EVALUATING FOREST SPECIES RESPONSE TO DIFFERENT CLIMATE CONDITIONS AS A BASE FOR SUSTAINABLE FOREST MANAGEMENT UNDER CLIMATE CHANGE

ANTÓNIO HENRIQUE COSTA GOMES SOARES CORREIA

SCIENTIFIC ADVISORS:
Ph.D Maria Helena dos Reis Noronha Ribeiro de Almeida
Ph.D Margarida Tomé
Ph.D Ander Arias

THESIS PRESENTED TO OBTAIN THE DOCTOR DEGREE IN
FORESTRY ENGINEERING AND NATURAL RESOURCES

2019

EVALUATING FOREST SPECIES RESPONSE TO DIFFERENT CLIMATE CONDITIONS AS A BASE FOR SUSTAINABLE FOREST MANAGEMENT UNDER CLIMATE CHANGE

ANTÓNIO HENRIQUE COSTA GOMES SOARES CORREIA

SCIENTIFIC ADVISORS:

Ph.D Maria Helena dos Reis Noronha Ribeiro de Almeida; Ph.D Margarida Tomé;
Ph.D Ander Arias (NEIKER Tecnália)

Jury:

President: Doutora Maria Teresa Marques Ferreira, Professora Catedrática, Instituto Superior de Agronomia, Universidade de Lisboa.

Members: Doutora Maria da Conceição Lopes Vieira dos Santos, Professora Catedrática, Faculdade de Ciências, Universidade do Porto; Doutor Filipe Duarte Santos, Professor Catedrático, Faculdade de Ciências, Universidade de Lisboa; Doutora Maria Helena Reis de Noronha Ribeiro de Almeida, Professora Associada, Instituto Superior de Agronomia, Universidade de Lisboa; Doutora Maria João Magalhães Gaspar, Professora Auxiliar, Escola de Ciências da Vida e do Ambiente, Universidade de Trás-os-Montes e Alto Douro; Doutora Nahia Gartzia Bengoetxea, Investigadora, Neiker-Tecnalia Basque Institute for Agricultural Research and Development, Espanha.

THESIS PRESENTED TO OBTAIN THE DOCTOR DEGREE IN

FORESTRY ENGINEERING AND NATURAL RESOURCES

Programa de doutoramento FCT (Sustainable Forests and Products, SUSFOR)

PD/BD/52405/2013

2019

Abstract

To anticipate European climate scenarios for the end of the century, we explored the climate gradient within the REINFFORCE (RÉseau INFrastructure de recherche pour le suivi et l'adaptation des FORêts au Changement climatiquE) arboreta network, established in 38 sites between latitudes 37◦ and 57◦, where 35 tree species are represented. Understanding how climate affects tree phenology, biotic and abiotic vulnerability, is a most important research subject under Climate Change. We focused on determining which climatic variables best explain their survival and growth, and identify which species that are more tolerant to climate variation and those whose growth and survival future climate might constrain. We used empirical models to determine the best climatic predictor variables that explain tree survival and growth, to predict the impact on the specific response of tree species to changing climate scenarios, to evaluate the loss and assess the risk of maintaining or changing species, under each scenario. Considering the scenarios described on IPCC's Fifth Assessment Report, predictions were run under two main Representative Concentration Pathways (RCP) 4.5 and 8.5. Precipitation-transfer distance was most important for the survival of broadleaved species, whereas growing-season-degree days best explained conifer-tree survival. Growth (annual height increment) was mainly explained by a derived annual dryness index (ADI) for both conifers and broadleaved trees. Species that showed the greatest variation in survival and growth in response to climatic variation included Betula pendula Roth, Pinus elliottii Engelm., and Thuja plicata Donn ex D.Don, and those that were least affected included Quercus shumardii Buckland and Pinus nigra J.F.Arnold. We also demonstrated that provenance differences were significant for Pinus pinea L., Quercus robur L., and Ceratonia siliqua L. A higher survival risk is expected for conifer species, especially for species like Calocedrus decurrens, Pseudotsuga menziesii, and Pinus nigra. For growth, high risk is indicated for Larix decidua, Pinus pinaster, and Betula pendula. Risk distribution points to higher risk at southern sites, and higher production potential for northern sites. Here, we demonstrate the usefulness of infrastructures along a climatic gradient like REINFFORCE to determine major tendencies of tree species responding to climate changes.

Keywords: climate response; climate adaptation; REINFFORCE; Pinus; Quercus; Cedrus; Eucalyptus; Betula; Pseudotsuga; Sequoia

Resumo

As alterações climáticas são reconhecidamente atualmente como um fato que ocorre com impacto nos sistemas naturais e humanos em todos os continentes. Ao longo da História, as populações humanas e os ecossistemas sofreram ajustes e adaptações ao clima, variabilidade climática e fenómenos extremos, com diferentes proporções de sucesso. No entanto, estima-se que as alterações climáticas estejam a ocorrer a um ritmo demasiado elevado para permitir uma adaptação natural dos sistemas. Compreender como o clima afeta a fenologia, a vulnerabilidade a danos bióticos e abióticos, revela-se de extrema importância para a antecipação dos efeitos das alterações climáticas sobre a floresta. O aumento esperado da temperatura potenciará um alongamento do período de crescimento, o qual poderá afetar a exposição a pragas e agentes patogénicos. Em conjunto com diminuição da quantidade de precipitação anual, ou o aumento da extensão da época sem chuva, proporcionará um aumento do stress hídrico, nas regiões mais a sul. Adicionalmente, os eventos climáticos extremos combinados com as alterações na fenologia potenciam consequências dramáticas, nomeadamente a antecipação do abrolhamento com exposição a geada. Não obstante, existe a previsão de um aumento de produtividade da floresta a norte, por conta do aumento de temperatura e concentração de CO2 atmosférico, permitindo acompanhar o acréscimo da procura de produtos florestais. Muitos trabalhos têm focado a modelação do comportamento futuro das espécies, procurando prever o efeito das condições futuras no material de regeneração florestal, através da sua distribuição atual. Outros, porém, utilizam modelos de base fisiológica com dados obtidos em ambiente controlado, para uma pequena amostra representativa da espécie. A informação gerada por estes meios é extremamente importante, embora recorram a necessárias simplificações de forma a permitir um melhor ajuste para os modelos. Uma dessas simplificações é a omissão da variabilidade genética intraespecífica, que afeta necessariamente de forma positiva ou negativa, a capacidade de uma espécie enfrentar as condições futuras, expressa na variação do comportamento ao longo dos gradientes climáticos. De forma a antecipar os efeitos das alterações climáticas na Europa que se esperam ocorrer até ao fim do século, neste trabalho propomos explorar o gradiente climático abrangido pela rede de *arboreta* REINFFORCE (RÉseau INFrastructure de recherche pour le suivi et l'adaptation des FORêts au Changement climatiquE), estabelecida em 38 locais entre as latitudes 37◦ e 57◦, onde estão instaladas 35 espécies, cuja variabilidade genética de cada espécie é representada por pelo menos 3 proveniências.

Como objetivo geral para este trabalho, procurámos determinar quais as variáveis climáticas com maior poder explicativo para o crescimento e sobrevivência destas espécies, e perceber que espécies apresentam uma maior tolerância á variabilidade climática, assim como aquelas que poderão sofrer maiores constrangimentos sob os cenários climáticos previstos.

Na primeira fase do estudo (Artigo I), nos dois *arboreta* da rede REINFFORCE localizados mais a sul (Lisboa e Sintra), foram monitorizadas 3 espécies, uma nativa (*Quercus robur* L.) e 2 não nativas (*Quercus rubra* L. e *Betula pendula* Roth). Foram avaliados o crescimento, fenologia foliar e danos por insetos, de acordo com os protocolos definidos para a rede REINFFORCE. A interação *Espécie x Site* revelou-se significante para sobrevivência e crescimento. Na fenologia observaram-se diferenças entre e dentro das espécies. Não foram observadas diferenças significativas para tolerância ao frio. A *Betula. pendula* apresentou um abrolhamento mais precoce em ambos os locais, consequentemente beneficiou do período de crescimento mais alargado e maior crescimento em altura, sendo menos afetada por danos por insetos, embora a sobrevivência tenha revelado suscetibilidade a temperatura mais elevada, onde a espécie *Quercus robur* apresentou melhor desempenho.

Na segunda fase do estudo (Artigo II), que beneficiou de toda a informação disponível na rede de 38 *arboreta* Reinfforce, utilizámos modelos empíricos para determinar as melhores variáveis climáticas preditoras para o crescimento e sobrevivência das plantas. A variável com a qual se obteve melhor ajustamento dos modelos para o crescimento de ambos os grupos de espécies foi o índice anual de aridez (Annual Dryness Index – ADI) que é calculado como a raiz quadrada do valor anual em graus de dia acima dos 5ºC, dividido pelo valor anual de precipitação. Para a sobrevivência, a variável que se revelou mais expressiva para o grupo das coníferas foi o valor em graus de dia acima de 5ºC para a época de crescimento (março-setembro); para as folhosas, a distância climática para a precipitação anual entre *arboterum* e local de proveniência do material, proporcionou um melhor ajustamento para a sobrevivência. Identificaram-se as espécies que apresentam maior e menor amplitude na variabilidade para o crescimento e sobrevivência ao longo do gradiente climático da rede. Isto revelou que algumas espécies se apresentam maior resistência aos efeitos da variação do clima.

Utilizando os modelos ajustados e as variáveis preditoras resultantes da fase anterior do trabalho, na terceira fase (Artigo III) calculou-se o risco em crescimento e sobrevivência inerentes a cada uma das espécies, através de uma metodologia probabilística, sob o efeito de 2 cenários de alteração climática, RCP 4.5 W/m2 e RCP 8.5 W/m2 e dois horizontes temporais, 2050 e 2080. O risco avaliado revelou que espécies importantes para produção florestal na Europa, como *Pinus pinaster*, *Betula pendula* e *Larix decidua*, apresentam valores elevados de risco, ou seja, de potencial perda de crescimento e sobrevivência, para os cenários previstos. Sob este contexto, foi possível identificar quais as espécies que apresentam menor risco, ou mesmo negativo, podendo apresentar alternativa viável para uma manutenção da produtividade a médio e longo prazo. São as espécies *Pinus ponderosa*, *Pinus brutia* e *Acer pseudoplatanus*. O híbrido *Eucalyptus x gundal*, apesar de apresentar um valor não negligenciável de risco de sobrevivência, particularmente para 2080, possui um potencial de crescimento elevado, compensando a opção por este material de regeneração florestal. Deve referir-se que os maiores valores de risco são observados nos locais onde as espécies apresentam atualmente melhor desempenho, e que o potencial de crescimento será mais elevado no centro e norte da rede. Para as localizações a sul, a conjugação do aumento de temperatura com a redução de disponibilidade hídrica, potencia o aumento do risco para espécies identificadas como tolerantes à secura, como a *Quercus suber*.

É importante referir que o presente estudo assenta nos dados dos primeiros 4 anos após a instalação das referidas espécies, sendo esta fase de extrema relevância para o estabelecimento de um povoamento e de grande suscetibilidade para as plantas. Estes resultados contribuem para uma compreensão global do potencial das espécies face às alterações climáticas, servindo de suporte para uma a tomada de decisão ao nível da indústria e política florestal, para fomentar uma floresta adaptada, capaz de manter a produtividade mesmo sob condições futuras mais adversas. O estudo corrobora ainda a importância da rede de *arboreta* REINFFORCE como ferramenta para monitorizar de forma contínua o impacto das alterações climáticas nas espécies florestais e proporcionar bases para a migração assistida de espécies, considerando os cenários de alterações climáticas.

Keywords: resposta ao clima; adaptação ao clima; REINFFORCE; Pinus; Quercus; Cedrus; Eucalyptus; Betula; Pseudotsuga; Sequoia

Acknowledgments

I would like to take this opportunity to acknowledge the support and friendliness that contributed to the execution and completion of the present work.

Firstly, to the REINFFORCE team – Francis, Rebeca, Christophe, Nahia, Maria José, Javier, Julio, Carmen, Richard and all the others who embraced the challenge to address the climate change adaptation by this means, and provided the data and knowledge that initiated the present work.

To Carla Faria, Ana Rodrigues, Rui, Maria, Lurdes, Madalena, Catarina Cruz and the other friends from ISA's staff, for their friendship and help to face the hard fieldwork.

To the thesis supervisor team and Professors who helped in the beginning and the end of the process, Ander Arias, Margarida Tomé, Manuela Branco, Helena Pereira, Francisco Castro Rêgo

To the Professors and Friends who left an imprint on my learning and personality throughout my journey, António Fabião, João Santos Pereira, António St. Aubin, José Tomé, and Hachemi Merauani who also helped me in the field with the collection and conservation of *Quercus ilex* and *Quercus suber* seeds.

To the Institutions and their Representatives, who facilitated the fieldwork, and sometimes endured the hard fieldwork side-by-side with me, Maria João Gaspar and UTAD, and Nuno Oliveira and Parques de Sintra - Monte da Lua

To Fellow SUSFOR students, with whom I exchanged life experiences and help with the hard Mathematical courses– André, Juan, Ana, Carla, Sofia, Teresa, Júnia and Raquel.

A special word of thanks to Professor Maria Helena Almeida, who provided both scientific and emotional guidance, helping to withstand the long, hard path, with whom I learned so much, not only for improving the researcher but also the character.

To my parents, for their understanding and support all along this stormy path.

To my family, Henrique, Margarida, and Patrícia, for their love and unwavering support, with whom I've learned to fight for what is really important, and that "impossible" is just a minor word… when your mind is set for the right goal!

Preamble

The REINFFORCE arboreta network

In order to implement a climate response study in the Atlantic Region, to assess field vegetable material performance, infrastructure was installed in 4 countries, uniting 18 partners around the problematic of Forest adaptation to Climate Change (EFI/IEFC, Neiker, HAZI, Xunta de Galicia, iuFOR, GAV, Azorina, DRRF, FPF, INRA, Forest Research and ISA). This infrastructure, named REINFFORCE Network, was installed in 2012 and aims to provide continuous information with less uncertainty. The network extends from Scotland (North) to Lisbon (South), and from Bordeaux (East) to the Azores (West), taking advantage of very different climatic conditions. This network is composed by 38 sites, called Arboreta, each one being a collection of exactly the same genetic material, composed by 35 species, represented by at least 3 provenances from its current distribution, in order to capture maximum species variability (Orazio et al, 2013). The North/South and East/West extension of this Network allows to explore a gradient of climate conditions specifically designed to mimic temporal expected changes and the range of predicted future climate scenarios.

The present work results from the first four years of data generated by this combined effort of measuring, monitoring and maintenance.

Contents

Chapter I – Introduction

Problem / Knowledge gap

For the past 25 years, Forest global area has decreased 1.29 billion hectares, mainly due to deforestation and climate-related constraints, albeit planted forest has shown an increase of 10.4 million hectares, also in areas considered highly susceptible to climate change effects (Payn et al. 2015). But can one say that the reforestation material being used is the most suited to cope with future climate conditions? When addressing the Climate Change impact on Forest Species, there is still an implicit uncertainty that constrains the application of acquired knowledge into new management options for Forest adaptation (Lindner et al. 2014). Yet, planning an adaptation towards an uncertain future has been recognized as a need to minimize the risks and maximize the opportunities that climate change presents to sustainable forest management (Edwards et al. 2012).

Prediction of future climate includes not only an increase in mean temperatures (IPCC 2014) in temperate latitudes but also greater variability in temperatures (Rigby and Porporato 2008). In addition to climate trends, extreme events had already been identified as a major cause of forest dieback (Bréda and Peiffer 2014). The future climatic scenarios for Portugal point to an increase in average summer temperatures from 0.3 to 0.7ºC in a short-term period (2016-2035), and up to 4.6ºC until 2100. As far as precipitation is concerned, the estimates suggest a reduction of annual rainfall from 20 to 40%, especially in Southern Portugal. Water stress will represent a leading constraint to primary production. The combined effects of drought and high temperatures will bring decreases in carbon assimilation in some areas. Changes in plant phenology, (i.e. increased growth period due to winter warming), together with elevated atmospheric carbon dioxide will not alter this trend. Another expression of the predicted climate change effect is the rising the risk of forest fires. Other extreme meteorological events will become more frequent, with non-periodic droughts (several years' duration) causing mortality and irreversible changes in the plant community, heat waves causing forest fires, storms generating strong winds and the consequent overthrow of trees, flash floods and soil erosion (Santos, F.D. and Miranda, P. 2006).

Climate change will require trees to cope with new biotic and abiotic environments and stresses, such as drought, temperature extremes, flooding, wildfire, and novel insect and disease pressures (Eriksson et al. 2013). Nevertheless, uncertainty constrains the application of acquired knowledge into new management options for Forest adaptation (Lindner et al. 2008, 2014). Current impact assessments with simulation models contain several simplifications, which explain the discrepancy between results of many simulation studies and the already observed changes in forest productivity and species distribution (Lindner et al. 2014). One of the simplifications is the failure to include species' phenotypic plasticity when modeling, due to a shortage of information on plasticity in response to future climate conditions.

Patterns of genetic variation vary greatly among species: some species are climatic specialists that exhibit strong differentiation over small geographic and climate scales, while others are generalists that show less differentiation across a wide range of environmental gradients. Some species can also exhibit multiple adaptive strategies over different portions of their range. Based on the knowledge of silvics and population genetics, as well as on studies of forest responses to past climate conditions, it is possible to anticipate that plants that are genetic specialists will be most vulnerable to climate change. This would be especially apparent during the regeneration and juvenile phases of growth, and in moisture-limited areas (Eriksson et al. 2013). Every species and every life stage of each species respond differently to changing climate variability. While all will respond to some extent to a general increase in temperature and a regional increase or decrease in precipitation, the climate seasonality with its seasonal shifts in extremes will very differently affect the many species that combine to make forest ecosystems. Many responses are to extremes rather than to means, and therefore larger uncertainties in the projections of climate extremes cause considerable uncertainties when assessing the likely response of forest ecosystems towards the end of the current century (Lindner et al. 2014).

Sustainable Forest Management is based on the principle of maintaining and enhancing the long-term health of forest ecosystems while providing environmental, economic, social, and cultural opportunities for current and future generations (Edwards et al. 2012). Genetic diversity is, in this context, a tool that should be used and made available for forestry management, providing adequate Forest Regeneration Material to withstand the challenges that emerge with Climate Change, mainly drought condition. Forest stand regeneration is, therefore, an opportunity to increase stand resilience, which can be achieved using best-fitted Forest Regeneration Material, from the proper provenance region (ENAAC, 2013). Genetically diverse and adapted seed as well as planting stock will provide the foundation for healthy forests and ecosystems in the future. If climate change proceeds as predicted, a major concern is that planting stock originating from fixed contemporary seed zones will be growing in sub-optimal conditions by the end of the century or sooner (Eriksson et al. 2013).

Research goal and objectives

The proposed work aims to improve our understanding on 35 forest species field performance established in 38 *arboreta*, located along a range of climatic conditions, from latitude 37° to 57° N, in a range of climatic conditions enabling to assess adaptation measures for Atlantic forest resources. This will allow reducing the uncertainty of species' behavior predictions in response to Climate Change, contributing to a successful Sustainable Forest Management.

To achieve the main goal, the work is divided into 2 chained objectives:

<u>Objective 1</u>- General climate response model

a) To identify the main climate variables explaining species' response variation along the network's range;

b) To determine which species present a significant different response within the network's climate range (phenotypic plasticity), using the full range of arboreta and all of the species represented;

c) To estimate how climate variation impacts each species' growth and survival, and determine the climate range that can be considered optimal

<u>Objective 2</u>-Using general response models as a basis to perform risk analysis

Estimate risk probabilities for survival and growth, under multiple climate change scenarios.

Thesis structure

The present thesis is organized in 3 chapters. The first chapter introduces the climate change problematic in the Forest context, including the proposed route to deal with the uncertainty, and to promote a better adapted forest. The second chapter consists of three original contributions, published or submitted to peer-review scientific journals. The last chapter consists of conclusions, final remarks, and references for the overall thesis. The Annex section provides the reader with the funding information for the present work, as well as the additional outputs generated by the study, for the purpose of dissemination of the results among the community.

Material and methods

Material

In order to assess field impacts that future climate conditions may induce in 35 forest species, a "Space for Time" approach is achieved using the REINFFORCE arboreta network. This will allow to simulate several expected climate conditions, to test species' plasticity and local adaptation capabilities, and to identify optimal and limiting climate conditions within the proposed range.

The arboreta network is composed of 38 arboreta that share the same plant material, and are ranged from Scotland to Portugal. Overall, there are 35 species in the network, 33 installed in all arboreta, plus *Fagus sylvatica* and *Larix x eurolepis* in part of the network. In each arboretum, the 33 species are represented by at least 3 provenances, selected from each species' current distribution range. Each provenance is represented by 12 plants, with 3 repetitions for 4 species (*Pinus pinaster*, *Betula pendula*, *Cedrus atlantica*, and *Quercus robur*), selected for assessing site heterogeneity, totalizing 36 plants (3x12). The network experimental design is fully described in Orazio et al. (2013). The harmonized data collection was done under a strict unified protocol (IEFC 2011). The present work focus on the 33 species existing in the full range of the network.

Methods

In order to fulfill the objectives, the following questions were addressed:

Question underlying Objective 1: Do some forest species present differential response to Climate conditions, in survival and growth, and can we identify the Climate variables that produce a significant impact in growth and survival on these species?

Question underlying Objective 2: Can we identify associated risk for selected species usage under the various climate change scenarios?

In table 1, a short description of material and methods is provided per article.

Table 1. Summary for data, statistical methodology, and software by article

Article		I	II	III
Material	Addressed topic	Growth, survival, pest attack and frost damage in response to climate	Growth and survival in response to climate	Growth and survival associated risk under climate change
	Species	*Betula pendula*, *Quercus robur*, *Quercus rubra*	33 species	33 species
	Study area	Lisboa and Sintra arboreta	38 arboreta	38 arboreta
Methods	Statistical approach	Generalized linear models ANOVA	Mixed-effect models	Probabilistic risk analysis
	Statistical software	SPSS R	R	R

Chapter II – Original contributions

Description of the original contributions

This doctoral thesis consists of 3 scientific articles (1 published papers and 2 submitted manuscript). The published article is presented in the original format, and the ones still under evaluation, although completed, are presented using the style of the chosen journal. Accordingly, the thesis includes the following contributions identified by Roman numerals (I-III):

Article I – Shahim, H., Correia, A.H., Branco, M., Almeida, M.H. (2018). Monitoring two REINFFORCE arboreta: first result on site, climate and genetic interaction showing the impact on phenology and biotic damages. Scientia Forestalis. DOI:

Article II – Correia, A.H.; Almeida, M.H.; Branco, M.; Tomé, M.; Cordero Montoya, R.; Di Lucchio, L.; Cantero, A.; Diez, J.J.; Prieto-Recio, C.; Bravo, F.; Gartzia, N.; Arias, A.; Jinks, R.; Paillassa, E.; PASTUSZKA, P.; Rozados Lorenzo, M.J.; Silva Pando, F.J.; Traver, M.C.; Zabalza, S.; Nóbrega, C.; Ferreira, M.; Orazio, C. Early Survival and Growth Plasticity of 33 Species Planted in 38 Arboreta across the European Atlantic Area. Forests 2018, 9, 630. DOI: https://doi.org/10.3390/f9100630

Article III – Correia, A.H.; Almeida, M.H.; Tomé, M.; Pereira, J.S.; Cantero, A.; Diez, J.J.; Prieto-Recio, C.; Gartzia, N.; Arias, A.; Jinks, R.; Paillassa, E.; Pastuszka, P.; Rozados Lorenzo, M.J.; Silva Pando, F.J.; Traver, M.C.; Zabalza, S.; Ferreira, M.; Cota, T.; Orazio, C. (2018) Probabilistic risk analysis for 33 forest species survival and growth under RCP 4.5 and 8.5 scenarios in western Europe using REINFFORCE arboreta network results. AFS. DOI:

The author of the present thesis shared the first authorship in article I and was the first author in article II and III.

