were small ($<$0.6 m tall) and outnumbered by taller, more competitive non-oak and hickory seedlings.

Initial harvests occurred in winter/spring 2019 and involved creating gaps that, post-harvest, comprised ~ 50% of the total stand area (Fig. 2). All merchantable trees ($>$30.5 cm DBH) were hand-felled and removed via skidders and forwarders. Non-merchantable stems (5.1–20.3 cm DBH) were slashed post-harvest and remained on site. Immediately after harvest, a midstory removal treatment (Loftis 1990) was conducted throughout all non-gap areas of the 25-ha stand, whereby mesophytic species (5.1–20.3 cm DBH) were deadened with a stem injection of herbicide in anticipation of increasing light from the gap into the forest matrix. The original prescription planned for gaps of two size classes: small (0.1 ha) and large (0.4 ha). These gap sizes represent the upper limit of gap sizes created during small-scale disturbance (e.g., gap-phase dynamics) (Runkle 1982) as well as under more intermediate scale/severity disturbance (e.g., tropical storm wind events) (McNab et al. 2004). Operationalizing an expanding gap irregular shelterwood system in a topographically challenging environment while considering road networks required to implement both initial harvests and future expansions led to larger gaps than originally planned. Following harvest, an assessment including all 70 gaps showed that the area of small and large gaps averaged 0.23 and 0.95 ha, respectively. A suite of ecological attributes was examined during post-harvest inventories to examine the spatial dynamics of responses to gap creation, including tree regeneration, vegetation structure and composition, carbon dynamics, soil microbial activity, water-use, and breeding bird communities, among others.

Early results demonstrate the ecological response to the initial irregular shelterwood harvest varies across the gap – forest transition. Light availability was highest in the gaps, with the northern edge and forest matrix receiving 63% and 11% of the daily light in the gap, respectively (Arteman 2024). Interestingly, photosynthetic rates and associated carbon gain values of oak and hickory were greater than yellow-poplar and red maple in both the gap and gap edge environment, but this pattern was not observed in seedling density metrics, where yellow-poplar dominated the gaps and oak and hickory in the gap edge. Productivity of the groundlayer vegetation and total belowground carbon allocation were highest in the center of the gaps and declined markedly at the edge and beneath the surrounding canopy (Snyder 2025). Species composition was least variable in gap centers, with plant cover dominated by *Rubus* species, yellow-poplar, and vines compared to locations with intact canopy cover. Mature trees bordering canopy gaps can exhibit growth releases due to the increased access to light, moisture, and/or nutrients (Pedersen and Howard 2004). Four years after harvest, overstory trees (≥ 12.7 cm DBH) directly adjacent to the gaps exhibited a 48% increase in growth compared to only 9% for trees within 25 m of the gap edge, with red maple and yellow-poplar more responsive to the edge environment than oak species (Reddy et al. 2025).

Subsequent analysis of seedling responses by species and size class will guide second-entry gap expansion to optimize oak and hickory regeneration and recruitment. Expansions will be focused on releasing competitive oak and hickory seedlings that developed in response to the creation of harvest gaps in the initial entry. If the patterns documented by Schnake et al. (2025) around group selection harvest gaps align with the Appalachian Femelschlag, expansions will be prioritized around the western and north-western edges where we may expect to find ‘hot spots’ for oak and hickory regeneration.

Climate Adaptation

The case studies presented in this paper largely focused on describing applications of ecological silviculture, silviculture with a strong basis in knowledge and understanding of natural dynamics, structure, and function in each respective forest ecosystem.

In each case, adaptation objectives were also achieved. In the Berea College Forest study, greater structural complexity and the creation of a wide gradient in light conditions (ranging 9–86% full sunlight) led to an increase in species diversity by facilitating regeneration of species across the shade tolerance spectrum (Patterson et al. 2022). The Southern Appalachian Femelschlag also increased within-stand structural complexity and, if recruitment to the canopy is successful, the regeneration of oak and hickory species near gap edges will increase relative adaptability compared to mixed mesophytic forests (Forrester et al. 2024).

