# *Development of tree quality, productivity, and diversity in oak (Quercus robur and Q. petraea) stands established by cluster planting*

***Thesis submitted in partial fulfillment of the requirements of the degree Doctor rer. nat. of the Faculty of Forest and Environmental Sciences, Albert-Ludwigs Universität Freiburg im Breisgau, Germany***

**by**

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*"There would be no physicians if there were no diseases, and no forestry science without deficiency in wood supplies."*

*Heinrich von Cotta (1763 – 1844)*

*I dedicate this thesis to my father*

TABLE OF CONTENTS

**LIST OF FIGURES**

## LIST OF TABLES

## APPENDIX

**LIST OF ARTICLES**

Four articles were written from this thesis for publication in peer reviewed journals which are listed below. These four articles are included as four chapters (Chapter Two – Five) in this thesis.

1. Saha, S., Kühne, C., Bauhus, J. (not yet submitted). Survival, growth and quality of *Quercus petraea* and *Q. robur* established in cluster plantings: a review of Central European experiences. (Chapter Two).
2. Saha, S., Kuehne, C., Kohnle, U., Brang, P., Ehring, A., Geisl, J,. Leder, B., Muth, M., Petersen, R., Peter, J., Ruhm, W., Bauhus, J. (2012): Growth and quality of young oaks (Quercus robur and Quercus petraea) grown in cluster plantings in central Europe: A weighted meta-analysis. *Forest Ecology and Management*, 283, 106-118. Link (Chapter Three).
3. Saha, S., Kuehne, C., Bauhus, J. (2013): Tree Species Richness and Stand Productivity in Low-Density Cluster Plantings with Oaks (*Quercus robur* L. and *Q. petraea* (Mattuschka) Liebl.). *Forests*, 4 (3), 650-665. Link (Chapter Four).
4. Saha, S., Kühne, C., Bauhus, J. (2014) Growth and stem quality of oaks (*Quercus robur* and *Q. petraea*) established in cluster plantings respond differently to intra- and interspecific neighborhood competition. *Annals of Forest Science*, 71, 381–393. Link (Chapter Five).

**Statement about articles and own contribution to each article**

I had great pleasure and satisfaction to work with various co-authors. To acknowledge their contributions I have retained the expression "we" or "our" in this thesis that occurs in different articles. I used an authorship index proposed by Hunt (1991) to clearly identify and demonstrate my contribution in these articles that constitute my thesis. Points from 0 to 25 indicate the contribution of each author to four categories (table next page). In all four publications, I have contributed the majority of work across all aspects of the research including development of concept and experimental design, data collection, database preparation, data analysis and preparation of manuscripts. The remaining chapters in addition to these articles were completely written by me.

| | Intellectual input | Practical input: data capture | Practical input: data processing/organizing | Literary input | Sum |
|---|---|---|---|---|---|
| ***Article 1*** | | | | | |
| Somidh Saha | 25 | 25 | 25 | 25 | 100 |
| Christian Kuehne | 15 | 10 | 10 | 15 | 50 |
| Jürgen Bauhus | 15 | | | 15 | 30 |
| ***Article 2*** | | | | | |
| Somidh Saha | 25 | 25 | 25 | 25 | 100 |
| Christian Kuehne | 5 | 25 | 10 | 10 | 50 |
| Ulrich Kohnle | 15 | 10 | | 10 | 35 |
| Peter Brang | | 25 | | | 25 |
| Andreas Ehring | | 25 | | | 25 |
| Julian Geisel | | 25 | | | 25 |
| Bertram Leder | | 25 | | | 25 |
| Micheal Muth | | 25 | | | 25 |
| Regina Petersen | | 25 | | | 25 |
| Jacob Peter | | 25 | | | 25 |
| Werner Ruhm | | 25 | | | 25 |
| Jürgen Bauhus | 25 | 10 | 15 | 15 | 65 |
| ***Article 3*** | | | | | |
| Somidh Saha | 25 | 25 | 25 | 25 | 100 |
| Christian Kuehne | 10 | 25 | 10 | 10 | 55 |
| Jürgen Bauhus | 20 | | 10 | 15 | 35 |
| ***Article 4*** | | | | | |
| Somidh Saha | 25 | 25 | 25 | 25 | 100 |
| Christian Kuehne | 10 | 25 | | 10 | 45 |
| Jürgen Bauhus | 20 | | | 15 | 35 |

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## SUMMARY

Pedunculate oak (*Quercus robur*) and sessile oak (*Q. petraea*) are likely to become increasingly important in Central Europe owing to their stability, tolerance of relatively warm climates, and their valuable timber. Although natural regeneration is often the preferred option for oak stand establishment in many regions of Central Europe, planting and seeding still play a major role in the reforestation of oak-dominated forests. Artificial regeneration is the only way to establish oak stands in situations where acorn sources are lacking. In particular, this is the case where coniferous stands are to be converted to oak forests, where competition from herbaceous and woody plants hinders the natural regeneration of oak, or where oak stands are to be established in cleared areas following storms or other disturbances. Planting oak seedling in rows with a high initial density (e.g. 5,000 – 7,000 seedlings ha$^{-1}$) is often used for artificial regeneration of oaks. However, high costs associated with site preparation (particularly in wind-thrown areas), planting, fencing and successive tending measures remain a matter of concern for conventional row planting of oaks. These considerations may apply equally to the artificial regeneration of other hardwood species.

Such factors motivated foresters and researchers to seek alternatives to the establishment of oak stands. Low-density planting, where the artificial regeneration of the desired species is complemented by natural regeneration of additional species is one such approach to reduce costs and to maintain successional processes and increase biodiversity at the same time. For oaks, low density planting in the form of widely spaced clusters with two different designs has been developed in Europe. Clusters comprising 20 to 30 seedlings are either 'nests' (nest planting) with very dense spacing of ca. 0.2 m between trees, or 'groups' (group planting) with 1 m between trees. In contrast to nests plantings, clusters in group plantations are encircled with a varying number of individuals of a trainer tree species (e.g. *Tilia cordata*, *Carpinus betulus*). Commonly, ca. 100 groups or 200 nests ha$^{-1}$ were planted in uniform distribution. This new oak regeneration technique became popular in the 1980s and 1990s to reforest wind-thrown area created by catastrophic winter hurricanes in the 1990s (*"Vivian"* and *"Wiebke"* in 1990 and *"Lothar"* in 1999). Although many cluster planting trials were established since then, no comprehensive analysis had been carried out to study growth and quality attributes related to timber production in oaks grown in cluster planting. In addition, natural regeneration in the space between the clusters, stand productivity and the influence of naturally regenerated trees on growth and stem quality of oaks grown in clusters had never been studied. Therefore, the objectives for this study were as follows: 1) to compare comprehensively survival, growth (diameter at breast height or DBH, height), stability (height-to-DBH ratio), and quality (stem form, crown shape, branch free bole length, potential future crop tree) of oaks grown in clusters when compared to conventional row planting; 2) to assess and compare tree species diversity and stand productivity in stands established through cluster and row planting; and to test further whether stand productivity in cluster planting stands may be influenced by species richness and density of the naturally regenerated and planted trees; and 3) to quantify influences from intraspecific and interspecific interactions on growth and quality of oaks in mixed stands established through cluster planting.

The first objective was addressed by synthesizing original forest inventory data gathered and collected from 25 trial pairs consisting of cluster and respective neighbouring row planting sites (ca. 5,000 seedlings $ha^{-1}$) located in Germany, Switzerland and Austria and carrying out a meta-analysis. The second and third objectives were addressed by analysing data from 7 cluster trials located in Baden-Württemberg and Hessen, Germany. Again, row plantings counterparts were used for the comparison of the investigated stand establishment methods.

The comprehensive mixed effect meta-analysis revealed that tree survival, growth and quality were significantly lower in nests than in neighbouring row planting counterparts. Intense intraspecific competition due to very low initial growing space (only 0.04 $m^2$ per seedling) was presumably one of the main reasons for low survival, unfavourable growth and quality development of oaks in nest plantings. However, in group plantings which provided larger initial growing space (1 $m^2$ per seedling), survival, growth and tree quality were similar or superior to row plantings. The meta-analysis also showed that tree quality benefitted from the presence of trainer trees in group plantings.

Species richness and diversity were significantly higher in cluster plantings than in row plantings. Basal area of naturally regenerated trees (e.g. *Betula pendula*, *Populus* spp., *Salix* spp., *Acer pseudoplatanus*, *Sorbus aucuparia*) contributed to ca. 43% of total stand basal in cluster plantings and was significantly higher than in row plantings. As a result total stand basal area did not differ significantly between the analysed stand establishment methods. Productivity of stand established through cluster planting was significantly related to density of naturally regenerated species.

Competition from mid- and late successional tree species had a stronger negative impact on growth of target oak trees than competition from oaks and early successional tree species. Intraspecific competition was sufficient to promote self-pruning in oaks grown in clusters. Additional, interspecific competition did not further advance the branch-free bole length of target oaks. Oaks grown in the inner part of groups showed higher probability to develop into potential future crop trees than oaks grown in the periphery of groups. This study also showed that in the majority of groups (80%) in a 20-year old stand at least one potential future crop tree developed.

Based on this study, it can be concluded that owing to high mortality, poor growth and inferior stem quality, oak nest planting should not be pursued further to establish oak stands. In contrast, oak group plantings can be recommended as a suitable alternative to conventional row planting. Significant environmental (high species richness and productivity), silvicultural (quality development in oaks) and economic (e.g. low site preparation and plantings cost) gains can be achieved with low-density planting of oaks in groups.

## ZUSAMMENFASSUNG

Aufgrund ihrer Sturmstabilität, ihrer Toleranz gegenüber eines wärmeren und trockeneren Klimas sowie ihres wertvollen Holzes werden Trauben- (*Quercus petraea*) und Stieleiche (*Q. robur*) sehr wahrscheinlich an Bedeutung im zukünftigen Waldaufbau Mitteleuropas gewinnen. Obwohl die natürliche Verjüngung heute oftmals die bevorzugte Methode bei der Begründung von Waldbeständen ist, werden Saat und Pflanzung bei der Begründung von Eichenbeständen auch weiterhin eine bedeutende Rolle spielen. Künstliche Verjüngungsverfahren sind der einzige Weg eichendominierte Wälder zu begründen, wenn Samenbäume fehlen. Das ist insbesondere dann der Fall, wenn Nadelholzforste zu Eichenbeständen umgebaut werden, wenn wüchsige Begleit- und Konkurrenzvegetation das natürliche Auflaufen und Aufwachsen von Eichensämlingen verhindern und wenn Eichenwälder nach Kahlschlag oder Sturmwurf auf Freiflächen begründet werden sollen. Reihenaufforstungen mit 5000 bis 7000 Eichenpflanzen $ha^{-1}$ sind ein häufig verwendetes Verfahren der künstlichen Begründung von Eichenbeständen. Jedoch sind die mit Flächenvorbereitung, Pflanzung, Zäunung und Pflegemaßnahmen verbundenen Kosten der konventionellen Reihenpflanzungen nach wie vor ein großes Problem, das auch Aufforstungen viele anderer Laubholzarten betrifft. Zugleich mangelt es den künstlichen Beständen zu dem häufig an einer ausreichenden Diversität der Gehölzvegetation.

Die mit der herkömmlichen künstlichen Begründung von Eichenbeständen verbundenen Nachteile veranlassten Forstpraktiker und –wissenschaftler nach alternativen Verfahren der Wiederbewaldung zu suchen. Pflanzungen mit geringen Ausgangspflanzzahlen, in denen die gewünschte und künstlich eingebrachte Zielbaumart durch die Naturverjüngung weiterer Arten ergänzt wird, ist ein derartiger Versuch die Kosten der Bestandesbegründung zu verringern und die Biodiversität gleichzeitig zu erhöhen. Für Eichenbestände wurden zum Ende des vergangenen Jahrhunderts so zwei verschiedene Arten sogenannter Clusterpflanzungen entwickelt und propagiert. Unter Clustern versteht man aus ursprünglich 20 bis 30 Pflanzen bestehende Nester mit anfänglich engem Pflanzverband von 0,2 x 0,2 m (Nesterpflanzung) oder aber Trupps mit einem weiteren Verband zwischen den gepflanzten Eichen von 1 x 1 m (Truppflanzung). Im Gegensatz zu den Nestern werden die Eichentrupps in der Regel mit einer variierenden Anzahl an Individuen einer schattenertragenden Baumart für die spätere Schaftpflege umfasst. Üblicherweise wurden etwa 100 Trupps oder aber 200 Nester $ha^{-1}$ bei gleichförmiger Verteilung über die aufzuforstende Fläche begründet.

Als Folge der verheerenden Sturmkatastrophen der 1990er Jahre (Vivian und Wiebke, Lothar) gewannen Nester- und Truppflanzung als Wiederaufforstungstechnik in Mitteleuropa an Aufmerksamkeit und Bedeutung. Obwohl aufgrund dieser verstärkten Beachtung seither diverse Clusterpflanzungen entstanden sind, ist eine umfassende Analyse von Wachstums- und Qualitätsparametern von Eichen aus Clusterpflanzungen noch nicht durchgeführt worden. Zugleich wurden die natürliche Gehölzverjüngung zwischen den Clustern und deren Einfluss auf die Entwicklung der Clustereichen sowie die übergeordnete Bestandesproduktivität von Clusteraufforstungen bisher noch nicht vergleichend untersucht. Die Ziele der vorliegenden Arbeit können daher wie folgt beschrieben werden: 1) Vergleich von Überlebensrate, Wachstum (Durchmesser auf Brusthöhe bzw. BHD, Baumhöhe), Stabilität (Höhe-BHD-Verhältnis) und Qualität (Stamm- und Kronenform, astfreie Schaftlänge, Vorkommen potentielle Z-Baum

Anwärter) von Eichen aus Cluster- und traditionellen Reihenaufforstungen; 2) Baumartendiversität und Bestandesproduktivität von Beständen aus Cluster- oder Reihenpflanzung, wurde erfasst und verglichen. Weiterhin wurde untersucht ob naturverjüngte und gepflanzte Individuen die Bestandesproduktivität in Beständen aus Clusterpflanzung beeinflussen; und 3) Quantifikation des Einflusses intra- und interspezifischer Interaktionen auf das Wachstum und die Qualität von Eichen in aus Clusterpflanzungen entstanden Mischbeständen.

Die für Untersuchungsziel 1 durchgeführte gewichtete Meta-Analyse basierte auf dem Vergleich von Eichen aus Cluster- und vergleichbar erwachsenen Reihenaufforstungen (etwa 5000 Pflanzen $ha^{-1}$). Die Rohdaten stammten von 25, zwischen 6 und 26 Jahre alten Bestandespaaren aus planaren bis montanen Lagen Deutschlands, der Schweiz und Österreichs. Die umfassende Auswertung der Datenreihen zeigte, dass Überlebensrate, Wachstum, Stabilität und Qualität von Nestereichen denen von Eichen aus Reihenpflanzungen vielfach signifikant unterlegen waren. Starke intraspezifische Konkurrenz aufgrund des sehr geringen anfänglichen Wuchsraumes einer jeden Nestereiche von 0,04 $m^2$ dürfte der Grund für die ungünstige Wachstums- und Qualitätsentwicklung in Nesteraufforstungen gewesen sein. Bei den analysierten Truppplanzungen mit einem ursprünglichen Wuchsraum von 1 $m^2$ je gepflanzter Eiche ergaben sich bei den untersuchten Parametern hingegen mehrheitlich keine signifikanten Unterschiede zu den Reihenaufforstungen. Eine ausreichend große Anzahl an Individuen einer dienenden Baumart (z.B. *Tilia cordata*, *Carpinus betulus*) hatte zu dem einen positiven Einfluss auf die Qualifizierung der Eichen in Trupps.

Die Daten der für Untersuchungsziel 2 und 3 durchgeführten Analysen stammten von 7 in Baden-Württemberg und Hessen gelegenen Eichenclusterflächen sowie von den Clusterpflanzungen jeweils unmittelbar benachbarten Reihenaufforstungen. Anzahl und Diversität der Gehölzarten waren in den Clusterpflanzungen gegenüber den Reihenaufforstungen signifikant erhöht. Der Anteil natürlich aufgelaufener Gehölze (z.B. *Betula pendula*, *Populus* spp., *Salix* spp., *Acer pseudoplatanus*, *Sorbus aucuparia*) an der Bestandesgrundfläche war mit durchschnittlich 43% in den Clusterflächen signifikant höher als in den Reihenpflanzungen, wodurch sich keine Unterschiede in der Bestandesproduktivität zwischen den beiden Pflanzverfahren fanden. Die Bestandesproduktivität von Beständen aus Clusterpflanzung war signifikant korreliert mit der Dichte der naturverjüngten Arten.

Konkurrenz spätsukzessionaler und intermediärer Baumarten hatte einen stärkeren negativen Einfluss auf das Wachstum von Clustereichen als Konkurrenz durch Eichen und frühsukzessionaler Arten. Während intraspezifische Konkurrenz ausreichend für die natürliche Astreinigung der Eichen in Clustern war, erhöhte zusätzliche interspezifische Konkurrenz die astfreie Schaftlänge untersuchter Clustereichen nicht. In der überwiegenden Mehrheit der untersuchten Trupps (80%) fand sich mindestens ein potentieller Z-Baum Anwärter. Die Wahrscheinlichkeit, sich zu einem Z-Baum Anwärter zu entwickeln, war dabei für Eichen im Inneren der Trupps signifikant größer als für jene, die den Außensaum formten.

Auf der Basis der Ergebnisse dieser Untersuchung lässt sich schlussfolgern, dass aufgrund der hohen Mortalität und dem daraus resultierenden ungünstigen Wachstumsgang und der schlechten Qualitätsentwicklung Nesterpflanzungen nicht länger als Verfahren zur Begründung von Eichenbeständen verwendet werden sollten. Die

Truppppflanzung kann hingegen als geeignete Alternative zur herkömmlichen traditionellen Reihenaufforstung empfohlen werden. Sowohl ökonomische (z.B. geringe Flächenvorbereitungs- und Pflanzkosten) wie auch waldbauliche (ausreichende Qualifizierung der Eichen) und ökologische Vorteile (hohe Artendiversität und Bestandesproduktivität) lassen sich mit der Pflanzung von Eichen in Trupps erzielen.

**RÉSUMÉ**

Dans les années à venir, il est vraisemblable que le chêne pédonculé (*Quercus robur*) et le chêne sessile (*Q. petraea*) deviennent des espèces de plus en plus importantes en Europe centrale en raison de leur stabilité, de leur tolérance aux climats relativement chauds, et de la grande valeur de leur bois. Bien que la régénération naturelle soit encore la meilleure façon d'établir des peuplements de chênes dans plusieurs régions d'Europe centrale, la plantation et l'ensemencement jouent un rôle majeur pour la reforestation des forêts dominées par le chêne. La régénération artificielle est la seule manière d'établir des peuplements de chênes lorsque des sources de glands sont manquantes, et ce, particulièrement dans les zones où des peuplements résineux doivent être convertis en forêts de chênes, où la compétition par d'autres plantes herbacées ou ligneuses freine la régénération du chêne, et où les peuplements de chênes doivent être établis dans des zones ouvertes à cause d'une tempête ou autre perturbation. La plantation de semis de chênes à une densité initiale élevée (e.g., 5000 à 7000 semis $ha^{-1}$) est souvent utilisée pour la régénération artificielle de chênes. Cependant, les coûts élevés associés à la préparation du terrain (particulièrement dans les zones de chablis), à la plantation, à la protection contre le broutage ainsi qu'aux soins sylviculturaux successifs soulèvent toujours des doutes au sujet de la plantation en rangées conventionnelle de chênes. Ces doutes pourraient s'appliquer également à la régénération artificielle d'autres espèces de feuillus.

Cette situation a motivé les forestiers et chercheurs à explorer des alternatives pour l'établissement de peuplements de chênes. La plantation à faible densité, où la régénération artificielle de l'espèce désirée est complétée par la régénération naturelle d'espèces additionnelles, est l'une de ces approches qui visent à réduire les coûts tout en maintenant les processus de succession naturelle et en augmentant la biodiversité. En Europe, deux différents patrons de plantation à faible densité avec bouquets espacés (ci-après nommés simplement plantation par bouquets; notez toutefois que les expressions « placeaux » et « parquets » sont parfois aussi utilisées en lieu et place de « bouquets ») ont été développés pour les chênes. Ces bouquets se trouvent sous la forme soit de « nids » (ci-après plantation en nids), avec un espacement très restreint d'environ 0,2 m entre les arbres, soit de « groupes » (ci-après plantation en groupes), avec un espacement de 1 m entre les arbres. Contrairement à la plantation en nids, les bouquets dans la plantation en groupes sont encerclés par un certain nombre d'individus d'une espèce accompagnatrice (e.g., *Tilia cordata*, *Carpinus betulus*). Selon ces patrons de plantation, la densité des bouquets – distribués uniformément au sein du peuplement – est habituellement de 100 groupes ou 200 nids par hectare. Cette nouvelle technique de régénération du chêne est devenue populaire dans les années 1980 et 1990 pour la reforestation des zones de chablis créées par les tempêtes hivernales catastrophiques des années 1990 (*Vivian* et *Wiebke* en 1990 puis *Lothar* en 1999). Bien que plusieurs essais de plantation par bouquets aient été établis depuis, aucune analyse globale n'a été menée afin d'étudier la croissance et les paramètres de qualité liés à la production de bois des chênes situés dans ces plantations. De même, aucune étude ne s'est attardée à la régénération naturelle entre les bouquets, à la productivité du peuplement, ou à l'influence des arbres régénérés naturellement sur la croissance et la qualité de tige de ces chênes. Par conséquent, les objectifs de cette étude étaient: 1) de comparer de manière globale la survie, la croissance (diamètre à hauteur de poitrine ou DHP, et hauteur), la stabilité (rapport hauteur-DHP) et la qualité (forme du tronc, forme du houppier, hauteur de bille sans branche, potentiel comme future tige

d’avenir) de chênes poussant en bouquets en comparaison avec la plantation en rangées traditionnelle; 2) Évaluer et comparer la diversité en espèces d’arbres et la productivité de peuplements établis par plantation en groupes ou par plantation en rangées; et tester si la productivité d’un peuplement établi par plantation en groupes est influencée par la densité et la richesse spécifique des arbres régénérés naturellement ainsi que des arbres plantés.; 3) de quantifier l’influence des interactions intraspécifiques et interspécifiques sur la croissance et la qualité des chênes dans des peuplements mélangés établis par plantation par bouquets.

Le premier objectif a été traité par le biais d’une synthèse de données provenant d’inventaires forestiers. Ces données sont issues de 25 paires d’essais de plantation en Allemagne, en Suisse et en Autriche. Une méta-analyse a été effectuée sur l’ensemble des 25 paires. Chaque paire était constituée d’une plantation par bouquets et d’une plantation traditionnelle en rangées (environ 5000 semis $ha^{-1}$), situées à proximité l’une de l’autre. Le second et le troisième objectif ont été atteints par l’analyse de sept essais de plantation par bouquets situés dans les länder de Bade-Wurtemberg et de Hesse, en Allemagne. Des plantations en rangées traditionnelles ont encore une fois servies de comparatifs pour évaluer les méthodes d’établissements.

La méta-analyse globale à effets mixtes a révélé que la survie, la croissance et la qualité des tiges étaient significativement plus faibles dans les plantations en nids par rapport aux plantations en rangées. Une intense compétition intraspécifique, due à un espace de croissance initial très faible (seulement 0,04 $m^2$ par semis), était probablement une des principales raisons de ces valeurs décevantes de survie, croissance et qualité des chênes dans les plantations en nids. En contrepartie, les chênes dans les plantations par bouquets – lesquelles offraient un espace de croissance initial plus grand (1 $m^2$ par semis) – arboraient une survie, une croissance et une qualité de tige supérieures à celles des chênes dans les plantations en rangées. La méta-analyse a aussi démontré que la qualité de tige bénéficiait de la présence des espèces compagnes dans les plantations par bouquets.

La richesse et la diversité spécifique étaient significativement supérieures dans les plantations par bouquets par rapport aux plantations en rangées. La surface terrière des arbres régénérés naturellement (e.g., *Betula pendula*, *Populus* spp., *Salix* spp., *Acer pseudoplatanus*, *Sorbus aucuparia*) dans les plantations par bouquets était significativement supérieure à celle observée dans les plantations en rangées. De plus, dans les plantations par bouquets, cette surface terrière d’arbres régénérés naturellement représentait environ 43% de la surface terrière totale du peuplement (arbres plantés et arbres régénérés naturellement). Par conséquent, la surface terrière totale ne différait pas significativement entre les méthodes d’établissement à l’étude. La productivité des peuplements établis par plantation en groupes était significativement reliée à la densité des espèces régénérées naturellement.

La compétition provenant des espèces d’arbres de milieu et de fin de succession avait un impact négatif plus important que la compétition des chênes et des espèces de début de succession. La compétition intraspécifique était suffisante pour promouvoir l’auto-élagage des chênes poussant au sein des bouquets. De plus, la compétition interspécifique n’a pas eu d’effet sur la hauteur de bille sans branche des chênes. Les chênes poussant dans la partie intérieure des groupes avaient une probabilité plus forte de se développer en futures tiges d’avenir que les chênes poussant en périphérie de ces groupes. Cette étude a aussi démontré que, pour un peuplement donné âgé de 20 ans établis par plantation en groupes, au moins une potentielle tige d'avenir se développe par groupe, et ce pour la majorité (80%) des groupes du peuplement.

À la lumière des résultats de cette étude, il peut être conclu que la plantation en nids ne devrait plus jamais être utilisée pour l'établissement de peuplements de chêne, et ce, en raison de la forte mortalité, de la faible croissance et de la qualité de tige inférieure observées. En contrepartie, la plantation de chênes par bouquets est recommandée comme alternative appropriée à la plantation en rangées. Des gains significatifs en termes environnementaux (richesse spécifique et productivité élevées), sylviculturaux (bon développement des tiges de chêne avec le potentiel de produire du bois de haute qualité) et économiques (e.g., faibles coûts de préparation du terrain et de plantation) peuvent être réalisés grâce à la plantation de chênes à faible densité et en groupes.

# CHAPTER ONE: INTRODUCTION

***Nearly 100 year old mixed oak stand in Mooswald, Freiburg, Germany.***

## 1.1 IMPORTANCE OF OAKS FOR CENTRAL EUROPEAN FORESTS AND FORESTRY

European forests and forestry are in transition. Climate change induces rising temperatures and resulting drought events are threatening tree survival, and losses in net primary productivity of forest ecosystems (Ciais *et al.*, 2005; Kölling and Ammer, 2006; IPCC, 2007; Hickler *et al.*, 2012). In addition to drought, an increase in the frequency of severe winter storms and subsequent bark beetle attacks have caused major forest damage and disturbances in recent decades (Leckebusch and Ulbrich, 2004; Albrecht *et al.*, 2010; Usbeck *et al.*, 2010). Therefore, close to nature forest management concepts and forestry practices promoting site-adapted and drought tolerant tree species, the maintenance of continuous forest cover, the conversion of monocultures to mixed forests and the conservation of species diversity have received increasing emphasis as possible adaptation measures (Drouineau *et al.*, 2000; Schonenberger, 2002; Knoke *et al.*, 2008). Because of their wide distribution range covering various edaphic and climatic conditions throughout Western, Central and Eastern Europe (Fig. 1.1), and their proven drought tolerance and storm stability (Burschel and Huss, 1997; Joyce *et al.*, 1998) pedunculate and sessile oak (*Quercus robur* and *Quercus petraea*) are believed to gain in proportion in Central European forests (Bolte *et al.*, 2009; Frischbier *et al.*, 2010). In addition, oak forests harbour various rare and endangered bird and insect species, and given proper management procedures, produce high value timber. Owing to these facts, interest has been growing among private, community and state forest owners to increase oak forest cover (Polley *et al.*, 2009). This in turn has stimulated research on oak silviculture in the last decades.

Pedunculate oak can tolerate continentally influenced climatic conditions, whereas sessile oak prefers oceanic and sub-continental climate. Pedunculate oak is highly adaptable to grow on acid soils as well as on those with high base saturation. It can tolerate flooding for long periods and is a frequent constituent of riverine forests. Sessile oak is also tolerant to all soils regardless of their pH-status and has the ability to withstand very dry conditions. Both species are light demanding and show best growth on fertile and well drained soils (Joyce *et al.*, 1998). However, silvicultural management systems do not vary between these two species because of the similarities in morphological and self-pruning characteristics, which vary as much within species, e.g. between provenances, than between species (Müller-Starck *et al.*, 1993; von Lüpke, 1998).

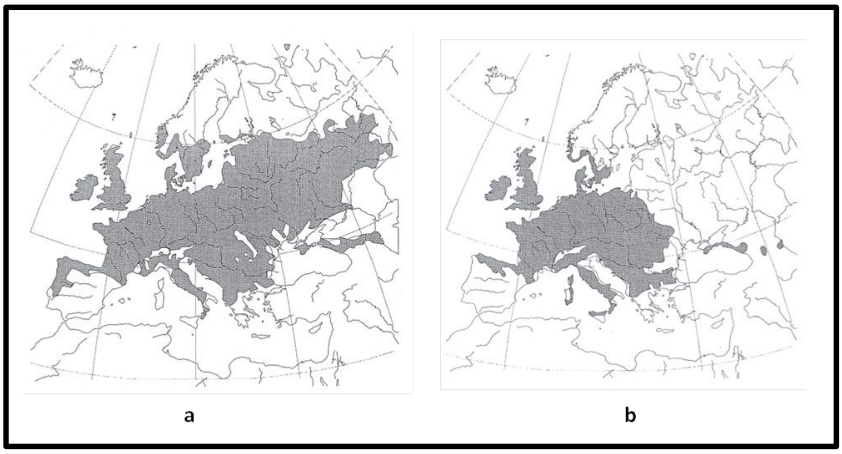


**Fig.1.1. Distribution of (a) pedunculate oak (*Quercus robur*), and (b) sessile oak (*Quercus petraea*) in Europe (Joyce *et al.*, 1998).**

## 1.2 TRADITIONAL METHODS OF OAK STAND ESTABLISHMENT

In addition to valuable environmental benefits, production of valuable oak timber for sawn products and decorative veneer is an important economic goal in oak forest management. For example, the commercial goal of oak management in Germany is typically to produce at least 60 - 80 high quality harvestable trees per hectare with a minimum target diameter at breast height of 60 cm and a branch free bole length of 6 - 10 m at the end of a 140 - 200 year production cycle (Spiecker, 1991; von Lüpke, 1998). Establishment of oak stands through natural regeneration is preferably conducted in large-scale regular shelterwood systems with a swift removal of the canopy following seedling establishment (von Lüpke, 2008). Natural regeneration of oaks lowers establishment costs, allows regular development of root systems and favours natural adaptation to local site conditions. However, in a range of situations, natural regeneration cannot be used as a mode of oak stand establishment because of several drawbacks. Natural regeneration of oaks is highly dependent on the availability of seed trees and seed production during mast years. This particularly poses a main constraint to the reforestation of wind-thrown areas, the afforestation of abandoned agricultural land, and the conversion of conifer monocultures to broadleaved forests. High risks associated with the damage and predation of acorns and seedlings by fungi, insects, deer, voles and snails among others can further impede successful natural regeneration of oaks (Kühne and Bartsch, 2005). Because of the limitations and difficulties regarding natural regeneration, only 50% of young (mean stand height < 4 m) oak stands in Germany have established by natural regeneration (BMELV, 2002). However, sowing and planting are reliable alternatives to natural regeneration for oak stand establishment (Anderson, 1951; Burschel and Huss, 1997; Joyce *et al.*, 1998; Röhrig *et al.*, 2006). Planting at high densities (i.e. 5,000 - 10,000 seedlings ha$^{-1}$) in closely spaced rows (2 x 1, 1.5 x 1, 1.5 x 1.5, 1 x 1 m) allows fast crown closure triggering intraspecific competition and promoting height growth, the development of straight stems and monopodial crowns as well as self-pruning (Schmaltz *et al.*, 1997; Ehring and Keller, 2006). However, the high establishment costs of artificially regenerated oak stands have always been a major concern for a long time. Today, the reforestation of 1 ha oak stand with 2 x 1 m spacing may cost ca. 15,000 Euro including the expenses for browsing protection. Furthermore, with the aim to establish a continuous oak canopy naturally regenerated trees of early- and mid-successional species are consequently being removed, thus reducing tree species diversity at early stand development stages.

## 1.3 OAK CLUSTER PLANTING DESIGNS

Oak cluster planting was developed as an alternative to overcome the limitations associated with traditional row planting by forest scientists in Poland and Germany towards the end of the last century. In cluster plantings, trees are either planted in groups of ca. 20 - 25 at 1 m spacing between trees (i.e. group planting), or in denser clusters comprising 20 - 30 oaks per m$^2$ (i.e. nest planting). In addition to oaks, trainer trees (e.g. *Carpinus betulus*, *Tilia cordata*, *Fagus sylvatica*) of a varying number (8 - 16 trees per group) are planted in group but not in nest plantings (see Chapter two for historical development and detail descriptions on cluster planting designs). In both cases, the clusters are spaced at a distance that defines the growing space of mature crop trees. Commonly this spacing was 7 x 7 m and 10 x 10 m between the centres of the clusters for nest and group planting, respectively. This indicates that more clusters were established than the anticipated number of final crop trees, since mature oaks with a diameter at breast height of > 60 cm may have a crown diameter of more than 12 m (Nutto, 2000).

The proponents of cluster planting put forward several hypotheses: (a) stem quality and growth of oaks in clusters would be comparable or better than that of oaks grown in traditional row planting and each cluster would produce at least one potential future crop tree, (b) oaks growing in the interior of the clusters would emerge as potential future crop trees, (c) trainer trees planted adjacent to groups would promote quality development of oaks within groups, and (d) space left between the clusters would promote natural regeneration of early and mid-successional tree species eventually increasing total tree species diversity (Fig.1.2). Many cluster planting trials were established between 1980 and 2000, particularly in order to reforest woodlands destroyed by catastrophic storms; namely *Vivian* and *Wiebke* (1991) and *Lothar* (1999) in Germany, Austria and Switzerland. Some of those trials have been studied and the results published as case studies. However, no comprehensive study has been conducted to test the above listed hypotheses and to evaluate the general suitability of cluster planting systems for oak stand establishment.


**Fig.1.2: Gaps between groups in 5 year old oak group planting stand located in Mooswald, Freiburg (afforestation in abandoned agricultural land) (Source: Google Map).**

## 1.4 RESEARCH OBJECTIVES

I aimed to test the effectiveness of cluster planting systems for establishing oak stands. My research focused on silvicultural options in oak stands established by cluster plantings and how they differ in comparison to stands established through traditional row planting. Based on a comprehensive literature review of existing publications on cluster plantings (see Chapter two) the following research objectives were formulated:

1. To compare oak survival, growth, and quality in cluster and traditional row plantings.
2. To assess and compare tree species diversity and stand productivity in cluster and row plantings and to assess the relationship between tree species diversity, density and stand productivity in cluster plantings.
3. To quantify influences from intraspecific and interspecific interactions on oaks grown in clusters.

## 1.5 STUDY AREA DESCRIPTION

Detailed descriptions of the study areas are provided in each consecutive chapter of this thesis. In short, the first research objective was addressed by synthesizing data from 25 cluster planting trials located in Germany, Austria and Switzerland. The second, third and fourth objectives were analysed based on data collected by myself from 7 cluster planting trials in the German federal states Baden-Württemberg and Hessen.

## 1.6 STRUCTURE OF THESIS

This thesis presents the findings, synthesis and implications for forest management of research conducted on oak cluster plantings from October 2008 to July 2012. Four chapters (Chapter Two to Five) are written in the format of manuscripts for publication in scientific journals. One of them has already been accepted for publication and one is under peer-review process. Two others are currently being prepared for submission. In total this thesis has been written in six chapters including this introduction.

Chapter Two reviews the existing literature in order to gather and summarize current knowledge on growth, quality and economic attributes of oak cluster planting systems in comparison to traditional row planting. In addition, this paper briefly describes the historical development of the concept of low-density cluster planting. This literature research aimed at highlighting key factors that influence growth and tree quality development.

Chapter Three investigates oak growth and quality development in cluster and row planting by comprehensive meta-analyses. This research aimed to explore the effectiveness of cluster planting for oak stand establishment in comparison to traditional row planting.

Chapter Four investigates whether tree species diversity in oak cluster plantings is higher than in row plantings and whether this diversity influences productivity in young oak stands. This research aimed at exploring the relationship between tree species diversity, density and stand productivity in cluster plantings.

Chapter Five investigates how intraspecific and interspecific interactions influence growth and branch free bole length of oak trees grown in cluster plantings. This research aimed at quantifying the influence of naturally regenerated and planted trees on growth and quality of cluster oaks. In addition, the hypothesis that oaks located in the interior of groups would develop higher stem quality than peripheral oaks was tested.

Chapter Six provides an overall synthesis of the findings of this study, management recommendations for establishing oak stands by cluster planting systems, and finally conclusions and directions for future research.