For article I, the thesis author collaborated in data analysis, field data gathering and manuscript writing.

For articles II and III, the thesis author was responsible the whole work, co-gathering the data, performing the data analysis, discussing results with co-authors and writing the manuscripts, under the guidance of the Ph.D. supervisor team. Thesis supervisor Dr. Maria Helena Almeida guided the author in his research training and participated as co-author in the articles. The supervisors and the author participated in formulating the scientific questions addressed in this thesis.

In Article I, a first exploration of the growth and survival data is performed at local level, using 2 arboreta from the REINFFORCE network, and 3 selected species from the established 35. Additional data for budburst time, pest damage and susceptibility to frost damage is collected in order to access the potential influence of these variables on growth and survival, in the studied locations, and eventually expanding the methodology to the entire arboreta network. In the 3 studied species (*Betula pendula*, *Quercus robur*, and *Quercus rubra*), no significant differences were found for frost damage, but the interaction between site and species showed to be relevant. The budburst time revealed significant differences between and within species, with Betula pendula presenting the earliest budburst date, which potentially originates a longer growing period. Nevertheless, under higher temperature survival it is negatively affected. This introductory study reveals the potential of the arboreta network to provide valid data on species response to climate conditions.

In Article II, a thorough analysis of the entire arboreta network data is performed, for the period between 2012-2016, corresponding to the establishment period. Several climate variables were tested in order to determine Climate influence on growth and survival, . Annual Dryness Index (ADI), growing degree days above 5º C and precipitation climate distance between the site and material origin contributed to the best explanation for growth and survival. The use of mixed-effect models allowed to build models for estimating the traits for all the range of the climate variables per species. For higher temperature and lower water availability, we observed that several species present a significant drop in performance, like *Pinus pinaster* and *Betula pendula*, and other present lower variation for the traits along the entire gradient.

In Article III, the risk analysis is performed by means of a probabilistic methodology (van Oijen et al. 2013), taking advantage of the estimated growth and survival for climate change scenarios RCP 4.5 and 8.5, calculated using the models fitted in article II. These estimates are calculated for the mid (2050) and long (2080) term, in order to provide a continuous range of possible situations, in order to better support decision-making with minor uncertainty. The results show a higher overall risk for conifer species' survival, and broadleaf species only present positive risk under the RCP 8.5 2080 scenario. There are some identified important European species that will undergo high risk, like *Betula pendula* and *Pinus pinaster*, but there are some species that are estimated to improve performance under climate change, and which can represent valid replacements.

I. Monitoring two REINFFORCE arboreta: first result on site, climate and genetic interaction showing the impact on phenology and biotic damages.

Shahim, H., Correia, A.H., Branco, M., Almeida, M.H. (2018). Monitoring two REINFFORCE arboreta: first result on site, climate and genetic interaction showing the impact on phenology and biotic damages. Submited to *Scientia Forestalis*.

TÍTULO: Avaliando dois *arboreta* da rede REINFFORCE: primeiros resultados sobre interacção local, climática e genética, demonstrando o impacto sobre fenologia e danos bióticos

TITLE: Monitoring two REINFFORCE Network Arboreta: first result on site, climate and genetic interaction showing impact on phenology and biotic damages

Resumo: Compreender como o clima afeta a fenologia das plantas e a sua vulnerabilidade biótica e abiótica é um assunto de extrema importância. Particularmente, quando o aumento da temperatura parece promover um alongamento do período de crescimento, o qual poderá afetar a exposição a pragas e agentes patogénicos. Adicionalmente, os eventos climáticos extremos combinados com as alterações na fenologia potenciam desfechos significantes, nomeadamente a antecipação da rebentação dos gomos com exposição a geada. Neste trabalho, foram monitorizadas 3 espécies, uma nativa (*Quercus robur* L.) e 2 não nativas (*Quercus rubra* L. and *Betula pendula* Roth), em 2 *arboreta* da rede REINFFORCE (Lisboa e Sintra). Foram avaliados o crescimento, fenologia foliar e danos por insetos, de acordo com os protocolos defenidos sob o projecto REINFFORCE. A interacção Espécie x Site revelou-se significante para sobrevivência e crescimento. Na fenologia observaram-se diferenças entre e dentro das espécies. Não foram observadas diferenças significativas para tolerância ao frio. A espécie *B. pendula* apresentou rebentação dos gomos mais precoce em ambos os locais, resultando num período de crescimento mais alargado e maior crescimento em altura, sendo menos afetada por danos por insetos, embora a sobrevivência tenha revelado suscetibilidade a temperatura mais elevada, onde a espécie Q. *robur* apresentou melhor performance. Este estudo corrobora a importância da rede de *arboreta* REINFFORCE como ferramenta para monitorizar o impacto das alterações climáticas nas espécies florestais e proporcionar bases para a migração assistida de espécies, considerando os cenários de alterações climáticas.

Abstract: Understanding how climate affects tree phenology, biotic and abiotic vulnerability, is a most important research subject. Particularly, climate warming appears to lengthen the growing season, which may affect the exposition to insect pests and pathogens. Also, extreme weather events combined with shifts in phenology may have dramatic consequences, such as early leaf flushing exposure to freezing events. In this study 2 *arboreta* were followed in the south most distribution of the REINFFORCE Network (Lisbon and Sintra) for 3 species, one native (*Quercus robur* L.) and 2 non-native (*Quercus rubra* L. and *Betula pendula* Roth). Plant growth, leaf phenology and insect damage were assessed according to protocols defined under REINFFORCE project. Species x site interaction was found significant for survival and growth. Phenology differed between and within all species. No difference found for frost tolerance. *B. pendula* had earlier bud burst at both sites, resulting in a longer growth period, and higher stem growth, being least affected by insect damage, although survival was affected under higher temperature, where Q. *robur* performed better. This study corroborates the importance of REINFORCE arboreta network as a tool to assess climate change impact on forest species and support assisted migration considering climate change scenarios.

Palavras-chave: *Betula pendula*, *Quercus robur*, *Quercus rubra*, fenologia, tolerância ao frio, danos por pragas

Keywords: *Betula pendula*, *Quercus robur*, *Quercus rubra*, phenology, frost tolerance, pest damage

1. Introduction

Climate change is now accepted as one of the most important phenomenon affecting the future of the world’s natural systems and, in turn, human society. Many published reports have presented significant evidence that climate changes over the past fifty years have affected several aspects of forest ecosystems. These include tree growth and dieback, invasive species problems, species distributions and migrations, seasonal patterns in ecosystem processes, demographics and even extinctions (IPCC, 2007a). Future climate scenarios in the Mediterranean region indicates a systematic 3 to 4 °C increase in average temperature and reduction in annual rain fall by 20 to 40% (IPCC, 2013). Consequently, in this region, species distribution may be mainly driven by the stress caused by the increase of arid and semi-arid regions (SANTOS, 2002). The combined outcome of droughts and high temperature~~s~~ will cause further lower carbon sequestration in some areas.

Forests also influence local climate (ELLISON, 2017), and thus afforestation programs may play a decisive role on climate regulation at both local and global levels. At the same time, due to climate change, trees are facing physiological stress, variations in phenology, and variations in the exposition to pests and diseases. Therefore, mutual interaction between forests and climate change has become a most important research issue. REINFFORCE project established a network of arboreta with the aim to improve our general understanding of species capacity to cope with climate changes. The same genetic materials was planted under 38 different climates, from the south of Portugal to the south of Scotland (along a range of latitudes from 37° to 58°) covering the European Atlantic temperate forests distribution. Programs like REINFFORCE create physical infrastructures to study adaptation of forest trees to climate change (ORAZIO*,* 2009, 2013).

Many forest ecosystems studies have correlated recent climate trends with changes in phenology as well as with changes in forest productivity (ROSENZWEIG, 2007). Such studies have indicated that climate warming appears to lengthen the growing season and increase tree growth rates in many boreal and temperate forests. However, for Mediterranean regions, studies suggested that the warming has contributed to measurable reductions in forest productivity through interactions with drought, fire and biotic disturbance (ROSENZWEIG, 2007). From our literature review there are few studies addressing the effect of climate on the tree phenology in Mediterranean climates and its impact on biotic and abiotic risks. For temperate regions, it was demonstrated that changes in phenology can affect ecological relationships, for example, by creating a mismatch between plant flowering time and the presence of insect pollinators (POST, 2007; ROSENZWEIG, 2007). On the other hand, as many herbivorous insect species can only develop on young plant material, there could be a mismatch between plant phenology and active larval stages. It may also occur on some insect species, that changes in the phenology of leaves growth or growing tips can cause shifts in the phenology of herbovirous insects larval development (VISSER, 2001). Intra-specific variability in plant phenology may further affects the window of exposition to herbivore insects (SAMPAIO, 2016).

In addition, changes in climate variables may have direct influence on insect pests and pathogens affecting both their survival and development. There is further evidence that warmer temperature is generally favorable for insects by shortening their life cycle (CURRANO, 2008; FRAZIER, 2006), although extreme hot temperature may also cause important insect mortality dependent on life stage and its phenology (e.g. SANTOS, 2011). It also can have indirect influence brought by the interactions between host species and their herbivores (AYRES, 2000).

Climate change indicators includes not only shifts in mean conditions but also changes in the frequency and timing of extreme weather events such as severe cold, spring frost and extended drought (SOLOMON, 2007; MARINO, 2011). Consequently, tree seedlings are responding to pressures of both mean, and extreme conditions. For example, mean temperature and the occurrence of late spring frost may strongly affect the emergence, development, growth, and survival of plants (FISICHELLI, 2014; SANTOS, 2002). Specifically, and as a by-product of warmer temperatures, the occurrence of frost after leaf total flushing is projected to become more common phenomenon in some parts of the world (MEEHL, 2000, GU, 2008). This scenario has a number of important ecological implications. In particular, the newly developed leaves are sensitive to frost events as they lack the structural rigor necessary to prevent damage. Depending on the timing of spring warmth, early and accelerated leaf development has the potential to increase the frequency and magnitude of leaf damage from freezing events (NORBY, 2003; INOUYE, 2008). Resultant lasting effects include the loss of stored carbon and nutrients as well as reduced photosynthetic carbon gain (GU, 2008; MARTIN, 2010), and utterly, increase mortality of young trees. Additional studies show that plant grown under elevated CO_2 present decreased freeze tolerance, making even the most freeze-tolerant species more vulnerable to potential frost damage at warmer freezing temperatures (WOLDENDORP, 2008). The most responsive species to these are likely to occur in the cool to cold climates at high latitudes and altitudes where seasonal temperatures and the length of frost-free period are important determinants of the growing season (CHEN, 1995). A freezing event will thus injure these freeze-tolerant plant species depending on the acclimation state of the plant which is also affected by elevated CO_2 levels (LOVEYS, 2006).

This study aimed to analyze budburst in one locally native (*Quercus robur* L.) and two non-native species (*Quercus rubra* L.*, Betula pendula* Roth) at two of the REINFORCE arboreta, and characterize they're survival, growth, physiological, pest attack and leaf phenology, in response to the climatic conditions on test sites. Each species is represented by contrasting provenances (in order to sample species' variability), since adaptive traits are related to geographic origin. This knowledge contributes for the selection of forest reproductive material to be used in afforestation programs, as well as support assisted migration to mitigate climate change effects.

2. Materials and Methods

2.1. Field description

The study took place at two arboreta: Lisbon (Lat: 38° 42' 51.07" N; Long: 9° 11' 31.66" W; altitude: 106 m) and Sintra (Lat: 38° 46' 48.29'' N; Long: -9° 24' 48.92'' W; altitude: 400 m). Lisbon arboretum was installed in spring 2012, and Sintra arboretum in winter 2012.

For this study, three broad leaves species were chosen, *Q. robur* (QURO)*, Q. rubra* (QURU)*, B. pendula* (BEPE). *QURO* is the only native to the studied area; *QURU* is native to North America. *BEPE* is mostly distributed in the Center and North of Europe, absent from the Iberian Peninsula except for some restricted high mountain areas (VAKKARI, 2009). *QURO* was represented by four provenances (FRAN from France; UNIT from UK; PAGO from Spain; POSA from Italy), *QURU* by two (FEST from France; VANA from Spain), and *BEPE* by three (NORD from France; KRAL from Krakova Slovakia; UNIT from UK). Provenances' detailed information is provided in supplementary material (S2). At least twelve seedlings were observed per provenance. For *QURO* and *BEPE*, 36 plants per provenance were installed. For *QURU*, 12 plants per provenance were installed. All of these plants were included in the study.

Sites differ on soil, climatic and meteorological characteristics observed during the period following arboreta establishment (Supplementary material S1; ORAZIO, 2013). Sintra is characterized by higher humidity and a fresher summer in comparison to Lisbon. Considering the difference between climate conditions observed at each arboreta and at provenance sites, observations revealed consistently higher temperature differential at Lisbon for the summer period, and at Sintra all year round, with particular higher differential for the winter period (Fig. 1). There was also higher precipitation deficit at Lisbon, and winter excess at Sintra.

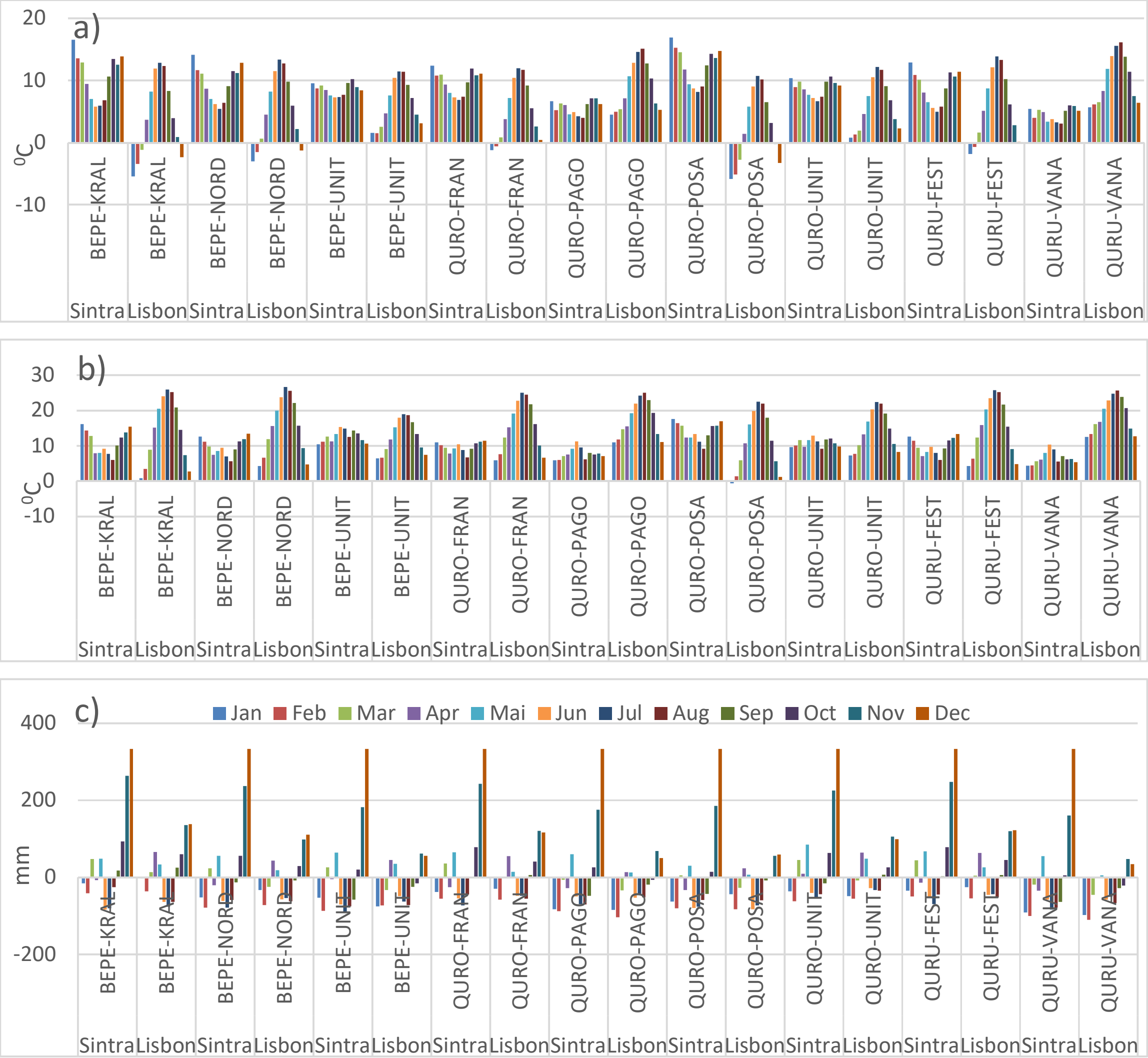


Figure 1 Meteorological variables difference between *arboreta* (2012 - 2014 data) and provenance site (1961 - 1990): a) Mean maximum temperature; b) Mean minimum temperature; c) Precipitation. BEPE- *Betula pendula*; QURO- *Quercus robur*; QURU-

Quercus rubra. Provenance designation and information are described on supplementary material S2 and ORAZIO (2013).

Note: provenance climate data (1961 – 1990) obtained from ClimateEU v4.63 software package, available at ***http://tinyurl.com/ClimateEU***, based on methodology described by Hamann et al. (2013)

Figure 1 **Diferença entre as variáveis climáticas dos** *arboreta* (2012-2014) e locais de proveniência (1961-1990): a) Média das temperaturas máximas; b) média das temperaturas mínimas; c) Precipitação. BEPE- *Betula pendula*; QURO- *Quercus robur*; QURU- *Quercus rubra*. As designações e informações sobre as proveniências de cada espécie estão descritas no material suplementar S2 e em ORAZIO (2013).

Nota: Dados climáticos para as proveniências (1961 – 1990) foram obtidos a partir do software ClimateEU v4.63, disponível em ***http://tinyurl.com/ClimateEU***, baseado na metodologia descrita por Hamann et al. (2013)

2.2. Meteorology

Temperature and precipitation were monitored hourly by an automatic local weather station placed at each *arboreta*.

Meteorological variables difference was calculated between *arboreta* observed data (2012 - 2014) and provenance site data (1961 – 1990) obtained from ClimateEU v4.63 software package, available at ***http://tinyurl.com/ClimateEU***, based on methodology described by Hamann et al. (2013)

2.3. Plant survival

Survival was evaluated in May 2014. Survival is expressed as the percentage of the living seedling recorded since plantation to 2014, for each provenance.

2.4. Growth measurement

Growth measurements were carried out in November 2013. Height (cm) was measured for the tallest living plant branch/bud using extensive pole, with 1 mm precision. Diameter (mm) was measured at 2 cm from ground with a digital caliper, with 0.01 mm precision, in two crossed measurements. Growth is determined as the difference between initial measurement, at installation, and 2013 measurement.

2.5. Phenology

At Lisbon, phenological status was evaluated weekly, from the last week of February 2014, until complete budburst. The best branch with highest numbers of buds in each direction (west, east, north and south) was chosen and tagged for follow-up. The buds in the tagged branches were closely observed every week to check the stage of development, following the phenology protocol defined under REINFFORCE project (reinfforce.iefc.net).

On the 3rd and 4th of March, the phenology observation was carried out at both Lisbon and Sintra, to compare phenology status at this specific time.

2.6. Insect damage

At the mid of April, when the leaves of all the seedlings have expanded, one field observation was done to monitor insect damage on the three species and all the 10 provenances. For that, the protocol of biotic damage defined under REINFFORCE project (reinfforce.iefc.net) was applied. Damage and severity, as expressed by the proportion of attacked leaves per branch, were registered.

2.7. Spring frost tolerance

Frost tolerance was evaluated for two species *(QURO* and *BEPE*) in the end of May, through cell membrane injury in leaf discs measuring electrolyte leakage conductivity, after artificial freezing. Each species was represented by three provenances. Seven seedlings from each provenance were sampled. Five fully expanded leaves from each seedling were collected, and a composite sample with one leaf disc per each seedling and per provenance was prepared in a vial tube. Three tubes per provenance and per species were placed in each freezing bath. Frost treatment was induced in a cryostat (Aralab, Lisbon, Portugal) with three baths containing an aqueous ethylene glycol solution. A controlled freezing program followed a constant cooling and thawing rate of 4 °C/ h and 2 h exposure to five target freezing temperatures (–3, –5, –6.6, –9, –10.5 °C). When the temperature of the bath was at –2 °C, about 0.5 g of finely crushed ice (from deionized water) was added to each tube to make contact with the leaf discs avoiding super cooling. Bath temperature was monitored via thermocouples sensors connected to a data logger (DL2, Delta-T). After the freezing treatment, 15 ml of deionized water was added to each tube, the tubes were then kept for 24 hours at water bath at 25 °C. Electrolyte conductivity was then measured in each tube (T1) with a K220 conductivity meter (Consort, Turnhout, Belgium). The samples were boiled in an autoclave at 120 °C for 10 min and held at 25 °C for 24 h before measurement of maximum electrolyte conductivity (T2). Relative injury (RI) was expressed as a ratio of electrolyte conductivity measured after freezing treatment to maximum electrolyte conductivity, RI = (T1/T2) *100 (ROCHA, 2013; COSTA E SILVA, 2008). RI was then used to calculate TL50 for each provenance (which is an assessment of the temperature that causes death to 50% of plants).

2.9. Statistical analysis

A generalized linear model was adjusted for survival, proportion of attacked leaves (insect damage), bud burst percentage, frost damage percentage, using a logit link, and height and diameter growth. ANOVA procedure was used to assess provenance (nested within species), species and site effect significance for height growth, diameter growth, number of days (since January 1st) until bud burst occurred (defined by reaching the stage number 10) and frost damage variables, in order to assess the effect of species and provenances. Model normality assumptions were verified through graphical analysis and Levene test. Wald Chi-square test was used for model significance. Fisher's least significant difference (LSD) was used for post-hoc multiple comparisons. Species effect on phenology was tested through Kruskal-Wallis, and comparison between species with Mann-Whitney.

