

Adapting Austrian forestry to climate change:

Assessing the drought tolerance of Austria's autochthonous tree species

(Erfassung des Potentials der autochthonen Baumarten Österreichs hinsichtlich ihrer Performance bei aktuellem und zukünftigem Klimastress)

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Kurzfassung

Bevor man in der Forstwirtschaft als Reaktion auf die Herausforderungen des Klimawandels unreflektiert auf fremdländische Baumarten setzt, sollte das Potential der in Österreich heimischen Arten gegenüber besonders wirksamen klimatischen Stressfaktoren wie Trockenheit oder Extremtemperaturen erfasst und genutzt werden. Dies wäre von Vorteil weil der Anbau fremdländischer Arten oftmals mit erhöhten biotischen und abiotischen Risiken verbunden ist. Ein weiterer wichtiger Aspekt der Verwendung von besser angepassten Herkünften einer Art (oder von besser geeigneten Arten derselben Gattung) liegt darin, dass das Risiko der mit einem Baumartenwechsel meist verbundenen Standortsveränderungen gering gehalten werden kann. Die von den dominanten Baumarten abhängigen Biozönosen und Nahrungsketten unterliegen dadurch nur geringfügigen Anpassungserfordernissen. Auch die lieferbaren Holzsortimente blieben so im Wesentlichen erhalten.

Um mögliche geeignete, hitze- und trockenresistente Baumbestände zu finden, wurden in diesem Projekt die Bandbreiten von 22 waldbaulich und ökosystemar bedeutsamen einheimischen Baumarten bezüglich ihres Anspruchs an den Wasserhaushalt mittels ökologischer Bioindikation charakterisiert. Man verwendet dazu die numerisch skalierten ökologischen Zeigerwerte nach Ellenberg, wie sie für die gesamte österreichische Flora verfügbar sind. Standortmerkmale wie der Wasserhaushalt werden durch die Berechnung eines mittleren Wertes aus den Einzelwerten aller in einem konkreten Bestand vorkommenden Arten indiziert. In Hinblick auf die im Zusammenhang mit dem Klimawandel erwarteten höheren Temperaturen und größere Trockenheit im Sommer, wurden die trockensten 10 Prozent der Standorte jeder Art lokalisiert und hinsichtlich ihrer Seehöhe und Exposition charakterisiert. Bäume aus diesen Beständen können als besonders trockenstresstolerant angesehen und in weiterer Folge zur Gewinnung von forstlichem Vermehrungsgut herangezogen werden. Der forstlichen Praxis wird damit die wichtige Information des „woher Nehmens“ geliefert, wenn es um den Umbau von Beständen in Richtung besser an zukünftigen Klimastress angepasster Waldökosysteme geht. Die verwendeten Datenpools dieses Projektes stehen allen interessierten Nutzern zwecks Herkunftssuche zur Verfügung.

Abstract

One option that has been muted as a potential climate change adaptation strategy for Forestry is the introduction of non-autochthonous provenances or non-native species which are thought to be better adapted to the projected changes in climate. However, such action should only be considered once autochthonous reproductive material has been proven to be inferior. If potentially adapted autochthonous provenances exist, utilisation of these sources would allow forestry in Austria to avoid (potentially unnecessary) ecological uncertainty and changes to the forest sector associated with large scale introductions of exotic species.

As warmer and drier summers have been expected for Austria, this study investigates the existence of potentially drought adapted provenances within the Austrian populations of 22 tree species of silvicultural and ecological importance. By calculating mean ecological indicator values of site moisture from vegetation relevés of the Austrian Vegetation Database this study demonstrates the range in moisture conditions tolerated by Austrian tree species. The sites were also analysed in terms of aspect and elevation to investigate non-climatic effects on site moisture conditions. Furthermore, the 10th percentile was taken as the cut off value to identify the dry sites inhabited by each of the respective species (i.e. the driest 10%). These sites represent the locations of potentially drought tolerant provenances and thus potentially useful sources of reproductive materi-

al in fostering climate change adaptation. For potential users interested in the locations of the provenances identified here, the data used and generated by this project will be made available upon request.

D-1 Introduction and Literature Review

According to the Intergovernmental Panel on Climate Change (IPCC), it is *very likely* that continued greenhouse gas emissions at or above current rates will induce larger changes in the global climate system over the next century than those observed during the 20th century (Meehl et al., 2007). Using 1980 to 1999 as a reference base, surface air temperatures for 2090 to 2099 simulated by multi-model ensembles are forecast to increase by 1.8 to 4.0°C depending on the emission scenario. Meanwhile, significant global changes in *inter alia* future precipitation patterns, atmospheric circulations and atmospheric chemistry have also been projected. As the state of the atmosphere is one of the most important general conditions for man's existence, the threat of climate change is forcing society to evaluate its position within the climate system e.g. how the forecasted climate changes may affect water quality and supply, food provision, spread of disease etc. (IPCC, 2007). One important part of the current research conducted under the umbrella of climate change is focused on the potential effects of climate change on the stability and integrity of forest ecosystems (Fischlin et al., 2007). Forests, just like other ecosystems, are complex dynamic systems of living organisms, interacting both with one another, and the substrate and atmosphere which constitute their abiotic environment (Kimmins, 1987). Any change in mean climate conditions will therefore affect ecosystem dynamics, potentially impacting on ecosystem function (integrity), and the resistance and resilience to natural disturbances (stability), and thus the socio-economic benefits which forests provide (see Bodin and Wiman (2007) and Dorren et al. (2004) for explanation of stability and integrity concepts). The world's forests constitute about 31% of the total land area and provide society with a wide range of products and services such as timber, fuel wood, recreation, carbon sequestration, and protection against natural hazards (FAO, 2010, FAO, 2011). However, the ability of forests to continue to perform such functions in the future will depend on future climatic conditions and how these ecosystems react. The IPCC have identified forests in particular as being potentially vulnerable to the projected changes in climate, due to the unprecedented short time over which the changes are likely to occur (Fischlin et al., 2007). The long life spans of trees, the most conspicuous components of forests, do not allow for rapid adaptation to environmental changes (Lindner et al., 2010). Consequently the future stability and integrity of the world's forests resources is likely to hinge upon the adaptive capacity of forest management i.e. the ability of management to help forest ecosystems accommodate the projected climatic changes (Millar et al., 2007).

One option that has been muted as a potential adaptation strategy is the introduction of non-autochthonous provenances or non-native species which are may be better adapted to the projected changes in climate (Bolte et al., 2010, Millar et al., 2007). Broadmeadow et al. (2005) for example recently demonstrated the "climate matching" approach as a potential adaptation strategy for Great Britain. By comparing projected climates for parts of the UK with the current climates of areas of Southern Europe, the study identified continental provenances which may be of use to UK forestry. While such interventions represent promising strategies to promote adaptability, there are of course potential drawbacks due to the ecological uncertainty involved with the introduction of non-native seed material, especially in the case of the introduction of exotic species (Richardson, 1998, Richardson and Rejmánek, 2011). Due to unwanted dispersal, such introductions may for example compromise conservation and biodiversity objectives such as the protection and enhancement of native broadleaved forests (Bolte et al., 2010, Engelmark et al., 2001). Furthermore, alternative provenances and species should only be considered once autochthonous provenances have been proven to be inferior (Kleinschmit et al., 2004). We suggest therefore that the introduction of non-native provenances should not be considered without first thoroughly assessing the potential of autochthonous species. Despite the talk of large scale non-native introductions

in Austria (e.g. the Douglas Fir provenance trials (Schultze and Raschka, 2002)) very little is known about the potential adaptability of Austria's own native tree species (Englisch and Karrer, 2001). This project thus aims to address this knowledge gap by using forest vegetation surveys from 17,095 sites to derive indirect estimates of the range of drought tolerance exhibited by Austria's autochthonous tree species. The objectives of the project are:

- 1) To gather data on the mean-, and amplitude in, drought tolerance of Austria's main autochthonous tree species.
- 2) To identify potential sites in Austria where the most drought tolerant provenances are located.
- 3) To complement the research conducted by a German-Russian project proposal (Drexler and Walentowski, 2011), investigating the potential use of provenances from continental Russia in German forestry.

D-1.1 Climate Change and Forestry in Austria

While the annual global mean surface air temperature is expected to increase, it is likely that mean annual temperatures in Europe will increase more than the global mean. According to the IPCC's regional simulations (Christensen et al., 2007), mean annual surface air temperatures in Europe will increase by roughly 2 to 5°C by the end of the 21st century. In the Mediterranean and central Europe, the simulated warming is likely to be largest during the summer. In terms of the mean change in annual precipitation, the regional projections suggest a 0 to 16% increase in northern Europe and a 4 to 27% decrease in southern Europe. Focusing on central Europe, the precipitation projections indicate that while winter precipitation is likely to increase, summer precipitation is likely to be reduced. In addition to the forecasts of mean changes, IPCC projections indicate that the daily and yearly temperature variability in central Europe is also likely to increase. While it is very uncertain whether extreme short-term precipitation will increase or decrease in central Europe, a decrease the number of summer precipitation days is likely. Consequently, the risk of temperature and precipitation extremes in summer such as droughts and heat waves is likely to increase in central Europe.

The need to assess the adaptive capacity of Austrian forestry is therefore very important given the projected changes in climate and the importance of forestry in Austria. Austria's forests represent extremely valuable national resources, performing vitally important protective functions in alpine areas, as well contributing to the environment, the quality of life, and the national economy (Federal Ministry of Agriculture, Forestry, Environment, and Water Management, 2008). According to the latest Austrian forest inventory (ÖWI) statistics, 47.6% of Austria's land area is classified as forest, with the total growing stock volume estimated at 1.135 billion m³ (ÖWI, 2007/2009). Of the total forest area (3.99 million ha), 84.4% produces yield. The ÖWI estimates that of 30.4 million m³ annual increment, 25.9 million m³ is utilised. Between 1988 and 2004 the estimated annual output of Austria's forest industry (fellings and net increment) ranged between 1.0 and 1.2 billion € (nominal) (Sekot, 2007). However, such a strict financial interpretation fails to recognise the total contribution of Austria's forests to its economy, ignoring important triggering effects elsewhere in the economy, as well the many ecosystem services that contribute significantly to public welfare. For instance, 20.5% of the total forest area is classified as protection forest, protecting people, buildings, and infrastructure from natural hazards such as avalanches, rock fall, debris flow, landslides, and severe erosion and flooding. Considering that the Eastern Alps dominate much of the Austrian landscape, it is no surprise that the protective functions provided by forests are particularly important within the Austrian context (Niese, 2011). Whether the current provision of goods and services can be sustained in the future will depend heavily on the reaction of Austria's forests to future changes in climatic conditions and how forest management adapts. While changes in mean climatic conditions will no doubt influence forest dynam-

ics, it is perhaps the projected changes in the temperature and precipitation variability, and the associated extremes such as drought and heat waves, which are cause for most concern. For example, where water was not a limiting factor, the moderate increase in air temperature over the last half a century or so appears to have had a positive impact on forest productivity, both globally (Boisvenue and Running, 2006), and on a national scale in Austria (Hasenauer et al., 1999). However, correlation between recent episodes of pronounced forest mortality and periods of extreme drought and heat (Allen et al., 2010) suggest that it may be *these* changes in climate which pose the biggest threat. To determine the vulnerability of Austria's forest to climate change, it is therefore important that the tolerance of extreme events such as drought be analysed.

Tab. D-1.1: Species contribution to the total above-ground forest volume in Austria

Species	Volume (1000 m ³)	%
Norway Spruce	694853 ± 13802	61,2
Silver Fir	49725 ± 2845	4,4
European Larch	75439 ± 2955	6,6
Scots Pine	74497 ± 3799	6,6
Austrian Pine	9154 ± 1617	0,8
Swiss Pine	4784 ± 896	0,4
Weymouth Pine	175 ± 74	0
Douglas Fir	635 ± 183	0,1
Other gymnosperms	351 ± 77	0
Total Volume Gymnosperms	909610 ± 16383	80,2
European Beech	108699 ± 4315	9,6
Oak	27429 ± 1803	2,4
Hornbeam	8992 ± 771	0,8
Ash	23705 ± 1439	2,1
Maple	15001 ± 827	1,3
Elm	1468 ± 190	0,1
Sweet Chestnut	1340 ± 257	0,1
Black Locust	2633 ± 574	0,2
<i>Sorbus</i> and <i>Prunus</i> sp.	3462 ± 268	0,3
Birch	6770 ± 481	0,6
Common Alder	8168 ± 1019	0,7
Grey Alder	3603 ± 423	0,3
Lime	3488 ± 453	0,3
White Poplar	4049 ± 572	0,4
Black Poplar	502 ± 178	0
Hybrid Poplar	2465 ± 552	0,2
Willow	2616 ± 381	0,2
Other Angiosperms	779 ± 134	0,1
Total Volume Angiosperms	225167 ± 6253	19,8
Total Stock Volume	1134780 ± 17994	100

(Total stock volume does not include the volume from protection forests with no yield; Species marked in red represent the species which are the subject of this study; data taken from (ÖWI, 2007/2009))

This study therefore investigates the potential drought resistance of the main autochthonous tree species. As Table D-1.1 shows, the Austrian forest stock is currently dominated by Norway spruce (*Picea abies*) which accounts for over 60% of the total volume in forests producing yield. Although Norway spruce is a dominant species among the potential natural forest communities found in Austria (Hauk, 2011), its current abundance and distribution has been heavily influenced by management practises. From the 18th Century onward when industrialization placed increased pressure on forest resources, and Norway spruce became favoured among forest managers due to its comparative tolerance of clear cut microclimates and its high initial growth (Hansen and Spiecker, 2005). Consequently Norway spruce has expanded beyond its natural geographical range, dominating sites which naturally support broadleaved species or mixed stands. While Norway spruce is currently Austria's most economically important forest tree species (Seidl et al., 2007), substantial volume contributions (>2%) are also made by Silver fir (*Abies alba*), European larch (*Larix decidua*), Scots pine (*Pinus sylvestris*), European beech (*Fagus sylvatica*), the Oaks (*Quercus petraea*, *Q. robur*, *Q. pubescens*, and *Q. cerris*) and Ash (*Fraxinus excelsior*). Together with Norway spruce, these species constitute over 90% of the volume in Austria's productive forests (Table D-1.1). However, while these species represent the main targets of this investigation, data on drought tolerance will also be presented for Austrian-, Swiss- and Mountain pine (*Pinus nigra*, *P. cembra*, and *P. uncinata*), Hornbeam (*Carpinus betulus*), Field maple (*Acer campestre*), Sycamore (*A. pseudoplatantus*), Wych elm (*Ulmus glabra*), Common- and Grey alder (*Alnus glutinosa* and *A. incana*), Large-leaved-, and Small-leaved Lime (*Tilia platyphyllos* and *T. cordata*), and White poplar (*Populus alba*).

D-1.2 Trees and Drought Stress

In order to aid the understanding of drought resistance, and the interspecific and intraspecific variation thereof, section D-1.2 will first introduce fundamental principles regarding tree responses to environmental stress. Following on, the section will then focus specifically on drought stress, explaining how this stress interferes with physiological function and the general strategies employed by trees to minimise the effects of drought stress. The review will then conclude, using species native to Austria as examples, with a short review of interspecific and intraspecific variation in drought resistance.

D-1.2.1 Environmental stress and tree response

Along with disturbances, environmental stress is the main factor limiting the increment and productivity of forests (Mandre et al., 2011). Stress, at both the individual tree and ecosystem level, can be defined as a deviation in any environmental factor beyond the optimum range, which reduces potential productivity (Niinemets, 2010). As abiotic and biotic factors fluctuate constantly and simultaneously within forest ecosystems, the development of stressful conditions is a completely "normal" ecosystem dynamic. This is well illustrated by the fact that most plants, including trees, often fail to achieve their full productive capacity due to resource deficiencies or external factors i.e. productivity is seldom limited by inherent physiological capacity (Kozlowski et al., 1991). The reaction of trees to environmental stresses has therefore concerned man for centuries (Kozlowski, 1979). However, more recently, the topic of tree and forest response to stress has gained added relevance due to current and projected global changes in environmental conditions, particularly changes in climate (Niinemets, 2010).

Investigating forest responses to stress is a complicated matter due to the various ways stress affects trees and the number of different stress factors which occur. The effect of stress, i.e. the response of the plant, may be experienced by all levels of the organism. However, the fundamental effect of stress is to interfere with normal physiological function, which depending on the magnitude and intensity of the stress, results in the retardation of growth and development and/or visible injury (Kozlowski et al., 1991). In his

Monograph *Tree Growth and Environmental Stresses*, Kozłowski (1979) distinguishes the effects of stress as either *plastic strains* or *elastic strains*. Stress causing plastic strain is recognizable by the rapid appearance of injury, whereby the organism affected does not recover its normal physiological function even when the stress is alleviated. Elastic strain on the other hand refers to stress effects, whereby physiological function is only temporarily impaired, returning to normal function once the stress is removed. Despite this distinction, elastic strains may develop into plastic strains, if the stress is maintained for long enough. This dynamic therefore suggests some sort of interplay between a magnitude- (i.e. the intensity of the stress) and temporal (i.e. the period over which the stress is maintained and the return interval of the stress) thresholds which determines whether a stress causes a temporary or irreversible impairment of function. This is illustrated by the *dynamic concept of stress* (Stocker, 1947, Selye, 1936, Selye, 1973), described in Larcher (2003). According to this conceptual model, an organism under stress passes through a sequence of characteristic phases. Following the onset of stress, the organism experiences a destabilization of the structural and functional conditions required for normal growth and function. If the stress is too intense, resulting in rapid impairment of function, an acute collapse of cell integrity occurs before any defensive measures can take effect. While the structural injury and loss/reduction of function is typically localised to the where the stress was/is applied, an irreversible impairment of function is, to an extent, felt by the whole organism, thus resulting in an *acute plastic strain*. If however, the impairment of function is not too rapid, the stressed organism may then enter a resistance phase, during which repair and defensive processes are stimulated e.g. the synthesis of proteins and protective substances. As these defensive mechanisms take effect, resistance is increased resulting in stability and normalization of function, sometimes even before the stress is alleviated. Such a recovery of function would therefore classify the stress effect as an *elastic strain*. However, if such a stress persists for too long, increases in intensity, or persistently re-occurs, the defensive and recovery capacities of the organism may become exhausted, essentially resulting in a *chronic plastic strain*. Consequently, whether stress elicits an acute plastic strain, a chronic plastic strain or an elastic strain depends on the capacity of the plant to resist and adapt to stress, the duration of the stress, and how the intensity of the stress varies over time.

Essentially all the fluctuating components of the biotic and abiotic environment represent potential stress factors. Stress may be induced by herbivores feeding on plant tissue, deficiency or excess of water, nutrients and radiation, too high or too low temperatures and various other unsuitable deviations in abiotic and biotic conditions (Larcher, 2003). As many of these factors often vary, stress is normally induced by a number of stress factors rather than just unsuitable deviations in one environmental condition. However, the strain felt by trees is complicated by the synergistic or even antagonistic effects of multiple stress factors (Niinemets, 2010). Two or more stresses may interfere with the magnitude- and temporal thresholds which the respective stresses must exceed if they are to impair function. For instance, abiotic stresses often compromise the defence mechanisms of plants, thus promoting infection by fungal pathogens (Kozłowski et al., 1991).

D-1.2.2 Drought stress

Water is one of the most common limiting environmental factors for plant growth, affecting almost every aspect of plant physiology and morphology. Water is the essential medium in which biochemical processes take place, and plant protoplasts are comprised of 85 to 90% water (Larcher, 2003). Furthermore, water is of course a reactant and product of photosynthesis, the process by which trees and all photo-autotrophs use solar energy to fix inorganic atmospheric carbon into carbohydrates (Kimmins, 1987, Kozłowski et al., 1991, Larcher, 2003). As very little water is absorbed over the leaf-

atmosphere interface, photosynthesis relies on the absorption of soil water by the roots and its subsequent vertical transport through the stem to the leaves. According to cohesion-tension theory of Dixon and Joly (1896) (see reviews by Meinzer et al. (2001) and Tyree and Ewers (1991)) the driving forcing of this vertical ascent is the vertical gradient of negative water potential created by the evaporative loss of water from the leaves. Evaporation from the leaf surface initially causes the air-water interface to retreat deeper into the finely porous spaces of the leaves. However capillary forces draw the interface back to the surface of the pores, thus transmitting tension to the water columns in the xylem conduits. As hydrogen bonding between water molecules promote cohesion within the water column, transpiration essentially 'pulls' water up from the soil into the roots, through the stem and up into the leaves.

According to Kozlowski et al. (1991), water stress occurs when water loss via transpiration exceeds absorption of water from the substrate, creating plant water deficits. These deficits result in a decrease in water content and cell turgor of plant tissues, which reduce cell enlargement and cellular function. Water deficits also decrease the potential energy of the remaining water, which can restrict the ascent of water through the stem. Like with many other stress factors, water stress is a normal part of plant life. Even when soil water isn't limiting, rapid loss of water from the upper tree leaves during hot sunny days causes temporary water deficits in the exposed leaves due to the increasing hydraulic resistance as one moves from the leaves to the stem and down to the roots. Consequently, during times of particularly high evaporative demand, recharge from the xylem cannot keep pace with the evaporative loss from the leaves. While these events result in temporary wilting and reduction in photosynthesis, the strain on the tree is often elastic. Shortly, after midday the stomata of leaves begin to close which, by reducing evaporative loss, steadily reduce the deficit as water ascends through the xylem into the leaves during the rest of the afternoon and the subsequent night time. Likewise, during this period the water ascending the stem is replaced by the water absorbed from the soil by the roots. However, if such conditions persist for longer periods e.g. during prolonged droughts, the strain on the tree may become plastic as recharge of tissue water becomes restricted. As soil water becomes depleted, the vertical pressure gradient over the soil-tree-atmosphere continuum is decreased, which together with subsequent increases in hydraulic resistance in the soil and the conducting tissue of the tree, reduces the vertical ascent of water. It is therefore during such periods when effects of water stress induce plastic strain, inducing symptoms such as significant decreases in vegetative and reproductive growth, reductions in vitality, and even dieback and mortality.