The potential for compatibility between ecological and adaptation silviculture is readily apparent in treatments co-designed by manager-scientist teams for three Adaptive Silviculture for Climate Change (ASCC) studies across the CHFR. This includes the Driftless Area ASCC study (IA, MN, WI; Fig. 1), the Ohio Hills ASCC study at Vinton Furnace State Forest and Experimental Forest in Ohio (Adams et al. in press), and a study proposed for the University of Kentucky Robinson Forest (KY). At a minimum, the ASCC studies investigate forest response to four treatments: resistance (reduce impacts and maintain relatively unchanged conditions), resilience (accommodate some change but encourage return to a desired reference condition), transition (intentionally accommodate change), and a passive no-action control (Nagel et al. 2017, 2025). Each of these three ASCC studies in the CHFR region include increased structural complexity, multi-cohort age structures, and regeneration of oak and hickory species in desired future conditions for both resilience and transition treatments. Generally increasing complexity and maintaining or increasing species diversity increases the adaptive capacity of these forest stands by providing a variety of successional pathways (D'Amato and Palik 2020). Encouraging regeneration of oak and hickory not only accomplishes objectives related to conserving native biodiversity, providing mast for wildlife, and producing valuable timber products, it is also expected to confer greater resilience to forests impacted by more extreme conditions and interacting stressors, considering the generally higher adaptability of these two genera (Iverson et al. 2012; Peters et al. 2020). To achieve these and other objectives, all three studies also prescribe irregular shelterwood methods combined with prescribed fire and midstory removal for the resilience and/or transition treatments.

The Driftless Femelschlag, described in greater detail above, is a variant of continuous cover irregular shelterwood (Table 2; Figs. 2, 3). The structure created is intended to increase resilience to impacts from anticipated water stress and conditions favorable for wildfire, largely by adding age diversity, reducing stand density, opening the midstory, and encouraging oak and hickory regeneration like the other ASCC studies mentioned. At the same time, the diversity of conditions created by this variant of irregular shelterwood is also expected to maintain existing species richness while providing suitable growing conditions for planted seedling stock (including assisted population enrichment (Clark et al. 2024a)) selected to increase the genetic diversity, functional redundancy, and response diversity (Elmqvist et al. 2003) of the tree community. These latter outcomes are more associated with adaptation than with ecological silviculture (D'Amato and Palik 2020).

The transition treatment collaboratively developed for an ASCC study proposed for the University of Kentucky Robinson Forest (KY) prescribes an extended irregular shelterwood (Table 2). In addition to objectives already mentioned, this silvicultural system should increase resource availability for canopy trees by lowering residual stocking to 60%. By reducing overall stand density, less competition for resources should confer greater resistance to drought and mitigate the risk of decline that can result from multiple, interacting climate-related stressors like invasive pests, pathogens, and extreme weather. Lastly, this treatment includes consideration of existing variability within each stand and will promote transition to an oak-pine forest type on drier soils (e.g., ridges and southern aspects) (Table 2).

Both the resilience and the transition treatments developed for the Ohio Hills ASCC study apply expanding gap irregular shelterwoods (Table 2, Adams et al. in press). While both treatments involve creating gaps of two sizes and harvesting approximately 20% of each stand in the first entry, the size and number of gaps created differs (Adams et al. in press). The resilience treatment created 0.04 and 0.1 ha gaps to encourage natural regeneration of oak and hickory species that can be released by gap expansion 10–15 years in the future. The transition treatment created fewer, larger gaps (0.2 and 0.4 ha in area) to actively shift species composition via artificial regeneration (including assisted population migration and range expansion (Clark et al. 2024a)) to accommodate anticipated conditions (Adams et al. in press).

The ASCC studies in the CHFR are new, so results are still forthcoming, but these operational-scale experimental applications of irregular shelterwood have great potential to add to existing knowledge and guide implementation in the region in the near future.

