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Early measures for forest stand establishment within the context of climate change in Europe

Frühe Maßnahmen zur forstlichen Bestandesbegründung im Kontext des Klimawandels in Europa

Benno Eberhard[1,2*], Sara Bergante[3], Karol Bronisz[4], Tiina Laine[5], Christophe Orazio[6], Raffaele Spinelli[2], Marcela van Loo[1]

Keywords: mechanical site preparation, drought, silviculture, biogeographic regions

Schlüsselbegriffe: mechanische Bodenvorbereitung, Trockenheit, Waldbaumaßnahme, biogeografische Regionen

Abstract

Under exacerbated environmental conditions due to climate change and more frequent and more severe disturbances the establishment of forest stands has become a challenge for forest managers. This study aims at comparing stand establishment methods on a European scale. We differentiated between five biogeographic regions to detect similarities and differences regarding current practices as well as trends considering the climatic background using an expert survey. Our results allowed identifying two clusters, one boreal cluster and one European mainland cluster. In both cases mechanical soil preparation and measures against drought are seen as

[1] Federal Research and Training Centre for Forests, Natural Hazards and Landscape (BFW), Institute of Forest Growth, Silviculture and Genetics, Seckendorff-Gudent-Weg 8, 1131 Vienna, Austria
[2] Consiglio Nazionale delle Ricerche-Istituto per la Bioeconomia (CNR IBE), Via Madonna del Piano 10, 50019 Sesto Fiorentino, Italy
[3] Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria – Centro di ricerca Foreste e Legno (CREA-FL). St. Frassineto Po 35, 15033 Casale Monferrato, Italy
[4] Warsaw University of Life Sciences, Department of Forest Management, Dendrometry and Forest Economics, Nowoursynowska Str. 159 building 34, room 1/84, 02-776 Warsaw, Poland
[5] Metsa Group, Asemakatu 7 3. Krs, 70110 Kuopio, Finland
[6] Institut Européen de la Forêt Cultivée (IEFC), 69 route d'arcachon, 33610 CESTAS, France
*Corresponding author: Benno Eberhard, benno.eberhard@gmx.at

key factors. Experts from the boreal region give high importance to appropriate plant material and fertilization for growth acceleration, and consider insects and fungi as a primary threat. In the mainland cluster, experts rely mainly on silvicultural measures and expect damage by game to be highly detrimental for stand establishment. Across Europe the preferable countermeasure to face drought is not irrigation but a combination of strategies related to mechanical site preparation, plant material, planting method, and silviculture. This study identifies three focal areas for forest practitioners to consider when establishing new forest stands:

(1) careful selection of the plant material;
(2) suitable site preparation and
(3) prudent deliberation on beneficial silvicultural options.

Zusammenfassung

Aufgrund der negativen Folgen des Klimawandels ist die forstliche Bestandesbegründung zu einer Herausforderung für Waldmanager geworden. Ziel der vorliegenden Arbeit ist es, Bestandesbegründungsmaßnahmen auf europäischer Ebene zu untersuchen. Nach Ausscheidung fünf biogeografischer Regionen wurde mithilfe einer Expertenbefragung ermittelt, welche Gemeinsamkeiten und Unterschiede bzw. welche Trends es hinsichtlich aktueller Praktiken zur Bestandesbegründung gibt. Die Ergebnisse zeigen, dass zwei Cluster unterscheidbar sind, ein borealer Cluster und ein europäischer Festlandcluster. In beiden Fällen gelten mechanische Bodenbearbeitung und Maßnahmen gegen Trockenheit als Schlüsselfaktoren bei der Bestandesbegründung. ExpertInnen der borealen Region legen großen Wert auf geeignetes Pflanzenmaterial und Düngung zur Wachstumsbeschleunigung und sehen Insekten und Pilze als zentrale Risikofaktoren. ExpertInnen des Festlandclusters setzen hauptsächlich auf waldbauliche Maßnahmen und betrachten den Wildeinfluss als Hauptschadensfaktor. Für alle Regionen besteht die erfolgversprechendste Maßnahme gegen Trockenheit nicht in Bewässerung, sondern in einer Reihe nachhaltiger Strategien zur Verbesserung der Wasserversorgung durch mechanische Bodenvorbereitung, geeignetes Pflanzenmaterial, geeignete Pflanzmethoden und Waldbau. Unsere Studie erlaubt folgende Empfehlungen für die forstliche Praxis der Bestandesbegründung:

(1) Wahl von geeignetem Pflanzmaterial,
(2) Maßnahmen der Bodenvorbereitung und
(3) wissensbasierte Anwendung waldbaulicher Maßnahmen.

1 Introduction

Early measures to ascertain the successful establishment of forest crops play a key role during the forest management cycle (Mc Carthy *et al.*, 2017; Orazio *et al.*, 2019). To achieve successful establishment on a particular site, the young plants need to develop a robust root system for stability as well as for sufficient water and nutrient uptake. During the juvenile stage, trees are highly sensitive to unfavourable site characteristics, to weed competition, and to eventually occurring human treatment deficiencies (Lyr, 1996; Ritchie & Dunlap, 1980). This holds true and is even exacerbated in the context of climate change (Norby & Jackson, 2000).

In Europe, 94% of the forests are semi-natural, 3.9% are plantations and 2.2% are classified as undisturbed. The forests provide the habitat for 454 native tree species (Rivers *et al.*, 2019) out of which 100 to 120 are of relevance for forestry (Alia *et al.*, 2021). In total, the share of conifers and broadleaves is 46% and 37%, respectively, the rest represents mixed forest stands. The average percentage of areas under special rules of conservation with mostly no wood harvest is 24%. The contribution of the single European regions to this figure reveals large differences, e.g. in Central-West Europe 92% of the forests are available for wood supply while in South-East Europe 53% are managed with a prevailing commercial purpose. Out of European forests, 66% are naturally rejuvenated (Forest Europe, 2020a), the rest is artificially reforested.

The choice of early measures for the forest stand establishment depends on the geographic region where the measures are applied (Ammer *et al.*, 2011; Ramantswana *et al.*, 2021). Even though tree species distribution and tree species diversity are driven by nature, the human intervention has an enormous impact on the forest coverage. In particular, the relevance and priority of establishment measures may differ from country to country and between regions from the North to the South and from the West to the East. In the Nordic region, site preparation after final felling is needed for a better seedling survival rate and increased growth (Sikström *et al.*, 2020). Even if mounding has replaced disc trenching as the most common site preparation method for planted seedlings, disc trenching is still in use when sowing seeds (Official Statistics of Finland, 2022). Mounding is also considered an efficient measure against the pine weevil (*Hylobius abietis L.*) damages (Löf, 2000). For Norway spruce (*Picea abies L. Karst.*) in Finland Luoranen & Viiri (2021) demonstrated a higher survival rate of the young plants in mechanically prepared spots in comparison to young plants in untreated patches. Polish studies revealed that mechanical site preparation is recommended not only to create optimum conditions for the pine growth in naturally regenerated sites after clear cut, but also when planting and seeding (Aleksandrowicz-Trzcińska *et al.*, 2017). For the successful establishment of sessile oak (*Quercus petraea Matt.*) and maritime pine (*Pinus pinaster Ait.*) in central France, mechanical site preparation has been identified as a key factor since it enables to control aggressive weeds such as moor grass (*Molinia sp.*) and eagle fern (*Pteridium aquilinum L. Kuhn*) (Auzuret *et al.*, 2014). In Italy, the management of poplar plantations that are expected to assume relevance in the future due to the steadily increasing demand for quality fiber and renewable energy sources (Anderson *et al.*, 2015), face intensive treatment. The key elements in this respect are insect control, fertilization, pruning, and irrigation which always more becomes an essential premise for the plant survival (Marchi *et al.*, 2022). Conversely, chemical weed control and fertilization activities are loosing importance, in full agreement with the FSC and PEFC regulations (Nermin & Francesco, 2021). For poplar plantations in Sweden (Böhlenius & Övergaard, 2015) demonstrated that the choice of plant material and mechanical site preparation are crucial for the stand establishment. Poplar plantations play a significant role also in the French forestry sector, where they are intensively managed, but not irrigated.

The success of one and the same measure may vary with the region of application (Löf *et al.*, 2012). In an experiment with conifer species the primary advantage of soil scarification was weed control (Munson *et al.*, 1993). In contrast, in boreal forests the most beneficial effect of the same measure was seen in the ability to break up the thick humus layer and to trigger the mineralization process, which leads to enhanced nutrient uptake (Schmidt *et al.*, 1996). And again, the same measure can bring yet a different benefit in semi-arid zones, where harrowing is applied mainly to decrease water evaporation and to increase infiltration (Querejeta *et al.*, 2001).

Available literature (Cortina *et al.*, 2004; Coyle & Coleman, 2005; Fiala *et al.*, 2010; Stanton *et al.*, 2002; Stanturf *et al.*, 2001; Steele *et al.*, 2021) suggest that three main groups of stand establishment measures can be classified:

(1) use of appropriate plant material,
(2) resistance to biotic damages,
(3) enhancement of site conditions and increase of resource availability.

The latter group includes three elements, mechanical site preparation, water supply, and nutrient supply (Cortina *et al.*, 2011). The provision of resources undeniably is a key requirement for plant growth. Apart from the fact that water as well as nutrients can be added from outside to a stand (irrigation, fertilization), there is a second strategy that aims to achieve the same goal by making efficient use of the resources that are already present in a stand. This is called the sustainable way of water and nutrient supply, within the framework of this study. All before-listed measures, if adopted properly, are competent to contribute to this effect: Mechanical site preparation, by loosening up compacted soils, increases infiltration rates, improves hydraulic conductivity, reduces water runoff, prevents water stagnation, slows down capillary evaporation, facilitates root penetration, and removes weed competition (Cortina *et al.*, 2011; Löf *et al.*, 2012; Lowery & Gjerstad, 1991). The plant material, by means of the stomatal behaviour and the root shape of the used exemplars, has impact on the uptake of water and nutrients (del Campo *et al.*, 2020). Right planting techniques might optimize the root geometry and this way also contribute to the successful uptake of resources (Lobet *et al.*, 2014; Steudle, 2001). And silvicultural measures, when directed to create favorable environmental conditions, maximize the use of available resources. This is comparable to techniques in agroforestry targeted to create positive interactions between plant layers, this way reducing transpiration (Padilla & Pugnaire, 2006).

This study aims to collect information about the main stand establishment techniques (measures) currently practised in Europe, and to detect trends in future reforestation strategies. It is of interest to view the captured measures against the climatic background within greater European regions such as north Europe, central west Europe, central east Europe, and the southern part of the continent. In analogy with the Köppen-Geiger climate map (Geiger, 1961) in the updated form according to Peel *et al.*, (2007), these regions in rough outlines exhibit the following climatic conditions: *North Europe* has a boreal climate with a rather evenly distributed precipitation. More northerly in this region, the characteristic is subarctic with cold winters and cool summers, while the southern part is humid continental with reasonably cold winters and mild summers. The temperature is specific to the climate zone *D* (*cold*) which means that the warmest month is beyond 10°C, and the coldest month is equal to or below 0°C. In *central west Europe*, the prevailing climate type is temperate oceanic with warm summers, no dry season, and a rather equally distributed rainfall. The temperature as being characteristic of the climate zone *C* (*temperate*) includes a warmest month beyond 10°C, and a coldest month ranging between 0°C and 18°C. In *central east Europe*, the dominating climate type is temperate continental which indicates reasonably warm summers, cold winters, no dry season, and also a principally evenly distributed rainfall. Also here, the temperature is typical for the climate zone *D* as described before. In *south Europe* where the temperature likewise represents the *C*-zone, three main climate types are predominating: The warm mediterranean climate includes drought periods with a precipitation of the driest month in summer being below 40 mm. The warm oceanic climate integrates hot summers with a mean temperature of the warmest month greater than 22°C, but no dry summers, according to the updated Köppen-Geiger climate map. The temperate oceanic climate, likewise present in south Europe, was already characterized above.

The following research questions are posed for the study:

1. What are the key aspects at the establishment phase?
2. What are the most severe problems/obstacles encountered during stand establishment?
3. Have the priorities of early measures changed during the last ten years in the context of global warming, and how are they expected to change within the upcoming ten years?
4. Are there patterns in the differences and/or similarities between climatic regions, and if so, how can these be interpreted?

2 Methods

The data acquisition for the study was done by a questionnaire survey. This technique was preferred to a literature review because it enables to strive for information about most recent developments in stand establishment practices, which may have not been documented through publication yet. Experts and practitioners tend to publish their methods with a time-lag and rather in national journals (grey literature) – not as international scientific papers. The survey technique provides a high level of uniformity and comparability of the gathered information (Brancato *et al.*, 2006).

The arrangement of Europe in large-scale biomes was oriented towards the concept of the European biogeographical regions as defined by the European Environment Agency (Cervellini *et al.*, 2020; Walday & Kroglund, 2002). Five regions were differentiated: Boreal, Atlantic, Continental, Atlantic-Continental, and Atlantic-Mediterranean. For each of these regions, practitioners and experts in the field were selected.

2.1 Survey design

The workflow for the survey followed the principal guidelines indicated in the specialized literature (Bird, 2009; Brancato *et al.*, 2006; Sarantakos, 2017). After defining the objective of the study, the conceptualization, operationalization, and pilot testing of the survey were achieved through expert group meetings attended by researchers and forest managers with expertise in this field. In agreement with the above-mentioned classification of stand establishment measures, the focus of the questionnaire was on three principal topics:

i) mechanical site preparation for reducing soil compaction,
ii) water supply, including irrigation and sustainable alternatives and
iii) nutrient supply, including fertilization and sustainable alternatives.

Irrigation was defined as water being carried from an external water source to a forest stand, while sustainable alternatives were defined as all measures to improve the benefit from the water already available in the stand.

2.2 Survey structure and implementation

Research questions one and two were intended to assess the key aspects for a successful stand establishment on the one hand (question one), and the principal risks on the other hand (question two). Both were open questions, and extent as well as level of detail of the given answers, was left to the choice of the respondents. Research question three aimed to determine the urgency of measures against drought, measures of fertilization against nutrient deficiency, measures of fertilization to accelerate growth, and measures against soil compaction, for the past (10 years back), the present, and the future (10 years from now). It represented closed and quantitative questions, and an ordinal scale ranging from one (very low) to five (very high) was adopted.

The questionnaire featured a two-part structure, whereby general information was collected in the first part and a description of concrete measures in the second part (supplementary material). The information needed to answer the research questions, was mostly sourced from part one. Part two was designed to contribute to a better understanding of the statements provided in the first part, especially for the aggregation of the answers into categories with the intention to reduce their complexity. The survey was issued in four languages: English, German, Italian, and Polish (see supplementary material). It was delivered as an e-mail attachment and the respondents filled out the form independently so that any bias caused by the presence of the interviewer was excluded.

2.3 Selection of the survey respondents

The respondents were searched within the before-listed five biogeographic regions. Five main countries were selected to represent the regions, Finland, Poland, France, Austria, and Italy. Additional five countries were added later: Norway, Slovakia, Hungary, Bulgaria, and Spain (see Table 1). The data collection was supported by the personal networks of the authors within these countries. This was advantageous since the success of a survey research to high degree depends on the willingness of the respondents to take their time and to properly fill out the questionnaires.

Table 1: European sub-areas, biogeographic regions, and countries (two-digit ISO country code) addressed by the survey. For the division criteria of the regions, see explanations in the text.

Tabelle 1: Teilgebiete, biogeographische Regionen und Länder Europas (Länderbezeichnungen gemäß ISO-Code), die für den Fragebogen ausgewählt wurden. Zu den Auswahlkriterien siehe den Text.

European sub-region	**Biogeographic Region**	**Representative countries**
North Europe / Fennoscandian region	*Boreal*	Finland (FI), Norway (NO)
East Europe	*Continental*	Poland (PL), Slovakia (SK), Hungary (HU), Bulgaria (BG)
West Europe	*Atlantic*	France (FR)
Central Europe	*Atlantic-Continental-*	Austria (AT)
South Europe	*Atlantic-Mediterranean*	Italy (IT), Spain (ES)

We targeted 65 senior experts (respondents) with a strong professional background in operational practice, public administration, or the academia. All respondents had expertise in the standard management systems (high forest, short-rotation plantation, and nursery) as adopted by FAO (2020).

2.4 Evaluation of the survey

Research questions one and two as being open questions elicited a large variety of answers by the respondents. Therefore, the provided answers were grouped to obtain a concise overview on the practices in place, and to make the outcome manageable for further analyses. For that purpose, two aspects out of all listed aspects per question were taken in consideration, respectively. The reason was that all filled questionnaires contained at least two entries for each of the two questions, but some contained not more than two entries. The process of aggregation comprised two steps, leading to several sub-categories which have been further condensed to main categories. An example might illustrate this: One filled questionnaire for question one (*What are the key aspects?*) provided the following answers:

1. choice of the appropriate tree species,
2. mulching the area,
3. slash removal previous to mulching in order to keep the mulch-layer thin.

In this case, the first two aspects were taken in consideration. Answer one was attributed to the sub-category *choice of the right tree species/clone*, and to the main category *silviculture*, and answer two was matched with the sub-category *soil preparation*, and with the main category *mechanical site preparation* (which besides the *soil preparation* contained *mechanized weed control* as second sub-category). In case of uncertainty about the meaning of given statements, a clarification was achieved through personal contacts between the lead author and the survey respondents, and through the lead author's visits to sites in Finland, Poland, Austria and Italy between July and October 2021.

On the assumption that early measures might have a positive effect on sustainable water/nutrient supply as explained above, in the context of question one (*What are the key aspects?*) it was possible to determine whether the practices described by the respondents were comprehended as sustainable methods of water or/and nutrient supply or not. This was done based on explicit reference associated with the answers to questions one and/or two, and/or by referring to the context (part two of the survey with description of concrete measures), and personal communications with the respondents. Again, an example might be helpful for the understanding: A respondent listed as a key aspect *deep site preparation*. As can be seen, there is no explicit statement available indicating that this measure might serve as sustainable method for the water supply. Even so, as principal problem (question two *What are the most severe problems?*) the respondent mentioned the *water scarcity*. Moreover, in the second part of the questionnaire (description of concrete measures) the same respondent described *deep ploughing* as a measure out of the complex mechanical site preparation, and explicitly stated that it should be done *at the end of the vegetative season prior to planting so that the soil has the chance to absorb and store the water during the winter*. Hence, in this case the listed key aspect *deep site preparation* was interpreted to serve as sustainable measure for the water supply, in the intention of the respondent.

