Natural Regeneration of Eastern Hemlock: A Review

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Abstract

Successful regeneration of eastern hemlock involves a complex biophysical process that commonly spans many years. Critical factors include a reliable source of seed, a suitable seedbed, a partially shaded environment, and several years of favorable moisture. Surface scarification appears critical as a means of site preparation. Even then, young hemlocks grow slowly, and commonly take several years to reach a size suitable for overstory release. Uniform partial cutting, shelterwood method, and patch cutting have all proven effective as strategies for regenerating hemlock. Reserve strip cutting also appears promising.

Silvical Characteristics of Eastern Hemlock *(Tsuga canadensis*)

Eastern hemlock has high shade tolerance (Burns 1923, Graham 1943, Baker 1949, Tubbs 1978, Lancaster 1985, Anderson and Gordon 1994, Tubbs 1996). It regenerates at even 5% of full sunlight (Hough 1960, Anderson and Gordon 1994, Tubbs 1996), and develops in as little as 20-25% light (Hough 1960, Logan 1973, Anderson and Gordon 1994). Saplings may not form growth rings under dense shade (Hough 1960), and those trees show little relationship between diameter and age (Marshall 1927). Due to its high shade tolerance, 50 to 100 year old understory hemlock may only be a few inches in diameter (U.S. For. Serv. 1970).

Hemlock has a shallow root system (Frothingham 1915, Clepper 1934, Lancaster 1985) and can thrive in shallow soil (Frothingham 1915, Clepper 1934), though roots develop down into deep soils as well (Frothingham 1915, Clepper 1934). It develops mycorrhizal associations for nutrient absorption (Harlow 1900). Root respiration may depend on changes in temperature and the rate of photosynthesis (Szaniawski and Adams 1974), and root growth rather than shoot growth may limit survival at low light levels (Anderson and Gordon 1994).

Hemlock grows in a range of soils (Frothingham 1915, Merrill and Hawley 1924, Fowells 1965, U.S. For. Serv. 1970, Godman and Lancaster 1990), and has low mineral nutrition requirements (Hough 1960). Even so, it develops best on wet-mesic to mesic sites (Farr and Tyndall 1992, Kotar 1996), and moist to very moist soils with good drainage (Frothingham 1915, Clepper 1934, Hough 1960, U.S. For. Serv. 1970, Tubbs 1978, Wendel et al. 1983, Godman and Lancaster 1990, Anderson and Gordon 1994, Tubbs 1996). It also occurs on dry, shallow tills (Frothingham 1915, U.S. For. Serv. 1970, Tubbs 1978, Anderson and Gordon 1994); sandy soils (U.S. For. Serv. 1970, Tubbs 1978); interspersed within wet swamps (Anderson and Gordon 1994); on some wet, swampy borders (Anderson and Gordon 1994); acidic soils (Wendel et al. 1983); loams (Frothingham 1915, U.S. For. Serv. 1970); silt loams with neutral soil reaction (Wendel et al. 1983); soils with impeded drainage (Frothingham 1915, Tubbs 1996); and on north or northwest facing rocky slopes (Wendel et al. 1983, Anderson and Gordon 1994).

Hemlock may grow better than hardwoods on dry, sandy, or rocky sites if the trees become established in non-drought years or in moist niches (Nienstaedt and Olson 1955). It is often found on lower slopes and flats, frequently bordering lakes that influence humidity levels over the site (Anderson and Gordon 1994). Hemlock does occur in pure stands (U.S. For. Serv. 1970, Farr and Tyndall 1992), and mixed with other species (U.S. For. Serv. 1970). It grows with eastern white pine *(Pinus strobus* L.*)* in stands originating after fire, windthrow, or other catastrophic disturbances (U.S. For. Serv. 1970). On favorable sites, hemlock usually forms a climax association (U.S. For. Serv. 1970). Yet on sites rich in nutrients, it succumbs to sugar maple (*Acer saccharum* Marsh.) and other associated hardwoods (Kotar 1996). Hemlock may never have dominated those sites in the past, and will not likely become a major component on them in the future (Kotar 1996).