# CHAPTER TWO: SURVIVAL, GROWTH AND QUALITY OF OAK TREES (*Quercus robur* AND *Q. petraea*) ESTABLISHED IN CLUSTER PLANTINGS: A REVIEW OF CENTRAL EUROPEAN EXPERIENCES

***22 year old 'Anderson's spaced group planting' of sitka spruce and mountain pine on poor peat, planted in 1926 at Inchnacardoch Forest, Great Britain (Anderson, 1951).***

***20 year oak nest planting planted by Szymanski in 1950s in Poland (Silviculture Department, Poznan University, Poland).***

## 2.1 INTRODUCTION

In the last three decades, forest management on public lands in central Europe has undergone a substantial paradigm shift from traditionally managed, even-aged systems to more irregular, uneven-aged close-to-nature silvicultural systems (Diaci, 2006; Puettmann *et al.*, 2008; Kohnle and Klädtke, 2010). Close-to-nature silviculture advocates the use of site-adapted species and the conversion of conifer monocultures by under-planting and admixing deciduous tree species (Kenk and Guehne, 2001). Efforts to convert pure conifer stands established outside of their natural range have been intensified following recent major forest disturbances and in the anticipation of climate change (Hanewinkel *et al.*, 2008; Yousefpour *et al.*, 2010). For example, severe winter storms have caused large-scale catastrophic damage, mainly in forests dominated by conifers in Central and Western Europe during the last 20 year (Albrecht *et al.*, 2010; Hanewinkel *et al.*, 2010; Usbeck *et al.*, 2010). And climate change models predict that the frequency and severity of such extreme wind events are likely to increase in the future (Leckebusch and Ulbrich, 2004). These disturbances have created opportunities for changing tree compositions to more site-adapted broadleaved species in Germany and other central European countries. This trend is likely to continue given in the prospects of climate change (Reif *et al.*, 2010).

The relatively storm-resistant and moderately drought-tolerant pedunculate and sessile oak (*Quercus robur, Q. petraea*) are likely to increase in importance as the climate warms (Roloff and Grundmann, 2008; Bolte *et al.*, 2009). In addition, pedunculate oak is one of the few tree species suitable for the production of high quality timber on sites that are prone to storm disturbance, owing to hydromorphic soil conditions, where vertical root growth of most other species is constrained. Hence, a quadrupling of the oak cover in the German federal state of Thüringen up to 16% of the total forested area was recommended as an adaptive management strategy against possible climate change impacts (Frischbier *et al.*, 2010). Furthermore oak forest cover increased by 8% (58,536 ha) from 1987 to 2002 in the former Western German states (BMELV, 2002). An increase in oak forest cover also resulted from the use of oak for the reforestation of wind-thrown areas after severe winter storms in 1991, *"Vivian"* and *"Wiebke"*, and in 1999, "*Lothar"*. Catastrophic damage in coniferous forests by these storms prompted forest managers to convert pure coniferous stand established in unsuitable sites to mixed forest of oak and other broadleaved trees. As a result, recent inventories reported 4.6% increases in oak forest cover (42,000 ha) from 2002 to 2008 in Germany (Polley *et al.*, 2009). It has been estimated that the total Norway spruce conversion area in 14 European countries amounts to at least 1.1 million ha (Spiecker *et al.*, 2004). In another forest conversion program, German federal state of Brandenburg has the long-term aim to convert more than 500, 000 ha of pure Scots pine stands into mixed forest with a high proportion of deciduous tree species such as oak (Landesforstanstalt Eberswalde, 2006).

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). The commercial goal of 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 - 200 year rotation period (Spiecker, 1991; von Lüpke, 1998). Maintaining the structural homogeneity of the crown layer in early stand development stages by initially planting at high densities was a primary goal in plantations managed under clear-felling systems to foster natural self-pruning (Anderson, 1951).

The number of oak seedlings $ha^{-1}$ in row planting has decreased since the 1990s (Ehring and Keller, 2006; Guericke *et al.*, 2008). However, high costs of site preparation, planting, fencing and tending remains a matter of concern. The irregular spatial distribution of potential future crop trees, the rigid thinning protocols, the lack of natural regeneration of other tree species are further undesirable attributes of this type of oak cultivation (Anderson, 1951; Szymanski, 1986; Gockel, 1995; Ehring and Keller, 2006). These factors have motivated European foresters and scientists to seek alternatives to conventional establishment of 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 young oak trees in natural forests may be related to irregular disturbances of the forest floor caused by wild boars (Szymanski, 1986). It was assumed that these irregularities disappear as the individual trees grow and eliminate competing trees and project their crowns over small unoccupied areas. However, stands may not consist of trees with desirable qualities such as size, stem form, crown shape, branching pattern and stability (Anderson, 1951). It was proposed that if dense clumps of stems are regularly distributed in a stand, there is a much greater choice for the selection of future crop trees during thinning operations leading to more regularly spaced trees (Anderson, 1951b; Szymanski, 1986). Moreover, the planting of a limited number of oak in clusters by mimicking natural regeneration dynamics, means fewer trees and less site preparation is needed to attain a sufficient number of potential future crop trees compared to traditional row planting (Anderson, 1951).

Oak clusters established with very close (0.2 x 0.2 m) and relatively wider (1 x 1 m) spacing became known respectively as “nest plantings” (Szymanski, 1986) or as “group plantings” (Gockel, 1995). Since both approaches have been used for reforestation and afforestation with oak, they will be jointly reviewed here. Although oak cluster plantings have become an accepted reforestation method in many parts of Central Europe, there has been no literature review of this approach. The potential advantages of cluster planting are: 1) a reduction in site preparation and establishment costs when compared to traditional row planting, without a reduction in silvicultural options, and 2) the promotion of the natural regeneration of other species, hence increases in tree species diversity between the clusters (Gussone and Richter, 1994; Gockel, 1995; Leder, 2007; Dong *et al.*, 2007a).

Here, we will focus on oak cluster plantings by comparing them to conventional row plantings (at least, 5000 oak seedlings planted $ha^{-1}$) drawing on the experiences from Germany, Poland and Switzerland, where many silvicultural trials for this system have been installed. Information from these trials is supplemented with that of other tree species from other countries. Following a brief account of the historical development of cluster plantings, we review several success indicators such as tree survival rate, tree growth and quality, and establishment costs for oak cluster plantings. Additionally we review vegetation diversity and natural regeneration potential in cluster planting.

## 2.2 THE HISTORY OF CLUSTER PLANTING

Ogievski, a forest scientist from the St Petersburg Institute of Forestry of Imperial Russia, was the first to translate observations of natural dynamics in oak forests into forest management practices. In the early 1910s he established oak cluster trials in the Russian Tula forest steppe on a clear-felled site (Pryakhin and Portnykh, 1949). In this original trial, 200 rectangular blocks $ha^{-1}$ measuring 2 m² (1 x 2 m), hereafter nests, were sown with 50 acorns per nest. The spacing between the nests was 4.5 x 4.5 m. The nest trials 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 state policy for shelter belt plantings without first properly testing its effectiveness. 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, Voronezh and Belorussia (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 literature in the early 1950s (Buchholz, 1949; Anderson, 1951). Subsequently, in 1952, inspired by results from Russian nest planting trials, Szymanski, the forest scientist from Poznan University, Poland, modified Ogievski's method. And subsequently the first experimental trials of oak nest plantings outside Russia were established in the Siemianice forest district, close to the lower Silesian highlands in south-central Poland. In his design, nests of 1 $m^2$ were planted with 21 one year old oak seedlings with 0.2 m spacing between seedlings (Fig. 2.1). He developed two different spacing protocols; either 4 x 4 m or 5 x 8 m between nests. *Larix decidua*, *Tilia cordata*, *Fagus sylvatica* and *Prunus* spp. trees were planted in rows in 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 plantation technique in Germany (Gussone and Richter, 1994). This motivated foresters in Germany to trial oak nest plantings in the 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 of Rhineland-Palatinate, Saxony-Anhalt, and Baden-Württemberg. These trials did not follow Szymanski's protocol exactly. Instead, 7 x 7 m spacing between nests was widely followed. The space between nests was either planted with shade-tolerant trainer species such as *Tilia cordata*, *Carpinus betulus*, and *Fagus sylvatica* or they were left for natural regeneration.

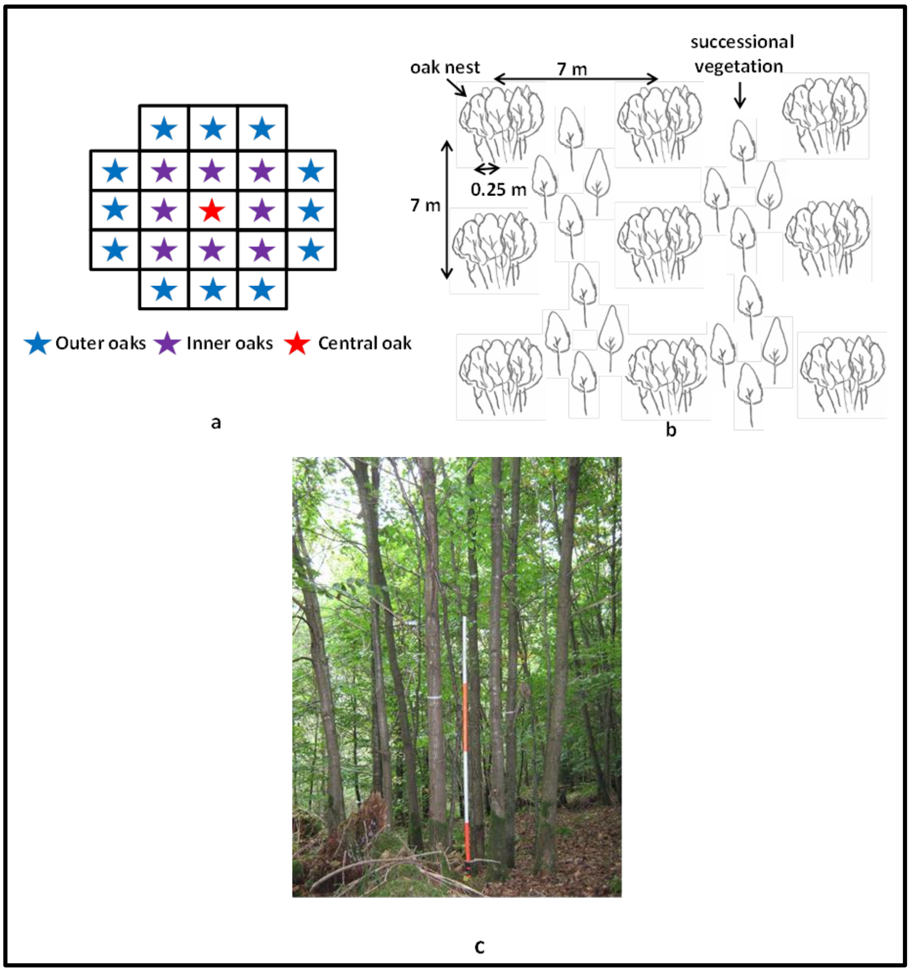


**Fig. 2.1: (a) Szymanski's (1986) nest design ; (b) 7 x 7 m spacing between the centres of nests were generally followed in German nest plantings; (c) 23 year old nest planting in Leonberg, Baden-Württemberg, Germany.**

Although Anderson mentioned the Russian trials in later publications, it was the silviculture professor at Edinburgh University who independently developed a cluster planting scheme of his own in the late 1920s for planting conifers that came to known as "Anderson's spaced group planting" (Anderson, 1930). He planted pine and sitka spruce 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. The inter group spacing ranged from 4 - 7 m. A series of spaced group plantings of different conifers and broadleaves were set up in Scotland and in the north of England 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 (Ironside, 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 (Joyce *et al.*, 1998). Anderson's ideas were forgotten and apparently did not influence later attempts with very similar designs such as oak group plantings researched by Gockel (1994).

In nest planting trials established in the 1980s in Germany, high mortality of planted seedlings was observed. This motivated Gockel 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 Schwarzenborn in Hessen (Fig. 2.2). Irrespective of the different 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 oaks and the deliberately planted trainer trees, taller seedlings (0.8 - 1.5 m tall) were planted to foster overcoming early plantation risks such as competition from vigorous ground vegetation and browsing. In addition, larger initial growing space (1 $m^2$ per seedling) was supposed to result in a more balanced and unrestricted crown development in the first few decades after establishment. 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, 2008). Group planting trials were established on wind thrown sites, clear cuts and abandoned agricultural lands in Lower Saxony, Baden-Wuerttemberg, Rhineland-Palatinate, Bavaria, Northern Switzerland and in Austria.

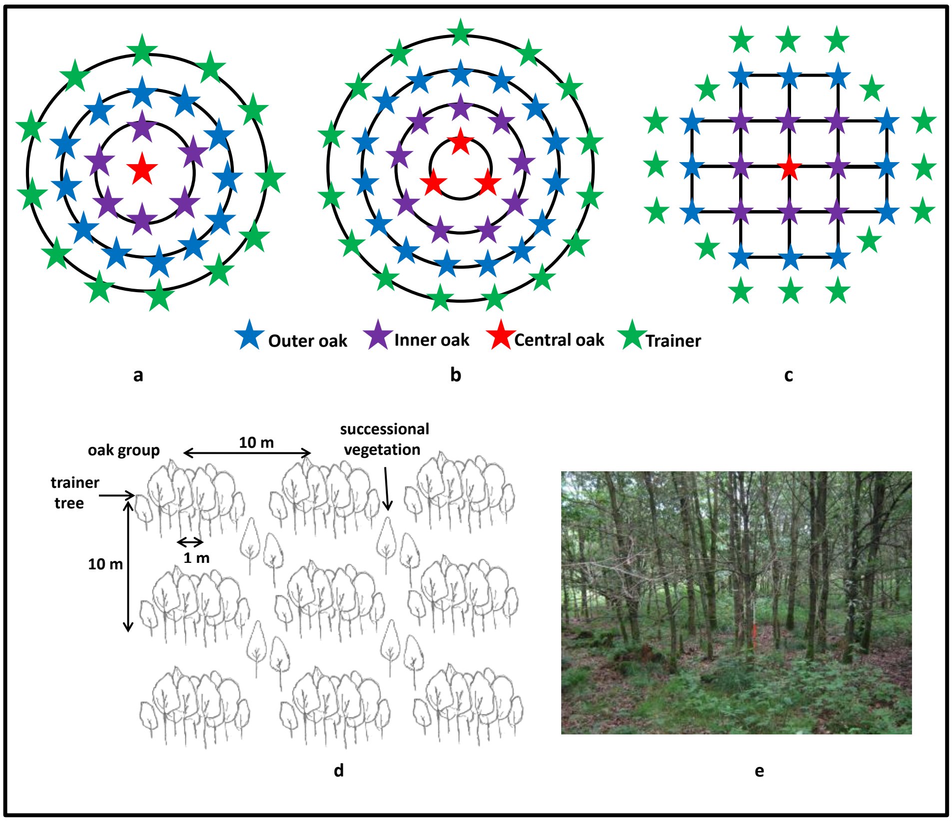


**Fig. 2.2: (a, b, c) Gockel's (1994) group planting design with 3 variants; (d) 10 x 10 m spacing was commonly followed between the centres of groups; (e) 20 year old group planting in Lerchenfeld, Hessen, Germany.**

## 2.3 SUCCESS OF OAK CLUSTER PLANTINGS

### 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 cost of replacing dead trees (Margolis and Brand, 1990). Hence, the survival rate of planted oaks was the most common indicator of success assessed in nest, group and row planting in studies. The main hypothesis examined in studies was that no difference in survival rates exists between cluster and row plantings of oaks of the same age on comparable sites. Early researchers (e.g. (Szymanski, 1986) claimed that: intraspecific competition between oaks in nests did not affect their survival and growth, nests minimize deer browsing and afford protection from the negative effects of drought, snow and frost by creating a favourable microclimate inside the clusters thereby increasing oak survival rates. However, later observations from German trials revealed that the survival rate of 23 year old oaks in nest plantings was very low (only 29%) and significantly less than in classical row plantings (Guericke *et al.*, 2008). These findings were consistent with reports from other researchers who observed low survival rates (< 40%) in 12 to 19 years old oak trees nest planting trials (Weinreich and Grulke, 2001; Leder, 2007). Additionally, the assumed positive effects that outer oaks in nests provided some protection from deer browsing to the inner oaks and that favourable microclimatic conditions existed inside clusters could not be confirmed (Weinreich and Grulke, 2001; Guericke *et al.*, 2008). Indeed, no significant difference was observed in oak survival rates between group and row planting (Petersen, 2007). The very small initial growing space of 0.04 $m^2$ used in nest plantings intensified intraspecific competition between oaks for light and space resulting in high mortality (Nutto, 2000; Weinreich and Grulke, 2001; Guericke *et al.*, 2008). In extremely dense oak nests, shading-induced asymmetric competition between high and low branches increased and resulted in higher lower branch mortality and eventually whole-tree mortality (Henriksson, 2001; Kint *et al.*, 2010). In addition, Nelder spacing experiments on 19 year old sessile oak have shown that the survival rate drops significantly (< 60%) when 2 year old seedlings were planted with a growing space of only 0.5 $m^2$ (Gaul and Stüber, 1996). To achieve high survival rates (> 80%) for planted oaks early on, at least 1.3 $m^2$ of initial growing space has been recommended (Gaul and Stüber, 1996). The significantly higher survival rate of oaks in groups versus nests could be the consequence of more growing space and a minimization of competition. In addition, the comparatively taller saplings in groups had a competitive advantage over the ground vegetation and experienced less deer browsing compared to those in nests (Petersen, 2007).

Based on previous analyses of oak cluster plantings Szymanski’s assumption of higher survival rates for oaks in nests compared to those in rows was not confirmed. Insofar, mortality rates in group planting were found comparable to those in row plantings, however, the group planting trials were all younger than the oldest nest planting trials.

## Height and DBH development

One main assumption of early proponents of cluster plantings was that oak height and DBH growth of oaks in cluster plantings would not differ significantly from conventional row planting (e.g. Szymanski 1986). However, as was subsequently shown, DBH and height of 23 year old oak trees in row plantings were 20% greater and 10% taller respectively than trees in nest plantings (Guericke *et al.*, 2008). In contrast, in comparatively young groups (7 - 11 year old) no significant difference was observed in DBH or height when compared with row plantings (Harari, 2008; Petersen, 2007). Within nests, relative abundance of 21 year old trees with good DBH (8 - 12 cm) and height (10 - 12 m) was comparatively higher in outer position than inner and central position in nest (Leder, 2007). In this study, Leder did not observe any competitive influence of other fast growing broadleaves on oaks in the nests due to lack of natural regeneration between the nests on nutrient-poor sites where competition by grass *Calamagrostis* spp. was also a problem for natural regeneration. Trend in DBH and height growth of oak trees in central, inner and outer position of groups was not assessed so far.

In general, intense intraspecific competition will reduce oak growth. Results from 14 - 21 year old sessile oak experimental spacing trials from Germany showed that height and diameter growth declined significantly when the initial growing space was less than 1 $m^2$ (Spellmann and Baderschneider, 1988; Gaul and Stüber, 1996; Schmaltz *et al.*, 1997).

Szymanski's claim of comparable oak growth in densely planted nests than widely planted rows cannot be accepted as studies on nest plantings showed inferior height and DBH growth than similar aged row planting. However, assessments of relatively younger group plantings have shown comparable diameter and height growth with row planting. Initial growing space, which determines intraspecific competition between oaks, is therefore an important factor influencing growth of oaks in clusters.

## Stability of oaks

Due to their habit of maintaining dry leaves during the winter, young oaks can easily be physically damaged by snow, particularly when the snow is wet (Röhrig *et al.*, 2006). Physical tree stability is classically measured as a ratio of height-to-DBH (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 classical row plantings.

No significance difference was observed in height-to-diameter ratios between nest and row plantings, and this also held true for groups (Guericke, 1996; Petersen, 2007; Dong *et al.*, 2007a; Guericke *et al.*, 2008). In general, the average height-to-DBH ratio (cm/cm) of oaks in clusters was below 150 in the majority of trials. Ideally, this ratio should not exceed values between 130 and 150 in order for young oak stands to withstand the risks of heavy snow loads (von Lüpke, 1991). While it appears that oak clusters are as stable as rows, the spatial patterns of stability within clusters varies in nest planting where edge trees have higher stability than inner and central oak tress (Leder 2007). However, it has not yet been studied in groups.

## Tree quality

Tree quality determines the value of the wood produced. Traditionally, silvicultural practices during the early stages of oak stand development following the establishment phase meant the occasional removal of poorly shaped dominant trees ("wolf trees") but generally, management inputs were kept low. 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 trunk quality and to ensure that the target number of crop trees is achieved at final harvest, it was recommended that potential crop trees be pre-selected in young stands (Leibundgut, 1976; Mosandl *et al.*, 1988; Schutz, 1993; Nutto, 1999). However, this means that the quality of such "potential future crop trees" can be assessed before they have reached the desired branch-free bole length.

A meaningful approach for assessing tree qualities, for example to identify future crop trees, is based on attributes such as stem straightness (stem form), recurrent growth habit, branch angle, crown shape and size, and branch free bole length (Mosandl *et al.*, 1988; Leder, 2007). Previous studies on oak cluster plantings assessed the tree quality attributes as described above, and counted the number of potential future crop trees $ha^{-1}$. Amongst those studies some compared these attributes with conventional row planting.

*Stem form, crown shape and branch free bole length*

Compared to conventional row planting, nest planting produced between 10% and 20% fewer oaks with straight upright stems and monopodial crowns, respectively, on assessment of 23 year old oaks in 4 nest planting trials (Guericke *et al.*, 2008). The innermost oaks in nests had better stem form and crown shapes than the outermost oaks although this aspect has been assessed only in a few studies (Szymanski, 1986; Leder, 2007). Several other studies were not able to verify this claim of a positive influence of outer oaks on inner and central oaks in nest plantings. In 8 - 11 year old oak trees in group plantings crown shape, stem form and branch free bole length were not different from row plantings (Harari, 2008; Petersen, 2007). However, in older oaks in nests (21 year), branch free bole length was significantly greater in row plantings than in nest plantings (Guericke *et al.*, 2008). Limited growing space in nest plantings triggered intense intraspecific competition for light and caused those oaks in nests to grow outwards causing their stems to lean and develop thick branches in lower parts of stems (around 3 - 4 m), whereas in row plantings, the lower stems were shaded after crown closure (Guericke *et al.*, 2008). This phenomenon was most pronounced in nest plantings when shade-providing trainer trees were absent or the space between nests not filled by naturally regenerated fast growing broadleaved trees (Guericke *et al.*, 2008). In contrast to nests, more initial growing space in groups and the presence of trainer species helped to attain straight stems and monopodial crowns and good branch free bole length (> 25% of average tree height), which was comparable to conventional row plantings (Rock, 2004; Harari, 2008).

*Number of potential future crop trees*

Based on conventional row plantings it has been suggested previously that, to achieve a number of 70 - 80 harvestable crop trees at the end of the rotation, 150 - 250 potential future crop trees ha$^{-1}$ would be required at age 20 year old stand (Spellmann and von Diest, 1990; Mosandl and Paulus, 2002b; Dong *et al.*, 2007b). Some studies on nest planting found between 150 - 200 potential future crop trees ha$^{-1}$ (an average of 80% of the nests had at least one potential future crop tree) after 10 - 20 year (Szymanski, 1986; Leder, 2007; Dong *et al.*, 2007a). However, in some cases substantially fewer potential future crop trees could be identified in nest plantings (Guericke *et al.*, 2008), where it is not clear what the underlying reasons might have been. This large difference in outcomes could be the result of different factors: removal of fast growing early successional trees growing in the space between the nests, variation in tree survival rates between the studies, the influence of deer browsing etc. (Gussone and Richter, 1994; Nutto, 2000; Weinreich and Grulke, 2001; Guericke *et al.*, 2008). In group plantings, where the assessment of tree qualities was done at a younger age (7 - 14 year old stands), no significant difference in the number of potential future crop trees ha$^{-1}$ was observed when compared to conventional row plantings (Ehring and Keller, 2006; Harari, 2008; Petersen, 2007). It was speculated that the presence of trainer trees within groups in addition to the larger growing space and less mortality compared to nest planting might have helped quality development of oaks. However, the influence of trainers on quality development was not statistically analysed.

In conclusion, the studies conducted so far do not provide an equivocal answer to the question whether nest plantings can produce a sufficient number of future crop trees, or whether outer oaks promote the tree quality of inner oaks. This is not surprising since many of the factors that can have a strong influence on the outcome of quality development (browsing, competition from naturally regenerated trees, etc.) had not been kept constant across the different experiments. In young oak groups, promising results have been obtained for tree quality when compared to row plantings, but more studies are required on older trials.

## Economic aspects

In comparison to conventional row planting, cluster planting systems may offer potential savings owing to a reduction in the number of planted seedlings and because of lower expenses for site preparation, tending operations and protection measures (Szymanski, 1986). Only a few studies have compared establishment and tending costs between cluster and row plantings and there are no comparisons of the costs between group and nest plantings.

A substantial reduction in establishment costs of up to 50% was found in early studies that compared oak group and conventional row plantings (Gockel *et al.*, 2001; Weinreich and Grulke, 2001). However, given the general trend to reduce seedling numbers in artificial regeneration, this advantage of cluster plantings may be gradually disappearing. Recent guidelines by some German state forest administrations and institutions regarding initial seedling numbers for wide-spaced oak row plantings (e.g. 3 x 1 m initial spacing, i.e. 3300 seedlings ha$^{-1}$) are now comparable to the numbers required for cluster plantings (Nutto, 2000; Ehring and

Keller, 2006; Guericke *et al.*, 2008). Furthermore, the presence of a sufficient number of additional seedlings between nests has been highly recommended to promote the development of favourable stem qualities for oaks established in nest plantings (Gussone and Richter, 1994). If these supplementary seedlings do not regenerate naturally and sufficiently as has been often observed, they need to be planted (Leder, 2007). Hence, whether cluster and especially nest plantings are more cost-efficient than row plantings or not depends on the reference used for comparison. In cases, where clusters need to be complemented with planting of additional trees between clusters, or when clusters are compared to low density row planting, they are likely not more cost efficient. Furthermore, if taller saplings are used in group plantings, the associated higher planting costs counterbalance any savings resulting from lower initial planting densities (Ehring and Keller, 2006; Petersen, 2007). However, site preparation costs may be lowered substantially, by up to 25% if seedlings are planted in groups only and the space between the groups is left for natural regeneration (Gockel *et al.*, 2001).

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 whole area required such costly treatments (Szymanski, 1994). However, other studies of oak nest plantings not only 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) but also recommended other protection measures, such as fencing have to be carried out regardless of the planting design (Gussone and Richter, 1994; Strobel, 2000). However, for nest plantings, there have been no economic assessments on subsequent tending operations. For very young Swiss group planting trials where oaks are 7 year old, no significant difference in tending expenses were found when compared with row plantings (Koch and Brang, 2005; Petersen, 2007). In contrast, higher costs when compared to row planting have been incurred for the time consuming search of clusters and their marking where they are embedded in vigorous competing vegetation (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). Differences in tending expenses between cluster and row plantings are not yet apparent at this early stage in the trials; therefore further investigations on subsequent tending expenses in older cluster plantings are needed.

## Vegetation diversity

Vegetation diversity was thought to be higher in cluster planting than in classical row planting because of the spaces left between clusters for natural regeneration (Gussone and Richter, 1994; Gockel, 1995; Leder, 2007; Dong *et al.*, 2007a). In the single study that was carried out to test this assumption, vegetation diversity and species evenness was significantly higher in a 9 year old group planting trial than in conventional row plantings (Rock *et al.*, 2003). Also, few studies have quantified natural regeneration between clusters. In 15 - 20 year old nest planting trials, up to 9000 stems $ha^{-1}$ of additional, primarily early successional species had been counted (Dong *et al.*, 2007a). In contrast, other studies found hardly any naturally regenerated woody vegetation between the oak clusters (Leder, 2007). No biomass or volume assessments comparing cluster and row plantings have been done to date.

## 2.4 CONCLUSION AND OUTLOOK

Majority of past studies on oak cluster planting reported that survival, growth and quality of young oak trees are comparable between young group and row plantation, however, inferior in nest planting than row planting. In general, our review shows that group plantings may have some advantages when it comes to these parameters over nest plantings. This review showed that initial growing space, browsing protection, presence of trainer trees are crucial factor for successful establishment of oaks both in nests and groups. However, comprehensive quantitative review involving multiple trials is necessary to ascertain the general trend in development of growth and quality attributes in oaks grown in cluster and row planting.  Influence of trainer trees species on quality and growth of oaks in cluster should be studied in future. Future research should also focus on assessment of biodiversity and biomass in cluster planting by comparing with traditional row planting. Influence of naturally regenerated trees on oak growth and quality development in cluster planting was not studied so far and future research should be done on this.

# CHAPTER THREE: GROWTH AND QUALITY OF YOUNG OAKS (*Quercus robur* AND *Q. petraea*) GROWN IN CLUSTER PLANTINGS IN CENTRAL EUROPE: A WEIGHTED META-ANALYSIS

***A potential oak future crop tree grown in 20 year old group planting stand, Kaisereiche, Hessen, Germany***

## 3.1 INTRODUCTION

Owing to their stability, tolerance of relatively warm climates, and their valuable timber, pedunculate oak (*Quercus robur*) and sessile oak (*Q. petraea*) are likely to become increasingly important in central Europe (Roloff and Grundmann, 2008; Bolte *et al.*, 2009; Reif *et al.*, 2010). For example, in the German state of Thüringen, it was recommended to quadruple oak cover to 16% of the total forested area as part of an adaptation strategy against possible climate change impacts (Frischbier *et al.*, 2010).

Although natural regeneration is the preferred option for stand establishment for many species in many regions of central Europe, planting and seeding still play a major role, especially in the reforestation of oak-dominated forests. Artificial regeneration is the only way to establish oak stands in situations where acorn sources are lacking. In particular, this is the case where coniferous stands are to be converted to oak forests, or where competition from herbaceous and woody vegetation hinders the natural regeneration of oak (Joyce *et al.*, 1998; Johnson *et al.*, 2002).

A typical commercial goal of oak management in central Europe is to attain at least 60 - 80 high quality harvestable trees per hectare with a minimum target diameter at breast height (DBH) of 60 cm and a branch free bole length of 6 - 10 m at the end of a ca. 120 - 150 year rotation (Spiecker, 1991; von Lüpke, 1998). Conventional planting of oak involves closely spaced rows with high initial densities of 5,000 - 10,000 seedlings $ha^{-1}$ (Burschel and Huss, 1997). The aim is to achieve a regular distribution of trees and structural homogeneity of the crown layer in the early stages of stand development to foster natural pruning (Anderson, 1951). The initial oak seedling numbers used in row plantings have been decreasing since the 1990s. However, high costs associated with site preparation (particularly in wind-throw areas), planting, fencing and successive tending measures remain a matter of concern (Ehring and Keller, 2006; Guericke *et al.*, 2008). Such factors motivated foresters and researchers to seek alternatives to the establishment of oak stands, one of these being the introduction of oak cluster planting in Europe, which followed two different designs.

The nest planting design was rediscovered from the early writings of German and Soviet foresters and re-described by the Polish silviculture professor Szymanski in the 1950s and 1960s (Buchholz, 1949; Tarasenko, 1962; Udod, 1969; Ceitel and Szymanski, 1975; Szymanski, 1977, 1986, 1994). Szymanski's planting trials involved so called nests (1 $m^2$ in size) consisting of 21 oak seedlings planted with an initial spacing of 0.2 x 0.2 m. He developed two protocols for nest planting allowing for either a 4 x 4 m or 5 x 8 m spacing between nests and the planting of various tree species in rows between the nests. In addition to promoting superior growth of oaks, Szymanski claimed that nests offered browsing protection. Encouraged by Szymanski's ideas, German and French foresters established oak nest planting trials in clear-felled and wind-throw areas across western Germany and Picardy region of France (Mangold, 1988; Gussone and Richter, 1994; Demolis *et al.*, 1997). The distance between the nests (centre to centre) in the German trials was usually 7 m while the space between the nests was either planted with trainer trees or left for natural regeneration.

Later, another type of cluster planting design, oak group planting, was introduced (Gockel, 1994) that used larger seedlings or saplings (0.8 - 1.5 m tall) and a wider initial spacing (1 x 1 m). Oak group planting designs differed in the total number of saplings per group (19 to 27) and in the number of additional, shade-tolerant trainer tree saplings per group. Trainer trees were commonly planted on the perimeter of clusters to shade oak stems thus preventing development of epicormic sprouts and to control ground vegetation. Irrespective of the group design, spacing between the group centres was kept at 10 x 10 m or 10 x 12 m, resulting in 80 - 100 groups $ha^{-1}$. Gradually, group planting trials were established in various German states (Gockel, 1995; Petersen, 2007), in Austria (Ruhm, 1995), and in Switzerland, where the designs were further modified; for example, 13 oak seedlings per group with 8 Norway spruce saplings as trainers (Koch and Brang, 2005). The assumed advantages of cluster planting were: 1) a reduction in site preparation and establishment costs compared to row planting, without a reduction in silvicultural options, and 2) the promotion of the natural regeneration of other species; hence greater biodiversity (Gussone and Richter, 1994; Gockel *et al.*, 2001; Leder, 2007; Dong *et al.*, 2007a). Here, we will focus on the analysis of the first assumption that clusters may provide the same long-term silvicultural options expressed as the number potential future crop trees as conventional row plantings. To specifically test this assumption, we will focus on the survival, growth and quality of oaks planted in clusters.

The second assumed advantage could not be tested because data for these variables have not been systematically collected in the trials included in this meta-analysis.

Silvicultural experiments or trials with similar research goals are often installed at local and regional scales; however, traditional meta-analyses using data from these studies are often not possible because results often remain unpublished. Combined data from such experiments are rarely synthesized owing to budget and time constraints or lack of knowledge about appropriate statistical tools. Meta-analysis based on primary data therefore, has been used only in few cases in applied ecology and agriculture (Gomez-Aparicio *et al.*, 2004; Tirol-Padre and Ladha, 2006; Claudet *et al.*, 2010a). So far there has been no meta-analysis to synthesize data from silvicultural regeneration trials. While the results from some cluster planting trials have been published, a comprehensive study on the general suitability of cluster plantings across various site types, genetic material and designs has not been carried out. We therefore used a meta-analytic framework to compare the survival, quality and growth of oaks in cluster planting trials with that of oaks in conventional row planting. None of the previous studies distinguished species-specific responses with regard to growth and quality development in cluster planting. The morphological, genetic and ecological differences amongst provenances within each of the species can be greater than between species (Müller-Starck *et al.*, 1993). In addition, silvicultural management of the two oaks does not differ (von Lüpke, 1998). Therefore, we assessed the influence of cluster planting on tree growth and quality for both oak species together.

We hypothesized that: (1) the survival, growth and quality of oak trees would be influenced by the type of clusters (nest or group); (2) the initial abundance of planted trainer trees surrounding the groups would positively influence the survival and quality of group-planted oak; (3) fencing would provide an additional advantage for survival, growth and quality of oak trees in nest plantings; and (4) effect sizes calculated from cluster – row planting pairs for the variables survival, growth and quality would be influenced by the age of planted oak trees.

## 3.2 MATERIALS AND METHODS

### 3.2.1 Meta-database and study area

Our approach differed from traditional meta-analyses in two respects. Firstly, we conducted a regional meta-analysis focused on temperate forests of Central Europe and thus eliminated sources of variation due to climatic differences that are inherent in global meta-analyses (Claudet *et al.*, 2010a). Secondly, by using original data we were not limited to data summaries from published reports and papers. However, like all meta-analytical procedures, our approach compared data from trials with different sampling designs but with similar research goals. We developed four criteria for selecting cluster planting trials for our meta-analysis data base as follows: 1) Each cluster planting trial (experimental group) had a row planting counterpart (control group) established under similar site conditions, located in close proximity to the cluster planting; 2) The age difference between experimental and control group pairs did not exceed two years; 3) Fencing and tending measures were conducted in a similar manner across the experimental and control group pair; and 4) Planting stock used in cluster and row planting were of the same genetic origin.

The final meta-data base consisted of 25 trials with pairs of cluster and row plantings located in Germany, Switzerland and Austria (Fig.3.1, Table 3.1).