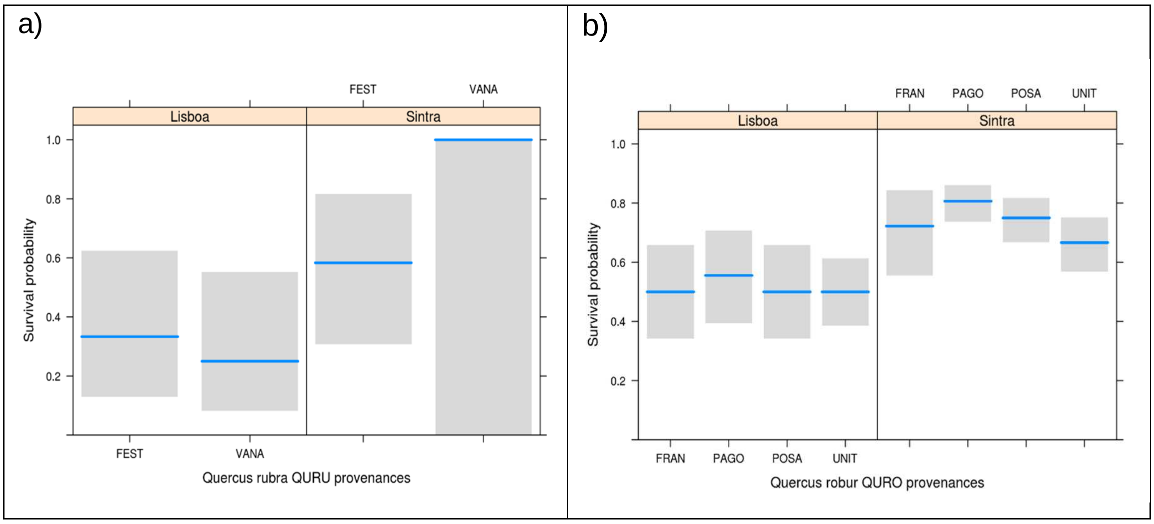
The analysis of phenological stages, bud burst, insect damage, and frost damage was done using SPSS software (ver. 22.0). Analysis of survival and growth was performed with R (ver. 3.3.2) software.

Graphics were generated with visreg package for R.

3. Results

3.1. Survival

Survival was higher at Sintra (Fig 2). Interaction site x species was found to be significant (table 1 in supplementary material S3). For the two non-native species, survival was much higher at Sintra than Lisbon, whereas for *QURO* differences in survival between the two sites were not so high (Fig. 2). At Sintra, survival was highest for *BEPE*, whereas at Lisbon, survival was highest for *QURO*.



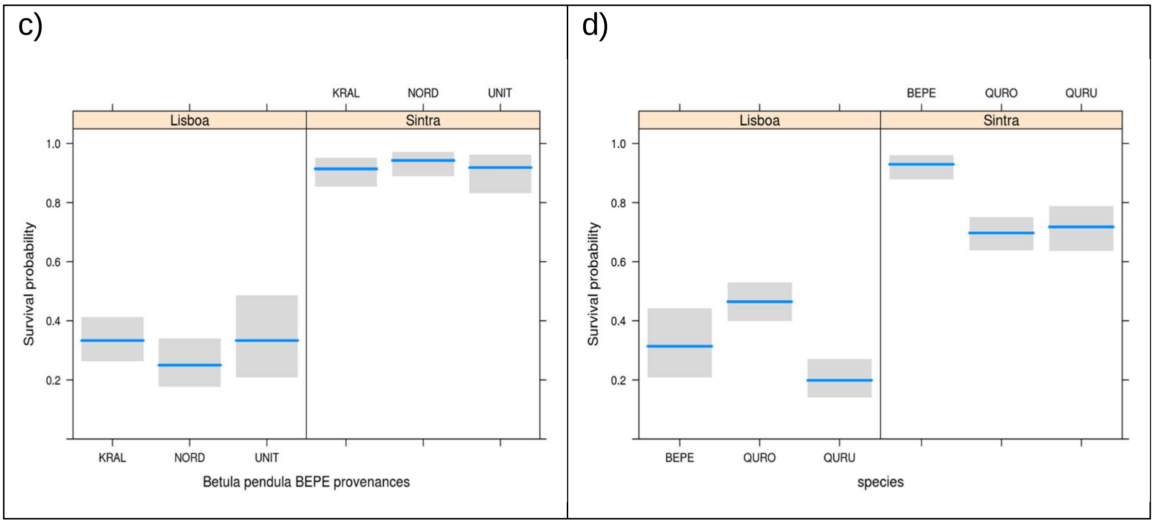


Figure 2 Probabilidade de sobrevivência estimada para as espécies/proveniências em Sintra e Lisboa, para plantações com 2 anos. a) *Quercus rubra*, b) *Quercus robur*, c) *Betula pendula*, d) todas as espécies. BEPE- *Betula pendula*; QURO- *Quercus robur*; QURU- *Quercus rubra*. As designações e informações sobre as proveniências de cada espécie estão descritas no material suplementar S2 e em ORAZIO (2013).

Nota:As linhas horizontais representam a probabilidade estimada. As barras cinza representam os intervalos de confiança de 95%. Os valores de significância podem ser consultados na tabela S3 dos materiais suplementares.

Figure 2 Estimated provenance/species survival probability at Sintra and Lisbon for 2-year plantation. a) *Quercus rubra*, b) *Quercus robur*, c) *Betula pendula*, d) All species. BEPE- *Betula pendula*; QURO- *Quercus robur*; QURU- *Quercus rubra*. Provenance designation and information are described on supplementary material S2 and ORAZIO (2013).

Note: Horizontal line represents estimated probability. Grey bars represent 95% confidence interval. Significance values can be consulted in the S3 table, on the supplementary material.

Table 1 Resultados da análise de “desvios” para os modelos lineares generalizados (teste do tipo III) em relação à sobrevivência.

Table 1 Analysis of deviance table for GLM (type III test) for survival.

Species	**Variance source**	***Chisq***	**Df**	***Pval***
BEPE	provenance	0.599	2	
	Site	297.560	1	***
	provenance: site	2.658	2	
QURO	provenance	5.5128	3	
	Site	24.3180	1	***
	provenance: site	1.2115	3	
QURU	provenance	0.2022	1	
	Site	1.5272	1	
	provenance: site	6.6433	1	**
All	species	48.66	2	***
	Site	330.41	1	***
	species: site	96.91	2	***

Nota: *Pval* código de significância (“***” < 0.0001 < ”**” < 0.001 < “*” < 0.05 < “.” < 0.1 < “ “ < 1)

3.2. Growth

Tree growth was higher in Sintra, regarding both height (F = 29.465, P < 0.001) and diameter (F= 97.318, P < 0.001). A significant *species: site* interaction was observed for height and diameter (Figure 3 in supplementary material S4).

No significant difference was found between provenances for height growth within species– either at Lisbon or Sintra (S4). For *BEPE*, *provenance* is almost significant (*P* = 0.08), with evidence that KRAL and NORD provenances have higher height growth values for Sintra (supplementary material S5).

As for diameter growth, *provenance* is significant for *QURU* (supplementary material S4), and FEST has significantly higher growth than VANA at Sintra (supplementary material S5, Figure 4).

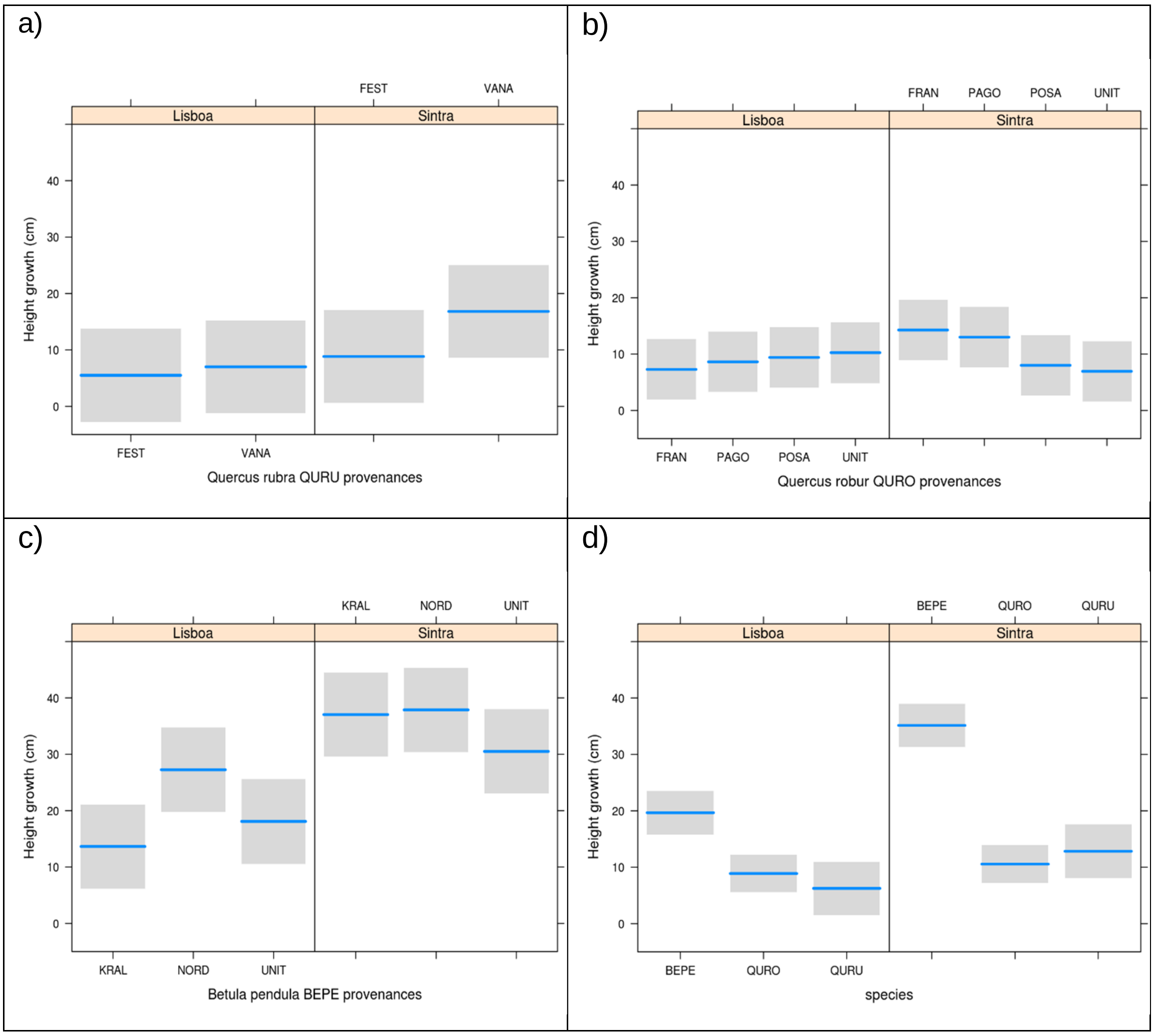


Figure 3 Crescimento médio em altura em Sintra e Lisboa para uma plantação com 2 anos. a) *Quercus rubra*, b) *Quercus robur*, c) *Betula pendula*, d) todas as espécies. BEPE- *Betula pendula*; QURO- *Quercus robur*; QURU- *Quercus rubra*. As designações e informações sobre as proveniências de cada espécie estão descritas no material suplementar S2 e em ORAZIO (2013).

Nota: As linhas horizontais representam o crescimento médio e as barras cinza representam o erro padrão. Os valores de significância podem ser consultados na tabela S4 dos materiais suplementares.

Figure 3 Provenance/species mean height growth at Sintra and Lisbon for 2-year plantation. a) *Quercus rubra*, b) *Quercus robur*, c) *Betula pendula*, d) All species. BEPE- *Betula* *pendula*; QURO- *Quercus robur*; QURU- *Quercus rubra*. Provenance designation and information are described on supplementary material S2 and ORAZIO (2013).

Note: Horizontal line represents mean and grey bars represent standard error. Significance values can be consulted in the S4 table, on the supplementary material.

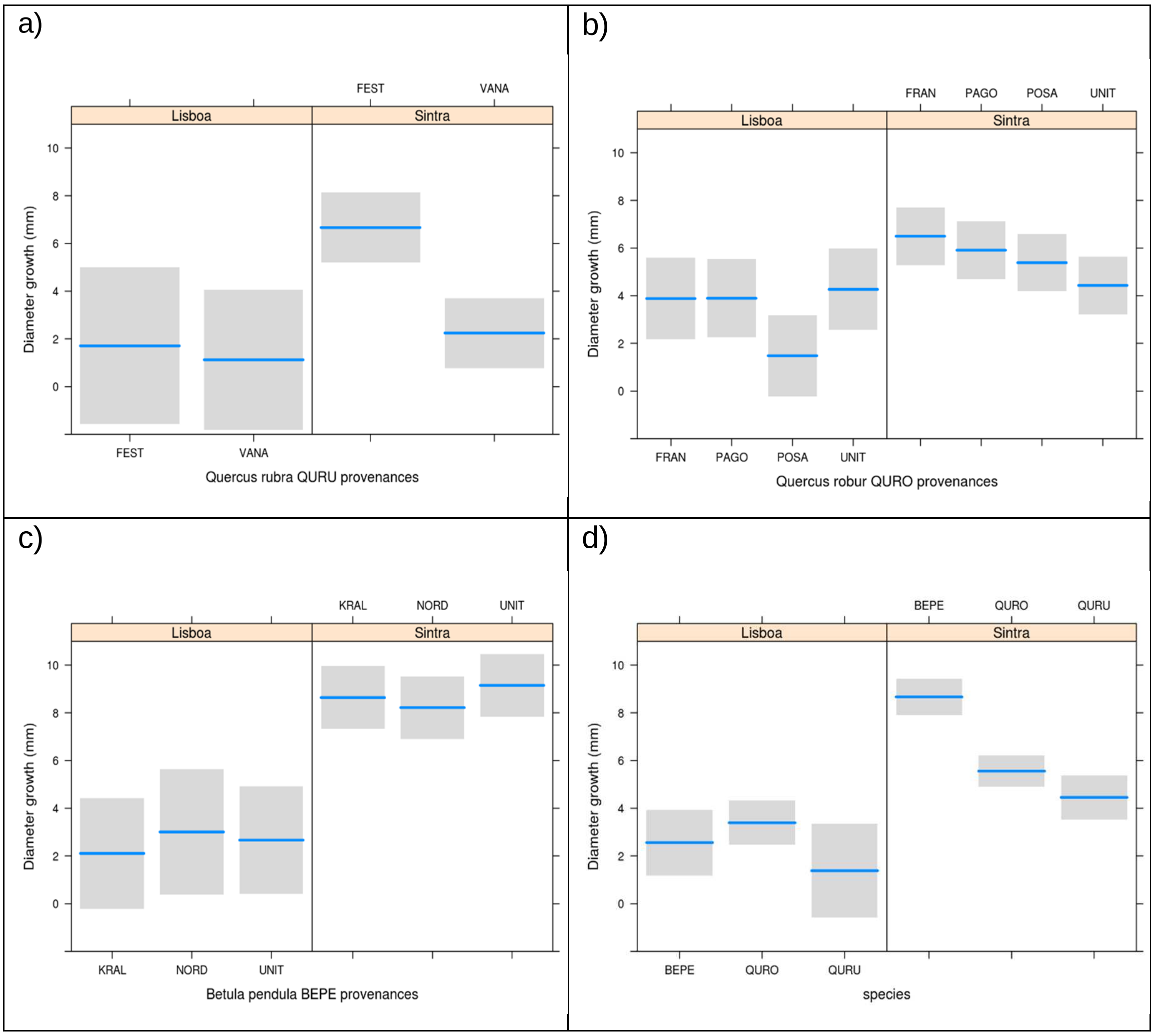


Figure 4 Crescimento médio em diâmetro (colo) para as espécies/proveniências em Sintra e Lisbon para uma plantação com 2 anos. a) *Quercus rubra*, b) *Quercus robur*, c) *Betula pendula*, d) todas as espécies. BEPE- *Betula pendula*; QURO- *Quercus robur*; QURU- *Quercus rubra*. As designações e informações sobre as proveniências de cada espécie estão descritas no material suplementar S2 e em ORAZIO (2013).

Nota: As linhas horizontais representam o crescimento médio e as barras cinza representam o erro padrão. Os valores de significância podem ser consultados na tabela S4 dos materiais suplementares.

Figure 4 Provenance/Species mean diameter growth at Sintra and Lisbon for 2-year plantation. a) *Quercus rubra*, b) *Quercus robur*, c) *Betula pendula*, d) All species. BEPE- *Betula pendula*; QURO- *Quercus robur*; QURU- *Quercus rubra*. Provenance designation and information are described on supplementary material S2 and ORAZIO (2013).

Note: Horizontal line represents mean and grey bars represent standard error. Significance values can be consulted in the S4 table, on the supplementary material.

3.3. Phenology

The three studied species significantly differed on the budburst date ($F_{2,81}$ = 18.22, P < 0.001). Kruskal-Wallis test also showed significant differences between species on the phenology stage observed in Lisbon arboreta during the period of three months since the first of March till the end of May (Z = 72.64, d.f. = 2, P < 0.001). All *BEPE'*s provenances have an early bursting comparing with the other species, while the two provenances of *QURU* showed the latest bursting (Fig 5). Further significant difference were found among the four provenances of *QURO* ($F_{3,54}$ = 3.56, P= 0.024), while the provenances of the other species showed no significant differences: *QURU* ($F_{1,5}$ = 0.042, P = 0.839), *BEPE* ($F_{2,26}$ = 1.81, P = 0.183).

Comparing bud bursting for each of the provenance between Lisbon and Sintra, six provenances, *BEPE* Nord, *BEPE* Unit, *QURO* Pago, *QURO* Posa, *QURO* Unit and *QURU* Vanna, were earlier to burst at Sintra. Two provenances *QURO* Fran and *QURU* Fest, showed similar bud burst timing in both locations. Only *BEPE* Kral was earlier to sprout in Lisbon than Sintra (Fig. 5). Nevertheless, when applying Mann-Whiteny test to compare the phenology stage in both sites at (3 and 4 March, 2014) no significant difference was found (Z = -1.044, d.f. = 1, P = 0.296).

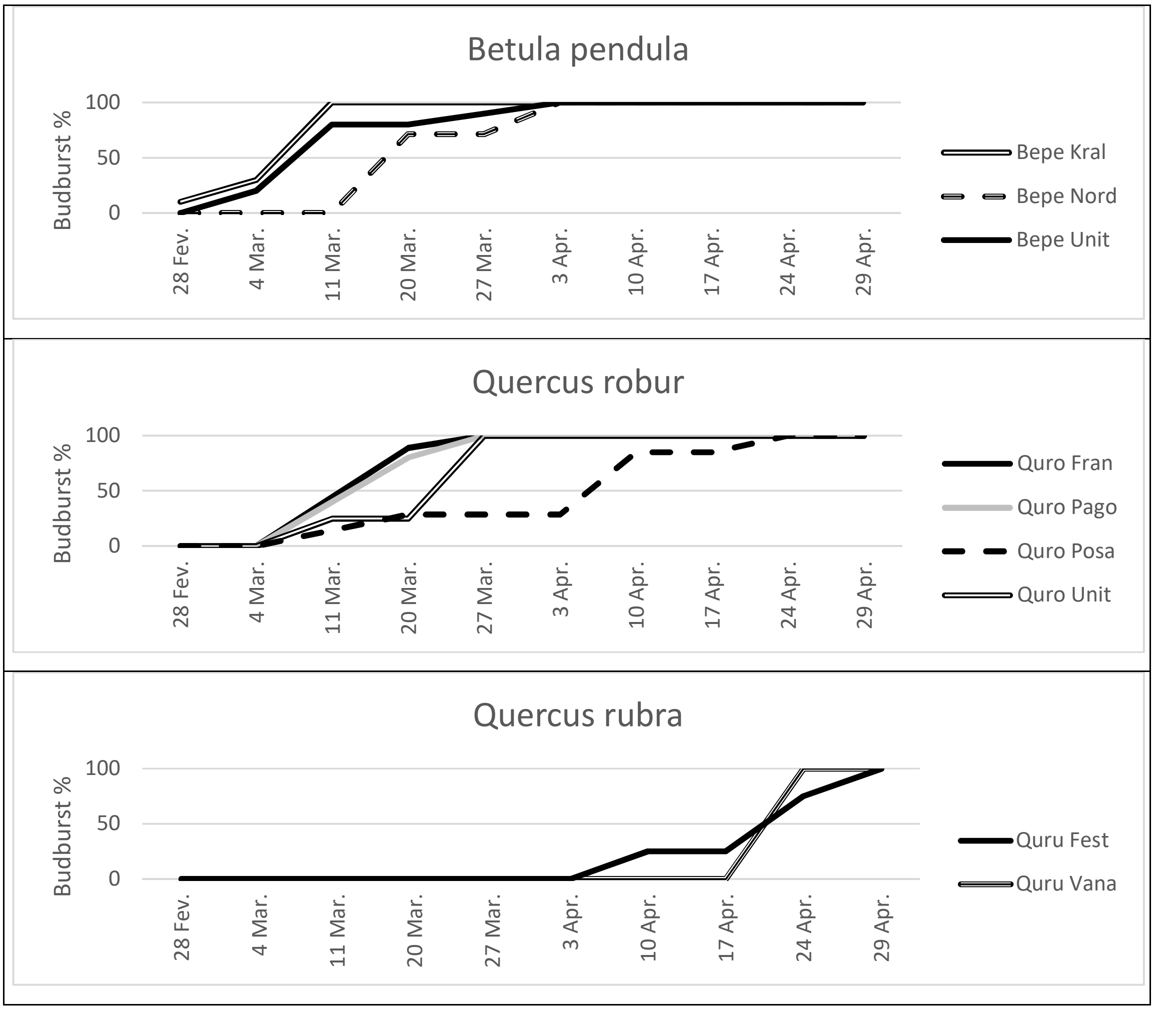


Figure 5 Evolução da rebentação dos gomos (percentagem do total de plantas observadas) por espécie e proveniência, durante o período de avaliação, no *arboretum* de Lisboa. BEPE- *Betula pendula*; QURO- *Quercus robur*; QURU- *Quercus rubra*. As designações e informações sobre as proveniências de cada espécie estão descritas no material suplementar S2 e em ORAZIO (2013).

Figure 5 Evolution of budburst (percentage of total observed plants) per species and provenance along observation period, at Lisbon arboretum. BEPE- *Betula pendula*; QURO- *Quercus robur*; QURU- *Quercus rubra*. Provenance designation and information are described on supplementary material S2 and ORAZIO (2013).

3.4. Insect damage

The main damage type observed consisted on chewed leaves (86 to 99% among all types of damage). Leaf miners, sap feeders, galls and skeletizers showed very low level of occurrence. The probability of suffering leaf damage was overall highest for *QURO* leaves at Sintra (0.49) (Table 2). At Lisbon, *QURU* had similar values of leaf damage as *QURO*, whereas in Sintra values were slightly but significantly lower in comparison with the congeneric native tree species (Tables 4). *BEPE* on the other hand showed the lowest probability of damage in both sites (0.09 and 0.18 at Lisbon and Sintra, respectively) (Table 2).

The comparison between the native species (QURO) with the average of the non-native species also revealed a significant difference on insect damage for both Lisbon ($F_{1,82}$ = 0.018, P < 0.001), and Sintra ($F_{1,185}$ = 0.013, P < 0.001).

The provenances of *BEPE* in Lisbon did not differ on the insect damage (Z = 2.25 , d.f. = 1, P= 0.13), nor did the provenances of *QURO* (Z = 3.61 , d.f. = 1, P = 0.057), or *QURU* (Z = 0 , d.f.= 1, P = 1.0). Yet, for Sintra, provenances of *QURO* differed significantly (Z = 4.32, d.f. = 1, P = 0.037). Still, there were no significant differences observed among the provenances of *BEPE* and *QURU* (Z = 2.58, d.f. = 1, P = 0.1) (Z = 3, d.f. = 1, P = 0.83).

Table 2 Percentagem de folhas apresentando danos (média ± erro padrão) para os arboreta de Lisboa e Sintra, para cada espécie.

Table 2 Percentage of damaged leaves (average ± standard error) at Lisbon and Sintra for each tree species.