2.5 Statistical analysis

For the evaluation of research questions one and two, the entries were counted (frequencies) per region and category and expressed as percentages of the total number of entries for a respective region and category. A statistical assessment of the region-specific differences was done by a Pearson's Chi square-Test. To that end, the percentages (question one) were converted into corresponding numeric values. For question three, not available values (NAs) were replaced by the respective median of available values, according to region, measure (against soil compaction, against drought, against nutrient deficiency), and time dimension (present, future, past) (Table 2). On that basis, the mean values were calculated for illustration purposes in the following text. Changes in the urgency of specific measures were gauged through the difference in their intensity rating between future and past, separately for each region. A statistical verification was done by a Kruskal Wallis-test (W. H. Kruskal & Wallis, 1952), followed by the Dunn-test as a post-hoc assessment of differences between the single pairings. For the evaluation of research question four, two techniques were applied, the PAM (Partitioning Around Medoids) technique (Kaufman & Rousseeuw, 2009), and the non-metric multidimensional scaling (nmds) algorithm (Borg & Groenen, 2005; Galbraith *et al.*, 2002). PAM is a clustering method of the medoid type (Rai & Singh, 2010), which represents observations as cluster centres (medoids) that best represent a particular cluster. As consequence, the medoid can be used to characterize a cluster in its essential traits. The PAM method has two major advantages: first, that categorical variables can be integrated and, second, that it is less sensitive to outliers. For mixed data types, consisting of numerical and categorical data (see Table 2), the Gower distance was applied to quantify the distance between individual points (Ranalli & Rocci, 2019). The number of clusters adopted for the analysis was selected after determining the Silhouette width. The estimate for the goodness of clustering was the Silhouette coefficient (Rousseew, 1987). For the nmds-plots, the Bray-Curtis dissimilarity measure was chosen. The estimation of the goodness of fit of the nmds model occured by the Kruskal stress type one which was interpreted along the rating scale (J. B. Kruskal & Wish, 1978): 0.2 and below (poor fit), 0.05 and below (good fit), 0.00 (perfect fit). The level of significance for all statistical analyses of this study was $\alpha=0.05$. All analyses were performed with the statistical software R (R Core Team, 2022).

Table 2: Overview of the info and data from the 43 filled surveys with the corresponding biogeographic region and country. Atl for Atlantic, Med for Mediterranean, Cont for Continental, Ess asp for Essential aspect, Mech SP for Mechanical site preparation, Pla meth for Planting method, Silv meas for Silvicultural measures, Plant mat for Plant material, Pr pro for Principal problem, Ins Fu for Insects/Fungi, Game d for Game damages, Silv ins for Silvicultural insufficiency, D for Against drought, F for Fertilization, N for Against nutrient deficiency, A for Promoting growth, SC for Against soil compaction, p for past, P for present, F for future, 1 stands for very low, 5 for very high.

Tabelle 2: Zusammenfassung der Daten aus den 43 ausgefüllten Fragebögen, gemäß biogeografischen Region und Ländern. Atl steht für Atlantisch, Med für Mediterran, Cont für Kontinental, Ess asp für Entscheidender Punkt, Mech SP für Mechanische Bodenvorbereitung, Pla meth für Pflanzmethode, Silv meas für Waldbaumaßnahme, Plant mat für Pflanzmaterial, Pri prob für Größtes Problem, Ins Fu für Insekten/Schadpilze, Game d für Wildschaden, Silv ins für Unzureichende Waldbaumaßnahme, D für Gegen Trockenheit, F für Düngung, N für Gegen Nährstoffmangel, A für Wuchsbeschleunigung, SC für Gegen Bodenverdichtung, p für Vergangenheit, P für Gegenwart, F für Zukunft, 1 bedeutet sehr gering, 5 sehr hoch.

No	Region	n	Country	Ess asp 1	Ess asp 2	Pr pro 1	Pr pro 2	Dp	DP	DF	FNp	FNP	FNF	FAp	FAP	FAF	SCp	SCP	SCF
1	Boreal		FI	Mech SP	Pla meth	Ins Fu	Drought	3	3	3	2	2	2	1	1	1	1	1	1
2	Boreal		FI	Mech SP	Plant mat	Ins Fu	Game d	5	5	5	2	2	2	3	3	3	1	1	1
3	Boreal		FI	Mech SP	Plant mat	Game d	Ins Fu	na	na	na	na	na	na	na	na	na	na	na	na
4	Boreal	8	FI	Mech SP	Plant mat	Drought	Game d	na	na	na	na	na	na	na	na	na	na	na	na
5	Boreal		FI	Mech SP	Plant mat	Drought	Ins Fu	5	5	5	4	4	4	2	2	3	1	1	2
6	Boreal		FI	Silv meas	Mech SP	Ins Fu	Ins Fu	na	na	na	na	na	na	na	na	na	na	na	na
7	Boreal		NO	Mech SP	Silv meas	Ins Fu	Ins Fu	1	1	1	1	1	1	1	1	1	1	1	1
8	Boreal		NO	Silv meas	Mech SP	Drought	Game d	2	2	2	1	1	1	1	2	3	1	2	3
9	Atl		FR	Silv meas	Plant mat	Drought	Drought	5	5	5	1	1	1	1	1	1	5	5	5
10	Atl	3	FR	Mech SP	Silv meas	Drought	Silv ins	1	3	5	3	4	4	2	2	1	2	2	3
11	Atl		FR	Mech SP	Silv meas	Game d	Game d	5	5	5	4	4	3	3	3	3	5	5	5
12	Atl Med		IT	Mech SP	Mech SP	Drought	Ins Fu	3	3	4	4	2	3	4	2	5	2	4	5
13	Atl Med		IT	Silv meas	Pla meth	Drought	Drought	5	5	na	3	3	na	3	2	na	5	4	na
14	Atl Med		IT	Mech SP	Plant mat	Drought	Drought	4	4	5	2	2	2	2	2	2	4	4	5
15	Atl Med		IT	Plant mat	Silv meas	Game d	Drought	3	3	3	1	1	1	1	1	1	1	1	1
16	Atl Med		IT	Plant mat	Silv meas	Drought	Drought	5	5	5	4	4	4	5	3	3	1	1	1
17	Atl Med	12	IT	Plant mat	Silv meas	Silv ins	Silv ins	2	2	2	3	3	4	2	2	3	3	3	3
18	Atl Med		IT	Pla meth	Plant mat	Drought	Drought	3	3	4	3	3	3	1	1	1	4	4	4
19	Atl Med		IT	Silv meas	Mech SP	Drought	Drought	4	5	5	4	3	2	1	1	1	2	5	5
20	Atl Med		IT	Silv meas	Plant mat	Silv ins	Drought	3	3	3	2	2	2	1	1	1	1	1	1
21	Atl Med		IT	Silv meas	Mech SP	Drought	Drought	5	5	5	2	2	1	2	1	1	1	1	1
22	Atl Med		ES	Plant mat	Silv meas	Drought	Drought	na	5	5	na	2	1	na	3	2	na	4	4
23	Atl Med		ES	Mech SP	Plant mat	Drought	Drought	5	5	5	2	3	2	2	2	2	4	4	4
24	Atl Cont		AT	Plant mat	Silv meas	Drought	Drought	3	4	5	1	1	1	1	1	1	3	4	5
25	Atl Cont		AT	Mech SP	Mech SP	Drought	Drought	5	5	5	3	2	4	1	1	1	3	3	3
26	Atl Cont		AT	Silv Meas	Mech SP	Drought	Drought	4	4	5	1	1	2	1	1	1	3	3	3
27	Atl Cont		AT	Mech SP	Silv meas	Drought	Drought	3	5	5	1	1	2	1	1	2	3	4	4
28	Atl Cont		AT	Plant mat	Pla meth	Drought	Drought	2	3	4	1	1	1	1	1	1	4	4	4
29	Atl Cont	11	AT	Mech SP	Mech SP	Drought	Silv ins	3	5	5	na	na	na	na	na	na	na	na	na
30	Atl Cont		AT	Silv Meas	Mech SP	Game d	Silv ins	4	4	5	1	1	1	1	1	1	1	1	1
31	Atl Cont		AT	Pla meth	Silv meas	Game d	Game d	1	2	3	1	1	1	1	1	1	1	1	1
32	Atl Cont		AT	Plant mat	Pla meth	Drought	Drought	2	2	3	na	na	na	na	na	na	na	na	na
33	Atl Cont		AT	Plant mat	Pla meth	Drought	Drought	4	5	5	1	1	1	3	3	3	4	5	5
34	Atl Cont		AT	Silv meas	Plant mat	Silv ins	Drought	3	3	4	na	na	na	na	na	na	5	5	5
35	Cont		BG	Silv meas	Mech SP	Drought	Drought	4	4	4	na	na	4	3	3	4	4	5	4
36	Cont		PL	Silv meas	Plant mat	Drought	Drought	3	4	4	2	3	2	1	1	1	4	5	4
37	Cont		PL	Mech SP	Silv meas	Drought	Game d	5	5	5	2	2	2	1	1	1	3	3	3
38	Cont		PL	Mech SP	Silv meas	Drought	Drought	na	na	na	na	na	na	na	na	na	na	na	na
39	Cont	9	PL	Mech SP	Pla meth	Drought	Drought	4	4	4	1	1	1	1	1	1	3	3	3
40	Cont		PL	Silv meas	Silv meas	Drought	Drought	1	1	5	1	1	1	1	1	1	1	1	1
41	Cont		SK	Silv meas	Mech SP	Drought	Game d	4	5	5	2	2	2	1	1	1	5	4	4
42	Cont		HU	Plant mat	Silv meas	Drought	Drought	3	3	3	1	2	2	1	2	2	4	4	4
43	Cont		HU	Silv meas	Plant mat	Drought	Game d	2	2	3	1	1	1	1	1	1	2	2	4

3 Results

In total, 65 potential respondents were contacted 43 of whom filled out the questionnaire. Table 2 offers an overview of the characteristics of the survey respondents and the answers to questions one and two (two entries per respondent, columns 4 to 7 respectively) and to question three (containing ordinal values from one to five in columns 8-19).

3.1 Most relevant aspects and threats at the establishment phase

The questions about the most relevant aspects (research question one) and threats (research question two) obtained a wide range of answers, eventually grouped into nine large main categories (Table 3). Five categories grouped the answers to question one (aspects), namely: mechanical site preparation, irrigation, plant material, planting method, and silviculture. Four categories grouped the answers to question two (threats) as follows: drought, insects/fungi, game damage, and insufficient silviculture. The preferences for the analyses have been counted as follows. Since two entries per survey were taken into account (see the explanation above) and 43 surveys were filled, in total 86 answers for each research question are available. For the amelioration of site conditions 28 votes were counted, 24 of which included mechanical site preparation, and 4 referred to irrigation. Out of the first 24, 16 referred to soil preparation as the main purpose of mechanical site preparation, and 8 to weed control as its principal scope. And finally, according to 23 out of these 24 votes, the referenced measure represents a sustainable way for the provision of water or/and nutrients, respectively. All remaining category-specific information provided by Table 3 are interpreted in a similar manner.

Table 3: Reduction of the survey answers to sub-categories (cursive) and main categories (in bold). Between brackets the numbers of respondents are inserted. The numbers in bold (23, 18, 7, 24) denote the surveys where the respective measure is characterized as sustainable method for water or/and nutrient supply.

Tabelle 3: Zusammenfassung der Fragebogenantworten zu Unterkategorien (kursiv) und Hauptkategorien (fettgedruckt). Zwischen Klammern ist die jeweilige Anzahl an Fragebögen angegeben. Die fettgedruckten Zahlen (23, 18, 7, 24) bezeichnen die Anzahl an Fragebögen, in denen eine jeweils genannte Maßnahme als nachhaltige Methode zur Wasser und/oder Nährstoffversorgung dargestellt ist.

<table>
<tr><th>Research question</th><th>Subcategories of the answers</th><th>Main categories of the answers</th></tr>
<tr><td rowspan="4">Question 1:
Essential aspects at stand establishment?</td><td>- Soil preparation (16)
disc-trenching, harrowing, subsoiling, rotovating, soil inversion, patch mounding, ditch mounding, drainage, micro catchments, retention and infiltration ditches…
- Mechanized weed control/mulching (8)
- Irrigation (4)</td><td>Mechanical site preparation (24/23) (Amelioration of site conditions)

Irrigation (4) (Amelioration of site conditions)</td></tr>
<tr><td>Right plant material (seedlings, clones, seeds)</td><td>Plant material (20/18)</td></tr>
<tr><td>Right planting method, preparation and storage of seedlings, clones, seeds…</td><td>Planting method (9/7)</td></tr>
<tr><td>- Regeneration method (e.g. choice of appropriate site, generation of good site conditions by cutting system…) (6)
- Choice of tree species/clones (8)
- Tree species mixture (1)
- Spacing (1)
- Cleaning, tending (3)
- Right timing of planting and further work steps, e.g. planting in autumn or fall, ploughing in autumn or fall… (10)</td><td>Silviculture (29/24)</td></tr>
<tr><td rowspan="4">Question 2:
Greatest problems at stand establishment?</td><td>- Drought (57)</td><td>Drought (57)</td></tr>
<tr><td>- Insects / Fungi (9)</td><td>Insects / Fungi (9)</td></tr>
<tr><td>- Game damage (13)</td><td>Game damage (13)</td></tr>
<tr><td>- Competing vegetation (3)
- Soil degradation (1)
- Soil compaction (1)
- Invasive species (1)
- Seed shortage/poor seed quality (1)</td><td>Silvicultural insufficiency (7)</td></tr>
</table>

Drought emerged as the most severe threat to stand establishment, since it was mentioned by 66% (57 out of 86) of the experts (Table 3). However, irrigation (its essential countermeasure) only scored four votes. Most respondents (*i.e.*, 84% or 72 out of 86) indicated silviculture (24), mechanical site preparation (23) plant material (18), and planting method (7) as the most beneficial measures when establishing a stand, and at the same time identified them as sustainable methods for the provision of water or/and nutrients (Table 3).

The distribution of votes differed significantly among regions (Figures 1A, 1B). When regional distributions were analysed, Pearson's Chi square Test yielded a $p < 0.001$ for question one (Figure 1A) and $p < 0.001$ for question two (Figure 1B), respectively.

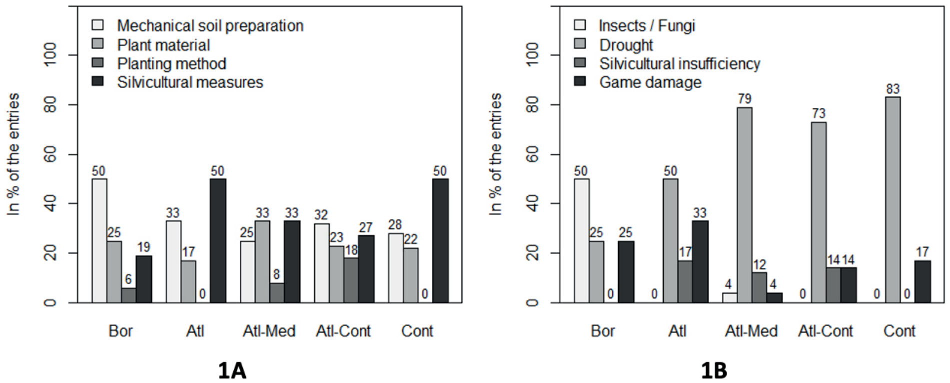


Figure 1: Region-specific illustration of the responses given to the research questions on the key aspects (1A), and the biggest problems (1B) at the stand establishment. The bars represent the percentages of the entries for each of the four assessed categories of measures. For a more detailed description of the categories please refer to Table 3.

Abbildung 1: Darstellung der Fragebogenantworten gemäß Regionen zur Frage nach den Schlüsselfaktoren (1A) und den Risikofaktoren (1B) bei Bestandesbegründung. Die Balken stellen die vier Maßnahmenkategorien in Prozent der Gesamtanzahl der Antworten für eine jeweilige Region dar. Eine detaillierte Beschreibung der Kategorien findet sich in Tabelle 3.

For the boreal region, the two fundamental aspects of stand establishment are mechanical site preparation and plant material. The most detrimental factor is insects/ fungi. In contrast, in all other parts of Europe, silvicultural measures, followed by mechanical site preparation, are considered most essential for a successful stand establishment, and drought is considered the most detrimental factor, followed by game damage (Figures 1A, 1B).

3.2 Expected relevance of measures in the future

Research question three targeted to assess the urgency of *measures against drought, fertilization activities, measures against soil compaction*, and eventually *other measures* (see the survey in the supplementary material) from the view of the experts. The aspect other measures was scarcely answered (23 respondents completed this part of the questionnaire out of 43, and only one entry was available for some of the five regions), therefore a statistical evaluation for other measures was not feasible. Figure 2A provides a region-wise illustration of future urgencies of the above-listed measures according to the experts. Figure 2A concentrates on the contrast between the urgencies in the future and in the past, again, according to the regions and the estimations of the experts.

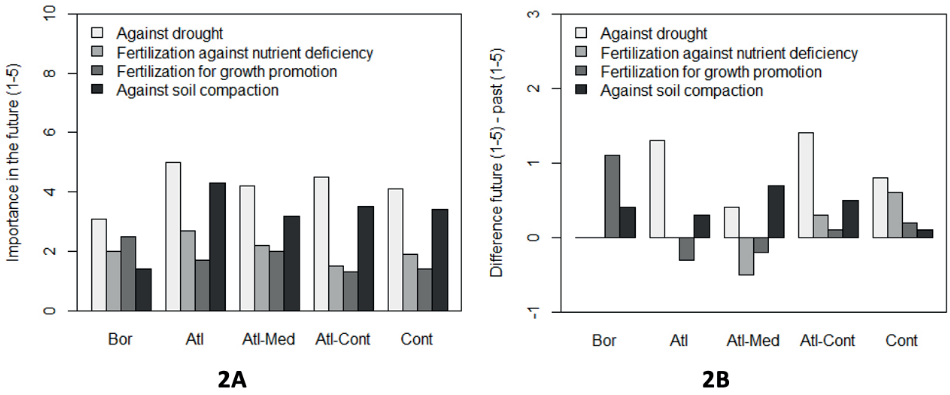


Figure 2: Importance of the listed four measures in the future according to biogeographic regions (2A). Change of importance of the measures (future compared to past) according to biogeographic regions (2B).

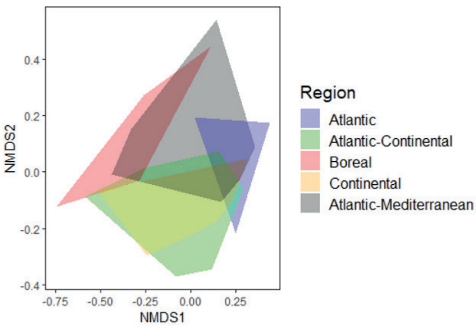
Abbildung 2: Bedeutung der in der Abbildung genannten vier Maßnahmen in der Zukunft, getrennt für alle biogeografischen Regionen (2A). Veränderung der Bedeutung der Maßnahmen (Zukunft minus Vergangenheit), getrennt für alle biogeografischen Regionen (2B).

In all regions measures against drought are expected to become the most important in the future (Figure 2A). When the future was compared with the past (Figure 2B), the importance of fertilization promoting growth is expected to increase significantly in the boreal region, while in all other regions the largest increase is expected for measures against drought and measures against soil compaction.

A Kruskal Wallis test and a Dunn test confirmed the statistical significance of the differences for measures *against drought* (p-value of 0.003), for *fertilization in favour of accelerating growth* (p-value of 0.016), and for measures *against soil compaction* (p-value of 0.015) (Table S1 in the supplementary material). Furthermore, significant differences were found to occur mainly in pairings where the Boreal region is represented, suggesting that different trends are present between the Boreal region on the one hand and all other regions on the other hand (Table S1 in the supplementary material).