The microclimate under hemlock stands is cooler than under hardwoods (Moore et al. 1924, Tubbs 1996). The soils there also show greater fluctuations in air temperature than those under neighboring stands (Friesner and Potzger 1932), with an average soil temperature slightly lower than under mixtures of American beech *(Fagus grandifolia* Ehrh.*)* and maple (Moore et al. 1924, Daubenmire 1931). Soil surfaces are also drier (Daubenmire 1931, Friesner and Potzger 1932, Friesner and Potzger 1936, Tubbs 1996) due to crown interception of precipitation (Tubbs 1996). As a result, pure hemlock stands seldom have an understory of tree regeneration (Daubenmire 1931, Tubbs 1996). Soils under established stands are also acidic (Fowells 1965, Godman and Lancaster 1990), ranging from pH 3.6 to 4.7.

Seed Development, Dispersal, and Germination

Hemlock is one of the most frequent and abundant cone producers among the eastern conifers (Crow 1996). It produces some seed annually (Ruth 1974), with good crops at 2 to 3 year intervals (Frothingham 1915, Merrill and Hawley 1924, Clepper 1934, Swift 1948, Hough 1960, Fowells 1965, U.S. For. Serv. 1970, Ruth 1974, Anderson and Gordon 1994). Seed production begins between 20 and 40 years of age (Hough 1960, Fowells 1965, Ruth 1974, Wendel et al. 1983, Anderson and Gordon 1994, Crow 1996), but later among trees in the shade (Frothingham 1915, Hough 1960, Fowells 1965, Ruth 1974). In fact, low-vigor trees beneath a dense canopy

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(Hough 1960, Anderson and Gordon 1994) and shaded portions of crowns (Tubbs 1996) do not produce seeds regardless of age (Hough 1960, Fowells 1965, Anderson and Gordon 1994, Tubbs 1996). Mature, dominant trees continue to produce seeds up to 450 or more years old (Hough 1960, Fowells 1965, Crow 1996).

Male and female strobili develop in clusters near the ends of lateral branches (Frothingham 1915, Hough 1960, Ruth 1974). Flowering varies from April to early June (Frothingham 1915, Hough 1960, Fowells 1965, Ruth 1974, Tubbs 1996), depending on the topography and climate (Frothingham 1915, Hough 1960, Fowells 1965). The male (staminate) flower is round, yellow, and approximately ¼-in long (Clepper 1934), becoming well formed by the end of July (Frothingham 1915, Hough 1960, Fowells 1965). Pollen disperses by wind (Frothingham 1915, Hough 1960) approximately 2 weeks following leaf bud burst (Frothingham 1915). It is sensitive to dry weather, a common cause of fertilization failure (Frothingham 1915, Tubbs 1996). Fertilization takes place within roughly 6 weeks following pollination (Frothingham 1915; Nienstaedt and Kriebel 1955; Olson et al. 1959a, 1959b). Then female (pistillate) flowers grow rapidly, and become mature cones by September or October (Frothingham 1915, Clepper 1934, Swift 1948, Hough 1960, Fowells 1965, Ruth 1974).

Cones change from pale green to dark brown during ripening (Frothingham 1915, Clepper 1934, U.S. For. Serv. 1970). They commonly measure between ½- to ¾-in long (Frothingham 1915, Clepper 1934, U.S. For. Serv. 1970), and ½- to ¾-in wide with scales expanded (Frothingham 1915). Cones remain on a tree during the first winter (Clepper 1934). Generally, between 30 and 60% of the seed is viable (Frothingham 1915), with the number per pound reported at 169,800 (Heit and Eliason 1940), 185,000 (U.S. For. Serv. 1970), 190,527 (Toumey and Stevens 1928), 400,000 (Frothingham 1915, Clepper 1934), and 132,000 to 360,000 (Hough 1960). Only about 20 scales in the central part of the cone bear seed (Hough 1960).