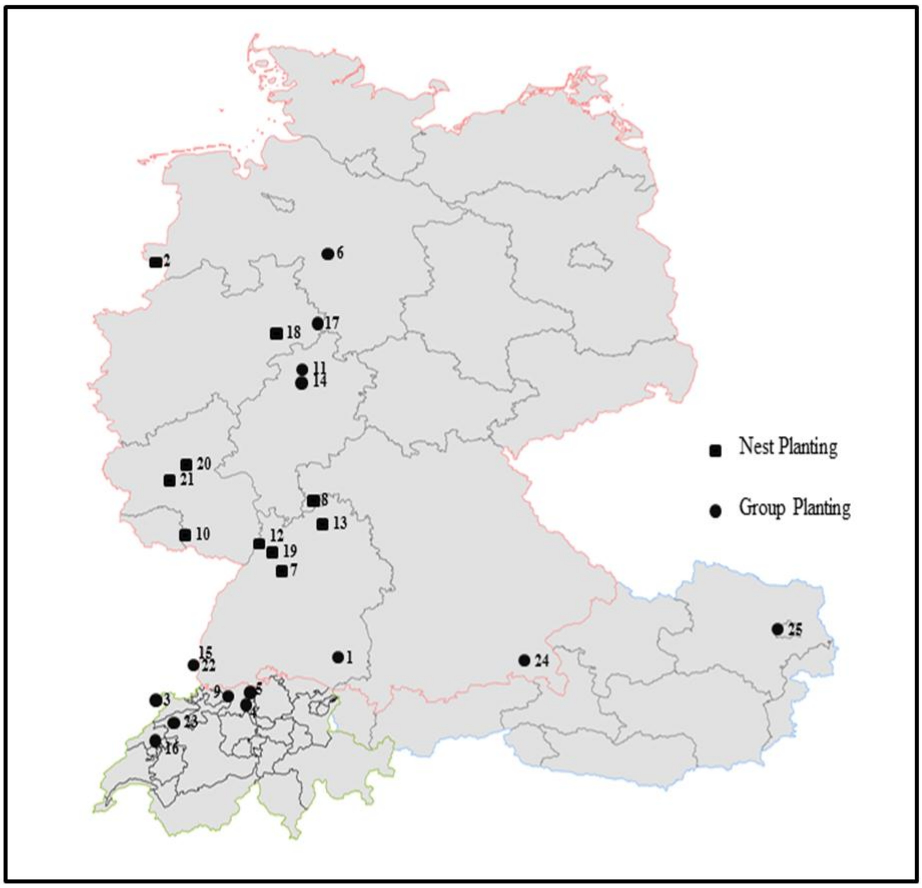


**Fig. 3.1: Location of oak cluster (nest and group) planting trials in Germany, Switzerland and Austria.**

**Table. 3.1: Site descriptions of trials (n.a. = information not available, ≈ approximately).**

| Trial number | Trial name | Elevation (m a.s.l.) | Mean annual temp. (°C) | Mean temp. in vegetation period (°C) | Number of days > 10°C daily mean | Mean annual rainfall (mm) | Mean daily rainfall in vegetation period (mm) | Soil types |
|---|---|---|---|---|---|---|---|---|
| 1 | Bad Schussenried | 610 | 7.7 | 14.6 | 153 | 851 | 468 | Stagnogleyic cambisol |
| 2 | Bentheim | 60 | 9.7 | 15.7 | 177 | 801 | 350 | Gleyic cambisol |
| 3 | Bonfol | 455 | ≈ 9 | n.a. | n.a. | 1100 | n.a. | Cambisol |
| 4 | Bremgarten | 362 | ≈ 9 | n.a. | n.a. | 1100 | n.a. | n.a. |
| 5 | Buelach | 417 | ≈ 8 | n.a. | n.a. | 1050 | n.a. | n.a. |
| 6 | Fuhrberg | 60 | 8.9 | 15.3 | 167 | 680 | 322 | Stagnosol |
| 7 | Gerlingen | 440 | 8.1 | 15.1 | 162 | 780 | 400 | Stagnogleyic cambisol |
| 8 | Gerscheim | 310 | 8.5 | 15.3 | 163 | 670 | 310 | Stagnogleyic cambisol |
| 9 | Habsburg | 450 | ≈ 8 | n.a. | n.a. | 1100 | n.a. | Cambisol |
| 10 | Johanniskreuz | 520 | 8.4 | 14.8 | 160 | 933 | 381 | Cambisol |
| 11 | Kaisereiche | 550 | 6.5 | 14 | 150 | 800 | 350 | Stagnogleyic cambisol |
| 12 | Kammerforst | 400 | 8.8 | 15.5 | 167 | 862 | 380 | Stagnic cambisol |
| 13 | Koenigheim | 380 | 8.1 | 14.8 | 157 | 750 | 330 | Cambisol |
| 14 | Larchenfeld | 550 | 6.5 | 14 | 150 | 800 | 350 | Stagnogleyic cambisol |
| 15 | Linkmatt | 210 | 10.3 | 16,9 | 185 | 874 | 457 | Stagnic gleysol |
| 16 | Murten | 565 | ≈ 8 | n.a. | n.a. | 1050 | n.a. | Cambisol |
| 17 | Neuhaus | 320 | 8.4 | 14.9 | 161 | 646 | 307 | Gleyic cambisol |
| 18 | Paderborn | 285 | 8.2 | 14.3 | 158 | 880 | 399 | Cambisol |
| 19 | Seehaus | 400 | 8.8 | 15.5 | 167 | 862 | n.a. | n.a. |
| 20 | Simmern | 440 | 7.9 | 14.1 | 152 | 795 | 348 | Stagnosol |
| 21 | Soonwald | 390 | 7.9 | 14.1 | 152 | 761 | 335 | Stagnogleyic cambisol |
| 22 | Stumpen | 210 | 10.3 | 16,9 | 185 | 874 | 457 | Stagnogleyic cambisol |
| 23 | Urtenen | 570 | ≈ 8 | n.a. | n.a. | 1100 | n.a. | n.a. |
| 24 | Wasserburg | 600 | 7.9 | 14,9 | 157 | 1001 | 562 | n.a. |
| 25 | Wieselburg | 300 | 10.2 | n.a. | n.a. | 750 | n.a. | Stagnosol |

**Table. 3.2: Description of cluster and row planting design in trials (C.b. = *Carpinus betulus*, T.c. = *Tilia cordata*, F.s. = *Fagus sylvatica*, A.g. = *Alnus glutinosa*, P.a. = *Picea abies*, s = reforestation in wind-thrown areas, c = reforestation in clear-cut areas, a = afforestation in abandoned agricultural land, ≈ approximately).**

| Trial No. | Tree Age | Spacing between oaks in clusters (m) | Spacing between clusters, centre to centre (m) | Clusters $ha^{-1}$ | Oaks per cluster | Trainer trees $cluster^{-1}$ | Distance between oak cluster and trainer trees (m) | Spacing within rows (m) | Presence of trainer in row | Trainer trees in rows $ha^{-1}$ | Trainer species (cluster & row) | Stand history | Fencing |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 12 | 1 x 1 | 10 x 10 | 55 | 19 | 10 | 1 | 2 x 1 | yes | ≈ 700 | C.b., T.c. | s | no |
| 2 | 21 | 0.25 x 0. 25 | 7 X 7 | 200 | 21 | | | 1.8 x 0.5 | no | | T.c. | c | no |
| 3 | 8 | 1.6 x 1.6 | 12 x 12 | 80 | 13 | 8 | 1.6 | 1.6 x 1.6 | no | | P.a. | s | yes |
| 4 | 8 | 1.6 x 1.6 | 12 x 12 | 80 | 13 | 8 | 1.6 | 1.6 x 1.6 | no | | P.a. | s | yes |
| 5 | 8 | 1.6 x 1.6 | 12 x 12 | 80 | 13 | 8 | 1.6 | 1.6 x 1.6 | no | | P.a. | s | no |
| 6 | 11 | 1 x 1 | 10 x 10 | 100 | 19 | 16 | 1 | 1.5 x 1 | yes | 1600 | P.a. | a | yes |
| 7 | 26 | 0.3 x 0.3 | 7 x 8 | 180 | 21 | | | 1.5 x 1 | yes | ≈ 1000 | T.c. | c | yes |
| 8 | 22 | 0.25 x 0.25 | 7 x 7 | 200 | 21 | | | 2 x 0.75 | yes | ≈1000 | | c | yes |
| 9 | 8 | 1.6 x 1.6 | 12 x 12 | 80 | 13 | 8 | 1.6 | 1.6 x 1.6 | no | | P.a. | s | yes |
| 10 | 19 | 0.25 x 0. 25 | 7 x 7 | 200 | 21 | 4 | 1.5 | 2 x 1 | yes | ≈ 1000 | F.s. | s | yes |
| 11 | 20 | 1 x 1 | 10 x 10 | 100 | 27 | 15 | 1 | 2 x 1 | yes | 900 | F.s. | a | yes |
| 12 | 19 | 0.2 x 0.2 | 10 x 5 | 200 | 21 | | | 3 x 0.75 | no | | | s | no |
| 13 | 22 | 0.25 x 0. 25 | 7 x 7 | 200 | 21 | | | 2 x 1 | yes | ≈ 900 | C.b., T.c. | s | yes |
| 14 | 20 | 1 x 1 | 10 x 10 | 100 | 27 | 15 | 1 | 2 x 1 | yes | 900 | F.s. | a | yes |
| 15 | 6 | 1 x 1 | 10 x 12 | 83 | 25 | 10 | 1 | 3 x 1 | yes | 500 | C.b., T.c. | a | yes |
| 16 | 8 | 1.6 x 1.6 | 12 x 12 | 80 | 13 | 8 | 1.6 | 1.6 x 1.6 | no | | P.a. | s | yes |
| 17 | 14 | 1 x 1 | 10 x 10 | 100 | 19 | 16 | 1 | 1.5 x 1 | yes | 1600 | C.b. | a | yes |
| 18 | 21 | 0.25 x 0. 25 | 7 x 7 | 200 | 21 | | | 1.8 x 0.5 | no | | T.c. | c | yes |
| 19 | 19 | 0.2 x 0.2 | 10 x 5 | 200 | 21 | | | 3 x 0.75 | no | | | s | no |
| 20 | 18 | 0.25 x 0. 25 | 7 x 7 | 200 | 21 | 4 | 1.5 | 2 x 1 | yes | ≈ 900 | F.s., A.g. | s | no |
| 21 | 20 | 0.25 x 0. 25 | 7 x 7 | 200 | 21 | 4 | 1.5 | 2 x 1 | yes | ≈ 900 | Bu | s | yes |
| 22 | 6 | 1 x 1 | 10 x 12 | 83 | 25 | 10 | 1 | 3 x 1 | yes | 500 | F.s., A.g. | a | yes |
| 23 | 8 | 1.6 x 1.6 | 12 x 12 | 80 | 13 | 8 | 1.6 | 1.6 x 1.6 | no | | P.a. | s | yes |
| 24 | 16 | 1 x 1 | 10 x 10 | 100 | 19 | 8 | 1 | 2 x 1.3 | yes | ≈ 700 | T.c. | s | yes |
| 25 | 16 | 1 x 1 | 10 x 10 | 100 | 25 | 12 | 1 | 2 x 1 | yes | 900 | C.b. | c | yes |

### 3.2.2 Selection of variables

We selected eight response variables: four for growth (survival rate, diameter at breast height (1.3 m), stem height, and height-to-diameter ratio as a measure of physical tree stability), and four for quality (stem form, crown shape, length of the lower trunk to the first live primary branch or branch free bole length, and the number of potential future crop trees). The survival rate was assessed as the ratio of live and dead oaks in each trial. Previous assessment of tree quality in young oaks used various morphological classifications of stem form and crown shape (Guericke, 1996; Gockel *et al.*, 2001; Leder, 2007; Dong *et al.*, 2007a). We transformed those classifications into a uniform system developed by Kuehne *et al.* (2013) with four classes for both stem form and crown shape in our meta-data base (Fig. 3.2). For some analyses, these classes were aggregated into "straight stem" (stem form class 1) and "bent stem" (stem form class 2, 3 and 4) for stem form and "monopodial crown" (crown shape class 1) and "non-monopodial crown" (crown shape class 2, 3, and 4) for crown shape. Effect sizes for stem form and crown shape for each trial were derived from the proportion of oaks with straight or bent stems and monopodial or non-monopodial crowns, respectively. Potential future crop trees were identified based on their vigour, stem straightness, monopodial crown and adequate branch free bole length. Vigour was estimated based on crown size and crown vertical class (e.g. dominant, co-dominant etc.) (Kuehne *et al.*, 2013). Based on that assessment, we calculated the proportion of potential future crop trees to non-crop trees for cluster and row planting trials.

Based on a literature review of cluster planting trials, we selected planting type (nest or group), fencing and the initial abundance of planted trainer trees as moderators or categorical grouping variables in the meta-analysis to gain further insight into the effects of trial characteristics on tree growth and quality (Table 3.2). The moderator "fencing" was only used in nest planting trials because all the group planting trials except for one were fenced. Trainer tree species (e.g. *Carpinus betulus*, *Tilia cordata*, *Fagus sylvatica*) had been planted in all group planting trials. Initial abundance of planted trainer trees in groups was classified as either moderate (8 - 12 trainers per group) or high (>12 trainers per group).

Varying data collection methods and measurement protocols resulted in differences in the data base structure among the 25 trials used in this study. Accordingly, calculations of the effect sizes on the different response variables were based on a variable number of trials (Fig. 3.4, 3.5 and 3.6).

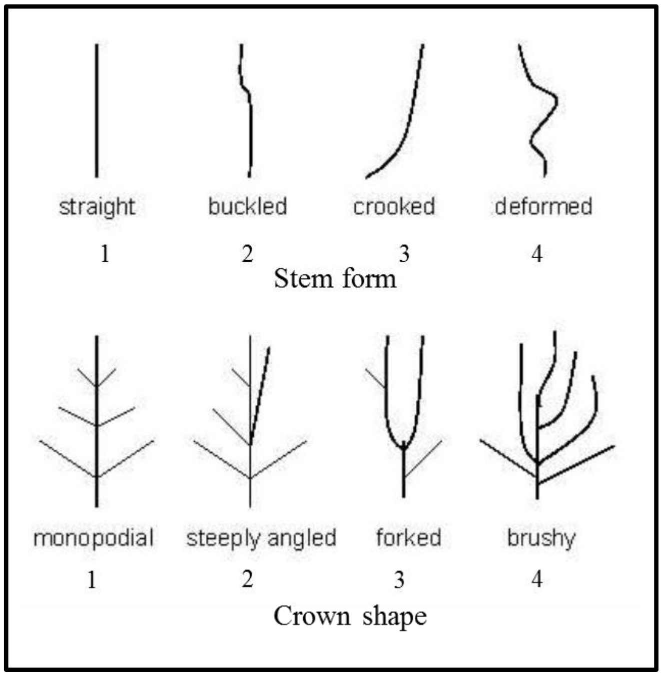


**Fig. 3.2: Morphological classification of stem form and crown shape.**

### 3.2.3 Statistical analysis

We used effect sizes to test for differences in response variables between cluster and row planting. We combined fixed and random effect models to mixed effect models using the categorical grouping variables described above. In fixed effect models, it is assumed that all incorporated trials have similar characteristics and therefore share a true effect size; estimates vary between the trials only due to sampling error (Fleiss, 1981; Hedges, 1982; Rosenthal and Rubin, 1982; Gurevitch and Hedges, 1999). This contrasts, with random effect models where true effect size is expected to vary among trials and the primary goal of the analysis is to quantify the variation in the effect parameter (Gurevitch and Hedges, 1999). Random effect models do not determine the dependence of effect size on important substantive characteristics of the trials (Gurevitch and Hedges, 1999) while fixed effect models can do so in a straightforward way by accounting for the overall variation among the trials. Real variation in effect sizes between the categories (e.g. nest planting *vs.* group planting) was substantial in the present study, which rendered fixed effects models inappropriate for our meta-analysis (Gurevitch and Hedges, 1999).

A mixed model approach in meta-analysis combines both random and mixed effect models and is therefore suitable for analysing differences between and within the categories, i.e. when categories (e.g. nest planting or group planting) are also internally heterogeneous (Stram, 1996; Gurevitch and Hedges, 1999). Thus, we calculated weights using variances from both fixed and random effects models and then, based on the derived weights, performed categorical random effect meta-analysis, which is also known as mixed effect models in meta-analysis and analogous to mixed effect models in ANOVA (Gurevitch and Hedges, 1993; Hedges and Vevea, 1996).

A meta-analysis using the mixed model approach was performed in three major steps (Rosenberg *et al.*, 2000): 1) fixed effects meta-analysis to determine the values of the summary statistics i.e. effect size, variance and total heterogeneity; 2) by using these summary statistics, we then calculated an estimate of the pooled trial variance (or between trial variance), necessary to generate the weights for the random effects models; and 3) the derived weights were finally used in a mixed effects model to calculate the global cumulative effect, total heterogeneity as well as the associated confidence intervals.

***Step 1: Fixed-effect categorical meta-analysis to develop summary statistics***

We calculated effect size response ratios (Osenberg *et al.*, 1997; Hedges *et al.*, 1999; Osenberg *et al.*, 1999a) for each continuous response variable (DBH, height, height-to-DBH ratio, and branch free bole length) in each trial:

$$\mathrm{E_i} = \frac{\mathrm{X_{Ci}}}{\mathrm{X_{Ri}}} \quad \ldots\ldots (1)$$

where $\mathrm{E_i}$ is the response ratio for a variable of the trial *i*, and $\mathrm{X_{Ci}}$ and $\mathrm{X_{Ri}}$ are the mean values of the metric for trial *i* in cluster (*C*) and row (*R*) planting, respectively. To obtain effect sizes for each target variable, we also derived the variances associated with these estimates in each trial:

$$\mathrm{v_i} = \frac{\mathrm{S_{Ci}^2}}{\mathrm{N_{Ci}X_{Ci}^2}} + \frac{\mathrm{S_{Ri}^2}}{\mathrm{N_{Ri}X_{Ri}^2}} \ldots\ldots (2)$$

where $\mathrm{v_i}$ is the variance associated with the effect size $\mathrm{E_i}$, and $\mathrm{X_{Ci}}$ and $\mathrm{X_{Ri}}$ are defined as above. $\mathrm{S_{Ci}}$ and $\mathrm{S_{Ri}}$ are the standard deviations associated with $\mathrm{X_{Ci}}$ and $\mathrm{X_{Ri}}$, respectively. $\mathrm{N_{Ci}}$ and $\mathrm{N_{Ri}}$ are the sample sizes in cluster and row plantings, respectively. This variance is affected by the sample size, which differed greatly among the trials. Thus, weighting was done as a reciprocal of its sampling variance:

$$\mathrm{w_i} = \frac{1}{\mathrm{v_i}} \quad \ldots\ldots (3)$$

where $\mathrm{w_i}$ is the weight associated with the effect size $\mathrm{E_i}$, and $\mathrm{v_i}$ is defined as above. The cumulative effect size ($\overline{\overline{\mathrm{E}}}$) was then calculated as:

$$\overline{\overline{\mathrm{E}}} = \frac{\sum_{i=1}^{n} \mathrm{w_i E_i}}{\sum_{i=1}^{n} \mathrm{w_i}} \ldots\ldots (4)$$

where $n$ is the number of trials, and $\mathrm{E_i}$ and $\mathrm{w_i}$ are defined as above. In addition to the cumulative effect size, it is also of interest to determine whether the set of effects sizes are homogeneous across trials. The total heterogeneity of the sample was calculated as:

$$\mathrm{Q_T} = \sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{w_i}\left(\mathrm{E_i} - \overline{\overline{\mathrm{E}}}\right)^2 \qquad (5)$$

and its significance was tested against a $\chi^2$ distribution with $n$ - 1 degrees of freedom.

We segregated our studies in more than one category (e.g. nest or group planting), thus a categorical meta-analysis is appropriate (Rosenberg *et al.*, 2000). For such a data structure, we calculated the overall cumulative effect size as defined above. In addition, the cumulative effect size for each category was calculated using only the trials belonging to that category as:

$$\overline{\mathrm{E_j}} = \frac{\sum_{\mathrm{i=1}}^{\mathrm{k_j}} \mathrm{w_{ij}E_{ij}}}{\sum_{\mathrm{i=1}}^{\mathrm{k_j}} \mathrm{w_{ij}}} \qquad (6)$$

where $\mathrm{k_j}$ is the number of the trials in the $j^{th}$ category, and $\mathrm{w_{ij}}$ and $\mathrm{E_{ij}}$ are the weight and effect size for the $i^{th}$ trial in the $j^{th}$ category. The variance of $\overline{\mathrm{E_j}}$ was calculated as:

$$\mathrm{s}^2_{\overline{\mathrm{E_j}}} = \frac{1}{\sum_{\mathrm{i=1}}^{\mathrm{k_j}} \mathrm{w_{ij}}} \qquad (7)$$

where $\mathrm{s}^2_{\overline{\mathrm{E_j}}}$ is the variance associated with $\overline{\mathrm{E_j}}$ , and $\mathrm{k_j}$ and $\mathrm{w_{ij}}$are as defined above.

The heterogeneity within the $j^{th}$ category, $\mathrm{Q_{Wj}}$, was calculated as:

$$\mathrm{Q_{Wj}} = \sum_{\mathrm{i=1}}^{\mathrm{k_j}} \mathrm{w_{ij}}\left(\mathrm{E_{ij}} - \overline{\mathrm{E_j}}\right)^2 \qquad (8)$$

where $\mathrm{k_j}$ , $\mathrm{w_{ij}}$ and $\mathrm{E_{ij}}$ are defined as above, $\overline{\mathrm{E_j}}$ is the cumulative effect size of $j^{th}$ category and its significance was tested against a $\chi^2$ distribution with $\mathrm{k_j} - 1$ degrees of freedom.

The difference among categories was statistically tested using an *F*-ratio of the model variance versus the error variance (Sokal and Rolhf, 1995).

In meta-analysis, we can partition the total heterogeneity, $\mathrm{Q_T}$ by following:

$$\mathrm{Q_T} = \mathrm{Q_M} + \mathrm{Q_E} \qquad (9)$$

where, $Q_M$ is the variation of the effect size explained by the fixed effects model, and $Q_E$ is the residual error variance not explained by the model (Hedges and Olkin, 1985). For categorical data, $Q_M$ is thus a description of the difference, among category cumulative effect sizes, and is calculated as:

$$Q_M = \sum_{k=1}^{m} \sum_{i=1}^{k_j} w_{ij} (\bar{E}_j - \bar{\bar{E}})^2 \text{……………………………………………………………………………………………(10)}$$

where $m$ is the number of categories, $k_j$ , $w_{ij}$, $\bar{E}_j$ as defined earlier, $\bar{\bar{E}}$ is the overall cumulative effect size. The residual error heterogeneity ($Q_E$) is identified through the summation of the individual within-category heterogeneity values, $Q_{Wj}$, or through the calculation of:

$$Q_E = \sum_{j=1}^{m} Q_{Wj} = \sum_{j=1}^{m} \sum_{j=1}^{k_j} w_{ik} (E_{ij} - \bar{E}_j)^2 \text{……………………………………………………………………………(11)}$$

where $m$, $k_j$ , $w_{ij}$, $\bar{E}_j$, $\bar{E}_j$ are defined as described above. Both $Q_M$ and $Q_E$ can be statistically tested for significance against the $\chi^2$ distribution with $m - 1$ degrees of freedom for $Q_M$ and $n - m$ degrees of freedom for $Q_E$.

***Step 2: Using summary statistics from fixed-effects meta-analysis to calculate between-trial variance to generate random weight***

In this step, we calculated a random component of the variation of the effect sizes between trials. Using the summary statistics derived from the first step, we calculated an estimate of the between trial variance (or pooled trial variance), $\sigma^2_{\text{between}}$. This was used to calculate the weights for the random effects ($w_{i(\text{random})}$,) as:

$$w_{i(\text{random})} = \frac{1}{v_i + \sigma^2_{\text{between}}} \text{…………………………………………………………………………………………(12)}$$

where $v_i$ was defined in step 1, and $\sigma^2_{\text{between}}$ for the categorical model with more than one category can be calculated as:

$$\sigma^2_{\text{between}} = \frac{Q_E - (n-m)}{\sum_{j=1}^{m} \left( \sum_{i=1}^{k_j} - \frac{\sum_{i=1}^{k_j} w^2{}_{ij}}{\sum_{i=1}^{k_j} w_{ij}} \right)} \text{…………………………………………………………………………………………(13)}$$

where $Q_E$ is the residual error heterogeneity from the fixed effects model, $n$ the total number of trials, $m$ the number of categories, $k_j$ the number of trials in the $j^{th}$ category, and $w_{ij}$ the fixed effects weight for the $i^{th}$ trial in the $j^{th}$ category.

***Step 3: Developing the final categorical random effects model***

In the final step, the newly derived weights (eq. 12) were used in the categorical random effect model or the mixed model (Rosenberg *et al.*, 2000) to perform the final meta-analysis. It includes random variation among trials within a category and fixed differences between the categories. The final model was then used for the calculation of the global cumulative effect sizes for response variables across all trials and the cumulative effect size of each category in the respective response variable.

We calculated the risk ratio for each variable with categorical outcomes by using a 2 x 2 contingency table. The risk ratio of a response variable is the rate of occurrences of an event in cluster and row planting (Greenland, 1987; Labbe *et al.*, 1987; Normand, 1999). Prior to the calculation of this effect size, we calculated rates of response of an event in trial *i* (Table 3.3).

**Table 3.3. Hypothetical responses for categorical variables in 2 x 2 contingency table in cluster and row planting.**

| | Cluster | Row | Total |
|---|---|---|---|
| Response | $A$ | $B$ | $A + B$ |
| No response | $C$ | $D$ | $C + D$ |
| Total | $N_{C_i} = A + C$ | $N_{R_i} = B + D$ | $N_{Total_i} = A + B + C + D$ |

The rate of response ($P_{C_i}$) for the cluster planting is:

$$P_{C_i} = \frac{A}{N_{C_i}} \quad \ldots\ldots (14)$$

And the rate of response ($P_{R_i}$) for the row planting is:

$$P_{R_i} = \frac{B}{N_{R_i}} \quad \ldots\ldots (15)$$

where $N_{C_i}$, and $N_{R_i}$ were the total number of sampled trees in cluster and row plantings of trial *i*, respectively. $N_{Total_i}$ was the grand total number of trees in cluster and row plantings in that trial. *A, B, C* and *D* were the number of hypothetical outcomes of a particular response variable (e.g. how many trees in cluster and row plantings in trial *i* had a straight stem?).

Following this step, we calculated relative risk as rate scores of clusters ($P_{C_i}$) relative to that of the rows ($P_{R_i}$):

$$RR = \frac{P_{C_i}}{P_{R_i}} \quad \text{……(16)}$$

where *RR* is the risk ratio of trial *i*, and $P_{C_i}$ and $P_{R_i}$ are defined as above.

Because this effect size is a ratio, no difference in the rate of treatment (cluster planting) and control (row planting) was represented as 1. Values of RR ranging from 0 to 1 represented studies, where the rate for the treatment category was lower than the rate observed for the control category, and values greater 1 represented studies where the rate for the treatment category exceeded that of the control category (Rosenberg *et al.*, 2000).

The variance of this effect size ( $v_{(RR)}$ ) can be calculated as:

$$v_{RR} = \frac{(1-P_{C_i})}{N_{C_i}} + \frac{(1-P_{R_i})}{N_{R_i}} \quad \text{……(17)}$$

where, $N_{C_i}$, $N_{R_i}$, $P_{C_i}$, and $P_{R_i}$ are defined as above.

After calculating the variance of this effect size, we followed a similar procedure to calculate the cumulative effect size as described for the earlier continuous variables.

For the meta-analysis, logarithmic transformation of response and risk ratios for individual trials and corresponding variances were performed. For the pooled cumulative estimates of response and risk ratios, the logarithmic transformation was reversed for easier interpretation (Agardh *et al.*, 2011). As the number of trials in our meta-analysis was rather low, we calculated effect size and 95% bootstrap confidence intervals based on 999 iterations (Adams *et al.*, 1997; Verschuyl *et al.*, 2011). We considered a combined effect to be significant, if the lower or upper limit of the derived confidence interval did not overlap 1, implying a significant difference between cluster and row plantings for the analyzed response variable.

The relationship between the age of planted oaks and effect sizes (log transformed) calculated from cluster–row planting pairs for each response variable was studied by Pearson correlation and linear regression analysis. All statistical analyses were done using MetaWin 2.0 and R 2.14.0 (Rosenberg *et al.*, 2000; R Developed Core Team, 2011).

## 3.3 RESULTS

### 3.3.1 Growth of oaks

As indicated by the global cumulative effect, the oak survival rate did not differ significantly between cluster plantings (nests and groups combined) and row plantings (Fig. 3.3). Whereas there was no significant difference between group and row plantings, the survival rate was significantly lower (52%) in nests than in row plantings (Fig. 3.4a). The survival rates of oaks in nests without fencing was significantly lower (73%) than in nests that were fenced (Fig. 3.5). Group plantings in trials with a moderate number of trainer trees did not display a significant difference in the survival rate when compared to row plantings. However, when row plantings were compared to group plantings involving a high number of trainer trees, survival rates in group plantings exceeded row plantings by 22% (Fig. 3.6a).

The global cumulative effect size for DBH was significantly lower (21%) in cluster plantings than in row plantings (Fig. 3.3). Compared to row plantings, DBH was significantly lower (39%) in nest plantings but not in group plantings (Fig. 3.4). Compared to row plantings, DBH was 29% lower in fenced nest planting trials, while in unfenced nest planting trials the difference amounted to 52% (Fig. 3.5). In groups, the number of trainer trees per cluster had no influence on DBH of oaks (Fig. 3.6).

The global cumulative effect size for height was not significantly different when clusters were compared to row plantings (Fig. 3.3) nor was there any difference between nests and groups (Fig. 3.4). However, protection from browsing had an obvious significant influence on tree height growth in nests. Height growth was similar between fenced nests and rows but in nests without fencing it was significantly lower (13%) (Fig. 3.5). No significant difference in corresponding cumulative effect sizes was found between groups planted with high or moderate numbers of trainer trees when compared to row plantings (Fig. 3.6a).

The global cumulative effect size of the height-to-DBH ratio was significantly higher (11%) in oak cluster plantings than in row plantings, indicating a lower physical stability in the former (Fig. 3.3). The height-to-DBH ratio of oaks in group and row planting trials did not differ, but was significantly higher (22%) in nests than in row plantings (Fig. 3.4a). The density of trainer trees did not influence the height-to-DBH ratio of oaks in group planting trials (Fig.3.6a).

### 3.3.2 Quality of oaks

Branch free bole length was significantly shorter (22%) in clusters than in row plantings. However, there was no difference in the branch free bole length between group and row plantings, whereas branch free bole length was significantly shorter (31%) in nests when compared to row plantings (Fig. 3.4). The difference in the initial abundance of trainer trees had no effect on branch free bole length in group plantings (Fig. 3.6b).

Crown shapes did not differ between cluster and row planting (Fig.3.3). The number of oaks with monopodial crowns, however, was 23% higher in groups when compared to row planting controls (Fig. 3.4b) and this effect was more pronounced for groups with high numbers of surrounding trainer trees (Fig. 3.6b). There was no significant difference between nests and row plantings. The proportion of monopodial crowns was significantly lower (24%) in nests without fencing compared to row plantings, whereas no difference was observed in fenced trial pairs (Fig. 3.5).

The global cumulative effect size of stem form did not differ significantly between cluster and row plantings (Fig. 3.3). Separate comparisons of groups and nests with row plantings also showed no significant difference in stem form. However, the number of straight stems appeared to be greater in groups than in nests. In groups with high numbers of initial trainer trees, the proportion of oaks with straight stems was more than double that of row plantings (Fig. 3.6b). In contrast, no significant difference was observed between row and group planting trials having moderate trainer densities.

The number of potential future crop trees was 37% lower in clusters than in row plantings but, most probably owing to the large variation, the observed difference was not statistically significant (Fig. 3.3). While the percentage of potential future crop trees in groups was equivalent to row plantings, groups having high initial densities of trainer trees, had 45% more potential future crop trees than groups having moderate initial densities of trainers (Fig. 3.6b). In contrast, 81% fewer potential crop trees were observed in nests (Fig. 3.4b) than in rows.