3.3 Identifying biogeographic clusters for early measures

Occurring similarities and dissimilarities in stand establishment practices between the regions are further illustrated and analyzed by two visualization techniques. The nmds algorithm depicts the 43 observations (Table 2) in a multidimensional space for which five dimensions were specified. The integrated convex hulls delineate the minimum areas of each of the biogeographic regions and make these regions evident. The PAM cluster analysis arranges the same 43 observations around the centers of the defined number of clusters. In our case, two clusters have been set since the respective value of Silhouette width for two clusters is the highest. The results of the two visualization procedures are illustrated in Figures 3A and 3B.



3A

3B

Figure 3: Visualization of the dissimilarities in stand establishment practices between the biogeographic regions by nmds plot (3A). Result of the custer analysis on similarities and dissimilarities in stand establishment practices under the assumption of two clusters (3B).

Abbildung 3: Visualisierung der Unterschiede in den Bestandesbegründungspraktiken zwischen den biogeographischen Regionen gemäß nmds Plot (3A). Ergebnis der Clusteranalyse zu den Gemeinsamkeiten und Unterschieden betreffend Bestandesbegründungspraktiken unter der Annahme von zwei Clustern (3B).

The Kruskal stress type 1 as an estimate for the accuracy of the nmds plot (Figure 3A), is 0.04 which signifies a good fit between the plotted and the real values/surveys. According to Figure 3A, Boreal ranges apart from most of the other regions, only with Atlantic-Mediterranean it has a strong overlapping. Continental and Atlantic-Continental to large extent cover the same area. Atlantic ranges far away from Boreal and rather tends to overlap with the two continental regions. The mediterranean region to noticeable extent covers the area between the boreal zone and the continental zone. The goodness of fit of the cluster model (Figure 3B) as quantified by the Silhouette coefficient is 0.15 for cluster one, 0.27 for cluster two, and 0.36 for the total model (see Table S2 in supplementary material), signifying a weak structure. Even so, it is evident from Figure 3B that the two outlined clusters are well differentiated with only two observations (surveys) ranging in the intersection zone. To interpret the abstract cluster landscape against the background of the real biogeographic regions, the results of the cluster landscape from Fig. 3B are linked with the biogeographic regions in Table 4.

Table 4: Linkage of the cluster landscape from Figure 3B with the biogeographic regions. The highlighted numbers denote the members of cluster one, all others belong to cluster two. The numbers in bold represent the medoids (centres) of the clusters.

Tabelle 4: Zuordnung der Clusterelemente von Abbildung 3B zu den jeweiligen biogeografischen Regionen. Die grau hinterlegten Felder dienen als Hervorhebung der Elemente, die zu Cluster eins gehören, alle anderen genannten Fragebögen gehören zu Cluster zwei. Die fettgedruckten Zahlen bezeichnen die Medoide (Zentren) der Cluster.

Survey no.	*Region*	*Cl*	*Survey no.*	*Region*	*Cl*
1	Boreal	1	24	Atlantic-Continental	2
2	Boreal	1	25	Atlantic-Continental	2
3	Boreal	1	26	Atlantic-Continental	2
4	Boreal	1	27	Atlantic-Continental	2
5	Boreal	1	28	Atlantic-Continental	2
6	Boreal	1	29	Atlantic-Continental	2
7	Boreal	1	30	Atlantic-Continental	1
8	Boreal	1	31	Atlantic-Continental	1
9	Atlantic	2	32	Atlantic-Continental	2
10	Atlantic	1	33	Atlantic-Continental	2
11	Atlantic	2	34	Atlantic-Continental	2
12	Atlantic-Medit	2	35	Continental	2
13	Atlantic-Medit	2	36	Continental	2
14	Atlantic-Medit	2	37	Continental	2
15	Atlantic-Medit	1	**38**	Continental	2
16	Atlantic-Medit	1	39	Continental	2
17	Atlantic-Medit	1	40	Continental	1
18	Atlantic-Medit	2	41	Continental	2
19	Atlantic-Medit	2	42	Continental	2
20	Atlantic-Medit	1	43	Continental	2
21	Atlantic-Medit	1			
22	Atlantic-Medit	2			
23	Atlantic-Medit	2			

Out of the 43 filled surveys, 17 belong to cluster one and 26 to cluster two. All representatives of the boreal region belong to cluster one. Atlantic-Mediterranean seems to be an intermediate region with a strong representation in cluster one (five surveys, see Table 4). Still, the majority of its elements belong to cluster two. Both Atlantic-Continental as well as Continental predominantly represent cluster two. This way, the results of the cluster analysis (Figure 3B, Table 4) are consistent with the outcomes of the nmds plotting (Figure 3A).

The described limitations notwithstanding, in the following sections we go along with the result of the cluster analysis and assume two clusters: a so-called *boreal clus-*

ter on the one hand, and a *European mainland cluster* on the other hand. The medoid (center) of the boreal cluster is represented by survey 4, the medoid of the European mainland cluster by the survey 38. The medoids express the main properties of the clusters, according to the PAM clustering method (Table 5).

Table 5: Characteristics of the medoids (centres) of the two clusters. Cl stands for Cluster, Ess asp for Essential aspect, Mech SP for Mechanical site preparation, Plant mat for Plant material, Silv meas for Silvicultural measures, Pr pro for Principal problem, Game d for Game damages, D for Against drought, F for Fertilization, N for Against nutrient deficiency, A for Promoting growth, SC for Against soil compaction, p for past, P for present, F for future, 1 means low, 5 very high.

Tabelle 5: Charakteristika der Medoide (Zentren) der beiden Cluster. Cl steht für Cluster, Ess asp für Entscheidender Punkt, Mech SP für Mechanische Bodenvorbereitung, Plant mat für Pflanzmaterial, Silv meas für Waldbaumaßnahme, Pr pro für Größtes Problem, Game d für Wildschaden, D für Gegen Trockenheit, F für Düngung, N für Gegen Nährstoffmangel, A für Wuchsbeschleunigung, SC für Gegen Bodenverdichtung, p für Vergangenheit, P für Gegenwart, F für Zukunft, 1 bedeutet sehr gering, 5 sehr hoch.

Medoid (center of clusters) characteristics																		
Cl	**No**	**Ess asp 1**	**Ess asp 2**	**Pr pro 1**	**Pr pro 2**	**Dp**	**DP**	**DF**	**FNp**	**FNP**	**FNF**	**FAp**	**FAP**	**FAF**	**SCp**	**SCP**	**SCF**
1	**4**	Mech SP	Plant mat	Drought	Game d	3	3	3	2	2	2	1	2	3	1	1	1
2	**38**	Mech SP	Silv meas	Drought	Drought	4	4	4	1	2	2	1	1	1	4	4	4

For cluster one (boreal cluster with its medoid in survey no. 4) the most important measures are mechanical site preparation and plant material, while the most severe problems are drought and game damage. Conversely, for cluster two (European mainland cluster with medoid in survey no.38) mechanical site preparation and silvicultural measures are the most important measures and drought the most severe problem.

4 Discussion

4.1 The main categories of establishment measures and threats to cope with

This study concentrated on the measures for successful establishment of forest crops and looked for similarities and/or differences between five biogeographic ecoregions (Boreal, Atlantic, Atlantic-Mediterranean, Atlantic-Continental, and Continental) in Europe. Data collection was carried out by a questionnaire survey. For the quantitative evaluation of the results of the survey on the most important measures at the establishment phase and the obstacles during the establishment, the variety of answers provided by the respondents were condensed to four categories including mechanical site preparation, plant material, correct planting, and silvicultural measures as salient aspects for successful stand establishment, and drought, insects/fungi, game damage, inadequate silvicultural strategies as most severe problems at stand establishment.

The overwhelming majority of the experts qualified the measures for successful stand establishment as sustainable strategies to face water or/and nutrient shortages. An equally large majority pointed at drought as the most severe future threat (Table 3). Experts also indicated that irrigation is currently just a secondary measure to overcome water scarcity: much more importance is attributed to silvicultural strategies (*i.e.*, right timing of planting, choice of tree species, and regeneration/cutting method), immediately followed by mechanical site preparation (Table 3). Nevertheless, financial support from the government or other sources for investments in irrigation (e.g., irrigation facilities, storage reservoirs for irrigation purposes) could influence that view and affect future strategies.

4.2 Priorities of stand establishment measures in the different biogeographic regions

In answer to the research questions one and two, the study found that mechanical site preparation and plant material are the most important measures for the boreal area (Figure 1A, Table 5). A preference for the plant material (*nurseries and tree breeding*) of the boreal biome as a distinctive feature was also found by (Kolström *et al.*, 2011) who scrutinized all climate change adaptation measures in forestry, based on the same European regions as adopted for the present study. In all other regions *i.e.* the European mainland regions, more importance is attached to silvicultural measures, followed again by mechanical site preparation (Figure 1A, Table 5), according to the here achieved results. When addressing the most urgent threats, insects and fungi raise the highest concern in the Boreal region, while game damage and drought are especially alarming in the other European regions (Figure 1B, Table 5). The boreal concern with insects and fungi likely reflects the current pine weevil (*Hylobius abietis L.*) infestation that is hitting the Scandinavian forests, favoured by the monospecific character of the stands in that area that nowadays are largely reforested by planting (Lalik *et al.*, 2021). Low tree species diversity in general, and specifically the small number of tree species used in the Nordic countries (Official Statistics of Finland, 2022) might decrease biodiversity, which is conducive to the mass spread of pests (Lundgren & Fausti, 2015). Conversely, in mainland Europe, drought is considered the main problem, followed by game damage (Figure 1B, Table 5). A further difference between the boreal region and mainland Europe is that respondents from the former area do not consider silviculture deficits to be a problem, while those from the latter one do consider it as an important issue (Figure 1).

When concentrating on the quantitative assessment of how significant measures are expected to be in the future according to the experts, especially when compared to the past (research question three), three measures are found to be different among the European regions at the selected significance level, and namely: measures against soil compaction, measures against drought, and fertilizing for growth acceleration (Table 1S supplementary material). Measures against drought will play a dominant role in the future in all regions, but their relevance will increase much more in mainland Europe than in the Boreal region (Figure 2B). Similarly, activities against soil compaction will become more relevant in mainland Europe than in the Boreal region. The most likely reason for that difference is that mechanical site preparation is already common in the boreal region, and therefore its application is not expected to increase as much as in mainland Europe, where mechanical site preparation is still relatively uncommon. That is not to say that its use will not increase in the Boreal region as well, and figure 2B shows that such increase will occur: it is just that its expected increase is not as large as estimated for mainland Europe.

Moreover, in the boreal region, great emphasis is placed on fertilization for growth acceleration (Figure 2B, Table 5), which is in significant contrast to mainland Europe (Table 4, Table 5) where fertilization is expected to be even less of importance than in the past (Figure 2B). When accomplished at the time of the planting or immediately after, fertilization is beneficial for tree growth and stem quality, depending on the involved tree species, the planting methods and the growth region (Marshall *et al.*, 2022; Smethurst, 2010). The basic understanding of fertilization refers to its application at the stand establishment (Smethurst, 2010). However, when directing the focus on a mere economic profitability, it is more viable to apply fertilization at a later stage of the stand development *e.g.* in the pole stage wood to shorten the time lag between the investment and the final harvest (Pukkala, 2017). By nature, the firstly listed understanding of the term (fertilization at stand establishment) was valid for the present study since it deals with *early measures at stand establishment*. In the Scandinavian countries fertilization practices, after introduction and widespread application in the 1960s gradually came out of fashion. Only over the recent years the interest has been increasing again (Lindkvist *et al.*, 2011). The positive expectations towards fertilization from the side of the practicioners of this region, might be motivated by the fact that in both boreal countries taken into consideration by the survey (*i.e.* Finland and Norway) the use of fertilizers to accelerate growth is encouraged by the respective governments as a way to increase CO2 storage through faster trees growth. Both countries, therefore, have great confidence in this measure as part of their climate change mitigation strategy (see forest.fi, 2020).

The results of a Dunn test concerning fertilization for enhancing growth disclose the boreal region being present in all pairs where significant differences are detected (Table 1S in supplementary material). Thus, the difference between Boreal and the rest of the regions in this respect is statistically substantiated. In total, when considering the measures against soil compaction, those against drought, and those for fertilization, the pairwise comparison by the Dunn test shows that Boreal is present in eight out of nine differing pairings (Table 1S in supplementary material). In outline, an exceptional position of Boreal in contrast to all other European biomes also reflects from (Kolström *et al.*, 2011): In this study, in four out of eight assessed categories of adaptation measures against climate change, Boreal markedly differs from the other regions. The identified distinction has bearing on the assumption of two clusters as will be discussed in the in the next paragraph.

4.3 The two clusters in stand establishment practices in Europe

In the before-said, two rather homogeneous regions became apparent, a boreal region and an area complecting the European mainland countries. Research question four explicitly raised the question about a grouping of the European regions in the context of measures for stand establishment. A cluster analysis conducted to this end evidenced, in outlines, two graphically distinguishable clusters (Figure 3B), the here so-called boreal cluster and the European mainland cluster. Since the boreal cluster as delineated by the cluster analysis, comprises elements that pertain to regions other than Boreal (Table 4), and since the associated accuracy coefficient points at a relatively weak cluster model (Table 2S in supplementary material), this distinction admittedly is carried by some abstraction and generalization. Even so, it was adopted out of the following considerations: Firstly, all surveys of the boreal region without exception range within one and the same cluster (cluster one). Secondly, the result of the cluster analysis is not interpreted in isolation but in conjunction with the above-presented statistical evaluations in the context of research question three (Table 1S in supplementary material), that clearly suggest that a difference between the boreal region on the one hand and all other European regions on the other hand, is given. Thirdly, the conformity of both approaches (the analyses to research question three, and the cluster analysis) is corroborated by the fact that the information contained by the medoids (which are a component of the performed cluster analysis) (Table 5) finds a clear correspondence in the (above debated) messages reflecting from the Figures 1A,B and 2A,B.

4.4 Interpretation of the identified stand establishment priorities in the context of climate change

According to the European Environment Agency (EEA, 2017) some far-reching trends as a result of climate change are to be expected for the European biogeographic regions. The corresponding main trajectories of relevance for this study, are: the boreal region will experience a *temperature rise*, an *increase in precipitation*, a *northward movement of species*, and an *increasing potential for forest growth and increasing risk of* *forest pests*, the continental region will face an *increase in heat extremes*, an *increase in risk of forest fire*, and a *decrease in summer precipitation*, the atlantic part of Europe will be confronted with an *increasing winter precipitation* and an *increasing damage risk from winter storms*, and the mediterranean countries will undergo an *increase in heat extremes*, an *increase in risk of droughts*, of *forest fires* and *desertification*, an *increase in risk of biodiversity loss*, and a *decrease in precipitation*.

The increasing *risk of forest pests* as predicted by the EEA report for the boreal region, finds a direct correspondence in the results of this study (Figure 1B). However, the most positive scenario is predicted for the boreal biome, as can be extracted from the before-referred statements. The expected *northward migration of tree species* in combination with the *increasing potential for forest growth*, might partly explain the efforts to improve the genetic stock in the boreal region (Figure 1A). An enlargement of the potential tree species pool by highly prospecting candidates such as Douglas-fir, Sitka spruce, lodgepole pine, and different poplars (Haapanen *et al.*, 2015), opens new possibilities for forestry. Though, the growth, the growth rhythm, and especially the flowering phenology of trees are determined not only by the water availability and the temperature but also by the phototrophic conditions of a region of interest (*e.g.* the night length governing the bud set *etc.*), which is much of importance for the performance of young trees in a non-domestic environment (Hannerz, 1998). In addition, various types of pests and pathogens might appear and compromise the success of introduced tree species (Yanchuk *et al.*, 2009). In this light, the need to elaborate much on the generation of approriate plant material as expressed by the practicioners of the boreal region, is better understandable.

In all other bioclimatic regions *i.e.* the here so-called European mainland regions, the negative expectations prevail, according to the EEA report. The most pressing scenarios are the *rise of temperature* and the *decline in precipitation* during the vegetation period, as can be seen from the assertions referred above. In this view, the statements of the experts of the European mainland are also better traceable since in their opinion the aspect of utmost importance is drought and the corresponding countermeasures. First of all, this holds true for the *warm mediterranean region* where drought periods by definition occur regularly, according to the Köppen-Geiger climate map (Peel *et al.*, 2007). Still, it is also valid for the other European mainland regions, according to the here achieved results (Figure 1B, Figure 2). To this must be added that the techniques for site preparation and against soil compaction which play a key role for the experts of these regions, overwhelmingly are seen as sustainable measures to face drought (Table 3). The more so, measures out of the category *silviculture* that are fundamental for the stand establishment in the eyes of the experts of these regions (Figure 1), nowadays play a key role in the fight against risks as contained by the EEA report and listed above (storm, pests, and biodeversity loss) (*e.g.* Tognetti *et al.*, 2022). The term *silviculture* in this connection might be considered just a synonym for the expression *climate smart forestry* which aims to build resilient forest ecosystems (Nabuurs *et al.*, 2018). Also with respect to the found relevance of silvicultural measures, therefore, the results of the study mirror the conditions and constraints that climate change has generated in the forests of the European continent.

Ultimately, the experts consulted for this study identified three groups of measures for stand establishment, which constitute the very core of the forestry strategies devised to face climate change: plant material selection, site preparation, and silviculture. To a large extent, this is in agreement with the suggestions outlined in (Forest Europe, 2020b). That report clearly states that "the best opportunity to enhance the adaptive capacity of forests is during a regeneration period (…) and in the early stand-development stages" (p. 34). In the context of the cited report, the strongest focus is on plant material. In that respect, concrete measures cover: the choice of tree species, genotypes, and provenances; the introduction of new species (non-natives); and the managed relocation of native species i.e. the so-called assisted migration (Williams & Dumroese, 2013). Secondly, that report points to the importance of provisioning water to the stands. As essential sub-strategies leading to this goal, it does promote irrigation methods (*e.g.* the building and restoring of small water reservoirs) but shows a clear preference for more sustainable alternatives. As such, it recommends specific measures within site preparation (*e.g.* weeding) and silviculture (*e.g.* suitable tree species combination). Our study fully agrees with those strategies by zooming in on the specific measures to be taken at the early development stage (*i.e.* plantation and establishment).

5 Conclusion

The evaluations of the survey on forest stand establishment practices in Europe led to the distinction of two regions: Boreal and mainland Europe. For the boreal region, most attention is on *mechanical site preparation*, followed by *plant material*. The most severe threat for this biogeographical context comes from the *insects*, and *fertilization for growth acceleration* is expected to be the most promising measure in the future compared to the past. Experts from mainland Europe, rate *silvicultural measures* as most important for successful reforestation, followed by *mechanical site preparation*. Here, the principal threat is seen in drought, followed by *game damage*. Measures *against drought and against soil compaction*, are considered as most beneficial for the stand establishment in the future. In all regions the listed key aspects for stand establishment overwhelmingly are seen as effective sustainable measures for the water procurement.

Based on these results, three guidelines for the future practice are expressed:

i) The most relevant threat in the future is drought.
ii) The most promising countermeasure against drought is not irrigation but
iii) rather any of the following techniques for sustainably increasing water use efficiency and availability, such as mechanical site preparation, appropriate plant material, and silvicultural strategies.

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Supplementary material

Table S1 shows the results of the Kruskal Wallis-test and the Dunn test on the differences between the biogeographic regions in terms of the importance that by the experts is attributed to the listed early measures for stand establishment in

i) the future and
ii) the future in contrast to the past.