Seed dispersal begins during fall following cone maturity (Frothingham 1915, Baldwin 1930, Hough 1960, Fowells 1965, Ruth 1974, Tubbs 1996), and may continue throughout winter (Frothingham 1915, Baldwin 1930, Hough 1960, Fowells 1965, Ruth 1974, Anderson and Gordon 1994, Tubbs 1996). Seeds that remain in the cones over winter are usually sterile (Frothingham 1915; Olson et al. 1959a, 1959b). Cone scales open in dry weather and close when moistened, or in times of high humidity (Frothingham 1915, Clepper 1934, Hough 1960, Fowells 1965, Tubbs 1996). As a consequence, seed disperses only in dry periods (Hough 1960, Fowells 1965, Tubbs 1996) and particularly during dry, windy days (Frothingham 1915; Hough 1960; Fowells 1965; Olson et al. 1959a, 1959b). This alternate opening and closing of the cone scales results in seed dispersal over a protracted period (Clepper 1934, Frothingham 1915). Varying winds distribute the seeds in many different directions (Frothingham 1915, Clepper 1934), and even for up to 1 mile across crusted snow in a strong wind (Frothingham 1915, Fowells 1965, Anderson and Gordon 1994, Crow 1996, Tubbs 1996). Yet most seeds fall within one tree height of the parent (Hough 1960, Tubbs 1996).

Rodents feed on seeds of eastern hemlock (Frothingham 1915, Abbot 1962, Fowels 1965), even rejecting larger ones of other species that contain natural repellants (Abbot 1962). This reduces the supply to some degree. Germination of those that escape predation generally occurs from March to late May (Lloyd 1900, Frothingham 1915, Baldwin 1930, Hough 1960), but as late as June or July at northern latitudes (Hough 1960, Fowells 1965). The germinative capacity is low (Frothingham 1915, Baldwin 1930, Hough 1960, Fowells 1965, La Madeleine 1980, Tubbs 1996) and variable (Stearns and Olson 1958), reportedly ranging from less than 25% (Frothingham 1915, Wendel et al. 1983), 20 to 30% (Hough 1960, Fowells 1965), 30 to 60% (Frothingham 1915), 44% (Toumey and Stevens 1928), and as high as 40 to 60% (Hough 1960).

Germination begins in spring as the temperatures rise (Olson *et al*. 1959a, 1959b), and becomes optimal with a constant temperature of 55-62 °F (Frothingham 1915; Olson et al. 1959a, 1959b; Ruth 1974; Wendel et al. 1983; Crow 1996). A high percentage of germination can occur at 44 to 64°F (Frothingham 1915, Wendel et al. 1983), but constant temperatures below 55°F or above 70°F hinder germination (Olson et al. 1959a, 1959b). Seeds require from 45 to 60 days to reach peak germinative energy (Frothingham 1915, Wendel et al. 1983).

Conditions for Seedling Establishment and Survival

Regeneration failures with hemlock have been attributed to low seed input, poor seedling establishment or limited recruitment among established seedlings (Waller et al. 1996), smothering from hardwood leaf fall (Hough 1960; Fowells 1965; Olson 1954; Olson et al. 1959a, 1959b; Anderson and Gordon 1994; Tubbs 1978, 1996), thick leaf litter (Friesner and Potzger 1932, Tubbs 1978, Anderson and Gordon 1994, Waller et al. 1996), excess moisture (Lloyd 1900, Baldwin 1934, Ward and McCormick 1982), allelopathy (Ward and McCormick 1982), unfavorable soil pH (Ward and McCormick 1982), competition from herbaceous vegetation (Wagner and Joseph 1996) and hardwoods (Lorimer 1996), too much shade (Frothingham 1915, Ward and McCormick 1982, Wendel et al. 1983), and too little shade resulting in sunscald (Frothingham 1915, Hough 1960, Ward and McCormick 1982, Wendel et al. 1983, Crow 1996). Yet even when most of the requisite conditions may seem favorable, only periodically do seedlings establish in large numbers (Lorimer 1996, Tubbs 1996, Waller et al. 1996). Even then, an abundance of seedlings does not necessarily portend a long-term regeneration success (Kotar 1996). Numerous seedlings may appear following favorable germination conditions, only to die during periods of drought within 2 or 3 years (Kotar 1996). In fact, studies indicate that 88% of seedlings may die during the first year, but that the chance of survival increases annually for the first 5 to 6 years.