Bréda et al. (2006) state that such severe symptoms are likely to result from an initial stress-induced hydraulic dysfunction followed by a subsequent deficit in carbon storage. During periods of prolonged drought, water potential in the xylem conduits becomes more and more negative, due to the substantial evaporative loss and the lack of recharge from the soil. According to the air seeding hypothesis of Zimmermann (1983), if water potentials in the xylem drop below a critical threshold, cavitation may occur whereby the increased tension within the conduit pulls air through the pits on the walls of the conduit. The conduit then quickly fills with water vapor and air resulting in an embolism, which blocks the vessel element/tracheid, thus severing the water column at that point. If the drought persists, and the evaporative demand remains high, a feedback effect known as "runaway embolism" (Tyree and Sperry, 1989) may develop. Due to the subsequent increase in hydraulic resistance through the tree, tension in the other xylem conduits is further increased, thus posing the risk of further cavitation and embolisms and thus severe hydraulic dysfunction. For more details on cavitation and embolism, the reader is referred to Cruziat et al. (2002), Meinzer et al. (2001), Tyree and Ewers (1991), and Tyree and Sperry (1989). The consequent increases hydraulic resistance, coupled with increased stomatal sensitivity during such drought events, and can lead to significant reductions photosynthetic production, due to the reduced water ascent and leaf-atmosphere gas exchange (Bréda et al., 2006, Rennenberg et al., 2006). While this

of course results in decreased growth, maintenance of metabolism via respiratory processes nevertheless continues, thus consuming carbon. Thus under such prolonged stress conditions, stored carbon reserves may become depleted, a phenomenon known as “carbon starvation” (McDowell et al., 2008). The stressed tree(s) subsequently run(s) the risk of pathogen/pest attack due to reduced synthesis of defence compounds or outright starvation. Considering the effects of drought stress, the projected increase in temperature and precipitation extremes are thus cause for much concern, not only because of potential decreases in productivity but also the likely increases in forest dieback. Several authors (Allen et al., 2010, Bréda et al., 2006, Rennenberg et al., 2006) have hypothesised that the recent episodes of large scale tree mortality (e.g. during the European heat wave of 2003) resulted from stress induced hydraulic dysfunction and subsequent depletion of non-structural carbon stocks.

Irrespective of the potential change in future precipitation patterns, periods of drought are nevertheless normal meteorological phenomena. Consequently, through evolution, trees have developed a number of morphological and physiological adaptations to cope during periods of limited rainfall. While temporary impairments of function are unavoidable consequences of drought, trees are equipped (to varying extents) with morphological and physiological defence strategies which minimise deleterious effects, thus maximising the chance of a return to normal function once the stress is alleviated. Kozłowski et al. (1991) distinguish between two types of adaptation to drought: *drought avoidance* and *drought tolerance*. As is perhaps apparent from the terminology, the strategies that allow trees to avoid drought represent the first line of defence. Although certain desert species avoid drought by completing their life cycle during a short period following winter rains, the ability to avoid drought in the temperate context essentially refers to the capacity to delay dehydration. Generally, the ability of a tree to postpone dehydration depends primarily on a tree's root structure, -water storage capacity in the xylem, and how the tree controls transpiration rates. A deep, extensively branched root system is a considerable advantage during drought periods, as it is the upper soil horizons which become depleted first. Resistance to drought often increases with age due in part to the development of a deeper and more extensive root network (Niinemets, 2010). Furthermore, dehydration can also be delayed by storing water within the stem and regulating water loss. For instance to defend against severe leaf water deficits on hot sunny days, trees begin to partially close their stomata soon after midday in order to reduce rapid evaporative loss. Leaf turgor is then re-established as water from the xylem moves into the leaves over the subsequent afternoon and evening. During hot sunny days stomata closure is primarily initiated by high vapour pressure deficits and incident shortwave radiation, while hormonal signals from the roots can cause stomata to close earlier during periods when soil water is depleted (Kozłowski, 1979, Kozłowski et al., 1991). However, Sperry (2000) argues that during such periods, the signal may actually come from the xylem conduits which are under increased tension and thus at risk of cavitation. In addition to stomatal closure, trees can also restrict water loss during periods of drought by shedding leaves and thus reducing the evaporative area (Kozłowski, 1979, Kozłowski et al., 1991). However, it is important to point out that closure of stomata, and particularly leaf shedding, can also be considered as symptoms of drought stress, due to the associated reductions in photosynthetic capacity.

As the capacity of a tree to avoid drought is of course limited, the mechanisms which help postpone dehydration can be exhausted during periods of particularly prolonged drought. Under such situations, the tissues and organs of the organism, especially the leaves, are subjected to severe dehydration. At this point, the extent to which a tree can avoid irreversible injury and resume normal function will depend of course on how much longer the drought proceeds and the inherent ability of the tree to tolerate dehydration (Kozłowski et al., 1991). While postponing dehydration is generally achieved by morphological structures and physiological processes at the organ- to organism level, dehydration tolerance is typically dependent on cellular properties and processes which lower

the water potential at which turgor is lost. Tolerance can for instance be increased by osmotic adjustment, whereby the accumulation of additional solutes allows maintenance of turgor-dependent processes at lower water potentials than would otherwise be possible (Kozlowski et al., 1991, Rennenberg et al., 2006). Elasticity of cell walls is also said to be an important factor in maintaining turgor at low water potentials. Furthermore, by lowering leaf osmotic potentials when soil water potentials are low, trees can re-establish stronger vertical gradients in water potential, thus promoting vertical water transport (Rennenberg et al., 2006).

D-1.2.3 Variation in drought tolerance

While all tree species possess some capacity to avoid and tolerate drought, certain tree species are more equipped than others to avoid and tolerate water stress. Due to geographical variations in substrate and climate, the pressure of natural selection has facilitated a wide inter-specific variation in drought avoidance and tolerance (Kozlowski et al., 1991). To illustrate this variation Table D-1.2 gives mean drought tolerance values (referring to both the ability to *avoid* and *tolerate* drought stress) collected by Niinemets and Valladares (2006) for a selection of different European species.

Tab. D-1.2: Mean drought tolerance values plus/minus one standard error of selected tree species according to Niinemets and Valladares (2006)

Species	Drought Tolerance
<i>Picea abies</i>	1.75 ± 0.41
<i>Abies alba</i>	1.81 ± 0.28
<i>Larix decidua</i>	2.31 ± 0.55
<i>Pinus sylvestris</i>	4.34 ± 0.44
<i>Fagus sylvatica</i>	2.40 ± 0.43
<i>Quercus robur</i>	2.95 ± 0.31
<i>Quercus petraea</i>	3.02 ± 0.15
<i>Quercus cerris</i>	4.29 ± 0.21
<i>Quercus pubescens</i>	4.10 ± 0.25
<i>Fraxinus excelsior</i>	2.50 ± 0.25

(Drought tolerance expressed over a scale of 1 to 5 with 1 being very drought intolerant and 5 being very drought tolerant. For details of how the index is calculated and where the data were sourced the reader is referred to Niinemets and Valladares (2006))

As it is hydraulic dysfunction which poses the greatest threat to a tree under drought stress, overall drought tolerance is generally a result of how well equipped the individual is to resist cavitation of the xylem conduits. While the irreversibility of embolism formation is still open to debate, recovery is nevertheless considered to be a slow and costly process (Bréda et al., 2006, Meinzer et al., 2001). Referring back to the terminology of Kozlowski et al. (1991), one would thus intuitively expect that a tree's resistance to cavitation depends on its ability to *avoid* the development of low water potentials in the xylem, and its capacity to tolerate low water potentials in the vessel elements/tracheids. However, evidence seems to suggest that physiological and morphological adaptations that avoid the development of critical tensions in the xylem conduits are more important than the ability to withstand low water potentials in the conducting tissue. For instance, Norway spruce (*Picea abies*), Silver fir (*Abies alba*), and Scots pine (*Pinus sylvestris*) are relatively similar to one another regarding their capacity to tolerate low xylem water potentials. According to the data collected by Martínez-Vilalta et al. (2004), the water potential causing a 50% loss of hydraulic conductivity in stems (Ψ_{50PLC}) for Norway spruce, Silver fir and Scots pine were -3.50 to 3.70, 3.70, and -3.10 to -3.57, respectively. However in comparison to Norway spruce and Silver fir, Scots pine is par-

ticularly tolerant of drought conditions, perhaps due to tighter stomatal control and deeper rooting systems which help inhibit the development cavitation-inducing water potentials in the stem (Irvine et al., 1998, Cochard, 1992, Zang et al., 2012). Meanwhile, Geßler et al. (2006) suggest that the relative drought intolerance of European beech (*Fagus sylvatica*) may be explained by the inadequacy of stomatal control mechanisms in preventing cavitation. On the other hand, the drought tolerance of Sessile oak (*Quercus petraea*) a species which typically replaces Beech on dry sites (Geßler et al., 2006), is reported to be a result of this species ability to maintain water potential in leaf and stem xylem tissue above critical cavitation thresholds (Cochard et al., 1996). In addition to stomatal control, cavitation avoidance may also depend on the specific hydraulic conductivity K_s ($\text{kg m}^{-1} \text{MPa}^{-1} \text{s}^{-1}$) of the tree (the total hydraulic conductivity K_h ($\text{kg m MPa}^{-1} \text{s}^{-1}$) divided by the sapwood cross-section (m^2)), as increasing hydraulic efficiency i.e. K_s reduces the water potential gradient required for a given transpiration rate, thus reducing the tension within the water column. For deciduous angiosperm tree species, Maherali et al. (2004) found from their meta-analysis that K_s increased with decreasing annual rainfall, indicating the potential importance of K_s in drought tolerance. Differences in K_s may also explain the difference in drought tolerance between Beech and Oaks such as Sessile oak and Pendunculate oak. Being ring-porous species, Oaks produce large diameter vessel elements in the earlywood, while diffuse-porous Beech produce narrower vessel elements dispersed evenly over a growth ring. As flow through a conduit under a given pressure gradient force is proportional to the fourth power of the conduit's radius (the Hagen-Poiseuille law), the large diameter vessel elements in the earlywood result in larger K_s values for Oaks than Beech (Steppe and Lemeur, 2007). While large vessels tend to be more vulnerable to embolism formation due to lower critical tensions (i.e. higher water potentials) required for cavitation, the increase in specific hydraulic conductivity in combination with tight stomatal control and deep extensive rooting systems may promote overall drought tolerance (Taneda and Sperry, 2008). Finally, while strategies that help to avoid cavitation are perhaps the most important in determining overall drought resistance, the ability to tolerate low leaf- and stem water potentials may also be significant. Both Aranda et al. (2005) and Raftoyannis and Radoglou (2002) demonstrate evidence that photosynthetic metabolism of Sessile Oak is less sensitive to low leaf water potentials than that of European Beech, perhaps due to leaf osmotic adjustment in the former. Such mechanisms allow the individual to maintain leaf turgor and restrict the reduction in stomatal closure, thus allowing leaf-atmosphere gas exchange to continue to some extent. Needle osmotic adjustment has also been mentioned by (Badalotti et al., 2000) as a potential reason for the superior drought tolerance of European larch (*Larix decidua*) compared to Norway spruce, despite the similarities between the two species with respect to xylem vulnerability to cavitation ($\Psi_{50\text{PLC}}$) (Charra-Vaskou et al., 2012).

Due to the prospect of increased summer drought threatening central Europe, there have been suggestions that forest management should take advantage of this interspecific variation in drought tolerance by regenerating stands with more drought tolerant tree species, utilising both native and non-native options (Millar et al., 2007, Bolte et al., 2010). However, considering the uncertain ecological consequences of introducing different species to new sites, especially exotic species (Richardson, 1998, Richardson and Rejmánek, 2011), such management options are not without substantial drawbacks. Furthermore, the introduction of new species should only be considered when the original species has been proven to be inferior. While the above review briefly highlights how certain species are, *on average*, more adapted to drought conditions than others, one must not forget 1) the adaptation of the respective species to other site-specific factors and 2) the intraspecific variation (i.e. variation within a species) in drought tolerance. Due to different site conditions, spatial variations in selection pressures can facilitate intraspecific variation in a number of important traits within a species range (Magnani, 2009, O'Brien et al., 2007). Investigations of drought responses in of provenances

sourced from different eco-climates have indicated adaptive variation in drought tolerance, specifically with respect to stomatal control, within the ranges of European beech (Rose et al., 2009) and Scots pine (Cregg and Zhang, 2001, Martinez-Vilalta et al., 2009). Consequently, the introduction of new or exotic species to a given stand could be thought of as a premature action, if one has not first considered the potential of marginal provenances as source of drought-adapted ecotypes.

While the above studies have demonstrated intra-specific adaptive variation over international scales, it is also possible that drought tolerant provenances exist within a country's borders. Kapeller et al. (2012) demonstrate the potential of using reproductive material from Austrian populations of Norway spruce from warmer and dryer regions in adapting Austrian forests to climate change. The authors admit however that the adaptive variation may have more to do with population history than local adaptation i.e. adaptations occurring outside of Austria and subsequent importation of reproductive material. Nevertheless, due to variations in site conditions over smaller spatial scales combined with the large within-population genetic diversity typical of woody plant species (Hamrick, 2004), there may be potential for autochthonous provenances to play a role within forestry's efforts to adapt to climate change.

D-2 Methods

D-2.1 Identification of drought-adapted provenances of Austrian tree species using relevés

Under the assumption that site-specific selection pressures facilitate adaptive variation at naturally regenerated sites, one would expect to find more drought adapted ecotypes/provenances within the drier regions of a species spatial distribution. With Austrian forestry is faced with the challenge of adapting to climate change, such areas within Austria may represent potentially useful sources of autochthonous reproductive material, although identifying these locations is difficult due to a lack of hydrologically relevant data at the spatial resolution required. Characterising the soil moisture situation of a site requires not only climatological data such as annual precipitation and mean annual temperature, but also information on altitude, aspect, slope, and micro-topography (Englisch et al., 1998). However, in the absence of such data, analysis of understory plant communities can provide important insights into abiotic site conditions such as dryness (Ellenberg, 1979, Ellenberg et al., 1991). In this study, ecological indicator values of site moisture were derived from vegetation data collected from almost 20,000 sites (Willner and Grabherr, 2007) to:

- 1) Explore the respective drought tolerances of Austria's autochthonous tree species, and within-species variation thereof.
- 2) Identify the driest locations where Austrian tree species are represented

In total 19,058 vegetation relevés were selected from the Austrian Vegetation database (Willner). Using updated ecological indicator values of Austrian flora (Englisch et al., 1991, Herzberger and Karrer, 1992, Karrer and Kilian, 1990), average moisture values (unweighted arithmetic mean) were derived for each relevé using the HITAB5 software package (Wiedermann, 1995). Some taxa were added or adapted according to taxonomical changes and few values for single taxa have been adjusted (Appendix A-3) The relevés were then filtered to select only those in which Austrian tree species were dominant or subdominant within at least one of the tree layers (i.e. "Braun-Blanquet code" ≥ 3 , which corresponds to a minimum canopy cover of more than 25%), and those in which the moisture values were calculated from 5 or more plant species. The relevés for each species were then ranked by ascending moisture indicator value, with the 10th percentile (i.e. the driest 10 %) distinguishing the relevés representing the most drought-adapted provenances of each species.

D-2.1.1 Database and choice of tree species:

As part of his phytosociological classification of Austria's forests and thickets, W. Willner compiled a database of almost 20,000 vegetation relevés. Each relevé contains data on the quantitative and qualitative vegetation composition, as well as site characteristics (altitude, aspect, geology, and soil type), geographical location, size of the sampling area, classification according to the Austrian classification system, and the authors who surveyed the plot. The database was updated with ecological indicator values for the vascular plants of Austria (Englisch et al., 1991, Herzberger and Karrer, 1992, Karrer and Kilian, 1990) in part adjusted to the current state of the art (Appendix A3).

There are 164 woody plant species in Austria, of which 73 species exhibit tree-like growth habits. Although some of the 73 species are rather rare, many of them make an important economic and/or ecological contribution to Austrian forestry to some extent. However, due to underrepresentation within the relevés database, not all species could be analysed. To gain robust insights from the relevés a relevé was only considered to

represent a tree species if the given species was present in at least one of the tree layers, with its canopy area covering more than 25% of the ground below (i.e. a “Braun-Blanquet code of at least 3). Applying these criteria resulted in 46 species being represented by at least 1 relevé (Table D-2.1). Of the 46, 22 were identified as being the most important from a silvicultural point of view and were subsequently analysed (*Picea abies*, *Fagus sylvatica*, *Pinus sylvatica*, *Quercus petraea* s.lat. + ssp. *petraea*, *Abies alba*, *Quercus robur*, *Larix decidua*, *Fraxinus excelsior*, *Carpinus betulus*, *Acer pseudoplatanus*, *Pinus nigra*, *Populus alba*, *Pinus cembra*, *Acer campestre*, *Quercus cerris*, *Quercus pubescens*, *Tilia cordata*, *Tilia platyphyllos*, *Alnus glutinosa*, *Alnus incana*, *Ulmus glabra*, *Pinus uncinata*).

Tab. D-2.1: Number of relevés for each tree species present as either dominant or subdominant in at least one vegetation relevé

Species	No. of Relevés	Species	No. of Relevés
<i>Picea abies</i>	4700	<i>Ulmus glabra</i>	95
<i>Fagus sylvatica</i>	2707	<i>Salix fragilis</i>	86
<i>Pinus sylvatica</i>	1145	<i>Pinus cembra</i>	83
<i>Fraxinus excelsior</i>	1133	<i>Populus x canadensis</i>	62
<i>Alnus incana</i>	890	<i>Prunus padus</i>	42
<i>Quercus petraea</i> s.lat.	809	<i>Betula pendula</i>	37
<i>Alnus glutinosa</i>	799	<i>Populus nigra</i>	35
<i>Carpinus betulus</i>	681	<i>Acer platanoides</i>	32
<i>Abies alba</i>	636	<i>Prunus avium</i>	29
<i>Acer pseudoplatanus</i>	475	<i>Betula pubescens</i>	25
<i>Quercus robur</i>	395	<i>Robinia pseudacacia</i>	24
<i>Larix decidua</i>	323	<i>Ulmus minor</i>	17
<i>Pinus nigra</i>	227	<i>Fraxinus ornus</i>	15
<i>Salix alba</i>	210	<i>Populus x canescens</i>	14
<i>Tilia cordata</i>	206	<i>Ulmus laevis</i>	10
<i>Ostrya carpinifolia</i>	183	<i>Quercus dalechampii</i>	5
<i>Quercus pubescens</i> s. lat.	175	<i>Castanea sativa</i>	4
<i>Populus alba</i>	170	<i>Populus tremula</i>	4
<i>Quercus cerris</i>	156	<i>Salix caprea</i>	2
<i>Tilia platyphyllos</i>	123	<i>Acer tataricum</i>	1
<i>Acer campestre</i>	113	<i>Sorbus aucuparia</i>	1
<i>Fraxinus angustifolia</i>	109	<i>Sorbus torminalis</i>	1
<i>Pinus uncinata</i>	105	<i>Tilia x vulgaris</i>	1

D-2.1.2 Calculation of average ecological indicator values

There are two ways to characterise site parameters at a given location based on the species composition of the herb layer: The calculation of an “average indicator value” or the presentation of “amplitude of the optima” of the respective species present. Generally, the former method is the one most often used, especially in countries where plausible ecological indicator values exist (see Englisch and Karrer (2001) and Diekmann (2003)).

The premise behind ecological indicator values is that under “optimal” conditions (sufficient nutrient and water supply, soil aeration, no competition etc.), the autecological optima and distribution over an ecological gradient (e.g. a gradient in light availability) of different plant species would strongly overlap with one another. However, in nature where abiotic conditions are often sub-optimal and competition is omnipresent, the given species exhibit significantly different amplitudes and optima i.e. the synecological amplitudes and optima (Figure D-2.1).

Many species demonstrate a clear synecological optimum along a given ecological gradient, thus allowing one to make assertions about abiotic site conditions based on the

herbaceous species present. Originally the ecological gradients over which species occur were non-numeric (e.g. Aichinger (1967)), although since Ellenberg (1979) the use of ordinal scales has become common practise. This allows species to be assigned with different “ecological indicator values” for a given site property based on where their respective synecological optima lie within the given gradient. For instance, the ecological indicator value of the “blue species” depicted in Figure D-2.1 would be about 7.2. Thus a site can be characterised by taking an average value of the ecological indicator values of the plant species present.

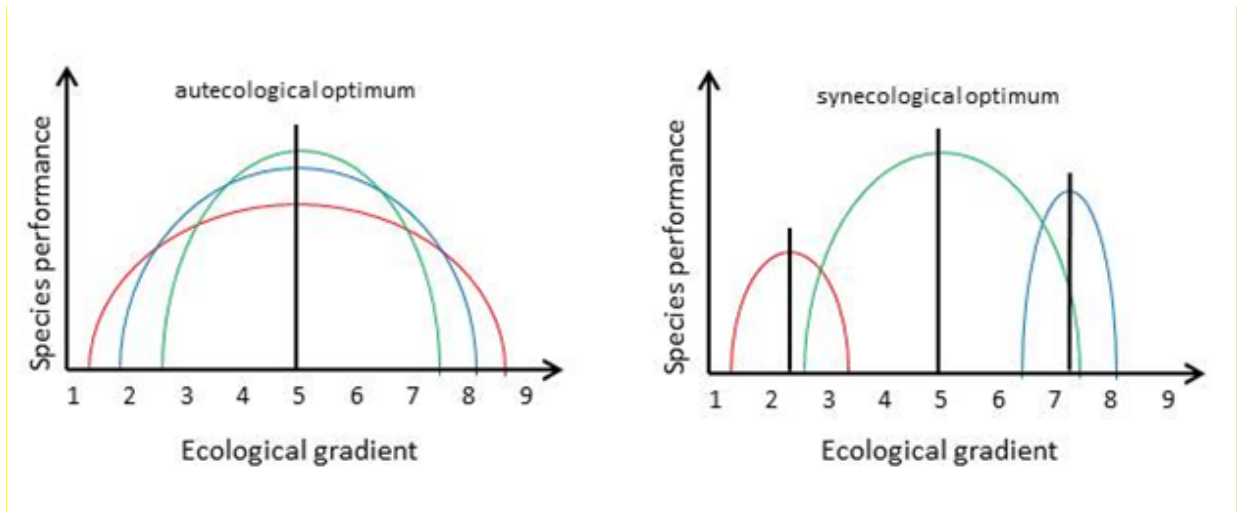


Fig. D-2.1: Conceptual model of autecological and synecological amplitudes and optima along an ecological gradient (fundamental and realised niche).