Table S2 contains the Silhouette coefficients as measures for the goodness of clustering.

The original version of the survey is also included in the supplementary material.

Conflict of interest statement

The authors declare no conflict of interest.

Author Contributions

Conceptualization, B.E., M.vL.; data collection, B.E., S.B., K.B., T.L., C.O., R.S., M.vL; methodology, 412 B.E., M.vL; software and analyses, B.E., writing – original draft preparation, B.E., M.vL, S.B., K.B., T.L., C.O., writing – 413 review and editing, B.E., S.B., K.B., T.L., C.O., R.S., M.vL; supervision, M.vL, funding acquisition, M.vL.

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Supplementary Materials

Tabe S1: Statistical assessments of the differences between the regions concerning the importance attributed to early measures for stand establishment in i) the future and ii) the future in contrast to the past. The table contains the results for the the measures as well as the post-hoc verification. For further details refer to the text.

Tabelle S1: Statistische Analyse der Unterschiede zwischen den Regionen betreffend die den Bestandesbegründungsmaßnahmen zugemessene Bedeutung, und zwar i) in Zukunft ii) in Zukunft im Unterschied zur Vergangenheit. Die Tabelle enthält die Ergebnisse zu den aufgelisteten Maßnahmen als auch zu den post-hoc Untersuchungen (paarweise Gegenüberstellung der einzelnen Regionen innerhalb einer jeweiligen Maßnahme). Weitere Details finden sich im Text.

	Urgency in the future	Difference between urgency in the future and the past	
	p-value	*p-value*	*p-value*
	Kruskal Wallis-test		
Measure			
Against drought	0.065	**0.003 ***	
Fertilization nutrients	0.178	0.054	
Fertilization growth	0.054	**0.016 ***	
Against soil compaction	**0.015 ***	0.618	
	Dunn test		
Pairs of regions	Against soil compaction	Against drought	Fertilization growth
Atl – Atl Cont	0.569	0.274	0.440
Atl - **Boreal**	**0.024 ***	0.266	**0.039 ***
Atl Cont - **Boreal**	**0.035 ***	**0.001 ***	**0.048 ***
Atl - Cont	0.481	0.918	0.369
Atl Cont - Cont	0.807	0.101	0.624
Boreal - Cont	**0.034 ***	0.222	0.149
Atl – Atl Med	0.485	0.796	0.605
Atl Cont – Atl Med	0.780	**0.031 ***	0.642
Boreal – Atl Med	**0.038 ***	0.296	**0.020 ***
Cont – Atl Med	0.915	0.883	0.440

*Significance level α < 0.05 **

Tabe S2: Silhouette coefficients as measures for the goodness of clustering.

Tabelle S2: Silhouette Koeffizienten als Maßzahlen für die statistische Genauigkeit der Clusteranalyse.

Goodness of clustering	
Cluster	Silhouette coeff
1	0.15
2	0.27
Model total	0.36

0 - 0.25 no structure 0.26 – 0.5 weak structure 0.51 – 0.75 middle structure 0.76 – 1 strong structure

Questionnaire

Early operations at stand establishment

The questionnaire contains two sections (to be filled):

1. General information on practices at stand establishment applied by your company

2. Description of the measures practiced by your company as to

a) Irrigation/Water supply + example for illustration

b) Mechanical site preparation + example for illustration

c) Fertilization + example for illustration

If you are not able to give information to a particular question, please feel free to skip.

However, we are grateful for any information. Please note, it is not required to give scientifically substantiated answers, it´s essential to communicate your personal experience and opinion!

Thank you!

Company:

Email adress:

Intensity levels ***1*** very low ***2*** low ***3*** medium ***4*** high ***5*** very high					
General information on practices applied by your company					
According to your opinion, what are nowadays the key aspects for successful stand establishment? What matters the most?					
In your company, what is the priority of the here listed measures at present? *From 1 to 5*	*Against drought*	*Fertilization against lack of nutrients*	*Fertilization for enhancing growth*	*Against soil compaction*	*Other measures (if available)*
	Please name other measures (if available)				
In your company, what was the priority of the here listed measures in the last 10 years? *From 1 to 5*	*Against drought*	*Fertilization against lack of nutrients*	*Fertilization for enhancing growth*	*Against soil compaction*	*Other measures (if available)*
In your opinion, what will be the priority of the here listed measures within the next 10 years? *From 1 to 5*	*Against drought*	*Fertilization against lack of nutrients*	*Fertilization for enhancing growth*	*Against soil compaction*	*Other measures (if available)*
During the last 10 years, could you observe an increase of the failure rate at stand establishment? Yes / No If so, to what percentage (see right hand)	< 10	10-30	30-50	50-70	>70
At present, what is the most essential problem at stand establishment (water scarcity, lack of nutrients, soil compaction, or other problem(s)?)					
Has this problem intensified during the last 10 years? ***1*** very low ***2*** low ***3*** medium ***4*** high ***5*** very high	1	2	3	4	5
If so (see previous question) to what percentage have the costs increased (approx..) – compared to the situation 10 years ago?	< 10	10-30	30-50	50-70	>70

Description of the measures applied by your company

The measures include three aspects: Irrigation/water supply, mechanical site preparation, fertilization.

In the following, in a first section please give a general explanation of the measure you want to describe, and in a second section please describe a concrete example for illustration, respectively.

How to classify a measure, is defined by the purpose. For example, if you practice soil scarification with the purpose of enhancing the water infiltration, please put it in the section *irrigation/water supply*, otherwise in the section *mechanical site preparation*.

Please note: It is not required to give scientifically substantiated answers, it´s essential to communicate your personal experience and opinion!

Irrigation/Water supply

In this context, the term irrigation comprises systems where the water is being transported to the stand, e.g. sprinklers, drip irrigation, irrigation with tanker…

In contrast, we define (alternative sustainable forms of) water supply as given when methods are applied for retaining, storing and re-distributing the available (rain)water on a particular site, e.g. by mulching…

What is the name of the measure?					
Which work steps are included, how do you proceed?					
Under which conditions do you use this method?					
What does one have to pay attention when using this method? What is your personal recommendation?					
What do you expect from this method? If omitting this method, what would probably happen?					
Did this method fulfil your expectation? *From 1 to 5* ***1*** very low ***2*** low ***3*** medium ***4*** high ***5*** very high	1	2	3	4	5
Has the use of this method intensified during the last 10 years? *From 1 to 5* ***1*** very low ***2*** low ***3*** medium ***4*** high ***5*** very high	1	2	3	4	5
What are the approx. costs per ha?					
According to your personal opinion, is this method reasonable? Why?					
Other remarks as to this method.					

Concrete example for the above-described method for irrigation / water supply Please designate the stand unambiguously, in case you report this stand also in another category, like mechanical site preparation or fertilization.	
What is the name of the measure illustrated by the following example (and described above)?	
Name of the stand (if available)	
Location (eventually coordinates)	
Sea level	
Slope exposition	
Slope inclination (approx.)	
Geomorphological characteristics (e.g. remarkable soil elevations and depressions…)	
Soil depth (organic layer, mineral soil layer, approx.)	
Included tree species and share of tree species (in tenths, referring to stem number)	
Spacing pattern/distances? Stem number/ha?	
If mixture: tree by tree or in mono-species patches?	
In what year occurred the stand establishment? In what season? What was the age of the trees at planting?	
What was the planting technique?	
What was the age of the plants when the here-described measure was applied?	
Why was the measure performed (reaction to problem, out of routine, preventively?)	
Costs/ha?	
Did the measure fulfil the expectation?	
Were there any further specific details at stand establishment and early operations on this stand?	

Mechanical site preparation					
What is the name of the measure?					
Which work steps are included, how do you proceed?					
Under which conditions do you use this method?					
What does one have to pay attention when using this method? What is your personal recommendation?					
What do you expect from this method? If omitting this method, what would probably happen?					
Did this method fulfil your expectation? *From 1 to 5* ***1*** very low ***2*** low ***3*** medium ***4*** high ***5*** very high	1	2	3	4	5
Has the use of this method intensified during the last 10 years? *From 1 to 5* ***1*** very low ***2*** low ***3*** medium ***4*** high ***5*** very high	1	2	3	4	5
What are the approx. costs per ha?					
According to your personal opinion, is this method reasonable? Why?					
Other remarks as to this method.					

Concrete example for the above-described method for mechanical site preparation Please designate the stand unambiguously, in case you report this stand also in another category, like irrigation/water supply or fertilization.	
What is the name of the measure illustrated by the following example (and described above)?	
Name of the stand (if available)	
Location (eventually coordinates)	
Sea level	
Slope exposition	
Slope inclination (approx.)	
Geomorphological characteristics (e.g. remarkable soil elevations and depressions…)	
Soil depth (organic layer, mineral soil layer, approx.)	
Included tree species and share of tree species (in tenths, referring to stem number)	
Spacing pattern/distances? Stem number/ha?	
If mixture: tree by tree or in mono-species patches?	
In what year occurred the stand establishment? In what season? What was the age of the trees at planting?	
What was the planting technique?	
What was the age of the plants when the here-described measure was applied?	
Why was the measure performed (reaction to problem, out of routine, preventively?)	
Costs/ha?	
Did the measure fulfil the expectation?	
Were there any further specific details at stand establishment and early operations on this stand?	

Fertilization					
What is the name of the measure?					
Which work steps are included, how do you proceed?					
Under which conditions do you use this method?					
What does one have to pay attention when using this method? What is your personal recommendation?					
What do you expect from this method? If omitting this method, what would probably happen?					
Did this method fulfil your expectation? *From 1 to 5* ***1*** very low ***2*** low ***3*** medium ***4*** high ***5*** very high	1	2	3	4	5
Has the use of this method intensified during the last 10 years? *From 1 to 5* ***1*** very low ***2*** low ***3*** medium ***4*** high ***5*** very high	1	2	3	4	5
What are the approx. costs per ha?					
According to your personal opinion, is this method reasonable? Why?					
Other remarks as to this method.					

Concrete example for the above-described method for fertilization Please designate the stand unambiguously, in case you report this stand also in another category, like mechanical site preparation or irrigation/water supply.	
What is the name of the measure illustrated by the following example (and described above)?	
Name of the stand (if available)	
Location (eventually coordinates)	
Sea level	
Slope exposition	
Slope inclination (approx.)	
Geomorphological characteristics (e.g. remarkable soil elevations and depressions…)	
Soil depth (organic layer, mineral soil layer, approx.)	
Included tree species and share of tree species (in tenths, referring to stem number)	
Spacing pattern/distances? Stem number/ha?	
If mixture: tree by tree or in mono-species patches?	
In what year occurred the stand establishment? In what season? What was the age of the trees at planting?	
What was the planting technique?	
What was the age of the plants when the here-described measure was applied?	
Why was the measure performed (reaction to problem, out of routine, preventively?)	
Costs/ha?	
Did the measure fulfil the expectation?	
Were there any further specific details at stand establishment and early operations on this stand?	

Additional:

Please just list measures for irrigation/water supply, mechanical site preparation, fertilization that are being practiced in your company and that have not been mentioned in the previous chapters:

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First data on rainfall interception in an Atlas cedar forest (*Cedrus atlantica* Manetti) in the Aurès (eastern Algeria)

Erste Daten zur Niederschlagsinterzeption in einem Atlaszederwald (*Cedrus atlantica* Manetti) im Aurès (Ostalgerien)

Toufik Benhizia[1], Salim Lebbal[1*] and Abdelghafour Abaidia[1]

Keywords: semi-arid forests, stemflow, interception, throughfall, climate change

Schlüsselbegriffe: semi-aride Wälder, Stammabfluss, Interzeption, Kronendurchlass, Klimawandel

Abstract

With climate change, data on throughfall, stemflow and rainfall interception in forests are much needed by hydrologists throughout the world, including the Mediterranean region. Such data are rare for Algeria, especially for cedar forests. Thus, the present study is interested in analysis of throughfall, stemflow and rainfall interception in a cedar forest dominated by *Cedrus atlantica* Manetti in the province of Batna (Eastern Algeria) and establishing models for forecasting the different rainfall fractions in this forest type. Specific containers (plastic bottles and collars) were installed at stems of 30 trees, under tree crowns and in an open area not covered by tree crowns between January 2018 and December 2019 to collect the different studied fractions of water (rainfall, throughfall and stemflow). Our results reveal that throughfall was with 65.41% of the total rainfall the greatest fraction in the studied cedar forest. Stemflow represented only a very small fraction of total rainfall with 3.86%. The mean rainfall interception was 30.72 % of the total rainfall. The relationships between rainfall, throughfall and stemflow were assessed by linear regressions. We found strong correlations between throughfall, stemflow and rainfall with coefficient of determination

[1] Department of Agronomic Sciences, Abbas Laghrour University, Khenchela, Algeria
*Corresponding author: Salim Lebbal, salim-leb@hotmail.com

R^2 ranging between 0.92 and 0.99. The equations developed by this study revealed that the studied cedar forest must receive at least 1.70 and 4.46 mm of rainfall, to trigger throughfall and stemflow, respectively.

Zusammenfassung

Angesichts des Klimawandels sind Daten über Kronendurchlass, Stammabfluss und Interzeptionin Wälder für Hydrologen auf der ganzen Welt, einschließlich der Mittelmeerregion, sehr gefragt. Dennoch sind solche Daten in Algerien, insbesondere für Zedernwälder, nicht verfügbar. Diese Studie beschäftigt sich mit der Quantifizierung des Kronendurchlass, des Stammabflusses und der Interzeption von Niederschlag in einem Zedernwald dominiert durch *Cedrus atlantica* Manetti in der Provinz Batna (Ostalgerien) und mit der Entwicklung von Modellen zur Vorhersage der verschiedenen Niederschlagsfraktionen in diesem Waldtyp. Zwischen Januar 2018 und Dezember 2019 wurden spezielle Behälter (Plastikflaschen und -manschetten) installiert an 30 Bäumen, unter Baumkronen und auf Freiflächen ohne Kronenbedeckung um die verschiedenen untersuchten Niederschlagsfraktionenzu sammeln.

Die Ergebnisse zeigten, dass der Kronendurchlass 65.41 % des Niederschlags im untersuchten Zedernwald betrug. Der Stammabfluss stellte nur einen sehr kleinen Teil des Gesamtniederschlags dar mit 3.86 %. Die mittlere Interzeption betrug 30.72 % des Gesamtniederschlags. Die Beziehungen zwischen Niederschlag, Kronendurchlass und Stammabfluss wurden mit linearen Regressionen analysiert. Wir beobachteten starke Korrelationen zwischen Kronendurchlass, Stammabfluss und Niederschlag mit Bestimmtheitsmass R^2 zwischen 0.92 und 0.99. Die in dieser Studie entwickelten Gleichungen ergaben, dass der untersuchte Zedernwald mindestens 1.70 bzw. 4.46 mm Niederschlag erhalten muss, damit Kronendurchlass bzw. Stammabfluss messbar ist.

1 Introduction

Rainfall is one of the most important sources of water in forest ecosystems and it is responsible for forest productivity, especially in seasonally dry forests (Tague *et al.* 2019; Missaoui *et al.* 2020; Yang *et al.* 2022; 2023; Zhao *et al.* 2023). Rainfall is the main input to the soil water balance and plays an important role in the water cycle and the plant-soil-atmosphere system (Biniak-Pieróg 2017; Klamkowski *et al.* 2011; Levia *et al.* 2017; Schwingshackl *et al.* 2017; Han *et al.* 2018; Magliano *et al.* 2019; Sun *et al.* 2022; Treder *et al.* 2022). The distribution of rainfall by trees is an important hydrological process, particularly in the context of climate change (Llorens & Domingo, 2007; Sadeghi *et al.* 2018; Yang *et al.* 2022; Zhao *et al.* 2023). The two main processes, evapotranspiration and interception, are strongly influenced by vegetation and its composition (Vicente *et al.* 2018). With climate change, any alterations in the precipitation or temperature regimes will directly affect the dynamics of the interception of rains by forests. Previous studies pointed out that with climatic variations, rainfall may be concentrated in a shorter time period with more intense rainfall events and in consequence higher drought risks (Benhamiche *et al.* 2014; Zhao *et al.* 2023). It is increasingly recognized that a better understanding of water use patterns and their response to climate change depends on our ability to better quantify the dynamics of rainfall fractions (Yang *et al.* 2023).

Therefore, an understanding of the redistribution of rainfall by the action of the forest cover is very useful to understand the water balance and the nutrients of the ecosystem, but also to develop the silvicultural practices, that mitigate the effects of climate change (Jeong *et al.* 2019; Tague *et al.* 2019; Shi *et al.* 2022; Zhao *et al.* 2023). During a rainfall event, the forest cover causes, on the one hand, a reduction in the rainfall amount reaching the forest floor, and on the other hand, a redistribution of the latter into three fractions, throughfall, stemflow and interception (Dohnal *et al.* 2014; Sadeghi *et al.* 2020; Jančo *et al.* 2021; Zhao *et al.* 2023). Throughfall penetrates the tree crowns, while stemflow is water running along the surface area of tree trunks (Lévia *et al.* 2017). The amounts of rainfall, that is captured by forest canopy and then returned to the atmosphere by evaporation, are often referred to as interception (Šraj *et al.* 2008; Dohnal *et al.* 2014; Jančo *et al.* 2021).

The Mediterranean area is more strongly affected by climate change than other regions globally (GIEC 2014; Lionello *et al.* 2018; IPCC 2021). The expected changes include hotter and drier summers as well as a general decrease in rainfall as large as minus 40% in certain regions (Barros *et al.* 2014; Peñuelas *et al.* 2017; Arar *et al.* 2020; Tuel *et al.* 2020).

The Atlas cedar, *Cedrus atlantica* Manetti, is endemic to North African mountains and constitutes the southwesternmost species of the genus *Cedrus* (Bouahmed *et al.* 2019). In Algeria, it constitutes a much values forest asset of remarkable ecological, economical and cultural importance (Médail & Quézel 2003). It is also classified as an endangered species and carries the status of a rare plant (Yahi *et al.* 2007; Touati *et al.* 2021). The Algerian cedar forests occupy an area of about 2089 km², where the stands located in the Aurès regions are the most xeric in Algeria (Arar *et al.* 2020) and they have suffered from tree mortality linked to drought and climate change for several years (Allen 2009; Yahi & Djellouli 2010; Kherchouche *et al.* 2012; Bezzih *et al.* 2021). Bouahmed *et al.* (2019) indicated that the decline of Algerian cedar forests is driven by a shift of climate towards drier conditions. This is problematic as Atlas cedar is characterized by strong height growth, that is highly sensitive to drought (Ladjal *et al.* 2007).

Growth-climate relationships for Atlas cedar showed a significant positive, cumulative and stable temporal effect of precipitation variability (Slimani *et al.* 2014). A negative growth shift was triggered by a climate shift towards drier conditions in the 1980s (Navarro-Cerrillo 2019). A very high decrease in suitable areas of Atlas cedar was forecasted based on the predictions of Arar *et al.* (2019) for 2070; which indicates that the species has little chance to survive under the conditions of future climate change scenarios. More arid conditions would raise Atlas cedar mortality rates and trigger compositional shifts toward forests dominated by species better able to tolerate drought, such as *Quercus ilex* (Navarro-Cerrillo 2019).

