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Lessons learned from oak cluster planting trials in central Europe

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Abstract

Oaks are becoming increasingly important for future forest management as the climate in central Europe warms. Owing to the high costs of conventional row planting, artificial oak stand establishment in the form of “clusters” became popular in central Europe beginning in the 1970s. In cluster plantings, oaks are either planted in groups of ca. 20–25 at 1 m spacing between trees (i.e. group planting), or in denser groups with 20–30 oaks m^{-2} (i.e. nest planting). In both cases, the clusters are spaced apart at a distance that represents the target density of future crop trees. A comprehensive review of the history, growth, tree quality development and economic aspects of oak cluster plantings suggests that initial growing space was the most important factor influencing development of oaks in clusters. Consequently, survival, growth, quality, and biomass production were comparable in group and row plantings, but lower in nest plantings. In addition, group plantings resulted in greater stand-level tree species diversity than nest or row plantings. We conclude that oak group planting is a comparatively inexpensive option for the artificial regeneration of oak-dominated broadleaved forests for a range of situations such as reforestation of disturbed areas or the afforestation of abandoned agricultural land. Future research needs regarding development and tending of forests established by oak group planting are highlighted.

Keywords: oak regeneration; tree quality and growth; species diversity and productivity; plant competition; forest restoration

Introduction

The relatively storm-resistant and moderately drought-tolerant pedunculate and sessile oak (*Quercus robur* L., *Q. petraea* (Mattuschka) Liebl.) are likely to increase in importance as the climate warms in Central Europe (Bolte et al. 2009; Roloff and Grundmann 2008; Hanewinkel et al. 2013). In addition, these two oak species are among the few tree species suitable for the production of high quality timber on sites with hydromorphic soil conditions that are prone to storm disturbance, where oaks in contrast to most other species can develop deep root systems. Hence, a quadrupling of the oak cover in the German federal state of Thuringia up to 16% of the total forested area was recommended as an adaptive management strategy against possible climate change impacts (Frischbier et al. 2010).

Oak forest cover in the former Western German states already increased by 8% or 58,536 ha from 1987 to 2002 (BMEL 2012). The observed increase in oak forest cover partly resulted from the use of oak for the reforestation of wind-thrown areas after the severe winter cyclones “in 1991 and 1999. Catastrophic damage in coniferous forests by these and subsequent storms prompted forest managers to convert pure coniferous stands established on unsuitable sites to mixed forest of oak and other broadleaved trees. As a result, the recent nationwide German forest inventory reported an additional increase in oak forest cover of 6.8% or 70,221 ha from 2002 to 2012 (BMEL 2012). This trend is likely to continue not only in Germany as it has been estimated that the total Norway spruce (*Picea abies* (L.) H. Karst) conversion area in 14 European countries amounts to at least 1.1 million ha (Spiecker et al. 2004). Furthermore, as part of an adaptive strategy to address predicted long-term changes in prevailing weather conditions, the German federal state of Brandenburg has the long-term aim to convert more than 500,000 ha of

pure Scots pine (*Pinus sylvestris* L.) stands into mixed forest with a high proportion of deciduous tree species such as oak (LFE 2007).

Until the end of the twentieth century, oak was artificially regenerated by sowing or by planting between 7,000 – 15,000 seedlings ha⁻¹ in closely spaced rows (Burschel and Huss 1997). Presently, a typical goal of commercial oak management in Germany is to produce at least 60 - 80 high quality harvestable trees ha⁻¹. The minimum target diameter of such trees at breast height (DBH) should be 60 cm with a branch free bole length of 6 - 10 m at the end of a 140 to 200-year rotation period (Spiecker 1991; von Lüpke 1998). Maintaining a homogenous crown layer during early stand development stages by planting at high densities was a primary goal in plantations managed to foster natural self-pruning and development of stem quality (Anderson 1951).

The recommended number of oak seedlings ha⁻¹ in row planting has decreased to about 5,000 seedlings ha⁻¹ since the 1990s (Ehring and Keller 2006; Guericke et al. 2008; ForstBW 2014). However, high costs of site preparation, planting, fencing and tending remain a matter of concern. The irregular spatial distribution of potential future crop trees, rigid thinning protocols, lack of natural regeneration of other tree species, and low species diversity are further undesirable attributes of this classic type of oak cultivation (Anderson 1951; Ehring and Keller 2006; Gockel 1995; Szymanski 1986). Overall, these factors motivated European foresters and scientists to seek alternatives to the conventional row planting approach for establishing oak stands.