For this study, all the species in the relevés were assigned moisture indicator values (“FeuchFwert” F-number) derived from a 1-12 scale (Englisch et al., 1991, Herzberger and Karrer, 1992, Karrer and Kilian, 1990). As forests occupy the terrestrial and semi-terrestrial portions of the scale, only levels from 1 to 9 are relevant. The indicator values were assigned to each species using the HITAB5 software package (Wiedermann, 1995) based on which of following descriptions is most applicable.

- 1 Present on dry soils, often on desiccating sites
- 2 Lies between 1 and 3
- 3 More frequently present on dry soils than fresh
- 4 Lies between 3 and 5
- 5 Present on fresh sites, never wet or dry sites
- 6 Lies between 5 and 7
- 7 Present on moist sites, but not on water saturated soils
- 8 Lies between 7 and 9
- 9 More frequently present on saturated (anaerobic) soils

The average moisture indicator value for each relevé was subsequently derived by calculating the arithmetic mean of the respective indicator values. Although, Englisch and Karrer (2001) argue that the average indicator value should be calculated as a weighted median, calculating the arithmetic mean is the method most often applied. While taking the mean of ordinal numbers is, statistically-speaking, invalid, calculation of arithmetic means is nonetheless common practise and thus allows comparison with other literature sources. However, means were not calculated for relevés containing only 5 or less species. Such relevés often represent sites where light availability at the forest floor is very poor with only very shade tolerant species occurring. Consequently, as very little regarding other abiotic site factors can be deciphered from such relevés, these relevés were omitted from the analysis.

To investigate the relationship between the calculated mean indicator values for moisture (M-value) and site climate, values of mean annual precipitation and mean annual mean temperature for the period 1971-2000 were assigned (where possible) to each relevé. This was done by aligning the floristic mapping grids (Niklfeld, 1994) of the corresponding relevés (if coordinates for the relevé were available) with grid-based annual precipitation and mean annual temperature data (Auer et al., 2010) using ARCGIS 10.2 (Figure D-2.1). For each species, the respective temperature and precipitation values of the dry sites (the driest 10%) and for the “residual sites” (the other 90%) were subsequently compared against one another via two sample t-tests (α 0.05) using SPSS v.10. Finally, to demonstrate the importance of site properties other than climatological variables in determining site soil moisture patterns, the calculated mean moisture indicator values were also compared against site parameters such as aspect, slope, and altitude via bar charts. Note: the site parameters were binned into graduated classes.

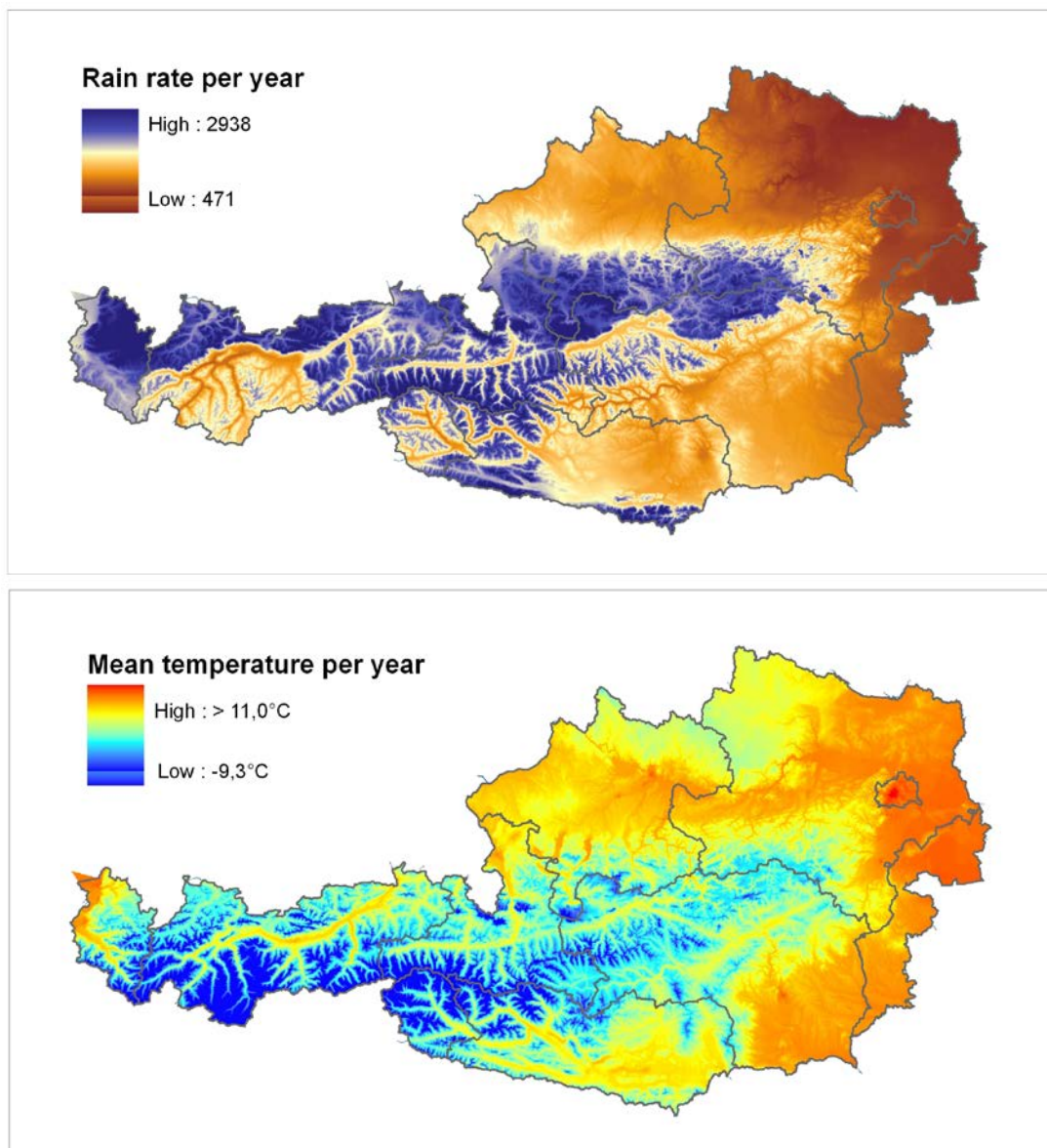


Fig. D-2.2: Grid based values of annual precipitation (above) and annual mean temperature (below) for Austria averaged over the period 1971 to 2010. Data source: Zamg-ÖKLIM, Auer et al. (2010), Map: ÖK 200, BEV.

D-3 Results

D-3.1 Characterisation of means and amplitudes of drought tolerance, and other ecological factors of Austrian tree species according to vegetation relevés

D-3.1.1 *Gymnosperm species*

D-3.1.1.1 *Abies alba*

According to the relevés, Silver fir was found occupying sites with a mean moisture value (M-value) between 4 and just above 7, although the distribution indicates optimal sites with M-values between 5 and 6, and a general avoidance of dry sites (Figure D-3.1). The general avoidance of dry conditions is also indicated by the prevalence of W-, N- and NE-exposed locations within the residual relevés (i.e. those not belonging to the 10th driest percentile) (Figure D-3.3), where, due to less intense incident radiation, evaporative demand is typically lower. The driest 10% recorded M-values of 4.93 and below and were strongly represented by SE to SW aspects. However, there was no significant difference in either annual precipitation or annual mean temperature between the driest 10% (the dry relevés) and the remaining 90% (the residual relevés) (Fig. D-3.4).

Silver fir is generally classified as a montane/submontane tree species, which is rather well illustrated by the elevation distribution of the Silver fir of both the dry and the residual relevés (Figure D-3.2). The fir relevés ranged from 300 to 1700 m a.s.l., with the highest dry relevés found at 1400 m.

D-3.1.1.2 *Picea abies*

A mean M-value of 5.41 was calculated for Norway spruce and similar to Silver fir, the optimum of Norway spruce appeared to be represented by sites with an M-value between 5 and 6. However, the wider distribution over the moisture scale (3.6-8.8) suggests a larger amplitude in drought tolerance than that of Fir (Figure D-3.1).

While the altitudes of the Spruce relevés range from 120 to 2000m a.s.l., a substantial proportion of residual relevés were located between 1300 to 1500 m. The driest relevés on the other hand demonstrated a more restricted range and more uniform distribution (Figure D-3.2). While the general pattern was similar to Fir, the dominance SE-, S- and SW-exposed sites in the dry relevés was more pronounced for Spruce (Figure D-3.3). Furthermore, relevés belonging to the driest 10% demonstrated significantly higher mean annual mean temperatures (6.3°C compared to 5.6°C) and lower mean annual precipitation (1289 mm compared to 1379 mm) than the residual relevés (Figure D-3.4).

D-3.1.1.3 *Larix decidua*

The European larch relevés demonstrated a slightly skewed distribution along the moisture gradient: a few relevés indicating considerable presence on dry soils, moist sites (M-Value >6.25) almost completely avoided, and an optimum M-value of 5.4 (Figure D-3.1).

Apart from a difference in range there was generally no clear distinction with respect to distribution over elevation between the dry and residual relevés. As Larch is an alpine species, often found in forest communities at the timber line, the range of the residual relevés reached just above 2000 m a.s.l. (Figure D-3.2). The dominance of southern exposures was very clear in the dry relevés of larch (almost half were either S-/SW-

exposed sites), despite a clear preference of the residual relevés for north-exposed sites (Figure D-3.3). Due to insufficient allocation of climate data to the Larch relevés, statistical comparison of the temperature and precipitation values of the dry and residual relevés could not be performed.

D-3.1.1.4 Pinus cembra

The rather narrow range in the moisture values indicates a clear preference of Stone pine for fresh soils: The optimum was an M-value of just above 5 (Figure D-3.1).

Together with Larch, Stone pine is a common species found at the timber line of the Alps, although unlike Larch, its range in elevation is more limited to higher altitudes: The residual relevés ranged from 1500 to 2270 m a.s.l., with the optimum lying between 1800 and 2000 m. The range of the dry relevés was narrower: 1700-2100 m a.s.l. (Figure D-3.2). Of the dry relevés, SW-exposed sites were the most represented, although the general distribution over the different aspects was rather uniform (Figure D-3.3). This was perhaps a result of the small number of dry relevés detailing the sites aspect (n=83). Due to insufficient allocation of climate data to the Larch relevés, statistical comparison of the temperature and precipitation values of the dry and residual relevés could not be performed.

D-3.1.1.5 Pinus nigra

Austrian pine is a very drought tolerant species which is well reflected by the distribution in M-values: Range in M-values from 2.6 to 4.8, dominance of relevés with M-values of between 3 and 4. The M-value of the 10th percentile was 3.15 (Figure D-3.1). Consequently, the Austrian pine relevés were generally located at lower elevations. The distribution ranged from 250 to 1330 m a.s.l., with the majority lying within submontane elevations. This elevation zone was also dominated by the dry relevés, although their distribution beyond this range, particularly at higher elevations (>900 m a.s.l.), was more limited (Figure D-3.2).

As a drought resistant species, the distribution between aspect of both the dry and residual relevés demonstrated a clear preference for the S to W exposures, where, all things being equal, evaporative demand is generally higher (Figure D-3.3). There was no significant difference in either annual precipitation or annual mean temperature between the dry relevés and the residual relevés (Figure D-3.4), perhaps due to the similar geographical distribution of both the dry and residual relevés (Figure D-3.12).

D-3.1.1.6 Pinus sylvestris

Scots pine is a light demanding species, although in terms of water requirements this species can be found at both ends of the moisture spectrum. This is represented to some extent by the wide distribution observed here: between 2.7 and 8.5. The M-value of 10th percentile was, at 3.37, very low (Figure D-3.1).

Scots pine also demonstrated a wide range in elevation, from 220 to 1890 m a.s.l., with elevations of around 700 m a.s.l. the most frequent. The range of the dry relevés was more restricted to lower elevations between 200 and 900 m a.s.l. (Figure D-3.2).

Like Austrian pine, the distributions between aspect of both the dry and residual relevés were similar although compared to the residual relevés, the dry relevés showed a stronger preference for SE- rather than SW-exposures (Figure D-3.3). However, unlike Austrian pine, relevés belonging to the driest 10% demonstrated significantly lower annual precipitation (698 mm compared to 999 mm) than the residual relevés. Meanwhile the difference in annual mean temperature was statistically insignificant (Figure D-3.4).

D-3.1.1.7 *Pinus uncinata*

From the relevés, Mountain pine exhibited a preference for fresh sites. The distribution in M-values for Mountain pine ranged from just below 4 to 5.5, with the most frequent M-values ranging between 4.5 and 5. The 10th percentile was at 4.20 (Figure D-3.1).

The distribution along the elevation gradient ranged from 800 to 1600 m a.s.l., although the range of the dry relevés was restricted to 800 to 1200 m a.s.l. (Figure D-3.2). The aspect distribution indicated a preference for flat sites or W- to N-exposures for the residual relevés, while the distribution of driest 10% favoured W-, SW- and E- exposures and less inclined sites (Figure D-3.3). Due to insufficient allocation of climate data to the Larch relevés, statistical comparison of the temperature and precipitation values of the dry and residual relevés could not be performed.

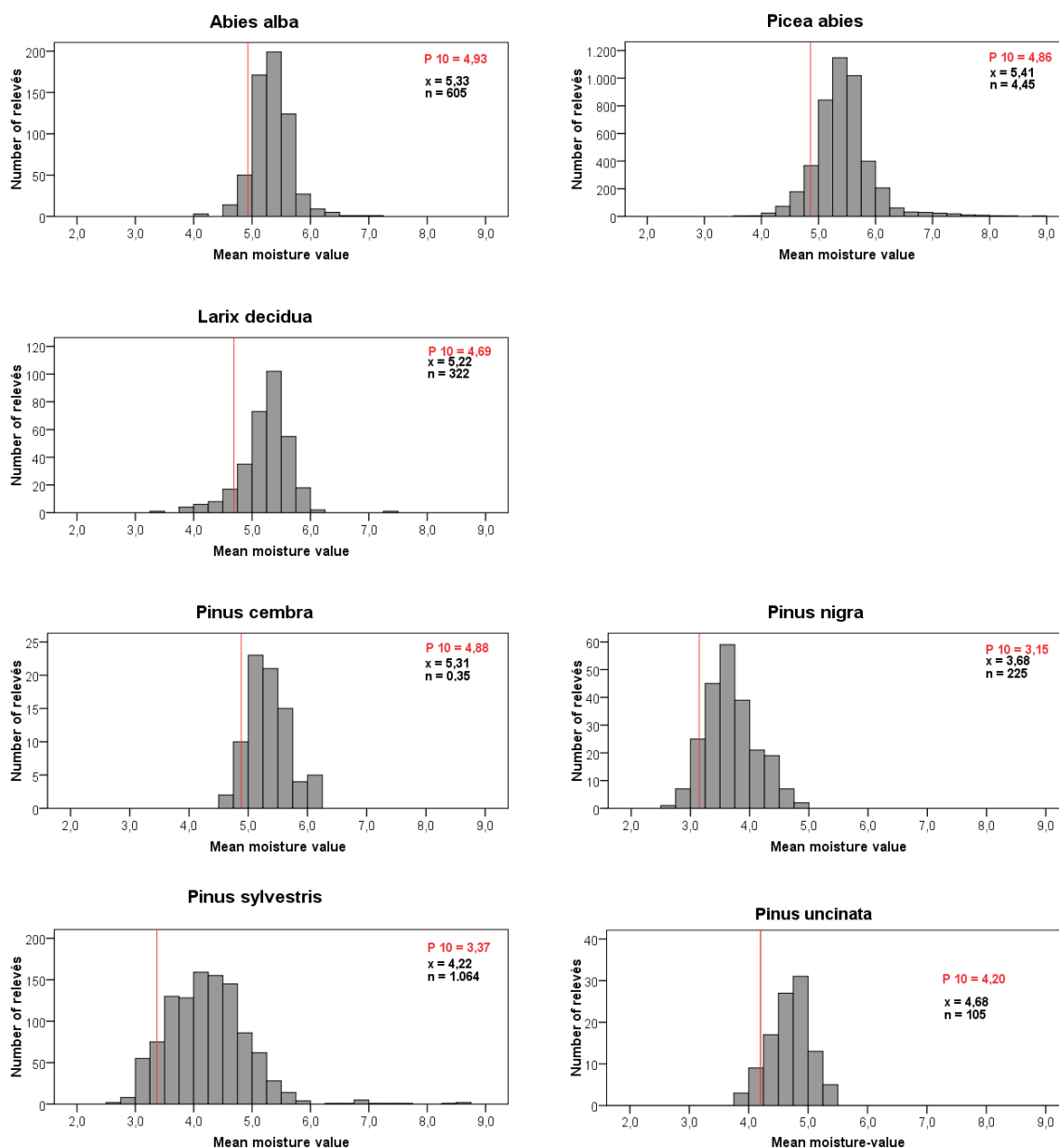


Fig. D-3.1: Distribution of the mean moisture values calculated from vegetation relevés for the Gymnosperm tree species.

(P 10: 10th Percentile, x: arithmetic mean, n: number of relevés).

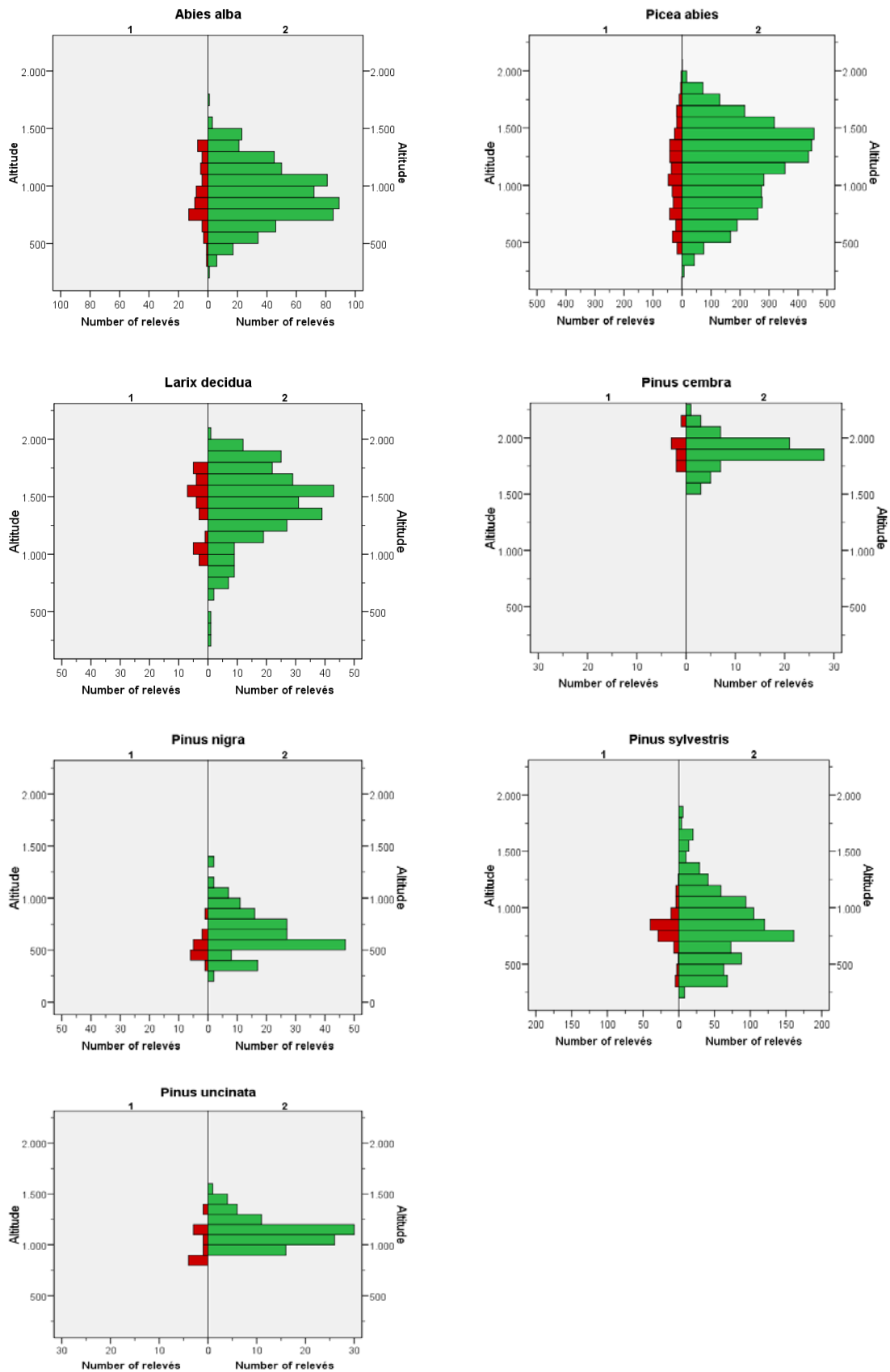


Fig. D-3.2: Distribution of the relevés for each gymnosperm species between elevation classes. 1 = red bars: Relevés belonging to the driest 10%, 2 = green bars: Residual Relevés.

