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Silvicultural potential of northern red oak and its regeneration – Review

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ABSTRACT: Northern red oak (*Quercus rubra* Linnaeus) is a promising species which could help to mitigate the sanitary problems. Northern red oak is also a commercial species and offers many environmental services. Northern red oak prefers rather dry acidic sites commonly found in Bohemia. The literature confirms that the species is quite fertile but acorn production is highly variable. Northern red oak seedlings develop a long tap root during their first year, which enhances their survival and performance. Different silvicultural systems are proposed and pros and cons are discussed in this review including their influences on forest floor and soil.

Keywords: ecological niche; acorn; silvicultural systems; soil

Northern red oak (*Quercus rubra* Linnaeus) was introduced into Europe from North America in 1691 and into Bohemia in 1799 (Réh 1989; Hejný, Slavík 1990). Northern red oak was introduced and used as an ornamental tree species that was found to grow very well and that enriched the fertility of the site on which it was planted. In arid areas northern red oak was used to replace domestic European oaks that suffered from dieback (Burkovský 1985; Čapek et al. 1985; Gubka, Špišák 2010). Štefančík (2011) found northern red oak to be more resistant to tracheomycosis diseases than domestic oak species. Northern red oak appears not only more resistant to diseases but also demonstrates better early growth and better adaptation to dry sites.

According to Dressel and Jäger (2002) suitable sites for northern red oak are those that are rather more acidic and dry, sites commonly found in northwestern Bohemia.

The range of northern red oak in Europe covers most of the continent except for most southern and northern parts. Central Europe seems to be the most suitable part due to optimal climatic conditions.

Acorn production and viability

Although northern red oak is quite fertile and produces a lot of acorns, this production is extremely variable between individual trees (Healy et al. 1999). The size of acorn crops can influence many components of the ecosystem, and both stand and individual tree variation in acorn production influence the regeneration and management (thinning) of oak forests. Differences in acorn production between the most productive and the least productive individual trees were about 11-fold for thinned and 28-fold for unthinned trees. The largest yearly acorn collection exceeded the smallest 135 times for the thinned treatment and 109 times for the unthinned treatment. Thinned and unthinned sample populations exhibited synchronous masting patterns, and good and poor producers within each population also exhibited year-to-year synchrony in acorn production (Healy et al. 1999).

The use of prescribed fire in North America has become more and more frequent as a tool in oak ecosystem restoration to reduce competition, increase light

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and improve seedbed conditions for germination of acorns and growth of oak seedlings; there are many studies on acorn germination and seedling performance after fire (Greenberg et al. 2012). Oak seedling establishment is dependent on the presence of viable acorns, which may be vulnerable to prescribed fire. Greenberg's study indicated that patchy, low-intensity dormant season prescribed fire in upland hardwood forests reduced viability of white oak and northern red oak acorns located on the leaf litter surface, but did not generally affect acorns in the duff or mineral soil. Shoot production by northern red oak germinants from acorns on the leaf litter surface (and less so in the duff) also decreased with increasing fire temperature (Greenberg et al. 2012).

Northern red oak regeneration and seedling growth

In many forests, advance regeneration represents an important "seedling bank" for replacing overstorey trees after canopy disturbance. However, long-term spatial and temporal dynamics of understorey tree seedlings is poorly understood, particularly in topographically complex areas. The seedling morphology with good growth of primary roots increases the survival rate of northern red oak namely in arid areas.

The resistance of northern red oak seedlings to worse growing conditions was tested many times. Low levels of light, moisture, and fertility significantly reduced growth, and effects of low moisture and low fertility were greater in full sun than in shade. However, the reduction in growth was not statistically significantly different, indicating greater stress tolerance for northern red oak than for other tested species (Kolb et al. 1990; Guo et al. 2001).