Significant contributions to this search for alternatives emerged from observations of regeneration dynamics in natural and semi-natural oak forests, where early stages of stand development are characterized by irregularly distributed trees (Anderson 1951). One of the

causes of this irregular distribution of naturally regenerated oak trees may be related to irregular disturbances of the forest floor caused by wild boars (Szymanski 1986). It was assumed that the resulting clustered distribution disappears as individual trees grow and eliminate competing neighbours. However, oak stands established in this way may lack a sufficient number of trees of desirable stem form and stability (Anderson 1951). Thus it was proposed that uniformly distributed clumps or cluster of sown or planted oaks would assure a more regular early spacing of trees and improve selection options of future crop trees (Anderson 1951; Szymanski 1986).

Several cluster planting methods, differing foremost in spacing of planted oaks as well as the number of clusters per unit area, evolved as a result of the above described theoretical considerations (Gockel 1995; Szymanski 1986). A large number of studies evaluating tree establishment, quality, growth, plant interactions, species diversity and stand productivity in early oak cluster planting trials have been published subsequently. However, effective implementation of the existing oak cluster planting methods in forest management and planning requires a comprehensive synthesis of those published findings. Consequently, the objectives of this review were to: i) provide a summary of the available published information on oak cluster planting and ii) identify research needs regarding this fairly new stand establishment technique.

We start with a historical perspective, which we consider important to understand the methods of cluster planting currently applied in re- and afforestation. We then focus on synthesising the existing information on tree growth and quality, issues related to stand dynamics such as species diversity and productivity as well as economic aspects of oak cluster planting by comparing it with findings from traditional row planting.

The history of cluster planting

Nest planting

Ogijewski, a forest scientist from the St Petersburg Institute of Forestry of Imperial Russia, was the first to translate observations of clustered natural regeneration in oak forests into forest management practices. In 1911, he established a large-scale oak cluster trial in the Russian Tula forest steppe on a clear-felled site (Pryakhin and Portnykh 1949). In that first trial, 200 rectangular plots or “nests” ha^{-1} (at a spacing of 7 x 7 m between nests) of 2 m^2 size (1 x 2 m), were sown with 50-100 acorns per nest. In a later modified variant, 25-50 one- or two-year-old oak seedlings were planted per nest (Szymanski 1986). The nest trial of Tula became popular in Russia after the communist revolution, and were widely promoted in many republics of the former USSR (Buchholz 1949). The new technique was promptly adopted by the Soviet agronomist Lysenko, who made it mandatory for shelter belt plantings.. As a result, thousands of hectares of oak shelter belts were established on agricultural land using this technique (Lysenko 1949). In addition, a few forestry trials with nest plantings were established in the Tula region of the Ukraine, and Belorussia, as well as close to the Russian city of Voronezh (Pryakhin and Portnykh 1949; Korjakin 1952; Bodrov 1956; Zelman 1961; Tolkachev 1976). However, the fate of these trials has not been properly documented.

Nest planting trials were first mentioned in German and British forest literature in the early 1950s (Anderson 1951; Buchholz 1950). Subsequently, in 1952, inspired by results from Russian nest planting trials, Szymanski, a forest scientist from Poznan University, Poland, established the first experimental trials of oak nest plantings outside Russia in the Siemianice forest district, close to the lower Silesian highlands in south-central Poland. His modified design comprised nests of 1 m^2 in size that were uniformly planted with 21 one-year-old oak seedlings resulting in

an inter-seedling distance of 0.2 m (Fig. 1). He developed two different planting protocols; either 4 x 4 m or 5 x 8 m between nests with European larch (*Larix decidua* Mill.), small-leaved linden (*Tilia cordata* Mill.), European beech (*Fagus sylvatica* L.) and sycamore maple (*Acer pseudoplatanus* L.) trees planted in rows between the nests. Szymanski and his colleagues published a series of articles on oak nest planting (Ceitel and Szymanski 1975; Szymanski 1977; Szymanski 1986), and also lectured on this approach in Germany (Gussone and Richter 1994). Szymanski's publications and lectures motivated forest managers and researchers in Germany to trial oak nest plantings in the German states of Lower Saxony, North Rhine-Westphalia and Schleswig-Holstein starting in 1986. Some trials were established on clear-felled sites and others on wind-thrown areas created by the 1991 storms in the German states Rhineland-Palatinate, Saxony-Anhalt, and Baden-Wuerttemberg (Dong et al. 2007a; Mangold 1988; Strobel 2000). These trials did not exactly follow Szymanski's protocol. Instead, 7 x 7 m spacing between nests gained wide acceptance (Guericke et al. 2008; Leder 2007). The space between nests was either planted with shade-tolerant trainer species such as linden, hornbeam (*Carpinus betulus* L.), and European beech or left for natural regeneration.