Seed and seedlings are particularly vulnerable to soil moisture stress (Frothingham 1915; Fowells 1965; Olson and Nienstaedt 1953; Olson et al. 1959a, 1959b; Coffman 1978; Ward and McCormick 1982; Wendel et al. 1983; Lancaster 1985; Anderson and Gordon 1994; Crow 1996, Tubbs 1996; Waller et al. 1996) and establishment depends upon the amount of precipitation received during several successive years following germination (Friesner and Potzger 1944), especially on organic soils (Collins 1990, Anderson and Gordon 1994). In experiments, seeds deliberately dried for between 2 and 6 hours were damaged at rates of 60 to 80%, respectively (Olson et al. 1959a, 1959b). Similarly, seedling mortality and root damage may follow exposure to full sunlight (Lancaster 1985, Tubbs 1996) after excessive release by cutting (Anderson and Gordon 1994) and high evaporation of soil moisture (Lancaster 1985)

Core samples reinforce these observations and indicate that hemlock establishment is sensitive to weather variations (Graham 1943), and particularly periods of drought (Frothingham 1915, Stickel 1933, Clepper 1934, Graham 1943, Hough 1960, Fowells 1965, Lanasa et al. 1996, Lorimer 1996, Tubbs 1978, Wendel et al. 1983, Wagner and Joseph 1996). In fact, establishment occurs in dry areas only during years with greater than normal rainfall (Hough 1960. Fowells 1965). Overall, reproduction of hemlock depends upon a good seed year, followed by a good germinating year, and then several years with favorable moisture conditions (Friesner and Potzger 1944, Waller et al. 1996).

Partial shade favors seed germination (Logan 1973, Nienstaedt and Olson 1955) and enhances seedling survival (Nienstaedt and Olson 1955, Tubbs 1996). Yet available reports disagree whether hemlock regenerates best on warm, moist sites (Frothingham 1915, Crow 1996), or on shaded, moist, cool sites (Hough 1960, Fowells 1965, Anderson and Gordon 1994). Also, reports vary about ideal ground conditions for seedling establishment. Good seedbeds reportedly include: exposed mineral soil (Frothingham 1915, Hough 1960, Davis and Hart 1961, Fowells 1965, Wendel et al. 1983, Lorimer 1996, Tubbs 1996); a mixture of mineral soil and humus (Olson 1954, Davis and Hart 1961, Wendel et al. 1983, Lancaster 1985, Anderson and Gordon 1994); soils rich in organic matter (Lloyd 1900, U.S. For. Serv. 1970); moist and well decomposed litter (Frothingham 1915, Baldwin 1930, Graham 1943, Hough 1960, Fowells 1965, Tubbs 1996, Wendel et al. 1983, Anderson and Gordon 1994); ground covered to some depth with decaying leaves and twigs (Harlow 1900, Frothingham 1915); burned areas (Maissurow 1941, Miles and Smith 1960, Lorimer 1996, Tubbs 1996, Waller et al. 1996); coarse, woody debris (Corinth 1996); moss mats on soil, rocks, and fallen trees (Frothingham 1915, Friesner and Potzger 1932, Olson 1954, Hough 1960, Fowells 1965, Wendel et al. 1983, Collins 1990, Anderson and Gordon 1994, Lorimer 1996); thin litter (Friesner and Potzger 1932, Olson 1954, Collins 1990, Lorimer 1996, Waller et al. 1996); sloping soil where the seeds can lodge and root (Friesner and Potzger 1932); pit and mound topography (Anderson and Gordon 1994); areas free of understory vegetation (Lancaster 1985), such as grass or other tightly growing herbaceous plants (Lloyd 1900); and soils with suitable acidity levels (Potzger and Friesner 1936).

Like other species with a small seed, conditions on undisturbed seedbeds will not commonly lead to establishment of large numbers of seedlings (Godman and Mattson 1976). New germinants grow slowly, with weak radicals that do not develop in unfavorable conditions (Godman and Mattson 1976). Though seed will germinate on rotten wood (Lloyd 1900, Frothingham 1915, Olson 1954, Hough 1960, Fowells 1965, Ward and McCormick 1982, Wendel et al. 1983, Anderson and Gordon 1994, Lorimer 1996, Tubbs 1996), seedlings grow and develop poorly in that medium (Tubbs 1996). Consistent with this, a survey in Wisconsin indicated that most of the reproduction occurred on road cuts, old logging roads, and along lakeshores and rivers (Eckstein 1996). Other evidence indicates that the most consistent regeneration occurs in proximity of a seed-bearing tree (Graham 1958, Anderson and Gordon 1994, Parshall 1995), and particularly in canopy gaps (Eckstein 1996), on shaded sites (Olson and Nienstaedt 1953, Ward and McCormick 1982, Lorimer 1996), along the edges of stands (Lloyd 1900, Ward and McCormick 1982), or under widely spaced or declining older trees (Ward and McCormick 1982).