Also natural regeneration of northern red oak could be hampered by dense understorey and canopy cover. Therefore, Hartman et al. (2005) proposed to reduce canopy cover to 25%, which leads to significantly more oak seedlings than all other treatments. Similar results were confirmed by many authors (Collins, Battaglia 2002; Spetich et al. 2002; Aldrich et al. 2005; Hartman et al. 2005; Craig et al. 2014; Dey 2014). In their study Spetich et al. (2002) used the term "Dominance Probability" which is the probability that a planted tree will live to attain a favourable competitive position (i.e., at least 80% of the mean height of dominant competitors) at a specified age. The reciprocals of the dominance probabilities provide silviculturally useful estimates of the numbers of trees that would need to be planted to obtain, on average, one competitively successful tree. At any specified time, dominance probabilities depend on initial seedling basal diameter before planting, site quality, intensity of weed control, and shelterwood percent stocking.

On the other hand, Major et al. (2013) found that canopy is not the driving variable for northern red oak regeneration as it is a tree species being moderately shade tolerant. Throughout central Europe, northern red oak exhibits prolific regeneration even when growing with shade-tolerant trees under closed canopy conditions. Major et al. (2013) found that despite high (94–98%) canopy closure in all the stands studied, the density of northern red oak regeneration (< 2 m in height) was greater than that of all other tree species combined, averaging 24 stems per square meter. Density of northern red oak seedlings reached 125 stems per square meter directly below seed trees; however, the lack of seedlings beyond 15 m from a seed tree suggested limited seed dispersal. Seedlings were less abundant at relatively fertile sites with lowest densities corresponding most closely to elevated soil calcium. These results correspond to the diagram (Fig. 1) proposed by Dressel and Jäger (2002).

Frey et al. (2007) tracked the recruitment, growth and survival of seedlings of masting tree species across different topographic positions from 1996 to 2005. Ridge and midslope positions had similar patterns, with high densities of northern red oak (> 200,000 seedlings per hectare) declining over time, and other species generally fluctuating at much lower densities (< 10,000 seedlings per hectare). Seedling heights generally increased with age for all species, but growth was slow, and many seedlings exhibited dieback in the valleys and ridges. These survival patterns likely reflect effects of light limitation (in the valley) and moisture limitation (in the ridge) associated with topographic position.

Ectomycorrhizal colonization (ECM) of northern red oak seedlings in response to different degrees of overstorey and understorey removal was investigated by Zhou et al. (1997). Ectomycorrhizal colonization (%) was significantly greater in the 50% canopy cover treatment than in the clearcut and uncut treatments during the first growing season. In contrast, during the second growing season, percent ECM in the 25% canopy cover treatment was significantly greater than in the clearcut treatment, but did not differ from the 75% cover and uncut treatments. Ectomycorrhizal colonization number per gram dry root was also significantly larger in the 25% canopy cover treatment than in the clearcut treatment.

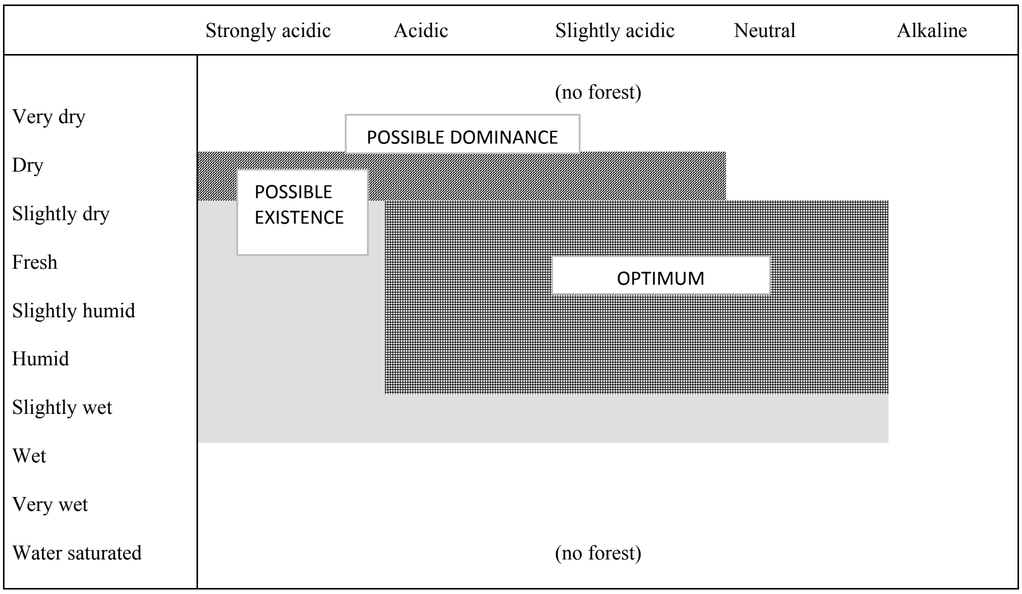

Fig. 1. Ecological niche of northern red oak (adapted from Dressel, Jäger 2002)