Group planting

Mark Anderson, a professor at Edinburgh University, independently developed a cluster planting scheme that came to be known as "Anderson's spaced group planting" (Anderson 1930), though he mentioned the Russian trials in later publications (Anderson 1951). He planted oak, European beech, Scots pine, and Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in 6 different design combinations ranging from 6 to 21 trees per group. The spacing between trees inside the groups was maintained at 1 - 2 m while inter-group spacing ranged from 4 - 7 m. A series of spaced

group plantings of conifers and broadleaves were set up in Scotland, northern England and Northern Ireland in the 1930s. This spaced group planting system inspired foresters in other areas and some plantations following this design were reported from the Belgian Congo (Donis 1956), Tunisia (Lu et al. 1975) and Malaysia (Ironsides 1954). However, there is no information on further developments or results from these group plantings in the United Kingdom or the other countries. Apparently, the interest in spaced group planting systems among British foresters waned after the 1950s due to the predominance of Sitka spruce monocultures in the United Kingdom (Joyce et al. 1998). Anderson's ideas were forgotten and apparently did not influence later attempts with very similar planting designs in Germany.

High mortality of planted seedlings in German nest planting trials established in the 1980s motivated Gockel (1995) to introduce a new oak cluster planting design with a wider initial spacing between the seedlings. In 1992 he planted the so-called "oak group planting" in circles and squares in the Federal Forests District of Schwarzenborn in Hesse, Germany (Fig. 2). Irrespective of the different group designs, the spacing between the centres of each group was kept at 10 x 10 m resulting in 100 groups ha⁻¹. With an initial spacing of 1 m between planted oaks and trainer trees, taller seedlings of 80-150 cm in height were planted to foster survival in the light of early plantation risks. In addition, the larger initial growing space of 1 m² per seedling was supposed to result in a more balanced and unrestricted initial crown development. Gockel's work inspired others and led to a number of modifications to the groups involving different numbers of oak seedlings as well as different numbers and species of trainer trees (Harari and Brang 2008). Group planting trials were established on wind-thrown sites, clear cuts and abandoned agricultural lands in Lower Saxony, Baden-Wuerttemberg, Rhineland-Palatinate,

Bavaria (Ehring and Keller 2006; Petersen 2007), France (Demolis et al. 1997), Northern Switzerland (Brang and Bürgi 2004) and Austria (Ruhm 1997).

Success and failure of oak cluster planting

Survival rate

The survival rate of planted trees in the first years is critical for reforestation success. Low survival results in economic losses through extended rotation periods and the additional costs of replacing dead trees (Margolis and Brand 1990). Hence, the survival rate of planted oaks was the most common indicator of success assessed in studies comparing nest, group and row plantings. The main hypothesis examined in these studies was that no difference in survival rates exists between the different approaches of oak establishment. Early proponents of cluster plantings claimed that intraspecific competition between oaks in nests would not affect their survival and growth, that nests minimize deer browsing and offer protection from the negative effects of drought, snow and frost by creating a favourable microclimate inside the clusters (Szymanski 1986). However, later observations from 12- to 23-year-old German nest planting trials revealed that less than 50% survived the first two decades after stand establishment, a rate significantly lower than in classical row plantings (Leder 2007; Weinreich and Grulke 2001). These findings were verified in a recent more comprehensive meta-analysis which reported mortality rates of planted oaks in 19- to 24-year-old nest plantings to be 80% higher than for oak trees planted in 2 x 1 m row plantings (Saha et al. 2012). Additionally, the assumed positive effects of outer oaks in nests providing protection from deer browsing to inner individuals, and favourable microclimatic conditions inside clusters, could not be confirmed (Guericke et al. 2008;

Weinreich and Grulke 2001). Very close initial spacing in nests triggers an early onset of shading induced asymmetric competition and self-thinning among oaks. Similar phenomena have been reported for other young and dense broadleaved stands (Henriksson 2001; Kint et al. 2010). In contrast, no significant difference was observed in oak survival rates between group and row planting (Petersen 2007). Results from previous Nelder spacing experiments also indicated that initial growing space of at least 1.3 m² is required to achieve survival rates of at least 80% in planted oak stands after ca. 20 years (Nelder 1962; Gaul and Stüber 1996). The superior survival rate observed in group plantings might also be partially attributable to the taller seedling size used which likely resulted in reduced competition from ground vegetation and less severe browsing of terminal shoots (e.g. shoulder height of the most common browser, roe deer (*Capreolus capreolus* L.), is between 65 to 75 cm) (Macdonald and Barret 1993; Dey and Parker 1997; Petersen 2007). Additionally, planted trainer trees in groups reduced oak mortality (Saha et al. 2012).