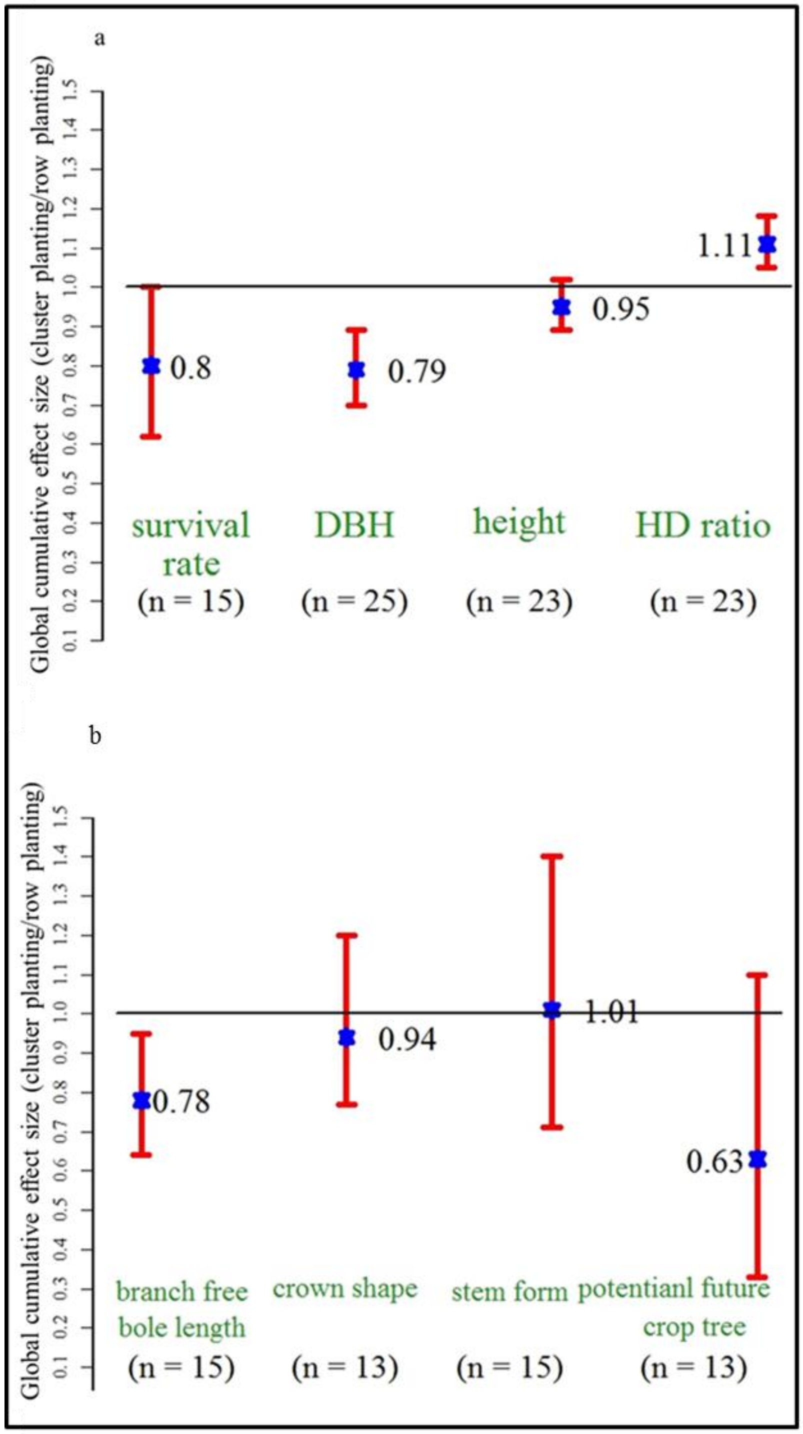


**Fig. 3.3: Summary effect sizes for oak growth (a) and quality (b) variables in cluster and row planting across trials.**

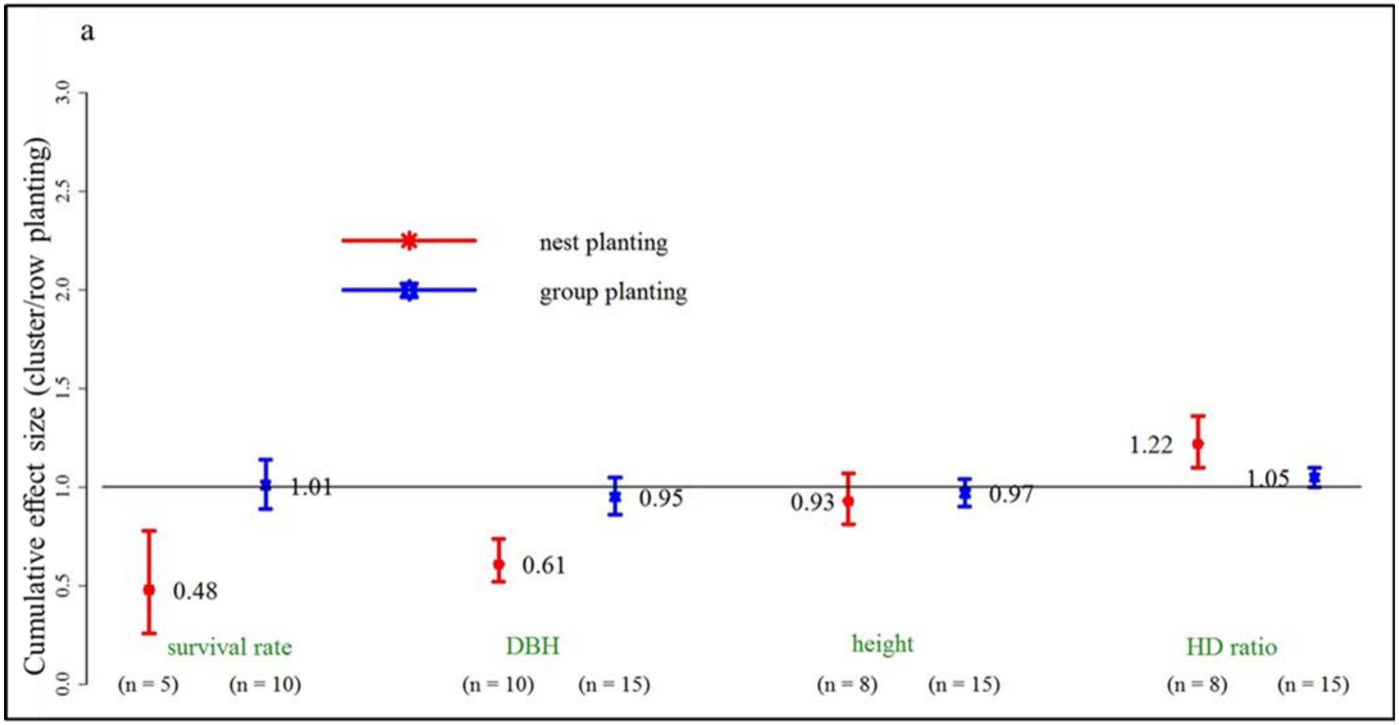


**Fig. 3.4a: Summary effect sizes for growth variables in the categories nest and group plantings.**

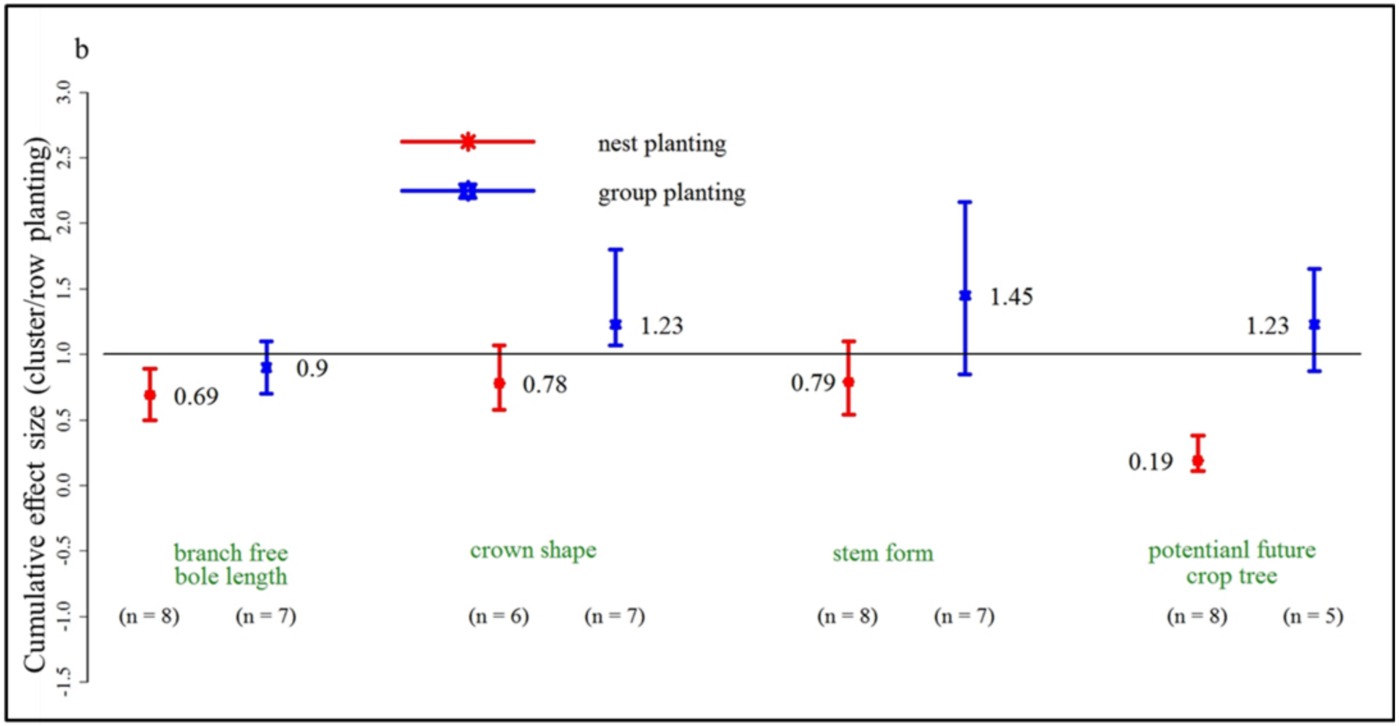


**Fig. 3.4b: Summary effect sizes for quality variables in the categories nest and group plantings.**

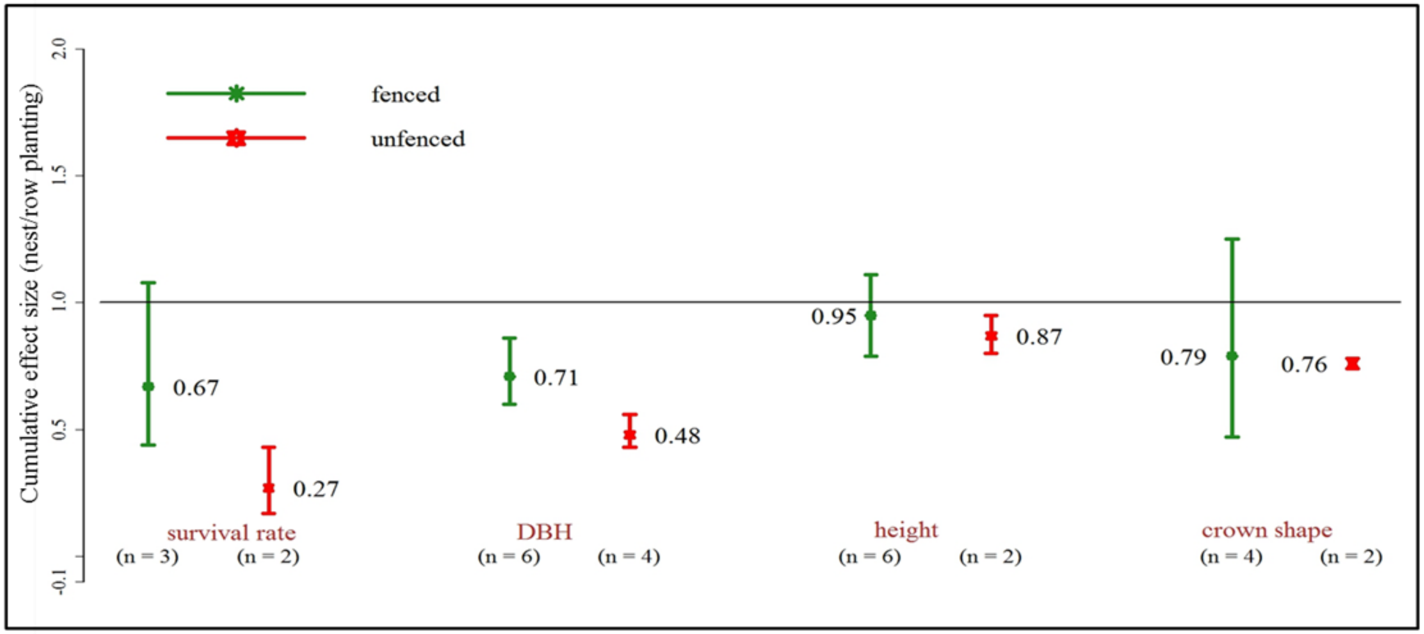


**Fig. 3.5: Summary effect sizes for response variables in fenced and unfenced categories of nest planting trials.**

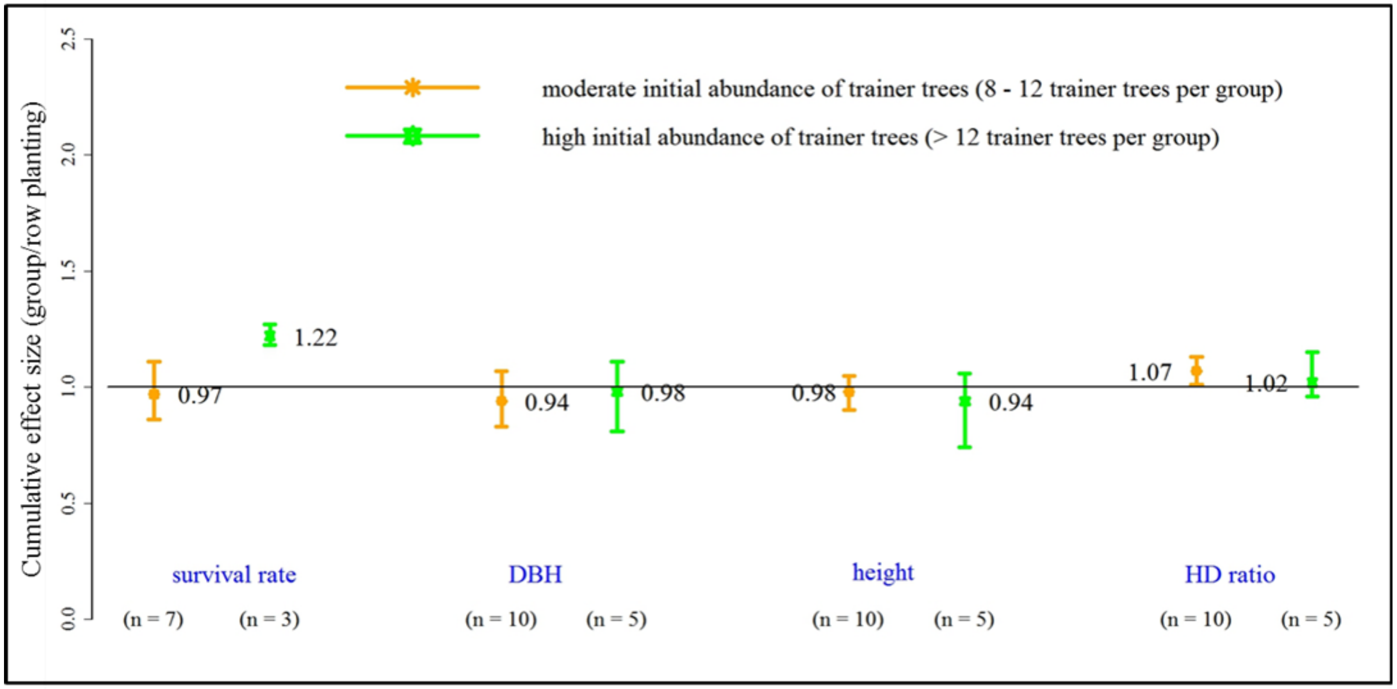


**Fig. 3.6a: Summary effect sizes for growth variables in group planting trials with either moderate or high trainer tree abundance.**

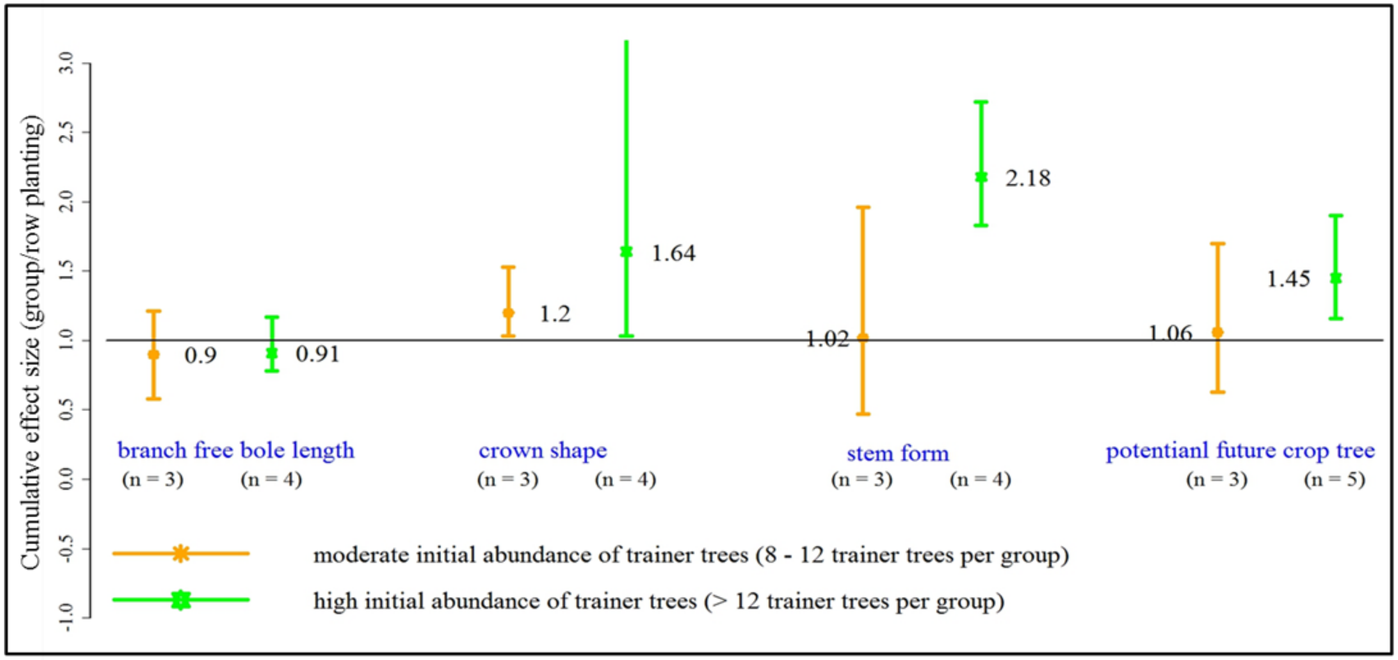


**Fig. 3.6b: Summary effect sizes for quality variables in group planting trials with either moderate or high trainer tree abundance.**

### 3.3.3 Tree age and effect size relationships

Effect size of DBH and potential future crop trees from nest and row planting pairs showed a significant positive correlation with the age of the planted oaks. Thus, effect size of these two variables increases and tended to approach 1 (i.e. no difference between nest and row) in older nest trials. In contrast, a negative correlation between height-to-DBH ratio and age was found in nest and row planting pairs (Table 3.4). In group planting and row planting pairs, effect size of crown shapes and plant age was positively correlated.

**Table. 3.4: Relationship between age of oak trees and response variables (* = $p < 0.05$, ** = $p < 0.01$).**

| | Group | | | Nest | | |
|---|---|---|---|---|---|---|
| Response variables | Pearson $r$ | $R^2$ | N | Pearson $r$ | $R^2$ | N |
| Survival rate | 0.58 | 0.33 | 10 | 0.38 | 0.15 | 5 |
| DBH | -0.4 | 0.16 | 15 | 0.92** | 0.86** | 10 |
| Height | -0.5 | 0.25 | 15 | 0.02 | 0 | 8 |
| Height-to-DBH ratio | 0.14 | 0.02 | 15 | -0.79** | 0.73** | 8 |
| Branch free bole length | -0.34 | 0.11 | 7 | 0.28 | 0.07 | 8 |
| Crown shape | 0.76* | 0.58* | 7 | -0.6 | 0.36 | 8 |
| Stem form | 0.36 | 0.13 | 7 | 0.06 | 0 | 6 |
| Potential future crop trees | 0.2 | 0.04 | 8 | 0.91** | 0.84** | 5 |

### 3.3.4 Heterogeneity in effect sizes

The global heterogeneity of effect sizes derived from the random effects model was significant for oak survival rate and crown shape in cluster plantings, if nest and group planting trials were combined for analysis. This indicates that tree survival and crown shape varied significantly between the trials. However, global heterogeneity of effect sizes for other response variables was not significant.

In mixed effects meta-analysis, we found that the heterogeneity of effect sizes between the nest and group plantings was significant for survival rate, DBH, height-to-DBH ratio, and the percentage of potential future crop trees. However, the residual error heterogeneity within the trials in each category was only significant for survival rate and crown shape.

Heterogeneity in the effect sizes between the fenced and unfenced nest planting trials was not significant except for DBH. This implied that modelling growth and quality responses in these categories of cluster plantings reduced the variation within the same type of category (e.g. nests or groups, fenced nests or unfenced nests). Differences in the initial planting density of trainer trees did not influence the homogeneity in effect sizes in group planting (Table 3.5).

**Table. 3.5: Effect size heterogeneity in meta-analysis (*vs.* = versus, * = $p < 0.05$, ** = $p < 0.01$, d.f. in parentheses).**

| Response variables | Total heterogeneity | Nest *vs.* Groups | | Fenced nests *vs.* Unfenced nests | | Groups with moderate *vs.* high trainer abundance | |
|---|---|---|---|---|---|---|---|
| | | between categories | residual error heterogeneity within category | between categories | residual error heterogeneity within category | between categories | residual error heterogeneity within category |
| Survival rate | 51.63** (14) | 30.61** (1) | 36.10** (13) | 3.62 (1) | 3.14 (3) | 3.29 (1) | 15.51 (8) |
| DBH | 28.88 (24) | 24.30** (1) | 25.98 (23) | 6.74* (1) | 8.08 (8) | 0.09 (1) | 13.40 (13) |
| Height | 21.95 (22) | 0.39 (1) | 20.97 (21) | 0.18 (1) | 4.85 (6) | 0.22 (1) | 16.15 (13) |
| Height-to-DBH ratio | 29.16 (22) | 8.92* (1) | 24.01 (21) | | | 1.10 (1) | 18.09 (13) |
| Branch free bole length | 8.23 (14) | 1.46 (1) | 11.24 (13) | | | 0 (1) | 2.63 (5) |
| Crown shape | 23.66* (12) | 5.50* (1) | 20.01* (11) | 0.02 (1) | 8.41 (4) | 0.53 (1) | 8.28 (5) |
| Stem form | 20.18 (14) | 4.87* (1) | 17.92 (13) | | | 3.25 (1) | 6.23 (5) |
| Potential future crop tree | 35.78 (12) | 25.69** (1) | 10.09 (11) | | | 0.51 (1) | 4.13 (6) |

## 3.4 DISCUSSION

### 3.4.1. Survival, growth and quality of oaks

Our meta-analysis showed that survival and growth of oaks clearly differed between the two analysed cluster types. In nest plantings, survival rate, DBH, height and height-to-DBH ratio were inferior compared to traditional row planting counterparts. In contrast, these parameters were found to be similar in group plantings and traditional row plantings. The meta-analysis also indicated that the quality of oaks planted in clusters was determined by the cluster planting type. Branch free bole length, crown shape, stem form and the number of potential future crop trees were either comparable or superior in group plantings compared to row plantings. However, tree quality in the nests was inferior to those planted in rows. Thus our first hypothesis that survival, growth, and quality of oak trees are influenced by cluster types is supported.

The significantly lower survival rate of oaks in nests compared to row plantings was likely a consequence of less growing space and more intensive competition, as indicated by the low diameters. Similar phenomena have been found in other young and dense broadleaved stands (Henriksson, 2001; Kint *et al.*, 2010). Based on a spacing experiment, Gaul and Stüber (1996) recommended an initial growing space of at least 1.3 $m^2$ to achieve survival rates of at least 80% in planted oaks after ca. 20 years. Whereas oak saplings in the group plantings have a similar initial growing space of 1 $m^2$, the initial growing space available to each sapling in nests is restricted to 0.04 $m^2$. Furthermore, the superior survival rate in groups when compared to nests might be partially attributable to the taller and more vigorous saplings with likely larger root systems, which could reduce competition from ground vegetation and negative impacts from deer browsing (Dey and Parker, 1997; Petersen, 2007). In terms of carbon allocation, height growth is a stronger sink for photosynthates than diameter growth (Waring and Schlesinger, 1985) and is usually insensitive to competition except at extremely close spacing (Lanner, 1985). In accordance with results from Nelder trials with oaks (Kuehne *et al.*, 2013), not even the most closely planted oaks (in nests) showed height growth reductions, when compared to row plantings. This indicates that in nests, height growth of surviving oaks was not limited by water or nutrients and may have been facilitated by the high mortality rate. However, with the concomitantly reduced diameter growth, trees in nests were physically less stable. Stability is of special interest in young oaks with respect of potential bending or breakage due to snow load, heavy rain and wind (von Lüpke, 1991; Rock, 2004; Röhrig *et al.*, 2006).

The poor quality of oaks in nests was likely induced by the close initial spacing causing them to interfere with each other and to buckle (Guericke *et al.*, 2008). Additionally, oaks growing at the perimeter of nests might have developed one-sided crowns, which resulted in a reduced branch free bole length. These quality issues have been attributed to the absence of either natural or planted trainer trees surrounding the nests (Guericke *et al.*, 2008). In contrast, self-pruning of trees and monopodial crown development were better promoted in more widely spaced group plantings with surrounding trainer trees than in row plantings. In row planting controls, variations in trainer tree densities did not seem to influence self-pruning and hence branch free bole length. Obviously, shading caused by the surrounding oaks was sufficient for self-pruning. Results from past studies on the influences of initial spacing on quality development in young oaks concur with our findings (Gaul and Stüber, 1996; Schmaltz *et al.*, 1997). Good development of crown shape, stem form and branch free bole length along with high survival rates in group plantings resulted in a higher proportion of trees qualifying as potential future crop trees.

Our meta-analysis indicated that oak groups planted with a high number of trainer trees had a higher survival rates than oaks planted in rows, whereas a moderate number of trainers had no such effect. We also showed that a high number of trainer trees around group plantings promoted the development of monopodial crowns and straight stems. However, the trainer tree effect did not extend to an increase in branch free bole length. These results are therefore in partial agreement with hypothesis two, assuming a positive influence of the initial abundance of trainers on oak tree survival and quality. Trainer trees might have provided protection to oaks by reducing competition from understorey species such as grass, ferns and black berries and fast growing early successional trees such as *Populus* spp., *Salix* spp. and *Betula* spp. (Gockel *et al.*, 2001; Harari, 2008). However, there has been no consistent recording of competing vegetation in the cluster planting trials to corroborate this assumption. This result is surprising since the conventional assumption for silvicultural management of oak for high quality timber is that the benefit of trainer trees is only derived after the first thinning, when they suppress the development of epicormic shoots in future crop trees. Common belief has it that until that time, self-pruning and development of straight stems is equally well facilitated by the competition among the cohort of oaks (Leibundgut, 1976; Spiecker, 1991; von Lüpke, 1998). Here, the early positive effect of trainer trees may have resulted from suppression of black berries (which can climb into oaks) and other fast-growing woody plants (Rock *et al.*, 2004). Whether the presence of shade-tolerant trainer trees plays a significant role in the self-pruning of oaks growing at the outer margin of young groups, remains to be investigated. In this study, we were not able to establish, whether this quality improvement of oaks was attributable to the specific effect of trainer trees or simply the effect of additional trees, which might have also occurred also if additional oaks had been planted.

We found that fencing increased oak tree survival, DBH, height, and height-to-DBH ratio. Presence of fencing in nest plantings improved crown shape. Hence, the third hypothesis, assuming a positive effect of fencing on survival, growth and quality of oaks in nests is supported. Young oak seedlings are generally highly susceptible to deer browsing (Gotmark *et al.*, 2005), which obviously contributed to high mortality rates in nests not protected by fencing. In the process of succession, the open spaces between the clusters become occupied with various plant species palatable to deer. Consequently this planting design could be more attractive to deer and more susceptible to browsing of oaks compared to row plantings (Rock *et al.*, 2003). Browsing affected oak crown shape in unfenced nests, more than that in unfenced row planting counterparts. Brushy and forked crowns are often a result of subsequent re-sprouting following the repeated browsing of the terminal shoot in unprotected oaks (Gotmark *et al.*, 2005). Furthermore, several case studies of nest plantings reported increased levels of browsing damage in nests *vs.* row plantings (Gussone and Richter, 1994; Guericke, 1996; Weinreich and Grulke, 2001), a result corroborated by our meta-analysis. The original claim by Szymanski (1986), that higher survival rates in unfenced nests versus row plantings were attributable to the protective function of the peripheral oaks to the browsing of interior oaks, clearly was not supported by our study.

Our results also indicated that differences in tree survival, growth and stability tend to decrease with stand age between nest plantings and row plantings, a finding that is partially consistent with hypothesis four, stating an effect of tree age on calculated effect sizes. Here, high mortality in nest plantings may have accelerated this congruence. However, this trend was not observed in groups, which had similar mortality rates when compared to row plantings.

Ultimately, the quality development of young stands can best be judged at the time of first thinning when crop trees have developed sufficient branch free bole lengths and are released from competition. If the number of crop trees, at that point, is not at an acceptable level, the final stocking of crop trees will be suboptimal. To assess the quality of younger stands, the number of potential future crop trees has been used as an indicator (Leibundgut, 1976; Mosandl *et al.*, 1988; Mosandl *et al.*, 1991; Spiecker, 1991). Numbers of 250-350 potential future crop trees ha$^{-1}$ have been suggested as a standard for conventional row planting (2 x 1 m spacing) for oak stands at the pole stage (Mosandl and Paulus, 2002; Röhrig *et al.*, 2006; Dong *et al.*, 2007b). In our analysis, we could not directly compare the total number of potential future crop trees in row and cluster plantings on a hectare basis. Instead, we compared the ratio of potential future crop trees to other oaks between clusters and row plantings. The negative effect size of potential future crop trees in clusters compared to row plantings was influenced by a very low percentage of future crop trees in nests. In planted groups however, low mortality and good quality development of oaks yielded comparable numbers of potential future crop trees compared to row planting controls. The selection ratio of oaks as crop trees would be approximately 1:50 at the final harvest when starting out with 2 x 1 m row plantings. The selection ratio in group plantings would be much lower, varying between 1:20 and 1:30. Therefore, obtaining a comparable ratio of potential future crop trees to non-crop trees between groups and row plantings suggests even better quality development in group plantings with respect to the crop tree selection ratio. This favourable quality development is also indicated by the high proportion of groups with at least one potential future crop tree, which is the most relevant measure of success. Previous case studies on 7 - 11 year old trials reported that 80 - 90% of the planted oak groups had at least one potential future crop tree (Gockel *et al.*, 2001; Ehring and Keller, 2006; Harari, 2007; Petersen, 2007). More studies on older group planting trials are required to verify these figures.

Our meta-analysis, combining eight nest planting trials, showed that the overall number of potential future crop trees was 80% lower in nest plantings than in row plantings. In one case study on 13 to 20 year old oak nest planting trials, 158 potential future crop trees ha$^{-1}$ had been reported (Dong *et al.*, 2007a). We assume that the favourable development of crop trees in nests in that case might have been facilitated by the dense natural regeneration of fast growing broadleaved and coniferous trees between the nests (Dong *et al.*, 2007a). This indicates that a large proportion of the variation in quality development of oaks in nests may be attributable to the development of vegetation in the matrix between nests. We recommend that this vegetation be monitored in future, to facilitate a better interpretation of the development of tree in nests and groups.

### 3.4.2 The use of meta-analysis and effect size heterogeneity

Meta-analysis is a strong statistical tool that is well accepted for research synthesis in the forest sciences (Paquette *et al.*, 2006; Ilstedt *et al.*, 2007; Verschuyl *et al.*, 2011) and applied ecology (Gurevitch *et al.*, 2001; Rosenvald and Lohmus, 2008; Claudet and Fraschetti, 2010b). Our study showed that this technique can also be effectively used for silvicultural trials with original inventory data. This approach was necessary because many of the trials included in this study had either not been comprehensively analysed, or had not been analysed for the variables of interest in this meta-analysis. Maintaining and sharing forestry or ecological data bases is becoming a common practice. Meta-analyses are also likely to gain importance in silvicultural research. Therefore, the importance of similar and comparable designs in silvicultural trials must be emphasized. Our ability to test hypotheses in a robust quantitative manner through meta-analyses might not be possible with the mere review of past case studies on cluster plantings, many of which have yielded contradictory results. For example, Guericke *et al.* (2008) reported that nest plantings would not provide enough potential future crop trees due to high mortality while other case studies reported sufficient numbers of potential future crop trees (Leder, 2007; Dong *et al.*, 2007a). Combining data from these contradictory studies in a meta-analytic framework improved our chances of finding clear general trends.

Owing to their large spatial scales and long durations, silvicultural trials are notoriously expensive and therefore often abandoned or not intensively utilised (Powers, 1999). Establishing research networks that apply common designs lending themselves to meta-analyses may help to share the costs amongst research institutions and allow more robust experiments that capture more environmental variation in space and time to be conducted. However, to achieve this, a large enough number of trials need to be included in such a network.

The significant heterogeneity of cumulative effect sizes found for some of the analysed treatment categories (e.g. group or nest for the moderator “planting type”) in our study could be the result of variation in the number of trials and sample sizes in several comparisons (Osenberg *et al.*, 1999b; Worm *et al.*, 2006). This variation was minimized by weighting, and therefore did not influence the overall trends in our meta-analysis (Claudet and Fraschetti, 2010b). Thus, directions of the cumulative effect size in different treatment categories remained unaffected. Furthermore, resampling our data to calculate bootstrap confidence limits minimized the influence of heterogeneity on the magnitude of effect size value. Another source of variability might have been different intensities of tending operations in the analysed trials. The significant residual error heterogeneity within nest or group planting category for oak survival and crown shape might have resulted from the variation in competitive influence of naturally regenerated broadleaved and coniferous tree species, which could not be quantified in this study.

## 3.5 CONCLUSION AND MANAGEMENT IMPLICATIONS

This study showed that the development of oaks in nest plantings was clearly inferior to traditional row plantings with respect to survival rate, growth and quality. In contrast, growth and quality of oaks planted in groups proved more or less equivalent to results achieved with traditional row plantings; some desirable attributes were found to be superior in oak group plantings. The presence and abundance of trainer species proved to be important for oak tree quality development in groups.

Based on these findings, group planting can be recommended as an alternative to row plantings for oak stand establishment. Planting in nests, which does not offer cost savings over group plantings did not meet the expectations of its original proponents and cannot be recommended for the future establishment of oak stands. Our study also indicated that the development of oaks in groups may be optimised by adjusting the number of trainer trees.

Whether it is sufficient to establish only as many oak groups as the number of anticipated future crop trees, cannot be answered by this study. If at the time of first thinning, one crop tree emerges from each group, all other remaining oaks in the group are to be removed to provide growing space for the crop tree. Any subsequent oak mortality would directly result in less than the optimal number of crop trees. Whether this planting design and tending approach is a sensible risk management strategy, must be assessed separately.

Most data sets obtained for our analysis did not include information about the tree species occurring between planted clusters. This however may be very important, not only for the development of oaks in clusters but for achieving other management goals such as those associated with biodiversity or biomass production. Future research should therefore focus on the influence that naturally regenerated woody species and planted trainer trees have on the development of oaks in clusters as well as on other stand level management goals. This especially holds true for naturally regenerated trees in nest trials, where the original planting design does not include trainer trees.

Based on this meta-analysis, group planting can be recommended for the regeneration of sessile and pedunculate oaks. The results are so encouraging that the technique should be tried for regeneration or restoring of other tree species in other parts of the world.

# CHAPTER FOUR: TREE SPECIES DIVERSITY AND STAND PRODUCTIVITY IN LOW-DENSITY CLUSTER PLANTINGS WITH OAKS (*Quercus robur* AND *Q. petraea*)

***Natural regeneration of Betula pendula between the groups in 20 year old stand, Kaisereiche, Hessen, Germany.***

## 4.1 INTRODUCTION

Traditional reforestation methods following disturbances or clear felling have aimed to assert fast control of forest sites through planting of desired tree species (Drouineau *et al.*, 2000). However, this approach comprises a number of disadvantages such as high costs for site preparation, plants and planting (Gockel, 1995; Ehring and Keller, 2006). In addition, the resulting stands often lack typical post disturbance characteristics such as high diversity of early-successional species which lead to complex food webs and other important ecosystem functions and processes of early stand development phases (Swanson *et al.*, 2010). In contrast, the use of natural regeneration processes only is very inexpensive, but offers reduced control over the future stand composition (Kenk, 1993), which should typically conform with long-term goals that may be described in so-called forest development types (Larsen and Nielsen, 2007). Whereas the species composition of natural regeneration may not conform to such long-term goals for the specific site, the natural regeneration that establishes through self-organization processes of disturbed ecosystems may increase their adaptability through new combinations of species and greater species diversity than is typically found in artificially regenerated stands (Fischer *et al.*, 2002; Jonasova *et al.*, 2010; Puettmann, 2011). A third way for the reforestation of disturbed or harvested sites consists of a combination of the two approaches, low density planting with natural regeneration in the remaining area (Drouineau *et al.*, 2000). This approach ensures a certain proportion of desired species in the future stand while maintaining natural processes and new species combinations at reduced costs, when compared to conventional planting. In addition, the potentially higher tree species diversity in these stands consisting of artificial and natural regeneration may result in higher productivity as has been observed in many other situations (Bauhus and Schemerbeck, 2012). Given the increasingly important production of biomass from forests for energy and solid-wood products, silvicultural systems have to use the available net-production area most efficiently. Hence, low-density plantings which lead to reduced production of forest biomass may not be desirable or acceptable.

One form of low density planting is the so called oak cluster planting, which was introduced in central Europe in the last two decades of the twentieth century as an alternative to row planting Nevertheless, idea of planting trees in cluster was older and practiced in United Kingdom and Russia in early twentieth century (see Chapter Two). Clusters are so called uniformly distributed ‘nests’ (nest planting) or ‘groups’ (group planting) that consist of 20 - 30 seedlings planted in an aggregated manner with 0.2 or 1 $m^2$ initial spacing and approximately 200 or 100 such clusters $ha^{-1}$, respectively (Szymanski, 1977; Szymanski, 1986; Gockel, 1994). Aiming at lowering the establishment costs while offering the opportunity to produce high quality timber, oak cluster plantings also provide vacant space, typically more than 60% of the area, for natural regeneration between clusters. While growth and quality development of oak cluster stands has been assessed and compared to row plantings (Saha *et al.*, 2012), the potential benefits of cluster plantings in terms of tree species diversity and stand productivity have not been quantified across a number of sites (Rock *et al.*, 2003).

In this study, we quantified tree species diversity and productivity over a range of sites in pairs of treatments with low density plantings using oak clusters (group or nest) and oak row plantings. In addition, we examined whether productivity of cluster planting stands depended on the density or species diversity of naturally regenerated trees. We hypothesized that (1) cluster planting would provide higher tree species diversity and stand productivity than traditional row planting, and (2) that overall stand productivity in cluster planting will be related to density and species richness of naturally regenerated and planted trees among clusters.

## 4.2 MATERIALS AND METHODS

### 4.2.1 Study sites

Seven locations with pairs of cluster and row plantations of oak (*Quercus robur* and *Q. petraea*) were sampled in kollin and montane sites in the German states of Baden-Wuerttemberg and Hessen, Germany (Table 4.1). Mean annual temperature at these sites and rainfall vary between 6.5 - 10.2°C and 670 - 832 mm, respectively, with the majority of precipitation occurring in the growing season between May and September. Soil types at the sites range from gleyic cambisols originating from alluvial deposits covered by loess to stagnosols originating from basalt loam, silt stone or sandstone (Michéli *et al.*, 2006). The resulting site conditions provide for moderate growth rates with oak exhibiting a mean annual increment of 7.5 - 8.5 $m^3$ $ha^{-1}$ $yr^{-1}$ over the first 100 years of a rotation. Oak reforestation took place between 1986 and 2000 after the previous stands of mainly coniferous species (*Picea abies*, *Pseudotsuga menziesii*) were uprooted by storm or clear-felled. Prior to planting, extensive site preparation including removal of slash and broken tree trunks was conducted at the row planting sites but usually not at the sites used for cluster plantings. As part of the basic planting design, a varying number of trainer trees were planted in all oak group and row plantations (Table 4.2). However, trainer trees were also added to the interspaces between nests in Gerlingen and Leonberg. In contrast, cherry trees (*Prunus avium*) were additionally planted between the groups of the Altenheim site. Each cluster and row planting was fenced off during the initial years after establishment. All reforestation sites were adjacent to forests, usually mature mixed oak as well as mixed and pure conifer stands. On average, the area of each inventoried cluster and row planting stand was about 1 ha in size, except the control row planting used for the cluster planting sites in Gerlingen and Leonberg (0.2 ha). We also used only one row planting stand as control for the group planting sites “Kaiserseiche” and “Lerchenfeld” because of the unavailability of another similar aged row planting growing under comparable site conditions as the cluster counterparts.