Chemical treatment of young plantations

Herbicide treatments on acidic sites are suspected to worsen the soil conditions. The addition of herbicide alone caused increased Al and $H^{(+)}$ concentrations and reduced Ca/Al ratios to critically low levels and subsequently reduced regeneration growth. The combination of herbicide and dolomitic lime and fertilizer resulted in the tallest, densest regeneration with the greatest species diversity (Schreffler, Sharpe 2003). Schuler and Robison (2006) studied the effects of fertilization, density and vegetation control on rising 1- and 3-year-old northern red oak plants over 3 years following the treatments. Broadcast fertilization proved very beneficial in accelerating stem growth and promoting self-thinning at both sites. Weeding (non-arborescent vegetation) treatments without thinning had no effect on stem height. Substantial increases in tree size were noted for oaks when thinning and weeding treatments were combined. These results demonstrate that stem growth and stand development are constrained by the availability of site growth resources, and can be silviculturally managed to promote stand development (Demchik, Sharpe 2001; Schuler, Robison 2006).

Hardwood bare root seedlings typically undergo transplant shock immediately following reforestation planting associated with moisture and/or nutrient stress. Broadcast field fertilization at outplanting with readily available nutrients has shown limited capacity to reduce nutrient stresses. Application of controlled-release fertilizer (CRF) in the outplanting hole could be a useful alternative to help improve fertilizer use efficiency and alleviate competition problems associated with broadcast fertilization, thereby promoting early regeneration success of outplanted seedlings. Jacobs et al. (2005) used CRF and found that release was evenly distributed between two consecutive years. Seedling survival was above 85% for all treatments. Compared to non-fertilized seedlings, the seedlings accelerated mean height and root-collar diameter growth by 52 and 33% in year 1 and 17 and 21% in year 2. Nitrogen and potassium uptake was increased 40 and 30% when compared with controls. The fertilizers could be useful also in specific silvicultural tasks such as reclamation of spoil banks. The importance of nursery nutrient loading as a new approach to enhance forest restoration on abandoned mine lands was evaluated by Salifu et al. (2009). Northern red oak and white oak (*Quercus alba* Linnaeus) seedlings were nitrogen loaded for 18 weeks at a bare root nursery. Subsequently, nursery-grown seedlings were outplanted the following year onto a mine reclamation site to evaluate effects of nursery N loading on first-year field performance. Nursery N loading promoted total plant dry mass production by 25–129% in northern red oak and 50–184% in white oak compared to unfertilized plants. Nitrogen loading increased N content 88–145% and K content from 16 to 71% for northern red oak and N content from 124 to 250% and K content from 16 to 93% for white oak relative to controls. When outplanted, N loading resulted in high seedling survival (> 84%) and increased total plant dry mass production from 14 to 30% for northern red oak and from 23 to 52% for white oak.

Nitrogen loading increased plant N uptake by 14 to 102% in northern red oak and 32-105% in white oak under field conditions (Jacobs et al. 2005).