In summary, based on previous analyses of oak cluster plantings it can be concluded that Szymanski's (1986) assumption of similar or even slightly higher survival rates for oaks in nests compared to those in rows was not corroborated. However, oak survival in group plantings was satisfactory and comparable to traditional row planting.

Height and DBH development

One main assumption of early proponents of cluster plantings was that DBH and height growth of oaks established in cluster plantings would not differ significantly from conventional row planting (Szymanski 1986). However, as was subsequently shown, average DBH and height of 23-year-old oak trees grown in row plantings were 20% greater and 10% taller, respectively, than

230 similar-aged oak trees from nest plantings (Guericke et al. 2008). Within nests, however, DBH
231 and height differed substantially depending on the position within the cluster. Relative
232 abundance of trees with satisfactory development was substantially lower for individuals from
233 the nest interior (Andrzejczyk and Glodowski 2010; Leder 2007). In contrast, no significant
234 difference was observed in DBH or height when 7- to 11-year-old group plantings were
235 compared to similar row plantings (Harari and Brang 2008; Petersen 2007). Findings were
236 confirmed in a recent meta-analysis where DBH was significantly lower by 39% in nest relative
237 to group plantings, though group and row plantings did not differ (Saha et al. 2012). Compared
238 to row planting, DBH was 29% lower in fenced nest planting trials, while in unfenced nest
239 planting trials the difference amounted to 52%. The height of oaks did not vary significantly
240 between nest, group and the row planting counterparts. Poor diameter growth of trees in nests
241 confirms results from German oak spacing trials that found a significant decline in diameter
242 growth when initial growing space was less than 1 m² (Gaul and Stüber 1996; Schmaltz et al.
243 1997; Spellmann and Baderschneider 1988).

244 In contrast to nest planting, the fundamental design of group plantings promotes oak diameter
245 and height growth. Older spacing experiments showed that an initial growing space of 1 to 1.5
246 m² per seedling reduces the impact of intraspecific competition on oak growth and promotes tree
247 quality (Schmaltz et al. 1997; Spellmann and Baderschneider 1988). This is reflected in results
248 derived from older group planting stands, where intraspecific competition did not influence
249 growth but promoted quality development (Saha et al. 2012). Nurse tree effects from early
250 successional species such as silver birch (*Betula pendula* Roth) and competition from naturally
251 regenerated trees of mid-successional species might also have promoted survival and tree quality
252 development in the group planting trials (Leder 1992; Leder 1996; Rock et al. 2004). However,

individuals of fast growing tree species may quickly overtop oaks in groups resulting in increased asymmetric competition for light and eventually hampering oak growth (von Lüpke 1991, 1998, 2008).

In conclusion, Szymanski's assumption of comparable growth of oaks growing in densely planted nests and in conventionally planted rows cannot be supported. However, assessments of relatively young group plantings have shown comparable diameter and height growth with row planting. Initial growing space, which determines early intraspecific competition between planted oaks, is therefore an important factor influencing growth of oaks in clusters.

Stability of oaks

Due to their habit of maintaining dry leaves during winter, young oaks can be easily physically damaged during wet snow events (Röhrig et al. 2006). Physical tree stability is classically assessed through the height to diameter ratio (HDR, Mosandl et al. 1991; von Lüpke 1991). Past studies on oak cluster plantings had hypothesized that there were no significant differences in tree stability between cluster and row plantings. However, average HDR was 20% greater in trees growing in nest plantings than their row planting counterparts, while mean HDR of oaks from group and row plantings were comparable (Saha et al. 2012). Poor diameter growth and inferior individual tree stability in nest plantings can again be attributed to the intense initial intra-specific competition (Saha et al., 2014).

Tree quality

Tree quality determines the value of the timber produced. Traditionally, silvicultural practices during early stages of oak stand development focus on the occasional removal of poorly shaped

dominant (wolf) trees. In general, management intervention is minimized to maintain a high stand density and thus promote stem quality development.. During the last four decades some forest scientists have stressed the importance of early positive selection of oaks with the most desirable traits. To promote stem quality and to ensure that the targeted number of crop trees is achieved at final harvest, it was recommended that potential future crop trees be selected in young stands before they have developed the desired branch-free bole length (Leibundgut 1976; Mosandl et al. 1988; Nutto 1999; Schutz 1993). However, this requires that the quality of such “potential future crop trees” can be assessed before they have reached that branch-free bole length. A suitable approach for assessing tree quality is based on the evaluation of individual tree attributes such as stem straightness and forking (stem form), crown shape and size, as well as overall branchiness, density of epicormic branches, and branch-free bole length (Leder 2007; Mosandl et al. 1988). Previous studies on oak cluster plantings assessed tree quality attributes as described above, and counted the number of potential future crop trees ha⁻¹. Some of these studies compared the results with findings from conventional row plantings.