Studies of rainfall interception have long received considerable attention worldwide (Gash *et al.* 1980; Llorens & Domingo 2007; Muzylo *et al.* 2009; Zhao *et al.* 2023) and remains an important topic for future environmental studies (Zhang *et al.* 2023). Many researchers have already recommended continuing studies on the redistribution of rainfall by forests, particularly for semi-arid and arid regions, to better understand the interception process in the context of climate change and to balance the water demands of humans and the ecosystem (Friesen & Van Stan 2019; Jeong *et al.* 2019; Ma *et al.* 2019; Levia *et al.* 2019; Yang *et al.* 2022; Zhao *et al.* 2023). It is noticed that the majority of available studies on rainfall interception have focused on cumulative annual amounts and not on individual values of interception by rainfall events (Muzylo *et al.* 2009). Although semi-arid environments represent a third of the world's land area (Li *et al.* 2020; Mirzabaev *et al.* 2022), little is known from a point of view of rainfall interception compared to other climates (Llorens & Domingo *et al.* 2007; Muzylo *et al.* 2009; Magliano *et al.* 2019).

Despite the obvious significance of this topic, there is currently no data on the interception of rainfall in Algeria by the action of the Atlas cedar. Our study aims fill this gap and to provide models to predict the interception of rainfall by traa canopies for the first time for the Atlas cedar. A novel aspect of our study is exploring rainfall interception for single events for an endemic species in a semi-arid climate.

2 Materials and methods

2.1 Measurements of rainfall, throughfall, stemflow and interception

The study was conducted on the interception of rainfall by the action of Atlas cedar, in an area located in the northeastern part of Algeria in the province of Batna (Fig. 1). More precisely, the Atlas cedar forest was located in the Larbaa mountains (35°39'50''N, 6°12'31''E) at an altitude of 1680 m with average tree density of 600 trees per hectare and an estimated leaf area index (LAI) between 1.7 and 2.5. We estimated LAI based literature (Breda 1999; Breda *et al.* 2002) and the observation that the canopy of our studied forests is relatively sparse and suffered from drought effects. The tree height ranged between 14 and 18 m and their age was approximated 90 years. Tree diameter at breast height ranged between 26 and 32 cm and the basal area of the studied cedar forest was 32 m^2/ha.

The data provided by the meteorological station of Ain Skhouna (35°75'79''N, 6°30'57''E), about 43 km in the northeast of the study site, revealed that the average rainfall in the Batna region over 25 years (1989-2013) was 332.83 mm with an average air temperature of 15.58 °C.

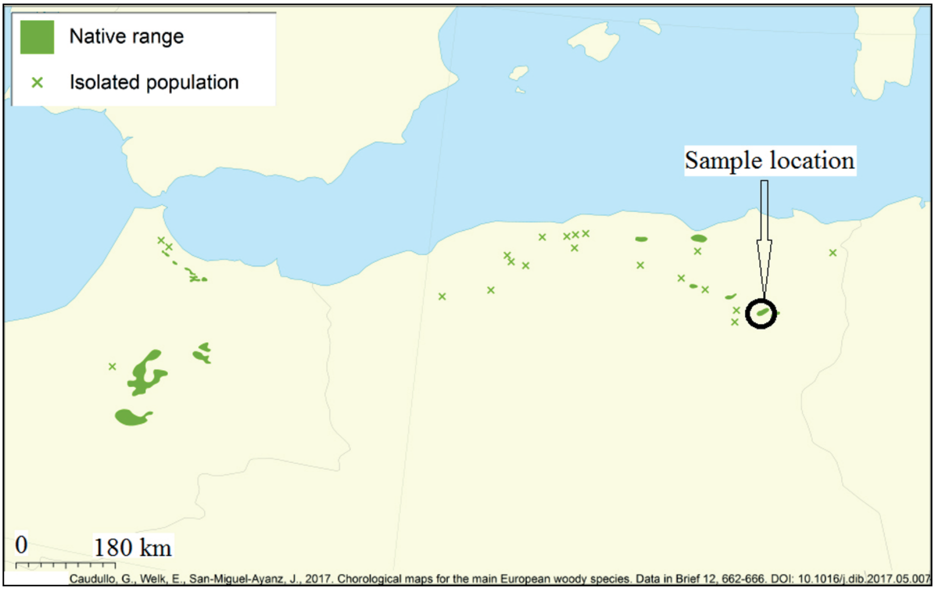

Figure 1: The location of the study site and distribution of Cedrus atlantica (Caudullo et al. 2020).

Abbildung 1: Der Standort des Untersuchungsortes und die Verbreitung von *Cedrus atlantica* (Giovanni et al. 2020).

The collectors used to measure rainfall, throughfall and stemflow were deduced from previous studies (Gash *et al.* 1980; Molina & del Campo 2012; Llorens & Domingo 2007; Attarod *et al.* 2015). Because of its adaptability to forecast rainfall interception, particularly for coniferous forests in semi-arid climates, the Gash model was chosen (Llorens & Domingo 2007; Muzylo *et al.* 2009). Water volumes (rainfall, throughfall and stemflow) were measured continuously (after each rainfall event) for two years from January 2018 until December 2019.

The different fractions of water were collected, just after a rainfall event finished, using plastic bottles with the upper part cut and turned into a funnel (Fig. 2). The receiving area for each bottle was 0.0227 m^2. Throughfall was quantified by four bott-les installed under the central and peripheral parts of each tree. Previous works have stated, that rain gauges should be placed not only in the central area of the crown, near the trunk of the trees, but also in the periphery to ensure more reliable results (Bartík *et al.* 2016; Dohnal *et al.* 2014; Minďáš *et al.* 2018). The bottles used to measure the throughfall were installed under crowns of 30 Atlas cedar trees, for a total of 120 bottles. Our overall surface for receiving throughfall water (2.72 m²) is considered sufficient to correctly estimate this fraction of rainfall (Rodrigo & Avila 2001; Llorens & Domingo 2007). On a bare plot further 20 bottles were placed identical to those used to measure the throughfall and in approximately eight meters distance from the Atlas cedar trees, to measure rainfall undisturbed by tree canopies.

Figure 2: Devices for collecting stemflow (A) and throughfall (B).

Abbildung 2: Geräte zum Sammeln von Stammabfluss (A) und Kronendurchlass (B).

Stemflow was measured using plastic collars fixed around the trunks of 16 trees and sealed with mastic. These collars were connected with a plastic container using a pipe. The collected rainfall volumes are converted into mm using the formula (Vialard-Goudou & Richard 1956):

$$P = 10 \times V/S \qquad (1)$$

with P rainfall (mm), S reception surface (cm^2) and V volume of water collected (cm^3).

Stemflow was calculated by dividing the collected volumes by the crown surface (Livesley *et al.* 2014). The interception in mm were estimated according to (Llorens & Domingo 2007; Moreno-Pérez *et al.* 2018):

$$I = P - Tf - Sf \qquad (2)$$

with I interception (mm), P rainfall (mm), Tf throughfall (mm) and Sf is stemflow (mm).

2.2 Data analysis

The results of rainfall, throughfall, stemflow and interception were subject to analysis of variance (ANOVA) at the 5% error threshold, using SPSS software version 10.0.5 (SPSS Inc.). The relationships between the different fractions studied (P, Tf, Sf, I) were estimated by linear regressions using Microsoft Excel 2013. We calculated the amount of rainfall needed to trigger Tf and Sf by reformulating the linear functions for Sf and Tf equal 0.1 mm.

3 Results

3.1 Rainfall

The results of two years of measurements showed that the cumulative daily rainfall was 773.6 mm, created by 118 days with rainfall. The year 2018 received more rainfall with 436.6 mm, compared to year 2019 with 337 mm.

Daily rainfall fluctuated between 0.9 and 56 mm with an average of 4.28 mm per day of rainfall. The distribution by rainfall class ranging from 0 to 60 mm and their frequencies are available in Table 1.

Table 1: Classes, frequencies and accumulations of daily rainfall.

Tabelle 1: Klassen, Häufigkeiten und Anhäufungen der täglichen Niederschläge.

Daily rainfall	2018			2019			Cumulative rainfall during both years (mm)
	Frequencies (Days)	Cumulative rainfall		Frequencies (Days)	Cumulative rainfall		
		mm	%		mm	%	
]0-5 mm]	43	122.2	27.99	30	76.5	22.70	198.7
]5-10 mm]	14	104.4	23.91	10	71.2	21.13	175.6
]10-20 mm]	6	82.0	18.78	11	155.3	46.08	237.3
]20-30 mm]	0	0.0	0.00	0	0.0	0.00	0.0
]30-60 mm]	3	128.0	29.32	1	34.0	10.09	162.0
Total	66	436.6	100	52	337.0	100	773.6

Table 1 demonstrated the dominance of rainfall less than or equal to 5 mm per day, throughout the study period. In 2018, most rainfall was created by rainfall events with 30-60 mm per day, while in 2019 most rainfall originated from events with 10-20 mm per day. It should be noted that only about 16% of days in the measurement period received rainfall greater 0 mm. From these 118 days with rainfall, 73 days has rainfall between 0 and 5 mm and the number of days with rainfall greater 30 mm was very low with 4 days out of 118. Surprisingly, the cumulative rainfall of these four days was 162 mm (19.66 % of the total rainfall).

3.2 Throughfall

Our results revealed that among 118 rainy days, only 92 events could trigger throughfall, penetrating the crowns of the Atlas cedar forest. Accumulation throughfall over two years was 509.32 mm, which represents an average of 65.41% of total annual rainfall. We note that the highest throughfall rate (68.69%) was recorded in year 2018 (Fig. 3), which was also received more rainfall compared to the year 2019 (436.6 and 337 mm, respectively).

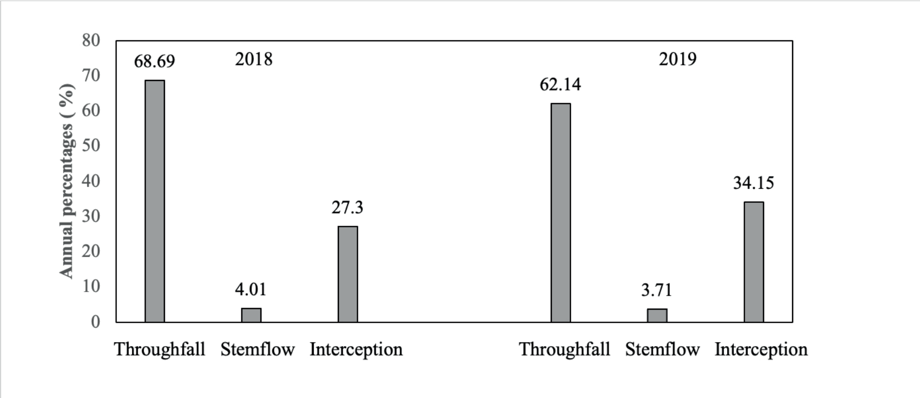

Figure 3: Annual percentages for throughfall, stemflow and interception during the study period.

Abbildung 3: Jährliche Prozentsätze für Kronendurchlass, Stammabfluss und Interzeption während des Untersuchungszeitraums.

The average daily throughfall for 2018 (0.82 mm/day) was much greater compared to the throughfall for the year 2019 (0.54 mm/day). It should also be noted that during the year 2019, the throughfall for the two months of June and July was nil. Throughout the study period, the largest amounts of throughfall were recorded between March and May. Figure 4 presents the monthly variations for the two years 2018 and 2019.

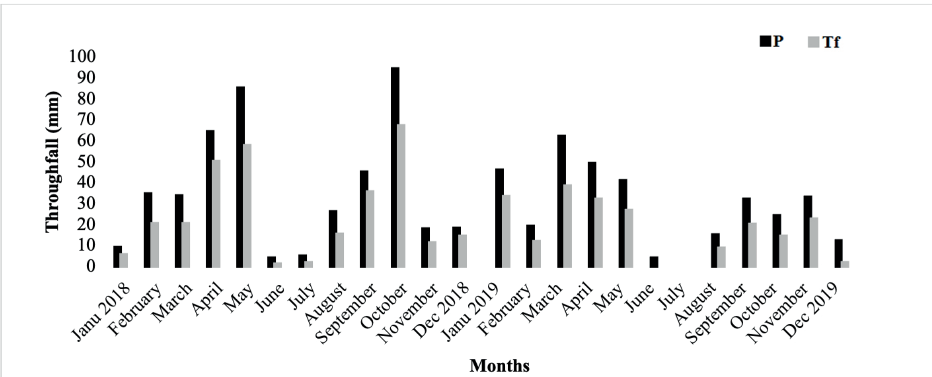

Figure 4: Monthly variation of throughfall during the study period.

Abbildung 4: Monatliche Variation des Kronendurchlasswährend des Untersuchungszeitraums.

3.3 Stemflow

The number of rainfall days that could trigger stemflows, through the cedar tree trunks, was only 37 days, that is a rate of 31.35% of the total number of rainfall days during our study period. The results also showed that the average stemflow rate was around 3.86%. The stemflow for 2019 was slightly higher than for 2018 (4.01 and 3.71%, respectively) (Fig. 3).

The average volume per rainfall event of water brought to the soils of the cedar forest through stemflow fluctuates between 0.03 and 0.05 mm for 2019 and 2018 respectively.

On an interannual scale, the two months of June and July were characterized by zero stemflow, while, the largest stemflows were recorded between March and May (2.2 - 3.4 mm) (Fig.5).

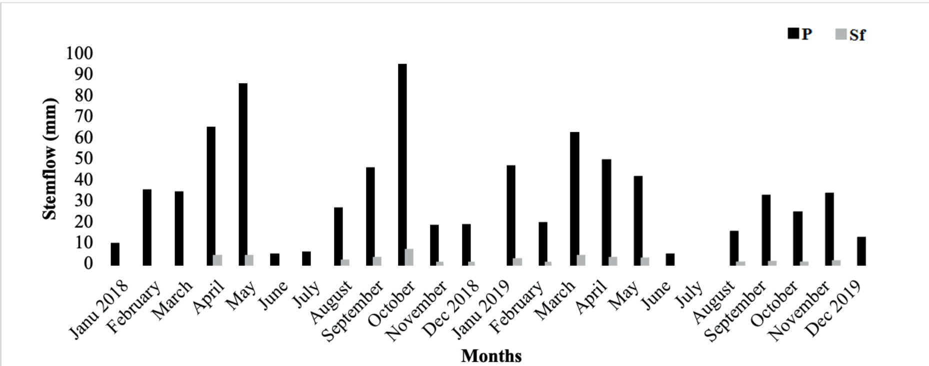

Figure 5: Monthly variation of stemflow volumes throughout the study period.

Abbildung 5: Monatliche Variation der Stammabfluss während des Untersuchungszeitraums.

3.4 Interception

The average interception rate found for this study is 30.72%. ANOVA analysis confirmed a significant difference between years (p= 0.010) (Table 2). The interception was higher in the least rainy year. It was 34.15% in 2019 (where the rainfall was 337 mm) and 27.30% in 2018 (where the rainfall was 436.6 mm) (Fig. 3). The mean interception varies between 0.32 and 0.33 mm per rainfall day throughout the study period.

As for the monthly variation, the ANOVA analysis revealed a significant difference (p= 0.002) (Table 2). The interception was much greater in March 2019 (20.2 mm) and May 2018 (24 mm) (Fig.6).

Table 2: ANOVA analysis of the studied parameters at an intra-annual and inter-annual scale. Asterisk indicate significant difference at $p < 0.05$.

Tabelle 2: ANOVA-Analyse der untersuchten Parameter auf einer inter- und intra-annualen Skala. Stern zeigt signifikante Unterscheide mit $p < 0.05$.

	P	Tf	Sf	I
Interannual variations	0.897	0.666	0.960	0.010 *
Intraannual variations	0.755	0.838	0.724	0.002 *

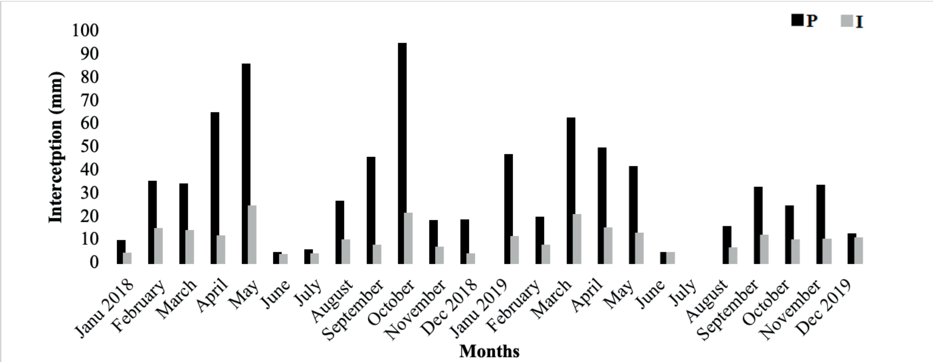

Figure 6: Monthly variation of rainfall interception throughout the study period.

Abbildung 6: Monatliche Variation der Niederschlagsinterzeption während des gesamten Untersuchungszeitraums.

3.5 Relationship between rainfall and throughfall

The results relating to the relationship between rainfall and throughfall during both years, under the Atlas cedar, are presented in Figure 7. The latter shows a positive linear relationship between throughfall (Tf) and rainfall (P) ($R^2 = 0.99$). There is a proportional relation between these two parameters.

The equations presented in Figure 7 show that Atlas cedar trees must receive at least 1.70 mm of rain to allow the rain to pass to the forest soils and subsequently feed the groundwater.

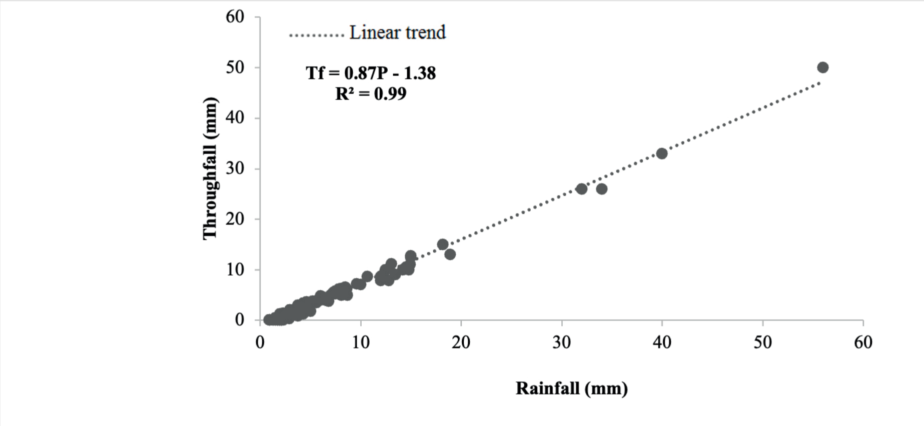

Figure 7: Relationship between rainfall and throughfall in the studied cedar forest.

Abbildung 7: Zusammenhang zwischen Niederschlag und Kronendurchlass im untersuchten Zedernwald.

3.6 Relationship between rainfall and stemflow

Figure 8 shows that stemflow is positively correlated with rainfall amounts (R^2 =0.92). The relationships between the rainfall and stemflow using a linear trend function are presented in Figure 8. By rearranging equation 8, we can conclude that the stemflow is triggered once 4.46 mm of rain is exceeded.