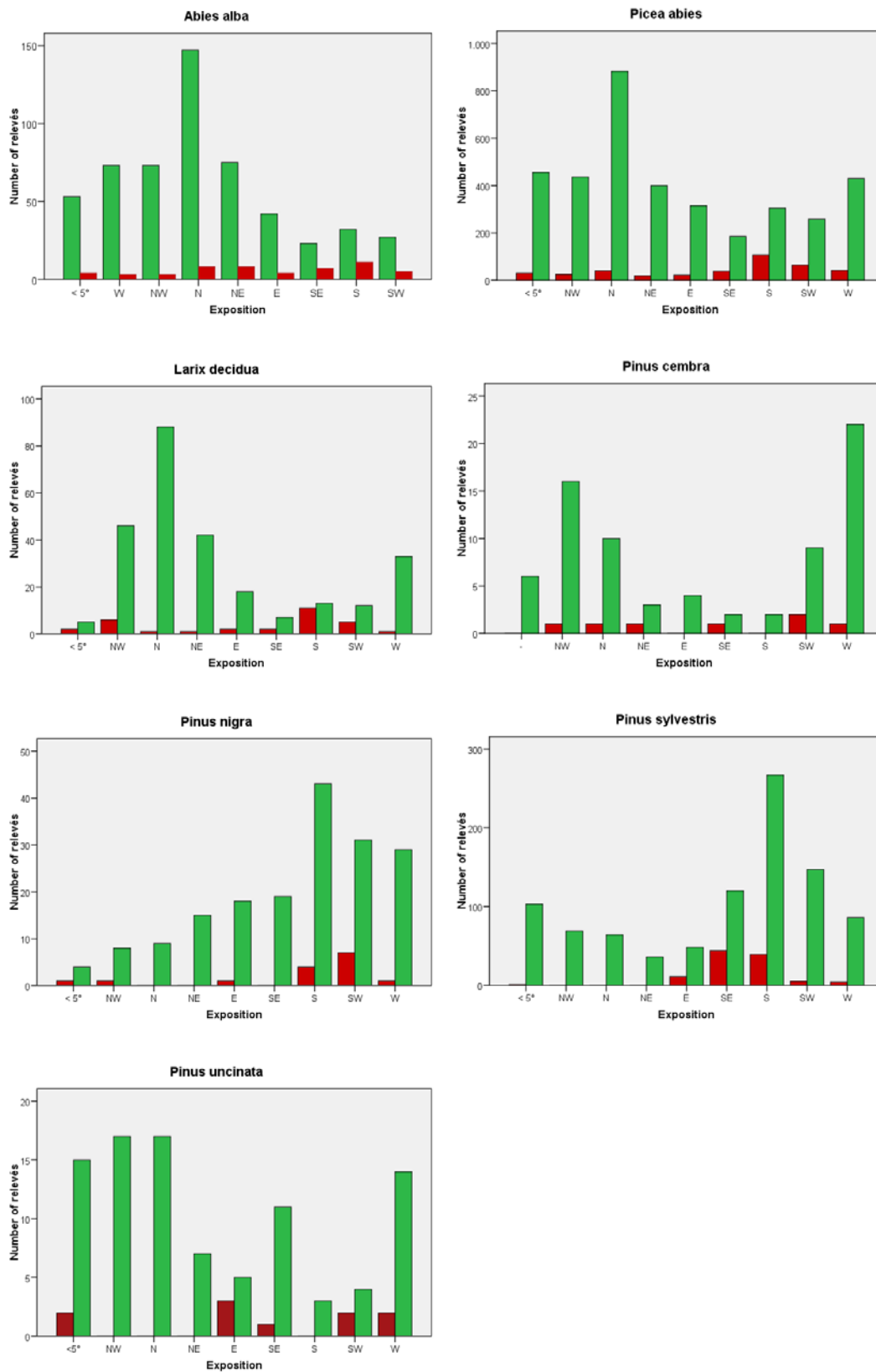


Fig. D-3.3: Distribution of the relevés for each gymnosperm species between aspect classes.

(Class <math><5^\circ</math> refers to flat sites with a slope inclination less than 5°); 1 = red bars: Relevés belonging to the driest 10%, 2 = green bars: Residual relevés.

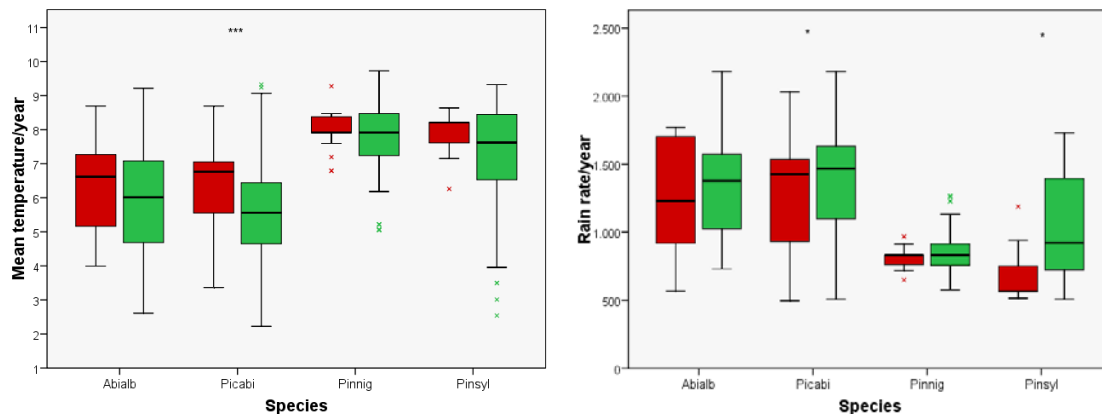


Fig. D-3.4: 30-year means of annual mean temperature (left) and annual precipitation (right) for the corresponding dry relevés (red) and residual relevés (green) for each gymnosperm species.

(Abialb: Silver Fir, Picabi: Norway spruce, Pinnig: Austrian Pine, Pinsyl: Scots pine), Significant differences between the dry and residual relevés represented as: * $p < 0,05$, ** $p < 0,01$ *** $p < 0,0001$, with no symbol indicating no significant difference.

D-3.1.2 Angiosperm species

D-3.1.2.1 *Acer campestre*

The M-values ranged from 3.4 to 6.6, although as the histogram depicts (Figure D-3.5), the lower M-values are poorly represented. The optimum appears to be around 5, while the M-value of the 10th percentile was 4.5. The distributions between elevation classes revealed that Field maple generally occurs at lower elevations, with elevations of around 300 m most common (Figure D-3.6). Furthermore, although data on aspect was limited for this species, the distribution of the residual relevés between aspect classes indicates that this species prefers flat sites with an inclination less than 5° (Figure D-3.7). There was no significant difference in either annual precipitation or annual mean temperature between the driest 10% and the residual relevés (Figure D-3.8 and D-3.9).

D-3.1.2.2 *Acer pseudoplatanus*

In comparison to Field maple, the distribution of Sycamore is rather narrower and finds itself more towards the moist part of the gradient. The M-values ranged from 4.7 to 6.5, with values around 5.5 the most frequent (Figure D-3.5). This species clearly prefers more fresh site conditions, as illustrated by the rather high 10th percentile value (5.26).

Both the dry and residual relevés of Sycamore also demonstrate a wide range in elevation (Figure D-3.6). The elevation of the residual relevés ranged from 100 to 1700 m a.s.l., while those of the dry relevés were restricted to lower elevations (200 to 1000 m a.s.l.). Generally, the N and NE aspect classes were strongly represented by the Sycamore residual relevés, although the distribution for the dry relevés was comparatively more uniform (Figure D-3.7). Relevés belonging to the driest 10% demonstrated significantly lower mean annual precipitation than the residual relevés (1339 mm compared to 1423 mm). Meanwhile the difference in annual mean temperature was statistically insignificant (Figure D-3.8 and D-3.9).

D-3.1.2.3 Alnus glutinosa

The Common alder occurs on sites right through the moist part the spectrum, from the fresh waterlogged. This is clearly illustrated by the moisture indicator values which range from just above 5 up to 9.2 (Figure D-3.5). Furthermore, apart from the tail ends, this species exhibits a rather uniform distribution over a large part of its range, with values between 5.5 and 8.5 frequently encountered. Compared to all the other species, the Common alder had the highest 10th percentile (5.82).

Its distribution over elevation ranged from 100 to 1000 m a.s.l., but the relevés were most often located between 200 and 400 m a.s.l. The dry relevés ranged from 200 to 600 m a.s.l. but showed a similar pattern in terms of which elevations were most frequently represented (Figure D-3.6). The dominance of the <5° aspect class in both the dry and residual distributions illustrated this species preference for rather non-inclined site conditions (Figure D-3.7). Despite no significant difference in mean annual precipitation, the dry relevés were with 8.2°C on average significantly warmer than the residuals with 7.6°C (Figure D-3.8 and D-3.9).

D-3.1.2.4 Alnus incana

As with Common alder, the Grey alder relevés produced a wide range in M-values over the fresh to wet parts of the moisture gradient (4.9 to 9.0). Similarly, Grey alder also produced a relatively high 10th percentile of 5.71. The pattern of distribution is however skewed towards the fresh part of the gradient, with M-values between 6 and 6.25 the most frequent (Figure D-3.5). Furthermore, a larger range in elevations for both the dry (400 to 1300 m a.s.l.) and residual (100 to 1700 m a.s.l.) relevés of Grey alder than Common alder was also observed (Figure D-3.6). The two species were however similar with respect to site inclination and aspect; dominance of flat sites within the residual relevés, with an even distribution among sloped aspects for the dry relevés (Figure D-3.7). Due to insufficient allocation of climate data to the Grey alder relevés, statistical comparison of the temperature and precipitation values of the dry and residual relevés could not be performed.

D-3.1.2.5 Carpinus betulus

The M-values derived for Hornbeam showed a normal distribution around a mean value of 5, ranging from 3.9 to 6.5 (Figure D-3.5). The 10th percentile value of 4.54 demonstrates some degree of drought tolerance within Austrian Hornbeam populations. The residual relevés of Hornbeam ranged from the lowest elevations in Austria up to 1300 m a.s.l., with elevations between 200 and 400 m the most frequent. The relative distribution of the dry relevés also mirrored this pattern (Figure D-3.6). Generally, Hornbeam relevés on flat or only slight inclined sites were the most common, although all aspect classes were well represented within the residual relevés. Flat or slightly inclined sites were also common among the dry relevés, though of the inclined sites, southern aspects (SE, S, SW) occurred more frequently (Figure D-3.6).

Of the compared climatic variables, the dry relevés were shown to receive significantly less annual precipitation (686) over the last 30 years than the residual sites (778 mm) (Figure D-3.8 and D-3.9).

D-3.1.2.6 Fagus sylvatica

With respect to distribution over the moisture gradient, European beech showed a similar pattern to Hornbeam (Figure D-3.5). However the slightly higher mean M-value (5.2) and 10th percentile (4.73) indicates that Beech is on average less tolerant of drought conditions than Hornbeam. The residual relevés of Beech spanned from the lowest elevations up to 1640 m. In the Northern Calcareous Alps, Beech can often be found in the

forest communities at the timber line. However the most drought tolerant provenances seem to be distributed further down slope, between 300 and 1000 m a.s.l. (Figure D-3.6).

North exposed sites were most frequently represented by the residual relevés, while dry sites were more evenly distributed (Figure D-3.7). Furthermore, both mean annual mean temperature (7.8/6.3°C) and annual precipitation (962/1307 mm) were significantly different between the dry and the residual sites (Figure D-3.8 and D-3.9).

D-3.1.2.7 Fraxinus excelsior

The distribution of Ash (Figure D-3.5) illustrates a preference for rather fresh site conditions: a fairly wide normal distribution (between 3.8 and 7.5) around a mean of 5.57, with a 10th percentile of 4.9. The elevations recorded for the Ash relevés ranged right up to 1340 m a.s.l., although the dry provenances appear to occupy lower elevations (generally below 500 m a.s.l.) (Figure D-3.6).

While all aspects were well represented by Ash relevés, flat/slightly inclined sites were the most frequent. Flat sites were also frequent among the dry sites, although of the aspects, southern exposed sites were more common (Figure D-3.7). As with Beech, both mean annual mean temperature (9.1/7.7°C) and annual precipitation (657/1121 mm) were significantly different between the dry and residual sites (Figure D-3.8 and D-3.9).

D-3.1.2.8 Populus alba

As a typical floodplain species, White poplar found its relevés distributed over the moist/wet part of the moisture gradient (Figure D-3.5), ranging from 5 to 9. Values between 5.5 and 6.5 were most frequently observed, with the 10th percentile calculated as 5.43. Due to a lack of additional data, conclusions regarding distribution between elevation and aspect classes, and climatic differences between dry and residual sites could not be made.

D-3.1.2.9 Quercus cerris

The M-values of Turkey oak were distributed between 3.2 and 5.6 (Figure D-3.5). The mean M value was calculated at 4.4 indicating an optimum on dry to slightly desiccating soils. While elevations ranged from 180 to 570 m a.s.l., the majority of both the dry and residual the relevés were found 200 and 300 m a.s.l. (Figure D-3.6).

For both the dry and residual relevés, a similar distribution among the aspects was observed; a dominance of flat/slightly inclined sites, with southern exposures the next most frequent (Figure D-3.7) A significant difference in mean annual precipitation was also observed between the dry (561 mm) and residual (628 mm) relevés (Figure D-3.8 and D-3.9).

D-3.1.2.10 Quercus petraea

The slightly skewed distribution of Sessile oak meant that while most frequently represented M-values (4.5-4.75) lay close the moist end of its range (5.7), the dry limit of this species distribution stretched right into the very dry parts of the moisture gradient (2.5) (Figure D-3.5). Most of the residual Sessile oak relevés and all of the dry sites were located below 500 m, with the majority at around 350 m a.s.l. However, residual relevés from sites as high as 1200m a.s.l. were also present (Figure D-3.7). Apart from the dominance of the flat sites among the residual relevés, SE to SW aspects were most common among both the dry and residual sites. Finally, both mean annual mean tempera-

ture (8.2/8.7°C) and annual precipitation (557/643 mm) were significantly different between the dry and the residual sites of Sessile oak (Figure D-3.8 and D-3.9).

D-3.1.2.11 *Quercus pubescens*

Downy oak exhibited a very similar distribution to that of Turkey oak, except for being shifted slightly further towards the drier end of the moisture gradient. The distribution ranged from 3.1 to 4.8, with a mean M-value and 10th percentile of 3.9 and 3.43, respectively (Figure D-3.5). Both the dry and residual relevés demonstrated very similar ranges in elevation, though the distribution within this range was opposite to one another: relative dominance of lower elevations among the residual sites, and vice-versa for the dry sites (Figure D-3.6). In both cases the south exposed sites were most frequent for Downy oak (Figure D-3.7). Although no significant difference in mean annual mean temperature was observed, the difference in mean annual precipitation between the dry and residual sites (562/580 mm) was significant (Figure D-3.8 and D-3.9).

D-3.1.2.12 *Quercus robur*

Of the Oaks, Pendunculate oak is the most competitive on moist sites, though the wide distribution over the moisture gradient illustrates the wide range in moisture tolerance within its Austrian population. This species demonstrated a normal distribution (between 3.2 and 8.0) around a mean of 5.1, with a 10th percentile of 4.48 (Figure D-3.5). In terms of elevation, Pendunculate oak relevés were found at elevations as high as 1100 m a.s.l., though the majority of the distribution of both the dry and residual relevés was restricted to the foothill zones (below 500 m) (Figure D-3.6). Many of the sites were found on rather flat terrain, though the frequency of southern exposed slopes was clearly larger for the dry relevés (Figure D-3.7). Again, as with Sessile oak, only the difference in mean annual precipitation between the dry and residual sites (562/580 mm) was significant (Figure D-3.8 and D-3.9).

D-3.1.2.13 *Tilia cordata*

The distribution of the Small-leaved lime showed a clear general preference for fresh sites (i.e. soils with a balanced water budget). A rather normal distribution around a mean M-value of about 5 (5.08) was observed, spanning a range from 3.4 to 6.3. The 10th percentile M-value was 4.59 (Figure D-3.5). While the relevés ranged from the foothills to montane elevations (maximum of 910m a.s.l.), the dry sites were restricted to the foothills and submontane zones (Figure D-3.6). The residual relevés indicated a tolerance of most aspects and inclinations, though N-exposed sites appear to be preferred. The more drought adapted provenances seem to be found more often on S- to SW- exposed sites (Figure D-3.7). There was no significant difference in either mean annual precipitation or mean annual mean temperature between the dry relevés and the residual relevés (Figure D-3.8 and D-3.9).

D-3.1.2.14 *Tilia platyphyllos*

In comparison to the other lime species above, Large-leaved lime had an almost identical mean M-value (5.00) (Figure D-3.5) and demonstrated similar patterns in distribution between the elevations classes (Figure D-3.6). However, in contrast to Small-leaved lime, Large-leaved lime demonstrated a more skewed distribution. Consequently, the marginal provenances of *T.platyphyllos* appear to be more drought tolerant (10th percentile of 4.40). Furthermore, this species demonstrated a slightly different distribution between different site classes: increased frequency in NE-, E-, and SE-exposed sites. Due to a lack of data on the aspects and inclination of the dry relevés, further conclusions could not be drawn. Finally, both mean annual mean temperature (9.5/8.5°C) and

annual precipitation (605/897 mm) were significantly different between the dry and the residual sites of Large-leaved lime (Figure D-3.8 and D-3.9).

D-3.1.2.15 *Ulmus glabra*

Wych elm sites were restricted to the fresh and moist parts of the gradients (M-values of 5.1 to 7.4, with a mean M-value of 5.7). The high 10th percentile (5.32) and drier limit of its range at 5.1 indicate very little drought tolerance within the Austrian populations of this species (Figure D-3.5). According to the residual relevés, range in elevation spanned from 290 to 1350 m a.s.l., though sites in foothills, and then submontane zones were most frequent (Figure D-3.6). The species also demonstrated a preference for inclined sites, particularly N- and S-aspects (Figure D-3.7). However, no clear patterns regarding elevation and site aspect and inclination were evident from the dry relevés. There was no significant difference in either mean annual precipitation or mean annual mean temperature between the dry relevés and the residual relevés (Figure D-3.8 and D-3.9).