Biotic and abiotic influences on young northern red oak stands

There is a significant discussion on atmospheric deposition of elements and its influence on forest ecosystems. Forests could serve as a significant sink for the depositions of airborne elements but there are different and very often opposite hypotheses on how the depositions influence forests. The actual question to ask is "what is the possible reaction of trees to elevated atmospheric CO_2 when combined with other stresses?" Dixon et al. (1995) tested Norway spruce (*Picea abies* (Linnaeus) H. Karsten) and northern red oak trees which were planted directly into the soil and exposed to 700 ppm of CO_2 in open-top chambers. There were large interspecific differences in response to naturally occurring drought during the second year of exposure to elevated CO_2. Both species had decreased assimilation rates. CO_2-treated northern red oak had no loss of photosynthetic enhancement when undroughted, whereas CO_2-treated Norway spruce showed a relative increase in assimilation rates only when droughted. The effect of CO_2 on radial growth of both species was less marked in the second growing season, but this may have been a result of different biomass partitioning as Norway spruce shoot extension had a different pattern of growth in elevated CO_2. Stomatal density and chlorophyll content were largely unaffected by the CO_2 treatment (Dixon et al. 1995).

Similar questions can be asked with reference to atmospheric deposition of nitrogen and its sink under different tree species. Micks et al. (2004) estimated the N sink strength in litter cohorts of two different ages tested in litterbags containing oak leaves, maple leaves, pine needles, or maple wood chips. Although the N sink strength of litter pools increased more strongly in the pine forest in response to elevated N inputs, the hardwood forest retained more N under both input levels, suggesting that it may be a larger sink for atmospheric N deposition than the pine forest (Micks et al. 2004).

There are many methods to improve acid and poor forest soil. Instead of liming a by-product of "flue gas desulfurization (FGD)" could be used that is produced when a dolomitic lime is used to remove SO_2 during the burning of high sulphur coal in electricity generating power plants. Crews and Dick (1998) evaluated the growth of northern red oak in an acid forest soil and water leachate quality when an FGD by-product was applied topically or mixed within the A horizon at rates equivalent to 0.25, 0.50, 1.0, 1.5, 2.0 and 2.5 times the soil requirement for lime. Soils were leached with deionized water on a monthly basis and the leachate samples were analysed for pH, conductivity, P, S, B and metals (Al, Ca, Cr, Cu, Fe, Mn, Er, Mg, Pb, Ti and Zn). Tree growth significantly increased ($P <$ 0.05) when the soil was treated with FGD and the greatest growth (75% increase over the untreated control) occurred when FGD was applied at 1.5 times the lime requirement rate. Boron toxicity symptoms were observed in plant tissue when an FGD by-product was applied at twice (or higher) the lime requirement rate. Sulphur concentration increased from less than 10 $mg \cdot l^{-1}$ (control soil) to 234 $mg \cdot l^{-1}$ (soil treated with FGD at 2.5 times the lime requirement) in the leachate four months after treatment. Boron also approached toxicity concentrations (approximate to 1 $mg \cdot l^{-1}$) in the leachate from soil treated at the highest rate during the initial leachings, but concentrations tended to decline with time (Crews, Dick 1998). Applying an FGD by-product onto acid forest soils has the potential to provide growth benefit to an important tree species (such as northern red oak) but care will need to be taken to avoid using FGD materials that may release toxic levels.

Northern red oak is assumed to be more resistant to drought than European oaks (Vivin et al. 1993; Dressel, Jäger 2002). Northern red oak was compared with two indigenous oaks (*Quercus robur* Linnaeus, *Q. petraea* Liebl). The effects of controlled soil water deficits on growth and water relations of young plants of these three species grown in large boxes were studied by Vivin et al. (1993). The plants were old enough to have developed normal root systems. Two species were planted in each box, and submitted to very similar patterns of water stress. Predawn leaf water potential, stomatal conductance, net assimilation rates, shoot elongation and mortality were monitored. The effect of an overall improvement in mineral nutrition on these parameters was also tested. During water deficit (decrease in predawn leaf water potential), the pattern of a decrease in gas exchange was similar for the three species. Thus, their ability to limit water deficit by reduction of transpiration was similar. On the other hand, the shoot growth of *Q. rubra* was more reduced than that of *Q. robur* for similar predawn leaf water potential; the growth of *Q. petraea* was the least sensitive. However, an increase of mineral nutrition improved the growth of both *Q. robur* and *Q. rubra*, but not that of *Q. petraea*. The mortality rate was highest in *Q. robur*, *Q. petraea* and lowest in *Q. rubra* (Vivin et al. 1993).