Species	Lisbon	Sintra
Betula pendula	9 ± 1.2 ^{a}	18 ± 0.7 ^{a}
Quercus robur	40 ± 1.3^{b}	49 ± 1.4^{c}
Quercus rubra	40 ± 4.8^{b}	31 ± 2.7 ^{b}

Nota: Os valores seguidos pela mesma letra não são significativamente diferentes dentro de cada arboreto. (α = 0.01)

Note: Values followed by the same letter per site do not differ significantly ($\alpha = 0.01$).

3.5. Spring frost tolerance

QURO and *BEPE* showed similar RI when subjected to negative temperatures ranging from -3 to -10.5 ºC (41.39 ± 1.73 vs. 39.05 ± 1.87, respectively). Calculated TL50 (supplementary material S6) was also similar between *QURO* (-7,18 ± 0,025 ºC) and *BEPE* (-7,05 ± 0,067 ºC).

No statistical effect found for provenance on frost damage, both for *QURO* ($F_{2,6} = 0.241$, P= 0.787) and *BEPE* ($F_{2,6} = 1.19$, P = 0.317). Fitting a generalized linear model for frost damage (with provenance nested in species effect), for TL50 -6.6 ºC temperature, no significant effect was found between species (Z = 0.42, d.f. = 1, P = 0.51).

4. Discussion

Although the REINFFORCE network’s full range is composed by 38 sites, this preliminary work aims to analyze a small window of locations. The two study sites are considered of particular interest, as they are the most southern located within the REINFFORCE arboreta range, characterized mainly by higher temperatures and dryer climate which may dramatically affect tree survival, growth and risk to abiotic and biotic factors.

Meteorological conditions differed between sites, maximum summer temperatures were lower and air humidity higher at Sintra in comparison with Lisbon. As soil type also differs, soil water extraction by plants at Lisbon arboretum (Loam-Sandy clay) would be more difficult, since soil matric potential is expected to be considerably lower. This could have had a major impact on plant survival and growth.

4.1. Survival and growth

The *site*, *provenance*: *site* and *species*: *site* significant effect, show how some species/provenance respond differently at each site, highlighting the relevance of the edaphoclimatic conditions, especially for survival. Sintra *arboretum* seems to be more favorable to the overall performance of all species. At Sintra, *BEPE* outperforms the other species in every aspect, with NORD and UNIT provenances standing out at height growth. Even at Lisbon, this species has a higher height increment than the others, although survival is compromised. Interestingly, *QURO* presented the higher survival rate at Lisbon, without having any superior effect on growth for that arboreta. *QURU* had the lowest survival at Lisbon, but does not differ in growth from the previous. *QURO* is known to have higher drought tolerance than *BEPE* (VAN HEES, 1997), sustaining it even under higher temperature (KUSTER, 2012), which helps explain its advantage at the lowest survival site (Lisbon) (Fig. 2, 3 and 4), as plants develop higher root growth under water stress, than under water availability (OSONUBI, 1981). For *BEPE*, drought impact is amplified by an increase in summer air temperature (KHARUK, 2013), so this corroborates for the higher mortality and lower growth rate observed at Lisbon *arboretum*. *BEPE*'s earliness of budburst contributes to its high annual growth rate (ZAPATER, 2012) as observed in our results, typical for pioneer species like this one (HYNYNEN, 2008). Drought can trigger an early investment in deep root growth resulting in slower above ground growth, so this explains the reduced diameter growth observed at Lisbon arboretum, according to Kuster (2012). There is also an observed difference for diameter growth in *QURO* between sites, although height growth was similar. In Kuster (2012), species presented a lower diameter to height growth ratio under high temperatures, varying greatly with provenance. So the assumption that the significant lower diameter growth observed for FRAN and POSA (Table 6) can be a direct influence of higher temperature and precipitation summer deficit from provenance conditions (Fig.1).

For *QURU*, growth increase also corresponds to lower differences for temperature and precipitation for the early growing season (May through July) as also found by LeBlanc (2011), and that under increasing water stress more growth is allocated to roots than shoots (JACOBS, 2009). So, FEST provenance shows higher growth at Sintra, and VANA the highest at Sintra.

4.2. Phenology

The strong relationship that has been found by Fu (2012) and Pletsers (2015) between winter temperature and dormancy release implies that even small changes in winter temperature can have large impacts on the timing of bud burst. As a reaction to global warming, the chilling requirement might not be fully met, and thus bud burst could then be delayed (KONNERT, 2015). Alternatively, in an environment where the chilling requirement is presently far exceeded, bud burst could occur earlier than at present, especially for early flushing species, under the influence of warmer winter and spring temperatures (HEIDI 1993; FU, 2012). When comparing the results of our bur burst observations on March 2014, at Lisbon and Sintra there were no significant differences between the two sites which might be justified by similar winter temperatures (but not summer temperature) (Fig.1), latitude and thus photoperiod is also similar as the two sites are near to each other. Yet, on each site there are clear differences among species, with earlier budburst for *BEPE* and among *Q. robur* provenances, which can be strongly related to provenance altitude, according to Alberto (2011). *Quercus rubra* is considered to be a late species for bud burst and flowering time in its native range (VIEITEZ, 2012), and our study confirms that the species keep this late bud burst pattern both in Lisbon and Sintra.

4.3. Insect damage

Insect damage tended to be higher for the native *QURO,* with overall significantly higher values of leaf damage than the non-native species. This could be justified by the fact that outside its native range plants will be benefit of a release from their native natural enemies (KEANE, 2002). Nevertheless, *QURU* also had higher levels of damage by herbivores even though it is a non-native species in the area. This result is justified due to the fact that this oak species' share close phylogenetic relationship with *QURO*, and thus is expected to have similar physical and chemical characteristics (ALI, 2012). Indeed, it is expected that the herbivores which feed on *QURO*, may also expand its host range to feed on the non-native oaks species *QURU* (BRANCO, 2015).

In contrast, *BEPE* was the one with lower insect damage in both sites. Unlike *Quercus* sp, *BEPE* does not have any phylogenetic close tree species (*i.e.* congeneric) native in the area of study, which therefore would reduce the hypothesis of host shifts (BRANCO, 2015). In alternative, from our results, *BEPE* was the first species to budburst, in March, and it is possible to hypothesize that bud burst may have occurred in a period when the activity of chewing insects was still low. If the leaves of *BEPE* were already matured when the feeding activity of insects was higher, then the leaf toughness and the amount of defensive compounds of these mature leaves could make them less edible for the insects (VAN ASCH, 2007). In fact, it is considered that early budburst might be a way of plants to escape herbivores (BOTH, 2009).

4.4. Spring frost tolerance

A number of relevant cold studies showed that *BEPE* and *QURO* have high cold tolerance during winter, and that the minimum lowest temperature for *QURO* can be as low as -40 and -35 for *BEPE (*MALIOUCHENKO, 2007; OLALDE, 2002*)*. However, the purpose behind doing this test at the end of May was to simulate the occurrence of late spring frost, and to test the hypothesis that the seedling will be very sensitive to frost, taking into consideration that the leaves were still new, thin and not harden yet.

The performed test showed that both species were highly tolerant to cold, and the chosen provenances within the species were not a significant factor in these results. Still, *BEPE* was a little more sensitive to frost than *QURO* which also confirm other relevant studies concerning the species tolerance to frost during the coldest month of the year *(*MALIOUCHENKO, 2007; OLALDE, 2002).

5. Conclusion

Although this study relies on very early stage results at two REINFFORCE arboreta, limiting the number of plants available for sampling, it is still considered as a starting point for further studies covering the Arboreta Network, allowing simultaneously 38 environments and an extended sampling for species and provenances.

Studies performed in natural conditions can be harder to control, with some probability to be affected by unexpected factors impacting the vegetable material beside the ones that are in direct study. Exactly for that, they are of extreme importance, allowing to test multiple impacts of those diverse factors on the material, even for the unexpected ones.

In the present study, plant growth and survival responded to temperature and precipitation differences. Main findings point out that climate constrains like high temperature and low water availability will impact tree species in the early stage of tree plantation in multiple ways. It may have a direct impact on growth, shortening the growth period, and lowering initial biomass productivity, highly important for an efficient plant establishment. Nevertheless, this effect can be mitigated with the use of early budburst species, initiating growth in a more favorable period.

Non-native tree species might provide escape to herbivore insects but only if phylogenetically distant from native ones. Provenances generally behaved differently at each *arboreta*, stressing the need for selection of material adjusted for each present/future condition.

In general, it is yet too early to extract finer results, considering that the arboreta network needs a long period of time to provide a conclusive result. Further studies will continue this research and deeper this subject by studying more species of the arboreta, under the full range of the network

Acknowledgements

Parques de Sintra - Monte da Lua for field logistics facilitation. Instituto Português do Mar e da Atmosfera for arboreta climate data. Pedro Nunes for contribution on pest monitoring. Eng. Carla Faria for Lisbon site maintenance coordination.

Fundings

European Regional Development Fund INTERREG ATLANTIC CTEA-02-0000-FEDER-000005 for network installation and maintenance, FCT PD/BD/52405/2013 PhD scholarship for corresponding author.

6. References

ALBERTO, F et al. Adaptive responses for seed and leaf phenology in natural populations of sessile oak along an altitudinal gradient.[s.I.]: *J Evol Biol* 24 (2011) 1442–1454

ALI JG.; Agrawal AA. Specialist versus generalist insect herbivores and plant defense. [s.I.]: Trends Plant Sci 17(2012): 293–302

AYRES, M. P. ; LOMBARDERO, M J ; Assessing the consequences of global change for forest disturbance from herbivores and pathogens. [s.I.]: Science of the Total Environment, 262(3) (2000), 263-286

BRANCO, M. et al. Host range expansion of native insects to exotic trees increases with area of introduction and the presence of congeneric native trees. [s.I.]: *Journal of Applied Ecology*, *52*(1) (2015), 69-77

CHEN, H.; BURKE, J.; and GUSTA, V. Freezing tolerance in plants: an overview. [s.I.]: Biological Ice Nucleation and its Applications (1995) 115–135

COSTA E SILVA, F. et al. Acclimation to short- term low temperatures in two Eucalyptus globules clones with contrasting drought resistance. [s.I.]: Tree physiology (2008) 10193:1-10

CURRANO, D.et al. Sharply increased insect herbivory during the Paleocene-Eocene thermal maximum. [s.I.]: Proceedings of the National Academy of Sciences of the United States of America (2008) 105(6): 1960–1964

ELLISON, D. et al. Trees, forests and water: Cool insights for a hot world, *In* _. Global Environmental Change. [s.I.]: Volume 43, 2017, Pages 51-61, ISSN 0959-3780, https://doiorg/101016/jgloenvcha201701002

FISICHELLI, N.; VOR, T.; AMMER, C. Broadleaf seedlings responses to warmer temperatures “chilhed” by late frost that favors conifers. [s.I.]: European Journal of Frost Research (2014) 10: 1007-1034

FRAZIER, R; HUEY, B.; BERRIGAN, D. Thermodynamics constrains the evolution of insect population growth rates: “warmer is better”. [s.I.]: American Naturalist (2006) 168: 512–520

FU, YH.; CAMPIOLI, M.; DECKMYN, G.; JANSSENS, I.A. The Impact of Winter and Spring Temperatures on Temperate Tree Budburst Dates: Results from an Experimental Climate Manipulation. [s.I.]: PLoS ONE (2012) 7(10): e47324 doi:101371/journalpone0047324

GU, L.; HANSON P.J.; POST, W.M. The 2007 Eastern US spring freeze: increased cold damage in a warming world. [s.I.]: BioScience, (2008) 58, 253–262

HYNYNEN, J. Et al. Silviculture of birch (Betula pendula Roth and Betula pubescens Ehrh) in northern Europe. [s.I.]: *Forestry* (2010) 83 (1): 103-119 doi: 101093/forestry/cpp035

INOUYE, D. Effects of climate change on phenology, frost damage, and floral abundance of montane wildflowers. [s.I.]: Ecology (2008) 89: 353–362

IPCC. Climate Change- Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change The Physical Science Basis IPCC Secretariat, Geneva, Switzerland. (2007) www.ipcc.ch

IPCC a. Climate Change 2007: Impacts, Adaptation and Vulnerability Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, PARRY, M.L.et al.(eds) Cambridge University Press, Cambridge, UK (2007) 976 p

IPCC. Climate Change 2013: The Physical Science Basis Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. STOCKER T.F. (eds) Cambridge University Press, Cambridge, UK and New York, NY, USA (2013)

JACOBS, D.F.; SALIFU, K.F.; DAVIS, A.S. Drought susceptibility and recovery of transplanted Quercus rubra seedlings in relation to root system morphology. [s.I.]: *Ann For Sci* 66 (2009) 504

KEANE R.M.; CRAWLEY M.J. Exotic plant invasions and the enemy release hypothesis. [s.I.]: *Trends in Ecology & Evolution* (2002) 17: 164 170 doi:101016/S0169-5347(02)02499-0

KHARUK, V.I. et al. Climate induced birch mortality in Trans-Baikal lake region, Siberia. [s.I.]: *Forest Ecology and Management*, Volume 289, 1 February 2013, Pages 385-392

KONNERT, M. et al. Use and transfer of forest reproductive material in Europe in the context of climate change. European Forest Genetic Resources Programme (EUFORGEN), Biodiversity International (2015), Rome, Italy xvi and 75 p

KUSTER, T.M. et al. Water regime and growth of young oak stands subjected to air-warming and drought on two different forest soils in a model ecosystem experiment. Plant Biol (Stuttg) 2013 Jan;15Suppl 1:138-47

LEBLANC, D.C.; TERRELL, M.A. Comparison of growth–climate relationships between northern red oak and white oak across eastern. North America *Canadian Journal of Forest Research*, 2011, Vol 41, No 10: pp 1936-1947

LOVEYS, B.R.; EGERTON, J.J.G.; BALL, M.C. Higher daytime leaf temperatures contribute to lower freeze tolerance under elevated CO2. [s.I.]: Plant, Cell and Environment (2006) 29: 1077–1086

MALIOUCHENKO, O. et al. Comparative phylogeography and population structure of European *Betula* species, with particular focus on *B pendula* and *B pubescens.* [s.I.]: Journal of Biogeography (2007) 34: 1601-1610

MARINO, G.P. et al. Reconstruction of false spring occurrences over the southeastern United States, 1901–2007: an increasing risk of spring freeze damage. [s.I.]: Environmental Research Letters (2011) 6:1 024015–024023

MARTIN, M. et al. Reduced early growing season freezing resistance in alpine treeline plants under elevated atmospheric CO2. [s.I.]: Global Change Biology (2010) 16: 1057–1070

MEEHL, G.A. et al. An introduction to trends in extreme weather and climate events: observations, socioeconomic impacts, terrestrial ecological impacts, and model projections. [s.I.]: Bulletin-American Meteorological Society (2000) 81: 413–416

ORAZIO, C, et al. Arboretum and Demonstration Site Catalogue: Resource Infrastructures for monitoring, adapting and protecting European Atlantic Forests under changing climate (REINFFORCE cataloge). [s.I.]: IEFC (2013).

ORAZIO, C.; LARA, F.; DI LUCCHIO, L. Species and genetic units' selection process for REINFFORCE arboreta. [s.I.]: European Forest Institute (2009) 1-21

OSONUBI, O.; DAVIES, W.J. "Root Growth and Water Relations of Oak and Birch Seedlings". [s.I.]: *Oecologia* 513 (1981): 343-50

PLETSERS, A. et al. Chilling temperature and photoperiod influence the timing of bud burst in juvenile *Betula pubescens* Ehrh and *Populus tremula* L trees. [s.I.]: Annals of Forest Science (2015) 72: 941

POST, E.; FORCHHAMMER, M.C. Climate change reduces reproductive success of an arctic herbivore through trophic mismatch. [s.I.]: Phil Trans Roy Soc B 363(1501) (2007) DOI: 101098

ROCHA. S. et al. Gall induction may benefit host plant: A case of a gall wasp and Eucalyptus tree. [s.I.]: Tree physiology (2012) 0-10

ROSENZWEIG, C. et al. Assessment of observed changes and responses in natural and managed systems In: Parry, M.L. et al. (eds) Climate Change: Impacts, Adaptation and vulnerability Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, UK (2007) p 79–131

SAMPAIO, T. et al. Does the geography of cork oak origin influence budburst and leaf pest damage? [s.I.]: Forest Ecology and Management (2016), 373, 33-43

SANTOS, F.; FORBES, K.; MOITA, R. Climate changes in Portugal scenarios, Impacts and adaption measures- SIAM project. Gradiva, Lisbon, Portugal. (2002) 456 pp

SANTOS, H. et al. Temperature niche shift observed in a Lepidoptera population under allochronic divergence. [s.I.]: Journal of evolutionary biology (2011) *24*(9):1897-1905

SOLOMON, S. et al. Climate Change 2007: The Physical Science Basis, Cambridge University Press, New York, NY, USA. (2007)

VAKKARI, P. Betula pendula - Technical guidelines for genetic conservation and use for silver birch EUFORGEN http://wwweuforgenorg/species/betula-pendula/ accessed in December 15, 2016

VAN HEES, A.F.M. Growth and morphology of pedunculate oak (Quercusrobur L) and beech (Fagus sylvatica L) seedlings in relation to shading and drought. [s.I.]: *Ann For Sci* 54 (1997) 9-18

VISSER, M.E.; HOLLEMAN, L.J.M. Warmer springs disrupt the synchrony of oak and winter moth phenology. [s.I.]: ProcRoyal society (2001) 268: 289–294

ZAPATER, M. et al. Differential response to soil drought among co-occurringbroad-leaved tree species growing in a 15- to 25-year-oldmixed stand. [s.I.]: *Annals of Forest Science*, Springer Verlag/EDP Sciences, 2012, 70 (1), pp31-39

II. Early Survival and Growth Plasticity of 33 Species Planted in 38 Arboreta across the European Atlantic Area

Correia, A.H.; Almeida, M.H.; Branco, M.; Tomé, M.; Cordero Montoya, R.; Di Lucchio, L.; Cantero, A.; Diez, J.J.; Prieto-Recio, C.; Bravo, F.; Gartzia, N.; Arias, A.; Jinks, R.; Paillassa, E.; PASTUSZKA, P.; Rozados Lorenzo, M.J.; Silva Pando, F.J.; Traver, M.C.; Zabalza, S.; Nóbrega, C.; Ferreira, M.; Orazio, C. Early Survival and Growth Plasticity of 33 Species Planted in 38 Arboreta across the European Atlantic Area. Forests 2018, 9, 630. DOI: https://doi.org/10.3390/f9100630 forests

MDPI

Article

Early Survival and Growth Plasticity of 33 Species Planted in 38 Arboreta across the European Atlantic Area

António Henrique Correia [1,*], Maria Helena Almeida [1], Manuela Branco [1], Margarida Tomé [1], Rebeca Cordero Montoya [2], Luisa Di Lucchio [2], Alejandro Cantero [3], Julio J. Diez [4], Cristina Prieto-Recio [4], Felipe Bravo [4], Nahia Gartzia [5], Ander Arias [5], Richard Jinks [6], Eric Paillassa [7], Patrick PASTUSZKA [8], María José Rozados Lorenzo [9], Francisco Javier Silva Pando [9], María Carmen Traver [10], Silvia Zabalza [10], Carina Nóbrega [11], Miguel Ferreira [12] and Christophe Orazio [2]

[1] Centro de Estudos Florestais, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal; nica@isa.ulisboa.pt (M.H.A.); mrbranco@isa.ulisboa.pt (M.B.); magatome@isa.ulisboa.pt (M.T.)
[2] European Forest Institute EFIATLANTIC, IEFC, Site de Recherches Forêt-Bois de Bordeaux-Pierroton 69, Route d'Arcachon, 33612 Cestas, France; rebecordero@gmail.com (R.C.M.); di.luisa@gmail.com (L.D.L.); christophe.orazio@efi.int (C.O.)
[3] HAZI Konsultoria, 48160 Euskadi, Spain; acantero@hazi.eus
[4] Sustainable Forest Management Research Institute, Universidad de Valladolid and INIA, 34491 Palencia, Spain; jdcasero@pvs.uva.es (J.J.D.); cristina.prieto@pvs.uva.es (C.P.-R.); fbravo@pvs.uva.es (F.B.)
[5] Neiker Tecnalia, 48160 Euskadi, Spain; ngartzia@neiker.eus (N.G.); agonzalez@neiker.eus (A.A.)
[6] Forest Research (FR), Alice Holt Lodge, Farnham GU10 4LH, UK; richard.jinks@forestry.gsi.gov.uk
[7] Institut Pour le Développement Forestier (IDF), 75008 Paris, France; eric.paillassa@cnpf.fr
[8] Institut National de la Recherche Agronomique (INRA), 75008 Paris, France; patrick.pastuszka@inra.fr
[9] Centro de Investigación Forestal (CIF), 15893 Galicia, Spain; maria.jose.rozados.lorenzo@xunta.es (M.J.R.L.); francisco.javier.silva.pando@xunta.es (F.J.S.P.)
[10] Gestión Ambiental de Navarra (GAN), 31004 Navarra, Spain; mctraver@ganasa.es (M.C.T.); szabalza@ganasa.es (S.Z.)
[11] Direçao Regional dos Recursos Florestais (DRRF), 9500-035 Ponta Delgada, Portugal; carina.a.nobrega@azores.gov.pt
[12] Furnas Monitoring and Research Centre, Azorina S.A., 9675-090 Furnas, Portugal; miguel.gc.ferreira@azores.gov.pt
* Correspondence: ahcorreia@isa.ulisboa.pt; Tel.: +351-962973091

Received: 11 August 2018; Accepted: 9 October 2018; Published: 11 October 2018

Abstract: To anticipate European climate scenarios for the end of the century, we explored the climate gradient within the REINFFORCE (RÉseau INFrastructure de recherche pour le suivi et l'adaptation des FORêts au Changement climatiquE) arboreta network, established in 38 sites between latitudes 37° and 57°, where 33 tree species are represented. We aim to determine which climatic variables best explain their survival and growth, and identify those species that are more tolerant of climate variation and those of which the growth and survival future climate might constrain. We used empirical models to determine the best climatic predictor variables that explain tree survival and growth. Precipitation-transfer distance was most important for the survival of broadleaved species, whereas growing-season-degree days best explained conifer-tree survival. Growth (annual height increment) was mainly explained by a derived annual dryness index (ADI) for both conifers and broadleaved trees. Species that showed the greatest variation in survival and growth in response to climatic variation included *Betula pendula* Roth, *Pinus elliottii* Engelm., and *Thuja plicata* Donn ex D.Don, and those that were least affected included *Quercus shumardii* Buckland and *Pinus nigra* J.F.Arnold. We also demonstrated that provenance differences were significant for *Pinus pinea* L.,

Forests **2018**, *9*, 630; doi:10.3390/f9100630 www.mdpi.com/journal/forests

Quercus robur L., and *Ceratonia siliqua* L. Here, we demonstrate the usefulness of infrastructures along a climatic gradient like REINFFORCE to determine major tendencies of tree species responding to climate changes.