Recommendations for Addressing Barriers to Implementation

While irregular shelterwood methods offer some potential advantages for facilitating natural regeneration of oak and hickory species compared with selection and conventional even-aged silvicultural systems, they do not guarantee successful regeneration of these species. Despite creating an appropriate light environment for species with intermediate shade tolerance, and some encouraging results related to oak regeneration, successful establishment, recruitment and upper canopy persistence of oak and hickory species is still hindered by common challenges (Clark et al. 2024c). To be successful, an irregular shelterwood needs to be applied as a full silvicultural system that addresses barriers to regeneration, recruitment, and long-term growth through practices like site preparation (e.g. Adams et al. in press), intermediate treatments (e.g. Loftis 1990; Ward 2008; Gottschalk et al. 2014), prescribed fire (e.g. Greenler and Saunders 2019), and strategic timing that is carefully informed by monitoring as illustrated by the case studies presented in this paper. These approaches, when tailored to the needs of a particular site, have potential to address long-standing challenges related to fire exclusion, mesophication, competition, and browse pressure.

Unfortunately, many landowners lack the resources necessary to implement additional treatments, monitor responses, and adapt management accordingly. The absence of pulpwood and other small diameter tree markets across most of the region means recommended treatments, such as midstory removal, require investment. Irregular shelterwood methods also produce more limited timber sale volumes and involve more complicated logging operations relative to even-aged methods. While these methods are feasible and profitable when stands are large enough, stand merchantability and landowner interest in maximizing immediate financial benefits (over long-term forest sustainability) presents a significant barrier to implementation, particularly on smaller properties. This may prevent irregular shelterwood methods from being appropriate on small woodlots managed by private landowners. If expanded, cooperative efforts that leverage access to multiple properties in order to increase the feasibility of conservation-minded forest management could address some of these limitations and enable wider adoption of irregular shelterwood methods. The Forest Bank program in Indiana, a conservation option offered by The Nature Conservancy and certified by the Forest Stewardship Council, provides one example that might be modeled elsewhere. Also, private landowners who have defaulted to managing forests and woodlands in the CHFR passively (or exploitatively through high-grading) because of resistance to the perceived disturbance created by harvest (e.g. Knoot et al. 2015) may be motivated by ecological and adaptation objectives and become more likely to actively manage their properties to conserve forest ecosystem function if presented with irregular shelterwood as an option.

Because irregular shelterwood systems are flexible and often employ multiple harvest entries with impacts intentionally varied across space and time, there is risk that some will perceive these systems as having no constraints, leading to exploitative cutting. Successful application of irregular shelterwood requires sufficient wood quantity and quality to support a series of harvests (Bédard et al. 2014); where that is not present, stand quality could be degraded rather than improved over time. Thus, confusion over definitions of irregular shelterwood methods and insufficient expertise for applying them effectively are also significant barriers. Although institutions like the USDA Forest Service have produced outreach materials that promote and describe irregular shelterwood methods (e.g. Kern 2021), clear and detailed guidance for how to apply them is largely absent from online materials provided by state agencies (Table 1). Improved communication of irregular shelterwood prescriptions and an increase in available demonstration sites will help address existing confusion around terminology and mitigate potential problems resulting from inappropriate application. The tension that exists between maintaining accessible terminology and effectively communicating nuance and complexity is not unique to silviculture, nor is it new. In the words of Frederick Baker (1934), "We have the [silvicultural] systems confused with rigidity; actually, they are just as flexible as silvical conditions require. To apply them flexibly requires a minimum of rules and a maximum of silvicultural art." Others have provided definitions and worked to connect similar terms in an effort to reduce confusion and facilitate better communication (Raymond et al. 2009; Ashton and Kelty 2018; Trentanovi et al. 2023; Palik and D'Amato 2024; Trerise et al. 2025). With this review, we aim to support that effort by providing examples of irregular shelterwood systems that have been tailored to specific forest types and sites within the CHFR with quantified structural objectives and outcomes so that foresters across the CHFR can see how others have applied the "art of silviculture" and hone their own practice.

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Data Availability The data presented in this review are available upon request from the authors. This review largely references previously published work, and the limited empirical data presented serve the purpose of generally supporting assertions made about Berea College Forest case study outcomes. Analysis of these data is ongoing and will be presented in another manuscript currently in preparation.

Declarations

Competing interests The authors declare there are no competing interests.

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