### 4.2.2 Sampling design and data collection

We established systematic strips along the lines of nests or groups and rows, respectively, covering at least one third of the area of each studied stand. We did not establish strips at the boundary of the stands to avoid influences from the surrounding forest, skidding trails and forest roads. Diameter at 1.3 m stem height (DBH) of all planted oaks and trainers within each strip were measured. Species and DBH of naturally regenerated woody vegetation (height > 1.3 m) were recorded in circular vegetation plots of varying diameters. In cluster plantings, plots with a radius of 2 m were placed between diagonally opposite nests or groups, respectively. In addition, 1 m radius vegetation plots were installed at the center of the groups to capture natural regeneration within the groups. No such plots were set up within the oak nests because they did not contain as other woody vegetation besides the densely planted oaks. Assuming that other woody species may voluntarily regenerate underneath the oak crowns, we installed also circular vegetation plots with a radius of 1 m between the rows. Those plots were spaced at a regular distance of 5 m within each strip.

**Table 4.1: Site descriptions and location of investigated cluster planting sites (modified from Gauer and Aldinger 2005).**

| **Sites** | **Location ( name of the nearest town and State)** | **Geographical area** | **Elevation m a.s.l.** | **Mean annual temp. (°C)** | **Mean annual rainfall (mm)** | **Soil types** | **Mean annual oak volume increment ($m^3$ $ha^{-1}$ $yr^{-1}$)** |
|---|---|---|---|---|---|---|---|
| Altenheim | Lahr, Baden-Württemberg | Upper Rhine valley | 143 | 10.2 | 832 | Gleyic cambisol | 8 |
| Gerlingen | Stuttgart, Baden-Württemberg | Neckar river basin | 440 | 8.1 | 780 | Stagnogleyic cambisol | 7.5 |
| Gerchsheim | Tauberbischofsheim, Baden-Württemberg | Franconian plateau | 310 | 8.5 | 670 | Stagnogleyic cambisol | 8 |
| Kaisereiche | Schwarzenborn, Hessen | Northwest Hessian mountain | 550 | 6.5 | 800 | Stagnogleyic cambisol | 8 |
| Königheim | Tauberbischofsheim, Baden-Württemberg | Neckar river basin | 380 | 8.1 | 750 | Cambisol | 8.5 |
| Lerchenfeld | Schwarzenborn, Hessen | Northwest Hessian mountain | 550 | 6.5 | 800 | Stagnogleyic cambisol | 8 |
| Leonberg | Stuttgart, Baden-Württemberg | Neckar river basin | 420 | 8.5 | 780 | Stagnogleyic cambisol | 7.5 |

**Table 4.2: Planting characteristics of studied cluster sites (Q.r. = *Quercus robur*, Q.p.= *Quercus petraea*, F.s. = *Fagus sylvatica*, C.b. = *Carpinus betulus*, T.c. = *Tilia cordata*).**

| **Location** | **Altenheim** | **Gerlingen** | **Gerchsheim** | **Kaisereiche** | **Koenigheim** | **Larchenfeld** | **Leonberg** |
|---|---|---|---|---|---|---|---|
| **Cluster type** | group | nest | nest | group | nest | group | nest |
| **Oak species planted** | Q.r. | Q.r. | Q.r. | Q.p. | Q.p. | Q.p. | Q.r. |
| **Age** | 10 | 26 | 22 | 20 | 22 | 20 | 23 |
| **Spacing between oaks in cluster (m)** | 1 x 1 | 0.3 x 0.3 | 0.25 x 0.25 | 1 x 1 | 0.25 x 0. 25 | 1 x 1 | 0.3 x 0.3 |
| **Clusters ha$^{-1}$** | 70 | 180 | 200 | 100 | 200 | 100 | 150 |
| **Oaks per cluster** | 19 | 21 | 21 | 27 | 21 | 27 | 21 |
| **Trainers per cluster** | 12 | | | 15 | | 15 | |
| **Trainer species** | T.c., C.b. | | | F.s. | | F.s. | |

### 4.2.3 Stand productivity assessment

Strips within cluster plantings were divided into (1) area occupied by clusters and (2) area left for natural regeneration. The area occupied by every single cluster was derived from allometric equations predicting crown width based on DBH and tree age for young oaks, *Carpinus betulus* and *Fagus sylvatica* (Nutto, 1999; Dubravac, 2002, 2003; Piboule *et al.*, 2005). Total crown projection area of clusters was then subtracted from the strip area to calculate the area occupied by natural regeneration. The accuracy of this field sampling design was validated at one nest and one group planting site, where additional comprehensive inventories in which all individuals within strips were recorded, and did not show significant difference to the plot based sampling within strips described above.

Productivity in an ecological sense is the rate at which an organism, population, or community assimilates energy or sequestrates carbon through biomass accumulation (Martin and Hine, 2008). Given the lack of repeated inventory data of cluster and row plantings, we could not determine the rate of biomass accumulation. However, standing volume of a forest stand or stand basal area at time of first commercial thinning has often been recognized as a proxy for stand productivity. From a practical point of view, this is the productivity up to this point in time that could be used through harvesting. Also, previous studies used stand basal area ($m^2\ ha^{-1}$) as a proxy for stand productivity to explore the relationship between tree species diversity and productivity (Erskine *et al.*, 2006; Jacob *et al.*, 2010). Moreover, stand basal area is strongly correlated with stand biomass (Vanclay, 1992). Therefore, we used stand basal area as a measure of stand productivity in this study. Based on the collected strip data we calculated basal area of planted trees (oak and trainer trees), basal area of naturally regenerated trees and total stand basal area (planted and natural regenerated trees) in cluster and row planting. In addition, total stand basal was also divided into different groups: (1) naturally regenerated early-successional species (*Betula pendula*, *Salix caprea*, *Poplus tremula*, *Pinus sylvestris*, *Sorbus aucuparia*); (2) naturally regenerated mid-successional species (*Fraxinus excelsior*, *Acer pseudoplatanus*, *Acer platanoides*, *Picea abies*, *Pseudotsuga menziesii*, *Prunus avium*); (3) planted shade-intolerant hardwoods (*Quercus* spp. *Prunus avium*); (4) planted shade-tolerant trainer trees (*Carpinus betulus*, *Tilia cordata*, *Fagus sylvatica*); (5) and naturally regenerated woody shrubs (*Frangula alnus*, *Sambucus nigra*, *Corylus avellana*).

### 4.2.4 Assessment of species richness and statistical analysis

Kolmogorov-Smirnov tests were used to test for normal distribution of stand basal area and diversity indices in each site. To account for the varying size of vegetation plots between the planting types, we used rarefaction to compare species richness between cluster and row planting. Rarefaction represents the means of repeated re-sampling of all pooled samples, i.e. the statistical expectation for the corresponding accumulation curves (Sverdrup-Thygeson *et al.*, 2010). Rarefaction curves were produced by repeatedly re-sampling the pool of *N* samples (in our case vegetation plots which represent a collection of individuals), at random and plotting the average number of species represented by 1, 2,……..*N* samples (Gotelli and Colwell, 2001). Rarefaction generates the mean expected number of species and confidence interval in a small collection of samples drawn at random from the large pool of *N* samples. The difference between rarefaction curves representing different treatments (e.g. nest *vs.* row, group *vs.* row) is statistically significant, when confidence intervals of means from two curves do not overlap.

Paired sample *t* test were used to test for differences in stand basal area, basal area of planted trees and natural regeneration between cluster and row planting pairs across all sites. Influence of area available for natural regeneration between clusters on species richness and stand basal area was quantified by linear regression and correlation analysis. Whether stand basal area was influenced by density of planted and naturally regenerated tree species or species diversity was tested by one-factorial analysis of covariance, by using density as covariate and species richness as factor. All statistical analyses were performed in IBM® SPSS® Statistics, Version 20 and R 2.14.0, package 'vegan' (R Development Core Team, 2011; IBM, 2012).

## 4.3 RESULTS

### 4.3.1 Tree species richness and stand basal area in cluster and row planting

With increasing number of sample plots, rarefaction curves of species richness became significantly higher (as indicated by the non-overlapping confidence intervals) in cluster plantings than in row plantings. This higher species richness in cluster plantings when compared to row plantings was more prominent in nest than in group plantings (Fig. 4.1). The gentle slope of rarefaction curves at high numbers of plots implies that the chance for encountering additional species was small and that a sufficient number of plots had been sampled to ascertain the differences between planting types.

Basal area of naturally regenerated tree species was significantly higher both in nest ($t$ = 8.36, d.f. = 2, $p < 0.01$) and group ($t$ = 4.33 , d.f. = 2, $p < 0.05$) than in row planting. As may have been expected, basal area of planted oak and trainer trees was significantly lower in nest ($t$ = -4.68, d.f. = 3, $p < 0.05$) and in group planting ($t$ = -5.80, d.f. = 2, $p < 0.05$) than in row planting. Total stand basal area consisting of naturally regenerated and planted trees was not statistically different in nest *vs.* row and group *vs.* row pairs across 4 and 3 sites respectively (Fig. 4.2).

*Betula pendula*, *Poplus tremula*, *Salix caprea* and *Sorbus aucuparia* were the most common early-successional tree species found in the natural regeneration between clusters. The proportion of total stand basal area represented by early successional trees was 25% on average. Mid-successional trees such as *Acer* spp., *Picea abies*, and *Fraxinus excelscior* contributed on average to 17.5% of stand basal area. Planted oaks and cherries contributed to 40% of basal area, whereas trainer trees and woody shrubs comprised approximately 14% and 5% of stand basal area, respectively (Fig. 4.3). The density (log-transformed) of naturally regenerated trees was positively related to the space available for natural regeneration between the clusters ($R^2$ = 0.31, Pearson's $r$ = 0.51, $p < 0.05$). Available space for natural regeneration between the clusters also significantly increased basal area of naturally regenerated trees ($R^2 = 0.45$, Pearson's $r = 0.68$, $p < 0.01$) (Fig 4.5). The unplanted area between clusters also influenced species richness ($R^2 = 0.21$, Pearson's $r = 0.46$, $p < 0.01$) and Shannon diversity ($R^2 = 0.31$, Pearson's $r = 0.50$, $p < 0.01$) of naturally regenerated tree species (Fig. 4.4).

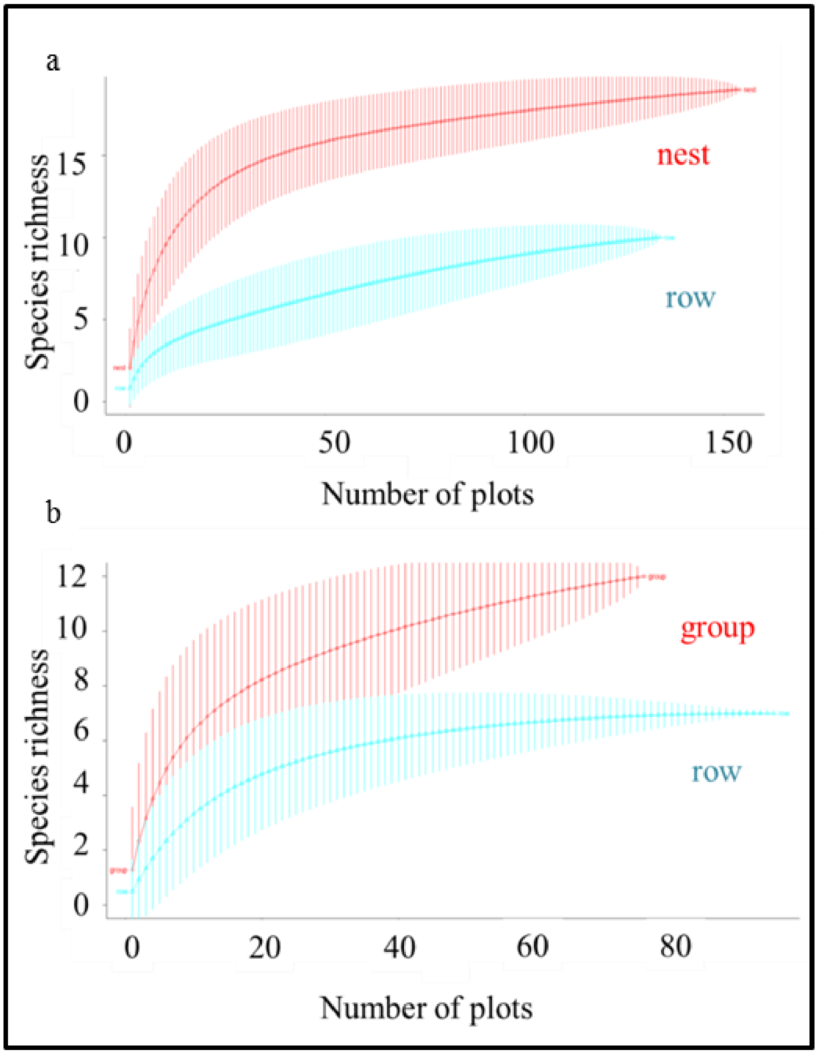


**Fig.4.1: Rarefaction curves for nest *vs.* row planting (a) and group *vs.* row planting (b), the number of species is standardized by number of vegetation plots (x axis) and accumulated with total number of species (y axis). Confidence intervals are shown by vertical lines.**

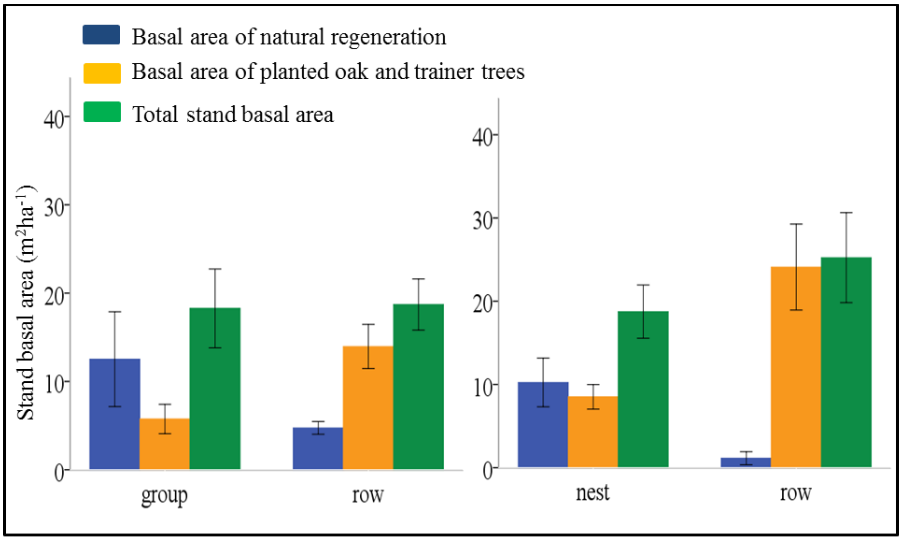


**Fig.4.2: Comparison of stand basal area between nest, group and row planting. * $p < 0.05$ level, ** $p < 0.01$ level. *Thin bars* denote standard error at 95% confidence interval.**

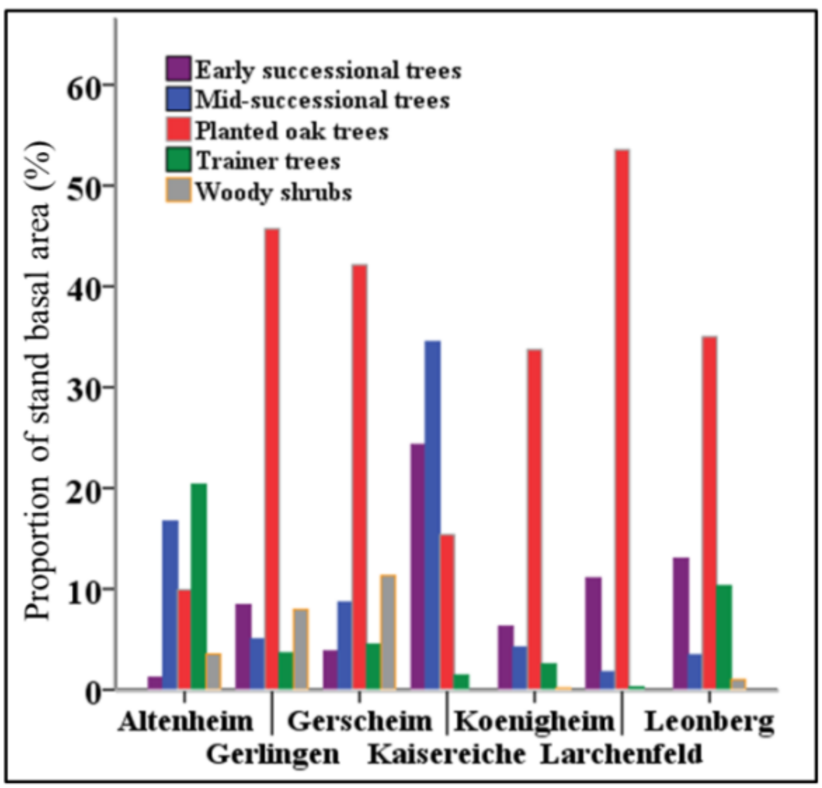


**Fig.4.3: Contribution of stand basal area from different tree groups in cluster planting stands.**

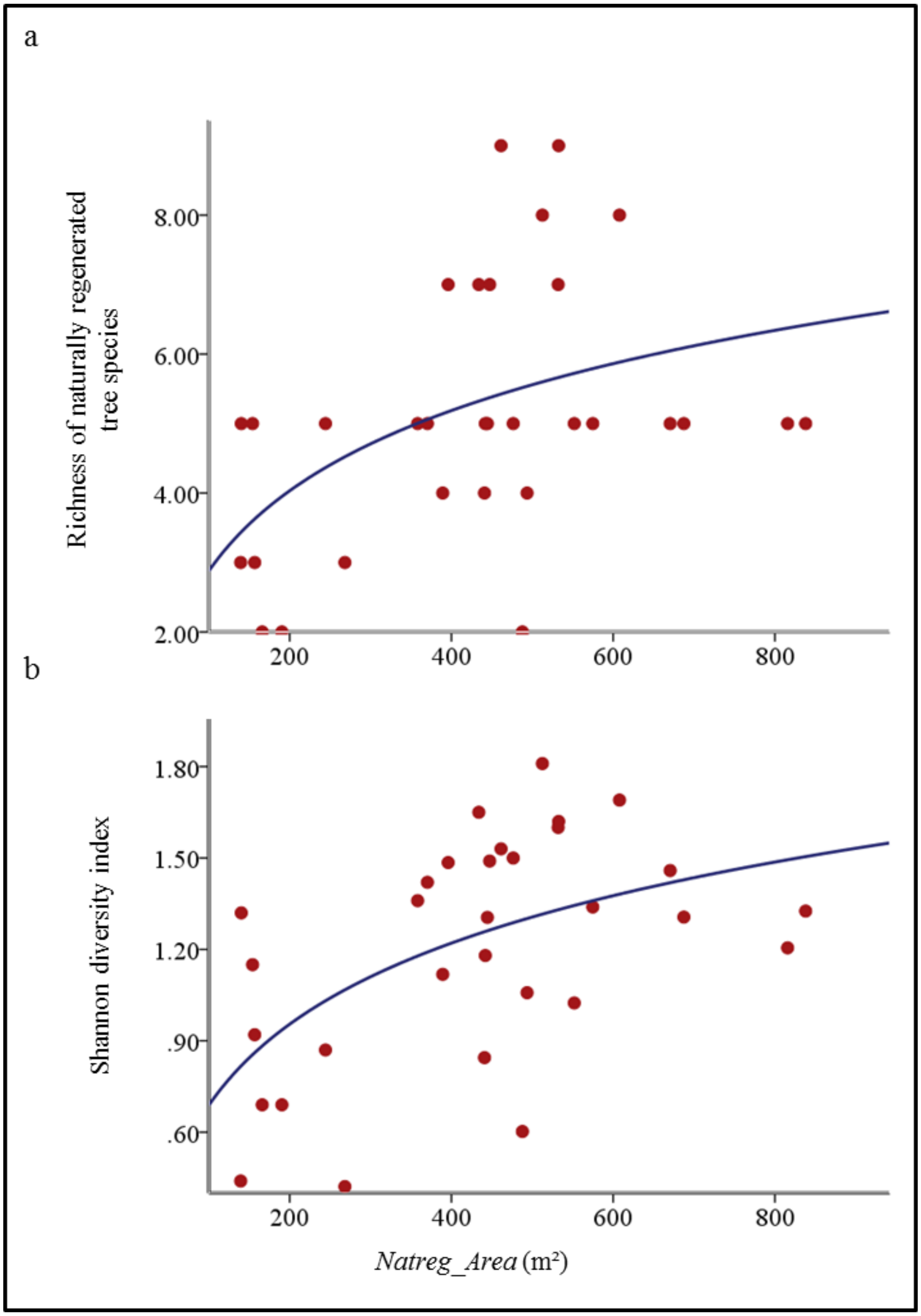


**Fig.4.4. Relationship between the area between clusters that is available for natural regeneration (*Natreg_Area* in m²) and (a) richness ($R^2$ = 0.21, $p$ < 0.05, N = 31), and (b) the Shannon diversity index ($R^2$ = 0.29, $p$ < 0.01, N = 31) of naturally regenerated tree species.**

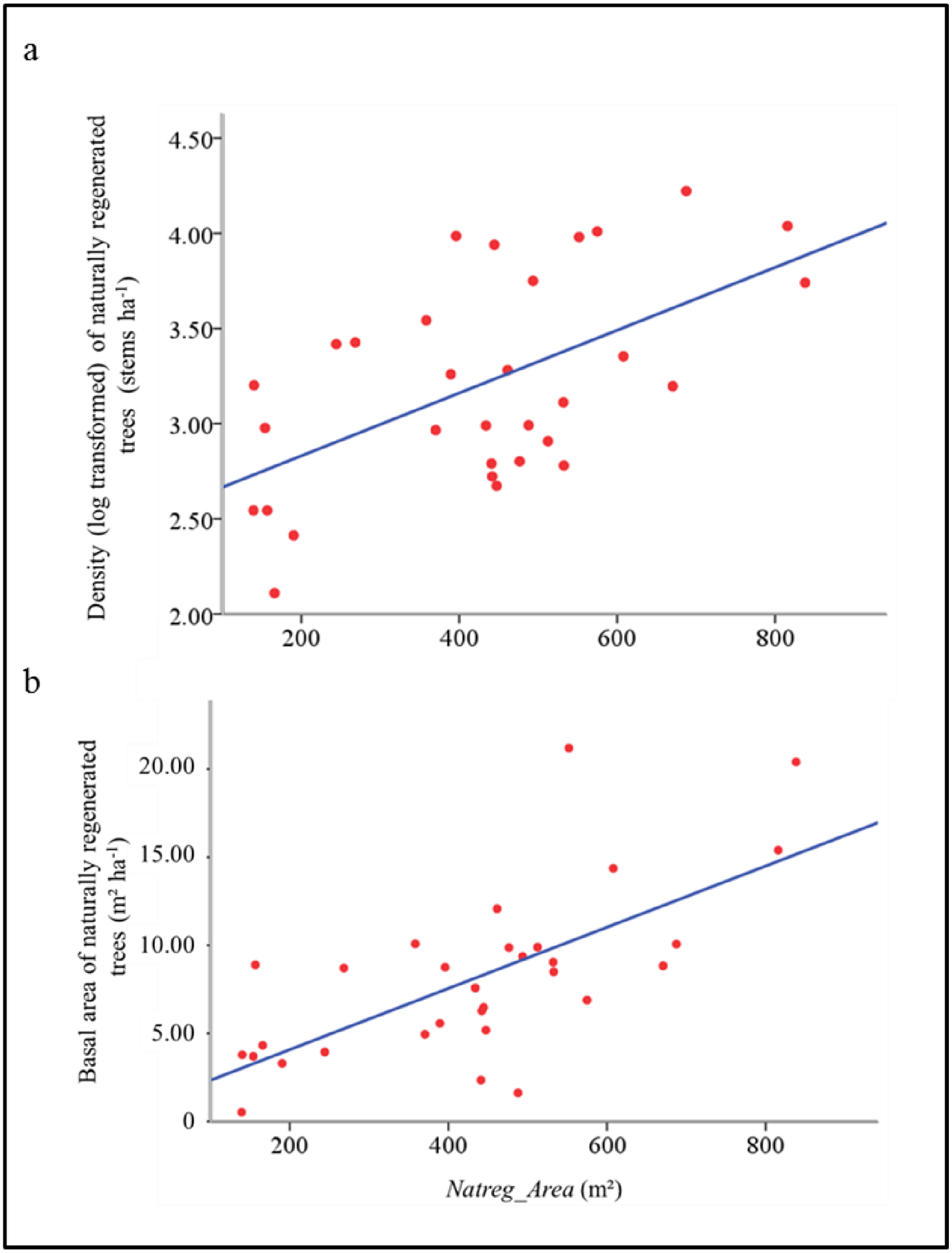


**Fig. 4.5. Relationship between available potential natural regeneration area (*Natreg_Area* in m²) and (a) density (log-transformed) ($R^2$ = 0.31, $p$ < 0.05, N = 31), (b) and basal area ($R^2$ = 0.45, $p$ < 0.01, N = 31) of naturally regenerated tree species.**

### 4.3.2 Influence of natural regeneration on stand basal area in cluster planting

Density of natural regeneration (stems > 1.3 m height) was 1100 and 6500 stems $ha^{-1}$ in nest and group planting, respectively (Fig.4.6). Univariate analysis of variance showed that stand basal area significantly increased with increased level of density of natural regeneration in cluster planting stands. However, tree species richness or diversity had no significant influence on stand basal area in cluster planting stands (Table 4.3).

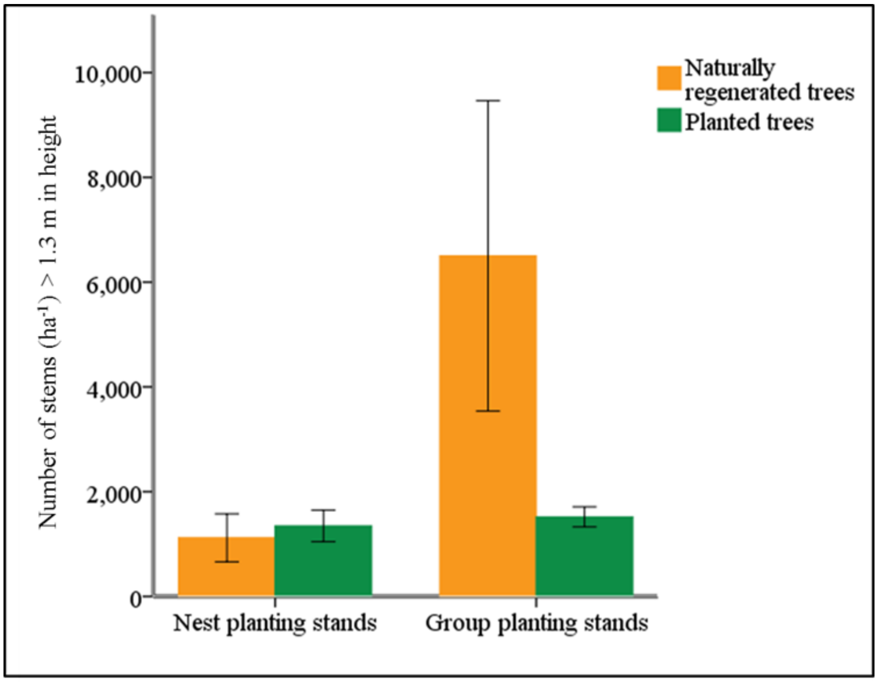


**Fig. 4.6 : Density of naturally regenerated and planted trees (>1.3 m height) grown in cluster planting stands.**

**Table 4.3: Influence of tree density and species richness on stand basal area. Tree density of planted and naturally regenerated trees was treated separately as covariate, and species richness was treated as factor in a one-factor univariate analysis of variance ($R^2$ = 0.39, $p$ = 0.083, N = 31, d.f. = degree of freedom).**

| **Source** | **d.f.** | **F value** | ***p* value** |
|---|---|---|---|
| Corrected Model | 8 | 2.0752 | 0.0838 |
| Intercept | 1 | 21.1840 | 0.0001 |
| Density of planted trees (stems $ha^{-1}$) | 1 | 0.9619 | 0.3374 |
| Density of naturally regenerated tree (stems $ha^{-1}$) | 1 | **5.7711** | **0.0252** |
| Species richness | 6 | 1.1934 | 0.3462 |

## 4.4 DISCUSSION

### 4.4.1 Tree species diversity and stand basal area in cluster and row planting

Tree species richness was significantly higher in both types of cluster planting when compared to traditional row planting. Stand basal area was similar between group and row plantings, and not significantly lower in nest plantings than in row plantings. Our findings corroborate results from Rock *et al.* (2003) who also found higher vegetation diversity in stands established through group planting when compared to row planting at two sites. High species richness in cluster plantings may have resulted from several factors. First, unplanted interspaces between clusters provided a longer window of opportunity for the establishment of early-successional species, whereas canopies closed quicker in the densely planted row plantings. Significant correlations between the area available for natural regeneration and the species richness and density of naturally regenerated trees supported this fact. Second, owing to the lack of site preparation in cluster plantings, old stand legacies (Swanson *et al.*, 2010) left between clusters e.g. broken tree stumps, mounds, coarse woody debris etc. might have provided more diverse conditions and micro-sites on the ground and thus facilitated establishment of seedlings of different species. Several studies on clear-felled and wind-thrown areas in central European temperate forests have shown that diverse tree communities comprising early-successional woody species established in areas with less intensive site preparation or where no salvage logging was varied out after windthrow (Wohlgemuth *et al.*, 2002; Jonasova *et al.*, 2010).

Cluster and row planting stands were surrounded by mature broadleaved and coniferous stands providing seeds for natural regeneration at the study sites. For example, high numbers of naturally regenerated seedlings of *Picea abies* in the “Kaisereiche” cluster planting was likely the result of its close proximity to an old Norway spruce stand, as has been found elsewhere (Jonasova *et al.*, 2010). Whether more species were found in cluster plantings than in row plantings through a richer seed or seedling bank in less disturbed sites, could not be ascertained in this study, in which ages of trees were not analyzed.

The prolific establishment of naturally regenerated tree species substantially increased total stand basal area in cluster plantings. Even though in low density plantings with groups only half the number of oak seedlings (ca. 2000 - 2500 $ha^{-1}$) were established when compared to traditional row plantings (ca. 5000 - 6000 $ha^{-1}$), total stand basal area was comparable among the two planting types with similar rate of survival in oaks. However, as shown for a large data-set, very close initial growing space (0.04 $cm^2$ per seedling) significantly lowered the survival rate of oaks in nest plantings when compared to row planting (Saha *et al.*, 2012). This must have also occurred in the stands of this study in the first decade after planting. The surviving oak trees (ca. 50% of stand basal area) and additional naturally regenerated trees between the nests produced a stand basal area that was not significantly lower than in row planting.

### 4.4.2 Influence of tree species richness and density on stand basal area in cluster planting

Our study showed that in young stands from cluster planting, total stand basal area increased with the density of naturally regenerated trees. This is in partial agreement with our hypothesis two. Larger unplanted spaces in low density plantings allowed fast-growing and light demanding trees to establish between clusters (Gockel *et al.*, 2001; Rock *et al.*, 2003; Dong *et al.*, 2007a). We did not find direct evidence of tree species richness to influence stand basal area. Instead basal area depended significantly on the density of natural regeneration in unplanted spaces between clusters. Species richness may have an influence on stand productivity in cluster plantings at a later stage of development, when greater levels of niche complementarity may develop owing to the different species traits (Morin *et al.*, 2011). This warrants further investigation through periodic inventories.

## 4.5 CONCLUSION

Our study provides the first assessment of tree species diversity and stand productivity in low-density cluster plantings established in wind-thrown and clear-felled areas. We demonstrated that both nest and group planting harbour higher levels of tree species richness than traditional row planting. Of critical importance in this system of stand establishment is the area between clusters that is available for natural regeneration of other species. If this area is colonized effectively, it not only contributes to tree species diversity, and thus likely to resilience and adaptability of the new stands, but also to production of woody biomass and hence carbon sequestration. Natural regeneration of early and mid-successional species compensated for the reduced basal area production of oaks in low-density group plantings. Hence, this form of low density planting appears to combine environmental and economic benefits. However, interactions between oaks and naturally regenerated species and their influence on growth and timber quality of oaks at the individual tree level should be researched separately. Further research should explore whether cluster plantings with other species may yield similar results.

# CHAPTER FIVE: GROWTH AND STEM QUALITY OF OAKS (*Quercus robur* AND *Q. petraea*) ESTABLISHED IN CLUSTER PLANTINGS RESPOND DIFFERENTLY TO INTRA- AND INTERSPECIFIC NEIGHBOURHOOD COMPETITION

***An oak tree (pointed by arrow) growing in cluster under neighbourhood competition in 10 year old group planting stand, Sölling, Lower Saxony, Germany.***

## 5.1 INTRODUCTION

Traditional reforestation methods aim to achieve full site occupancy at an early stage of stand development through the planting of a sufficient number of individuals of the desired tree species (Drouineau *et al.,* 2000). However, this conventional approach has a few disadvantages including high costs for site preparation, plants and planting (Gockel, 1995; Ehring and Keller, 2006). In addition, the resulting early stand development phases often lack typical post-disturbance characteristics such as highly diverse early successional vegetation leading to complex food webs and maintaining other important ecosystem functions and processes (Swanson *et al.,* 2010). Therefore, reforestation methods have been developed that combine low density planting of target species with natural regeneration in the remaining area (Drouineau *et al.,* 2000). Cluster planting is an example of low density planting designs aiming to save planting costs, promote natural succession of other species as well as foster development of high quality hardwood trees in young stands (Saha *et al.,* 2012). The planting of oaks in widely spaced clusters was introduced in Central Europe in the 1980s and 1990s as an alternative to traditional row planting, which used higher seedling densities (e.g. 5000 - 6000 seedlings $ha^{-1}$ compared to 2500 - 3000 $ha^{-1}$). Oak clusters can be defined as uniformly distributed ‘nests’ (nest planting) or ‘groups’ (group planting) that consist of 20 - 30 seedlings planted in an aggregated manner with 0.2 or 1 $m^2$ initial spacing and approximately 200 or 100 such clusters per hectare, respectively (Gockel, 1995; Szymanski, 1986). Trainer trees from shade-tolerant species such as *Carpinus betulus*, *Tilia cordata*, and *Fagus sylvatica* are commonly planted at varying densities at the periphery of the oak groups, although this was not done for the nest plantings analysed in this study. The spaces left unplanted between clusters are usually occupied by natural regeneration of woody plants, often of early- and mid-successional tree species. These may increase tree species richness and contribute significantly to stand productivity (see Chapter Four).

Conventional management of oaks for high quality timber aims at crown closure of stands within 10 - 15 years after establishment to promote intraspecific competition and thus self-pruning of trees (Röhrig *et al.,* 2006). For a fully stocked oak stand, a typical silvicultural goal is to select 80 - 100 future crop trees $ha^{-1}$ at the time of the first commercial thinning. These should be vigorous trees that have a branch free bole of ca. 8 - 10 m, a straight stem and be fairly evenly spaced (von Lüpke, 1998). Whether this goal can be achieved with the low density cluster planting design may be questioned for two reasons. Firstly, the natural regeneration of other tree species occurring between clusters may grow faster than oaks and pose strong competition to oaks, thus reducing the probability that vigorous oaks develop within clusters. Secondly, quality development of oak stems may not proceed as desired, if there is significant variability in crown closure and hence competition between neighbouring trees. For example, if trees between clusters regenerate much later, only sparsely, or grow substantially slower, self-pruning of oaks in clusters, in particular of trees in the perimeter of clusters, may be delayed (Guericke *et al.,* 2008; Leder, 2007; Petersen, 2007). The early proponents of cluster planting assumed that the protection of inner oaks by outer oaks from interspecific competition and browsing would facilitate inner oaks to develop into potential future crop trees (Szymanski, 1986; Gockel, 1995). Recent findings on the importance of interspecific competition confirm this hypothesis (Saha *et al.,* 2012). It has also been suggested that there must be enough interspecific competition from naturally established trees between the clusters to ensure that the oak trees self-prune and thereby improve quality (Dong *et al.,* 2007). These assumptions, however, were never tested and the effects of naturally regenerated and planted trainer and con-specific trees on the development of oaks established and grown in clusters have not been quantitatively evaluated.

Previous studies on the effect of fast growing broadleaved tree species (e.g. *Betula pendula, Poplus* spp., *Salix* spp.) on diameter and height growth as well as on stem quality of oaks in conventional stands established by row planting yielded contradictory results (Rock *et al.,* 2004; Leder, 1992). In the majority of these studies, competition was not quantified and, moreover, intraspecific and interspecific interactions were not separated (Leder, 1992; Ammer and Dingel, 1997; Petersen *et al.,* 2009; Rock *et al.,* 2004). Therefore, we aimed to analyse the effects of intraspecific and interspecific interactions on growth and quality of oaks grown in cluster plantings by quantifying the competitive influence of neighbouring trees. Specifically, we aimed to test the following hypotheses:

1) The effect on growth of young oaks in nest and group plantings differs between competitive influences exerted (a) intraspecifically by other oaks, and interspecifically by (b) pioneers (early successional tree species) and (c) mid and late-successional tree species.