Stem form, crown shape and branch-free bole length

Compared to conventional row planting, nest plantings produced 10% fewer oaks with straight, upright stems and 22% fewer trees with monopodial crowns. In group plantings, the number of trees with favourable stem form or crown shape was respectively 45% and 23% greater than in row planting (Guericke et al. 2008). In addition, branch free bole lengths of oaks growing in groups were comparable to oaks from conventional row plantings (Harari and Brang 2008; Rock 2004). However, average length of the branch-free bole of oaks in nests was 41% shorter than in row plantings (Saha et al. 2012). Limited growing space in nest plantings triggered intense

intraspecific competition for light and caused the outermost oaks to grow outwards and develop lean, crooked stems and one-sided crowns with thick lower branches (Guericke et al. 2008). This was most pronounced in nest plantings without shade-providing trainer trees or where the space between nests was not filled by natural regeneration of other broadleaved trees (Guericke et al. 2008). As a result, the most vigorous oak trees from the perimeter of nests exhibited the least favourable overall quality, significantly limiting future selection options (Koch and Brang 2005). The tendency of oaks to grow towards the light (Leibundgut 1976) likely resulted in the dominance of poor stem forms and crown shapes in nest plantings (Nagel and Rumpf 2010). It can be concluded that intraspecific competition in nest plantings is initially very high and the resulting accelerated self-thinning within individual nests provides unfavourable conditions for tree quality development, because intraspecific competition is largely replaced by interspecific competition (Andrzejczyk and Glodowski 2010; Saha et al. 2014). Hence, early loss of oak neighbours in nests inhibits the rise of green crowns and concomitant self-pruning. In contrast, the wider spacing between oaks within groups appears to maintain the initial planting pattern over the first few decades of stand development and thus fosters stem quality development through intraspecific interactions.

Number of potential future crop trees

Based on observations from conventional row plantings, it has been suggested previously that to achieve a final number of 70 - 80 harvestable crop trees, 150 - 250 potential future crop trees ha⁻¹ would be required at age 20 (Dong et al. 2007b; Mosandl and Paulus 2002; Spellmann and von Diest 1990). Several studies reported contradicting results on the number of potential future crop trees identified in nest planting case studies. These numbers vary between 18 – 116 crop trees ha⁻¹

¹ with only 29% of all planted oak nests having a crop tree on average (Guericke et al. 2008) to 150 - 200 crop trees ha⁻¹ with an average of 80% of the planted oak nests having at least one potential future crop tree after 10 - 20 years (Dong et al. 2007a; Leder 2007; Szymanski 1986). It is not clear what the underlying reasons for the observed discrepancy might have been but possible factors include differences in the removal of fast growing early-successional trees, variation in tree survival rates due to browsing, use of different genetic material, and varying crop tree selection criteria (Guericke et al. 2008; Gussone and Richter 1994; Nutto 2000; Weinreich and Grulke 2001).

A comprehensive meta-analysis combining data from various sites, however, reported that the proportion of potential future crop trees was 80% lower in nest planting stands than in row planting counterparts (Saha et al. 2012). The same investigation also found no significant difference in the number of potential future crop trees ha⁻¹ between group and conventional row plantings, an outcome that supports earlier studies (Ehring and Keller 2006; Harari and Brang 2008; Petersen 2007). Although the number of planted seedlings was on average nearly 40% lower in group than row planting, an equal number of potential crop trees per unit area was found for both stand establishment methods. Therefore, tree quality development was much more efficient in group plantings compared to conventional row planting (Demolis et al. 1997; Saha 2012).

Necessity of trainer trees in group planting

Findings from the aforementioned meta-analysis (Saha et al. 2012) suggested that trainer trees likely protect inner oaks in groups and that the competition imposed by these individuals is beneficial for quality development. Moreover, the protective function of trainer trees is further

corroborated by the positive effect of an increasing number of initially planted trainer trees per group on oak survival rate, stem form and percentage of potential future crop trees. Trainer trees might have suppressed other vegetation such as *Rubus* spp. and the establishment of more competitive tree species (Rock et al. 2004). However, no effect of planted trainer trees and voluntary regeneration of mid-successional tree species on the length of the branch free bole of oaks grown in groups was found (Saha et al. 2012; Saha et al. 2014). It was rather found that in 10- to 26-year-old oak stands and irrespective of cluster or row planting, self-pruning of oaks triggered by intraspecific competition would suffice for tree quality development. The observed positive effect of trainer trees in group plantings thus was not a species-specific influence but rather a facilitative effect of additional trees. As stands become older, these trainer trees can develop into strong competitors for oaks (Saha et al. 2014). Thus they should be monitored and possibly removed or preferably coppiced, if they overgrow the oaks in clusters (Joyce et al. 1998; Otto et al. 2009).