Seedling Development

Seedlings have a low light requirement, and establish better in shade than full sun (Hough 1960, Logan 1973). Yet in a moist soil and if protected from wind, hemlock saplings thrive in fairly strong light (Hough 1960). Best early height growth occurs at 25-45% light, and dry-matter production of seedlings peaks at 45% light (Logan 1973).

Seedlings form tap roots during the first year (Frothingham 1915, Clepper 1934), and a few laterals (Hough 1960). The former eventually disappear as a lateral root system develops (Frothingham 1915, Clepper 1934, Friesner and Potsger 1944). These shallow roots are sensitive to drying of the surface soil (Frothingham 1915, Friesner and Potzger 1932). So establishment and good early growth depend upon adequate growing season moisture and favorable temperatures (Anderson and Gordon 1994; Friesner and Potzger 1932, 1944; Graham 1941; Hough 1960; U.S. For. Serv. 1970; Wendel *et al*. 1983; Lancaster 1985; Lorimer 1996; Tubbs 1996; Waller et al. 1996).

The young trees develop slowly during the first growing season, reaching 1.0 to 1.5 inches by autumn (Lloyd 1900, Frothingham 1915, Hough 1960, Fowells 1965, Lancaster 1985). Later growth rates vary with exposure to light (Frothingham 1915). Seedlings and saplings may grow as little as 4 inches over a 3 year period in low light (Lloyd 1900), or up to 8 to 12 inches/year in light to moderate shade (Hough 1960). In full sun and with adequate moisture, seedlings may grow at least 18 inches per year (Hough 1960). However, hemlock grows best in full sunlight

after the saplings have reached 5 to 10 feet tall (Nienstaedt and Olson 1955, Tubbs 1996).

An abundance of well-developed advance regeneration capable of dominating canopy openings provides the best evidence of a successful regeneration effort (Kotar 1996). Hemlock trees are considered fully established upon reaching 3 to 5 feet in height (Frothingham 1915), but should be at least 9-10 feet tall to insure development into overstory positions when competing with hardwoods (Kelty 1986). Such well-developed understory saplings commonly respond well to release from overhead competition (Frothingham 1915, Marshall 1927, Graham 1943, Olsen and Nienstaedt 1953, Nienstaedt and Olson 1955, Hough 1960, Fowells 1965, Tubbs 1978, Lancaster 1985, Wendel et al. 1983, Fajvan and Seymour 1993, Anderson and Gordon 1994). Those with live crown ratios of at least 50% respond quickly (Hough 1960, Anderson and Gordon 1994), while others with ratios of less than 30% respond more slowly (Hough 1960, Anderson and Gordon 1994). Further, hemlock growing under a hardwood overstory will respond better to release than those found under a hemlock overstory (Hough 1960). After overstory removal, hemlock saplings may add 4 inches of diameter over a 10 year period (Fowells 1965). The older a sapling when released, the greater its response (Marshall 1927, Lancaster 1985).