2) Intraspecific and interspecific competition do not differ in their influence on quality development (measured as branch free bole length) of young oaks grown in cluster plantings.

3) Quality development of oaks in the inner part of groups is superior compared to that of oaks at the perimeter. Inner oaks therefore have a higher probability of emerging as potential future crop trees.

## 5.2 MATERIALS AND METHODS

### 5.2.1 Study sites

Seven locations with stands established as group or nest plantings of oak (*Quercus robur* and *Q. petraea*) were sampled in Baden-Württemberg and Hesse, Germany (Table 4.1). Mean annual temperature and rainfall vary among these sites between 6.5 - 10.2°C and 670 - 832 mm, respectively, with the majority of precipitation occurring in the growing season between May and September (Gauer and Aldinger, 2005). The dominant soil type across study sites is a stagnosol originating from basalt loam, silt stone or sandstone, with the exception of Altenheim (gleyic cambisol), originating from alluvial deposits covered by a layer of loess. The resulting site conditions provide for moderate growth rates of oak, which are according to yield tables equivalent to a mean annual increment of 7.5 - 8.5 $m^3 ha^{-1} yr^{-1}$ over a 100 year rotation (Table 4.1).

On average, the area of each inventoried stand was about 1 ha. Reforestation with oaks took place between 1986 and 2000 after previous stands of mainly coniferous species (*Picea abies*, *Pseudotsuga menziesii*) were uprooted by storms or clear-felled. Manual site preparation prior to planting was restricted to patches where the oak clusters were planted. As part of the basic planting design, a varying number of trainer trees were planted around oak groups (Table 4.2).

The stands were fenced off during the very first years after establishment to avoid browsing of seedlings. All reforestations were adjacent to existing forests, usually mature mixed oak as well as mixed and pure conifer stands. Few naturally established pioneer, mid and late successional trees were removed once in stands at Gerlingen and Lerchenfeld 5 - 8 years after planting. However, those tending operations were only carried out in the periphery of clusters and tree species were not pre-selected before removal. No tending operations were carried out at other sites. Nevertheless, at the time of our inventory, when stands were 20 - 26 year old, pioneer as well as mid and late-successional species were abundant, which may be partially attributable to coppicing of the removed trees. Mean height and diameter at 1.3 m height (DBH) of oaks grown in cluster plantings ranged between 6 - 9.5 m and 5 - 11.5 cm, respectively, and length of the branch free bole varied from 3.3 to 4.6 m (Table 5.1 and 5.2).

### 5.2.2 Sampling design and data collection

We established systematic inventory strips along rows of nest or groups to cover at least 1/3 of the area of each stand. Strips were not established at the boundary of stands to avoid edge effects, skidding trails and forest roads. Within inventory strips, we measured DBH of all oaks and trainer trees and recorded stem form and crown type of all cluster oaks in the summer of 2010 and 2011. Stand specific height curves based on DBH were developed to calculate tree height of all individual oaks. We calculated tree height to DBH ratio (HD ratio) as an indicator of individual tree stability. High HD ratio indicate poor physical tree stability, which is relevant for young oaks in situations of snow load. Vigorous, dominant or co-dominant cluster oaks of the upper canopy with straight stems and monopodial crowns were classed as potential future crop trees and served as target trees for the competition analysis. In fertile sites, where size asymmetric competition for light is prevalent, dominant and co-dominant trees would exert higher competitive pressure on the selected target trees (Pretzsch and Biber, 2010). Based on this assumption, trees with heights equal or greater than 2/3 of the respective target tree were selected as competitors in a circle with a radius of 3 m around target trees. Species identity, distance, and DBH, of each competitor within that circle were recorded. Apart from intraspecific competitors (oaks), all other competing trees were classified into two broad groups based on their occurrences in successional dynamics: (a) pioneers, which included early-successional species: *Betula pendula*, *Salix caprea*, *Salix alba, Poplus tremula*, *Pinus sylvestris, Sorbus aucuparia* and (b) mid- and late-successional species: *Fraxinus excelsior*, *Acer pseudoplatanus*, *Acer platanoides*, *Picea abies*, *Pseudotsuga menziesii*, *Carpinus betulus*, *Tilia cordata*, *Fagus sylvatica*. In addition to successional status, these species groups differ in their shade-tolerance and hence in their ability to cast shade, which is higher in the latter group *(Tonioli et al.*, 2001; McLeod *et al.*, 2001). To quantify competition intensity, Hegyi's competition index was calculated (Hegyi 1974). Hegyi's index has been successfully used to quantify tree competition and proved to be equally suitable as other height and crown based indices in young, mixed broadleaved stands in Germany (Ammer *et al.*, 2005).

Testing of the third hypothesis was restricted to group plantings, since the original location of oaks within nests could not be determined owing to high mortality rates. To address the third hypothesis, we used all oaks inventoried in the group plantings, which were divided into "inner oaks" and "outer oaks"

### 5.2.3 Statistical analysis

Generalized linear modeling (GLM) with an identity link function was used to test for the effects of aggregated competition (both intra- and interspecific) and competition exerted by the different tree groups on DBH, height, HD ratio and branch free bole length of target oaks. We used the maximum likelihood method for parameter (β) estimation in GLM analysis. Finally, *Chi square* and *Wald-test* statistics were used to test for the significance of the whole model and parameters, respectively. Parameter estimates (β) of GLM were used as magnitude of competitive effect from different tree groups on oaks. For a significant effect, confidence interval of a parameter estimate should not touch the zero line.

Binary logistic regression was used to test for the influence of tree position in groups on the occurrence of potential future crop trees. GLM analysis was used to test for the influence of competitive interactions between type of competition and target tree location on the length of branch free bole. We used the R 2.14.0 open-source statistical program for analysis (R Development Core Team, 2011).

## 5.3 RESULTS

### 5.3.1 Influence of competition on DBH, height, HD ratio and branch free bole length of target trees

*Nest planting*

In the 4 nest planting stands, each target oak had on average 2 competing trees from either pioneer or mid- and late-successional species and 4 competing oaks (Fig. 5.1). The average DBH of target oaks was significantly higher ($p < 0.05$) than in competing oaks. However, DBH did not differ significantly ($p > 0.05$) between target oaks and interspecific competitors. Interestingly, DBH did not vary significantly ($p > 0.05$) between pioneers and mid- and late-successional competitors across 4 nest planting stands (Table 5.2). The average distance between target trees and competing oaks was about 1 m. Competitors of pioneer as well as mid and late-successional trees were located on average 2.08 and 2.18 m from target oak trees, respectively (Table 5.3).

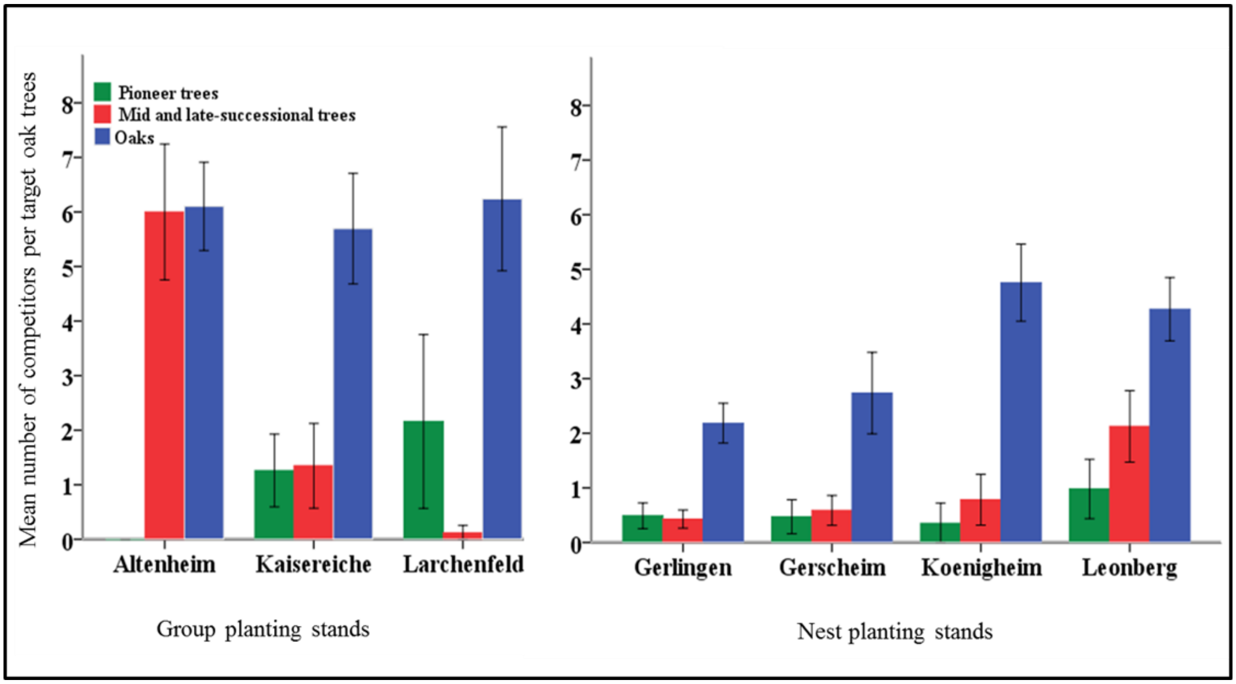


**Fig. 5.1: Number of competing trees per target oaks in 7 different stands of cluster planting. Thin bar represented standard error of mean.**

**Table 5.1: Mean DBH and height of oaks growing in cluster planting stands (*S.E.*= standard error, *N* = number of oaks inventoried).**

| Site | DBH | | | Height | | | Stand age (year) |
|---|---|---|---|---|---|---|---|
| | mean (cm) | *S.E.* | *N* | mean (m) | *S.E.* | *N* | |
| **Altenheim** | | | | | | | 10 |
| Inner oaks | 5.11 | 0.17 | 133 | 6.68 | 0.09 | 133 | |
| Peripheral oaks | 5.69 | 0.13 | 225 | 6.99 | 0.07 | 225 | |
| All (inner + peripheral oaks) | 5.47 | 0.1 | 358 | 6.88 | 0.05 | 358 | |
| **Kaisereiche** | | | | | | | 20 |
| Inner oaks | 5.57 | 0.19 | 178 | 4.78 | 0.23 | 105 | |
| Peripheral oaks | 6.13 | 0.45 | 202 | 5.97 | 0.9 | 122 | |
| All (inner + peripheral oaks) | 5.87 | 0.26 | 380 | 5.42 | 0.5 | 227 | |
| **Lerchenfeld** | | | | | | | 20 |
| Inner oaks | 7.88 | 0.26 | 148 | 6.95 | 0.32 | 140 | |
| Peripheral oaks | 9.26 | 0.23 | 230 | 8.7 | 0.28 | 223 | |
| All (inner + peripheral oaks) | 8.72 | 0.18 | 378 | 8.02 | 0.22 | 363 | |
| **Gerlingen** | 11.67 | 0.36 | 169 | 9.37 | 0.14 | 169 | 26 |
| **Gerchsheim** | 7.28 | 0.26 | 236 | 8.71 | 0.15 | 236 | 22 |
| **Koenigheim** | 6.58 | 0.18 | 472 | 8.05 | 0.13 | 472 | 22 |
| **Leonberg** | 7.01 | 0.14 | 460 | 8.34 | 0.08 | 460 | 23 |

**Table 5.2: Mean DBH, height and branch free bole length of target oaks and competitors (*S.E.* = standard error, *N* = number of target oaks and competitors in each cluster planting stand).**

| Sites | Cluster type | Target oak trees DBH (cm) | | Height (m) | | Branch free bole length (m) | | | | Competitors of pioneer species DBH (cm) | | | Competitors of mid and late-successional species DBH (cm) | | | Competing oaks (intraspecific) DBH (cm) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **mean** | ***S.E.*** | **mean** | ***S.E.*** | **mean** | ***S.E.*** | ***N*** | ***% of total height*** | **mean** | ***S.E.*** | ***N*** | **mean** | ***S.E.*** | ***N*** | **mean** | ***S.E.*** | ***N*** |
| **Altenheim** | **group** | 7.84 | 0.3 | 7.97 | 0.11 | 3.7 | 0.14 | 28 | 46 | n.a. | n.a. | n.a. | 6.06 | 0.13 | 172 | 6.25 | 0.12 | 170 |
| **Kaisereiche** | **group** | 8.48 | 0.61 | 6.75 | 0.71 | 4.61 | 0.28 | 24 | 68 | 8.38 | 0.8 | 29 | 9.03 | 0.58 | 33 | 7.32 | 0.18 | 117 |
| **Lerchenfeld** | **group** | 10.84 | 0.47 | 10.45 | 0.6 | 4.62 | 0.23 | 25 | 44 | 9.22 | 0.5 | 55 | 11 | 2.93 | 3 | 9.88 | 0.24 | 159 |
| **Gerlingen** | **nest** | 13.48 | 0.62 | 10.09 | 0.18 | 3.3 | 0.19 | 50 | 33 | 11.69 | 0.88 | 24 | 9.97 | 0.67 | 19 | 12.25 | 0.39 | 97 |
| **Gerchsheim** | **nest** | 10.33 | 0.54 | 10.37 | 0.18 | 4.21 | 0.2 | 35 | 41 | 11.83 | 0.97 | 18 | 13.7 | 1 | 28 | 9.33 | 0.29 | 103 |
| **Koenigheim** | **nest** | 9.71 | 0.39 | 10.42 | 0.19 | 3.93 | 0.24 | 40 | 38 | 8.17 | 0.99 | 9 | 11.72 | 2.01 | 18 | 9.23 | 0.25 | 172 |
| **Leonberg** | **nest** | 9.18 | 0.29 | 9.58 | 0.12 | 4.22 | 0.26 | 55 | 44 | 8.05 | 0.46 | 49 | 8.21 | 0.29 | 112 | 8.58 | 0.18 | 209 |

Aggregate competition from surrounding trees strongly affected DBH and HD ratio of target oaks in the nest plantings. Interspecific competition from mid- and late-successional species had a stronger effect than intraspecific competition. Height of target oaks was neither affected by intraspecific nor interspecific competition (Fig. 5.2). In contrast, intraspecific competition significantly increased length of the branch free bole, whereas interspecific competition had no effect on this parameter of tree quality (Fig. 5.2) (see Appendix 5.1 for model details).

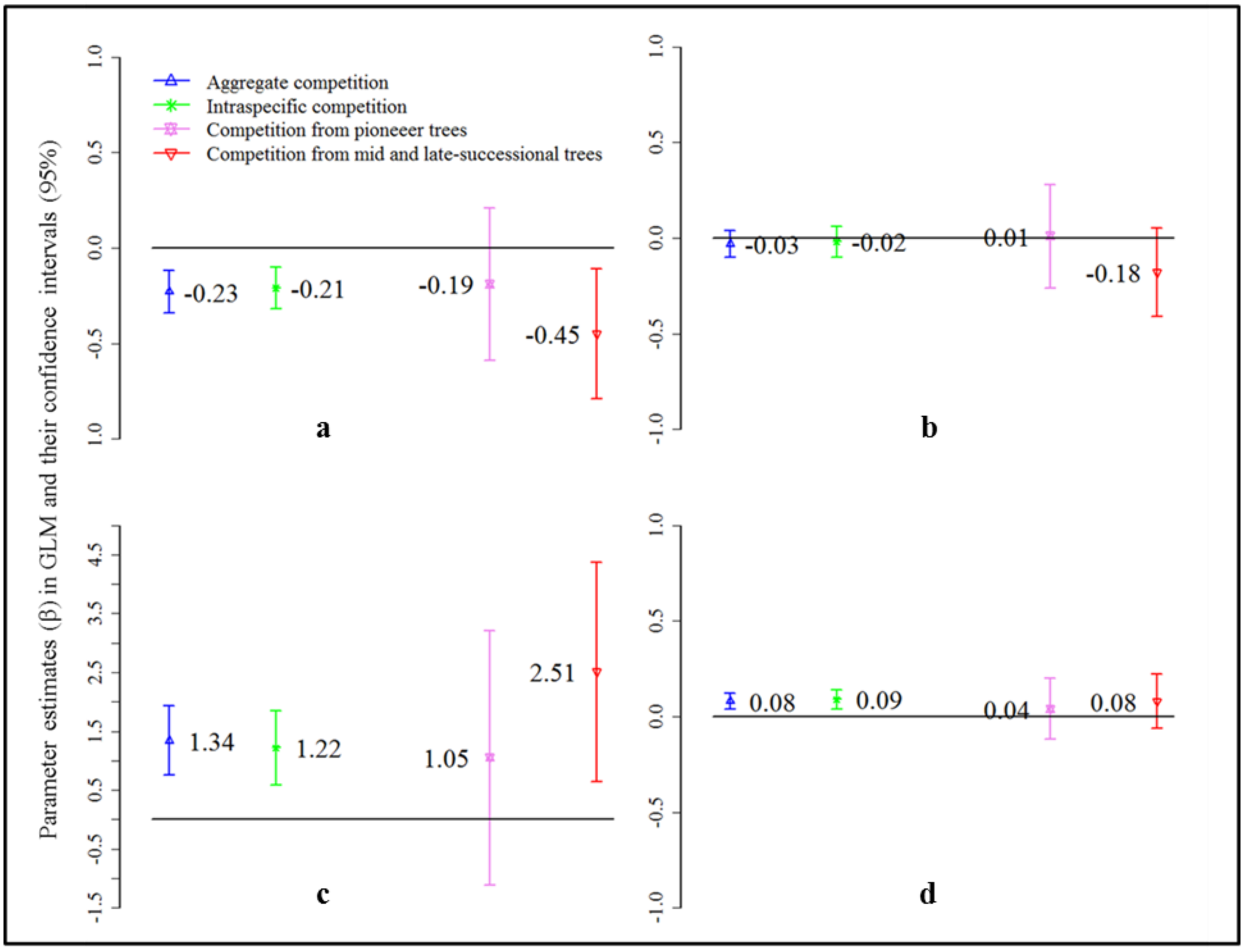


**Fig. 5.2: Influence of neighbourhood competition on (a) DBH, (b) height, (c) height-to-diameter (HD) ratio) and (d) branch free bole length of oaks grown in four 22 to 26-year-old nest planting stands. Thin bars represent standard error of parameter estimates and should not touch zero line for a significant effect.**

*Group planting*

On average, each target oak was surrounded by 2 competing pioneers, one competing tree of mid- and late-successional species, and 6 competing oaks in the group planting stands at Kaisereiche and Lerchenfeld (Fig. 5.1). Competition from pioneer species was absent at Altenheim but target oaks were surrounded by 6 competitors from mid- and -late successional species as well as 6 planted oaks (12 competing trees in total). In Altenheim, DBH was significantly higher in target trees than in conspecific oaks and in mid- and late-successional competitors. However, it did not vary significantly ($p > 0.05$) between competing oaks and mid and late-successional trees. In contrast, in Kaisereiche and Lerchenfeld, average DBH of target oaks did not differ significantly ($p > 0.05$) from that of pioneer and mid- and late-successional trees. No significant differences ($p > 0.05$) were found in tree DBH between pioneer, mid and late-successional trees (Table 5.2). The average distance between target oak trees and other competing oaks within clusters was 1.81 m. Competitors of both pioneer and mid- and late-successional tree species were on average located at 2.09 and 2.14 m distance from target oak trees, respectively (Table 5.3).

Height, DBH, and HD ratio of target oaks were negatively influenced by aggregate competition from surrounding trees (Fig. 5.3 and 5.4). Intraspecific competition significantly reduced DBH and height growth of oaks in the 10-year-old Altenheim group planting. Competition from mid and late-successional trees, however, had no significant influence (lower GLM estimates). While slenderness, measured as HD ratio, was significantly increased by aggregate and intraspecific competition, intraspecific or interspecific competition had no significant effect on branch free bole length at Altenheim (Fig. 5.3). The observed interaction pattern changed in the two 20-year-old group planting stands at Kaisereiche and Lerchenfeld. Here, intraspecific competition had clearly no significant effect on DBH and height, whereas this may not be excluded for pioneer trees ($p = 0.0649$ for DBH). In contrast, competition from trees of mid and late-successional trees had a strong negative influence (higher GLM estimate) on DBH and height growth. However, only intraspecific competition had a significant positive effect on the length of the branch free bole (Fig. 5.4) (see Appendix 5.1 for model details)..

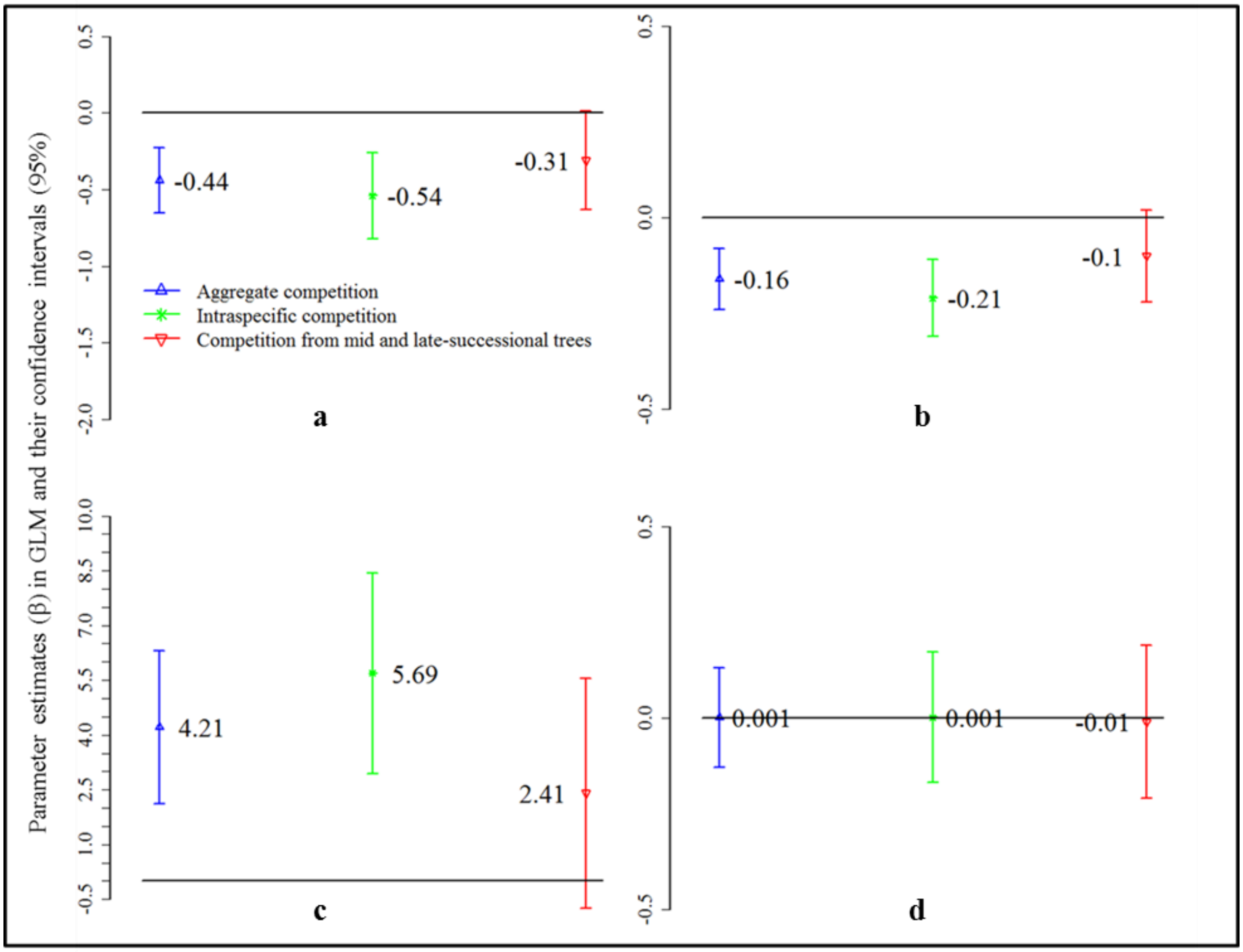


**Fig. 5.3: Influence of neighbourhood competition on (a) DBH, (b) height, (c) stability (HD ratio) and (d) branch free bole length of oaks grown in one 10-year-old group planting stand. Thin bar represented standard error of parameter estimates and should not touch zero line for a significant effect.**

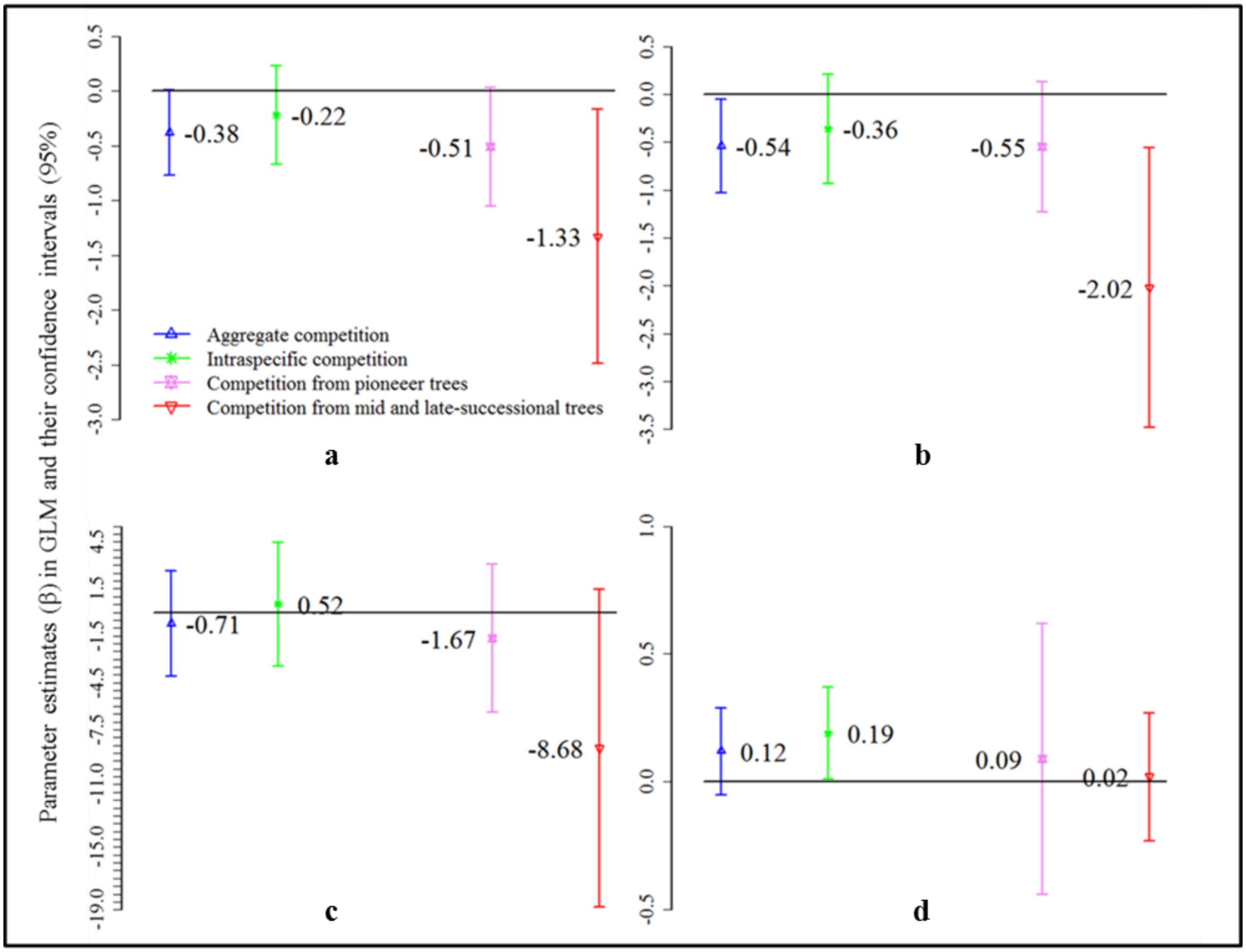


**Fig. 5.4: Influence of neighbourhood competition on (a) DBH, (b) height, (c) stability (HD ratio) and (d) branch free bole length of oaks grown in two 20-year-old group planting stands. Thin bar represented standard error of parameter estimates and should not touch zero line for a significant effect.**

**Table 5.3: Mean distance between target oaks and competitors (*S.E.* = standard error).**

| **Sites** | **Type of competitors** | | | | | |
|---|---|---|---|---|---|---|
| | **Competing oaks (m)** | | **Pioneer trees (m)** | | **Intermediate competitors (m)** | |
| | **mean** | ***S.E.*** | **mean** | ***S.E.*** | **mean** | ***S.E.*** |
| **Altenheim** | 1.72 | 0.05 | n.a. | n.a. | 1.92 | 0.05 |
| **Kaisereiche** | 1.87 | 0.05 | 2.08 | 0.14 | 2.27 | 0.09 |
| **Lerchenfeld** | 1.84 | 0.05 | 2.1 | 0.08 | 2.23 | 0.52 |
| **Gerlingen** | 1.03 | 0.04 | 2.63 | 0.08 | 2.4 | 0.11 |
| **Gerchsheim** | 0.9 | 0.07 | 1.5 | 0.25 | 2.07 | 0.14 |
| **Koenigheim** | 1.07 | 0.09 | 2.46 | 0.25 | 2.39 | 0.13 |
| **Leonberg** | 1.06 | 0.03 | 1.76 | 0.12 | 2.03 | 0.06 |

**Table 5.4: Influence of spatial location of oak trees within groups on the probability of occurrence of potential future crop trees (binary logistic regression analysis), (β = log odd ratio, *S.E.* = standard error in 95% confidence interval, d.f.= degree of freedom).**

| **Response variable** | **Predictors** | **β** | ***S.E.* β** | **Wald's $\chi^2$** | **d. f.** | **Chi-square test** |
|---|---|---|---|---|---|---|
| Potential future crop tree (yes or no) (N = 1098) | Constant | -2.23 | 0.13 | 282.45 | 1 | |
| | Position in group (1 = inner section, 2 = periphery) | 0.59 | 0.18 | 10.14 | 1 | $\chi^2$ = 10.17, $p$ = 0.0014 |

### 5.3.2. Distribution of potential future crop trees within groups

On average, 80% of the sampled groups had at least one and 50% at least two trees that met the criteria for potential future crop trees. At the stand level, the number of potential future crop trees amounted to a mean of 200 trees $ha^{-1}$. The majority (60%) of these high quality trees were located in the inner section of groups. This finding was corroborated by the logistic regression analysis, which revealed a significantly higher probability of occurrence for potential future crop trees in the inner section of groups than in the outer circle of trees (Table 5.4).

Using GLM analysis, we tested whether the influence of competitive interactions on attainment of branch free bole length varied between potential future crop trees located either in the inner or outer sections of groups. Intraspecific competition had a stronger positive influence on branch free bole length in potential future crop trees located in the inner section of groups than in the outer section. In addition, interspecific competition showed significant negative effect on branch free bole length on oaks in the outer section of groups (Table 5.5). Although not statistically significant ($p > 0.05$); competition from pioneer trees, conspecific oaks and aggregate competition was higher in inner oaks than peripheral oaks, and competition from mid and late successional trees was lower in inner oaks than outer oaks (Fig. 5.5).

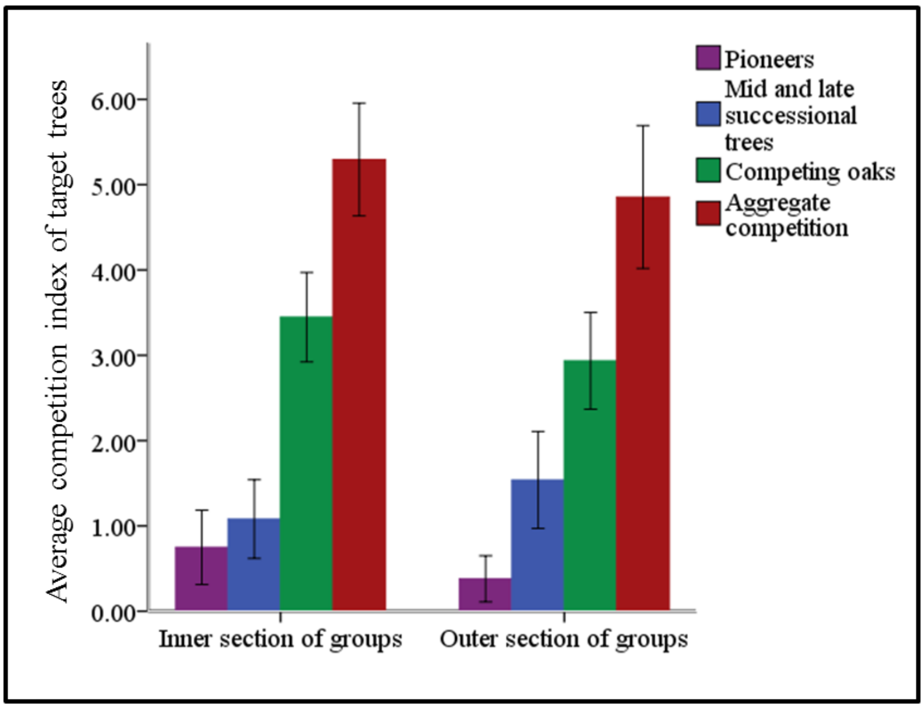


**Fig. 5.5: Comparison of competition indexes of potential future crop trees (target trees) in between inner and outer section of groups divided in different successional groups ($N_{inner\ section} = 44$, $N_{outer\ section} = 34$, thin bars represent standard error of mean at 95% confidence interval).**

**Table 5.5: Influence of spatial location (inner section in groups vs. periphery) and competitive interactions (intraspecific *vs.* interspecific) on branch free bole length in potential future crop trees.**

| **Models** | **Independent variables** | **Model estimates (β)** | **Standard error of β** | **95% Wald confidence interval** | | **Wald χ² value** | **d.f.** | ***p* value** |
|---|---|---|---|---|---|---|---|---|
| | | | | **Lower** | **Upper** | | | |
| BFBL ~ Location*Intraspecific competition | Intercept | 4.0316 | 0.2862 | 3.4707 | 4.5925 | 198.4439 | 1 | 0.000 |
| | Inner section ~ Intraspecific competition | 0.1277 | 0.0808 | -0.0307 | 0.286 | 2.4979 | 1 | 0.1140 |
| | Periphery ~ Intraspecific competition | 0.0043 | 0.0959 | -0.1836 | 0.1921 | 0.002 | 1 | 0.9645 |
| | Maximum likelihood estimate | 1.346 | 0.2156 | 0.9835 | 1.8424 | | | |
| BFBL ~ Location*Interspecific competition | Intercept | 4.5899 | 0.1905 | 4.2166 | 4.9632 | 580.7293 | 1 | 0.0000 |
| | Inner section ~ Interspecific competition | -0.0388 | 0.0837 | -0.2028 | 0.1251 | 0.2153 | 1 | 0.6426 |
| | Periphery ~ Interspecific competition | -0.3163 | 0.1011 | -0.5144 | -0.1182 | 9.7906 | 1 | 0.0018 |
| | Maximum likelihood estimate | 1.25 | 0.2002 | 0.9135 | 1.7113 | | | |

## 5.4 DISCUSSION

Our study showed that intra- and interspecific neighbourhood competition influenced growth and quality of oaks in cluster plantings in different ways. It appeared that growth of oaks was most strongly influenced by intraspecific competition in young groups, whereas in older groups interspecific competition from mid- and late-successional species was most important. Whereas intraspecific competition had a significant positive effect on branch free bole length of target oaks in older oak nest and group plantings, a facilitative effect of interspecific interactions on the self-pruning dynamics was not observed.

### 5.4.1 Influence of neighbourhood competition on DBH, height and HD ratio

The magnitude of neighbourhood competition on DBH, height and HD ratio varied among conspecific oaks, pioneer and mid and late- succession trees. This result is consistent with the first hypothesis.

*Intraspecific competition*

Strong intraspecific competition between the closely planted oaks within the nests reduced diameter growth and resulted in more slender trees. The high HD ratios indicate that competition for light became intense and encouraged trees to allocate more of their resources to height growth rather than to diameter growth, in order to maintain their position in the canopy (Waring and Schlesinger, 1985). This result is supported by a recent meta-analysis, which found poor tree stability in densely planted oak nests compared to more widely spaced oak row plantings *(Saha et al.,* 2012). The impact of intraspecific competition on tree growth and stability appeared to be stronger in young groups than in older groups. In the older groups, target trees might have had more time to assert a dominant influence on their immediate neighbourhood and were thus less sensitive to competition from neighbours. However, owing to the lack of replicates for these different ages, this possible “age effect” cannot be ascertained.

When compared to the groups, intraspecific competition in nests was more intense and mortality rates of planted oaks were greater, resulting in fewer trees per cluster over time (Leder, 2007; Guericke *et al.,* 2008; Saha *et al.,* 2012). The resulting continuously high intraspecific competition inside nests strongly affected DBH and stability of target oaks early on, as reported previously from oak spacing experiments (Gaul and Stüber, 1996; Gürth and Velasquez, 1991).