In conclusion, studies evaluating quality development in oak cluster plantings clearly demonstrated that stem quality development is inferior in nest compared to row plantings. In contrast, promising results have been obtained for oaks established in groups. However, further studies are required in older group planting trials to monitor how oak tree quality proceeds with stand development and under varying site and stand conditions.

Economic aspects

In comparison to conventional row planting, cluster planting systems may be financially advantageous owing to a reduction in the number of planted seedlings and lower expenses for

368 site preparation, tending, and protection measures (Szymanski 1986). Only few studies have
369 compared establishment and tending costs of cluster and row plantings while there are no cost
370 analyses that compare group and nest plantings. A substantial reduction in establishment
371 expenses of up to 50% was found in studies that compared oak group and conventional row
372 plantings (Gockel et al. 2001; Weinreich and Grulke 2001). However, given the general trend to
373 reduce seedling numbers in artificial regeneration, this advantage of cluster plantings may be
374 gradually disappearing (Kühne et al. 2014). Recent guidelines by some German state forest
375 administrations and institutions regarding initial seedling numbers for wide-spaced oak row
376 plantings (e.g. 3 x 1 m initial spacing, i.e. 3300 seedlings ha⁻¹) would significantly reduce the
377 establishment costs (Nutto 2000; Ehring and Keller 2006; Guericke et al. 2008; ForstBW 2014).
378 Wide initial spacing, however, has a detrimental effect on overall stem quality due to delayed
379 self-pruning (Kuehne et al. 2013). Artificial pruning may be required in such situations to
380 achieve a sufficient number of potential future crop trees. Whether or not later pruning activities
381 would offset the cost saved by low density row planting has not been studied. Furthermore, the
382 presence of a sufficient number of additional seedlings between clusters has been highly
383 recommended to promote the development of favourable stem qualities, particularly in oak
384 stands established through nest planting (Gussone and Richter 1994). If these supplementary
385 seedlings do not regenerate naturally and in high enough density, as has been often observed,
386 they need to be planted (Leder 2007). Hence, whether cluster and especially nest plantings are
387 more cost-efficient than row plantings or not depends on the reference used for comparison. In
388 cases, where clusters need to be complemented with planting of additional trees between
389 clusters, or when clusters are compared to low density row planting, they are likely not more cost
390 efficient in the establishment phase.

The number of clusters to be planted can also be optimized to reduce costs without hampering silvicultural goals. Forest managers in southwestern Germany, for example, currently plant 40 to 70 clusters ha^{-1} instead of the 100 proposed originally (Ehring and Keller 2006; Saha 2012; Kühne et al. 2014). The number of groups could be further reduced if sufficient natural regeneration of desirable tree species establishes between the clusters in a timely manner (Gockel et al. 2001). A low number of clusters per unit area further offers reduction in stand establishment expenses as site preparation activities can be limited to the few cluster locations. This holds especially true for wind thrown sites where costly broad-scale residue and slash removal as well as soil alteration necessary for mechanical row planting can be neglected. However, whether a reduction in the number of clusters is economically beneficial, depends not only on the savings in establishment costs but also the subsequent costs and tree volume and value production.

Early advocates of the cluster design also predicted reductions in tending costs in young stands because weeding and tending operations were supposed to focus only on planted nests or groups whereas in traditional row plantings, the entire planted area requires such expensive treatments (Szymanski 1994). However, other studies of oak nest plantings called for early tending operations such as the removal of naturally regenerated early successional species to secure the long-term management goal (Dong et al. 2007a; Guericke et al. 2008). However, for nest plantings, there have been no economic assessments on subsequent tending operations. No significant difference in tending expenses were found for 7-year-old Swiss oak group planting trials when compared with similar aged row plantings (Koch and Brang 2005). In contrast, higher costs when compared to row planting have been incurred for the time-consuming search of groups and their marking where they were embedded in vigorous competing vegetation

without uniform spacing or proper marking (e.g. wooden poles in the centre of the group as a marker) (Ehring and Keller 2006).

In summary, oak group plantings are likely more cost-efficient if large-scale site preparation measures are needed to conduct mechanical row planting (Petersen 2007). Cost efficiency in group plantings can be increased further by reducing the number of groups to be planted per unit area, and by regular spacing between groups. However, differences in tending expenses between group and row plantings are not yet apparent at this early stage of existing trials; therefore, further investigations on subsequent tending measures in older group plantings are needed.