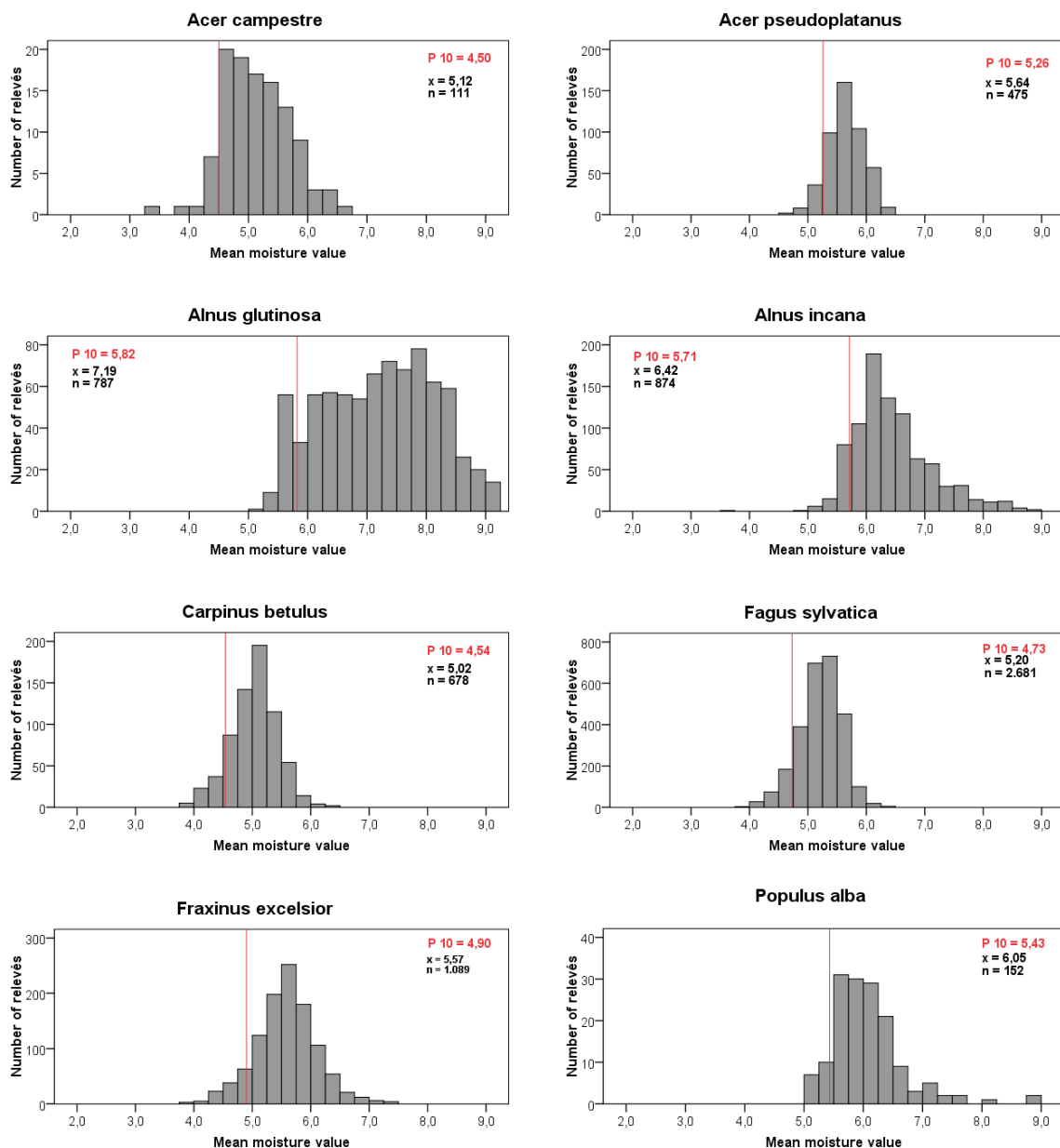


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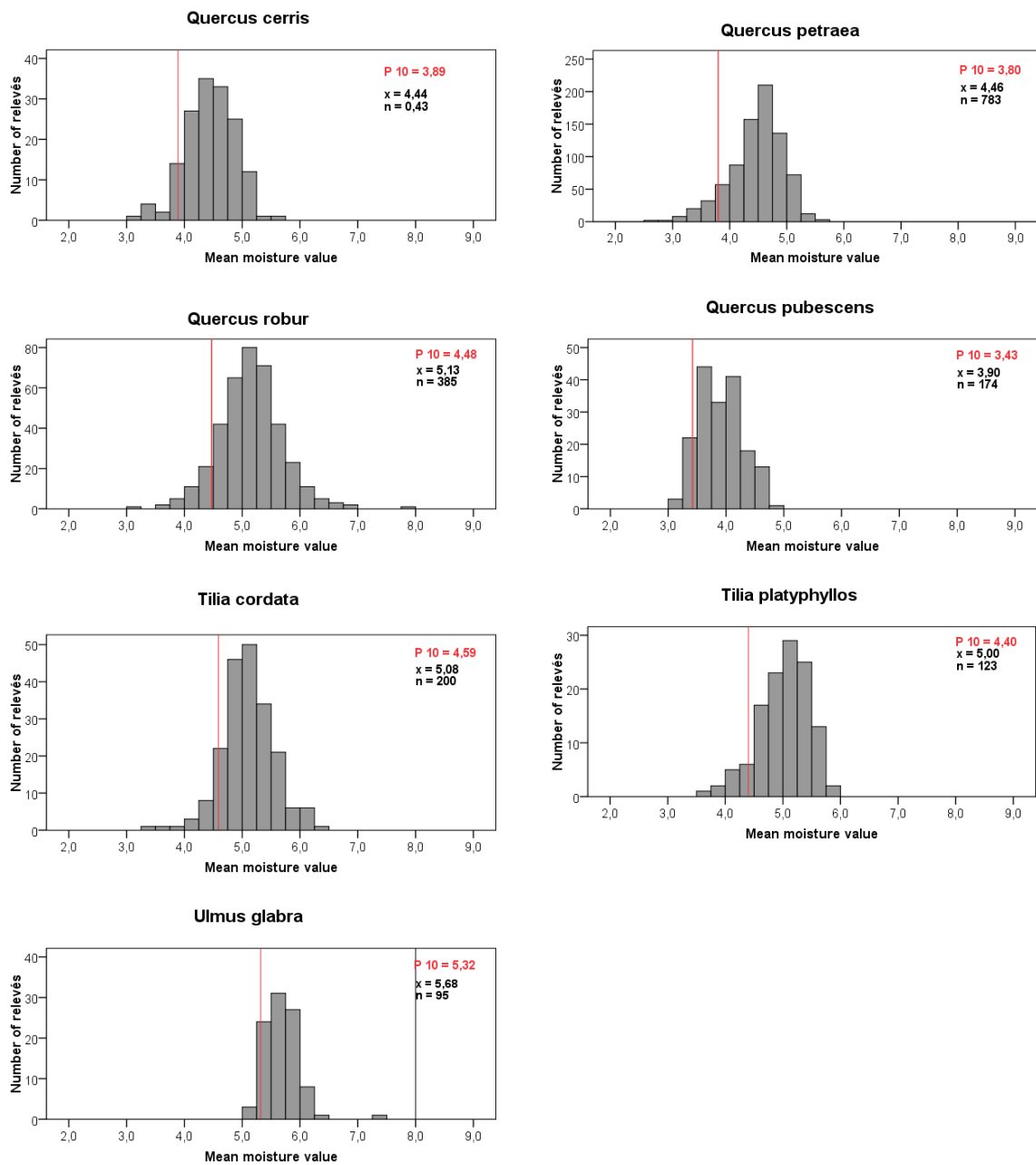


Fig. D-3.5: Distribution of the mean moisture values calculated from vegetation relevés for the Angiosperm tree species.

(P 10: 10th Percentile, x: arithmetic mean, n: number of relevés)

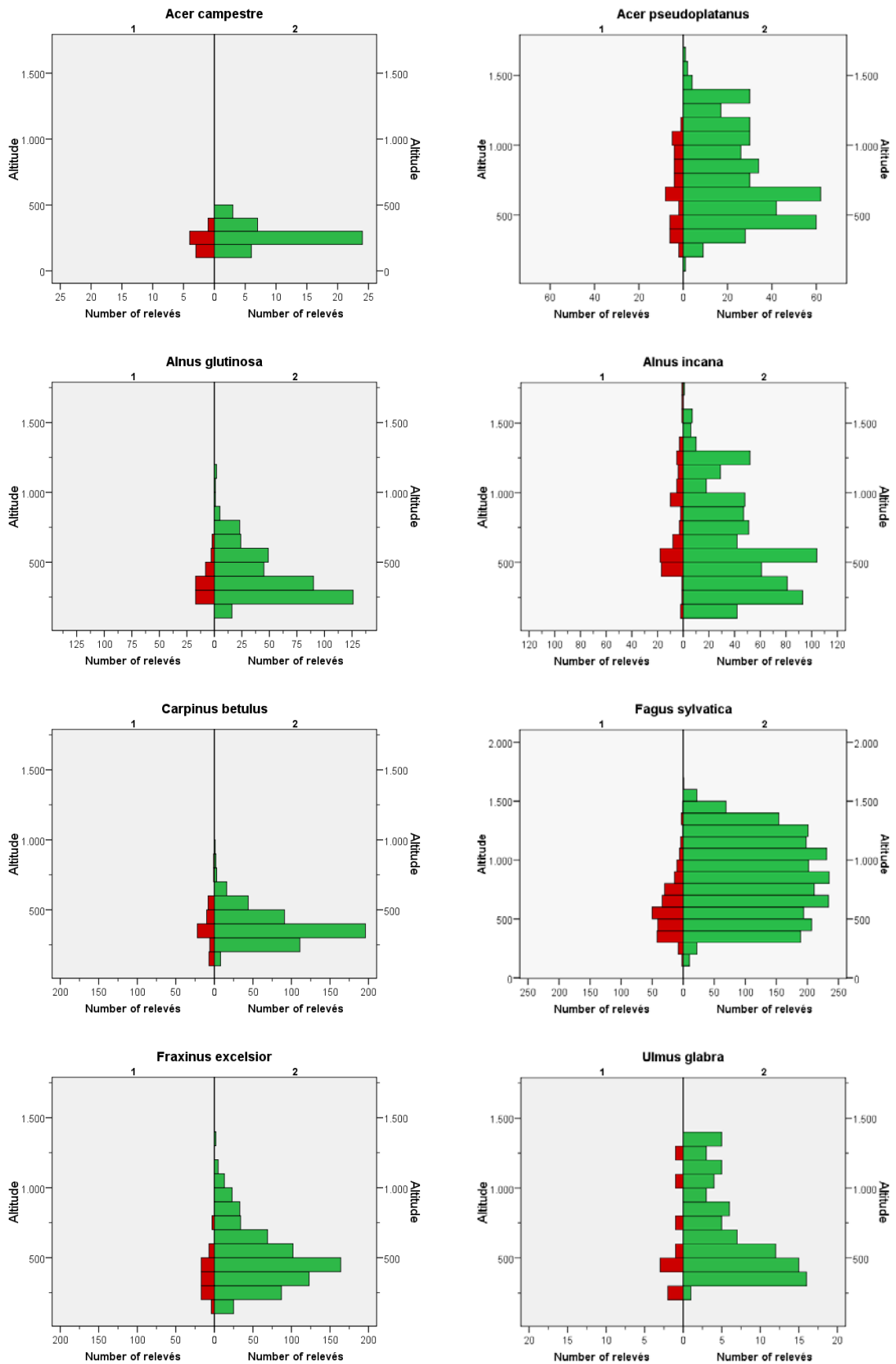


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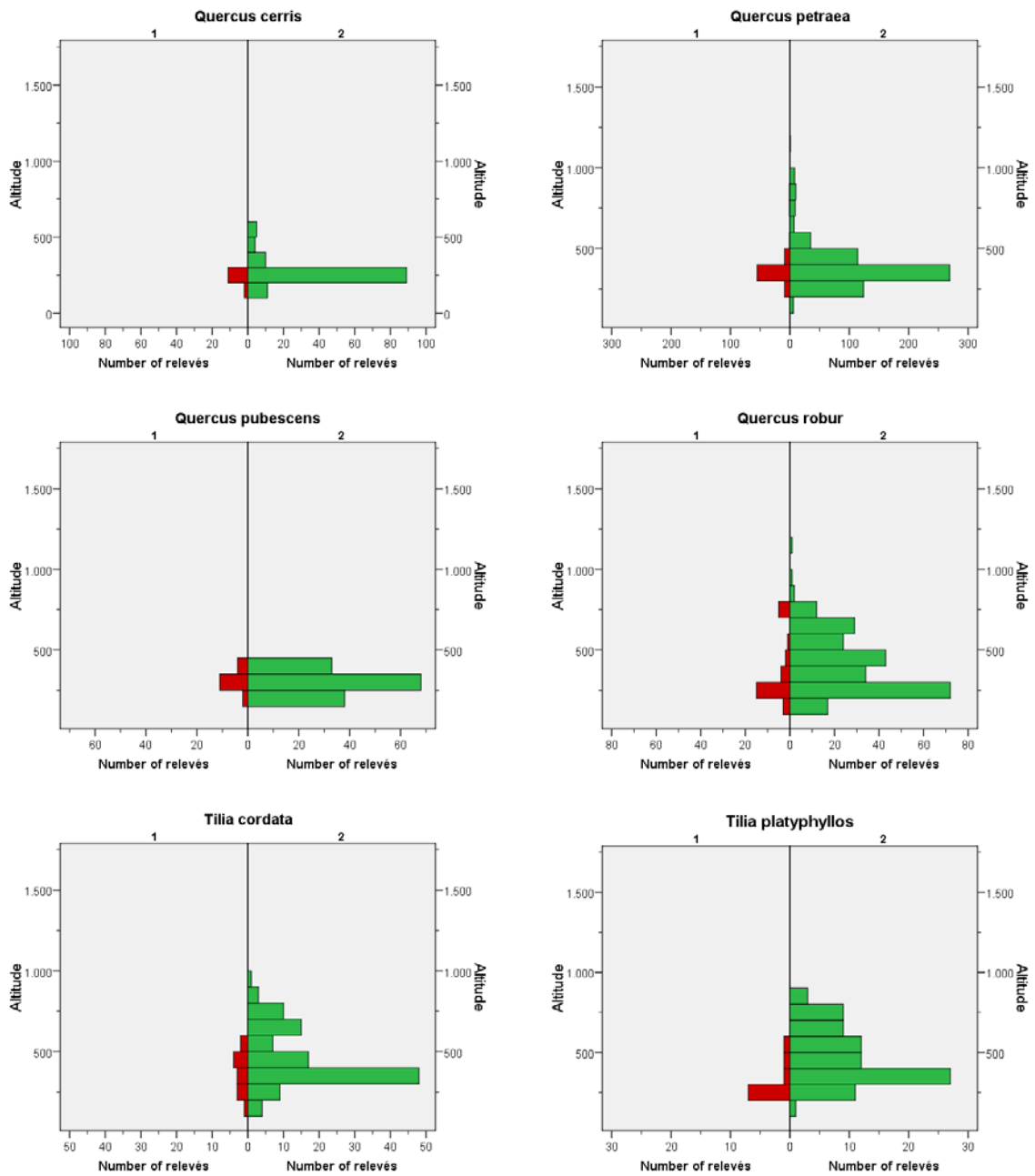


Fig. D-3.6: Distribution of the relevés for each angiosperm species between elevation classes. 1 = red bars: Relevés belonging to the driest 10%, 2 = green bars: Residual Relevés.

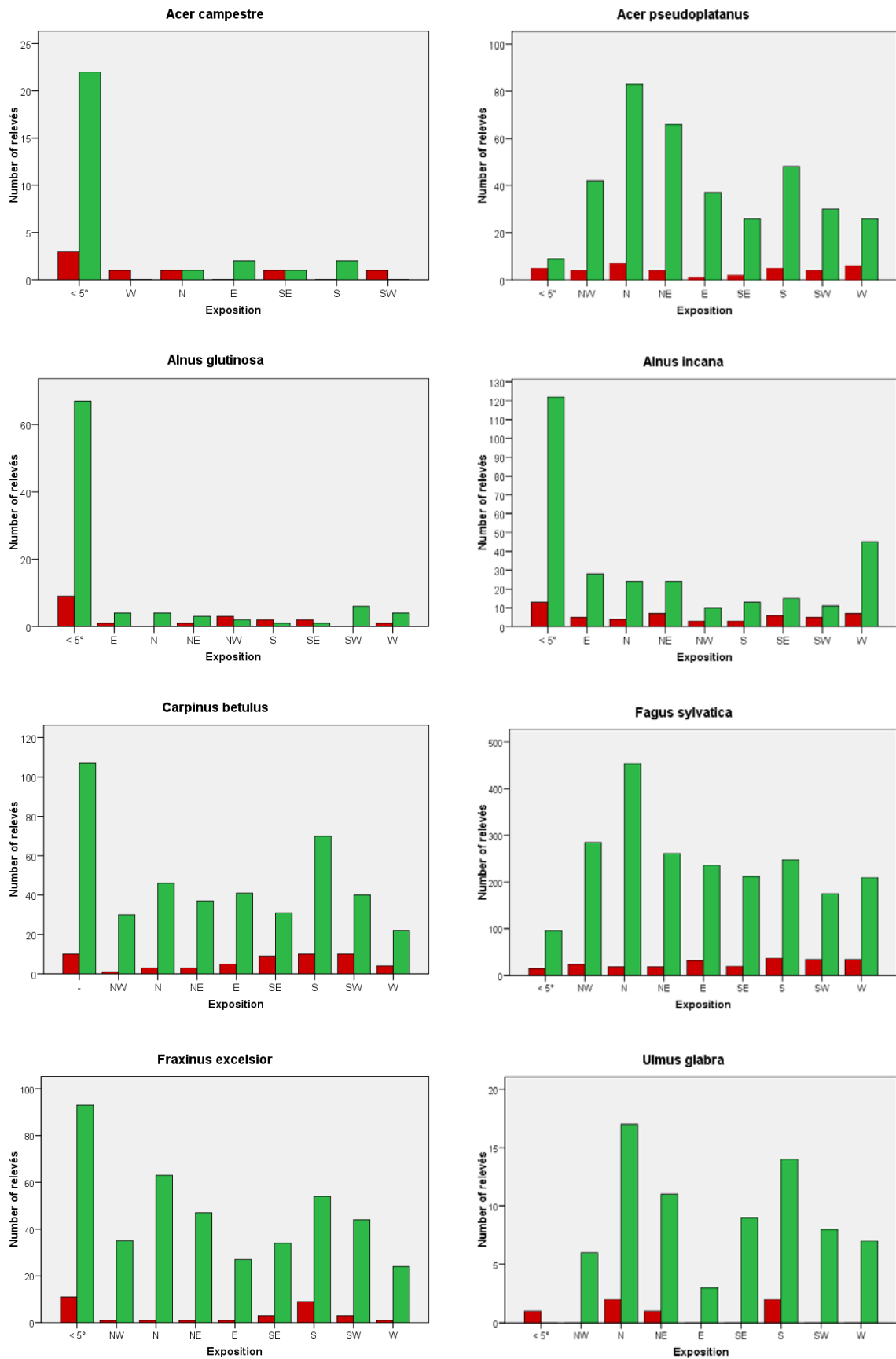


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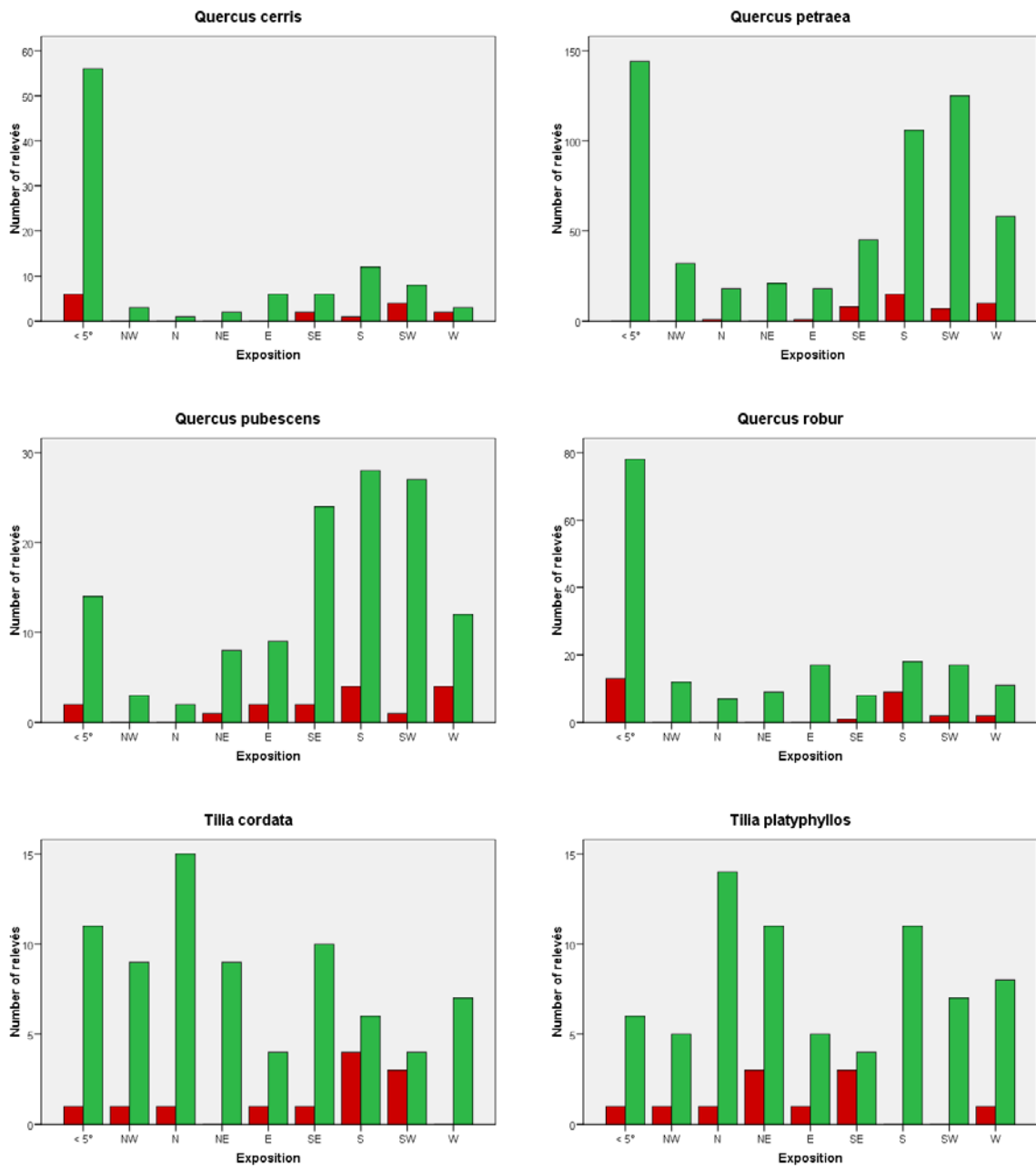


Fig. D-3.7: Distribution of the relevés for each angiosperm species between aspect classes (Class <math><5^\circ</math> refers to flat sites with a slope inclination less than 5°).

1 = red bars: Relevés belonging to the driest 10%, 2 = green bars: Residual relevés.

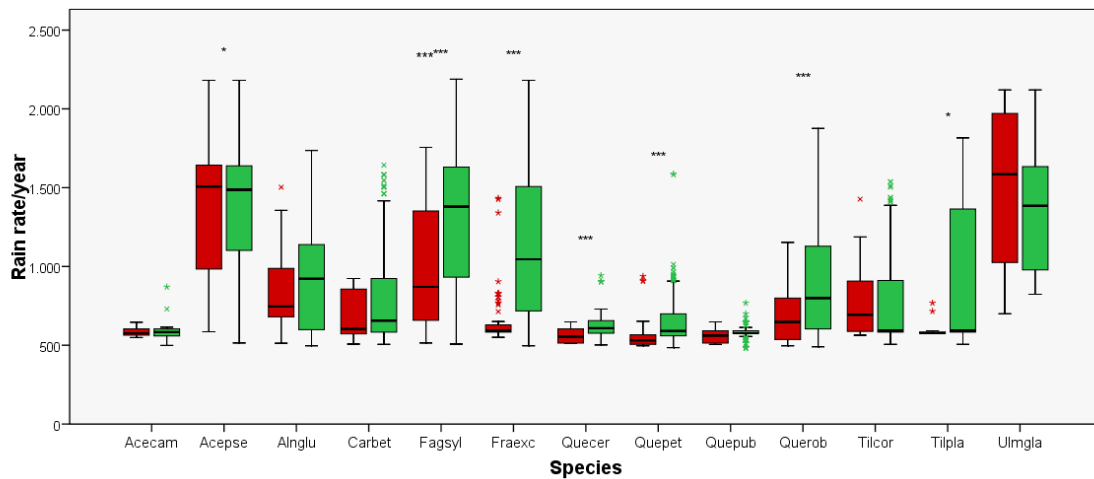


Fig. D-3.8: 30-year means of annual precipitation for the corresponding dry relevés (red) and residual relevés (green) for each angiosperm species.

(Acecam: Field Maple, Acepse: Sycamore, Alnglu: Common alder, Alninc: Grey alder, Carbet: Hornbeam, Fagsyl: European beech, Fraexc: Ash, Quecer: Turkey oak, Quepet: Sessile oak, Querob: Pendunculata oak, Tilcor: Small-leaved lime, Tilpla: Large-leaved lime, Ulmgla: Wych elm), Significant differences between the dry and residual relevés represented as: * $p < 0,05$, ** $p < 0,01$ *** $p < 0,0001$, with no symbol indicating no significant difference.