Keywords: climate response; climate adaptation; REINFFORCE; *Pinus*; *Quercus*; *Cedrus*; *Eucalyptus*; *Betula*; *Pseudotsuga*; *Sequoia*

1. Introduction

Predicted scenarios for the European climate at the end of the century point to a slight reduction in annual precipitation and an extension of rain seasons. Projected rise of global mean surface temperature by the end of the 21st century (2081–2100) relative to 1986–2005 is likely to be 0.3–1.7 °C for the lowest emission scenario (Representative Concentration Pathway—RCP 2.6) and 2.6–4.8 °C for the highest emission scenario (RCP8.5) [1]. The frequency of occurrence of extreme events is expected to increase, particularly the number of days with spring frost and periods of water stress for plants, leading to a decrease in productivity, and an increase in pest and disease activity [2–4]. Extreme events, such as drought and heat waves, have already been identified as a major cause of forest dieback [5–7]. In the future climate, trees will experience new biotic and abiotic environments and stresses, such as drought, temperature extremes, flooding, wildfire, and novel insect and disease pressures. The occurrence of extreme temperatures may be a relevant climatic indicator for plant stress. Physiologically, however, the effects of extreme heat or cold are confounded with other factors. For example, heat stress acts in conjunction with higher air humidity, wind speed, and radiation [8]. Higher temperatures are often associated with drought stress, which is dependent on water availability that varies seasonally in both temperate and Mediterranean climates. Regarding cold damage, temperate plants are particularly vulnerable to frost damage in spring, when leaves and flowers are developing after bud burst [9].

In the long term, evolutionary mechanisms can enable species to adapt to such changes, but it is likely that species and population responses will be too slow compared with the expected speed of climate change. Genetic diversity is, in this context, a tool that should be used and made available for forestry management. Providing forest-regeneration material with species–site–climate matching from appropriate provenance regions [10] is an opportunity to increase stand resilience and withstand the challenges that emerge with climate change. Production periods of forests are long, ranging from 20 to 80 years or longer, and a major concern is that planting stock originating from fixed contemporary seed zones will be growing in suboptimal conditions by the end of the century or sooner [2]. Patterns of genetic variation vary greatly among species; some species are climate specialists that exhibit strong differentiation over small geographic and climate scales, while others are generalists that show less differentiation across a wide range of environmental gradients [11,12]. Some species can also exhibit multiple adaptive strategies over different portions of their range [2]. Therefore, it is important to identify how different genetic material might respond to future climatic scenarios. As pointed out in Reference [13], we need to define which trade-offs between growth performance and sustainability are the most appropriate to cope with extreme events. In that sense, understanding and modeling tree-species response to climate change is a valuable tool to predict the consequences of climate change on forests and develop forest adaptation strategies. Several limitations apply when using climate models to understand the likely effects on forest ecosystems. Forests do not always linearly respond to changes in climate parameters such as annual temperature and precipitation. Many responses are to extremes rather than to means and, therefore, greater uncertainties in the projections of climate extremes cause considerable uncertainties when assessing the likely response of forest ecosystems towards the end of the current century. So, climate-model results diverge much more at the regional compared to the continental and global levels [10].

Although several species-distribution models have been studied, some aspects of plant responses have to be simplified because of incomplete information or understanding of mechanisms [4,5]. In particular, phenotypic plasticity fails to be considered by most models, mainly due to a lack of specific information. Typically, climate-envelope models of species distribution are based on species presence and absence records and do not identify population-level genetic variation in responses to environmental factors. However, with the migration of populations and species to outside their present distribution ranges, the environment and genetic interaction need to be considered [14]. On the other hand, models based on climate indicators, such as temperature and degree days, could fail to express physiological impacts on plants that have secondary growth, lignification, or thicker cell walls [15,16].

In order to study climate responses of trees within the Atlantic Region [17] of Europe, an infrastructure network of test sites was installed in four countries, involving 18 partner organizations in a project on forest adaptation to climate change. Established in 2012, this network, named the REINFFORCE Network (RÉseau INFrastructure de recherche pour le suivi et l'adaptation des FORêts au Changement climatiquE), extends from Scotland (North) to Lisbon (South), and from Bordeaux (East) to the Azores (West), taking advantage of very different climatic conditions. The north–south and east–west extent of this network allows responses such as survival and growth to be measured along gradients of climatic factors covering expected changes and the range of predicted future climate scenarios [18]. Each test site is planted with the same 33 species with three mandatory provenances each, with additional provenances selected by each partner [18].

The aim of the present work is to determine which climatic variables can best explain variation in survival and growth, and use the information to determine which species are likely to be more tolerant to climate variation, and those for which the future climate will bring higher constraints on growth and survival. This modeling work helps to understand how different species and provenances within species may respond differently to climate change.

2. Materials and Methods

2.1. REINFFORCE Arboreta Network

This network consists of 38 planting sites, called arboreta, each one of which contains a collection of exactly the same base material of 33 species ideally represented by three mandatory provenances selected from contrasting climate conditions within its current distribution range, in order to capture maximum species variability [18]. However, *Eucalyptus* spp. and *Quercus shumardii* Buckland are represented by only one provenance. Additional provenances were selected by each partner and installed locally; these are not included in the present analysis. The network was planted in the spring of 2012. The network's climatic gradient provides a variation of 9 °C for mean temperature and 900 mm for precipitation, and can be viewed in Supplementary Materials S1.

Growth and survival monitoring followed the REINFFORCE field protocol (reinfforce.iefc.net).

Species were selected through a joint literature review, specialist opinion, and decision-support methodology based on the PROMETHEE algorithm [19] (http://www.iefc.net/newsite/sitereinfforce/ 2012-processus-de-selection-des-especes-pour-les-arboretums-de-reinfforce), and availability on commercial suppliers (Figure 1). Seed was either sourced from commercial suppliers or, when important chosen provenances were unavailable, specifically collected from local populations within the provenance region.

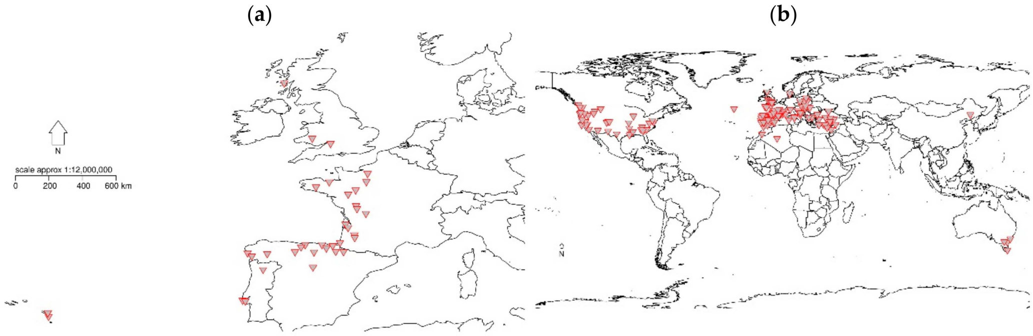


Figure 1. (**a**) Europe map showing the distribution of REINFFORCE (RÉseau INFrastructure de recherche pour le suivi et l'adaptation des FORêts au Changement climatiquE), arboreta network (red triangles). (**b**) World map showing distribution of material provenance regions used for the establishment of the REINFFORCE arboreta network (red triangles) [18].

Selected seed lots were sent to a centralized nursery in southeastern France for seedling production and preparation. Once plants reached their target sizes, they were then distributed to each arboretum.

A minimum of 36 trees of the same species (12 trees from each one of the 3 provenances) were established in all arboreta. Each provenance is represented by 12 trees planted together in a plot, but in heterogeneous sites the 12 trees were split in 2 plots of 6 trees. In each arboretum, 3 replications of 4 species (*Pinus pinaster* Aiton, *Betula pendula* Roth, *Cedrus atlantica* (Manetti ex. Endl.) Carrière, and *Quercus robur* L.) were planted randomly in order to assess site heterogeneity [18].

A list of species, provenance, and coding can be found in Supplementary Materials S2.

2.2. Plant Assessment Data

For all plants, data were recorded at planting and then annually at the end of the growing season as total shoot height (transformed to yearly growth) and survival over the period from 2012 to 2016.

Within the complete dataset, only one data point was excluded for growth, where the height of one plant was abnormally higher, probably due to recording error.

2.3. Climate Data

Daily weather data were recorded by local automatic weather stations, and recorded parameters were transformed to 2012–2016 period averages. There was minor occasional information missing on site weather due to difficulties with automatic weather stations, which represented no impact on analysis-period averages. An initial group of climatic variables considered relevant for modeling was selected from the available ones in both Worldclim [20], for the provenance site, and the local arboreta weather stations (Table 1). Growing season was standardized to the period from April to September, as in Reference [21]. Growing Season Degree Days (GSDD) was calculated as the sum of °C above 5 °C per day for each year and growing season. An Annual Dryness Index (ADI) was calculated as the square root of GSDD divided by annual precipitation (P) [21,22]. For a visualization of this index along the REINFFORCE arboreta network, see Supplementary Materials S10.

Table 1. Tested variables, units, and transformations.

Explanatory Variable	**Code**	**Unit**	**Transformation**
Mean daily air temperature	T_mean	°C	1/100
Mean Maximum daily temperature	T_max	°C	1/100
Mean Minimum daily temperature	T_min	°C	1/100
Extreme Minimum air temperature	Ext_T_min	°C	1/100
Extreme Maximum air temperature	Ext_T_max	°C	1/100
Annual Precipitation	*p*	mm	1/1000
Growing Season Precipitation	GSP	mm	1/1000
Summer Precipitation	SP	mm	1/1000
Growing Season Degree Days >5 °C	GSDD	°Cd	1/10,000
Degree Days >5 °C	DD5	°C	1/10,000
Annual Dryness Index	ADI	√°Cd/mm	
Growing Season Dryness Index	GSDI	√°Cd/mm	
Dependent Variable	**Code**	**Unit**	**Transformation**
Yearly Height Growth	Height	cm	Log
Survival	Survival	Alive/Dead binary	LOGIT

Provenance (seed origin) climate data for the 1970–2000 period were extracted from the Worldclim dataset [20], at 1 km^2 spatial resolution. Growing Degree Days were estimated using the Greer method [23].

In this study, we accounted for the effect of climatic distance [21,24,25] from provenance to arboreta-site conditions, as well for site-specific edaphoclimatic effect [26,27].

2.4. Statistical Analysis

Initial screening of the data using boxplots (Supplementary Materials S4–S9) identified that *Eucalyptus* 'Gundal' (EUGU-GUN), which is a hybrid *Eucalyptus gunnii* × *dalrympleana*, had a distinct growth-data variation (Supplementary Materials S8), and was modeled separately. From bibliographic analysis [28–31], it was decided that conifer and broadleaf species were to be analyzed as separate groups due to a possible differential response to environment variables.

Height growth and survival traits response to climate were modeled at the species level, with the genetic differences between the provenances included. Our approach was adapted from the methodology in References [21,25], using a mixed-effects model, separating fixed and random effects, and variation sources. The fixed effects account for 3 levels of variation in plant responses:

1. The effect of meteorological conditions at the arboreta sites (Term A), expressing the plastic response of the genetic unit along the arboreta gradient.
2. The effect of climatic transfer distance, (Term D) expressed by the differential between climate at the arboreta site and climate at the provenance site, revealing the plasticity-linked plant adaptation to site conditions.
3. The interaction term A × D.

The full model is as follows:

$Y_{ijkl} = \mu + \beta_0 + \beta_1 A_i + \beta_2 A_i^2 + \beta_3 D_{ij} + \beta_4 D_{ij}^2 + \beta_5 (A_i \times D_{ij}) + \beta_6 S_k + \beta_7 E_i + \beta_8 P_j (S_k) + e_{ijkl}$ (1) where:

Y_{ijkl}—Individual tree height for the *l*th tree for the *j*th Provenance from the *k*th Species, on the *i*th arboretum, or log-odds for survival;

A_i and A_i^2—the value of a Climate variable observed at the *i*th Arboretum;

D_{ij} and D_{ij}^2—the value of Climate distance for a climate variable between the *i*th arboretum and *j*th provenance site;

$A_i \times D_{ij}$—the interaction between A and D terms;

S_k—Species effect of the *k*th species;

E_i—Site effect at the *i*th arboretum due to factors other than climate;

$P_j(S_k)$—Provenance effect of the *j*th provenance nested within the *k*th corresponding species; e_{ijkl}—error term; with A, D, A × D being fixed effects, and S, E, P(S) being random effects.

For the A and D terms, we tested both linear and quadratic climate-variable terms to account for nonlinearity in the response between species and climate conditions, as suggested in many studies [21,25,32–35]. As stated in Reference [21], this interaction is the expression of plasticity, and the ability to adjust to new environments experienced at the planting sites. The amplitude of the trait values associated with survival and growth shown in the different environments of the arboreta network demonstrates the adaptation capacity of the genotypes under evaluation. Phenotypic plasticity may contribute to the fitness of a genotype, especially if it is a long-lived species with a wide distribution encompassing many different site conditions. If this is the case, natural selection increases the frequency of genotypes with high phenotypic plasticity [36].
We fitted linear mixed effects models for height growth, and logistic regression through generalized linear mixed effects for the binary survival variable using the *lmer* and *glmer* functions from the *lme4* package in R [37]. The dependent Yearly Height Growth variable was log-transformed to ensure meeting normality assumptions, and Survival was modeled using the logit link function and binomial error distribution.

2.5. Selecting Variables

Some independent variables were transformed because the scale ratio between dependent and some independent variables was large enough to impact model convergence (Table 1). Temperature (Mean Monthly Maximum, Mean Monthly Minimum, Mean Yearly, Extreme Yearly Maximum, Extreme Yearly Minimum), Precipitation (Annual, Growing Season), Growing Degree Days [38], and Growing Season Growing Degree Days (April–September) were the independent variables tested for model fitting.
Each independent variable was fitted as its linear and its quadratic form, and considered as independent variables. Model's predictor variables were tested for multicollinearity magnitude by considering the size of the Variance Inflation Factor (VIF), excluding each one when VIF > 3 [39].
Models were firstly fitted using Maximum Likelihood (ML) estimation to allow for comparison between models with different fixed factors. Fixed-factor inclusion on the model was evaluated by running χ^2 Likelihood Ratio test and comparing the Akaike Information Criterion (AIC) between extended and reduced models. After model selection, the model was refitted with Restricted Maximum Likelihood (REML) and presented in the Results section.

2.6. Random Effects

Site term (E) accounts for all site effects other than climate (mainly edaphic). The Species (S) and Provenance nested within Species (P(S)) terms account for variation generated by evolutionary drivers [40,41] that are not captured by fixed-effect terms as selection due to factors other than climate. Random intercepts and slopes on fixed effects were tested for species and provenance within Species. The significance of random-effect inclusion in the final model was evaluated by running an χ^2 likelihood ratio test and comparing the Akaike Information Criterion (AIC) between models with and without random effects, fitted through ML.

2.7. Model Selection

For linear model-fitting comparison, AIC was applied to models as an estimator of the relative quality of statistical models for a given dataset. The model or nested model with lower AIC represented the best fitting one.

Pseudo-R^2 with Marginal R^2 represented the variance explained by fixed factors, and Conditional R^2 interpreted as variance explained by the model (both fixed and random factors) [42,43]. For the logistic model, the Concordance index (C index) was used in order to verify a standard measure of the predictive accuracy of a logistic regression model [44]. For each dependent variable, the best fitting model was selected for each of the species groups (conifer and broadleaf).

3. Results

The best fitting model for Survival has site-linear GSDD for the conifer group (Table 2) and linear Annual Precipitation Climate Transfer Distance for the broadleaf species as significant explanatory variables (Table 3).

Table 2. Summary of selected mixed effect models for Survival, showing fixed-effect estimates, statistical significance, random effect on intercept and slope, and explained variance proportion for random parts, Akaike's Information Criterion (AIC), and Concordance index for mixed models. Summary for all species, grouped by conifer and broadleaf.

			Survival			
		Conifer			**Broadleaf**	
Fixed Part	**Estimate**	**% Variance**	***p* Value**	**Estimate**	**% Variance**	***p* Value**
Intercept	4.661		<0.001	1.918		<0.001
Precipitation Climate Distance/100				−0.022		0.001
Site Growing Season Degree Days >5 °C	−1.527		0.026			
Random Part						
Site *(Intercept)*		11.845			39.088	
Species *(Intercept)*		57.277			30.402	
Provenances within Species *(Intercept)*		4.352			30.510	
Species *(Slope)*		26.527				
AIC	12,497.9			10,932.6		
C Index	0.719			0.730		

Table 3. Summary of selected mixed-effect models for Yearly Height Growth, showing fixed-effect estimates, statistical significance, random effects on intercept and slope, and explained variance proportion for random part, AIC, and adjusted R^2 for mixed models. The table presents the summary for all species, conifer and broadleaf group d, except *Eucalyptus* 'Gundal', which can be found in Supplementary Materials S3.

			Yearly Height Growth (Log)			
		Conifer			**Broadleaf**	
Fixed Part	**Estimate**	**% Variance**	***p* Value**	**Estimate**	**% Variance**	***p* Value**
Intercept	3.339		<0.001	3.142		<0.001
Site ADI^2	−69.006		<0.001	−39.903		0.046
Random Part						
Site *(Intercept)*		0.007			0.012	

Species *(Intercept)*		0.019		0.031
Provenances within Species *(Intercept)*		0.015		0.002
Species *(Slope)*		99.933		99.933
Residual		0.026		0.023
AIC	17,370.589		21,208.356	
R^2 marginal	0.108		0.035	
R^2 conditional	0.651		0.641	

Both the A and the D terms appeared as significant explanatory variables, although for the selected model for Conifer group, the model included only the site-specific term (A). For growth, only site-specific (A) explanatory terms showed significance in the fitted models. The best fitting models for height growth included the quadratic Annual Dryness Index (ADI) term as an explanatory variable, for both species groups.

3.1. Random Effects

Species, Provenance (nested within Species), and Site random-factor inclusion significantly improved the model fit. The Species random effect captured most of the variance percentage, while the Site effect, representing other factors, such as edaphic features, had a lower expression except for Broadleaf survival. Species had significant intercept and slope random effects, with the random-slope component associated with ADI accounting for more than 99% of the growth-model random variance, revealing a species-specific response to the variable (Table 3). As for Survival, the random slope accounted for lower variation in the conifer group, and was not significant for the broadleaf (Table 2).

For broadleaf Survival, the model's highest random-variance partition was allocated to site.

Provenance effects within Species account for a high percentage of Survival variance, but are much lower for height growth trait. Nevertheless, they proved to be significant for the selected models.

3.2. Survival

Increasing GSDD tends to decrease species survival in the conifer group (Figure 2, Table 2). However, species differences are apparent. Survival of *Pinus brutia* Tenore (PIBU) and *Cedrus libani* A.Rich (CELI) tends to increase with temperature, while survival of *Pinus elliottii* Engelm. (PIEL), *Sequoia sempervirens* (D. Don) Endl. (SESE), and *Thuja plicata* Donn ex D.Don (THPL) decreased greatly at GSDD above 1500.

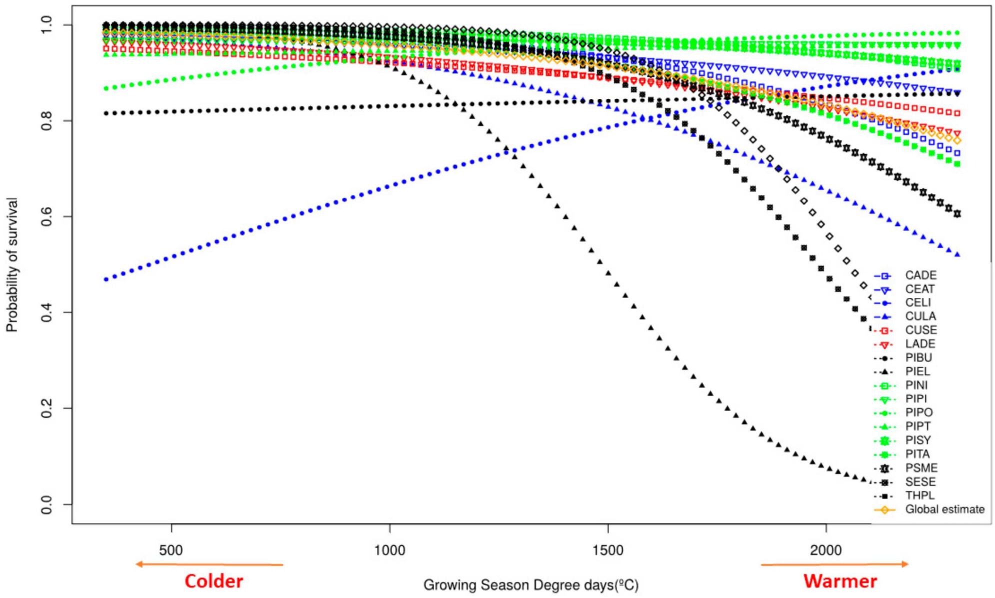


Figure 2. Estimated probability of survival plot for the explanatory variable “Growing Season Degree Days above 5 ˚C” in the conifer species group. The orange line shows the model’s estimated response. Additional lines show the predicted variation from the global estimate for each conifer species.

The model fitted for Survival of broadleaved species shows a trend where transferring material to a site with lower precipitation than a provenance site had a negative impact on survival. It also shows that species’ survival improves with transference to sites with higher precipitation than at a provenance location (Figure 3).

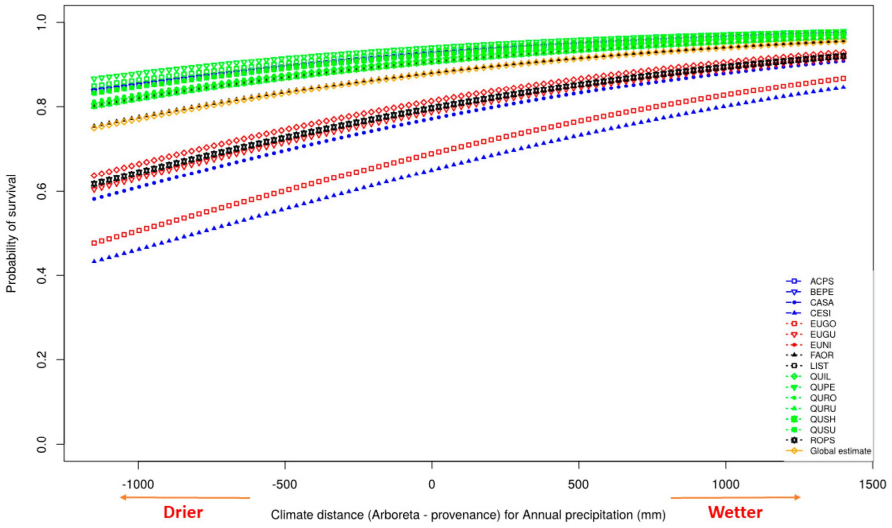


Figure 3. Estimated probability of survival for the explanatory variable “Climate distance for Annual Precipitation”, in the broadleaf species group. Climate difference was calculated from “Climate variable at the test site-climate variable at a provenance site”. The orange line shows the model’s estimated response. Additional lines show the predicted variation from the global estimate for each broadleaf species.

The highest variation between provenances within species occurred in *Ceratonia siliqua* L. (CESI), *Quercus robur* (QURO), THPL, *Pinus pinea* L. (PIPI), PIEL, and *Calocedrus decurrens* Torrey (CADE) (Figures 4 and 5).