Tree species diversity and stand productivity in cluster planting

The area between clusters, on average almost two thirds of the stand area in cluster plantings, remains for natural regeneration. The establishment of early- and mid-successional tree and shrub species in the interspaces between clusters has been prolific in formerly forested sites that are surrounded by remaining forests (Saha et al. 2013). Several studies in Central European forests have shown that diverse tree communities comprising mostly early-successional woody species can establish in extensively treated or unmanaged clear-felled and wind-thrown areas (Jonasova et al. 2010; Wohlgemuth et al. 2002). This voluntary regeneration significantly increased species diversity in cluster plantings when compared to row planting counterparts. Cluster planting in areas embedded in a matrix of existing forests provides ample opportunities for the establishment of diverse tree species communities at early stages of stand development (Saha 2012). Natural regeneration between clusters may be much lower when afforesting abandoned agricultural land, where fewer tree propagules are available or vigorous ground

vegetation inhibits establishment of woody plants. However, there is limited information on natural regeneration in cluster planting stands established on abandoned agricultural land. Naturally regenerated early- and mid-successional species contributed almost half of total stand basal area in cluster plantings and thus compensated for the reduced number of oaks in group plantings (Saha *et al.*, 2013). Moreover, the observed increase in tree species diversity had a positive effect on stand basal area which confirms results of previous studies on diversity-productivity relationships in temperate forest ecosystems in Europe (Morin *et al.* 2011; Vila *et al.* 2007). This diversity effect may be caused by the complementarity resource use of species that differ in height growth and shade-tolerance leading to canopy stratification (Bauhus *et al.* 2004; Körner 2005; Morin *et al.* 2011). Belowground niche separation between fine roots of oaks and other species and nurse tree effects by early successional trees (e.g. *silver birch*) might further facilitate efficient resource use in cluster planting stands (Saha *et al.* 2014, Stark *et al.* 2014). However, these belowground interactions between oaks and naturally regenerated trees are largely unexplored.

Early successional tree species increase total forest diversity leading to more complex food webs (Swanson *et al.* 2010). The promotion of these species as an integral component of forest management practices was thus recommended to enhance ecosystem services of managed forests in central Europe (Reif and Walentowski 2008). However, , growth of commercially important species (e.g. oaks) may be hampered by these fast growing species, thus they were usually removed as part of early stand tending in conventionally managed stands. Cluster planting schemes offer an opportunity to avoid these undesired interspecific interactions by spatially separating planted oak clusters and areas left for natural regeneration of other woody species during the first few decades of stand development. Moreover, by varying the number of groups

per unit area and therefore the distance between groups the cluster planting design can be adjusted to vary the proportions of oak and other species.

Some forest practitioners argue that the diversification of forest stands may complicate future management (Kerr 1999). However, in cluster planting, managers only need to focus on potential future crop trees emerging from each cluster. Tending operations to remove naturally regenerated competitors can focus on the interior and the periphery of clusters (Saha et al. 2014) (Fig. 3). The remaining vegetation between the clusters therefore could be maintained and managed for the promotion of biodiversity, the production of biomass or high value logs from species like silver birch, wild cherry (*Prunus avium* L.), or sycamore maple (Fig.3).

Risks and benefits of cluster planting – an outlook

Every forest management system needs defined targets for guidance and to evaluate management success. However, inherent potential risks may hamper the achievement of those targets, in particular in natural and semi-natural systems that are not under strict human control. Potential future crop trees are such a potential target in oak stands managed for high value timber production (Abetz and Kladtke 2002). How many future crop trees per unit area are needed after the first commercial thinning, which commonly takes place in 35 to 50-year-old stands, is a matter of ongoing debate. Whereas the aim may be to obtain between 60 - 80 harvestable oak trees ha⁻¹ at the end of the rotation, the question is whether a substantial number of reserve future crop trees are required to achieve that target. A study on the development of potential future crop trees in oak stands established by row planting showed that 9 - 14 % of such trees either died (by pathogen attack, wind and snow damage) or were downgraded in quality (e.g. epicormic

sprouting) (Spellmann and von Diest 1990a). However, a loss in future crop trees is sometimes seen as the result of flawed management decisions during early selection, promotion and tending rather than a failure of the silvicultural system oriented towards future crop trees (Abetz 1980; Abetz and Ohnemus 1999).

The special situation in cluster planting stands is that after the first commercial thinning there will be at most only one future oak crop tree for each initially planted cluster. Any further mortality of crop trees or downgrading owing to poor development in tree quality will immediately affect the overall silvicultural aim and likely the economic outcomes. Unfortunately, there is no information regarding the mortality rates of future crop trees from cluster-plantings, since existing trials have not yet reached the age of first commercial thinning.