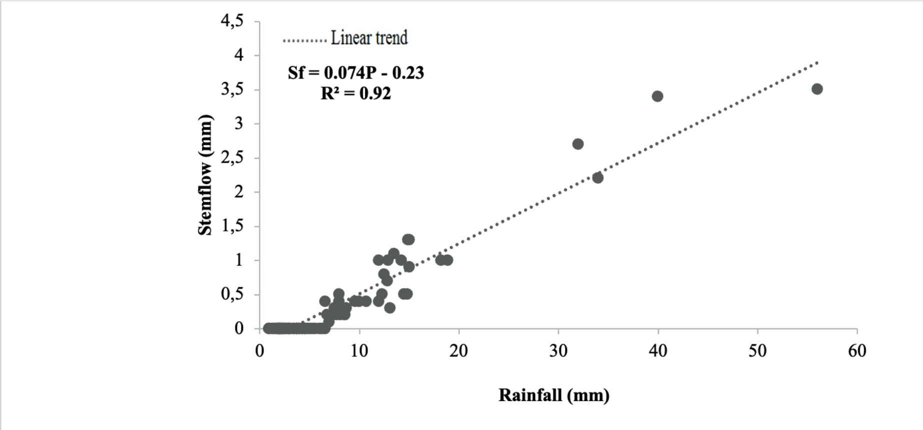

Figure 8: Relationship between rainfall and stemflow in the studied cedar forest.

Abbildung 8: Zusammenhang zwischen Niederschlag und Stammabfluss im untersuchten Zedernwald.

3.7 Relationship between rainfall and interception

Figure 9 shows that the volumes of interception are negatively correlated with the volumes of rainfall with coefficient of determination R2 varies between 0.18 and 0.63.

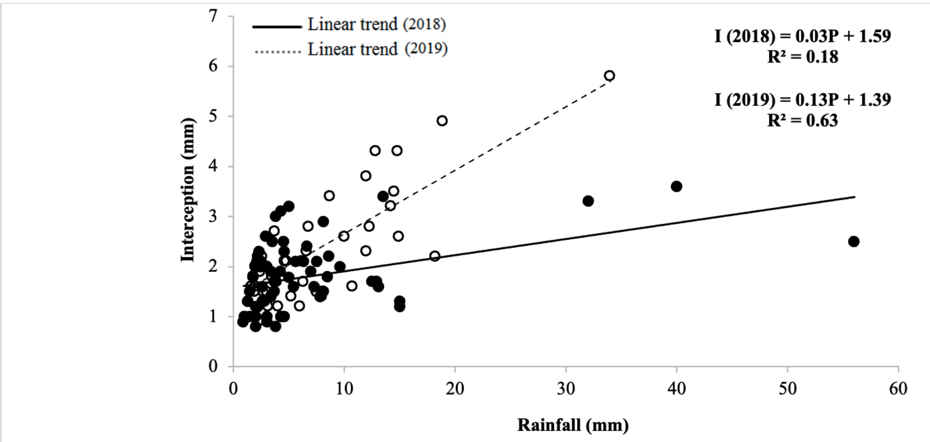

Figure 9: Relationship between rainfall and interception.

Abbildung 9: Zusammenhang zwischen Niederschlag und Interzeption.

4 Discussion

4.1 Rainfall

The average annual rainfall of 386.8 mm is higher than the average rainfall (332.83 mm) of the Batna region for a period of 25 years (1989-2013). Nevertheless, hydrologists are interested not only in annual rainfall, but also in rainfall events, as the latter are more important for throughfall, stemflow and interception than annual rainfall sums. In the present investigation, rainfall events were dominated by rainfall below 5 mm with an average of 4.28 mm per event.

Similarly, Benhizia *et al.* (2020) found, forthe Aleppo pine in a semi-arid region, that the daily rainfall was low, as daily rainfall higher than 30 mm was rare, but when it occurs, it can constitute a very significant proportion of the annual rainfall (33.52%). Moreover, other researchers stated, that in semi-arid and Mediterranean climates, daily rainfall of less than 10 mm constitutes almost all of the rainfall (Pérez-Suárez *et al.* 2013; Llorens *et al.* 2018). Our results suggest that the rainy days that can pass through the canopy of the Atlas cedar and feed the soil and the water table are much reduced. Indeed, Andreu *et al.* (2001) indicated that only daily rainfall greater than 15 mm was capable of producing groundwater recharge.

Vicente *et al.* (2018) have already asserted that rainfall events will become less frequent, which directly affects the deep percolation to groundwater. Similarly, Barros *et al.* (2014) and Vicente *et al.* (2018) reported that drought conditions are also expected to intensify, which could trigger plant mortality and species replacement events and consequently the forest water balances will be affected.

4.2 Throughfall

Studies on throughfall under the action of the Atlas cedar in a forest environment are rare or even nonexistent. Sensoy and Tanyel (2022) published the only study on *Cedrus libani* in an urban environment. Unfortunately, these researchers worked on rainfall greater than 10 mm and they found a throughfall rate of 51%. This rate is considered low compared to the present study (65.41%).

The scarcity of work on the redistribution of rainfall under the action of the Atlas cedar in forest environments led us to compare our results with studies that have worked on other conifers. The throughfall rate of the present study remains high compared to the results of Benhizia *et al.* (2020) which found for an Aleppo pine forest, a throughfall that varies between 51.36 and 56.95%. However, rainfall volumes and their characteristics as well as forest cover are not the same. The rainfall volumes of the present study are higher than the results of the latter researchers (386.8 vs.

312 mm). This difference may be, on the one hand, responsible for the increase in the rate of throughfall in our cedar forest and, on the other hand, dead branches and cones are abundant in the pine forest studied by the aforementioned researchers; and they are not too abundant in our cedar forest. Thus, Jeong *et al.* (2019) have claimed that for conifers, the drainage is low for stands characterized by dead branches because of the additional gain of rainwater from dead branches.

Besides, several previous studies stated that the throughfall in coniferous forests varied between 48.5 and 85% (Rapp & Romane 1968; Cape *et al.* 1991; Barbier *et al.* 2009; Zhou *et al.* 2013; Fan *et al.* 2014; Sun *et al.* 2014; Aydın *et al.* 2018; Jeong *et al.* 2019; Magliano *et al.* 2019; Dong *et al.* 2020; Yan *et al.* 2022).

Because the intra-annual variation was considerable, it must be pointed out here that the low throughfall, between June and August in the studied cedar forest, can negatively affect the germination of the Atlas cedar. Furthermore, Bentouati and Oujehih (1999) mentioned that the growth of Atlas cedar forests in the Aurès is conditioned by the substrate and the rainfall. They indicated that the total production of cedar forests in the Aurès is between 31 and 1007 m^3/ha depending on rainfall, density and age of the forest trees. In our case, it seems that cedar forests that rest on deep soils will benefit more from throughfall compared to stands that grow on soils not deep.

4.3 Stemflow

Studies on stemflow are not very abundant, particularly for conifers. Among these rare studies, some revealed a stemflow rate that fluctuates between 0.6 and 1.74% (Llorens *et al.* 1997; Llorens & Domingo 2007; Xiao *et al.* 2007; Ma *et al.* 2019; Dong *et al.* 2020). The stemflow rate found in the present study (3.86%) is relatively high compared to the results of the aforementioned researchers. The difference can be attributed to daily rainfall patterns and stand characteristics. Therefore, Fan *et al.* (2014) claimed that stemflow rate is closely related to daily rainfall amounts. Besides, the rate found by the present study can be very beneficial for cedar forests. Stemflow represents a minor proportion compared to throughfall, but it can concentrate 17.9 to 56.6 times the amount of precipitation in the soil profile adjacent to the root zone (Zhao *et al.* 2023).

Furthermore, other studies indicated that the stemflow represents only a very small proportion of rainfall and its rate ranges between 0.8 and 9.1% depending on precipitation, density, diameter and height of trees (Barbier *et al.* 2009; Saito *et al.* 2013; Pérez-Suárez *et al.* 2014; Aydın *et al.* 2018; Dong *et al.* 2020; Yang *et al.* 2022).

4.4 Interception

The interception rate of the present study (30.72%) is relatively low compared to the results of Benhizia *et al.* (2020) who found an average interception rate of 42.5% in an Aleppo pine forest, although Keim *et al.* (2006) found for *Pinus spp* an interception rate of 28.5%. Nevertheless, the average rainfall found in the present study (386.8 mm) is higher than that found by Benhizia *et al.* (2020) (311.95 mm). In addition, the cumulative rainfall between 30 and 60 mm in the present study, is greater than that in the study of Benhizia *et al.* (2020). Consequently, the low interception found in the present study can be attributed to rainfall concentrated on four days among 118 rainy events.

The other factor that probably reduced the interception rate in the present study, is the reduced number of dead branches and cones on the cedar trees compared to the pine trees where they were abundant. Indeed, some researchers have already reported that cones and dead branches can significantly modify the redistribution of rainfall by the action of conifers due to the additional water gain of rain by the latter (Shinohara et al. 2010; Jeong et al. 2019).

Besides, the time between two successive rainfalls can also influence the interception rate. Rodrigo and Avila (2001) have set the canopy drying time at 4 hours, whereas Cape *et al.* (1991) estimate it at 12 hours. Moreover, the rainfall regime of the Mediterranean is probably the first to be responsible for the interception rates (Bellot *et al.* 1999; Llorens *et al.* 2018).

Nevertheless, the interception rate found in our study remains, in general, close to the results recorded in coniferous forests. Thus, previous studies have reported interception rates between 8 and 81% under coniferous species (Llorens *et al.* 1997; Xiao *et al.* 2007; Barbier *et al.* 2009; Zhou *et al.* 2013; Fan *et al.* 2014; Aydın *et al.* 2018; Dong *et al.* 2020; Jančo *et al.* 2021; Yang *et al.* 2022).

Regarding the significant interannual variation, Moreno-Pérez *et al.* (2018) stated that the interception rate is higher during dry years.

4.5 Relationships with rainfall

The equations found in the present study, that elicit the relationship between rainfall, throughfall and stemflow are consistent with previous studies. Indeed, several researchers (Magliano *et al.* 2019; Dong *et al.* 2020; Zhao *et al.* 2023) have already reported these positive correlations between rainfall, throughfall and stemflow. They indicated that a major rainfall event tends to favor a higher percentage of throughfall and stemflow.

The volume necessary to trigger the throughfall in the Atlas cedar (1.70 mm), is close to that found by Benhizia *et al.* (2020). The latter found a volume of 1.9 mm, for the Aleppo pine in the Aurès (Eastern Algeria). Similarly, Dong *et al.* (2020) claimed that the rainfall capable of generating throughfalls in the *Pinus tabuliformis* stand is between 1.5 and 1.9 mm depending on the age.

On the other hand, the volume necessary for the initiation of stemflow (4.46 mm) is less compared to that found by Benhizia *et al.* (2020), which found a volume of 6 mm is required to start stemflow in Aleppo pine. Moreover, the volumes capable of triggering throughfall and stemflow in the present investigation are higher compared to those stated by Zhang *et al.* (2023) who claimed that the average rainfall required for the initiation of throughfall and stemflow, in the forest canopies, begins on average at 1.2 and 3.3 mm, respectively. This difference can be attributed to the bark properties of cedar but and to the hydrophobous dust accumulating on the needles and trunks of trees, especially after long drought periods.

Furthermore, the difference in rainfall volumes triggering the stemflow in cedar and pine forests is most likely due to the presence of dead branches on Aleppo pine trunks, especially for the first few meters from the level of the soil. Dead branches attached to the stem trunks will likely hinder the stemflow in Aleppo pine and Cedar forests.

Applying the developed equations suggests that rainfall exceeding 5 mm will contribute to the water supply of Atlas cedar forests.

5 Conclusions

Our study presents the first data on the redistribution of rainfall in an Algerian Atlas cedar forest. The results of the two years of measurements recorded a cumulative rainfall of 773.6 mm distributed over 118 events of rain, including only four events with rainfall above 30 mm. Moreover, the rate of rainfall that crossed the crowns of the Atlas cedar trees by throughfall and stemflow was 65.41% and 3.86% respectively, while the interception rate was 30.72%. Thus, the interception was considerable and varied between 0.32 and 0.33 mm per rainfall day throughout the study period.

The aforementioned data are important and they can help foresters for effective management, in particular to balance the water demand of a forest ecosystem and the demand for water by humans. Thinning and removal of dead branches in dense Atlas cedar forests may be beneficial by increasing the amount of rainfall reaching forest soils and increasing the groundwater recharge with positive effects on water supply to societies and ecosystems. This study of rainfall interception has theoretical and practical importance in providing insight into the roles of certain climatic variables and cedar stand traits in the redistribution of rainfall, which can help determine of the impacts of reforestation with cedar on the local water balance.

As a perspective and to bring new knowledge relating to rainfall interception under the action of cedar forests in Aures (eastern Algeria), it is recommended to consider the following rarely considered meteorological variables: rainfall intensity, wind speed and wind direction, vapor pressure deficit and the number of wetting/drying cycles within a given rainfall event.

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Investigating the structure of the mosaics of developmental phases in mixed oriental Beech virgin forests in northern Iran

Untersuchung der Struktur der Bestandesentwicklungsphasen in den Orientbuchenurwäldern im Norden des Iran

Seyed Bagher Mirahmadi[1], Asadollah Mataji[1*], Sasan Babaie Kafaki[1], Reza Akhavan[2]

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Schlüsselbegriffe: Bestandesentwicklungsphasen, Initialphase, Optimalphase, Zerfallsphase, Lücken, Waldökologie, Urwald, naturnaher Waldbau

Abstract

Close-to-nature forestry is a promising approach for satisfying the criteria of sustainable forestry. This draws attention to natural forests as a comprehensive source of information for forest management. The purpose of this study is to investigating the structure of mosaics of developmental phases and to determine their area based on structural parameters as identification keys in oriental beech virgin forests, which are rarely studied. To this aim, one 10 hectare area in parcel 513, series 5, Eshkateh-Chal forestry project was selected and the location, species type, stem number, gap area, diameter at breast height and tree height of all trees taller than 7.5 centimeters were measured. We also measured standing and lying dead trees (snags and logs). Based on our results, five developmental phases of innovation, regeneration, optimal, aging and degradation were identified in the study area. The results showed that the highest and lowest number of trees were related to the innovation phase (393 trees per

[1] Department of Forestry, Faculty of Natural Resources and Environment, Science and Research Branch, Islamic Azad University, Tehran, Iran
[2] Research Institute of Forests and Rangelands, Agricultural Research Education and Extension Organization (AREEO), Tehran, Iran
*Corresponding author: Asadollah Mataji, a_mataji2000@yahoo.com

hectare) and the aging phase (148 ha^{-1}) respectively. In the study area the phases of innovation, regeneration, optimal, aging, and degradation covered 30.5%, 18.8%, 14.0%, 10.8% and 25.9%, respectively. The highest number of dead trees (41 ha^{-1}) was observed in the degradation phase. Except for the optimal phase, where the abundance of snags was higher, in all developmental phases the abundance of logs was higher than that of snags. 2.5% of the study area were covered with canopy gaps and 7.7% with expanded gaps. Our results on tree dimensions and deadwood presence suggest that the studied intact stands were old growth and their structure deviated considerably from managed forests. Silvicultural interventions can be designed to emulate the developmental phases of virgin forests.

Zusammenfassung

Naturnaher Waldbau ist ein vielversprechender Ansatz zur Erfüllung der Kriterien nachhaltiger Forstwirtschaft. Natürliche oder naturnahe Wälder können als Referenz und Informationsquelle für das Waldmanagement dienen. Ziel dieser Studie ist es, die Struktur und Abfolge der Bestandesentwicklungsphasen und deren Anteile in Orientbuchenurwäldern zu untersuchen. Zu diesem Zweck wurde eine 10 Hektar große Probefläche im Parzelle 513, Serie 5 des Forstbezirkes Eshkateh-Chal ausgewählt. Die Lage, Baumart, Anzahl, Lückengröße, Brusthöhendurchmesser und Baumhöhe aller Bäume mit einem Durchmesser größer als 7.5 cm wurden gemessen. Außerdem wurden stehende und liegende tote Bäume gemessen. Basierend auf den Ergebnissen wurden im Studiengebiet fünf Entwicklungsphasen identifiziert: Etablierung, Regeneration, Optimierung, Reife und Degeneration. Unsere Ergebnisse zeigen, dass die höchste und niedrigste Stammzahl in der Etablierungsphase (393 Stämme pro Hektar) und der Reifephase (148 ha^{-1}) auftreten. Von der Gesamtfläche des Studiengebiets machen die Entwicklungsphasen Etablierung, Regeneration, Optimal, Reife und Degeneration 30.5 %, 18.8 %, 14.0 %, 10.8 % bzw. 25.9 % der Fläche aus. Die höchste Anzahl toter Bäume (41 ha^{-1}) wurde in der Degenerationsphase beobachtet. Ausgenommen von den Optimalphase, in der die stehenden toten Bäume häufiger waren als liegende tote Bäume, war in den anderen Entwicklungsphasen die Anzahl liegenden toter Bäume höher als die von stehenden. Von der Gesamtfläche der untersuchten Bestände sind 2.5 % von Baumkronenlücken und 7.7 % von weitläufigen Lücken bedeckt. Unsere Ergebnisse zu Baumdimensionen und Totholz weisen darauf hin, dass die untersuchten intakten Bestände naturnahe Wälder sind und deren Struktur der Bestände sich deutlich von bewirtschafteten Wälder unterscheidet. Waldbauliche Eingriffe können entwickelt werden, um die verschiedenen Evolutionsphasen nachzubilden.

1 Introduction

The old-growth beech forests (*Fagus orientalis* Lipsky) in the north of Iran with trees that are older than 350 years old and usually with a diameter at breast height greater than 110 centimeters (Amini *et al.*, 2009) are a part of temperate deciduous forests, concerning their evolutionary history, are valuable on the international level and considering plant diversity are among the rich forests of the world (Zenner *et al.*, 2019: Moridi *et al.*, 2021: Parhizkar *et al.*, 2021). These forests have expanded at altitudes higher than 750 meters above sea level in the northern parts of the Alborz mountain range on the southern part of the Caspian Sea, whose range extends over 800 kilometers from east to west. The Hyrcanian forests are one of the last remnants of natural deciduous forests (Knapp, 2005; Sagheb-Talebi *et al.*, 2014). There is always a great interest in better understanding the characteristics of these diverse forest communities to manage optimally and multipurpose planning, to preserve diversity in these forests (Fazlollahi *et al.*, 2022).

More than 80% of land ecosystems in the world have been destroyed by human and natural disturbances (Zhu and Liu, 2004). In forest ecosystems, natural disturbances are the source of environmental heterogeneity and vast changes in the temporal and spatial scale of stands and they play an important role in determining the structure, function and dynamics of ecosystems (Oliver, 1981; Paine and Levin, 1981; Pickett and White, 1985). Determining the dynamic of forest stands to expand sustainable forestry and appropriate management strategies is very essential (Oikonomakis & Ganatsas, 2012) and are possible by reviewing the changes in the structure of forest stands over time which consists of behavior and condition of forest stands during and after the occurrence of existing disturbances (Ford-Robertson, 1971).