Silvicultural Practices

Hemlock has regenerated naturally with minimal site disturbance beneath canopy openings, but success seems related to habitat type, opening size, and presence of advance regeneration (Pubanz 1996). Tenth-acre openings proved successful in areas with at least 75% of the basal area in sawtimber-size hemlock and yellow birch *(Betula alleghaniensis* Britton*)* (Pubanz 1996). Regeneration also occurred after thinning, salvage cuts, or selection cuts implemented over a 20-year period (Brogger 1996). Partial shade from residual overstory trees reduces surface temperatures, and the shading lessens competition from shade-intolerant trees and herbaceous plants (Tubbs 1996). Maintenance of between 70 and 80% canopy cover with scattered gaps should facilitate hemlock regeneration (Lorimer 1996). Hemlock generally succeeds in these small openings, but saplings often become overtopped by faster growing hardwoods in large ones (Lorimer 1996, Parshall 1995). Locating the canopy openings adjacent to seed-bearing hemlock trees helps to insure adequate seed dispersal (Crow 1996). Cuttings should be done in good seed years whenever possible (Davis and Hart 1961). Sixty year rotations have been recommended for free-to-grow hemlock, because older trees decline in growth (Marshall 1927). Advance regeneration should be left in place (Tubbs 1996).

Scarification (Lutz and Cline 1956, Hix and Barnes 1984, Anderson and Gordon 1994, Jordan et al. 1996, Lanasa et al. 1996, Lorimer 1996, Schmidt and McWilliams 1996, Strong 1996, Tubbs 1996), prescribed burning (Frothingham 1915, Hix and Barnes 1984, Anderson and Gordon 1994, Lorimer 1996), other soil disturbance (Crow 1996), and removal of hardwood competition (Davis and Hart 1961, Lorimer 1996, Schmidt and McWilliams 1996, Tubbs 1996) facilitate regeneration. Site preparation should mix the organic and mineral soil, and eliminate understory competition before or immediately after a cut (Frothingham 1915). Removing the humus layers or mixing the humus and mineral soil in shaded areas has provided good seedbeds that lasted for up to 3 years (Wendel et al. 1983). A consistently higher number of eastern hemlock has germinated in scarified plots compared to unscarified ones (Becker et al. 1996), but managers should coordinate site preparation with the occurrence of good seed crops (Godman and Mattson 1976), since successful regeneration depends upon a combination of adequate seed dispersal and favorable climatic and seedbed conditions (Miles and Smith 1960).

Hemlock rarely germinates or becomes established in open areas (Lancaster 1985), and strip cutting has produced varying results. Despite good seed years, hemlock has failed in clearcut strips of different widths, and in ones oriented both north-south and east-west (Lutz and Cline 1956). Some seedlings have developed on burned areas and moss beds, but a thick unscarified litter layer precludes establishment elsewhere (Lutz and Cline 1956). In one experiment, strip cutting worked well in mature stands not previously under management (Lancaster 1985). However, in similar stands, strip widths should not exceed one-half of the dominant tree height, and site preparation should remove competing hardwoods (Lancaster 1985).

In Wisconsin, light selection cutting, shelterwood method, group selection cutting, and cutting large canopy gaps have all been recommended as reproduction methods. So has deferral of any cutting (Eckstein 1996). New stands have successfully established after a combination of two- or three-stage shelterwood method (Anderson and Gordon 1994, Lancaster 1985) with site preparation (Frothingham 1915, Pubanz 1996). This approach is considered the most reliable method for securing hemlock regeneration in the Lake States (Tubbs 1978, Wendel et al. 1983, Lorimer 1996). It compensates for slow seedling development during the first 2 years by reducing moisture stress and inhibiting hardwood establishment (Lancaster 1985). However, the seed cutting should not create openings greater than one-half the height of the main canopy seed trees (Lancaster 1985).

A two-cut shelterwood method works best on poorly to moderately well-drained soil of a sandy loam or finer texture (Tubbs 1978). The seed cut should leave 110 ft^2/ac of basal area in evenly spaced trees, or 50% crown cover of the best dominants (Tubbs 1978, Lancaster 1985). Scarify the site prior to (Tubbs 1978, Wendel et al. 1983, Lanasa et al. 1996) or just following (Wendel et al. 1983, Lanasa et al. 1996) the seed cut, mixing the humus and upper mineral soil on at least 60% of the area (Wendel et al. 1983, Lanasa et al. 1996). Also, control competing hardwood understory trees (Tubbs 1978, Wendel et al. 1983, Lancaster 1985). Schedule a removal cut when the hemlock reproduction

becomes well-established (Tubbs 1978), reaching 4 to 5 feet tall (Wendel et al. 1983, Lancaster 1985).