Also foliar herbivory could influence the growth and performance of oak seedlings. There is a hypothesis that foliar herbivory would increase belowground carbon allocation (BCA), carbon rhizosphere deposition and N uptake. Frost and Hunter (2008) investigated this hypothesis by using an isotope with northern red oak seedlings. Plant BCA links soil ecosystems to aboveground processes and can be affected by insect herbivores, though the extent of herbivore influences on BCA is not well understood in woody plants. Microcosms containing 2-year-old northern red oak seedlings were subjected to herbivory or left as undamaged controls. Contrary to the hypothesis, herbivore damage reduced BCA to fine roots by 63% and correspondingly increased the allocation of new C to foliage. However, C recoveries in soil pools were similar between treatments, suggesting that exudation of C from roots is an actively regulated component of BCA. Herbivore damage also reduced N allocation to fine roots by 39%, apparently in favour of storage in taproot and stem tissues. Oak seedlings respond to moderate insect herbivore damage with a complex suite of allocation shifts that may simultaneously increase foliar C, maintain C rhizosphere deposition and N assimilation (Frost, Hunter 2008).

The impact of deer on regenerations and young stands of broadleaves was studied by Long et al. (2007). In a long-term study, they found that the composition of the overstorey and understorey has an important impact on browsing. As deer browsing heavily influences forest regeneration, typical measures to ensure forest regeneration included physical barriers or direct control of deer densities. Miller et al. (2009) examined browse species preferences and changes in herbivory rates in 1–6-year-old regeneration areas from 2001 to 2004. Woody vegetation reached the maximum plot coverage by the 4th growing season. However, the establishment of less abundant woody species, such as northern red oak, may be inhibited when browsed greater than or proportionally to occurrence. However, the browsing could not be the final stage as the study of Bobiec et al. (2011) proposed. Wooded pastures grazed by livestock are believed to be landscapes that provide favourable conditions for spontaneous regeneration of oaks. A key mechanism for oak regeneration in these systems is "associational resistance", spatial association with unpalatable plants which offer protection against herbivory. There is little knowledge on how oak regenerates without livestock grazing and in the presence of only wild large herbivores. The study was conducted in an area (114 ha) abandoned from agricultural use and in the early 1980s incorporated into the Bialowieza National Park, Poland. Its ungulate community consists of native red deer, European bison, roe deer, moose and wild boar. Secondary succession has led to the development of a mosaic habitat including tree and tall shrub groves (29% of the area), open meadow communities (60%), and edge, transitory zone between groves and meadows (11%). The systematic inventory assigned oaks to 6 height classes, dichotomous shape characteristic (regular vs. "bonsai" saplings), as well as a habitat definition, in particular the characteristics of woody vegetation in the immediate surroundings of oaks. A selection of 17 oaks was subject to coring for the comparison of growth dynamics. Oak density was highest inside groves, with 504 oaks per hectare, and in the edge zone (493 oaks per hectare) and lowest in meadows (47 oaks per hectare). Most of the 0–5-m oaks (62%) grew without another woody plant species within 1 m radius. The remaining oaks (38%) were associated mainly with *Rubus idaeus* Linnaeus and saplings of *Carpinus betulus* Linnaeus and *Populus tremula* Linnaeus – all highly ungulate-preferred species. The age (0.5 m a.g.l.) of northern red oaks in grove and edge habitats varied from 11 years to 37 years, indicating continuous recruitment since agricultural abandonment. The resistance of northern red oak to wind damage is well known. It can even resist to hurricane as presented by Greenberg and McNab (1998).

Management of northern red oak stands

Korpel (1974) is one of many scientists who proposed a silvicultural technique which is based on intervention in favour of the final crop trees, not the whole stand. The rest of the stand is left to a "self-thinning regime". This technique represents significant savings of labour and costs (Togár 1979; Korpel 1984; Remiš 1988; Štefančík 1991).

Phytosanitary problems and oak dieback also influenced its management (Račko 1987). In such cases Štefančík (1987) proposed only sanitary selection in young oak stands, namely if the stands have more than 5% of dying trees. In this context the northern red oak is a good solution which gives not only a safer production but also an esthetical improvement especially in recreational and urban forests (Réh 1967, 1989; Štefančík 1992).