Oriental beech or eastern beech (*Fagus orientalis* Lipsky) belongs to the family *Fagaceae*. It is a deciduous broad-leaved tree which reaches height of 30-40 meters. In rare instances, trees up to 50 meters in height can be found. In general, oriental beech has a similar appearance to European beech (*Fagus sylvatica*). Both beech species are characterized by their smooth and silver-grey stem. The stem colour of oriental beech is a lighter grey than European beech (Sagheb-Talebi *et al.*, 2014). The spatio-temporal dynamics of the natural European beech (*Fagus sylvatica* L) and oriental beech forests (*Fagus orientalis* Lipsky) have been derived by the scattered and frequent occurrence of gaps on a small scale and by occasional disturbances on the medium and large scale, such as wind disturbances (Korpel, 1995; Sagheb-Talebi and Schütz, 2002; Nagel *et al.*, 2006; Sefidi *et al.*,2011; Zenner *et al.*, 2019). Developmental phases are defined to reflect important environmental processes, such as regeneration, growth, and mortality, which shape the horizontal and vertical structure of a forest during its life cycle (Leibundgut, 1959, 1993; Korpel, 1995). These phases represent multiple structural features of the forest and provide a practical temporal framework to improve our understanding of how structural variation of natural processes evolves (*e.g.*, Huber, 2011; Amiri *et al.*, 2013). Although there is no consensus on the exact definition of developmental phases or even the exact number of them, and no standardized set of criteria are known to distinguish between developmental phases (Leibundgut, 1959; Zukrigl *et al.*, 1963; Mayer, 1984; Emborg *et al.*, 2000; Král *et al.*, 2010; Zenner *et al.*, 2019), but generally, similar to the European natural beech forest, three main developmental stages (initial, optimal and decay stage) are accepted (Leibundgut, 1993; Korpel, 1995), which include several developmental phases (Korpel, 1995).

The identification and explanation of the developmental phases in forest stands are very important because the structural characteristics of the stand in each developmental phase are different (Sagheb-Talebi and Mataji, 2007). Depending on the point of time that the stand is analyzed, or in which developmental phase, it can show different results in terms of density, basal area, and volume between phases and developmental stages (Sefidi *et al.*, 2014; Parhizkar *et al.*, 2021). The developmental cycle occurs in every part of the forest which results in the shifting mosaic of the developmental phase and the total area of each phase is almost directly related to the length of the corresponding period (Emborg *et al.*, 2000). By evaluating developmental phases and the dynamics process of virgin forests, considering the potential of the habitat and benefiting from the knowledge of close to nature silviculture, it is possible to adapt a suitable method to maintain the principle of continuity of production and sustainability of the forest (Mataji, 2002). Thus, evaluating the evolution of forest stands should be conducted separately based on developmental phases (Amini *et al.*, 2018).

The first step in understanding forest ecosystems is investing in their stability and persistence over time. With the knowledge and awareness of this, it is possible to choose appropriate silviculture methods and how to intervene in the forest stands properly. The closer the plans and silviculture interventions are to management applied by nature, the more optimized the protection, productivity, and sustainability of the forest will be. Thus, conserving these valuable sources for the next generations is better conducted and the responsibility and the role of forest ecosystems will be fulfilled to a greater extent. In the Hyrcanian forest, the analysis of developmental phases and stages is emphasized by many studies (Mataji *et al.*, 2014: Moridi *et al.*, 2015; Sefidi *et al.*, 2015; Zenner *et al.*, 2019; Moridi *et al.*, 2021), however, there is still limited knowledge in this domain and none of these researches have focused on the zoning of developmental stages and the identification of developmental phases. Considering the importance of the Hyrcanian forests, this study was conducted with the aim of investigating the structure of the mosaics of developmental phases and determining the area of each of them based on structural characteristics as identification keys in the oriental beech virgin forests in one 10-hectare area.

2 Method and Materials

2.1 Study region

The studied area is located in parcel No. 513, Series 5 of the Eshkatehchal forestry project, in Ramsar 30 watershed, in the northern latitude of 36°49'N to 36°53'N and the eastern longitude of 50°22'E to 50°30'E. Figure 1 shows the location of the studied area.

The average annual rainfall of the region is 1215 mm and the average annual temperature is 15.8 °C. Autumn is the most rainy season with 465 mm of rainfall and spring is the least rainy season with 144 mm. Based on the Ambergris climate curve, the studied area has a cold humid climate. In addition, the vital dry season in the region is short. From the point of view of rock stratigraphy, the studied parts are composed of limestone and marl sediments that belong to the Cretaceous period and the end of the second era. Soil type is rundzin and the forest type is mixed beech.

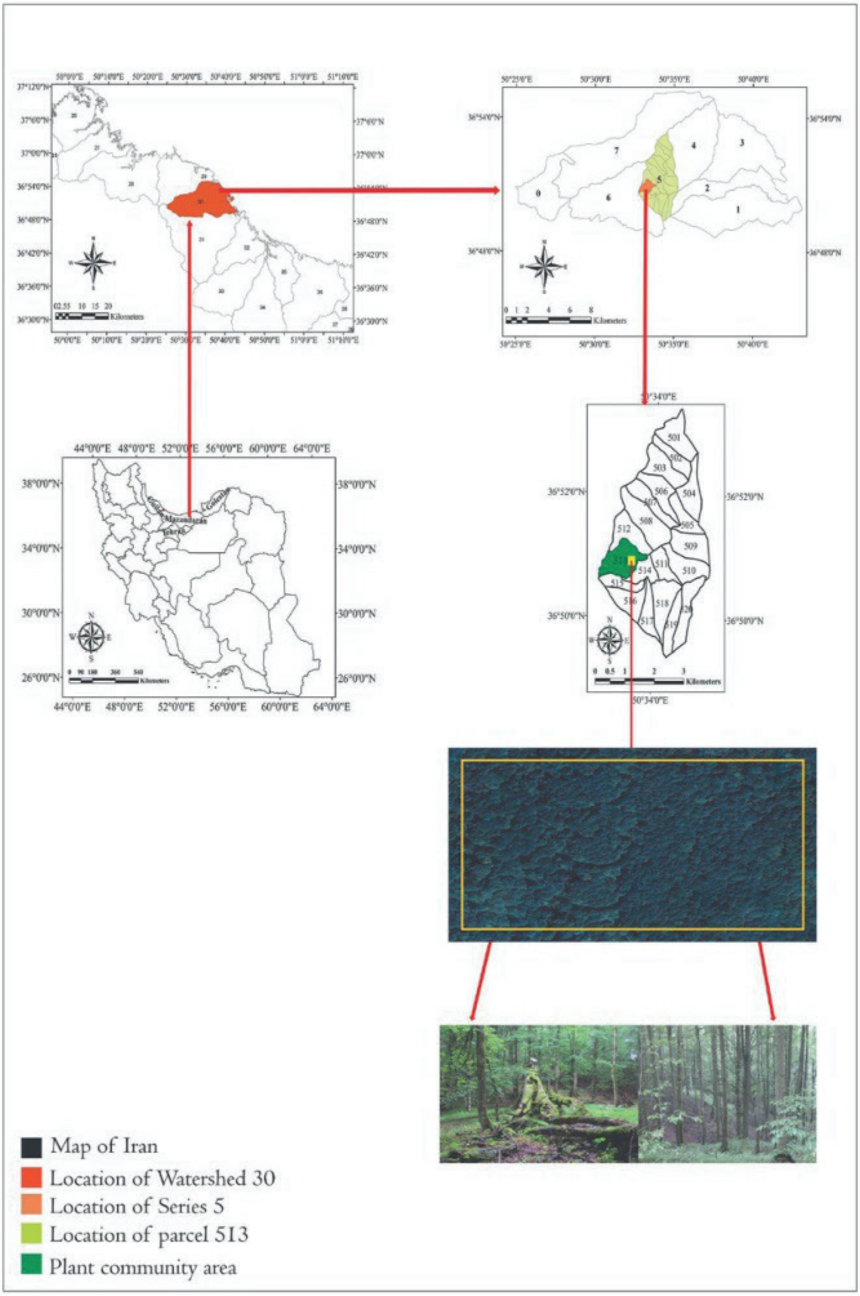

Figure 1: The geographical location of the studied area.

Abbildung 1: Geografische Lage des Studiengebiets.

2.2 Methodology

Considering the purposes of the study, the 10-hectare plot in parcel No. 513 was determined and separated based on the indicators and criteria for determining the developmental stages in nature. To investigate the structure of the stands, a full inventory approach was used. The trees' location was conducted by measuring and recording the distance and the azimuth of the individuals relative to each other. The quantitative characteristics of the live and dead trees, including the species, diameter at breast height (DBH), basal area, the volume for live stems and type, number and volume for dead trees, and also the number and size of gaps were calculated for all stems over 7.5 cm at the breast chest diameter.

Using the azimuth parameter and the distance of trees within each other and taking advantage of the following trigonometry relationships, the location of each tree was determined on the initial map, and then considering the species and the diameter at the breast height trees, the final distribution map of trees was created.

$X = L \times \sin(\alpha)$

$Y = L \times \cos(\alpha)$

X length difference between two points; Y width difference between two points α: azimuth of trees relative to one another; L the distance of trees within each other

In order to measurement of gaps and determine their area, the trigonometry method was used (Lima, 2005). So first by moving around the canopy gaps, the location of the image of the bumps and depression of the crown around the gaps was determined on the ground, and then by the placement in the approximate center of the gap, azimuth and the sloped distance and the slope of the each of the marked points were determined, measured and recorded. This action was conducted on expanded gaps as well, with the difference that in expanded gaps all the measurements and readings were done up to the stems of the surrounding trees. During the field collection of each gap, the center of each gap was first determined. Next, with placement in the center of each gap by using the trigonometry method, and by measuring distance and azimuth relative to each corner of the gap (the image of the end of canopy gap edge trees on the ground), the area of each canopy gaps among the forest crown was measured and calculated using trigonometry (Lima, 2005).

$$A_i = [p_i\,(p_i - a_i)(p_i - b_i)(p_i - c_i)]^{0.5}$$

$$p_i = (a_i + b_i + c_i)/2$$

Where A_i is the area of each triangle and a, b, and c are the sides of each triangle. By summing the obtained levels, the area of each gap (A_{gap}) was calculated:

$A_{gap} = A_1 + A_2 + ... + A_n$

To estimate the volume of trees, the following function was used:

V = F x A x H

Where A = basal area at 1.3 m above ground, H = tree height F = the form factor. According to Moridi *et al.* (2016), the form factor was considered 0.42.

We also identified and recorded dead tree species, total length, form (log, snag, or stump), diameter at both ends, diameter at the midpoint (for stumps, only the diameter at the midpoint was recorded), and decay class. To calculate the volume of dead trees, Newton's formula was used (Harmon and Sexton, 1996) for snag and log volume:

$$V = \frac{L\,(A_b + 4A_m + A_t)}{6}$$

Where, V = volume of dead trees in m^3, L = length of dead trees, and A_b, A_m and A_t = the cross-sectional area at the base, middle, and top of dead trees, respectively.

The decay classes in the current study included five classes for snags and logs (Akala, 2010):

- Class 1. Snag or log with intact bark and all wood sound; intact structure and wood's original colour.
- Class 2. Bark broken up into patches and partly fallen off; wood still maintains its structural integrity and original colour; the outer layers started to soften because of rot.
- Class 3. Bark completely absent; all wood structure has started to soften; the soft outer layers disintegrate easily (knife test); the core is still solid and the colour has already started to fade.
- Class 4. Bark totally absent; texture small and soft; shape oval.
- Class 5. Wood structure soft and powdery; wood partially covered with moss and vegetation, mixed with the forest soil.

The separation of the mosaics of the developmental phases was conducted using structural indicators and parameters including the existence of the gap, dead trees, regeneration, height, diameter, basal area, volume, and the spatial distribution of all trees based on the identification keys mentioned in the following studies (Leibundgut, 1993; Korpel, 1995; Emborg *et al.*, 2000; Mataji *et al.*, 2014; Sagheb-Talebi *et al.*, 2003). There are different phases in each stage. During the initial stage, trees are going toward a higher height and diameter class. Their volume increases and trees found in all strata (upper, middle, and lower). The percentage of canopy and density of trees is high per hectare, and small gaps which are usually a result of the breaking of smaller branches, are filled by the canopy cover of other trees (Leibundgut, 1993; Korpel, 1995). In the optimal stage, there are two phases: mature and aging. This stage begins when the dominant trees ultimately reach the upper canopy layer. Compared to the previous stage, the number of trees decreases, but the volume of trees increases. The decay stage comprises building, pioneer, regeneration, and degradation phases (Emborg *et al.*, 2000; Mataji *et al.*, 2014). The decay stage begins when density and stand volume are decreasing and amounts of dead wood are increasing. In a slowly decaying stand, shade-tolerant tree species regenerate and recruit underneath persistent canopy gaps. During this stage, old trees begin to degenerate, and due to various reasons including the breaking of large branches, death of trees, and windfall, many gaps are formed in the canopy (Mataji *et al.*, 2014). The presence of dead trees and regeneration in the openings accentuate vertical irregularity and uneven-agedness. With an increasing proportion of young trees and a decreasing proportion of old and mature trees, the forest transitions to the initial stage (table 1).

Table 1: Criteria for distinguishing among the three main development stages (Akhavan et al., 2012).

Tabelle 1: Unterscheidungskriterien zwischen den drei Hauptentwicklungsphasen.

Criteria	Initial stage	Optimal stage	Decay stage
Number of stand stories	Number of stand stories More than 2	Usually 1 to 2	More than 2
Number of trees/unit area	High	Medium	Low
The proportion of trees in timber size	The highest amount in small and medium sizes	The highest amount in medium and large sizes	The highest amount in large and extra-large sizes
The proportion of trees in canopy strata	The highest in lower and middle stories	The highest in upper story	The highest in middle and upper stories
Stand volume	Medium	High	Low
The proportion of volume in timber size	Usually highest amount in medium and large sizes	Usually highest amount in medium and large sizes	Usually highest amount in large and extra-large sizes
Dead wood volume	Medium	Low	High
Proportion of dead wood volume in timber size	Usually highest amount in large and extra-large sizes	Usually highest amount in small and medium sizes	Usually highest amount in extra-large sizes
Gap	Present	Usually absent	Present
Regeneration	Group-wise and present in gaps	Little and scattered over the whole area	Group-wise and present in gaps

After using the aforementioned identification keys using the model proposed by various researchers (Korpel, 1982; Emborg, 2000; Leibundgut, 1993; Mataji *et al.*, 2014), developmental phases were carefully determined and the area of each phase was determined as a polygon on the map. Then, having the map and determining the exact area of each polygon of different developmental phases, a visual interpretation is undertaken within each of the polygons in the forest and conforming to the generated map. Therefore, the edges and borders of the polygons were carefully closed and ultimately, the final map of the developmental phases of the target area was prepared. Quantitative variables such as DBH, basal area, volume, characteristics of dead trees, number of gaps, species composition, diameter and height of regeneration were calculated in the Excel (version 2013) and SPSS (version 25) software. Excel was used to draw the graphs. In order to determine the size of the gaps and calculate the area, Auto CAD was used to separate and draw the polygons of the maps of the developmental phases.

3 Results

In the present study 2109 trees with diameters greater than 7.5 centimeters were identified and measured over an area of 10 hectare. The average number of trees in each hectare is 210 and the average volume in hectare was 414.8 $m^3 ha^{-1}$. The mean and median of the diameter were 30.52 and 21.5 cm respectively. *Fagus orientalis Acer velutinum*, *Alnus subcordata*, and other species account for 65.3%, 19.3%, 9.0%, and 6.4% of the species respectively. Other species in the present study included *Carpinus betulus*, *Acer cappadocicum*, *Quercus castaneifolia*, *Prunus avium* and *Ulmus glabra*. Also, the amount of standing volume for *Fagus orientalis*, *Acer velutinum*, *Alnus subcordata* and other species was measured as 74.6%, 16.1%, 7.2%, and 2.1%, respectively. The results of drawing the diagram of the number in diameter classes at the scale of 10 hectare showed that the distribution of trees in the diameter classes is decreasing exponentially (Figure 2). At the beginning, the distribution diagram decreases with a sharp slope, that decrease does not follow a specific order in high diameter classes, and it is mainly imbalanced state and sometimes it increases and decreases alternately.

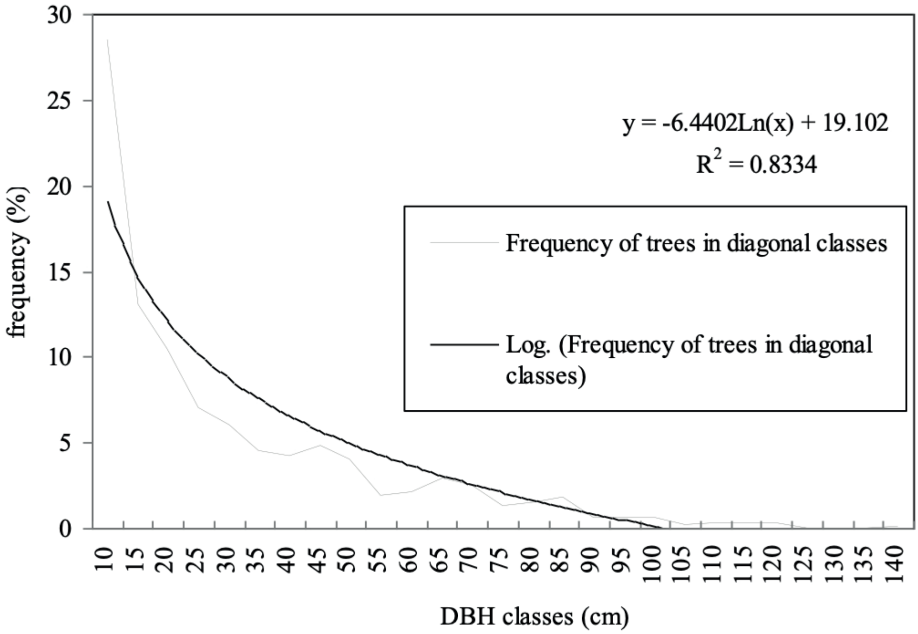

Figure 2: Distribution of trees along the diameter gradient for the 10 hectare orient beech forest.

Abbildung 2: Verteilung der Bäume entlang der Durchmesserklassen im 10 Hektar großen Orientbuchenwald.

After the collection of the data about the stand structure and the location of trees, different groups in terms of similarity, and differences in various statistical parameters were identified, including the mean or median of the diameter or the number of gaps and the amount of canopy opening, the number and the volume of live trees and the number and volume of dead trees. Overall, based on the findings of this study, five developmental phases of innovation, regeneration, optimal, aging and degradation were identified in the study area, which takes the form of 42 irregularly shaped polygons with variable areas, where the developmental phases of regeneration and innovation have the highest distribution with 12 polygons. The aging phase has the lowest distribution with three polygons (Figure 3). The areas of polygons varied in the range of 214 to 10621 m². The smallest and the largest recorded polygon belonged to the developmental phases of regeneration and innovation respectively. The innovation (30480 m²) and aging phases (10767 m²) occupied the highest and lowest area, respectively, in the 10-hectare stand. The average area of the polygons of different developmental phases ranged from 1569 to 3589 m². The regeneration phase has the lowest and the aging phase has the highest of the mentioned characteristic (Table 1).