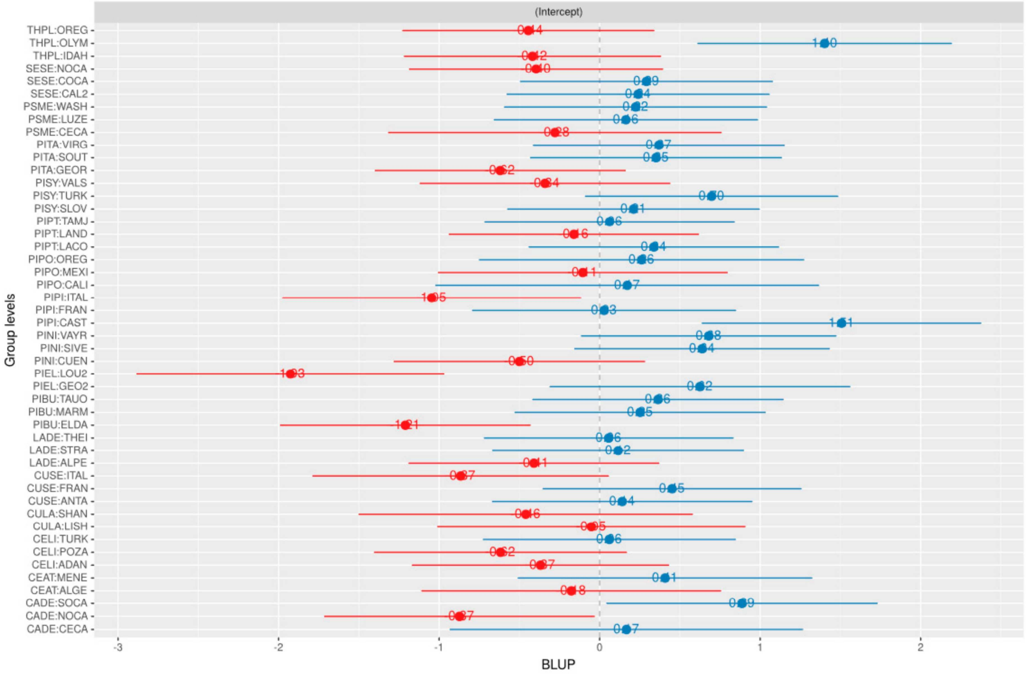


Figure 4. Best linear unbiased predictor for provenance nested within species random effects for survival within the conifer group. Dots represent variation from the global mean estimate, with 95% confidence intervals. Red dots and lines represent negative-effect differences; blue dots and lines represent positive-effect differences.

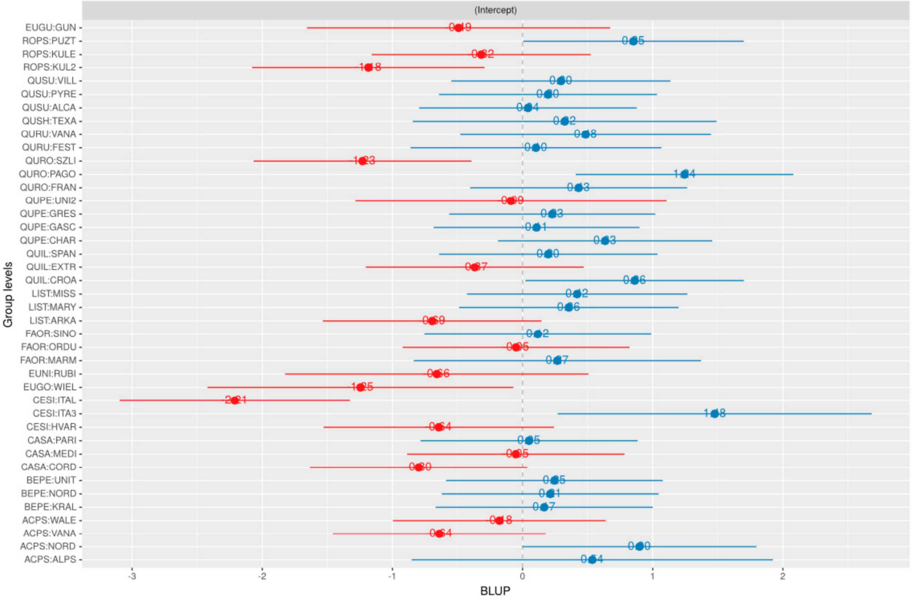


Figure 5. Best linear unbiased predictor for the provenance nested within species random effect for survival within the broadleaf group. Dots represent the variation from the global mean estimate, with 95% confidence intervals. Red dots and lines represent negative-effect difference; blue dots and lines represent positive-effect differences.

3.3. Growth

For height growth in both species groups, ADI was the climate variable that provided the best model fit. For nearly all species, height growth decreased as the index increased (Figures 6 and 7), that is, with decreasing precipitation and increasing accumulated temperature above 5 °C. This trend is particularly strong in the conifer group (Figure 6), in which CELI has the most constant growth along the ADI gradient, followed by PIPI, which exhibits higher growth values overall (Figure 6).

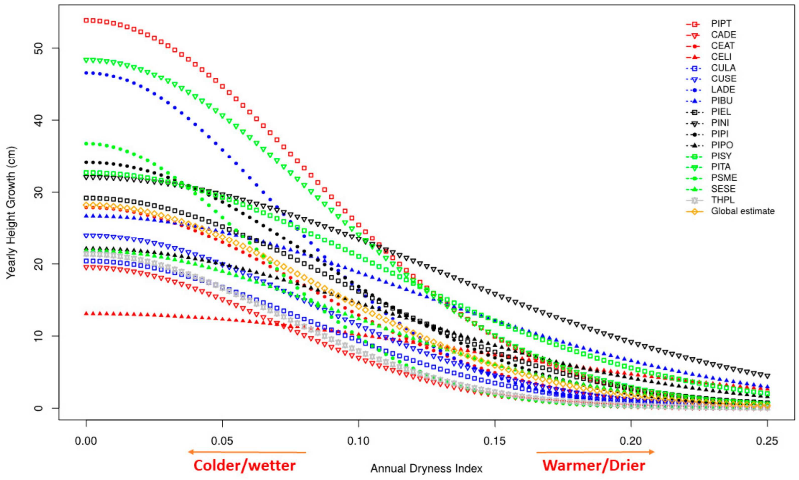


Figure 6. Estimated yearly height growth for explanatory variable ADI in the conifer species group. Orange line expresses the model's estimated response. ADI is calculated as $\sqrt{\text{degree days} > 5\,^{\circ}\text{C}}$/mean annual precipitation. Additional lines express the predicted variation from the global estimate for each conifer species.

The species with the greatest growth decrease with increasing ADI was *Betula pendula* (BEPE) (Figure 7). However, the trend was weaker in some other species. Height growth of *Eucalyptus globulus* Labill. (EUGO) was reasonably constant along the ADI gradient, with even a slight growth increase at higher ADI values. CESI showed an opposite trend, with low growth at low ADI and increasing growth at higher ADI (Figure 7). The growth model for EUGU had the best fit using two predictor variables, "Mean Annual Temperature" and "Annual Precipitation"; although the first was not statistically significant, it was considered for the final model because it improved the AIC index. Higher growth was estimated for sites with high annual precipitation and mean temperature (Figure S1 in Supplementary Materials S3).

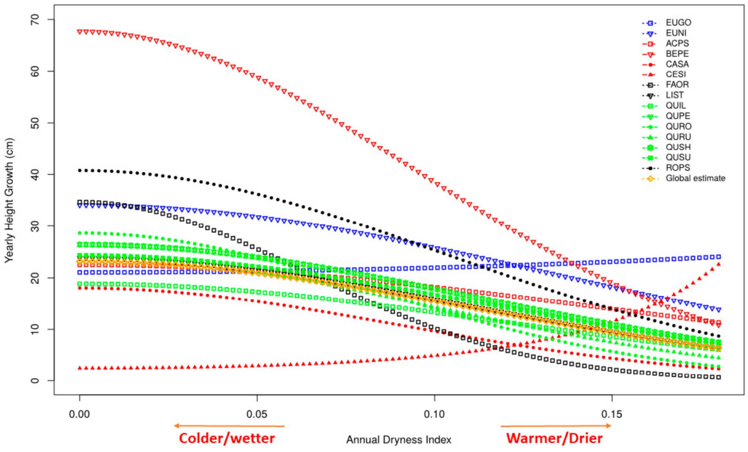


Figure 7. Estimated yearly height growth for explanatory variable ADI in the broadleaf species group. Orange line expresses the model's estimated response. ADI is calculated as $\sqrt{\text{degree days} > 5\ ^{\circ}\text{C}}$/mean annual precipitation. Additional lines express the predicted variation from the global estimate for each broadleaf species.

Explained growth random variation by provenance effect was low, yet not negligible. The highest growth within species variation was found for *Acer pseudoplatanus* L. (ACPS), *Quercus ilex* L. (QUIL), THPL, *Pinus taeda* L. (PITA), and CADE (Figures 8 and 9).

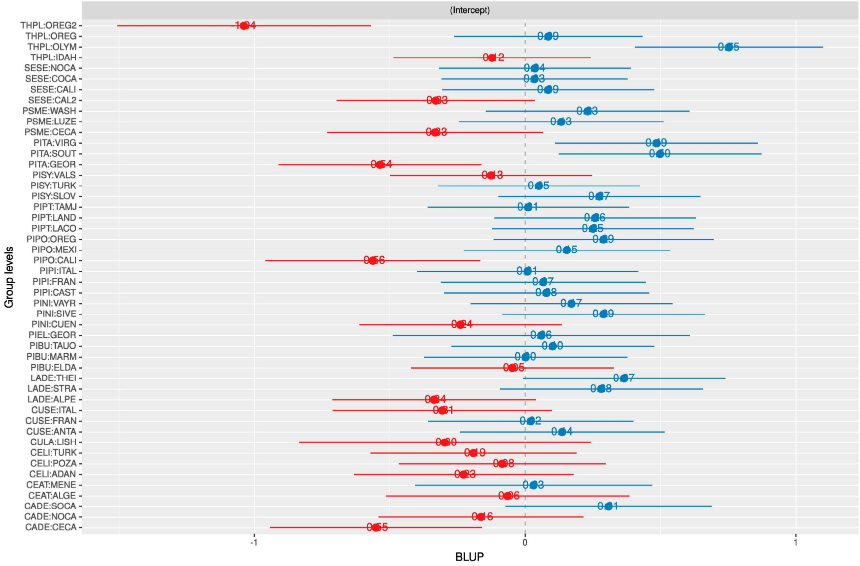


Figure 8. Best linear unbiased predictor for the provenance nested within species random effect, for yearly height growth on the conifer group. Dots represent the variation from the global mean estimate, with 95% confidence interval. Red dots and lines represent negative-effect differences, and blue dots and lines represent positive-effect differences.

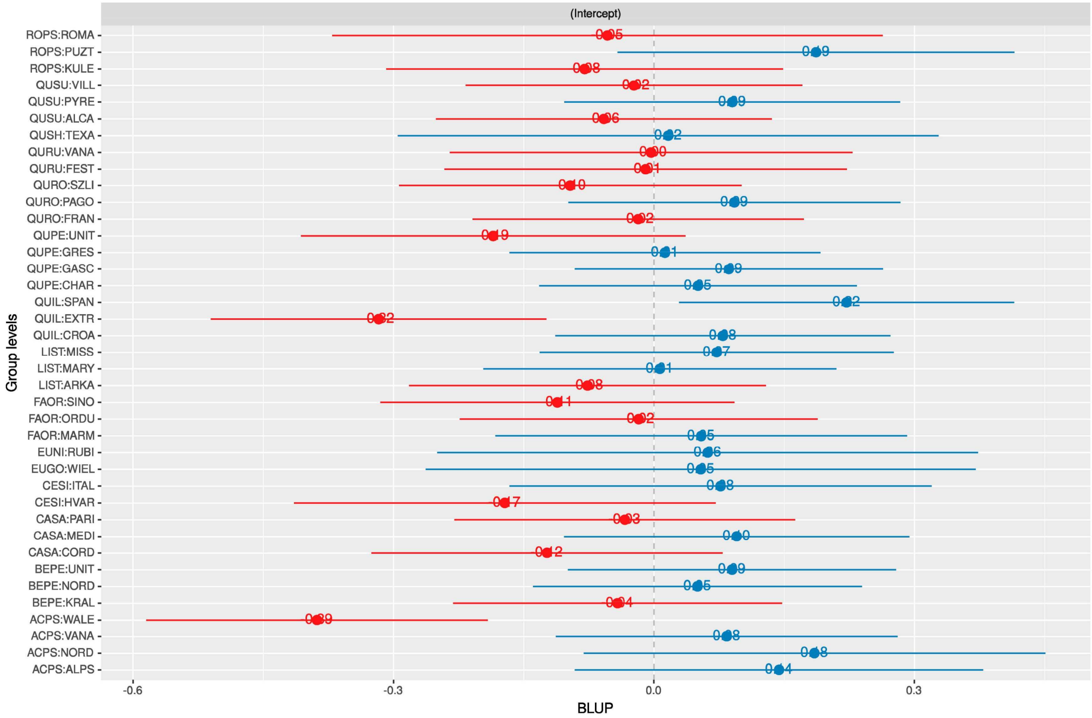


Figure 9. Best linear unbiased predictor for the provenance nested within species random effect for yearly height growth within the Broadleaf group. Dots represent the variation from the global mean estimate, with 95% confidence interval. Red dots and lines represent negative-effect differences; blue dots and lines represent positive-effect differences.

4. Discussion

As recognized in the Food and Agriculture Organization (FAO) of the United Nations [45], a further prerequisite for the use of adapted genetic resources in increasing the resilience of future production systems is improved knowledge of these resources: where they are found, what characteristics they have (e.g., resistance to drought or disease), and how they can best be managed. Within the present context, the REINFFORCE arboreta network has been established as an important tool for assessing species performance, and for supplying information for reducing uncertainty at short-, mid-, and long-term periods. Within this aim, we attempted to increase the knowledge about forest-tree responses to climatic conditions at the levels of functional groups, species, and within species variation, identifying the main drivers that would explain field performance along climate gradients. One of the advantages for this approach is the absence of assuming specific predicted scenarios, allowing an exploration of a multiplicity of conditions, and overcoming the uncertainty derived from these predictions, which may sometimes mislead management options [46].

The main functional basis for dividing species into two groups, broadleaves and conifers, is the overall differences in their leaf lifespans, and their individual phylogenetic histories that underlie differences in other phenotypic features such as leaf structure, crown architecture, and wood composition [47], all of which translate into different adaptation strategies and resilience capability. In our study, best-fit models differed between the conifer and broadleaf groups, particularly for survival. Transfer distance for annual precipitation (P) was the significant factor explaining broadleaf survival, and GSDD at the planting site was most significant for the conifer group. These results agree with the differential adaptability capacity by each group, higher for broadleaf, as water-use efficiency increase, or growth response to temperature increase [29,48].

EUGU required a separate explanatory model to be fitted with site temperature and precipitation included as the fixed effects (Supplementary Materials S3), differing in that way from the other broadleaf and eucalyptus species. This naturally occurring hybrid, produced from selected material [49] does present very high growth capability, as already observed in other studies [50], and also considerable variability along the arboreta network (Supplementary Materials S8).

4.1. Growth

For both species groups, the site ADI was the most significant fixed-effect variable explaining variation in height growth. The significance of the quadratic term indicates that the response is nonlinear with higher ADI values, having the most negative impact on growth for both conifers and most broadleaved species. This means that a higher accumulated temperature, combined with lower precipitation, limits height growth of most of these species. This is consistent with Reference [51], where all coastal redwood (*Sequoia sempervirens*) provenances planted outside their natural range grew much more slowly at the xeric test site than the mesic test site, regardless of climate (dryness) at their provenance location. Typically, height growth is greatest and constant at low ADI, and then decreases with increasing ADI. For example, within the ADI range 0–0.02, there is only a slight inflection of the growth response curve for *Betula pendula*, meaning higher stability than in the 0.02–0.25 range,

where there is a rapid decrease in growth response. Moreover, each species responds with a different magnitude to this climatic index. *Pinus pinaster* had the highest growth at ADI values close to 0,

whereas PITA and *Larix decidua* Mill. (LADE) showed the highest plasticity for this trait, expressed by variability across the gradient. For higher ADI values (higher accumulated temperature, lower precipitation), these two species also showed the highest drop in estimated growth potential. Within the broadleaf group, BEPE, *Robinia pseudoacacia* L. (ROPS)*,* and *Liquidambar styraciflua* L. (LIST) showed the greatest response to increasing ADI with a considerable drop in estimated growth potential at higher ADI values. *Quercus* species, as well as EUGO and *E. nitens* H. Deane & Maiden (EUNI) showed less variation along the ADI gradient. Overall, variation in height growth showed no significant relationship with climate transfer distance effects, so, apparently, growth appears to respond directly to site climate.

Overall, variation between provenances within species suggests that genetic variation within species was captured but had low expression in the model. Nevertheless, it is possible to identify those that differ positively or negatively to the climate index, relative to the global mean.

In general, site random effects explained a low percentage of variance (<1%), except for with *Eucalyptus* 'Gundal', which was >50%, and probably reflects very low or null genetic variation in this clone. This signifies the importance of selecting the appropriate site for establishment, as well as the genetic material [52].

For E. 'Gundal', estimated growth was positively influenced by increasing precipitation and temperature, with a greaterer response to temperature (higher fixed-effect estimate), and a high plasticity along the gradient. According to the Institut Technologique Forêt Cellulose Bois-construction Ameublement (FCBA) [49], this hybrid shows tolerance to moderate drought, and its productivity is directly dependent on water availability. Despite the global and regional expected increase for forest growth under climate change [53] resulting from temperature increase and CO_2 fertilization, the current results reinforce that genetic-material selection needs to be considered as an adaptative management option in order to take advantage of the referred conditions.

4.2. Survival

For survival, the most significant fixed effect differed between the two species groups, with annual precipitation transfer distance being most significant for broadleaved species, and site GSDD for the Conifer. The fitted term for broadleaved species has a positive slope, indicating that survival increased at planting sites that are wetter than the provenance sites, and decreased where sites are drier. It has been suggested that greater survival should occur at sites with minimal transference distance values [21], but our results point to species' slightly suboptimal survival when grown at sites with equivalent provenance climatic conditions, although these differences are expressed less in *Quercus* species. The decrease in survival at negative transfer distances was greatest for species that had lower overall survival, such as *Ceratonia siliqua* and *Eucalyptus globulus*. However, the random factor associated with slopes was not significant in the best-fitting model, which means that all species follow the same trend along the gradient, varying from the overall mean by the random intercept for site, species, and provenance. For the broadleaf group, site edaphic characteristics are highly relevant, agreeing with Reference [21], explaining over 39% of the model's variance, against less than 12% of the explained variance for conifers.

The best model for conifers showed an overall significant negative linear effect of growing-season degree days on survival, modified by different intercepts and slopes for species. In general, *Pinus* species showed less variation in survival along the gradient of accumulated temperature. The exception is *Pinus taeda* and *Pinus elliottii*, which seem to be consistent with References [54–56], where higher temperature at the beginning of summer seemed to constrain survival and growth. *Pinus elliotti* exhibited the largest decrease in survival as site growing-season degree days increased. Though conifers tend to be less responsive to temperature than broadleaved species, there is an indication that survival of species that originate in colder climates decreases more as temperature increases [48]. The significant influence of degree days is linked with temperature and duration of the growing season, which, for some species, represents early bud burst, taking advantage of water availability in drought-conditioned environments.

4.3. Trade-Offs for Adaptation

Should we focus on species with lower variation along a climate gradient in order to tackle the uncertainty issue? If we consider a *win-win* approach to the problem, we would select species that would perform better in an extended range of warmer and drier climates, and still additionally enhance forest productivity in current conditions. Nevertheless, we face some constraints for species performance, such as that introducing more drought-tolerant species in order to mitigate climate change might not necessarily be successful due to trade-offs between drought tolerance and growth plasticity [57].

Overall, there is a general response of species and species groups to temperature and precipitation variation. Higher temperature alone can result in decreasing survival and growth. Low annual precipitation, especially during the growing season, also negatively impacts survival and growth. Trait variation between provenances within species is significant, with higher expression for survival, supporting that a correct provenance selection can improve the species' response trend [58], as observable for *Pinus pinea*, *Quercus robur*, or *Ceratonia siliqua* (Figures 4 and 5). However, greater gains were achieved when selecting a more resilient or adaptable species because higher fitness corresponds to better performance. *Quercus shumardii* and *Pinus nigra* J.F.Arnold seem to be two species that present fewer trade-offs between survival and growth, and a less plastic response to climate gradient.

We do need to point out that this study is made on observations on four-year-old established seedlings, and although this is an extremely important phase for forest production, we cannot deduce a direct connection to mature-plant responses or forest-product quality. This preliminary work on the present material does present important information for species performance after establishment, improving existing basic knowledge for species selection as a base for more resilient and adapted forests. Further work will be conducted on the same material, expanding knowledge at the physiological level and in terms of productivity. The arboretum design used in this study has the advantage of allowing side-by-side comparison of many species. However, there is an inevitable balance between the number of species studied, and the numbers of provenances within species and the numbers of individuals per plot that can be included. This implies that we cannot assure complete coverage of the entire species genetic variation, we can only assume to capture the variation based on selected material that originated from contrasting climatic conditions. This design also generated constraints for data analysis, mainly due to the unbalanced experimental design caused by unequal mortality at the site, species, and provenance level.

5. Conclusions

In this study, we used empirical models to detect the best climatic-predictor variables explaining tree growth and survival. We used data from a network of 38 arboreta, each with 33 species and three provenances, established along a latitudinal range in the first four years following establishment. In the present climate range, we concluded that the best predictors for plant survival differed between conifer and broadleaf. Precipitation transfer distance was most important for broadleaf survival, whereas growing-season degree days mostly explained conifer tree survival. Growth performance was mainly explained by the ADI for both conifer and broadleaf. However, significant differences were found between species on growth and survival response to climatic variables. Moreover, provenance within species had a high expression in the variability of both traits, yet provenance variability was more expressive for survival, revealing the importance of considering this information on climate-response models. We identified species more prone to underperform within climatic variation, such as *Betula pendula*, *Pinus elliottii*, *Thuja plicata*, and the ones less affected, such as *Quercus shumardii* and *Pinus nigra;* we also demonstrated that provenance variation is more important for *Pinus pinea*, *Quercus robur*, and *Ceratonia siliqua*.

Here, we demonstrated the usefulness of infrastructures such as REINFFORCE along climatic gradient to determine major trends in the response of tree species to climate change. This information will be most useful for future forestry-adaptation management to climate change. Our work is based on the first four years after establishment. Future work is required to follow long-term tree growth and survival.

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/9/10/630/s1, S1: Climate gradient along REINFFORCE network (1971–2000 normal); S2: Species and provenance description, with coding present on this work; S3: Fitted model results table and plot for eucalyptus 'gundal' growth; S4: Plotting survival vs. mean annual temperature and annual accumulated precipitation for broadleaf group; S5: Plotting survival vs. mean annual temperature and annual accumulated precipitation for conifer group; S6: Survival percentage for broadleaf species; S7: Survival percentage for conifer species; S8: Boxplot for yearly height growth per broadleaf species along REINFFORCE arboreta gradient; S9: Boxplot for yearly height growth per conifer species, along REINFFORCE arboreta gradient; S10: Arboreta classification for annual dryness index.

Author Contributions: Conceptualization, data acquisition, funding management, formal analysis: C.A.H., A.M.H., O.C., C.D.R., D.L.L., C.A., C.J., P.C., B.F., G.N., A.A., J.R., J.H., P.E., P.P., L.M., P.F., T.M., Z.S., N.C. and F.M.; writing—review and editing, C.A.H., A.M.H., B.M., T.M., J.R. and O.C.

Funding: The establishment of the REINFFORCE arboreta network was funded by INTERREG Space Atlantic, and the corresponding author was funded by Fundação para a Ciência e Tecnologia with grant number PD/BD/52405/2013.