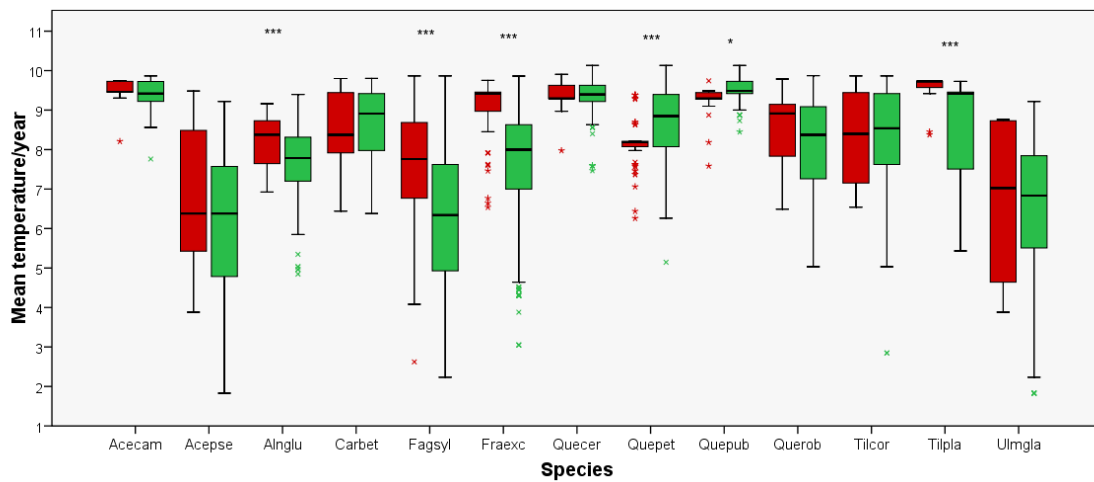


Fig. D-3.9: 30-year means of mean annual mean temperature for the corresponding dry relevés (red) and residual relevés (green) for each angiosperm species.

(Acecam: Field Maple, Acepse: Sycamore, Alnglu: Common alder, Alninc: Grey alder, Carbet: Hornbeam, Fagsyl: European beech, Fraexc: Ash, Quecer: Turkey oak, Quepet: Sessile oak, Querob: Pendunculata oak, Tilcor: Small-leaved lime, Tilpla: Large-leaved lime, Ulmgla: Wych elm), Significant differences between the dry and residual relevés represented as: * $p < 0,05$, ** $p < 0,01$ *** $p < 0,0001$, with no symbol indicating no significant difference.

D-3.2 Geographical distribution of the relevés and locations of potentially drought tolerant provenances

D-3.2.1 *Gymnosperms*

D-3.2.1.1 *Abies alba*

Geographical distribution of the relevés where Silver fir was either dominant or subdominant:

The majority of the 632 relevés were located around the northern, southern and eastern borders of the Alps (Figure D-3.10). Due to missing data regarding the coordinates of relevés from Zwettl, Obersulzbachtal, Sauwald und Mühlviertel, many of these could not be assigned to grids on the map below. Furthermore, in comparison to the actual distribution of Fir within Austria, regions such as Waldviertel, Innviertel, and East Styria's Hügelland are also underrepresented by the relevés.

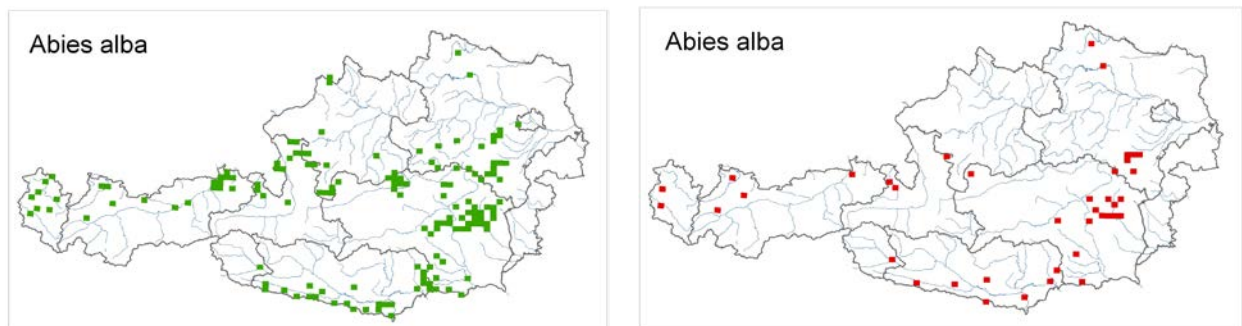


Fig. D-3.10: Grid cells corresponding to the vegetation relevés of Silver fir.

Green: grids corresponding to all locatable relevés (52% of the total relevés were assigned grids), Red: grids corresponding to the locations of the relevés of the driest 10% (90% were assigned grids).

Locations of the relevés belonging to the driest 10%:

The dry relevés were scattered rather widely across Austria, though they generally avoided the zones of the North-eastern Alps with very high rainfall. However, a large proportion can be found in the Gamperdona Valley, the Lech Valley Alps, the Leogang Mountains the “Thermenregion” and the East and West Styrian mountains. Several of the dry relevés can also be found in the dry regions south of the Alps (between Lienz and the Lavant Valley), while two relevés were also sourced from dry regions of the Waldviertel.

D-3.2.1.2 *Larix decidua*

Geographical distribution of relevés where Larch was either dominant or subdominant:

The 323 relevés were distributed rather well over the Alpine regions of Austria, with the exception of Vorarlberg, where only 3 were present (e.g. the Brander Valley). The Tyrolean regions of the Northern Calcareous Alps (Lechtaler Alps, Karwendel and the Mieminger Range) are well represented, while contributions from Styrian- (Ennstaler Alps, Gesäuse, Hochschwab, Schneealpe), Salzburg- (Steinernes Meer, Kleinarlal, Postalm, Osterhorn, Untersberg, Schafberg, Tennengebirge), Upper Austrian- (Dachstein, Hölleengebirge, Sengsengebirge) and Lower Austrian- (Rax, Göller) parts of the Northern Calcareous Alps were also significant. Contributions were also made by the Central Alps (Stubai Alps, the Samnaun, Langau, Knittelfeld, and the Koralpe) and the Southern Calcareous Alps (the Karawanken, the Karnische Alps and the Villacher Alps). When

compared to the actual distribution within Austria, areas such as Pinzgau, the Nock Mountains, the Niedere Tauern and the southern slopes of Hohe Tauern, Mühl- and Waldviertel, were rather underrepresented by the relevés of the data pool.

Due to the lack of assignment of grid cells to the relevés, a graphical representation is not given.

Locations of the relevés belonging to the driest 10%:

The majority of dry relevés were located in the dry stands in the Virgen Valley/East Tyrol, the Tyrolean Interior Alps, and several in the Northern Limestone Alps (Lechtaler Alps, Mieminger Range).

D-3.2.1.3 Picea abies

Geographical distribution of relevés where Norway spruce was either dominant or sub-dominant:

For Norway spruce 4452 relevés were available for analysis. As only 24% could be assigned grid cells (Figure D-3.11), a more precise written description of the distribution over Austria is given below.

Burgenland: A few relevés came from the Günser Mountains.

Carinthia: southern slopes of the Hohe Tauern, Weißensee area, Spittal an der Drau, Karawanken, Nockberge, St. Veit an der Glan, Villach (Dobratsch, Gerlitz, Kanzianiberg), Klagenfurt Basin (Gurkniederung, Hermagor, Klopeiner See Lavant Valley), Loibl area, Lesachtal (Gailtaler und Karnische Alpen), Koralpe.

Lower Austria: Waldviertel (Weinsberger Forest, Litschau, Heidenreichstein, Gmünd, Zwettl, Waidhofen an der Thaya, Thayatal near Hardegg, Wild, Kamptal, Ostrong and Jauerling), foothills of the Alps (Amstetten), Northern Calcareous Alps (Dürrenstein, Lunz, Göller, Neuwald, Rothwald, Hohe Wand, Rax-Schneeberg), and the Wechsel.

Upper Austria: Northern Calcareous Alps (Dachstein Nord, Bad Aussee, Gmunden, Traunstein, Höllengebirge, surrounding of Molln, Kirchdorf an der Krems, Sengsengebirge), Mühlviertel (Böhmerwald, Freistadt, Windhaag, Rohrbach, Wegscheider Bergland), Alpine foothills (Braunau am Inn, Mondsee, Mattighofen, Ranshofen).

Salzburg: Hohe Tauern (Ammertal, Hollersbachtal, Obersulzbachtal), Northern Calcareous Alps (Leoganger Steinberge, Untersberg, Gaisberg, Hochkönig, Tennengebirge, Steinernes Meer), Lungau (Tamsweg, Gerlosplatte), Zell am See.

Styria: Northern Calcareous Alps (Ennstaler Alps, Aflenzer Staritzen, Mitterbach, Bruck an der Mur, Veitsch, Hochschwab), Ennstal, Mürztal (Krieglach), Wechsel, Fischbacher Alps, Joglland, Murtal (Murau, Unzmarkt, Judenburg), Murauer Nockberge, Neumarkter Sattel, Hartberg, Graz, Schöckl, Hochlantsch, Koralpe, Gleinalm, Bad Radkersburg, Hebalm, and the East-Styrian Hügeland.

Tyrol: Northern Calcareous Alps (Außerfern, Karwendel, Kaisergebirge, Lechtaler Alps, Außerfern, Mieminger Kette), Kitzbühel, Nauders Reschenpass, Landeck, Imst, Innsbruck Schwaz, Kufstein, Interior Alps (Pitztal, Ötztal, Tuxer Alpen), East Tyrol (Lienz).

Vorarlberg: Bludenz, Brandnertal, Bregenz, Dornbirn, Gamperdonatal, Gadental, Kleines Walsertal, Walgau.

Locations of the relevés belonging to the driest 10%:

The dry sites of Norway spruce are well distributed widely over Austria, though noticeable absences include Vorarlberg, Mühlviertel, and the Koralpe. Interestingly, relevés from the lowlands commonly comprising of more thermophilous species are not represented therein.

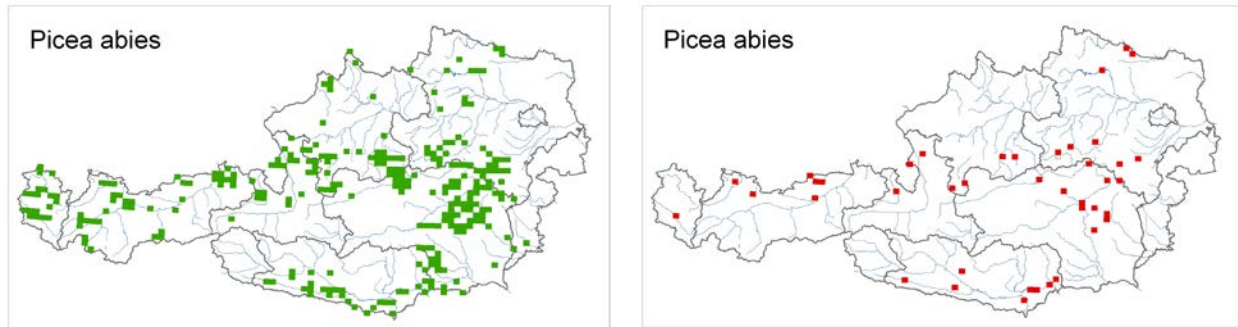


Fig. D-3.11: Grid cells corresponding to the vegetation relevés of Norway spruce.

Green: grids corresponding to all locatable relevés (24% of the total relevés were assigned grids), Red: grids corresponding to the locations of the relevés of the driest 10% (21% were assigned grids).

D-3.2.1.4 *Pinus nigra*

Geographical distribution of relevés where Austrian pine was either dominant or sub-dominant:

The 227 relevés of Austrian pine were almost completely concentrated around the eastern edge of the Alps. Natural sites are found in the Thermenalpen, secondary sites found in Steinfeld. 55 of the Austrian pine relevés came from Carinthia, though these are not shown on the map below (Figure D-3.12) as these relevés could not be assigned to grid cells. The sporadic occurrence of Austrian pine observed in Burgenland was however not represented by the Austrian pine relevés.

Locations of the relevés belonging to the driest 10%:

The distribution of the dry sites was also limited to the Eastern edge of the Alps.

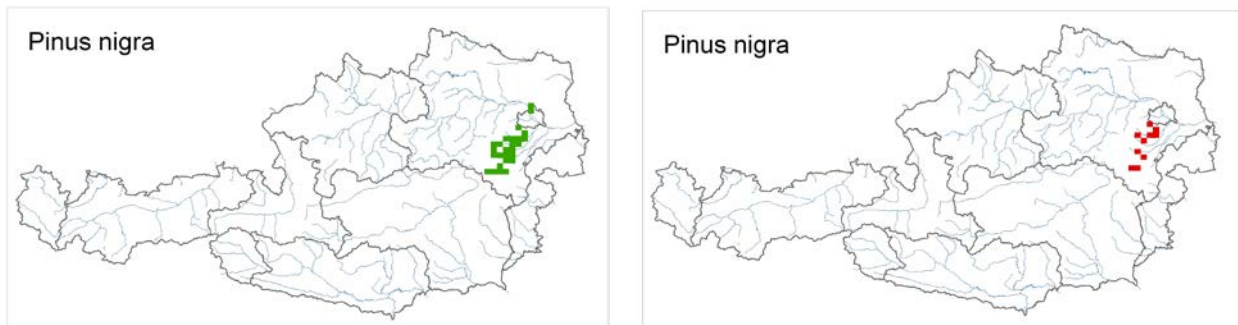


Fig. D-3.12: Grid cells corresponding to the vegetation relevés of Austrian pine.

Green: grids corresponding to all locatable relevés (67% of the total relevés were assigned grids), Red: grids corresponding to the locations of the relevés of the driest 10% (100% were assigned grids).

D-3.2.1.5 *Pinus sylvestris*

Geographical distribution of relevés where Scots pine was either dominant or sub-dominant:

A total of 1064 Scots pine relevés were available from the database. As the map (Figure D-3.13) illustrates, the geographical distribution is dominated by the eastern Waldviertel, the Oberinntal of Tyrol, the northern edge of the Alps, the Thermenalpen, Southern Carinthia, West-Styrian Bergland, and Southern Burgenland. Of the relevés not assigned grid cells, the following areas are represented: Mühlviertel (including the Bohe-

mian Forest), Sauwald, Waldviertel (Weinsberger Forest, Waidhofen an der Thaya), the Northern Foothills (Trauntal bei Wels), the Northern Calcareous Alps in Salzburg, Styria and Lower Austria, the Interior Alps of Tyrol (Ötztal), Villach, the Lavant Valley and the Koralpe area.

Considering the known range of Scots pine in Austria, the areas of Nockberge, the Gailtaler Alps, Bucklige Welt, central Burgenland, Innviertel, were conspicuous by their absence.

Locations of the relevés belonging to the driest 10%:

Many of the 106 dry sites occurred in the dry areas of the Interior Alps such as along the Upper Inn Valley. Nevertheless, areas such as the Manhartsberglinie, the Mur Valley north of Graz, and Southern Carinthia, were also represented.

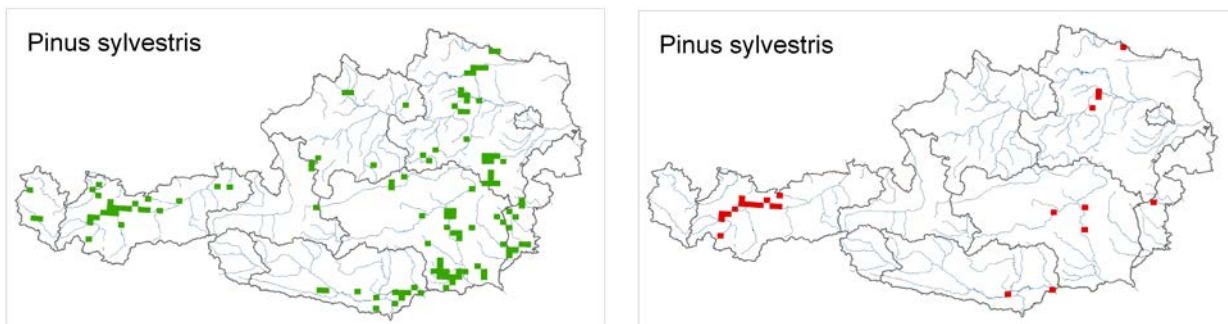


Fig. D-3.13: Grid cells corresponding to the vegetation relevés of Scots pine.

Green: grids corresponding to all locatable relevés (33% of the total relevés were assigned grids), Red: grids corresponding to the locations of the relevés of the driest 10% (94% were assigned grids).

D-3.2.1.6 Pinus cembra

Geographical distribution of relevés where Stone pine was either dominant or subdominant:

The 80 relevés of Stone pine were mainly distributed between: the edge of the intermediate and interior Alps of Tyrol (including Ampass, Weerberg), the Central Alps of Salzburg (Pinzgau: Obersulzbachtal), parts of the Northern Calcareous Alps (Totes Gebirge, the Dachstein massif, the Ennstaler Alps), and to some extent the Eastern Alps (the Murauer Nock Mountains and the Nockberge National Park).

Due to the lack of assignment of grid cells to the relevés, a graphical representation is not given.

Locations of the relevés belonging to the driest 10%:

The 8 dry relevés demonstrated a rather scattered distribution: Ampass, Weerberg, the Obersulzbach Valley, The Nockberge National Park, and the Murauer Nock Mountains.

D-3.2.1.7 Pinus uncinata

Geographical distribution of relevés where Mountain pine was either dominant or subdominant:

The 105 relevés of Mountain pine were located in Vorarlberg (the Gaden-, and, Gamperdon Valley) and Randalpen, Intermediate-, and Interior Alps of Tyrol. Due to the lack of assignment of grid cells to the relevés, a graphical representation is not given.

Locations of the relevés belonging to the driest 10%:

The 10 dry sites were located along the Mieminger range, and isolated areas of North Tyrol.

D-3.2.2 Angiosperms

D-3.2.2.1 *Acer campestre*

Geographical distribution of relevés where Field maple was either dominant or subdominant:

The 113 relevés where Field maple was dominant/subdominant were distributed between Lower Austria and Burgenland. Many were located in the Wachau region, with contributions also coming from the Weinviertel, Vienna, the Thermenregion, the Leitha Mountains, Leitha floodplain, the March and Danube floodplains, the Hainburg Mountains, the southern Vienna Basin, and Central Burgenland.

Locations of the relevés belonging to the driest 10%:

Dry sites are found in the Wachau region (Dürnstein), Vienna (Leopoldsberg), the Leitha Mountains, the Weinviertel, and central Burgenland.

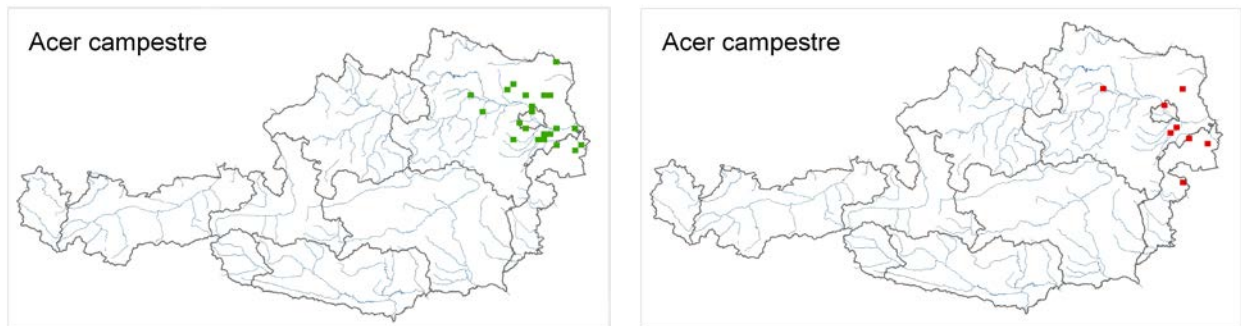


Fig. D-3.14: Grid cells corresponding to the vegetation relevés of Field maple.

Green: grids corresponding to all locatable relevés (50% of the total relevés were assigned grids), Red: grids corresponding to the locations of the relevés of the driest 10% (82% were assigned grids).

D-3.2.2.2 *Acer pseudoplatanus*

Geographical distribution of relevés where Sycamore was either dominant or subdominant:

Particularly large contributions to the Sycamore relevés came from the Northern Calcareous Alps of Vorarlberg (Klostertal, Bregenzerwald), Salzburg, Upper Austria (Höllengebirge) and Lower Austria (Ötscher region), as well as several sites from the Bohemian Massif (Sauwald). Styria contributed sites from the Niedere Tauern, and the Western Hügelland, as well as from the East- and Central Styrian Mountains. Isolated sites from the Interior- and Intermediate Alps, as well as sites from the Lavant Valley in Carinthia also contributed.

Locations of the relevés belonging to the driest 10%:

The 47 dry sites were scattered over an area from Vorarlberg in the East right over to the Hainburger range in the West. Nevertheless a concentration of sites just south of Vienna was observed.

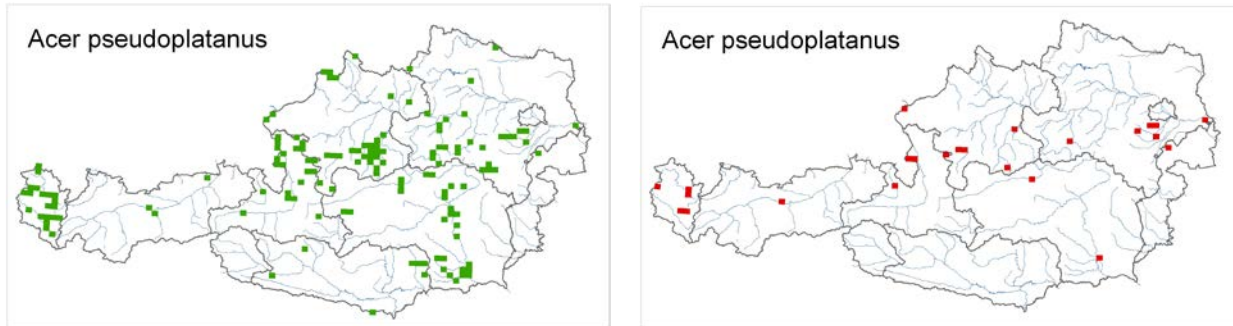


Fig. D-3.15: Grid cells corresponding to the vegetation relevés of Sycamore.