On dry sites and in overmature stands, a three-cut shelterwood method will inhibit grass and brush invasion (Tubbs 1978). Recommended overstory densities vary from 70 to 80% canopy cover following the first cut (Tubbs 1978, Wendel et al. 1983, Lancaster 1985, Anderson and Gordon 1994, Jordan et al. 1996, Lanasa et al. 1996, Strong 1996). Scarify prior to cutting (Tubbs 1978, Wendel et al. 1983, Lanasa et al. 1996), or depend upon logging during the snow-free period to encourage soil disturbance (Lancaster 1985, Anderson and Gordon 1994). Control hardwood competition (Anderson and Gordon 1994, Tubbs 1978, Wendel et al. 1983). After 8 to 12 years (Anderson and Gordon 1994, Tubbs 1978), reduce the crown cover to 50% (Tubbs 1978, Wendel et al. 1983, Anderson and Gordon 1994), again discriminating against hardwoods (Tubbs 1978, Lancaster 1985, Anderson and Gordon 1994). At this point, schedule the logging for winter to protect the regeneration (Lancaster 1985, Anderson and Gordon 1994). After another 10 years, remove the overstory (Anderson and Gordon 1994). Regeneration should have reached 4 to 5 feet tall by this time (Tubbs 1978, Lancaster 1985, Anderson and Gordon 1994). It may be necessary to supplement the cutting with direct seeding (Anderson and Gordon 1994), using a sowing rate of 0.5 lb/ac (Tubbs 1978).

Selection system has been recommended in the east (Anderson and Gordon 1994, Lorimer 1996), but not in the Lake States (Lancaster 1985). While often preferred due to the presence of advance regeneration (Davis and Hart 1961), uneven-aged silviculture seems to speed the replacement of hemlock by hardwoods at upland sites (Lorimer 1996). In mixed stands, single-tree selection cutting has successfully established hemlock regeneration (Lanasa et al. 1996), increased the proportion of hemlock (Wendel et al. 1983, Lanasa et al. 1996), and increased the growth of hemlock regeneration (Wendel et al. 1983). In these cases, schedule the logging for snow-free periods (Davis and Hart 1961, Anderson and Gordon 1994) when the soil is not frozen (Davis and Hart 1961). This will help to break up the soil, mix it with humus, and reduce root competition to some degree (Davis and Hart 1961). Cutting cycles of 10 years are recommended (Anderson and Gordon 1994), with a residual stocking of 130 ft^2/ac in stands with at least 50% hemlock (Lancaster 1985). Leaving 35% of the residual trees in the pole class (5 and 10 inches dbh) and the remainder in larger stems will ensure continuous ingrowth to sawtimber, and encourage regeneration on appropriate seedbeds (Lancaster 1985).

Group selection method has also been recommended (Merrill and Hawley 1924, Marshall 1927). In past trials, some hemlock, and much larger quantities of hardwoods, developed in the group openings (Lutz and Cline 1956), and the hardwoods quickly overtopped the hemlock. Even so, group selection generally proved more successful than the shelterwood method in those trials (Lutz and Cline 1956). When used, the group openings should not likely exceed one-tenth acre, or have a width exceeding one-half the height of adjacent residuals.

Agents Damaging to Regeneration

Regeneration may fail due to browsing by white-tail deer (*Odocoileus virginianus* Miller) (Frothingham 1915; Stoeckler et al. 1957; Graham 1958; Hough 1960; Fowells 1965; Jordan and Sharp 1967; Anderson and Loucks 1979; LaMadeleine 1980; Farr and Tyndall 1992; Anderson and Katz 1993; Abrams and Orwig 1996; Crow 1996; Davis et al. 1996; Lanasa et al. 1996; Lorimer 1996; Schmidt and McWilliams 1996; Tubbs 1978, 1996), even in favorable habitats and stand conditions (Lorimer 1996). In areas with a high deer pressure, few seedlings grow more than 6 inches before being browsed (Swift 1948, Lorimer 1996). Areas receiving deep snow and not used as winter cover by deer often have good regeneration and little evidence of browsing (Anderson and Loucks 1979, Lorimer 1996). Snowshoe hare (*Lepus americanus* Erxleben) also feed on hemlock regeneration (Swift 1948, Sage 1986), and eastern hemlock is highly rated as a food for porcupine (*Erithizon dorsatum* Linnaeus)(Stoeckler 1950).