*Interspecific competition*

The DBH of interspecific competitors neither varied between successional groups nor with target oaks, however, magnitude of competitive effects on target oaks varied between successional groups. The negligible influence of pioneer trees on DBH, height and tree stability may have resulted from a lower density of such trees, a lower density of their crowns which permits more light to penetrate (Tonioli *et al.,* 2001; McLeod *et al.,* 2001). In contrast, the mid and late-successional trees (e.g. *Acer pseudoplatanus, Picea abies*) were often more numerous than individuals of pioneer species. In contrast to pioneers, they developed dense crowns and restricted light penetration to the middle and lower part of crowns of target oaks and hence reduced their photosynthetic capacity (Ammer and Dingel, 1997). As a result, the magnitude of the competitive influence from trees of mid- and late-successional species on DBH and height of target oaks in both nest and group plantings was substantially stronger than that of early-successional species. Our results support previous studies on tree interactions in dense and young mixed-species mixture which showed stronger competitive effects of mid- and late-successional trees than of pioneers on oaks (Leder, 1996; Ammer and Dingel, 1997). Although an early tending operation of low intensity had removed some competitors at the periphery of groups in Gerlingen and Lerchenfeld, this may not have had a substantial influence on the overall magnitude of the different sources of competition. First, the tending operations did not target particular species for removal. Secondly, no early tending took place in other sites, where the same results were obtained. Third, regeneration of trees was abundant between the clusters and the canopy was totally closed at the time of field data collection at all sites (Chapter Four).

In young stands, pendunculate and sessile oak can tolerate mild competition from pioneer tree species such as *Betula pendula* or may even benefit from nurse effects such as reduced frost or improved nutrient cycling (Leder, 1996; Rock *et al.,* 2004). However, similar nursing effects on oaks have not been reported for mid- and late-successional tree species. To the contrary, the influence of late-successional tree species such as *Fagus sylvatica*, *Carpinus betulus*, and *Acer pseudoplatanus* on the growth of oaks appears to be mostly negative once these trees are as tall as oaks or overtop them (Olano *et al.,* 2009; von Lüpke, 1998). This is likely attributable to higher light interception and their more aggressive acquisition of growing space when compared to the early-successional species (Pretzsch and Biber, 2010).

### 5.4.2 Influence of neighbourhood competition on branch free bole length

Aggregate neighbourhood competition did not influence branch free bole length of potential future crop trees in the young group planting. In young groups, the canopies had only recently closed and steep-angle branches emerging from the lower stem had not yet been shed. However, intraspecific competition promoted branch free bole length of target oaks in older group and nest plantings. This is in partial agreement with our second hypothesis. Thus, companion oak trees have an important role for the qualitative development of future crop trees within clusters. Our study did not find a facilitative effect of interspecific competition on the quality of target oak trees. Results from a previous study according to which a sufficient number of naturally established trees between oak nests fostered the qualification of oaks could not be verified here (Dong *et al.,* 2007). Why competition from neighbouring trees of mid- and late-successional species affected DBH and height growth without influencing self-pruning dynamics of oaks remains unclear. However it is partly reflected in our results that potential future crop trees in the outer part of clusters, owing to the heterogeneous light conditions prevailing there, have a tendency to retain living branches in lower part of the bole which support the earlier assumption from Leder (2007). Another remaining question, as to whether the function of intraspecific competition on the quality development of cluster oaks in low-density plantings could be be assumed, at least in part, by interspecific competition, can be further evaluated through the analysis addressing the third hypothesis.

### 5.4.3 Influence of within-group position on occurrences of potential future crop trees

The higher probability of the occurrence of potential future crop trees in inner than in outer sections of groups is in agreement with hypothesis three. Trees situated in the inner part of groups experienced mostly intraspecific competition, which has been shown to suffice for the desired crown lift and development of a branch free lower bole (Fischer, 2000, Kuehne *et al.*, 2013). However, this result indicates that quality development is restricted or slowed in oak trees that experience more interspecific than intraspecific competition (outer trees of groups). These trees received less aggregate competition when compared to trees experiencing mostly competition from conspecific oaks, because of low density of naturally regenerated competitors and variation in proportion of pioneer vs. mid and late-successional trees. This suggests that there is little potential to reduce the number of trees in oak groups to replace outer trees with naturally regenerated trees.

## 5.5 CONCLUSION AND MANAGEMENT IMPLICATIONS

This is the first study to provide quantitative support for the assumptions made by early proponents of cluster plantings that owing to the prevalence of intraspecific competition the improvement in stem quality of oak trees is better, or advances faster, in the inner part of group plantings than in the outer circle (Anderson, 1930; Szymanski, 1986; Gockel, 1995). On the one hand, the spatial separation of oaks from pioneers and mid and late-successional trees reduces the impact of interspecific competition. On the other hand, oaks in groups with 1 m² of initial growing space per tree do not only protect each other from interspecific competition but also facilitate self-pruning dynamics and tree quality development. In contrast, very close spacing in nest plantings triggers high intraspecific competition leading to early mortality and hence the disintegration of intra-specific groups.

Additional interspecific competition did not offer advantages to the quality development of oaks but negatively affected height and diameter growth. Vigorous trees of early- and mid-successional species growing inside or in close proximity of groups thus should be removed as part of early stand tending operations. In addition, the practice of planting trainer trees already at the same time as oaks may be questioned, since these mid- to late-successional species (e.g. *Tilia cordata*, *Carpinus betulus*, *Fagus sylvatica*) exerted a strong competitive influence on oaks.

**Appendix 5.1: Influence of competition on DBH, height, stability (HD ratio) and branch free bole length of target oaks grown in clusters (generalized linear model). Model "*a*" represents the overall influence of aggregate neighbourhood competition, whereas, Model *"b"* partitioned that influence into that of oaks (intraspecific) and of pioneer and mid and late-successional tree species (β = slope of model parameters, *S.E.* = standard error in 95% confidence interval, d.f.= degree of freedom).**

| Site | Response variables | Model | Whole model likelihood ratio $\chi^2$ | d.f. | *p* value | Independent variables | Model estimates (β) | Standard error of β | 95% Wald confidence interval | | Wald $\chi^2$ value | d.f. | *p* value |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Lower | Upper | | | |
| **Altenheim (10 year old groups)** | DBH (N=28) | *a* | 13.425 | 1 | 0.0002 | Intercept | 10.6077 | 0.7059 | 9.2242 | 11.9912 | 225.838 | 1 | 0.0000 |
| | | | | | | Aggregate competition | -0.4362 | 0.1051 | -0.6421 | -0.2302 | 17.2259 | 1 | 0.0000 |
| | | | | | | Estimate of maximum likelihood | 1.493 | 0.399 | 0.8843 | 2.5211 | | | |
| | | *b* | 14.4809 | 2 | 0.0007 | Intercept | 10.587 | 0.6968 | 9.2214 | 11.9526 | 230.88 | 1 | 0.0000 |
| | | | | | | Intraspecific | -0.5402 | 0.1408 | -0.8161 | -0.2642 | 14.7153 | 1 | 0.0001 |
| | | | | | | Mid and late-successional | -0.3108 | 0.1611 | -0.6265 | 0.005 | 3.7213 | 1 | 0.0537 |
| | | | | | | Estimate of maximum likelihood | 1.438 | 0.3843 | 0.8516 | 2.4278 | | | |
| | Height (N=28) | *a* | 12.8914 | 1 | 0.0003 | Intercept | 8.989 | 0.2669 | 8.4659 | 9.512 | 1134.58 | 1 | 0.0000 |
| | | | | | | Aggregate competition | -0.1608 | 0.0397 | -0.2386 | -0.0829 | 16.3722 | 1 | 0.0001 |
| | | | | | | Estimate of maximum likelihood | 0.213 | 0.057 | 0.1264 | 0.3603 | | | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *b* | 14.7355 | 2 | 0.0006 | Intercept | 8.978 | 0.2597 | 8.4689 | 9.487 | 1194.77 | 1 | 0.0000 |
| | | | | | Intraspecific | -0.2113 | 0.0525 | -0.3142 | -0.1084 | 16.2035 | 1 | 0.0001 |
| | | | | | Mid and late-successional | -0.0989 | 0.0601 | -0.2166 | 0.0188 | 2.7141 | 1 | 0.0995 |
| | | | | | Estimate of maximum likelihood | 0.2 | 0.0534 | 0.1183 | 0.3374 | | | |
| HD ratio (N=28) | *a* | 12.3586 | 1 | 0.0004 | Intercept | 77.8623 | 7.1885 | 63.7732 | 91.9514 | 117.323 | 1 | 0.0000 |
| | | | | | Aggregate competition | 4.2184 | 1.0702 | 2.1207 | 6.316 | 15.5358 | 1 | 0.0001 |
| | | | | | Estimate of maximum likelihood | 154.851 | 41.3857 | 91.7108 | 261.461 | | | |
| | *b* | 14.5541 | 2 | 0.0007 | Intercept | 78.1893 | 6.9527 | 64.5623 | 91.8164 | 126.469 | 1 | 0.0000 |
| | | | | | Intraspecific | 5.6909 | 1.4051 | 2.9369 | 8.4449 | 16.4036 | 1 | 0.0001 |
| | | | | | Mid and late-successional | 2.4096 | 1.6076 | -0.7413 | 5.5604 | 2.2466 | 1 | 0.1339 |
| | | | | | Estimate of maximum likelihood | 143.173 | 38.2645 | 84.7944 | 241.743 | | | |
| Branch free bole length (N=28) | *a* | 0 | 1 | 0.9993 | Intercept | 3.7032 | 0.4357 | 2.8492 | 4.5572 | 72.2365 | 1 | 0.0000 |
| | | | | | Aggregate competition | 0.0001 | 0.0649 | -0.1271 | 0.1272 | 0 | 1 | 0.9993 |
| | | | | | Estimate of maximum likelihood | 0.569 | 0.152 | 0.3369 | 0.9606 | | | |
| | *b* | 0.0201 | 2 | 0.99 | Intercept | 3.7405 | 0.4381 | 2.8818 | 4.5992 | 72.8896 | 1 | 0.0000 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Intraspecific | 0.0013 | 0.0885 | -0.1722 | 0.1749 | 0.0002 | 1 | 0.9879 |
| | | | | | | Mid and late-successional | -0.0143 | 0.1013 | -0.2129 | 0.1842 | 0.02 | 1 | 0.8875 |
| | | | | | | Estimate of maximum likelihood | 0.569 | 0.1519 | 0.3367 | 0.9599 | | | |
| **Kaisereiche and Larchenfeld ( 20 year old groups)** | DBH (N= 50) | *a* | 3.5248 | 1 | 0.0605 | Intercept | 11.3992 | 0.9568 | 9.5239 | 13.2745 | 141.941 | 1 | 0.0000 |
| | | | | | | Aggregate competition | -0.3788 | 0.1982 | -0.7674 | 0.0097 | 3.652 | 1 | 0.0560 |
| | | | | | | Estimate of maximum likelihood | 7.625 | 1.525 | 5.1524 | 11.2847 | | | |
| | | *b* | 7.5617 | 3 | 0.056 | Intercept | 11.3845 | 0.9589 | 9.5051 | 13.2639 | 140.96 | 1 | 0.0000 |
| | | | | | | Intraspecific | -0.221 | 0.2308 | -0.6733 | 0.2313 | 0.9169 | 1 | 0.3383 |
| | | | | | | Pioneer | -0.5084 | 0.2754 | -1.0482 | 0.0314 | 3.408 | 1 | 0.0649 |
| | | | | | | Mid and late-successional | -1.3278 | 0.5914 | -2.4869 | -0.1686 | 5.0404 | 1 | 0.0248 |
| | | | | | | Estimate of maximum likelihood | 7.034 | 1.4067 | 4.7527 | 10.4094 | | | |
| | Height (N= 50) | *a* | 4.555 | 1 | 0.0328 | Intercept | 11.2143 | 1.2095 | 8.8438 | 13.5849 | 85.9679 | 1 | 0.0000 |
| | | | | | | Aggregate competition | -0.5423 | 0.2479 | -1.0282 | -0.0563 | 4.783 | 1 | 0.0287 |
| | | | | | | Estimate of maximum likelihood | 11.827 | 2.4397 | 7.8938 | 17.7201 | | | |
| | | *b* | 8.7955 | 3 | 0.0321 | Intercept | 11.098 | 1.2096 | 8.7272 | 13.4687 | 84.1828 | 1 | 0.0000 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Intraspecific | -0.3584 | 0.2911 | -0.929 | 0.2121 | 1.5161 | 1 | 0.2182 |
| | | | | | Pioneer | -0.5473 | 0.3474 | -1.2282 | 0.1337 | 2.4813 | 1 | 0.1152 |
| | | | | | Mid and late-successional | -2.0205 | 0.746 | -3.4827 | -0.5583 | 7.335 | 1 | 0.0068 |
| | | | | | Estimate of maximum likelihood | 11.192 | 2.2384 | 7.5626 | 16.5635 | | | |
| HD ratio (N=50) | *a* | 0.1722 | 1 | 0.6782 | Intercept | 83.6767 | 8.323 | 67.3639 | 99.9896 | 101.076 | 1 | 0.0000 |
| | | | | | Aggregate competition | -0.7162 | 1.7244 | -4.096 | 2.6636 | 0.1725 | 1 | 0.6779 |
| | | | | | Estimate of maximum likelihood | 576.988 | 115.3976 | 389.8761 | 853.9 | | | |
| | *b* | 3.7624 | 3 | 0.2883 | Intercept | 83.713 | 8.3786 | 67.2913 | 100.135 | 99.8265 | 1 | 0.0000 |
| | | | | | Intraspecific | 0.5209 | 2.0165 | -3.4314 | 4.4733 | 0.0667 | 1 | 0.7961 |
| | | | | | Pioneer | -1.6794 | 2.4061 | -6.3953 | 3.0365 | 0.4872 | 1 | 0.4852 |
| | | | | | Mid and late-successional | -8.6848 | 5.1676 | -18.8131 | 1.4435 | 2.8245 | 1 | 0.0928 |
| | | | | | Estimate of maximum likelihood | 537.01 | 107.4021 | 362.8627 | 794.736 | | | |
| Branch free bole length (N= 50) | *a* | 1.7125 | 1 | 0.1907 | Intercept | 4.0923 | 0.4305 | 3.2485 | 4.936 | 90.3558 | 1 | 0.0000 |
| | | | | | Aggregate competition | 0.1177 | 0.0892 | -0.0571 | 0.2926 | 1.7421 | 1 | 0.1869 |
| | | | | | Estimate of maximum likelihood | 1.544 | 0.3087 | 1.0431 | 2.2846 | | | |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *b* | 3.0718 | 3 | 0.3807 | Intercept | 3.9879 | 0.4347 | 3.136 | 4.8399 | 84.1746 | 1 | 0.0000 |
| | | | | | | Intraspecific | 0.1861 | 0.1056 | -0.0209 | 0.3931 | 3.1041 | 1 | 0.0781 |
| | | | | | | Pioneer | 0.0851 | 0.2704 | -0.4448 | 0.6151 | 0.0991 | 1 | 0.7529 |
| | | | | | | Mid and late-successional | 0.0189 | 0.1258 | -0.2277 | 0.2654 | 0.0226 | 1 | 0.8806 |
| | | | | | | Estimate of maximum likelihood | 1.502 | 0.3005 | 1.0151 | 2.2233 | | | |
| **Gerlingen, Gerscheim, Koenigheim, Leonberg ( 22 - 26 year old nests)** | DBH (N=168) | *a* | 16.9281 | 1 | 0 | Intercept | 13.1201 | 0.4838 | 12.1719 | 14.0683 | 735.479 | 1 | 0.0000 |
| | | | | | | Aggregate competition | -0.2329 | 0.0552 | -0.3411 | -0.1247 | 17.8103 | 1 | 0.0000 |
| | | | | | | Estimate of maximum likelihood | 14.014 | 1.5291 | 11.3159 | 17.3555 | | | |
| | | *b* | 18.4283 | 3 | 0.0004 | Intercept | 13.1187 | 0.4812 | 12.1756 | 14.0618 | 743.292 | 1 | 0.0000 |
| | | | | | | Intraspecific | -0.2128 | 0.0586 | -0.3277 | -0.0979 | 13.1728 | 1 | 0.0003 |
| | | | | | | Pioneer | -0.185 | 0.2029 | -0.5826 | 0.2127 | 0.8311 | 1 | 0.3620 |
| | | | | | | Mid and late-successional | -0.4544 | 0.1745 | -0.7963 | -0.1124 | 6.7817 | 1 | 0.0092 |
| | | | | | | Estimate of maximum likelihood | 13.889 | 1.5155 | 11.2153 | 17.2012 | | | |
| | Height (N=168) | *a* | 0.6801 | 1 | 0.4095 | Intercept | 10.9927 | 0.323 | 10.3596 | 11.6258 | 1158.13 | 1 | 0.0000 |
| | | | | | | Aggregate competition | -0.0304 | 0.0368 | -0.1026 | 0.0418 | 0.6815 | 1 | 0.4091 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Estimate of maximum likelihood | 6.248 | 0.6817 | 5.0448 | 7.7373 | | | |
| | *b* | 2.4861 | 3 | 0.4778 | Intercept | 10.9984 | 0.321 | 10.3693 | 11.6276 | 1174.02 | 1 | 0.0000 |
| | | | | | Intraspecific | -0.0177 | 0.0391 | -0.0944 | 0.0589 | 0.2052 | 1 | 0.6506 |
| | | | | | Pioneer | 0.0078 | 0.1353 | -0.2575 | 0.273 | 0.0033 | 1 | 0.9542 |
| | | | | | Mid and late-successional | -0.1791 | 0.1164 | -0.4073 | 0.049 | 2.369 | 1 | 0.1238 |
| | | | | | Estimate of maximum likelihood | 6.181 | 0.6744 | 4.9908 | 7.6545 | | | |
| HD ratio (N=168) | *a* | 18.9321 | 1 | 0 | Intercept | 90.1755 | 2.6308 | 85.0193 | 95.3317 | 1174.94 | 1 | 0.0000 |
| | | | | | Aggregate competition | 1.3434 | 0.3001 | 0.7553 | 1.9316 | 20.0401 | 1 | 0.0000 |
| | | | | | Estimate of maximum likelihood | 414.402 | 45.215 | 334.6174 | 513.211 | | | |
| | *b* | 20.0996 | 3 | 0.0002 | Intercept | 90.2454 | 2.6192 | 85.1118 | 95.3789 | 1187.15 | 1 | 0.0000 |
| | | | | | Intraspecific | 1.229 | 0.3192 | 0.6034 | 1.8545 | 14.8263 | 1 | 0.0001 |
| | | | | | Pioneer | 1.0561 | 1.1043 | -1.1083 | 3.2205 | 0.9146 | 1 | 0.3389 |
| | | | | | Mid and late-successional | 2.5192 | 0.9497 | 0.6577 | 4.3806 | 7.0358 | 1 | 0.0080 |
| | | | | | Estimate of maximum likelihood | 411.533 | 44.9019 | 332.3001 | 509.657 | | | |
| Branch free bole length (N=162) | *a* | 12.7804 | 1 | 0.0004 | Intercept | 3.3074 | 0.1974 | 2.9205 | 3.6942 | 280.787 | 1 | 0.0000 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Aggregate competition | 0.0807 | 0.0221 | 0.0373 | 0.1241 | 13.298 | 1 | 0.0003 |
| | | | | Estimate of maximum likelihood | 2.147 | 0.2386 | 1.727 | 2.6696 | | | |
| *b* | 13.1174 | 3 | 0.0044 | Intercept | 3.3061 | 0.197 | 2.9201 | 3.6921 | 281.772 | 1 | 0.0000 |
| | | | | Intraspecific | 0.0844 | 0.0236 | 0.0382 | 0.1306 | 12.8389 | 1 | 0.0003 |
| | | | | Pioneer | 0.0413 | 0.0798 | -0.1151 | 0.1977 | 0.2682 | 1 | 0.6045 |
| | | | | Mid and late-successional | 0.076 | 0.069 | -0.0592 | 0.2111 | 1.2126 | 1 | 0.2708 |
| | | | | Estimate of maximum likelihood | 2.143 | 0.2381 | 1.7234 | 2.6641 | | | |

# CHAPTER SIX: SYNTHESIS

***High quality birch (Betula pendula) trees growing between groups in 20-year-old stand in Kaisereiche, Hessen.***

This chapter summarizes the key findings of the thesis and discusses implications for the use of cluster planting methods as regeneration technique for establishment of oak stands. It also explores future research directions and provides final conclusions.

## 6.1 SUMMARY OF RESULTS

The concept of cluster planting was seemingly independently developed in Russia and Great Britain at the beginning of the last century and that renewed interest in this regeneration technique in the 1980s was mainly triggered by large-scale forest disturbances of not site-adapted conifer monocultures resulting from severe storm events (Chapter Two). The majority of published case studies on oak cluster plantings reported contradictory findings on oak growth and quality development, emphasizing the need for a comprehensive research effort in a meta-analytical framework combining multiple trials for the evaluation of the general suitability of oak cluster plantings as a method for oak stand establishment. Limited initial growing space for individual oaks, browsing pressure and competition from naturally regenerated woody plants were most commonly discussed as factors causing low survival and poor growth in nest plantings. Conversely, larger initial growing space and presence of trainer trees were assumed to have a positive effect on growth and quality of oaks grown in group plantings. Based on the outcome of the review I selected moderators or independent variables, namely planting type, presence of fencing and density of trainer trees, which were later used in the meta-analysis. Additionally, the reviewing process highlighted the knowledge gap in relation to the potential of natural tree regeneration in the interspaces between the clusters and its influence on the oaks in clusters.

The meta-analysis demonstrated that survival rate, diameter and height growth and individual tree stability of oaks planted in groups did not differ significantly from traditional row plantings (Chapter Three). In contrast, all investigated growth parameters with the exception of tree height were significantly lower in nest plantings when compared to their row planting counterparts. Oak survival in group plantings was positively influenced by a high number of initially planted trainer trees. Fencing positively influenced survival as well as diameter and height growth in nest plantings.

The comparison of oak group and row plantings revealed a better performance of the groups with regard to the development of desirable crown types and no differences in relation to the quality parameters stem form, branch free bole length and percentage of potential future crop trees. A high number of initial trainer trees significantly increased the percentage of stem and crown types indicating good tree quality as well as the proportion of potential future crop trees. In nest plantings, however, branch free bole length and the percentage of potential crop trees were significantly lower when compared to row plantings.

Tree species richness was significantly higher in nest and group plantings than in row plantings (see Chapter Four). Basal area of naturally regenerated trees was also significantly higher in groups than row plantings and a similar trend was found in nest and row planting pairs. Naturally regenerated species contributed to 43% of total stand basal area in cluster plantings. Density and richness of other (non-oak) tree species increased significantly with the area available for natural regeneration. Total stand basal area which combined naturally regenerated and planted trees, therefore did not differ between stands established through cluster or row planting. Density of naturally regenerated trees was the most important factor for stand basal area in cluster plantings.

Diameter and height growth of target oak trees grown in older group plantings were strongly negatively influenced by competition from mid-successional trees (Chapter Five). In contrast, intraspecific competition alone did not affect height and DBH of target oaks in these group planting trials. Both intraspecific and interspecific competition significantly affected oak DBH in nest plantings, whereas, tree height was neither affected by intraspecific nor interspecific competition.

a

b

**Fig. 6.1: Natural regeneration of (a) *Sorbus aucuparia* between the groups in Kaisereiche; (b) *Betula pendula* and legacies of old stands such as dead wood and stumps between nests in Leonberg.**

Intraspecific competition promoted branch free bole length in older group plantings as well as in the nest planting stands. As a result, the vast majority of investigated groups had at least one potential future crop tree with the majority of these located in the interior of clusters. This finding was further corroborated by logistic regression analysis revealing that the probability of the occurrence of potential future crop trees was significantly higher in inner parts when compared to the periphery of the groups.

## 6.2 DISCUSSION AND MANAGEMENT IMPLICATIONS

### 6.2.1 Survival, growth and quality of oaks grown in cluster plantings

With an initial growing space of 1 $m^2$ for each oak seedling, group plantings showed high oak survival rates, whereas in nest plantings, with an initial growing space of 0.04 $m^2$ per seedling, high morality of planted oaks was observed. Very close initial spacing will have triggered an early onset of shading induced asymmetric competition and self-thinning among oaks nest. Similar phenomena have been reported for other young and dense broadleaved stands (Henriksson, 2001; Kint *et al.*, 2010). In addition, results from previous spacing experiments also indicated that initial growing space of at least 1.3 $m^2$ is required to achieve survival rates of at least 80% in planted oak stands after ca. 20 year (Gaul and Stüber, 1996). The superior survival rate observed in the group plantings might be also partially attributable to the taller saplings used which likely resulted in reduced competition from ground vegetation and less severe deer browsing of terminal buds and shoots (Dey and Parker, 1997; Petersen, 2007).

Poor diameter growth and inferior individual tree stability in nest plantings (Chapter Three) can also be attributed to the intense initial intra-specific competition. This was supported by the results described in Chapter Five which showed intraspecific competition significantly lowered DBH of oaks grown in nests. The findings are consistent with results from past studies, which also indicated high mortality, restricted diameter growth and low stability in nests as described in Chapter 2 (Weinreich and Grulke, 2001; Guericke *et al.*, 2008).

In contrast to the nest planting method, the fundamental design of the group plantings promoted oak diameter and height growth which did not differ from row plantings (see Chapter Three and Five). Past studies showed that an initial growing space of 1 to 1.5 $m^2$ per seedling reduces the impact of intraspecific competition on oak growth and promotes tree quality (Spellmann and Baderschneider, 1988; Schmaltz *et al.*, 1997). This is reflected in results derived from the older stands established through group planting analysed in Chapter Five, where intraspecific competition did not influence growth but promoted quality development. Nurse tree effects from early successional species such as *Betula pendula* and competition from naturally regenerated trees of mid-successional species might have promoted survival and tree qualification, in the group planting trials, respectively (Leder, 1992; Leder, 1996; Rock *et al.*, 2004). However, individuals of fast growing tree species may quickly overtop the oaks in groups resulting increased asymmetric competition for light and eventually hamper oak growth (von Lüpke, 1991, 1998, 2008). Because of the high abundance of good quality oaks found in the interior of the groups, dominant early- and mid-successional competitors on the periphery of groups should therefore be removed during pre-commercial tending operations to foster growth and qualification of potential future crop trees in a prolonged time period of intraspecific competition.

Very close initial spacing can force oaks to deviate from their perpendicular stem axis and to develop crooked stems (Leibundgut, 1976; Nagel and Rumpf, 2010). The tendency to grow towards the light in openings and at edges whenever oak trees are overtopped likely resulted in the dominance of poor stem forms and crown shapes in nest plantings. In addition, the most vigorous oaks in nest were usually found at the perimeter of clusters, where they had often developed one-sided crowns in response to a lack of competing neighbours (Leder, 2007; Guericke *et al.*, 2008). This resulted in brushy crown types and inhibited self-pruning dynamics (Fig 6.2). High quality oaks therefore were rare in nest planting stands, as reflected by the significantly lower percentage of potential future crop trees (Chapter Three). It can be concluded that intraspecific competition in nest plantings is initially very high (Chapter Five) but the accelerated self-thinning within individual nests within in stand matrix where competitors in the surrounding of nests may be absent or not as effective as other oaks retards tree qualification processes (Leder, 2007; Guericke *et al.*, 2008). The effects interspecific competition from other species differs from those of intraspecific competition on quality development of oaks (Chapter Five). Hence, the early loss of oak neighbours in nests creates less favourable conditions for the rise of the green crown and concomitant self-pruning.

a b

**Fig.6.2: Crooked stems (a) and one-sided crown development (b) in oaks grown in nests.**

In contrast, trees with straight stems and monopodial crowns were much more frequent in more widely spaced group plantings (Chapter Three). The wider spacing between oaks within the groups assured the preservation of the initial planting pattern over the first few decades of stand development and therefore fostered the quality development of stems in the oak trees through mostly intraspecific interactions. The importance of the initial group pattern was reflected in a finding of Chapter Five showing that the majority of potential future crop trees were found in the interior part of groups. Oaks in the perimeter of groups should thus be maintained and promoted until qualification of the future crop trees is accomplished and mid-story shade-tolerant trainer trees can fulfil the trainer function (Fig. 6.3).

The findings of this study regarding the function and effects of trainer trees surrounding oak groups appear at first sight not consistent and require further discussion. The meta-analysis suggested that these trainer trees likely protected the inner oaks in groups and that their competition was beneficial for quality development. The positive effect of increasing initial numbers of trainer trees per group on survival rate, stem form and percentage of potential future crop trees reported in Chapter Three appears to prove that protective function. Trainer trees might have suppressed other vegetation such as black berries and the establishment of more competitive tree species (Rock *et al.*, 2004). However, both the meta-analysis and the competition study revealed no effect of trainer and mid-successional trees on the length of the branch free bole of oaks grown in groups. It was rather found that in young oak stands (10 – 26 year old) and irrespective of cluster or row planting, self-pruning of oaks triggered by intraspecific competition would suffice for tree quality development. It can therefore be concluded that the observed positive effect of trainer trees in group plantings (Chapter Three) was not a species-specific influence but rather a facilitative effect of the presence of additional trees. In addition, as stands become older, these trainer trees developed into strong competitors for the oaks (Chapter Five). Thus they should be constantly monitored and possibly removed or preferably pollarded or coppiced, if they overgrow the oaks in cluster.

Based on the findings of this thesis it can be concluded that the group planting method can be regarded as a suitable alternative to traditional row planting for artificial regeneration of oak forests. The nest planting technique, however, does not provide a similar establishment success and offers fewer silvicultural options with regard to the production of quality oak timber.

### 6.2.2 Tree species diversity and stand productivity in cluster planting

On average, almost two thirds of the ground area in stands established through low-density cluster planting remains for natural regeneration. The establishment of early- and mid-successional tree and shrub species in the interspaces between clusters has been found to be often prolific in formerly forested sites that are surrounded by remaining forests (Chapter Four). Several studies in Central European forests have proven that diverse tree communities comprising mostly early-successional woody species can establish in extensively treated or unmanaged clear-felled and wind-thrown areas (Wohlgemuth *et al.*, 2002; Jonasova *et al.*, 2010). The establishment of naturally regenerated tree and shrub species significantly increased species diversity in cluster plantings when compared to row planting counterparts. Whether more species and individuals were found in cluster plantings than in row plantings because of a more numerous and richer seedling bank in less disturbed cluster sites, could not be ascertained in this study. However, based on the findings of this thesis it can be clearly stated that 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. The observed dynamics might change or at least be retarded in cluster afforestations on abandoned agricultural land, where fewer tree propagules are available or site conditions such as vigorous ground vegetation inhibit the establishment of woody plants. However, there is so far only 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 the total stand basal area in cluster plantings and could compensate for the reduced number of oaks in group plantings. Spatial separation between planted oaks and naturally regenerated trees might lead to efficient use of light and below ground niche separation for water and nutrient use.

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 *et al.* 2010). However, prevailing selection systems aiming to maintain continuous crown cover prohibit the regeneration of these early-successional tree species. Furthermore, growth of commercially important species (e.g. oaks) may be hampered by these fast growing species, thus they are usually removed as part of early stand tending in traditionally managed stands. Group planting offers an opportunity to solve these problems 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 varying management priorities of forest owners.

Some forest practitioners argue that the diversification of forest stands may complicate future management because of complex interactions between multiple species (Kerr, 1999). However, in group planting managers only need to focus on potential future crop trees emerging from each group. Tending operations to remove naturally regenerated competitors can focus on the periphery of clusters (Chapter Five). The remaining vegetation between the groups therefore could be maintained and managed for the promotion of biodiversity, the production of biomass or high value veneer logs from species like *Betula pendula* or *Acer pseudoplatanus* (Fig. 6.3.)

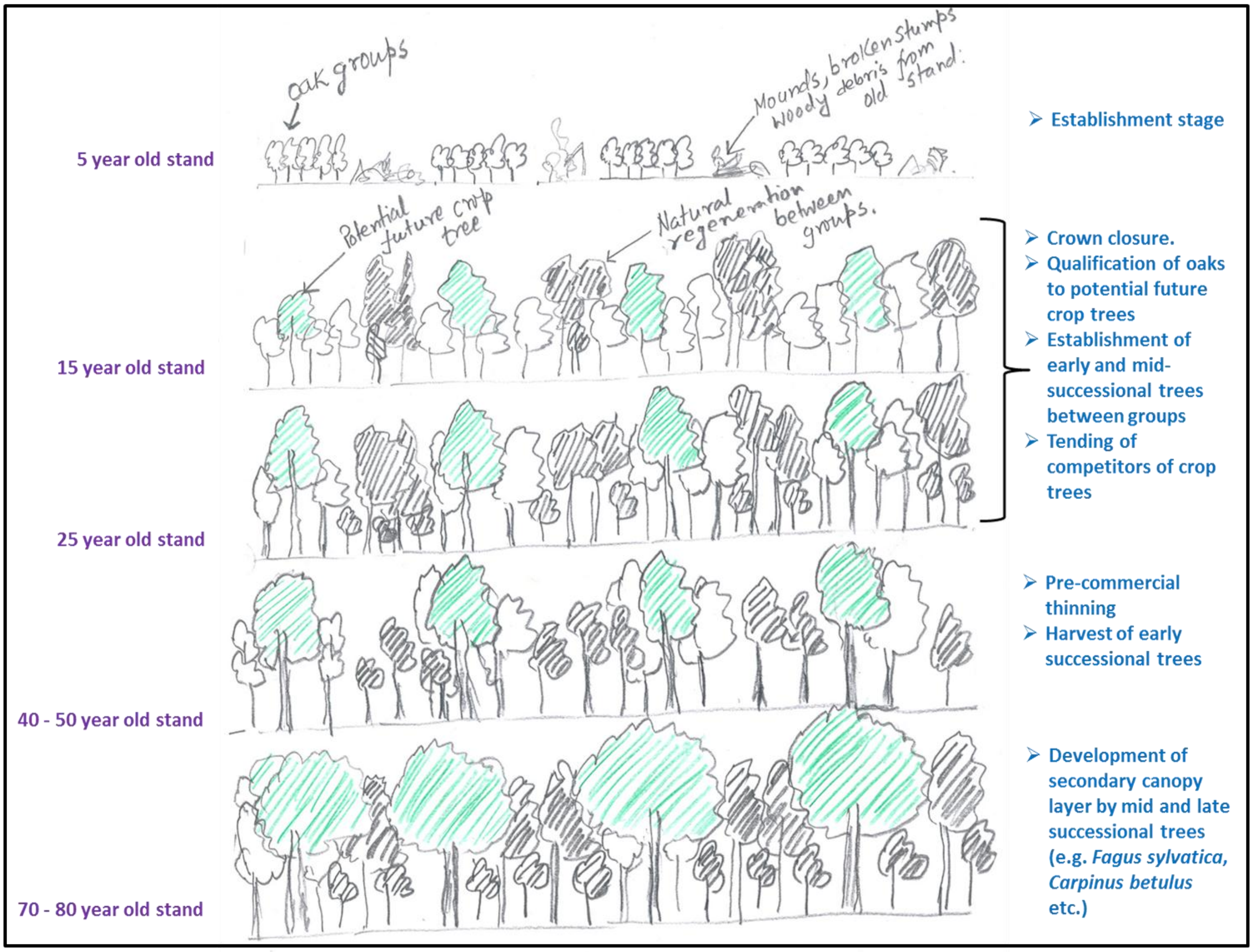


**Fig.6.3: Possible development of structure in oak stands established through group planting.**

## 6.3 RISKS AND BENEFITS OF GROUP PLANTING – AN OUTLOOK

Every economic system needs defined targets for success. However, inherent potential risks may hamper the achievement of those targets, in particular in natural systems that are not under strict human control. Potential future crop trees (see definition in *Tree Quality* section in Chapter Two) are such targets in oak stands managed for high value timber production (Abetz and Kladtke, 2002). How many future crop tree ha$^{-1}$ are needed after the first pre-commercial thinning, which commonly takes place in 40 - 50 year old stands, is a matter of ongoing debate. Whereas the aim may be to obtain between 60 - 100 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 development of potential future crop trees after first pre-commercial thinning in oak stand 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, 1990). However, this is sometime seen as failures during early selection, promotion, tending and thinning 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 as many future oak crop trees left as there were clusters. That is in case that one future crop tree develops from each cluster. Thus, 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 outcome of stand management. Unfortunately, there are no figures on the mortality of future crop trees from cluster-plantings, since the trials have not yet reached the age of first commercial thinning. However, in a situation with fewer future oak crop trees than were aimed for the potential of naturally regenerated trees between the groups may be crucial to compensate for losses in oak crop trees.