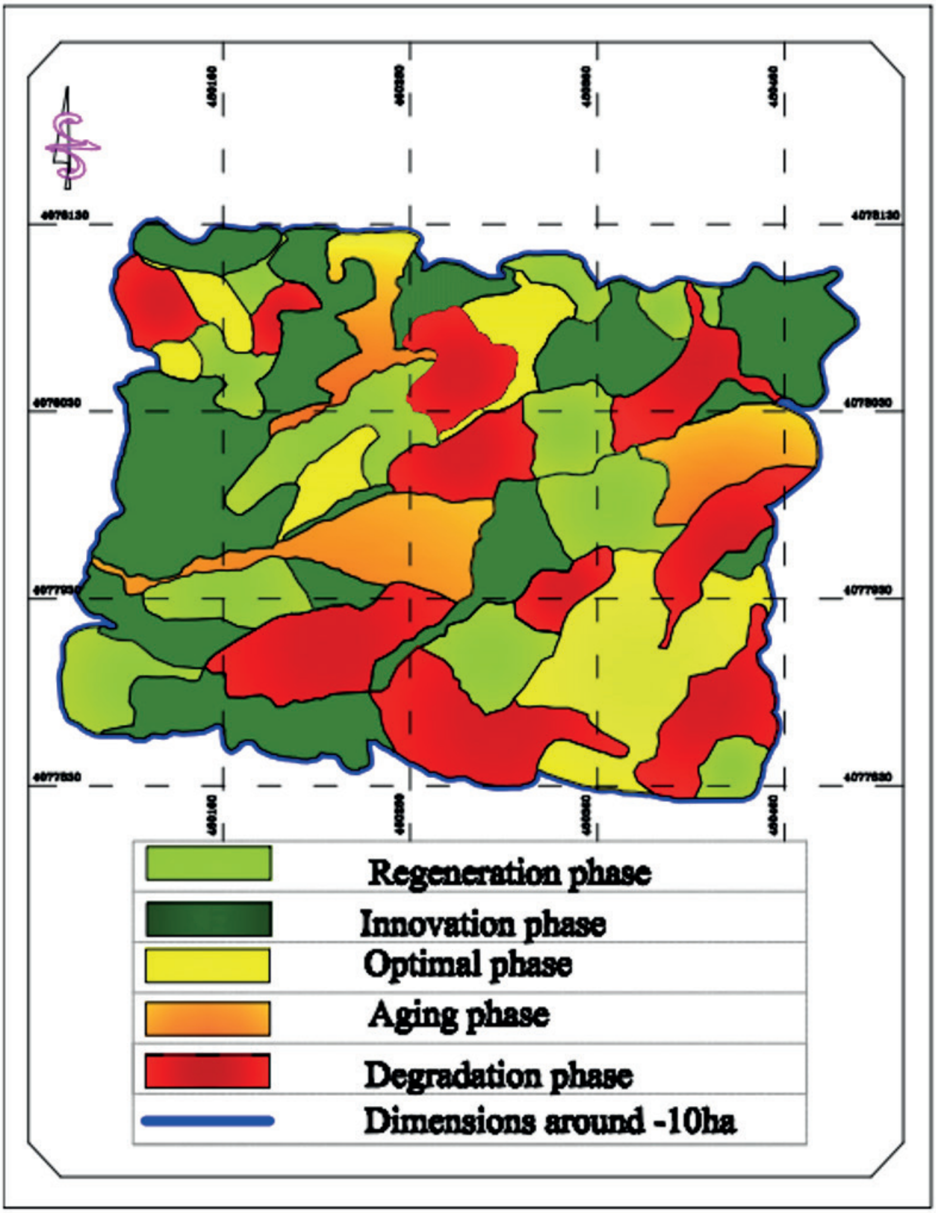

Figure 3: Display of mosaic zoning of the developmental phases in the studied area.

Abbildung 3: Darstellung des Mosaiks der Entwicklungsphasen im Studiengebiet.

The investigation of the quantitative characteristics in the studied area shows that the highest number of trees (393 trees per hectare) are in the innovation phase and the lowest number (148 ha^{-1}) are in the aging phase. The highest and lowest presence of the beech species was measured in the innovation (287 ha^{-1}) and degradation phase (108 ha^{-1}), respectively. Also, the highest basal area of live beech trees was measured (36.4 m^2 ha^{-1}) in the aging phase, and the lowest amount for other species was measured (2.4 m^2 ha^{-1}) in the optimal phase. Additionally, the highest volume of live trees in different developmental phases in the study area in the aging phase was for beech trees (525.4 m^3 ha^{-1}) and the lowest amount of volume of live trees in the study area in the optimal phase was for other species (26.9 m^3 ha^{-1}) (Table 2).

Table 2: The mean of the quantitative characteristics of the trees by developmental phases and based on species in the studied area.

Tabelle 2: Durchschnittliche quantitative Merkmale der Bäume nach Entwicklungsphasen und nach Baumarten im Studiengebiet.

Characteristic	Species	Developmental phases				
		Regeneration	Innovation	Optimal	Aging	Degradation
Stem number (ha^{-1})	Beech	113	287	235	135	108
	other species	174	106	15	14	84
	Total	287	393	250	149	192
Basal area (m^2 ha^{-1})	Beech	10	14.7	24.9	36.4	14.6
	other species	11.4	10.7	2.4	4.8	20.2
	Total	21.4	25.4	27.3	41.2	34.8
Volume (m^3 ha^{-1})	Beech	139.6	170.5	302.2	525.4	203.6
	other species	127.4	117.6	26.9	55.7	241.4
	Total	267	288.1	329.1	581.1	445
Polygon numbers		12	12	5	3	10
Average polygon area (m^2)		1569	2540	2799	3589	2593
Min-max range (m^2)		214- 3412	330- 10621	430- 8350	2655- 4712	744- 4707
Total Area (m^2)		18828	30480	13995	10767	25930
Share (%)		18.8	30.5	14.0	10.8	25.9

The total number of 197 dead trees was identified in the studied stands, of which 66 stems were standing dead trees and 131 of them were fallen dead trees. The highest number of dead trees (106 stems) was observed in the polygons of the degradation phase and the lowest numbers (14 stems) were observed in the optimal phase (Table 3). The volume of dead trees was 31.9 $m^3\ ha^{-1}$, where 33.1% are snags and 66.9% are logs. The highest and lowest volume of dead trees, belongs to the trees which are in the decay classes 2 and 5. The examination of dead trees in different developmental phases shows that the highest and lowest average volume of dead trees was observed in the degradation phase (88.42 $m^3\ ha^{-1}$) and the optimal phase (0.24 $m^3\ ha^{-1}$) respectively. In almost all developmental phases, the highest amount of dead trees has been observed in decay class two (Table 4).

Table 3: Relative abundance of deadwood by type and species in each developmental phase.

Tabelle 3: Relative Häufigkeit des Totholzes nach Art und nach Entwicklungsphasen in jeder Phase.

Type of deadwood	Species	Developmental phases				
		Regeneration	Innovation	Optimal	Aging	Degradation
Snag	Beech	15.6	28.1	53.8	35.8	2.8
	Other species	12.5	6.2	15.4	7.1	26.4
	Total	28.1	34.3	69.2	42.9	29.2
Log	Beech	25	21.9	15.4	0	18.9
	Other species	46.9	43.8	15.4	57.1	51.9
	Total	71.9	65.7	30.8	57.1	70.8

Table 4: The average volume of dead trees by decay classes and divided by the type of dead trees in each developmental phase.

Tabelle 4: Durchschnittliches Volumen der Sträucher nach Zersetzungsgradklasse und nach Totholz in jeder Entwicklungsphase.

Developmental phases	Type deadwood	Mean volume by decay class (m^3 ha^{-1})					
		1	2	3	4	5	Total
Regeneration	Snag	3.684	6.651	1.588	0.052	0.000	11.975
	Log	3.177	6.370	11.010	1.666	0.028	22.251
	Total	6.861	13.021	12.598	1.719	0.028	34.227
Innovation	Snag	0.129	0.036	0.036	0.000	0.000	0.202
	Log	0.052	0.011	0.000	1.787	0.275	2.125
	Total	0.181	0.048	0.036	1.787	0.275	2.327
Optimal	Snag	0.150	0.084	0.007	0.000	0.000	0.241
	Log	0.042	0.013	0.000	0.000	0.000	0.052
	Total	0.150	0.084	0.007	0.000	0.000	0.293
Aging	Snag	0.136	0.104	0.008	0.000	0.000	0.248
	Log	0.000	0.000	0.000	0.000	11.677	11.677
	Total	0.136	0.104	0.008	0.000	11.677	11.925
Degradation	Snag	6.385	2.215	9.379	11.745	1.207	30.929
	Log	4.747	24.598	13.413	12.089	2.650	57.497
	Total	11.131	26.813	22.792	23.833	3.857	88.426

Overall, 62 gaps were identified in the study stands. The total area of the canopy and expanded gaps were calculated as 2520 and 7740 m² respectively. In general, 2.5% of the analyzed stands are composed of expanded gaps and 7.7% were comprised of canopy gaps (Table 5). The investigation of gap characteristics in the polygons of different developmental phases indicated that the number and the ratio of the canopy and expanded gaps in the degradation phase are more than those of other developmental phases.

Table 5: Characteristics of the canopy and expanded gaps in each developmental phase.

Tabelle 5: Eigenschaften von Kronenlichtungen und weitläufigen Lichtungen in jeder Entwicklungsphase.

Developmental phase	Count	Gap relative abundance (%)		Average area (m^2)		Total area (m^2)	
		expanded gap	canopy gap	expanded gap	canopy gap	expanded gap	canopy gap
Regeneration	11	8.0	1.8	141	32	1556	349
Innovation	6	1.8	0.4	90	18	541	109
Optimal	3	2.3	0.3	102	13	306	38
Aging	3	1.7	0.3	60	10	179	29
Degradation	39	19.6	7.6	132	51	5158	1994
Total	62	7.7	2.5	129	41	7740	2520

4 Discussion

4.1 The mosaics of developmental phases

The identification of developmental phases in beech forests is necessary to choose appropriate forestry methods. Each of the polygons in the developmental phases is a coherent spatiotemporal unit and is here assumed to have constant location as they evolve through time. In total, five development phases were identified in the present study. Similar developmental phases were identified in the European beech forests by Leibundgut (1959), Oliver and Larson (1996), Mayer *et al.* (1987), and Emborg *et al.* (2000), and in the beech forests of Iran by Mataji *et al.* (2014). Based on the results of the present study, the measured quantitative characteristics were dissimilar between different phases, so the smallest and largest identified polygons were measured from

214 and 10621 m² respectively. There have been many studies regarding the developmental stages and phases in Hyrcanian forests (Nobahar *et al.*, 2018; Moridi *et al.*, 2021a; Moridi *et al.*, 2022, Kakavand *et al.*, 2020, Sefidi *et al.*, 2014), which all of them have been studied in one-hectare sample plots, that due to the uneven-aged and irregularity of the Hyrcanian forests, the zoning of stages or developmental phases cannot have a regular geometric shape and regular one-hectare plots should not be considered for their study. Alibabaei *et al.*, (2023), in the study of spatial patterns and structural characteristics of the oriental beech forests in the optimal stage, identified 11 polygons that have the features of the optimal stage in the entire parcel 327 of Kheiroud forest where the largest and smallest area of polygons were measured as 3745 and 1679 respectively. This study identified five developmental phases of regeneration, innovation, optimal, aging, and degradation in the studied stands. Sefidi *et al.* (2014), in the study of the late successional stage dynamics in natural Oriental beech (*Fagus orientalis* Lipsky) stands in northern Iran, concluded that beech stands be placed in three development stages of volume growing up, volume accumulations and volume transition. The volume growing stage embraces gap forming, understory initiation and regeneration phases, the volume accumulation stage includes volume stability, lightning and stem exclusion phases, and the volume transition stage includes gap making, old growth and volume degradation phases. Emborg *et al.* (2000) in the investigation the structural dynamics of Suserup Skov, a near-natural temperate deciduous forest in Denmark, reported the area of innovation, aggradation, optimal, aging, and degradation phases to be 5%, 20%, 34%, 38% and 4%, respectively. Kral *et al.* (2014) in a study entitled patch mosaic of developmental stages in central European natural forests along vegetation gradient, concluded that the mean patch size of the mosaic of four developmental stages showed a relatively narrow range of 570-800 m² in all study sites and censuses. The Growth stage was usually the most abundant (covering 25-50% of the stand), and had the highest mean patch size, ranging between 590 and 2800 m². The Growth stage patches also had the most complex shapes. On the contrary, the Breakdown stage usually had the opposite values, forming constantly small (250-720 m²), simple and scattered patches in the mosaic. Sefidi (2012) report reverse J-shape curve to the mixed beech stands. The same results reported in the oriental beech stands in the north of Iran (Nedyalkov and Asli, 1971; Sagheb-Talebi *et al.*, 2004; Marvie Mohadjer *et al.*, 2009) and in European beech forest (Leibundgut, 1993; Meyer *et al.*, 2003; Cancino and Gadow, 2002).

4.2 Stand characteristics description

The number of trees per hectare in the innovation phase was higher than those of other phases, and the lowest value of this characteristic was for the aging phase, which is in line with the results of forest structure assessment in Neka region (Sagheb-Talebi *et al.*, 2020) and Kheiroud forest (Moridi *et al.*, 2021). Therefore, it can be concluded that the high density of trees in the innovation phase, and consequently, the high competitive pressure for light and nutrition, culminates in trees removing in the subsequent phases. The mean number of removed trees from the stand in the regeneration, optimal, degradation, and aging phases compared to the innovation phase were 106, 143, 201, and 245 trees per hectare respectively. Moreover, based on the findings of this study, with the reduction of the number of trees as they move on from the regeneration phase to the aging phase, the average basal area of trees increases. Different researchers have used the mean of the basal area of trees in order to determine the development stages of the forest and also to examine and compare virgin and managed stands, and express that as the stand's age increases and it passes through development phases and stages, the mean of development area increases (Spies and Franklin, 1991; Ziegler, 2000). Franklin *et al.* (1981) in the study of the characteristics of old forests, concluded that young and old stands had the same average basal area and only the old stands had a greater and twice as high diameter change coefficient than the young stands.

4.3 Dead trees

Understanding the quantitative and qualitative characteristics and the role of dead trees in the forest leads to the increasing of knowledge and awareness of forest specialists in order to apply the most appropriate management of natural stands. With the knowledge and awareness of these features, interventions made in line with the natural process of stand evolution will be with the least deviation from nature (Moridi *et al.*, 2017). Based on the findings of the present study, most dead trees in the phases of regeneration, innovation, degradation, and aging were fallen dead trees. Moridi *et al.* (2015) reported that average deadwoods volume was 24 $m^3\ ha^{-1}$. This value was 23 $m^3\ ha^{-1}$ in beech forests, Turkey (Atici, 2008), and was 30-85 $m^3\ ha^{-1}$ in mixed beech forests, Albania (Mayer *et al.*, 2003). Factors affecting the accumulation of deadwoods in a forest are the age and management history of a stand as well as the rotting speed (Mayer *et al.*, 2003; Christensen *et al.*, 2005). Difference in tree species in various places can also have a significant impact on the deadwood volume in forests (Tinker and Knight, 2001). Kakavand *et al.* (2017) examined the quality and quantity of dead trees in the intermediate stage of the beech forests in the Grozban section of the Kheiroud forest reported the amount of standing and fallen dead trees as 31% and 69%, respectively. Also, analyzing the amount and volume of dead trees in unmanaged forests of Shafarud, the amount of standing and fallen dead trees are reported as 22% and 78%, respectively (Amanzadeh *et al.*, 2013). Rahanjam *et al.* (2018) in a qualitative and quantitative analysis of dead trees in Hyrcanian natural stands in Kheiroud forests, reported the volume of standing and fallen dead trees as 22% and 78% respectively, which are consistent with the results of the present research. Only in the optimal phase were the amount of standing dead trees more than logs, this issue can be due to the closed canopy and the loss of trees due to lack of light, especially the weaker trees in the lower layer. The highest and lowest volume of dead trees per hectare were observed in the degradation and optimal phases respectively, where in the degradation phase, most of this volume was located in the fallen dead trees. In the late successional stages in beech stands this issue can be due to internal disturbance and also the presence of thick trees left from the previous development phase and subsequently falling them, that in the volume of dead trees increases a lot in this phase. In fact, when trees reach the end of their physiological life, they are severely affected by natural disturbances, such as wind and fall, and due to their large dimensions, they take up a lot of volume. In the optimal phase, dead trees had the lowest volume of deadwood compared to other phases, which is due to the small diameter of dead trees that have been eliminated as a result of competition for light. Sefidi and Mohadjer (2010) reported similar findings and this is consistent with the findings of the study of Parhizkar et al. (2011) in the natural beech forests of Kelardasht. The variety of tree diversity in different areas can also considerably affect the volume of dead trees in forests (Tinker and Knight, 2001).

4.4 Canopy gaps

The canopy gaps are the result of different types of natural or unnatural disturbances and biological processes, such as intra- and interspecies competition or mortality (Vahedi, 2021). The considerable difference between the area of the canopy and expanded gap shows that in most gaps, the distance from the last point of the branch extended towards the center of the gap to the point of the tree's establishment was long and the advancement of the canopy is substantial, especially the lateral branches. In fact, with the passage of time, due to the closing of the large gaps from their periphery to the center, they turn into smaller gaps (Mataji *et al.*, 2019). In other words, there is a balance between the advancement of decay in deadwood, as the gap makers, the closing of gaps, longevity of gaps and the growth of the canopy of the surrounding tree as gap fillers. However, it should be mentioned that numerous factors, including environmental conditions and ecological factors such as light, humidity, nutrient elements, etc., can fluctuate the aforementioned balance in different seasons and periods. In the study area the most and biggest gaps are in the degradation and regeneration phases respectively. The ratio of the area of the gaps to the total area of the area was 7.7%. Parhizkar *et al.* (2019) in the unmanaged forest, the proportion of the area of the gaps to the total area of the plot was reported as 10.7% and in the managed forest as 6.3%. Other researchers have reported the range of the gap area to the stand area from 3 to 41.4% (Mataji *et al.*, 2008; Nagel and Svoboda, 2008; Kenderes *et al.*, 2009; Kucbel *et al.*, 2010; Bottero *et al.*, 2011; Sefidi *et al.*, 2011; Rugani *et al.*, 2013; Kian *et al.*, 2017). The results of the present research are in this range. The creation of gaps and their size depends on various factors, including wind, snow, drought, soil features, and the characteristics of tree species (Scharenbroch and Bockheim, 2007; Nagel and Svoboda, 2008). Therefore, the observed difference in the ratio of the gap area to the area of the studied area is not unexpected to be seen. Depending on the ratio of the closing of gaps and the events that cause the creation of new gaps or the enlargement of a gap, the ratio of the area of the gaps to area surface of the entire forest varies by approximately 10 percent (Splechtna and Gratzer, 2005; Feldman *et al.*, 2018).

5 Conclusions

Considering that it is the first time in Iran that developmental phases with variable area and irregular geometric shape have been investigated, as a result, it can be said that the results obtained from this research regarding the structure of the forest can provide the least amount of information for developmental phases to date in Iran's beech forests, which managers can use as a reference point to expand management plans and implement close-to-nature silviculture guidelines in order to protect and restore this forest ecosystem. Because up to now, all the researches about developmental phases have been done in one-hectare sample plots, which is flawed, because the zoning of developmental stages or phases, do not have a regular geometric shape, and regular one-hectare plots.

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