Green: grids corresponding to all locatable relevés (82% of the total relevés were assigned grids), Red: grids corresponding to the locations of the relevés of the driest 10% (74% were assigned grids).

D-3.2.2.3 *Alnus glutinosa*

Geographical distribution of relevés where Common alder was either dominant or sub-dominant:

786 relevés representing Common alder were available, but due to the lack of assignment of grid cells to the relevés, a graphical representation cannot be given to illustrate the overall distribution in Austria. The distribution is thus described as follows:

Contributions from the Bohemian Massif: Mühlviertel including the Sauwald and central (Zwetl, Waidhofen) eastern parts (Taffa Valley, Gföhl, Thaya Valley, Kamp Valley, Loisbach Valley) of the Waldviertel.

Contributions from the Panonian Basin: The March- und Leitha floodplains, the Leithagebirge, the Neusiedlersee area and the valleys of Lafnitz, Pinka and Strem.

Contributions from the Northern foothills: north of the Untersberg Massif in Salzburg, at the Obertrumer Lakes and along the river Erlauf (Wieselburg); few in the Wienerwald.

Contributions from Kufstein, Tyrol (Drau Valley at Dölsach) and floodplain or bog sites in the Klagenfurt Basin (Keutschacher Seental, Spittal, Pusarnitz, Pressegger See, Klagenfurt, Sattnitz, Hohenthurn, Arnoldstein, Greifenburg, Faaker See).

Relevés from South and South-East Styria (Sulmtal, Leutschach, and Grabenland) complete the list.



Fig. D-3.16: Grid cells corresponding to the dry vegetation relevés (the driest 10%) of Common alder (55% were assigned grids).

Locations of the relevés belonging to the driest 10%:

Dry sites are found in the Waldviertel (Horn Basin, Kamp Valley, Langenlois), Flachgau, Wienerwald, the Leitha floodplain, West Styrian Hügelland (Sulmtal), the South-east Styrian Grabenland, and Pörschach in Carinthia.

D-3.2.2.4 *Alnus incana*

Geographical distribution of relevés where Grey alder was either dominant or subdominant:

874 relevés for Grey alder were available, but due to the lack of assignment of grid cells to the relevés, a graphical representation cannot be given to illustrate the overall distribution in Austria. As a mountain species, the Grey alder relevés are found predominantly in the alpine regions of West Austria.

Tyrol: Lech and Inn Valleys, and the Kaisergebirge.

Salzburg: Flachgau, Pongau (Eben, Hochgründeck range), Tennengau (Salzach-Auen), Lungau, Pinzgau (Hollersbachtal, Obersulzbachtal), and the Hochkönig area.

Styria: Generally from Enns Valley (Grimming), Packer Moorland, Gleingraben and the Neumarkter Sattel.

Carinthia: Southern slopes of the Hohe Tauern (Stappitzer See), the Möll, Gail- und Drau Valley, and the Karawanken and the Carinthian Alps.

Outside of the Alps, the Danube Valley (Wallsee) and Inn floodplains (Braunau) also contribute. Despite the large dataset, certain regions in the Waldviertel, Vorarlberg, the Kitzbühler-, and Fischbacher Alps, and the upper Mur Valley are noticeable absentees.

Locations of the relevés belonging to the driest 10%:

Dry sites were scattered between Upper and Lower Austrian Alpine foothills, the Lech and Inn Valleys, Pinzgau, Hochkönig, and the Leoganger Steinberge, but also around the Drau and Möll Valley and the Karawanken.

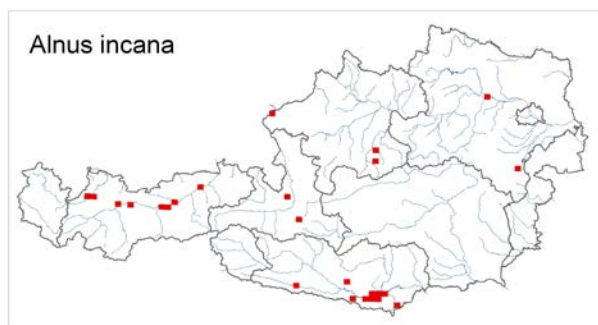


Fig. D-3.17: Grid cells corresponding to the dry vegetation relevés (the driest 10%) of Grey alder (55% were assigned grids).

D-3.2.2.5 *Carpinus betulus*

Geographical distribution of relevés where Hornbeam was either dominant or subdominant:

Of the total 679 relevés, 85% were assigned grid cells. Consequently, the geographical distribution of the relevés is well illustrated by Figure D-3.18. The distribution ranges from the Salzburg Flachgau to the upper Danube Valley, through the southern and eastern Waldviertel, towards the Weinviertel. Significant numbers of relevés also came from the Wienerwald, the Leithagebirge, Central and Southern Burgenland, the Mur Valley north of Graz, and the East- and West Styrian Hügelland.

Locations of the relevés belonging to the driest 10%:

Dry sites of Hornbeam were located in the Danube Valley near Aschach, the eastern Waldviertel, Wachau, the Thermenregion, the Leithagebirge, and the Mur Valley north of Graz and the Hügelland south of Graz (Figure D-3.18).

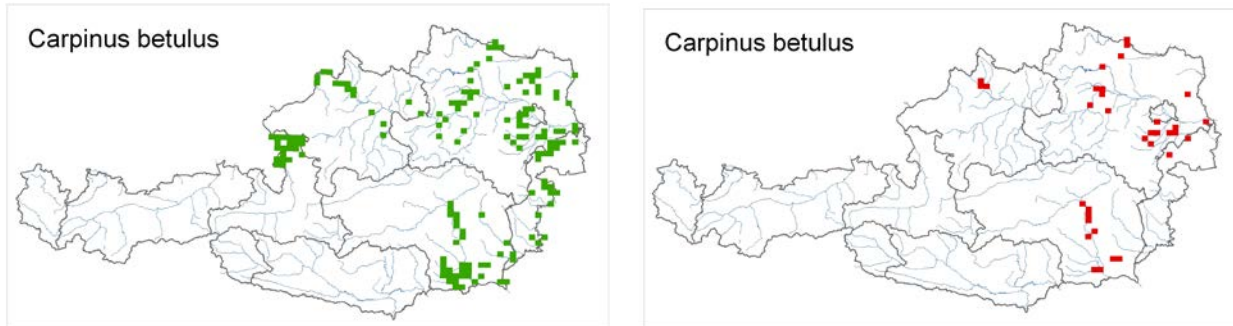


Fig. D-3.18: Grid cells corresponding to the vegetation relevés of Hornbeam.

Green: grids corresponding to all locatable relevés (85% of the total relevés were assigned grids), Red: grids corresponding to the locations of the relevés of the driest 10% (99% were assigned grids).

D-3.2.2.6 *Fagus sylvatica*

Geographical distribution of relevés where European beech was either dominant or sub-dominant:

Of the total 2681 relevés, 91% were assigned grid cells. Consequently, the geographical distribution of the relevés is well illustrated by Figure D-3.19. The Beech relevés as shown below were distributed over much of Austria. From Vorarlberg, through the Northern Calcareous Alps right to the Wienerwald, Beech occurrence is almost continuous. A concentrated area of occurrence around the Southern Alps is also conspicuous. Gaps in the distribution are caused by the limits to the natural range of Beech (e.g. in the foothills and Interior Alps) and by anthropogenic interventions in the Bohemian Massif. Furthermore, comparison with the actual distribution (Figure D-3.20), illustrates the underrepresentation of e.g. the Mühl- and Waldviertel, and the East Styrian Hügelland.

Locations of the relevés belonging to the driest 10%:

Relatively few dry sites with Beech were found in the West. Significant clusters are located rather in the Eastern part of the country: The Danube Valley near Aschach, Wachau, the eastern Waldviertel, the Dunkelsteiner Wood and Wienerwald, the Thermenregion, the Mur valley between Bruck und Graz, and the Leithagebirge (Figure D-3.19). Dry Beech sites can also be found in the Klagenfurt Basin and the Karawanken.

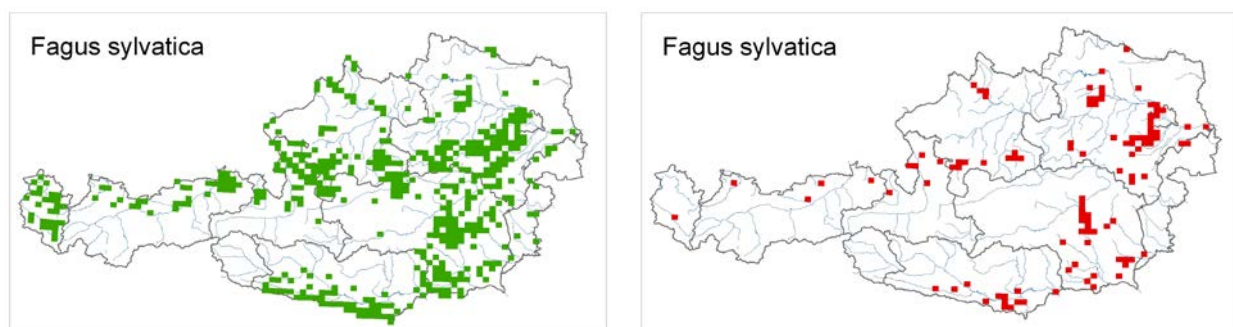


Fig. D-3.19: Grid cells corresponding to the vegetation relevés of European beech.

Green: grids corresponding to all locatable relevés (91% of the total relevés were assigned grids), Red: grids corresponding to the locations of the relevés of the driest 10% (91% were assigned grids).

The example of Beech illustrates the practical use of the results of this dataset and other such studies Figures D-3.21 and D-3.22 show the dry relevés separated between two forest ecoregions (Kilian et al. (1994)). The identification of potentially drought adapted

provenances for the different forest ecoregions could help identify useful sources of reproduction material to help Austrian forestry adapt to the project changes in climate.

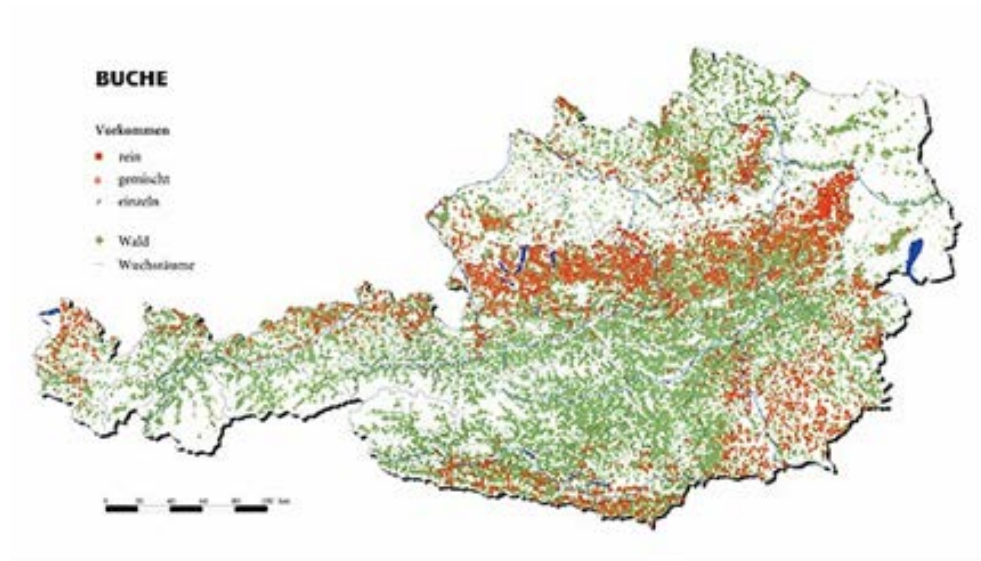


Fig. D-3.20: Distribution of European beech (*Fagus sylvatica*) within Austria according to forest inventory data (Schadauer et al., 2006).

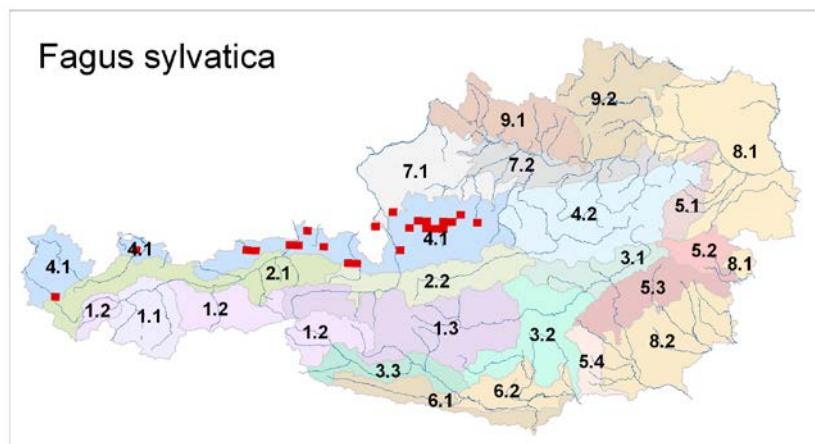


Fig. D-3.21: Grid cells corresponding to the locations of the European beech relevés of the driest 10% located within Forest Ecoregion 4.1.

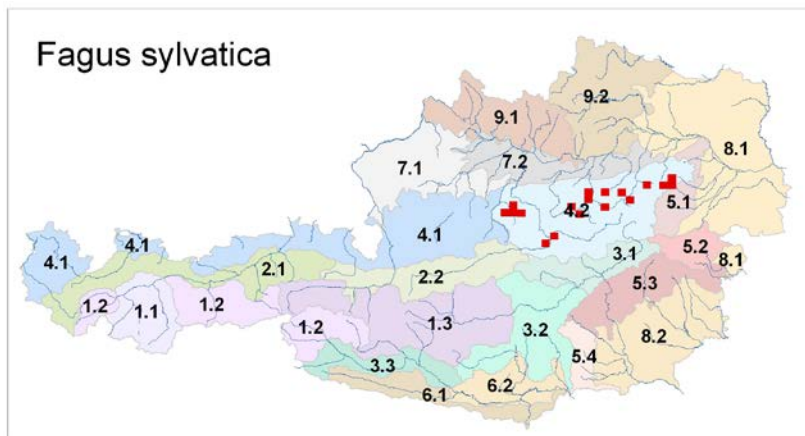


Fig. D-3.22: Grid cells corresponding to the locations of the European beech relevés of the driest 10% located within Forest Ecoregion 4.2.

D-3.2.2.7 *Fraxinus excelsior*

Geographical distribution of the relevés where Ash was either dominant or subdominant:

In total 1097 Ash relevés were available, of which 58% could be assigned with grid cells. The majority were sourced from the parts of the Northern Calcareous Alps (Vorarlberg, Salzburg, Upper Austria, and the Wienerwald), areas where Ash most often occurs. The rest of the relevés were generally scattered between the Bohemian Massif, the northern Foothills, South-west Styrian Hügelland and the Koralpe. However the areas of Nockberge and the East-Styrian Hügelland were conspicuous by their absence.

Locations of the relevés belonging to the driest 10%:

The dry sites of Ash were almost only found in Eastern Austria (Thermenregion, the Leitha region, the Wienerwald, Kamp Valley, and the Traun Valley near Wels), though two sites were found far West: Montafon and the Upper Inn Valley.

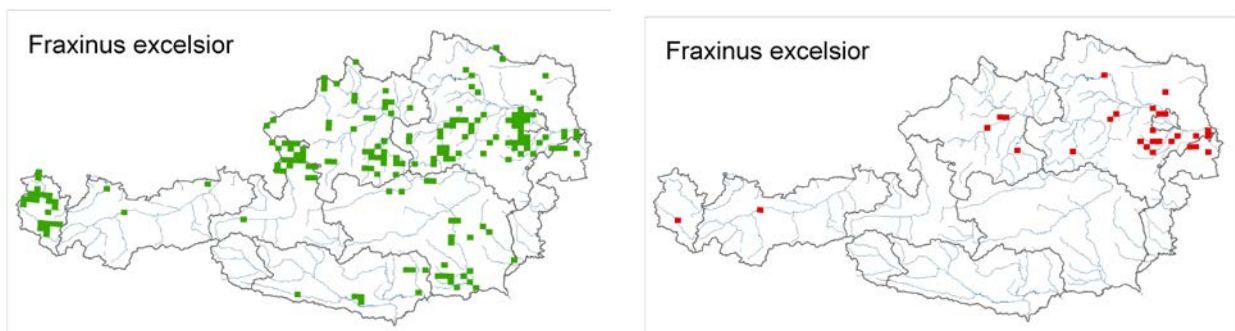


Fig. D-3.23: Grid cells corresponding to the vegetation relevés of Ash.

Green: grids corresponding to all locatable relevés (58% of the total relevés were assigned grids), Red: grids corresponding to the locations of the relevés of the driest 10% (83% were assigned grids).

D-3.2.2.8 *Quercus cerris*

Geographical distribution of relevés where Turkey oak was either dominant or subdominant:

All the 156 relevés of Turkey oak came from the Pannonian regions (westernmost plots from the Pulkau- and Lower Traisen Valley). The majority are gathered around the Leiser Mountains Wienerwald, Vienna Basin, Leithagebirge, and Central Burgenland.

Locations of the relevés belonging to the driest 10%:

The dry sites were located in the Pulkau Valley, the St. Pölten area, the Leithagebirge and in the Weinviertel (Zaya, Hochleitenwald).

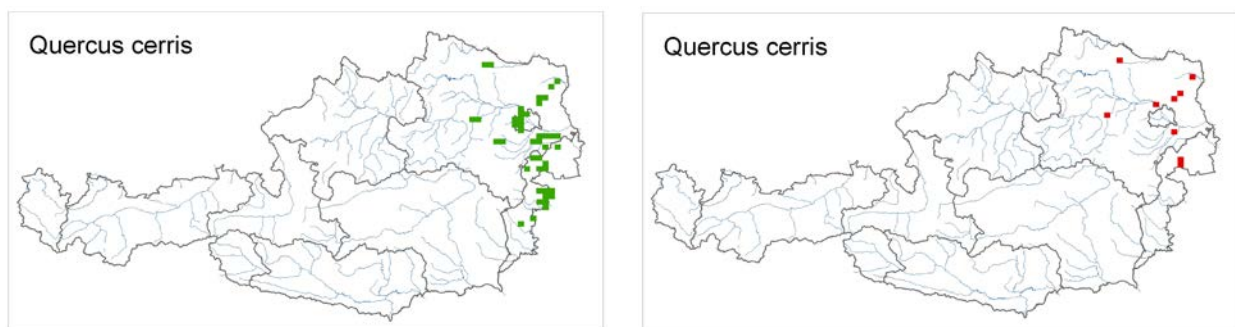


Fig. D-3.24: Grid cells corresponding to the vegetation relevés of Turkey oak.

Green: grids corresponding to all locatable relevés (94% of the total relevés were assigned grids), Red: grids corresponding to the locations of the relevés of the driest 10% (93% were assigned grids).

D-3.2.2.9 *Quercus petraea*

Geographical distribution of relevés where Sessile oak was either dominant or subdominant:

A total of 798 relevés were available for Sessile Oak. As above, the distribution of the relevés was confined to Eastern Austria, though its range spreaded further than just the Pannonian area. A minority of western relevés were found in the Upper Inn and Gail Valleys. The upper Danube Valley, the Wald- and Weinviertel, the Wienerwald and the hills of Burgenland and Styria were represented by the relevés. The distribution also stretched into the Alps and the northern foothills, though these particular relevés could not be assigned grid cells and are thus not illustrated in Figure D-3.25.

Locations of the relevés belonging to the driest 10%:

Of the 79 dry relevés, the majority were confined to the eastern Waldviertel (Thaya Valley National Park, Manhartsberglinie, and Wachau), though several were also present outside this region (Weinviertel, Bruck an der Mur, and the Kanzianibergnear Villach).

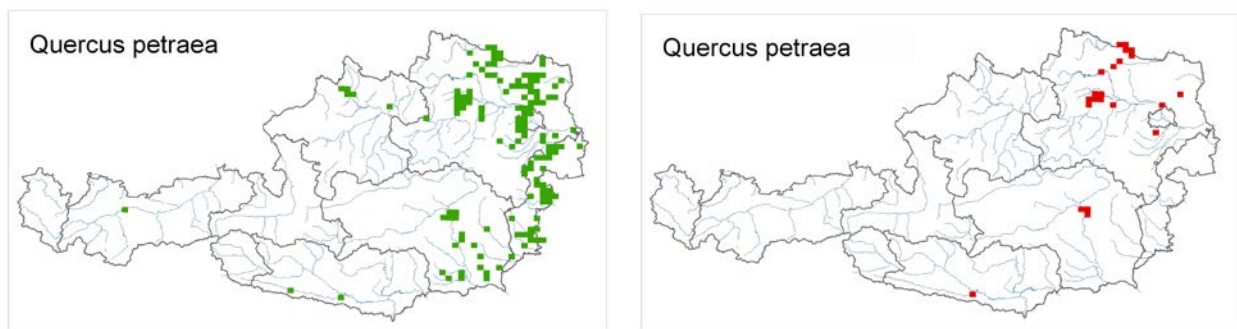


Fig. D-3.25: Grid cells corresponding to the vegetation relevés of Sessile oak.

Green: grids corresponding to all locatable relevés (87% of the total relevés were assigned grids), Red: grids corresponding to the locations of the relevés of the driest 10% (93% were assigned grids).