It is clear that the solution to the potential risk of losing future crop trees that have emerged from clusters cannot simply be an increase in the number of clusters. On the one side, this would partially diminish the benefits regarding cost saving through planting fewer trees and the increased tree species diversity. On the other side, an increased number of clusters would lead to spacing of future crop trees that would eventually be too narrow in sections of the stands, where no losses of crop trees occur. The above mentioned risk of low numbers of potential future crop trees may also be compensated by increasing the distance between the groups and planting of fast growing valuable broadleaves or conifers (e.g. *Prunus avium, Pseudotsuga menziesii*) between groups. This can be an attractive option for forest owners interested to develop mixed forests and to obtain financial returns earlier from these stands. I had spoken to several foresters in Baden-Württemberg and Lower Saxony who think 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. *Poplus tremula* and *Betula pendula*) can be produced from cluster planting stands in shorter periods. However, these perspectives have not been scrutinized through economic modeling.

## 6.4 GROUP PLANTING WITH OTHER SPECIES

This study focused on low-density planting 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 those species (e.g. *Acer pseudoplatanus, Prunus avium*) which need early selection in young stands to enhance qualification process by self-pruning of lower trunk by intraspecific competition. In addition, this technique can be opted when uniform distribution of potential future crop trees in stand is a management goal for developing a dominated cohort of target tree species.

Further, the technique may be recommended to restore abandoned agricultural lands. Because afforestation in abandoned agricultural land with tree species such as oaks, which need close initial spacing for quality development should not be done in large spacing. However, planting in groups not only suffice initial growing space criteria for such species but also reduce cost which is an important factor for afforestation in abandoned agricultural land. Budgetary concerns often delay afforestation programs in such lands. Some abandoned agricultural lands had already been successfully restored in Germany (Ehring and Keller, 2006; Petersen, 2007). Large afforestation programs (e.g. bottomland afforestation program in Eastern Mississippi, USA) often have a shortage of funds and are thus forced to plant in 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). Here, group plantings can offer savings in planting cost while minimising reductions in tree quality development on a sufficient number of trees. Cluster planting can also be used for restoration of degraded open lands. A similar kind of low density cluster planting design (*"woodland islets"*) was successfully used for afforestation purposes in degraded land in Spain (Benayas *et al.*, 2008).

## 6.5. USE OF META-ANALYSIS IN RESEARCH SYNTHESIS IN SILVICULTURE

My thesis showed for the first time that meta-analysis can be effectively used for synthesizing original inventory data of multiple silvicultural trials (Chapter Three). Combining data from various and often contradictory studies on cluster plantings in a meta-analytic framework improved the overall understanding of this silvicultural technique and through identifying clear, general trends. Motivated by the success of this study, I encourage researcher in the field of experimental silviculture to establish research networks that apply common study designs, develop meta-data bases and perform meta-analyses for research syntheses.

## 6.6 CONCLUSION

Based on the results presented in this thesis and their interpretation, I would recommend foresters not to pursue the nest planting technique for oak stand establishment. In contrast, oak group planting 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 also the natural regeneration of mostly early-successional tree and shrub species in the interspaces of the groups increases woody species diversity and stand productivity and allows forest managers to establish natural processes and functions bound to early-successional stand development phases. Planting trainer trees should be continued in group plantings because of their protective and facilitative function on oak tree development in the stand establishment phase. However, at later stand development stages trainer trees should be monitored carefully and must be removed or pollarded, if the growth of potential future crop trees is interfered. Naturally regenerated competitors should also be removed in the periphery of the groups to preserve the initial cluster design and to foster intraspecific competition driven oak tree qualification. Future research should focus on comprehensive cost-benefit analysis and the modelling of the growth dynamics of group planting stands.

# REFERENCES


Abetz, P., 1980. Zum Konzept einer Z-Baum-orientierten Kontrollmethode. Allgemeine Forst- und Jagdzeitung 151, 65-58.

Abetz, P., Kladtke, J., 2002. The target tree management system. Forstwiss. Cent.bl. 121, 73-82.

Abetz, P., Ohnemus, K., 1999. Varification of the future-crop-tree-norms (ZB-norm) for beech in a thinning experiment. Allg. Forst Jagdztg. 170, 157-165.

Adams, D.C., Gurevitch, J., Rosenberg, M.S., 1997. Resampling tests for meta-analysis of ecological data. Ecology 78, 1277-1283.

Agardh, E., Allebeck, P., Hallqvist, J., Moradi, T., Sidorchuk, A., 2011. Type 2 diabetes incidence and socio-economic position: a systematic review and meta-analysis. Int. J. Epidemiol. 40, 804-818.

Albrecht, A., Hanewinkel, M., Bauhus, J., Kohnle, U., 2010. How does silviculture affect storm damage in forests of south-western Germany? Results from empirical modeling based on long-term observations. Eur. J. For. Res., 1-19.

Ammer, C., Dingel, C., 1997. Investigating the effects of strong competition by inferior tree species on growth and quality of young European oaks. Forstwiss. Cent.bl. 116, 346-358.

Ammer, C., Ziegler, C., Knoke, T., 2005. Assessing intra- and interspecfic competition in thickets of broadleaved tree species. Allg. Forst Jagdztg. 176, 85-94.

Anderson, M.L., 1930. A New System of Planting. Scottish Forestry Journal 44(2), 78-89.

Anderson, M.L., 1951. Spaced group-planting and irregularity of stand-structure. Empire Forestry Journal 30, 328 - 341.

Bauhus, J., Schemerbeck, J., 2012. Silvicultural options to enhance and use forest plantation biodiversity. In: Bauhus, J., van der Meer, P., Kanninen, M. (Eds.), Ecosystem Goods and Services from Plantation Forests. Earthscan London, pp. 96-139.

Benayas, J.M.R., Bullock, J.M., Newton, A.C., 2008. Creating woodland islets to reconcile ecological restoration, conservation, and agricultural land use. Front. Ecol. Environ. 6, 329-336.

BMELV, 2002. Bundeswaldinventur. In: Polley, H. (Ed.). Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz.

Bodrov, V.A., 1956. The prospects of raising Oak by the nest method. [Russian]. Agrobiologija (Agrobiology). 5, 142-144.

Bolte, A., Ammer, C., Lof, M., Madsen, P., Nabuurs, G.J., Schall, P., Spathelf, P., Rock, J., 2009. Adaptive forest management in central Europe: Climate change impacts, strategies and integrative concept. Scand. J. Forest Res. 24, 473-482.

Brang, P., 2009. Forschungsprojekt "Extensive Verjüngungsverfahren nach Lothar" Versuchsflächen in der Schweiz. In, WSL, Birmensdorf, http://www.wsl.ch/projects/extverj/plots/buel-de.ehtml, accessed on 27.04.2012.

Buchholz, A., 1949. Neue Strömungen in der sowjetischen Waldwirtschaft. Zeitschrift für Weltforstwirtschaft 13, 131-139.

Burschel, P., Huss, J., 1997. Grundriss des Waldbaus: ein Leitfaden für Studium und Praxis. Parey, Berlin.

Ceitel, J., Szymanski, S., 1975. Biological and economic effectiveness of methods of nest planting for the establishment of Oak in mixed plantations. [Polish]. Prace Komisji Nauk Rolniczych i Komisji Nauk Lesnych. 40, 3-19.

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogee, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, C., Carrara, A., Chevallier, F., De Noblet, N., Friend, A.D., Friedlingstein, P., Grunwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J.M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J.F., Sanz, M.J., Schulze, E.D., Vesala, T., Valentini, R., 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437, 529-533.

Claudet, J., Osenberg, C.W., Domenici, P., Badalamenti, F., Milazzo, M., Falcon, J.M., Bertocci, I., Benedetti-Cecchi, L., Garcia-Charton, J.A., Goni, R., Borg, J.A., Forcada, A., de Lucia, G.A., Perez-Ruzafa, A., Afonso, P., Brito, A., Guala, I., Le Direach, L., Sanchez-Jerez, P., Somerfield, P.J., Planes, S., 2010a. Marine reserves: Fish life history and ecological traits matter. Ecol. Appl. 20, 830-839.

Claudet, J., Fraschetti, S., 2010b. Human-driven impacts on marine habitats: A regional meta-analysis in the Mediterranean Sea. Biol. Conserv. 143, 2195-2206.

Demolis, C., François, D., Delannoy, L., 1997. Que sont devenues les plantations de feuillus par points d'appui? Office National des Forêts, Bulletin Technique, 27-37.

Dey, D.C., Gardiner, E.S., Kabrick, J.M., Stanturf, J.A., Jacobs, D.F., 2010. Innovations in afforestation of agricultural bottomlands to restore native forests in the eastern USA. Scand. J. Forest Res. 25, 31-42.

Dey, D.C., Parker, W.C., 1997. Morphological indicators of stock quality and field performance of red oak (Quercus rubra L.) seedlings underplanted in a central Ontario shelterwood. New For. 14, 145-156.

Diaci, J., 2006. Nature-based forestry in Central Europe: alternatives to industrial forestry and strict preservation. Studia Forestalia Slovenica 126.

Dong P.H., Eder W, Muth M, 2007a. Eichen-Nesterpflanzungsversuche in Rheinland-Pflaz - Ergebnisse eines 15jährigen Beobachtungszeitraums. In, Eiche im Pfälzerwald. Forsschunganstalt für Waldökologie und Forstwirtschaft Rheinland-Pflaz, Trippstadt, pp. 4-22.

Dong P.H., Eder W, Muth M, 2007b. Traubeneichen-Läuterungsversuche im Pfälzerwald. In: P.H., D. (Ed.), Eiche im Pfälzerwald. Mitteilungen aus der Forschungsanstalt für Waldökologie und Forstwirtschaft Rheinland-Pfalz Forschungsanstalt für Waldökologie und Forstwirtschaft Rheinland-Pfalz, Trippstadt, pp. 57-77.

Donis, C., 1956. Closed forest of the [Belgian] Congo and the present position of its silviculture. [French]. Bull. agric. Congo belge. 47, 261-320.

Drouineau, S., Laroussinie, O., Yves Birot, Terrasson, D., Formery, T., Roman-Amat, B., 2000. Joint Evaluation of Storms, Forest Vulnerability and their Restoration. Discussion paper 9. European Forest Institute, Joensuu, Finland.

Dubravac, T., 2002. Regularity of growth of crown structures of peduncled oak and common hornbeam depending on DBH and age in Carpino betuli-Quercetum roboris Anic et Raus 1969 community. In, College of Forestry. Zagreb University, Zagreb, p. 196.

Dubravac, T., 2003. Developmental dynamics of crown diameters in peduncled oak and common hornbeam related to diameter brest height and age (Croatian). Rad. Sumar. inst. 38, 35-54.

Ehring, A., Keller, O., 2006. Eichen-Trupp-Pflanzung in Baden-Württemberg. AFZ/Der Wald 9, 491-494.

Erskine, P.D., Lamb, D., Bristow, M., 2006. Tree species diversity and ecosystem function: Can tropical multi-species plantations generate greater productivity? For. Ecol. Manage. 233, 205-210.

Fischer, A., Lindner, M., Abs, C., Lasch, P., 2002. Vegetation dynamics in central European forest ecosystems (near-natural as well as managed) after storm events. Folia Geobot. 37, 17-32.

Fischer, H., 2000. Quality improvement of young sessile oak (*Quercus petraea* Liebl.) exclusively due to intraspecific competition. [German]. Forst und Holz. 55 (12), 377-382.

Fleiss, J.L., 1981. Statistical methods for rates and proportions, Second Edition. John Wiley & Sons, New York, New York

Frischbier, N., Profft, I., Arenhövel, W., 2010. Die Ausweisung klimawandelangepasster Bestandeszieltypen für Thüringen (Thuringian tree species recommendations for adaptation to climate change). Forst und Holz 65, 28 - 35.

Gauer, J., Aldinger, E., 2005. Mitteilungen des Vereins für Forstliche Standortskunde und Forstpflanzenzüchtung, Freiburg i. Br.

Gaul, T., Stüber, V., 1996. Der Eichen-Nelder-Verbandsversuch Göhrde [The Oak-Nelder-Experiment Göhrde]. Forst und Holz 51, 70-75.

Gockel, H., 1994. Soziale und qualitative Entwicklungen sowie Z-Baumhäufigkeiten in Eichenjungbeständen. Die Entwicklung eines neuen Pflanzschemas „Die Truppflanzung“. In, Forstwiss. Fachbereich. Georg-August-Universität Göttingen, Göttingen, p. 168.

Gockel, H., 1995. Die Trupp-Pflanzung, Ein neues Pflanzschema zur Begründung von Eichenbeständen. Forst und Holz 50, 570 - 575.

Gockel, H., Rock, J., Schulte, A., 2001. Aufforsten mit Eichen-Truppflanzungen. AFZ/Der Wald 5, 223-226.

Gomez-Aparicio, L., Zamora, R., Gomez, J.M., Hodar, J.A., Castro, J., Baraza, E., 2004. Applying plant facilitation to forest restoration: A meta-analysis of the use of shrubs as nurse plants. Ecol. Appl. 14, 1128-1138.

Gotelli, N.J., Colwell, R.K., 2001. Quantifying biodiversity: procedures and pitfalls in the measurement and comparison of species richness. Ecol. Lett. 4, 379-391.

Gotmark, F.G., Berglund, A., Wiklander, K., 2005. Browsing damage on broadleaved trees in semi-natural temperate forest in Sweden, with a focus on oak regeneration. Scand. J. Forest Res. 20, 223-234.

Greenland, S., 1987. Quantitative methods in the review of epidemiologic literature. Epidemiol. Rev. 9, 1-30.

Guericke, M., 1996. Versuche zur Begründung von Eichenbeständen durch Nesterpflanzung. Forst und Holz 51, 577-583.

Guericke, M., Petersen, R., Blanke, S., 2008. Wachstum und Qualität von Eichennestern in Nordwestdeutschland. Forst und Holz 63, 58-63.

Gurevitch, J., Curtis, P.S., Jones, M.H., 2001. Meta-analysis in ecology. In, Advances in Ecological Research, Vol 32. Academic Press Ltd, London, pp. 199-247.

Gurevitch, J., Hedges, L.V., 1993. Meta-analysis: combining the results of independent studies in experimental ecology. In: Scheiner, S., Gurevitch, J. (Eds.), Design and analysis of ecological experiments. Chapman & Hall, New York, New York, pp. 378-398.

Gurevitch, J., Hedges, L.V., 1999. Statistical issues in ecological meta-analyses. Ecology 80, 1142-1149.

Gürth, P., Velasquez, C., 1991. Qualitätsuntersuchungen an Eichenjungbeständen im Markgräflerland. Forst und Holz 46, 671-677.

Gussone, H., Richter, A., 1994. Eichen-Nester – Zweiter Bericht der Versuche mit Nesterpflanzungen in Norddeutschland. Forst- und Holzwirt 49, 300-304.

Hanewinkel, M., Breidenbach, J., Neeff, T., Kublin, E., 2008. Seventy-seven years of natural disturbances in a mountain forest area - the influence of storm, snow, and insect damage analysed with a long-term time series. Can. J. For. Res.-Rev. Can. Rech. For. 38, 2249-2261.

Hanewinkel, M., Hummel, S., Albrecht, A., 2010. Assessing natural hazards in forestry for risk management: a review. Eur. J. For. Res. 130, 329-351.

Harari, O., 2007. Truppflanzungs-Experimente mit Stieleiche und Bergahorn in der Schweiz. Ergebnisse der Erhebungen 2007. In. Eidg. Forschungsanstalt für Wald, Schnee und Landschaft (WSL), Birmensdorf,Zurich, p. 24.

Harari, O., 2008. Truppflanzungs-Experimente mit Stieleiche und Bergahorn in der Schweiz. Ergebnisse der Erhebungen 2007. In. Eidg. Forschungsanstalt für Wald, Schnee und Landschaft (WSL), Birmensdorf,Zurich, p. 24.

Hedges, L.V., 1982. Estimation of effect size from a series of independent experiments. Psychological bulletin 92, 490.

Hedges, L.V., Gurevitch, J., Curtis, P.S., 1999. The meta-analysis of response ratios in experimental ecology. Ecology 80, 1150-1156.

Hedges, L.V., Olkin, I., 1985. Statistical methods for meta-analysis. Academic Press, New York, New York.

Hedges, L.V., Vevea, J.L., 1996. Estimating effect size under publication bias: Small sample properties and robustness of a random effects selection model. J. Educ. Behav. Stat. 21, 299-332.

Hegyi, F., 1974. A simulation model for managing Jack-pine stands. In, Growth models for tree and stand simulation, pp. 74-91.

Henriksson, J., 2001. Differential shading of branches or whole trees: survival, growth, and reproduction. Oecologia 126, 482-486.

Hickler, T., Vohland, K., Feehan, J., Miller, P.A., Smith, B., Costa, L., Giesecke, T., Fronzek, S., Carter, T.R., Cramer, W., Kuhn, I., Sykes, M.T., 2012. Projecting the future distribution of European potential natural vegetation zones with a generalized, tree species-based dynamic vegetation model. Glob. Ecol. Biogeogr. 21, 50-63.

Hunt, R., 1991. Trying an authorship index. Nature 352, 187.

IBM, 2012. IBM® SPSS® Statistics. Version 20. In, Somers,New York,USA.

Ilstedt, U., Malmer, A., Elke, V., Murdiyarso, D., 2007. The effect of afforestation on water infiltration in the tropics: A systematic review and meta-analysis. For. Ecol. Manage. 251, 45-51.

IPCC, 2007. Impacts, Adaptation and Vulnerability,Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., Linden, P.J.v.d., Hanson, C.E. (Eds.), IPCC Fourth Assessment Report: Climate Change 2007 (AR4). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Ironside, G.E., 1954. Spaced group planting. Malayan Forester. 17, 203-206.

Jacob, M., Leuschner, C., Thomas, F.M., 2010. Productivity of temperate broad-leaved forest stands differing in tree species diversity. Ann. For. Sci. 67, 9.

Johnson, P.S., Shifley, S.R., Rogers, R., 2002. The Ecology and Silviculture of Oaks. CABI Publishing, New York.

Jonasova, M., Vavrova, E., Cudlin, P., 2010. Western Carpathian mountain spruce forest after a windthrow: Natural regeneration in cleared and uncleared areas. For. Ecol. Manage. 259, 1127-1134.

Joyce, P.M., Huss, J., McCarthy, R., Pfeifer, A., Hendrick, E., 1998. Growing broadleaves COFORD, Dublin.

Kenk, G., Guehne, S., 2001. Management of transformation in central Europe. For. Ecol. Manage. 151, 107-119.

Kenk, G.K., 1993. New perspectives in German oak silviculture. Ann. Sci. For. 50, 563-570.

Kerr, G., 1999. The use of silvicultural systems to enhance the biological diversity of plantation forests in Britain. Forestry 72, 191-205.

Kint, V., Hein, S., Campioli, M., Muys, B., 2010. Modelling self-pruning and branch attributes for young Quercus robur L. and Fagus sylvatica L. trees. For. Ecol. Manage. 260, 2023-2034.

Knoke, T., Ammer, C., Stimm, B., Mosandl, R., 2008. Admixing broadleaved to coniferous tree species: a review on yield, ecological stability and economics. Eur. J. For. Res. 127, 89-101.

Koch, R., Brang, P., 2005. Extensive Verjüngungsverfahren nach Lothar. In. Eidg. Forschungsanstalt für Wald, Schnee und Landschaft (WSL), Birmensdorf,Zürich, p. 34.

Kohnle, U., Klädtke, J., 2010. Drei Jahrzehnte naturnaher Waldbau in Baden-Württemberg. AFZ/Der Wald 65, 22-25.

Kölling, C., Ammer, C., 2006. Waldumbau unter den Vorzeichen des Klimawandels. Zahlen der Bundeswaldinventur zeigen Anpassungsschwerpunkte. AFZ/Der Wald 61, 1086-1089.

Korjakin, D.A., 1952. Characteristics of the growth of Oak in plantations established by Ogievskii's method. [Russian]. Lesnoe Khozyaistvo. 5.

Körner, C., 2005. An introduction to the functional diversity of temperate forest trees. In: Scherer-Lorenzen, M., Körner, C., Schulze, E.-D. (Eds.), Forest Diversity and Function: Temperate and Boreal Systems. Springer-Verlag Berlin, Berlin, pp. 13-37.

Kuehne, C., Kublin, E., Pyttel, P., Bauhus, J., 2013. Growth and form of Quercus robur and Fraxinus excelsior respond distinctly different to initial growing space: results from 24-year-old Nelder experiments. Journal of Forestry Research. 24, 1-14.

Kühne, C., Bartsch, N., 2005. Fructification and seedling development of pedunculate oak (Quercus robur) in floodplain forests of the Upper Rhine Valley. Forstarchiv 76, 16-23.

Labbe, K.A., Detsky, A.S., Orourke, K., 1987. Meta-analysis in clinical research. Ann. Intern. Med. 107, 224-233.

Landesforstanstalt Eberswalde, 2006. Aktuelle Ergebnisse und Fragen zur Situation der Eiche und ihrer Bewirtschaftung in Brandenburg. In. Ministerium für Ländliche Entwicklung, Umwelt und Verbraucherschutz des Landes Brandenburg. (http://www.brandenburg.de/sixcms/media.php/4055/b25eiche.pdf, last accessed on 01.03.2013)

Lanner, R.M., 1985. On the insensitivity of height growth to spacing. For. Ecol. Manage. 13, 143-148.

Larsen, J.B., Nielsen, A.B., 2007. Nature-based forest management - Where are we going? Elaborating forest development types in and with practice. For. Ecol. Manage. 238, 107-117.

Leckebusch, G.C., Ulbrich, U., 2004. On the relationship between cyclones and extreme windstorm events over Europe under climate change. Glob. Planet. Change 44, 181-193.

Leder, B., 1992. Weichlaubhölzer [Broadleaf pioneer species]. In, Schriftenreihe der Landesanstalt für Forstwirtschaft Nordrhein-Westfalen.

Leder, B., 1996. Weichlaubhölzer im Eichen- und Buchen-jungbeständen. Forst und Holz 51.

Leder, B., 2007. Wachstum und qualitative Entwicklung von Eichennestern. AFZ/Der Wald 1, 420-423.

Leibundgut, H., 1976. Grundlagen zur Jungwaldpflege - Ergebnisse zwanzigjähriger Untersuchungen über die Vorgänge der Ausscheidung, Umsetzung und Qualitätsentwicklung in jungen Eichenbeständen. Mitteilungen Eidgenössische Anstalt für das Forstliche Versuchswesen 52, 311-371.

Lockhart, B.R., Ezell, A.W., Hodges, J.D., Clatterbuck, W.K., 2006. Using natural stand development patterns in artificial mixtures: A case study with cherrybark oak and sweetgum in east-central Mississippi, USA. For. Ecol. Manage. 222, 202-210.

Lu, C.M., Lee, H.T., Rin, U.C., 1975. Planting in widely spaced groups: a promising technique for enriching the maquis. [French]. In, Bulletin d'Information Institut National de Recherches Forestieres, Tunisia.

Lysenko, T.D., 1949. Experimental sowing of forest belts in clusters. [Russian]. Sovetskaya Agronomiya. 3, 4-17.

Mangold, S., 1988. Versuche mit Eiche-Nesterpflanzungen. Forst und Holz 43, 460-461.

Margolis, H.A., Brand, D.G., 1990. An ecophysiological basis for understanding plantation establishment. Can. J. For. Res.-Rev. Can. Rech. For. 20, 375-390.

Martin, E., Hine, R., 2008. A Dictionary of Biology. Oxford University Press.Oxford Reference Online. http://www.oxfordreference.com.

McLeod, K.W., Reed, M.R., Nelson, E.A., 2001. Influence of a willow canopy on tree seedling establishment for wetland restoration. Wetlands 21, 395-402.

Michéli, E., Schad, P., Spaargared, O., Dent, D., Nachtergaele, F., 2006. World reference base for soil resources. In, World Soil Resources Reports. Food and Agricultural Organization of the United Nations., Rome, p. 128.

Morin, X., Fahse, L., Scherer-Lorenzen, M., Bugmann, H., 2011. Tree species richness promotes productivity in temperate forests through strong complementarity between species. Ecol. Lett. 14, 1211-1219.

Mosandl, R., Burschel, P., Sliwa, J., 1988. Die Qualität von Auslesebäumen in Eichenjungbeständen. Forst und Holz 43, 37-41.

Mosandl, R., Elkateb, H., Ecker, J., 1991. Investigations of various thinning treatments in young oak stands. Forstwiss. Cent.bl. 110, 358-370.

Mosandl, R., Paulus, F., 2002. Rationelle Pflege junger Eichenbestände. AFZ/Der Wald 57, 581-584.

Müller-Starck, G., Herzog, S., Hattemer, H.H., 1993. Intrapopulational and interpopulational genetic-variation in juvenile populations of *Quercus robur* L. and *Quercus petraea* Liebl. Ann. Sci. For. 50, S233-S244.

Nagel, R.-V., Rumpf, H., 2010. Der Eichenverbandsversuch Ahlhorn: Ergebnisse nach 35-jähriger Beobachtungsdauer. Forst und Holz 65, 14-19.

Normand, S.L.T., 1999. Meta-analysis: Formulating, evaluating, combining, and reporting. Stat. Med. 18, 321-359.

Nutto, L., 1999. Neue Perspektiven für die Begründung und Pflege von jungen Eichenbeständen.Ergebnisse einer Untersuchung zur Kronenentwicklung, Astreinigung und Dickenwachstum junger Stiel- und Traubeneichen in Europa. Freiburger Forstliche Forschung, 147-150.

Nutto, L., 2000. Wachstum und Qualität von Eichen aus Nesterpflanzung. AFZ/Der Wald 1, 401-403.

Olano, J.M., Laskurain, N.A., Escudero, A., De La Cruz, M., 2009. Why and where do adult trees die in a young secondary temperate forest? The role of neighbourhood. Ann. For. Sci. 66, 8.

Osenberg, C.W., Sarnelle, O., Cooper, S.D., 1997. Effect size in ecological experiments: The application of biological models in meta-analysis. Am. Nat. 150, 798-812.

Osenberg, C.W., Sarnelle, O., Cooper, S.D., Holt, R.D., 1999a. Resolving ecological questions through meta-analysis: Goals, metrics, and models. Ecology 80, 1105-1117.

Osenberg, C.W., Sarnelle, O., Goldberg, D.E., 1999b. Meta-analysis in ecology: Concepts, statistics, and applications. Ecology 80, 1103-1104.

Paquette, A., Bouchard, A., Cogliastro, A., 2006. Survival and growth of under-planted trees: A meta-analysis across four biomes. Ecol. Appl. 16, 1575-1589.

Petersen, R., 2007. Eichen-Trupp-Pflanzung – erste Ergebnisse einer Versuchsfläche im NFA Neuhaus. Forst und Holz 62, 19-25.

Petersen, R., Schüller, S., Ammer, C., 2009. Early growth of planted pedunculate oak (*Quercus petraea*) in response to varying competition by birch (*Betula pendula*) over 8 years. Forstarchiv 80, 208 - 214.

Piboule, A., Collet, C., Frochot, H., Dhote, J.F., 2005. Reconstructing crown shape from stem diameter and tree position to supply light models. I. Algorithms and comparison of light simulations. Ann. For. Sci. 62, 645-657.

Polley, H., Henning, P., Kroiher, F., 2009. Baumarten, Altersstruktur und Totholz in Deutschland : Ergebnisse einer Kohlenstoffinventur auf Bundeswaldinventur-Basis. AFZ/Der Wald 64, 1074-1075.

Powers, R.F., 1999. If you build it, will they come? Survival skills for silvicultural studies. For. Chron. 75, 367-373.

Pretzsch, H., Biber, P., 2010. Size-symmetric versus size-asymmetric competition and growth partitioning among trees in forest stands along an ecological gradient in central Europe. Can. J. For. Res.-Rev. Can. Rech. For. 40, 370-384.

Pryakhin, I.P., Portnykh, Y.P., 1949. Patch methods of raising Oak from shelterbelts. [Russian]. Agrobiologija (Agrobiology). 1, 75-84.

Puettmann, K.J., 2011. Silvicultural Challenges and Options in the Context of Global Change: "Simple" Fixes and Opportunities for New Management Approaches. J. For. 109, 321-331.

Puettmann, K.J., Coates, K.D., Messier, C.C., 2008. A critique of silviculture: managing for complexity. Island Pr.

R Development Core Team, 2011. R: A Language and Environment for Statistical Computing. In. R Foundation for Statistical Computing, Vienna.

Reif, A., Brucker, U., Kratzer, R., Schmiedinger, A., Bauhus, J., 2010. Forest Management in Times of Climate Change - Synergies and potential conflicts between forestry and nature conservation. Naturschutz und Landschaftsplanung 42, 261-266.

Reif, A., Walentowski, H., 2008. The assessment of naturalness and its role for nature conservation and forestry in Europe. Waldökologie, Landschaftsforschung und Naturschutz 6, 63 - 76.

Rock, J., 2004. Zur Entwicklung der Astdurchmesser junger Eichen in Trupppflanzungsbeständen. Forstarchiv 75, 143-149.

Rock, J., Gockel, H., Schulte, A., 2003. Vegetationsdiversität in Eichen-Jungwüchsen aus unterschiedlichen Pflanzschemata. Beitr. Forstwirtsch. u. Landsch. ökol. 37, 11-17.

Rock, J., Puettmann, K.J., Gockel, H.A., Schulte, A., 2004. Spatial aspects of the influence of silver birch (Betula pendula L.) on growth and quality of young oaks (Quercus spp.) in central Germany. Forestry 77, 235-247.

Röhrig, E., Bartsch, N., Lüpke, v.B., 2006. Waldbau auf ökologischer Grundlage. Eugen Ulmer, Stuttgart.

Roloff, A., Grundmann, B., 2008. Bewertung von Waldbaumarten anhand der KlimaArtenMatrix. Allgemeine Forstzeitschrift 63, 1086–1088.

Rosenberg, M.S., Adams, D.C., Gurevitch, J., 2000. MetaWin: Statistical Software for Meta-Analysis, Version 2.0. In. Sinauer Associates Inc., Sunderland, Massachusetts.

Rosenthal, R., Rubin, D.B., 1982. A simple, general-purpose display of magnitude of experimental effect. J. Educ. Psychol. 74, 166-169.

Rosenvald, R., Lohmus, A., 2008. For what, when, and where is green-tree retention better than clear-cutting? A review of the biodiversity aspects. For. Ecol. Manage. 255, 1-15.

Ruhm, W., 1995. Begründung von Eichenbeständen - alternative Verfahren In, FBVA-Berichte, Vienna, pp. 99-103.

Saha, S., Kuehne, C., Kohnle, U., Brang, P., Ehring, A., Geisel, J., Leder, B., Muth, M., Petersen, R., Peter, J., Ruhm, W., Bauhus, J., 2012. Growth and quality of young oaks (Quercus robur and Q. petraea) grown in cluster plantings in central Europe: a weighted meta-analysis. For. Ecol. Manage. 283, 106-118.

Schmaltz, J., Fröhlich, A., Gebhardt, M., 1997. Die Qualitätsentwicklung in jungen Traubeneichenbeständen im Hessischen Spessart. Forstarchiv 68, 3-10.

Schonenberger, W., 2002. Windthrow research after the 1990 storm Vivian in Switzerland: Objectives, study sites, and projects. Forest Snow and Landscape Research 77, 9-16.

Schutz, J.P., 1993. High-quality oak silviculture in switzerland - concepts of education and production in the marginal range of European oak. Ann. Sci. For. 50, 553-562.

Sokal, R.R., Rolhf, F.J., 1995. Biometry. Freeman, San Francisco.

Spellmann, H., Baderschneider, A., 1988. Erste Auswertung eines Traubeneichen-Pflanzverbands-und Sortimentsversuches im Forstamt Hardegsen/Solling. Forst und Holz 19, 447-450.

Spellmann, H., von Diest, W., 1990. Entwicklung von Z-Baum-Kollektiven in langfristig beobachteten Eichen-Versuchsflächen. Forst und Holz 45, 573-580.

Spiecker, H., 1991. Controlling the diameter growth and the natural pruning of Sessile and Pedunculate oaks (*Quercus petraea* (MATT.) LIEBL. and *Quercus robur* L.). Schriftenreihe der Landesforstverwaltung Baden-Württemberg.

Spiecker, H., Hansen, J., Klimo, E., Skovsgaard, J.P., Sterba, H., von Teuffel, K. (Eds.), 2004. Norway spruce conversion-Options and consequences. EFI Research Reports No. 18. Brill Academy, Leiden, The Netherlands.

Stram, D.O., 1996. Meta-analysis of published data using a linear mixed-effects model. Biometrics 52, 536-544.

Strobel, G., 2000. Eichen-Biogruppen. AFZ/Der Wald 1, 396 – 398.

Sverdrup-Thygeson, A., Skarpaas, O., Odegaard, F., 2010. Hollow oaks and beetle conservation: the significance of the surroundings. Biodivers. Conserv. 19, 837-852.

Swanson, M.E., Franklin, J.F., Beschta, R.L., Crisafulli, C.M., DellaSala, D.A., Hutto, R.L., Lindenmayer, D.B., Swanson, F.J., 2010. The forgotten stage of forest succession: early-successional ecosystems on forest sites. Front. Ecol. Environ. 9, 117-125.

Szymanski, S., 1977. Application of Ogijevski's nest method of artificial regeneration of oak on fertile sites. [Polish]. Sylwan. 121, 43-55.

Szymanski, S., 1986. Die Begründung von Eichenbeständen in "Nest-Kulturen". Forst- und Holzwirt 41, 3-7.

Szymanski, S., 1994. Ergebnisse zur Begründung von Eichenbeständen durch die Nestermethode. Beitr.Forstwirtsch.u.Landsch.ökol. 28, 160-164.

Tarasenko, V.P., 1962. Thinnings in nest-planted Oak on light-chestnut soils of the south Ergeni region. [Russian]. Agrobiologija (Agrobiology). 3, 424-9.

Tirol-Padre, A., Ladha, J.K., 2006. Integrating rice and wheat productivity trends using the SAS mixed-procedure and meta-analysis. Field Crop. Res. 95, 75-88.

Tolkachev, L.N., 1976. Comparative yield of line plantations and 'nest' plantations of Oak. [Russian]. Lesnoe Khozyaistvo 6, 36-38.

Tonioli, M., Escarre, J., Lepart, J., Speranza, M., 2001. Facilitation and competition affecting the regeneration of Quercus pubescens Willd. Ecoscience 8, 381-391.

Udod, V.E., 1969. Silvicultural evaluation of row and nest plantings of Oak in various site conditions. [Russian]. Lesnoi Zhurnal, Arkhangel'sk. 12(3), 147-149.

Usbeck, T., Wohlgemuth, T., Pfister, C., Volz, R., Beniston, M., Dobbertin, M., 2010. Wind speed measurements and forest damage in Canton Zurich (Central Europe) from 1891 to winter 2007. Int. J. Climatol. 30, 347-358.

Vanclay, J.K., 1992. Assessing site productivity in tropical moist forests - a review. For. Ecol. Manage. 54, 257-287.

Verschuyl, J., Riffell, S., Miller, D., Wigley, T.B., 2011. Biodiversity response to intensive biomass production from forest thinning in North American forests - A meta-analysis. For. Ecol. Manage. 261, 221-232.

von Lüpke, B., 1991. Einfluss der Konkurrenz von Weichlaubholz auf das Wachstum junger Traubeneichen. Forst und Holz 46, 166-171.

von Lüpke, B., 1998. Silvicultural methods of oak regeneration with special respect to shade tolerant mixed species. For. Ecol. Manage. 106, 19-26.

von Lüpke, B., 2008. Einfluss unterschiedlicher Hiebsformen auf die Naturverjüngung eines Traubeneichen-Buchen-Mischbestandes. . Forstarchiv 79, 4 - 15.

Waring, R.H., Schlesinger, W.H., 1985. Forest ecosystems: concepts and management. Academic Press, Florida.

Weinreich, A., Grulke, M., 2001. Vergleich zwischen Nesterpflanzung und konventioneller Begründung von Eichenbeständen. Freiburger Forstliche Forschung 25, 41-54.

Wohlgemuth, T., Kull, P., Wüthrich, H., 2002. Disturbance of microsites and early tree regeneration after windthrow in Swiss mountain forests due to the winter storm Vivian 1990. Forest Snow and Landscape Research 77, 17-47.

Worm, B., Barbier, E.B., Beaumont, N., Duffy, J.E., Folke, C., Halpern, B.S., Jackson, J.B.C., Lotze, H.K., Micheli, F., Palumbi, S.R., 2006. Impacts of biodiversity loss on ocean ecosystem services. Science 314, 787.

Yousefpour, R., Hanewinkel, M., Le Moguedec, G., 2010. Evaluating the Suitability of Management Strategies of Pure Norway Spruce Forests in the Black Forest Area of Southwest Germany for Adaptation to or Mitigation of Climate Change. Environmental Management 45, 387-402.

Zelman, D.P., 1961. Growth and formation of Oak stands in relation to stand structure and density. [Russian]. Agrobiologija (Agrobiology). 5.