Silvicultural systems integrate both regeneration and intermediate operations in an orderly process for managing forest stands. The clearcutting method of regeneration favours the development of species that are moderately intolerant to shade. In fact, clearcutting is the most proven and widely used method of successfully regenerating oak species. The seed-tree method of regeneration favours the establishment of light-seeded species. Mechanical soil scarification may be necessary if the desired species requires bare mineral soil for establishment. The shelterwood method of regeneration can provide for the development of heavy-seeded species, but has produced highly variable results with oak (Meadows, Stanturf 1997).

Shelterwood silviculture is also used to regenerate oaks. However, competition from other species may deter oak regeneration when the traditional shelterwood techniques are used. The shelterwood-burn technique is a relatively new tool for regenerating oak-dominated stands on some upland sites while simultaneously minimizing undesirable hardwood intrusion with prescribed fire (Lanham et al. 2002; Wang et al. 2005; Royse et al. 2010; Fan et al. 2012).

Elliot and Knoepp (2005) evaluated the effects of three regeneration methods (clear cut, shelterwood and group selection) on plant diversity and soil resource availability in mixed-hardwood ecosystems. The soil samples were analysed for extractable calcium, magnesium, potassium, cation exchange capacity, pH, bulk density, A-horizon depth, total carbon, and nitrogen. The species diversity of overstorey, understorey, and herbaceous layer was evaluated as well. The clear cuts proved better soil conditions in terms of physical and chemical properties as litter was decomposed more quickly and physical characteristics were not so much influenced by used mechanizations.

The influence of harvest methods on forest floor and nutrients in forest soil is discussed frequently these days. The results of Johnson et al. (2016) compare the impact of two different methods: (*i*) stem only harvest (SOH) and (*ii*) whole tree harvest method (WTH). Although differences between harvest treatments were not statistically significant ($P > 0.05$), average diameter, height, basal area and biomass were 8–18% lower in the WTH than in the SOH treatment 33 years after harvest whereas they differed by 2% 15 years after harvest. In contrast to results 15 years post-harvest, total forest floor mass and nutrient contents were twofold greater in the WTH than in the SOH treatment at 33 years post-harvest. Soil total C concentrations increased significantly ($P < 0.05$) over the first 15 years post-harvest in both harvest treatments. Decreases in soil C between 15 and 33 years post-harvest were not statistically significant. Soil total N increased significantly in both harvest treatments over the first 15 years post-harvest. Consistent decreases in soil total N occurred in the WTH treatment between years 15 and 33 post-harvest that bordered on statistical significance whereas total N was stable over that time period in the SOH treatment. Harvest treatment effects on both Ca^{2+} and Mg^{2+} observed at 15 years post-harvest are still observable and significant at 33 years post-harvest, although decreases between 15 and 33 years were found. Treatment effects and changes in soil exchangeable Ca^{2+} and Mg^{2+} are consistent with known inputs from decomposing logging residues, inputs from atmospheric deposition, and increments in forest floor and vegetation. No treatment effects were found for soil extractable P, but steady decreases over time were found. Neither treatment nor time effects were found for soil exchangeable K^{+} (Johnson et al. 2016). Similar effects are known on former farm soils (Podrázský, Štěpáník 2002).

CONCLUSIONS

Northern red oak is a species which could help to maintain oak forests in lowlands in Central Europe, namely in arid areas that are healthy and productive. The ecological niches of northern red oak lie on acidic and dry sites which could be the case for many places in this country. Northern red oak is a species that produces a lot of acorns and therefore its production guarantees safe natural regeneration. Moreover, northern red oak seedlings have long primary taproots which secure seedling tolerance to summer dry periods even in the first year of germination critical for one-year broadleaved seedlings. The northern red oak stands proved to be resistant to wind damage and therefore it could improve the stand stability of our forests where wind damage is the most important abiotic influence on forest management. The recent literature proposes as thinning the intervention in favour of the final crop trees. The clear cut method on limited areas or shelterwood systems with low canopy cover to secure enough light for northern red oak seedlings seem to be the most commonly proposed silvicultural systems.

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