Hemlock within enclosures has survived and developed better than seedlings on unprotected sample plots (Graham 1958, Sage 1986, Strong 1996, Tighe and Zuidema 1996), because browsing greatly reduces seedling development (Anderson and Loucks 1979). Growth does not differ between seedlings browsed once, and those browsed two or more times (Sage 1986). Within areas of protracted deer browsing, hemlock is more seriously damaged than sugar maple (Anderson and Loucks 1979, Crow 1996), and sugar maple frequently becomes the most important species in the reproduction strata (Anderson and Katz 1993). In such stands, the hemlock component may have a bell-shaped diameter distribution, because deer prevent regeneration and reduce the seedling and sapling age classes (Anderson and Katz 1993). So deer must be controlled for successful regeneration to occur (Anderson and Loucks 1979, Sage 1986), with deer density remaining low for 6-8 years to insure adequate seedling growth (Stoeckler et al. 1957).

Germinating seed and seedlings die from damping-off fungi (Frothingham 1915; Olson 1954; Olson et al. 1959a, 1959b; Hough 1960; Kilpatrick 1985; Ruth 1974; Ward and McCormick 1982; Crow 1996). *Fusarium moniliforme* has been isolated from 10% of the seed examined, and probably contributes to losses (LaMadeleine 1980). Root rot *(Armillaria sp.)* colonizes only overmature trees and those affected by drought (Graham 1943).

Though prescribed fire may help as a site preparation tool in promoting regeneration (Frothingham 1915), fires damage or kill established hemlock seedlings (Frothingham 1915, Merrill and Hawley 1924, Clepper 1934, Graham 1941, Hough 1960, Fowells 1965, Tubbs 1996). Regeneration may be inhibited in areas with a low fire frequency (Lorimer 1996), but fire may also inhibit hemlock

regeneration by destroying the organic component of the soil (Frothingham 1915).

Management Implications

Successful regeneration of eastern hemlock involves a complex biophysical process that may span several years. It requires a reliable source of seed with suitable conditions for germination and for early establishment, followed by several years of favorable moisture. Sustained development requires a consistently bright (but partially shaded) and moist environment, and freedom from prolonged intensive browsing. Recurring deficits in these and other requisite factors often interrupt the regeneration process. Good initial seedling density appears important, but many die during early years. Presence of abundant and well-distributed advance seedlings at least 3 feet tall gives a better measure of success. Since hemlock seedlings grow slowly, it may take up to two decades for tall ones to develop.

Available sources provide no consensus about the most suitable reproduction methods. Light partial cutting, creating small openings, and shelterwood seed cutting leaving a uniform cover of upper canopy trees have worked best. Opening widths should not exceed ¾ to 1 times the height of adjacent residual trees. With uniform partial cutting, these openings might cover only one-half the height of adjacent residuals. Following any reproduction method, the residual stand should contain well-distributed hemlock trees of seed-bearing ages.

To enhance the reproduction potential of any cutting, supplemental treatments should include deliberate site preparation to scarify the surface and mix the humus with mineral soil, and to remove any competing broad-leafed woody understory. Though sometimes recommended, relying on skidding to disturb the surface does not appear appropriate, due to the inconsistency of its effects across the stand area, and the potential for uncontrolled skidding to accelerate erosion on slopes. Any cutting plan should include deliberate measures to protect advance hemlock regeneration (e.g., controlling skidding), and to keep it partially shaded until the trees reach at least 5 feet tall (up to 10 feet on sites favorable to hardwoods). Hemlock saplings with a live crown ratio of at least 50% offer the best promise for release, as these develop the best.

Success in regenerating eastern hemlock takes more than casual cutting. It requires deliberate control of residual stand density and spacing to ensure a bright but partially shaded and cool environment, retention of adequate numbers of sexually mature hemlocks to provide good seed dispersion across the regeneration area, appropriate site preparation to create a suitable seedbed and control interfering woody plants, and the good fortune of favorable soil moisture over a long series of consecutive years. The chances for successfully regenerating hemlock seem best at those sites less favorable to hardwoods.

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