Acknowledgments: We would like to acknowledge Carla Faria and Ana Rodrigues from ISA, Nuno Oliveira from PSML, and Maria João Gaspar from UTAD for helping with fieldwork and logistics; and IPMA for helping with meteorological data.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analysis, or interpretation of the data; in the writing of the manuscript; and in the decision to publish the results.

References

1. IPCC. Summary for Policymakers. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2014; pp. 1–32.
2. Erickson, V.; Aubry, C.; Berrang, P.; Blush, T.; Bower, A.; Crane, B.; Gwaze, D.; Hamlin, J.; Horning, M.; Johnson, R.; et al. Genetic resource Management and Climate Change: Genetic Options for Adapting National Forests to Climate Change. *USDA For. Serv. For. Manag.* **2012**. Unnumbered publication.
3. Regato, P. *Adapting to Global Change Mediterranean Forests*; IUCN-The World Conservation Union: Malaga, Spain, 2008; ISBN 978-2-8317-1098-3.
4. Climate Change in Portugal–SIAM Scenarios–Impacts and Adaptation Measures. Available online: https://www.researchgate.net/publication/260554169_Climate_Change_in_Portugal_-_SIAM_ Scenarios_-_Impacts_and_Adaptation_Measures (accessed on 10 August 2018).
5. Natalini, F.; Alejano, R.; Vázquez-Piqué, J.; Cañellas, I.; Gea-Izquierdo, G. The role of climate change in the widespread mortality of holm oak in open woodlands of Southwestern Spain. *Dendrochronologia* **2016**, *38*, 51–60. [CrossRef]
6. Ciesla, W.M.; Donaubauer, E. *Decline and Dieback of Trees and Forests: A Global Overview*; Food and Agriculture Organization United Nations (FAO): Rome, Italy, 1994; p. 120.
7. Auclair, A.N.D. Extreme climatic fluctuations as a cause of forest dieback in the Pacific Rim. *Water Air Soil Pollut.* **1993**, *66*, 207–229. [CrossRef]
8. De Boeck, H.J.; Van De Velde, H.; De Groote, T.; Nijs, I. Ideas and perspectives: Heat stress: More than hot air. *Biogeosciences* **2016**, *13*, 5821–5825. [CrossRef]
9. Augspurger, C.K. Spring 2007 warmth and frost: Phenology, damage and refoliation in a temperate deciduous forest. *Funct. Ecol.* **2009**, *23*, 1031–1039. [CrossRef]
10. Lindner, M.; Fitzgerald, J.B.; Zimmermann, N.E.; Reyer, C.; Delzon, S.; van der Maaten, E.; Schelhaas, M.-J.; Lasch, P.; Eggers, J.; van der Maaten-Theunissen, M.; et al. Climate change and European forests: What do we know, what are the uncertainties, and what are the implications for forest management? *J. Environ. Manag.* **2014**, *146*, 69–83. [CrossRef] [PubMed]
11. Scharnweber, T.; Manthey, M.; Criegee, C.; Bauwe, A.; Schröder, C.; Wilmking, M. Drought matters–Declining precipitation influences growth of *Fagus sylvatica* L. and *Quercus robur* L. in north-eastern Germany. *For. Ecol. Manag.* **2011**, *262*, 947–961. [CrossRef]
12. Salmela, M.J. Rethinking local adaptation: Mind the environment! *For. Ecol. Manag.* **2014**, *312*, 271–281. [CrossRef]
13. Bréda, N.; Peiffer, M. Vulnerability to forest decline in a context of climate changes: New prospects about an old question in forest ecology. *Ann. For. Sci.* **2014**, *71*, 627–631. [CrossRef]
14. Chakraborty, D.; Wang, T.; Andre, K.; Konnert, M.; Lexer, M.J.; Matulla, C.; Schueler, S. Selecting populations for non-analogous climate conditions using universal response functions: The case of douglas-fir in central Europe. *PLoS ONE* **2015**, *10*, e0136357. [CrossRef] [PubMed]
15. Adams, S.H. The Impact of Changing Climate on Tree Growth and Wood Quality of Sitka Spruce. Ph.D. Thesis, University of Glasgow, Glasgow, UK, 2014.
16. Hacura, J.; Gryc, V.; Vavrcˇík, H.; Hozová, J. The Effect OF Drought on Cell Wall Thickness and Radial Dimension of Tracheids of *Picea abies* (L.) karst. *Wood Res.* **2015**, *60*, 175–188.
17. Biogeographical Regions. Available online: https://www.eea.europa.eu/data-and-maps/data/ biogeographical-regions-europe-3 (accessed on 19 September 2018).
18. Orazio, C.; Debets, R.C.; Cantero, L.D.L.A.; Casero, J.D.; Recio, C.P.; Bravo, F.; Bengoetxea, N.G.; González, A.A.; Jinks, R.; Paillassa, E.; et al. *Arboretum and Demonstration Site Catalogue REINFFORCE*

(REsource INFrastructures for Monitoring, Adapting and Protecting European Atlantic FORests under Changing Climate); IEFC-EFIATLANTIC: Cestas, France, 2013; ISBN 978-2-9519296-1-9.

19. Mareschal, B.; Brans, J.P.; Vincke, P. *Prométhée: A New Family of Outranking Methods in Multicriteria Analysis*; ULB Institutional Repository, ULB (Universite Libre de Bruxelles): Brussels, Belgium, 1984.
20. Fick, S.E.; Hijmans, R.J. WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. *Int. J. Clim.* **2017**, *37*, 4302–4315. [CrossRef]
21. Sáenz-Romero, C.; Lamy, J.B.; Ducousso, A.; Musch, B.; Ehrenmann, F.; Delzon, S.; Cavers, S.; Chałupka, W.; Dag˘das¸, S.; Hansen, J.K.; et al. Adaptive and plastic responses of *Quercus petraea* populations to climate across Europe. *Glob. Chang. Biol.* **2017**, *23*, 2831–2847. [CrossRef] [PubMed]
22. Rehfeldt, G.E.; Worrall, J.J.; Marchetti, S.B.; Crookston, N.L. Adapting forest management to climate change using bioclimate models with topographic drivers. *Forestry* **2015**, *88*, 528–539. [CrossRef]
23. Greer, B.T.; Still, C.; Howe, G.T.; Tague, C.; Roberts, D.A. Populations of aspen (*Populus tremuloides* Michx.) with different evolutionary histories differ in their climate occupancy. *Ecol. Evol.* **2016**, *6*, 3032–3039. [CrossRef] [PubMed]
24. Matyas, C. Modeling climate change effects with provenance test data. *Tree Physiol* **1994**, *14*, 797–804. [CrossRef] [PubMed]
25. Leites, L.P.; Robinson, A.P.; Rehfeldt, G.E.; Marshall, J.D.; Crookston, N.L. Height-growth response to climatic changes differs among populations of Douglas-fir: A novel analysis of historic data. *Ecol. Appl.* **2012**, *22*, 154–165. [CrossRef] [PubMed]
26. Beauregard, F.; de Blois, S. Beyond a Climate-Centric View of Plant Distribution: Edaphic Variables Add Value to Distribution Models. *PLoS ONE* **2014**, *9*, e92642. [CrossRef] [PubMed]
27. Sampson, D.A.; Wynne, R.H.; Seiler, J.R. Edaphic and climatic effects on forest stand development, net primary production, and net ecosystem productivity simulated for Coastal Plain loblolly pine in Virginia: Carbon fluxes of coastal plain loblolly pine. *J. Geophys. Res.* **2008**, *113*. [CrossRef]
28. Ma, J.; Hu, Y.; Bu, R.; Chang, Y.; Deng, H.; Qin, Q. Predicting Impacts of Climate Change on the Aboveground Carbon Sequestration Rate of a Temperate Forest in Northeastern China. *PLoS ONE* **2014**, *9*, e96157. [CrossRef] [PubMed]
29. Frank, D.C.; Poulter, B.; Saurer, M.; Esper, J.; Huntingford, C.; Helle, G.; Treydte, K.; Zimmermann, N.E.; Schleser, G.H.; Ahlström, A.; et al. Water-use efficiency and transpiration across European forests during the Anthropocene. *Nat. Clim. Chang.* **2015**, *5*, 579–583. [CrossRef]
30. Sanchez, A.; Hughes, N.M.; Smith, W.K. Leaf/shoot level ecophysiology in two broadleaf and two needle-leaf species under representative cloud regimes at alpine treeline. *J. Plant Ecol.* **2016**, *9*, 762–772. [CrossRef]
31. Orazio, C.; Stojnic, S.; Stojanovic´, D.; Gartzia, N.; Hayes, S. The Influence of Climate Change on European Forests and the Forest Sector. Available online: http://www.efiatlantic.efi.int/files/attachments/efiatlantic/2012_rokfor/efi_rokfor_climate_change_a4_210113.pdf (accessed on 8 August 2018).
32. Wang, T.; O'Neill, G.A.; Aitken, S.N. Integrating environmental and genetic effects to predict responses of tree populations to climate. *Ecol. Appl.* **2010**, *20*, 153–163. [CrossRef] [PubMed]
33. Kapeller, S.; Lexer, M.J.; Geburek, T.; Hiebl, J.; Schueler, S. Intraspecific variation in climate response of Norway spruce in the eastern Alpine range Selecting appropriate provenances for future climate. *For. Ecol. Manag.* **2012**, *271*, 46–57. [CrossRef]
34. Valladares, F.; Matesanz, S.; Guilhaumon, F.; Araújo, M.B.; Balaguer, L.; Benito-Garzón, M.; Cornwell, W.; Gianoli, E.; van Kleunen, M.; Naya, D.E.; et al. The effects of phenotypic plasticity and local adaptation on forecasts of species range shifts under climate change. *Ecol. Lett.* **2014**, *17*, 1351–1364. [CrossRef] [PubMed]
35. Yang, J.; Pedlar, J.H.; McKenney, D.W.; Weersink, A. The development of universal response functions to facilitate climate-smart regeneration of black spruce and white pine in Ontario, Canada. *For. Ecol. Manag.* **2015**, *339*, 34–43. [CrossRef]

36. Eriksson, G.; Ekberg, I.; Clapham, D. *Genetics Applied to Forestry*; Department of Plant Biology and Forest Genetics, Swedish University of Agricultural Sciences: Uppsala, Sweden, 2013; ISBN 978-91-576-9187-3.
37. Bates, D.; Mächler, M.; Bolker, B.; Walker, S. Fitting Linear Mixed-Effects Models Using lme4. *J. Stat. Softw.* **2015**, *67*. [CrossRef]
38. Anandhi, A. Growing degree days–Ecosystem indicator for changing diurnal temperatures and their impact on corn growth stages in Kansas. *Ecol. Indic.* **2016**, *61*, 149–158. [CrossRef]
39. Zuur, A.F.; Ieno, E.N.; Elphick, C.S. A protocol for data exploration to avoid common statistical problems. *Methods Ecol. Evol.* **2010**, *1*, 3–14. [CrossRef]
40. Fine, P.V.A. Ecological and Evolutionary Drivers of Geographic Variation in Species Diversity. *Annu. Rev. Ecol. Evol. Syst.* **2015**, *46*, 369–392. [CrossRef]
41. Franks, S.J.; Weber, J.J.; Aitken, S.N. Evolutionary and plastic responses to climate change in terrestrial plant populations. *Evol. Appl.* **2014**, *7*, 123–139. [CrossRef] [PubMed]
42. Nakagawa, S.; Schielzeth, H. A general and simple method for obtaining R2 from generalized linear mixed-effects models. *Methods Ecol. Evol.* **2013**, *4*, 133–142. [CrossRef]
43. Johnson, P.C.D. Extension of Nakagawa & Schielzeth's R^2_{GLMM} to random slopes models. *Methods Ecol. Evol.* **2014**, *5*, 944–946. [CrossRef] [PubMed]
44. Austin, P.C.; Steyerberg, E.W. Interpreting the concordance statistic of a logistic regression model: Relation to the variance and odds ratio of a continuous explanatory variable. *BMC Med. Res. Methodol.* **2012**, *12*. [CrossRef] [PubMed]
45. *Coping with Climate Change: The Roles of Genetic Resources for Food and Agriculture*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2015; ISBN 978-92-5-108441-0.
46. Keenan, R.J. Climate change impacts and adaptation in forest management: A review. *Ann. For. Sci.* **2015**, *72*, 145–167. [CrossRef]
47. Wyka, T.P.; Oleksyn, J.; Zytkowiak, R.; Karolewski, P.; Jagodzin´ski, A.M.; Reich, P.B. Responses of leaf˙ structure and photosynthetic properties to intra-canopy light gradients: A common garden test with four broadleaf deciduous angiosperm and seven evergreen conifer tree species. *Oecologia* **2012**, *170*, 11–24. [CrossRef] [PubMed]
48. Way, D.A.; Oren, R. Differential responses to changes in growth temperature between trees from different functional groups and biomes: A review and synthesis of data. *Tree Physiol.* **2010**, *30*, 669–688. [CrossRef] [PubMed]
49. Melun, F.; Sud-ouest, S.; Sivaillan-Les-Lamberts, D. De Eucalyptus Gundal: Une Espèce Remarquable Pour la Production de Biomasse. Available online: https://www.fcba.fr/sites/default/files/gundal_fcba_info.pdf (accessed on 10 August 2018).
50. Leslie, A.D.; Mencuccini, M.; Perks, M. The potential for Eucalyptus as a wood fuel in the UK. *Appl. Energy* **2012**, *89*, 176–182. [CrossRef]
51. Dagley, C.M.; Berrill, J.-P.; Johnson, F.T.; Kerhoulas, L.P. *Adaptation to Climate Change? Moving Coast Redwood Seedlings Northward and Inland*; General Technical Report (GTR): PSW-GTR-258; U.S. Department of Agriculture, Forest Service: Albany, CA, USA, 2017.
52. Resende, R.T.; Soares, A.A.V.; Forrester, D.I.; Marcatti, G.E.; dos Santos, A.R.; Takahashi, E.K.; e Silva, F.F.; Grattapaglia, D.; Resende, M.D.V.; Leite, H.G. Environmental uniformity, site quality and tree competition interact to determine stand productivity of clonal Eucalyptus. *For. Ecol. Manag.* **2018**, *410*, 76–83. [CrossRef]
53. Kirilenko, A.P.; Sedjo, R.A. Climate change impacts on forestry. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 19697–19702. [CrossRef] [PubMed]
54. Houle, G.; Delwaide, A. Population structure and growth-stress relationship of *Pinus taeda* in rock outcrop habitats. *J. Veg. Sci.* **1991**, *2*, 47–58. [CrossRef]
55. Nedlo, J.E.; Martin, T.A.; Vose, J.M.; Teskey, R.O. Growing season temperatures limit growth of loblolly pine (*Pinus taeda* L.) seedlings across a wide geographic transect. *Trees* **2009**, *23*, 751–759. [CrossRef]

56. Parker, K.C.; Jensen, C.; Parker, A.J. The Growth response of slash pine (*Pinus elliottii*) to climate in the Georgia Coastal Plain. *Dendrochronologia* **2014**, *32*, 127–136. [CrossRef]
57. Gratani, L. Plant Phenotypic Plasticity in Response to Environmental Factors. *Adv. Bot.* **2014**, *2014*, 17. [CrossRef]
58. Breed, M.F.; Stead, M.G.; Ottewell, K.M.; Gardner, M.G.; Lowe, A.J. Which provenance and where? Seed sourcing strategies for revegetation in a changing environment. *Conserv. Genet.* **2013**, *14*, 1–10. [CrossRef]

III. Probabilistic risk analysis for 33 forest species survival and growth under RCP 4.5 and 8.5 scenarios in western Europe using REINFFORCE arboreta network results.

Correia, A.H.; Almeida, M.H.; Tomé, M.; Pereira, J.S.; Cantero, A.; Diez, J.J.; Prieto-Recio, C.; Gartzia, N.; Arias, A.; Jinks, R.; Paillassa, E.; Pastuszka, P.; Rozados Lorenzo, M.J.; Silva Pando, F.J.; Traver, M.C.; Zabalza, S.; Ferreira, M.; Cota, T.; Orazio, C. (2018) Probabilistic risk analysis for 33 forest species survival and growth under Climate Change scenarios in western Europe. Submitted to *AFS*.

1.Title: **Probabilistic risk analysis for survival and growth of 33 forest species under climate change scenarios in western Europe**

2.Authors:

António Henrique Correia[1,*] , Maria Helena Almeida[1], Margarida Tomé[1], João Santos Pereira[1], Alejandro Cantero[3], Julio J. Diez[4], Cristina Prieto-Recio[4], Nahia Gartzia[5], Ander Arias[5], Richard Jinks[6], Eric Paillassa[7], Patrick Pastuszka[8], María José Rozados Lorenzo[9], Francisco Javier Silva Pando[9], Miguel Ferreira[12], Tânia Cota[13] and Christophe Orazio[2]

[1] Centro de Estudos Florestais, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal; ahcorreia@isa.ulisboa.pt (*A.H.C.); nica@isa.ulisboa.pt (M.H.A.); magatome@isa.ulisboa.pt (M.T.), jspereira@isa.ulisboa.pt (J.S.P)

[2] European Forest Institute EFIATLANTIC, Site de recherches forêt-bois de Bordeaux-Pierroton 69, Route d'Arcachon 33612 Cestas France cristophe.orazio@efi.int

[3] HAZI Konsultoria, 48160 Euskadi, Spain; acantero@hazi.eus

[4] Sustainable Forest Management Research Institute, Universidad de Valladolid and INIA, 34491 Palencia, Spain; jdcasero@pvs.uva.es (J.J.D.); cristina.prieto@pvs.uva.es (C.P.)

[5] Neiker Tecnalia, 48160 Euskadi, Spain; ngartzia@neiker.eus (N.G.); agonzalez@neiker.eus (A.A.)

[6] Forest Research (FR), Alice Holt Lodge, Farnham, GU10 4LH, UK; richard.jinks@forestry.gsi.gov.uk

[7] Institut pour le Développement Forestier (IDF), 75008 Paris France; eric.paillassa@cnpf.fr

[8] Institut National de la Recherche Agronomique (INRA), 75008 Paris France; patrick.pastuszka@pierroton.inra.fr;

[9] Centro de Investigación Forestal (CIF), 15893 Galicia, España; maria.jose.rozados.lorenzo@xunta.es (M.J.R.L.); francisco.javier.silva.pando@xunta.es (F.J.S.P.)

[10] Direçao Regional dos Recursos Florestais (DRRF), 9500-035 Ponta Delgada Portugal; carina.a.nobrega@azores.gov.pt

[12] Furnas Monitoring and Research Centre, Azorina S.A., 9675-090 Furnas Portugal; miguel.gc.ferreira@azores.gov.pt

[13] Instituto Português do Mar e da Atmosfera, Rua C do Aeroporto, 1749-077 Lisboa, Portugal; tania.cota@ipma.pt

3. Short Title – Risk for 33 species under climate change

4.Contributions of authors

Conceptualization, data acquisition, funding management: António Henrique Correia, Maria Helena Almeida, Christophe Orazio, Alejandro Cantero, Julio J. Diez, Cristina Prieto-Recio, Nahia Gartzia, Ander Arias, Richard Jinks, Eric Paillassa, Patrick Pastuszka, María Lorenzo, Francisco Silva

Pando, Miguel Ferreira. Current climate data: Tânia Cota. Formal Analysis, Writing-Review & Editing: António Henrique Correia, Maria Helena Almeida, Margarida Tomé, João Santos Pereira, Tânia Cota, Christophe Orazio.

5. Fundings – “The establishment of the REINFFORCE arboreta network was funded by INTERREG Space Atlantic, and the corresponding author was funded by Fundação para a Ciência e Tecnologia with grant number PD/BD/52405/2013”.

6. Acknowledgements

We would like to acknowledge Carla Faria and Ana Rodrigues from ISA, Nuno Oliveira from PSML and Maria João Gaspar, from UTAD, for helping with fieldwork and logistics; IPMA for helping with meteorological data.

7. Total number of characters – 39 506

8. Number of figures

6 figures in body text

Title of the paper: Probabilistic risk analysis for survival and growth of 33 forest species under climate change scenarios in western Europe.

Key message: The concern about the selection of resilient genetic material for forest plantations able to cope with future climate effect is addressed through a probabilistic risk analysis for 33 species survival and growth, performed for RCP 4.5 and 8.5, mid and long term. Results point to a higher survival risk for conifer species, and an overall higher risk for southern sites.

Abstract:

The increasing concern about the selection of resilient genetic material for forest plantations able to cope with future climate affect both forest managers and policymakers. Most of the currently available information for material performance originates from simplified assumptions. Empirical models considering intraspecific variability offer an opportunity to reduce uncertainty. Using these models to predict the impact on the specific response of tree species to climate scenarios allows to evaluate the loss in growth and survival of a plantation, and assess the risk taken maintaining or changing species, under each scenario. Considering the scenarios described on IPCC’s Fifth Assessment Report, caution mandated to run predictions under 2 main ones: Representative Concentration Pathway (RCP) 4.5 and 8.5. Taking advantage of Reinfforce arboreta network, established in 38 sites between latitudes 37° and 57° where 33 species are represented at least by 3 provenances, it was possible to estimate the risk for each species facing these conditions, for the establishment period. The main results point to an expected survival risk higher for conifer species than broadleaf, especially high for

species like *Calocedrus decurrens*, *Pseudotsuga menziesii*, and *Pinus nigra*. For growth, high risk is indicated for *Larix decidua*, *Pinus pinaster*, and *Betula pendula*. Risk distribution points to higher risk at southern sites, and higher production potential for northern sites.

Context:

Aims: Provide a more realistic calculation on the loss or gain in height growth and survival for each species, under 2 climate change scenarios, assess vulnerability variation, and finally determine the risk associated with the future usage of each species, taking advantage of using data from REINFFORCE arboreta network and previously established climate response models for 33 species.

Methods: In this work, a probabilistic risk analysis is conducted using growth and survival data estimated by models from previous work. Two time horizons were considered (2050 and 2080), for each RCP 4.5 and 8.5.

Results: The main results point to an expected survival risk higher for conifer species than broadleaf, especially high for species like *Calocedrus decurrens*, *Pseudotsuga menziesii*, and *Pinus nigra*. For growth, high risk is indicated for *Larix decidua*, *Pinus pinaster*, and *Betula pendula*. Risk distribution points to higher risk at southern sites, and higher production potential for northern sites.

Conclusion: For future conditions, northern latitudes will originate an overall lower risk, and southern productive species can be considered for usage. This will be mediated by higher temperature and sufficient water availability. For southern latitudes, the risk will become higher.