It is clear that the solution to the potential risk of losing future crop trees that have emerged from clusters at later stages of stand development cannot simply be an increase in the number of clusters. Though this would diminish cost savings gained through planting fewer trees and benefits of increased tree species diversity, increased numbers of clusters would result in insufficient spacing between crop trees in areas where no mortality occurs. The above mentioned risk of low numbers of potential future crop trees may also be compensated by increasing the distance between groups and between-group planting of fast-growing valuable conifers or broadleaves (e.g. Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) or wild cherry) between groups. This can be an attractive option for forest owners interested in developing mixed forests and obtaining early financial returns. Responses from several foresters in Baden-Wuerttemberg and Lower Saxony, Germany revealed that 40 - 50 harvestable oak trees instead of 80 - 100 oaks ha⁻¹ would be an acceptable number, if high value trees of other species and/or a sufficient biomass from fast-growing species (e.g. European aspen (*Populus tremula* L.) and silver

birch) can be produced from cluster planting stands in shorter periods. However, these alternative options have not been assessed through economic modeling. This risk can also be mitigated if additional crop trees can be designated from natural regeneration occurring between groups. However, information on this is lacking.

Cluster planting with other species

So far cluster planting studies were carried out for artificial regeneration of oaks. However, cluster plantings offer similar benefits and may be equally suitable for other species. In particular, cluster planting can be used for regeneration of other broadleaved species which require appropriate neighbourhood density to facilitate self-pruning of the lower trunk.

Besides the focus on high-quality timber production, cluster planting methods can also be used to pursue other forest management objectives followed by as afforestation and restoration. For example, large afforestation programs (e.g. bottomland afforestation program in eastern Mississippi, USA) often have a shortage of funds and are thus forced to plant trees at wide spacing to achieve area targets with the consequence of the development of trees with low stem quality (Lockhart et al., 2006; Dey et al., 2010). In such situations, planting in groups would not only provide an appropriate initial growing space for such species but ensure that large areas can be covered with limited numbers of plants. Some abandoned agricultural lands have already been successfully restored in Germany using the group planting method (Ehring and Keller 2006; Petersen 2007). A relatively similar low density cluster planting design of holm oak (*Quercus ilex* L.) described as “woodland islets” was successfully used for afforestation purposes on degraded land in Spain (Benayas et al. 2008). Cluster plantings of various coniferous species were also recommended to restore Swiss high-elevation mountain forests (Schöneberger 2001).

Recently, cluster plantings of silver fir (*Abies alba* Mill.) and Pilgerodendron (*Pilgerodendron uviferum* (D. Don) Florin) were trialled in Italy and Chile, respectively, for the purpose of forest restoration (Bannister 2015; Fiorentini et al. 2015; Bannister et al. 2016).

Conclusions

Based on the results presented in this review, we conclude that the success of oak cluster plantings depends on a number of factors, most importantly the planting density within clusters. The nest planting approach is not a suitable option for oak stand establishment aiming at valuable timber production. In contrast, oak group planting with 1900 to 3100 seedlings ha⁻¹ can be used as an alternative to traditional row planting with ca. 5,000 seedlings ha⁻¹. Group planting represents a reforestation method that not only offers the opportunity to produce high quality oak timber, but promotes natural regeneration of additional tree species between the groups. This increases woody species diversity and possibly also productivity, and allows natural successional processes to take place. This review also shows that forestry trials which are commonly cost intensive and often forgotten in the course of time, sometimes regain importance as societal and economic demands in relation to forests change (Powers 1999). We showed that initial growing space initial size of the seedlings, and presence of trainer trees are crucial factors for the successful establishment and subsequent qualification of oaks in cluster plantings. Future research should focus on the tending, cost-benefit analyses and modeling of growth dynamics of group planting stands.

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Draft

(a)

(b)

(c)

Fig. 1: (a) Szymanski's (1986) nest design; (b) 7 x 7 m spacing between the centres of nests were generally followed in German nest plantings; (c) 23-year-old nest planting in Leonberg-Stuttgart, Baden-Wuerttemberg, Germany.

193x184mm (96 x 96 DPI)

Fig. 2: (a, b, c) Gockel's (1994) group planting design with 3 variants; (d) 10 x 10 m spacing was commonly followed between the centres of groups; (e) 20-year-old group planting in Lerchenfeld-Schwarzenborn, Hesse, Germany.

248x189mm (96 x 96 DPI)

Fig.3: Possible development of forest structure in oak stands established through group planting.

240x209mm (300 x 300 DPI)