D-3.2.2.10 *Quercus pubescens*

Geographical distribution of relevés where Downy oak was either dominant or subdominant:

As with Turkey Oak, the relevés of Downy oak seemed to favour the Pannonian area. Though significant numbers were found in the Wachau and Thaya Valley National Park, the majority came from the Weinviertel, Wienerwald, Thermenregion, and Northern and Central Burgenland. Some relevés were however found in the Klagenfurt basin, from Kanzel near Graz and the central Inn Valley near Zirl, though grid cells could not be assigned to these relevés.

Locations of the relevés belonging to the driest 10%:

The dry sites of Downy oak were located in the Thaya Valley National Park, Wachau, the Weinviertel (e.g. the Bisamberg), the Thermenregion, and the Leithagebirge (Figure D-3.26). Dry sites were also found in parts of Carinthia, Styria and Tyrol, though these sites could not be assigned to grid cells on the map above.

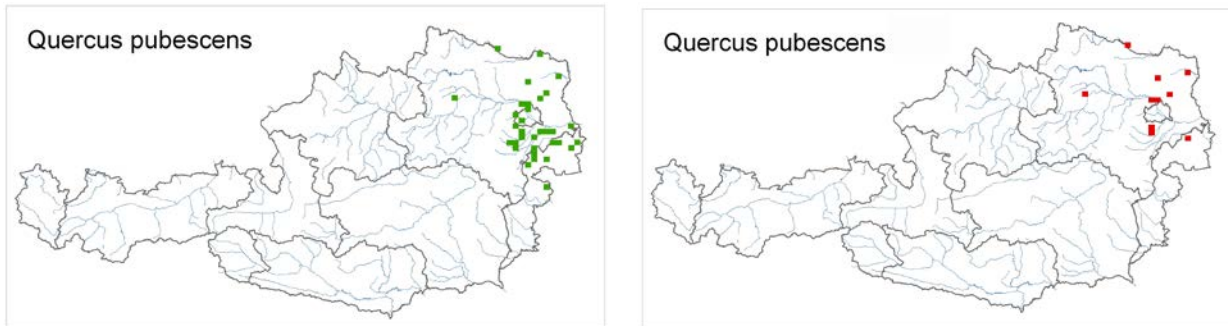


Fig. D-3.26: Grid cells corresponding to the vegetation relevés of Downy oak

Green: grids corresponding to all locatable relevés (100% of the total relevés were assigned grids), Red: grids corresponding to the locations of the relevés of the driest 10% (100% were assigned grids).

D-3.2.2.11 *Quercus robur*

Geographical distribution of relevés where Pendunculate oak was either dominant or subdominant:

Pendunculate oak is the native *Quercus* species, which penetrates deepest into the Oceanic regions of Austria (Figure D-3.27). The distribution of the 385 *Q.robur* relevés was spread between Montafon, the Inn Valley, Flachgau, the Mühlviertel, the northern Waldviertel, the Weinviertel, the Industrieviertel, Northern and Southern Burgenland, the upper Mur Valley, Southern Styria, and the Carinthian Basin.

Locations of the relevés belonging to the driest 10%:

The majority of the 38 dry sites were distributed along an almost straight transect that stretched from the Manharts mountain range to the Traisen Valley. Nevertheless, a considerable amount of sites were concentrated around the eastern Weinviertel and Leithagebirge. Isolated sites were also located in the Inn Valley, the Carinthian Basin, and the Mur Valley north of Graz.

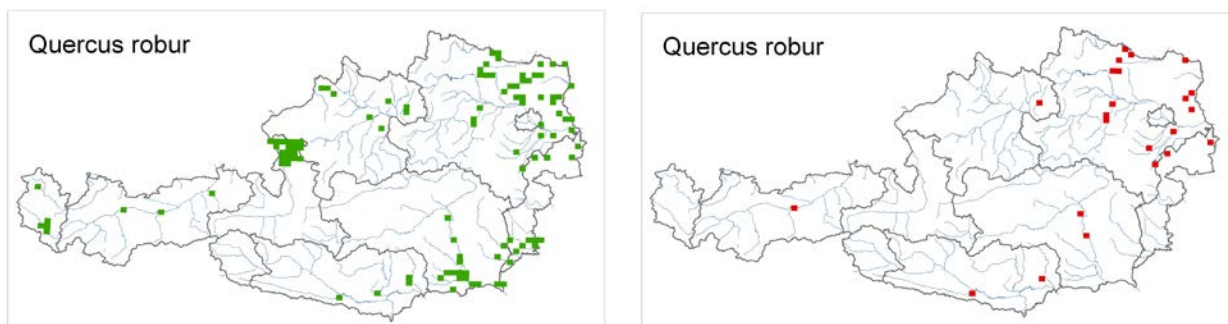


Fig. D-3.27: Grid cells corresponding to the vegetation relevés of Pendunculate oak.

Green: grids corresponding to all locatable relevés (65% of the total relevés were assigned grids), Red: grids corresponding to the locations of the relevés of the driest 10% (84% were assigned grids).

D-3.2.2.12 *Tilia cordata*

Geographical distribution of relevés where Small-leaved lime was either dominant or subdominant:

Most of the 200 relevés generally came from Vorarlberg (the Rhein Valley and Montafon), the Inn Valley, and Flachgau. Nevertheless, the Alpine foothills (Traun flood-

plains), the Mühl-, Wald- and Weinviertel, the Danube floodplains, the Leithagebirge, the Mur Valley north of Graz and Southern Styria.

Locations of the relevés belonging to the driest 10%:

Apart from one site in the Inn Valley, the dry sites of *T.cordata* were restricted to the east of Austria: Wachau, the Danube floodplains, the Mur Valley, and the Klagenfurt Basin.

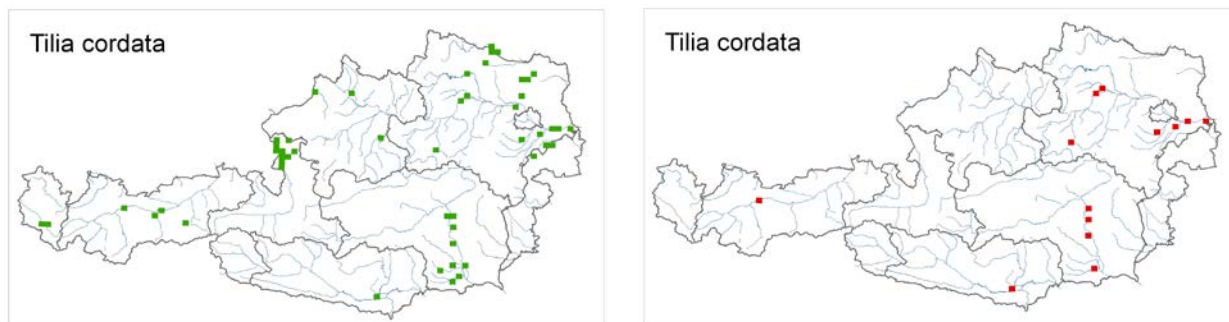


Fig. D-3.28: Grid cells corresponding to the vegetation relevés of Small-leaved Lime.

Green: grids corresponding to all locatable relevés (71% of the total relevés were assigned grids), Red: grids corresponding to the locations of the relevés of the driest 10% (70% were assigned grids).

D-3.2.2.13 *Tilia platyphyllos*

Geographical distribution of relevés where Large-leaved lime was either dominant or subdominant:

Similar distribution to *T.cordata*. The majority of the Large-leaved lime relevés came from: Vorarlberg (Rheintal, Montafon), the Tyrolean Inn Valley, Flachgau, upper Danube Valley, Thaya Valley National Park, Thermenregion, and the Hainburger Mountains and the Leithagebirge.

Locations of the relevés belonging to the driest 10%:

Dry sites of Large-leaved lime found only in and south of Vienna, the Wienerwald, the southern Vienna Basin, and the Hainburger Mountains.

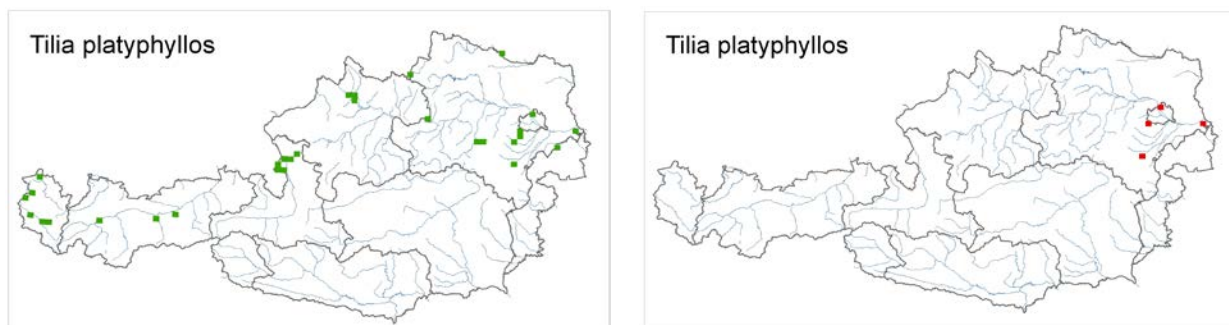


Fig. D-3.29: Grid cells corresponding to the vegetation relevés of Large-leaved Lime.

Green: grids corresponding to all locatable relevés (80% of the total relevés were assigned grids), Red: grids corresponding to the locations of the relevés of the driest 10% (100% were assigned grids).

D-3.2.2.14 Ulmus glabra

Geographical distribution of relevés where Wych Elm was either dominant or subdominant:

Most of the 95 Wych elm relevés came from Vorarlberg and an area spanning from the South Styrian Hügelland to the Koralpe.

Locations of the relevés belonging to the driest 10%:

The dry sites of Wych elm were distributed as follows: several in Vorarlberg, one in Flachgau and one in the northern Alpine foothills of Upper Austria, and two in the Wienerwald.

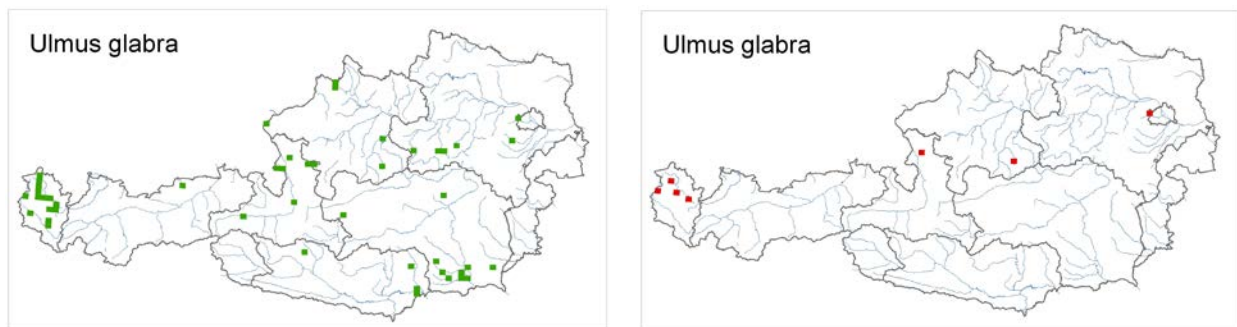


Fig. D-3.30: Grid cells corresponding to the vegetation relevés of Wych Elm.

Green: grids corresponding to all locatable relevés (88% of the total relevés were assigned grids), Red: grids corresponding to the locations of the relevés of the driest 10% (89% were assigned grids).

D-4 Discussion

D-4.1 Potential of drought adapted autochthonous provenances in helping Austrian forestry adapt to climate change

According to the Austrian Forest Act (Das Österreichische Forstgesetz 1975; see Rechtsinformationssystem des Bundes (RIS)) provenances from the same forest ecoregion represent those best adapted to the respective site conditions i.e. soil and climate conditions. The Forest Reproductive Material Act (Forstlichen Vermehrungsgutgesetz 2002; see Müller and Strohschneider (2004)) subsequently states that these provenances thus represent the best sources of reproductive material to maintain the optimal performance of Austria's forests i.e. the optimal provision of production, welfare and protective functions. However, with the threat of climate change looming, the validity of these assumptions will depend on whether these provenances remain the best adapted under future site conditions.

Currently, relatively few data sources exist, which forest managers can consult when selecting the most appropriate reproductive material for a given site. Regarding performance in terms of timber production (i.e. yield potential), extensive data on yield and increment from several thousand plots in Austria, covering the main production forest species, is made available by the national forest inventory (see Schadauer (2009)). However, this data only provides an indication of production potential, and importantly, production potential under current site conditions; the data gives no indication of any sort of performance under future site conditions. Austrian forestry is therefore in need of additional data so as to select the provenances best suited to the likely changes in climate i.e. increases in mean temperatures and drought incidence (Christensen et al., 2007, Schöner et al., 2011).

This study demonstrates the potential of using the Austrian Vegetation Database (Willner) (Willner & al., 2012) in identifying the provenances likely to be best adapted to future climate conditions. Like the Austrian forest inventory, this database is very extensive in its spatial coverage with over 36,000 vegetation relevés taken from all over Austria. By deriving ecological indicator values of site moisture, this study demonstrates the relative range in site moisture conditions over which 22 Austrian tree species occur. Furthermore, the driest sites identified here (i.e. the driest 10%), potentially represent the provenances of each species most adapted to drought conditions. While inter-population variations in phenotype may result from acclimation mechanisms (Magnani, 2009), site specific selection pressures (natural or even artificial e.g. negative selection thinning based on vitality), if allowed to proceed over several generations, are likely to have facilitated some adaptation to drought due to the high within-population genetic variation typically of trees (Hamrick, 2004). While the indirect ecological indicator values which are derived give no indication of yield potential, by identifying e.g. drought tolerant provenances, the data may at least help managers promote stability. This represents a key objective within the emerging sustainable forest management paradigm, where the optimal provision of functions and products (e.g. promoting biodiversity and protective functions) is delivered by maximising ecosystem function rather than maximising yield (Bodin and Wiman, 2007, Führer, 2000, Larsen, 1995).

Generally many of the potentially drought adapted populations identified (i.e. the driest 10%) were as expected located in the warm and dry regions of Austria (Figure D-2.2). Many were found for instance in the Pannonian region of the Vienna Basin. As this area is subject to rather intensive agriculture, most of the dry sites were located on the margins of this area e.g. along the Manhartsberglinie, the area of Wachau or the Thermenlinie, where due to the higher reliefs, these areas are less suitable for agriculture purposes than say the Leiser- and Hainburg Mountains, and the Leithagebirge. The dry

sites of Turkey and Downy oak, Field maple and Austrian pine were found limited to these particular areas. In addition to the Pannonian areas, other dry areas such as the inner Alps, the Styrian Randalpen and the South-eastern foothills were also identified as potential locations for drought adapted provenances of Pendunculate oak and Hornbeam. Furthermore the dry sites of Scots pine were also restricted to the drier eastern parts of the country.

The two sample t-tests indicated that reduced precipitation (30 year mean annual precipitation) was a decisive factor distinguishing between the dry and residual sites of Norway spruce, Scots pine, European beech, Hornbeam, Sycamore, Ash, Large-leaved lime, and Turkey-, Sessile-, and Downy oak (Figure D-3.4 and D-3.8). Furthermore, due to increasing evaporative demand with increasing temperature, it was also shown that the dry sites of European beech, Norway spruce, Ash, Sessile oak, Large-leaved lime were on average significantly warmer than the corresponding residual sites.

Despite the often significant difference in the mean climatic variables between the dry and residual sites, it was also evident that topographical features such as aspect were also relevant in terms of site dryness. For example, southern-exposed (SW, SE, S) slopes where due to higher incident radiation, evaporative demand is typically higher, were particularly frequent amongst the dry sites of Silver fir, Norway spruce, Larch, Hornbeam, European beech, Turkey-, Pendunculate, and Sessile oak, Ash and Small-leaved lime (Figure D-3.3 and D-3.7). The data also revealed a role played by elevation; the dry sites of Stone-, Austrian-, Scots-, and Mountain pine, Field maple, Sycamore, European beech, Ash, Small-leaved lime, and Sessile-, and Pendunculate oak were typically more frequent at lower elevations than the corresponding residual sites (Figure D-3.2 and D-3.6). However, this may indirectly correspond to a precipitation effect due to increased orographic precipitation with increasing elevation. Finally, the data may also indicate a relationship between hydrological soil properties and the ecological indicator values derived. For example many of the dry sites of European beech, Norway spruce, Silver fir, Wych elm and Sycamore were found within the Northern and Southern Calcareous Alps, where precipitation is relatively plentiful. This observation may be due to the low water holding capacity of the thin rendzina soils typical of these regions. Nevertheless, the dry sites of the two Lime species and Ash were, despite their wide distribution, limited almost exclusively to areas of low rainfall. In case of the azonal Alder species specifically dry stands cooccur geographically in between the other typically wet sites independently from the overall precipitation regime.

These variations in dryness due to factors such as topography and hydrologically-relevant soil properties may be particularly significant when identifying drought adapted provenances within areas where the climate is rather spatially homogenous e.g. within forest ecoregions. Due to the large distribution of Beech and thus the number of available relevés, it was possible to identify potentially drought adapted populations for different forest ecoregions (Figure D-3.21 and D-3.22). Due to the uncertainty surrounding the introduction of new untested provenances (Bolte et al., 2010), the identification of potentially drought adapted provenances in the different ecoregions would at very least provide greater flexibility to forest managers looking to foster adaptation to climate change. However, these provenances must nonetheless be screened themselves via provenance trials/pot experiments to confirm whether or not they are superior with respect to drought resistance. Such experiments are planned as part of a collaboration with the project of Drexler and Walentowski (2011).

While the results here illustrate the potential of the Austrian Vegetation Database in facilitating the adaptation of Austrian forestry to climate change, there are significant weaknesses in the database, particularly the geographic data of the relevés. In some cases, precise geographic coordinates have been assigned to the relevés. However, in many cases the relevés have only been assigned to quadrants of the floristic map according to Niklfeld (1994), which being 5 geographic minutes long, and 3 geographic

minutes wide, represent rather rough indications of where the sites and the potential provenances lie. Furthermore, a substantial number of relevés possess no geographic information. Thus in this respect there is considerable room for improvement.

If an identified autochthonous provenance still proves to be inadequate in terms of adapting to climate change, forest management may nonetheless look at provenances of the same species from abroad or new exotic species (Bolte et al., 2010, Millar et al., 2007). However, as the data of this study indicates, forest managers may not need to look abroad for alternative species more resistant to drought stress. As Figure D-4.1 shows, rather drought tolerant provenances for a number species already exist here in Austria e.g. Austrian-, and Scots pine, and Downy-, Sessile-, and Turkey oak. While the suitability to other site specific factors would of course need to be considered (e.g. soil pH, light and nutrient requirements etc.), the data nevertheless illustrate that there is enough potential within Austria's autochthonous tree species for them to at least be considered alongside alternative adaptation strategies such as exotic provenances or species. For instance, stands of Pendunculate oak which are identified as vulnerable to climate change could be steadily adapted to climate change by steadily introducing more drought tolerant *Quercus* species such as Sessile oak.

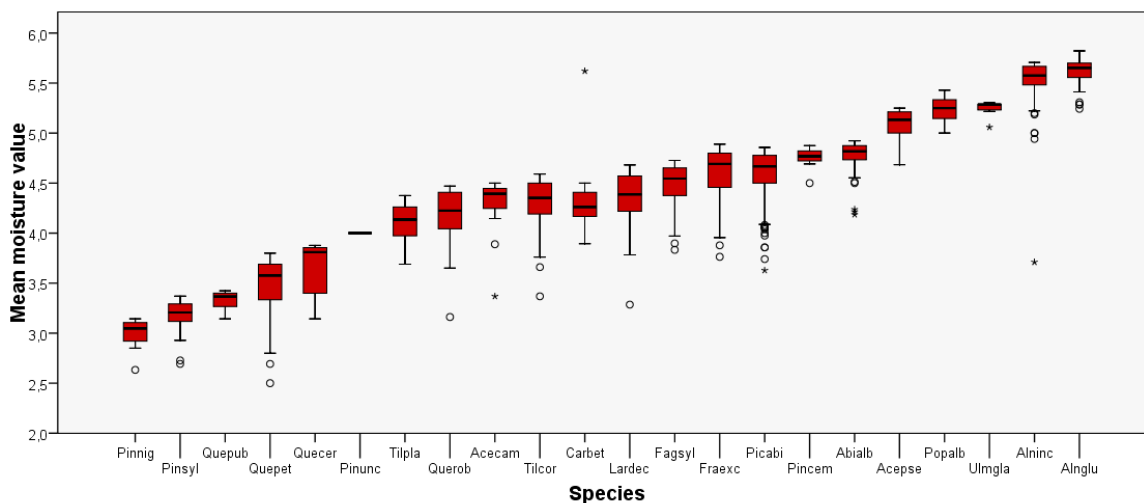


Fig. D-4.1: Moisture indicator values for the driest 10% for a number species.

(Abialb: Silver fir, Acecam: Field maple, Acepse: Sycamore, Anglu: Common alder, Alninc: Grey alder, Carbet: Hornbeam, Fagsyl: European beech, Fraexc: Ash, Lardec: Larch, Picabi: Norway spruce, Pincem: Stone pine, Pinnig: Austrian pine, Pinsyl: Scots pine, Pinunc: Mountain pine, Quecer: Turkey oak, Quepet: Sessile oak, Querob: Pendunculate oak, Tilcor: Small-leaved lime, Tilpla: Large-leaved lime, Ulmgla: Wych elm).

While the pressure of climate change continues to force the case of foreign provenances or exotic species (Millar et al., 2007, Broadmeadow et al., 2005), their introduction, particularly exotic species, may have negative ecological effects (Bolte et al., 2010, Engelmark et al., 2001, Richardson, 1998, Richardson and Rejmánek, 2011). It is therefore important that in trying to adapt to the projected changes in climate, forestry does not ignore the autochthonous options available to it. This study illustrates that a potentially significant amount of inter-, and intraspecific variation in drought tolerance is available within Austrian tree populations. The next steps are to assess this potential and to design effective ways of incorporating it into the strategies which will help Austrian forestry adapt to climate change.

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