Keywords: Climate change, Vulnerability, Representative Concentration Pathway, 33 forest species

1. Introduction

Changing climate conditions may cause stress in forests and affect the fitness in present day locations. The concern about the selection of genetic material for forest plantations able to cope with future climate influences managers and policy makers. Most of the currently available information for material performance originates from simplified assumptions, involving models that do not consider species plasticity and genetic variation at provenance level, nor behavior at more extreme conditions observable outside current species distribution, beyond the marginal growth areas, as is the case with climate envelope models. As a consequence, these results are not matching with empirical knowledge and not appropriate for decision making. It is important to assess the overall risk for each climate scenario based on field information. Globally, in Northern latitudes, the climate prediction is for an extensive increase in Forest productivity, due to temperature increase and CO2 fertilization (Kirilenko and Sedjo 2007). However, in Southern areas where drought periods will be more frequent and longer (Santos, F.D. and Miranda, P. 2006; IPCC 2014), water will be the main constraint to productivity. Water availability is a crucial factor for growth and survival, therefore is an issue to be considered. Indeed, in previous work, annual dryness index (AID) was identified as the climate variable that best explained growth (annual height increment) (Correia et al. 2018). For Europe, the estimate for future growth is similar to the global prediction, but there is indication that the growth slows down at longer term (after 2050), and that there is differentiation between Atlantic and Continental Europe (Kirilenko and Sedjo 2007). Yet, looking at a Regional and local scale, several constrains for plant development emerge, mainly the increase of the dry period, the frequency of heat waves, off-season frost damage, leading to loss of performance, and higher susceptibility to pest damage (Santos, F.D. and Miranda, P. 2006). The impact of these factors on productivity will vary with the genetic material used for forest establishment, as we can observe in several studies (Lindner et al. 2008; Correia et al. 2018), and therefore a generalization of productivity increase under climate change needs to be validated at the local scale. Some genetic material presents vulnerabilities when exposed to climate variation. Yet there is evidence that some traits present a resilience, and even present a productivity increase for a specific temperature interval, beyond which there is an estimated loss in productivity(Wang et al. 2010). It is imperative to identify the most resilient genetic material, compare species and provenances vulnerability and decipher the risk involved in maintaining “business as usual” species or opting either for alternative species or provenances. According to FAO (Food and Agriculture Organization of the United Nations 2013), “vulnerability and risk assessments generally involve a climate sensitivity analysis and an evaluation of the capacity of ecosystems and communities to adapt to climate change. Following FAO guidelines on this matter (Food and Agriculture Organization of the United Nations 2013), in order to analyze the sensitivity of forests and forest-dependent communities to changing climatic conditions, the forest manager, in partnership with other stakeholders, should determine:

- the current and expected stresses on the forest area;
- the known climatic conditions, and how these affect the forest area;
- the projected change in climatic conditions and the likely impact(s) of these changes on forests;
- the expected stress variation for a system, resulting from impacts by climate change.”

One straightforward approach to reduce uncertainty and produce consistent information is to apply models that account for intraspecific variation for the required traits, and that express the species variation along a gradient that extends beyond the natural distribution, as in Correia et al. (2018). Then, test multiple scenarios to allow predicting variation along time, for each climate conditions, and provide an interval for the possible future responses. The inherent probability of occurrence of each scenario has to be considered for policy making, the definition of guidelines and the selection of proper material for afforestation.

Our study aimed at providing a more realistic calculation on the loss or gain in height growth and survival for each species, under 2 climate change scenarios, assess vulnerability variation, and finally determine the risk associated with the future use of each species. We take advantage of using data from REINFFORCE arboreta network (Orazio et al. 2013) and previously established climate response models for 33 species (Correia et al. 2018), for computing contemporary and predicted performance response under future climate change scenarios, considering the probability of occurrence for each scenario. The REINFFORCE arboreta network allows for observing the response to edaphoclimatic effects for each of these species, and comparing them directly, since they are established side-by-side, on an extended climatic gradient along Atlantic Europe. In previous work conducted on this arboreta network data for the first four years (Correia et al. 2018), specific models were fitted in order to evaluate the response to climate gradient along Atlantic Europe, to identify the most explanatory climate indicator, and to identify the variation between and within species, for growth and survival traits.

2. Material and methods

From the literature (Hynard and Rodger; IPCC 2014; Capellán-Pérez et al. 2016), we selected 2 Representative Concentration Pathways (RCPs): 4.5 W/m2 radiative forcing, corresponding to a moderate Climate change, and 8.5W/m2 radiative forcing, a more drastic change. Accordingly, RCP 4.5 W/m2 scenario has expected probability of reaching 0.9-2° C mean annual temperature increase by 2050 of 50%, and expected probability of reaching 1.1-2.6° C increase by 2080 of 90%; RCP 8.5 W/m2 scenario has expected probability of reaching 0.9-2° C increase by 2050 of 99%, and expected probability of reaching 2.6-4.8° C increase by 2080 of 88%.

Arboreta site climate base data, for the 2012-2016 period, was extracted from EWMF ERANet, from prediction and reassessment models (Berrisford et al. 2009; Dee et al. 2011). Provenance climate data for 1970-2000 period were extracted from the Worldclim database (Fick and Hijmans 2017). Predicted climate data for 2050 and 2080, under both selected pathways, were calculated with ClimateEU v4.63 software package, available at http://tinyurl.com/ClimateEU, from HadGEM2-ES global model, based on the methodology described by (Hamann et al. 2013).

Following the methodology described in (van Oijen et al. 2013), we calculated the survival and growth risk per species, under the 2 RCP and 2-period projections.

The formulation is as follows:

E(sys|env non-hazardous)	(A)
E(sys|env hazardous)	(B)
Vulnerability=A−B	(C)
P(env hazardous)	(D)
Risk=C∗D	(E)

In (A) and (B) we calculate the expected value of the system (sys) variable response (growth or survival), under the environmental (env) hazardous or non-hazardous conditions. We assume here the present climate conditions as the non-hazardous, and the conditions under the predicted RCPs as the hazardous conditions. So, in (C), the Vulnerability is calculated as the difference between the system response under present and predicted climate scenarios.

We then adopt the probability of occurrence of each RCP, for the specific projected period, as the probability of occurrence of hazardous environmental conditions (C).

Finally, in (E), we calculate the Risk as the product of Vulnerability by the probability of occurrence of each scenario.

Growth and Survival were estimated for the range of the arboreta network using previous fitted models in Correia et al. (2018). Growth was estimated using Annual Dryness index (ADI) as a predictor variable, for both broadleaf and conifer species. ADI was calculated as the square root of the Annual Growing Degree Days > 5 °C, divided by the Annual Precipitation (Sáenz-Romero et al. 2017). Survival was calculated for broadleaf using Annual Precipitation Climate distance as a predictor variable. This variable was calculated as the difference between the precipitation observed at the establishment site and the precipitation observed at the Forest regeneration material provenance site. For conifer, survival was calculated through the growing season degree-days above 5 °C predictor variable. This variable was calculated as the Growing Degree Days>5 °C added from April to September (Sáenz-Romero et al. 2017).

Statistical models for growth and survival took into account the within-species genetic variability, at provenance level.

The species coding and information is provided in the supplementary material S36.

3. Results

Climate prediction for REINFFORCE arboreta sites reveals a global increase in mean temperature under the 2 RCPs and for the 2 projected periods (Fig.1), this raise can reach 2°C. For the predicted precipitation, there is a higher variation within the network. Mainly there is an expected precipitation volume increase for most of the sites, but for 15 arboreta (central, south and inland) there is a clear drop in annual precipitation amount from currently observed, as much as 43% (Fig.2). This quite unusual result is due to the location of some of the sites on the western coast of continents with strong Atlantic climate (Orazio et al. 2013).

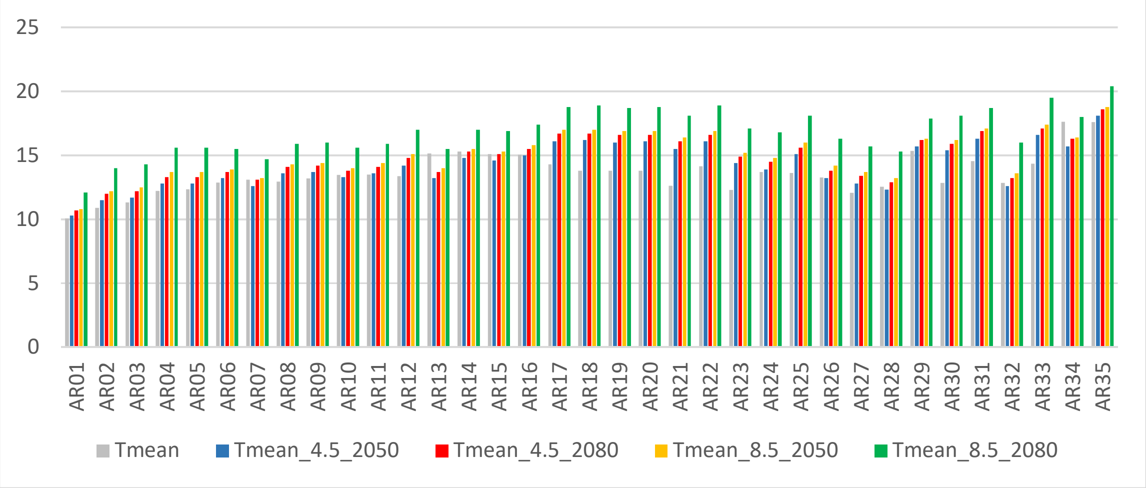


Figure 1. Characterization of current and predicted mean temperature for each scenario, for the REINFFORCE arboreta network. Arboreta sites are coded from AR01 to AR35 (Orazio et al. 2013). Current mean temperature corresponds to 1970-2000 normal (Tmean). Mean temperature is estimated for RCPs 4.5 and 8.5, and for 2 time periods, 2050 and 2080. Vertical axis refers to temperature in °C.

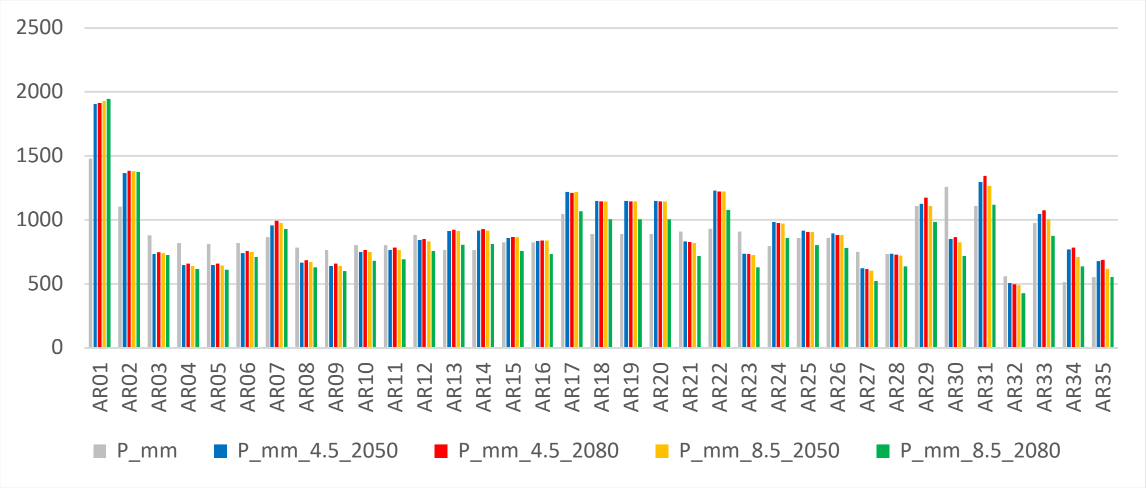


Figure 2. Characterization of current and predicted annual precipitation for each scenario, for the REINFFORCE arboreta network. Arboreta sites are coded from AR01 to AR35 (Orazio et al. 2013). Current annual precipitation corresponds to 1970-2000 normal (P_mm). Annual precipitation is estimated for RCPs 4.5 and 8.5, and for 2 time periods, 2050 and 2080. Vertical axis refers to precipitation value in mm.

3.1. Survival

The predicted risk for survival presents different tendencies for both groups. Broadleaf trees show null risk except for the long-term RCP 8.5 scenario, where *Ceratonia siliqua*, *Eucalyptus globulus*, *Eucalyptus gundal*, *Castanea sativa*, and *Quercus suber* undergo a higher risk (Figure 3). *Ceratonia siliqua* is the only species presenting a significantly negative risk for 2050 RCP 8.5 scenario. For the Conifer group, we observe as much as a 15% risk for survival loss for the middle term, reaching 37% on the long-term (Figure 4). Species showing higher risk are *Cuninghamia lanceolata*, *Calocedrus decurrens*, *Pinus taeda*, and *Pseudotsuga menziesii*. *Pinus nigra* presents a lower risk for mid-term RCP4.5, but high values for the more extreme scenario in the long term.

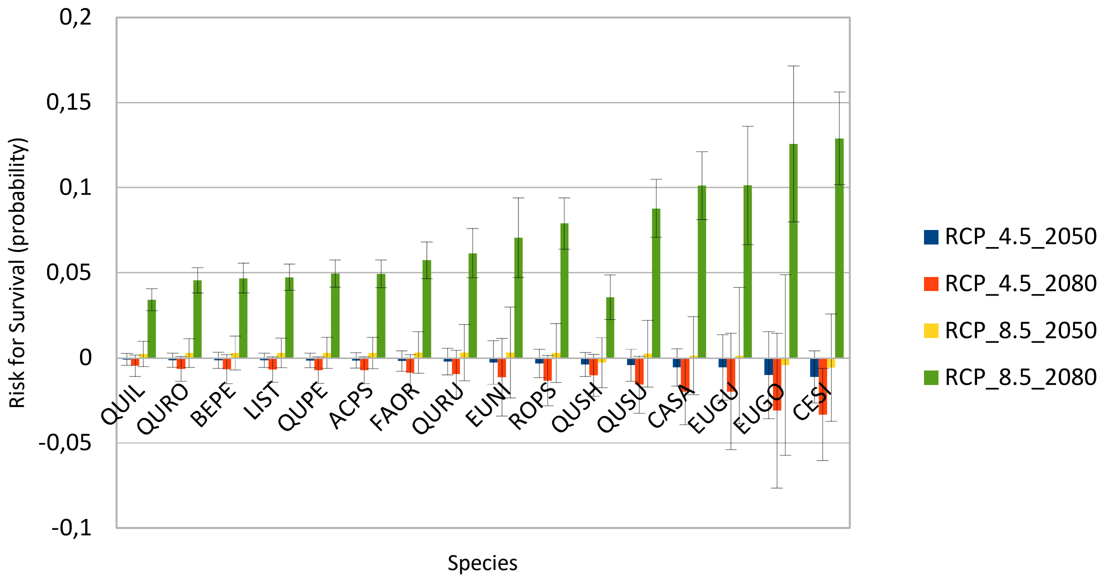


Figure 3. Survival risk estimation for broadleaf species, for the global REINFFORCE arboreta network. The Risk is estimated for RCPs 4.5 and 8.5, and for 2 time periods, 2050 and 2080. Vertical axis refers to the risk of survival loss in probability. Bars represent the mean Risk for the arboreta network. The represented interval on each individual bar is the standard error for the Risk values along the arboreta network.

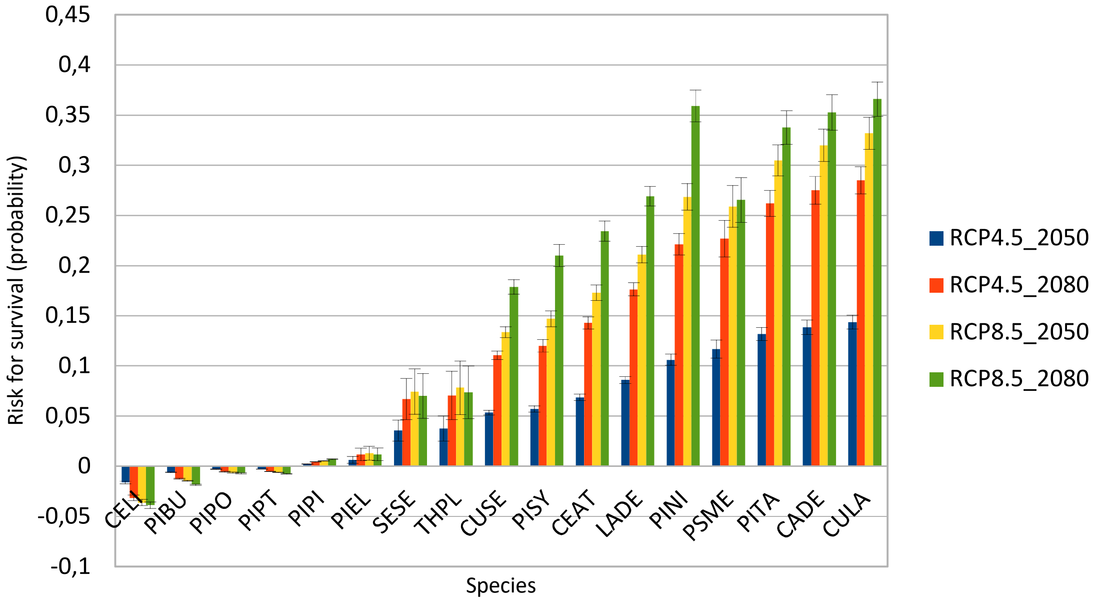


Figure 4. Survival risk estimation for conifer species, for the global REINFFORCE arboreta network. The Risk is estimated for RCPs 4.5 and 8.5, and for 2 time periods, 2050 and 2080. Vertical axis refers to the risk of survival loss in probability. Bars represent the mean Risk for the arboreta network. The represented interval on each individual bar is the standard error for the Risk values along the arboreta network.

3.2. Growth

As for growth, we can observe that there is a higher risk incidence for the conifer group and that for the broadleaf group there are 3 species with negative growth associated risk. Species presenting higher risk are *Betula pendula*, *Fagus orientalis*, *Larix decidua*, *Pinus pinaster*, *Pseudotsuga menziessi* and *Pinus taeda*. *Betula pendula*, *Pinus pinaster* and *Larix decidua* present as much as 10 cm risk for growth loss per year, for RCP 8.5 in 2080.

The 3 species that will improve growth potential under all scenarios are *Eucalyptus gundal*, *Ceratonia siliqua*, and *Eucalyptus globulus*, since they present a negative value for growth risk, with an accentuated expansion potential to the north, where they will find more favorable conditions for temperature and water availability.

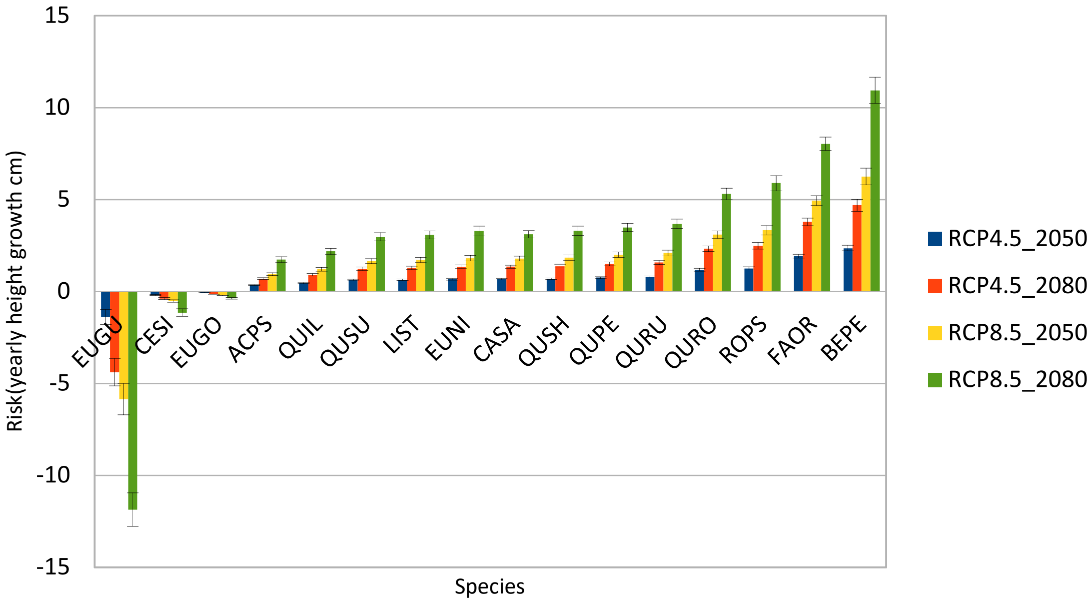


Figure 5. Growth risk estimation for broadleaf species, for the global REINFFORCE arboreta network. The Risk is estimated for RCPs 4.5 and 8.5, and for 2 time periods, 2050 and 2080. Vertical axle refers to the risk of growth loss in cm. Bars represent the mean Risk for the arboreta network. The represented interval on each individual bar is the standard error for the Risk values along the arboreta network.

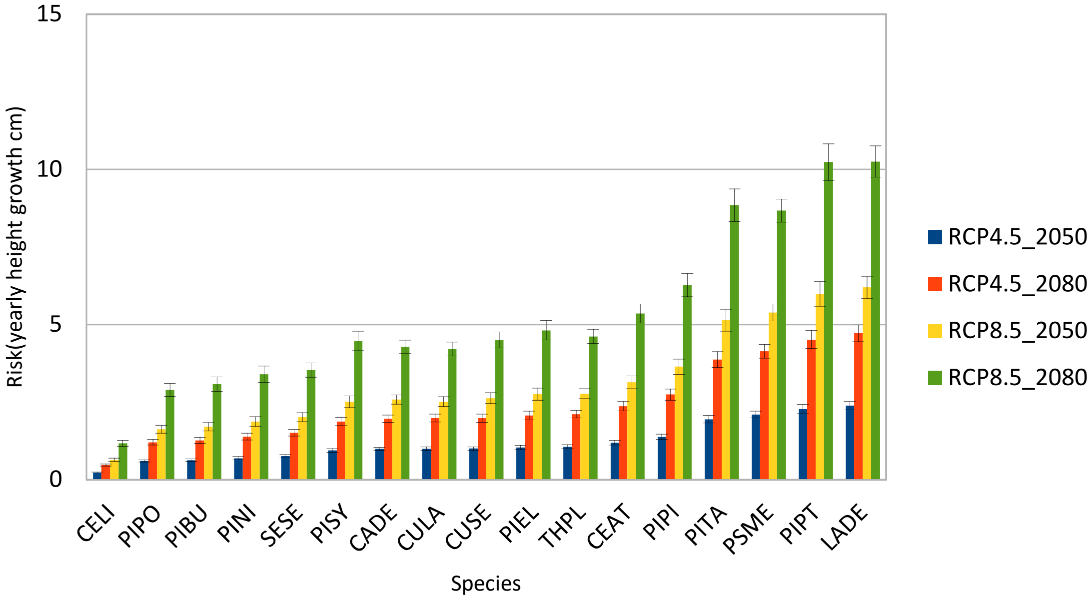


Figure 6. Growth risk estimation for conifer species, for the global REINFFORCE arboreta network.

The Risk is estimated for RCPs 4.5 and 8.5, and for 2 time periods, 2050 and 2080. Vertical axle refers to the risk of growth loss in cm. Bars represent the mean Risk for the arboreta network. The represented interval on each individual bar is the standard error for the Risk values along the arboreta network.

4. Discussion

Our results contrasts with other predictions and assessments in 2 ways. Where other predictions indicate a considerable increase in Forest productivity at global and regional level (Kirilenko and Sedjo 2007), our results estimated a decrease in growth for most of the species, accentuated for long term under both RCPs. As for the predicted overall survival decrease (Allen et al. 1998), our results show that this trend is only observed for conifer species, as for broadleaves the risk for survival at early stages seems to be low, except for the RCP 8.5, in the long term. Nevertheless, species that are currently being planted in lower latitudes as *Eucalyptus globulus* and *Ceratonia siliqua* will present a further risk for survival and growth in the future for this region.

4.1. Survival

In order to calculate the risk for survival, we used precipitation climate distance and growing season degree days as independent variables. This climate distance was calculated considering the climate normal from 1970-2000 for the provenance data. Although it would be possible to predict the climatic variations for the provenance sites, we assume that the material's genetic variation expresses the conditions submitted in past and in the considered period.

The expected risk showed to be higher for conifer species. In concordance with González-Muñoz et al. (2014), Broadleaf presents negative or close to 0 values, except for RCP 8.5 in 2080. This implies that for a great extension of Atlantic Europe we can expect an increase in broadleaf survival for a moderate climate change, which is an interesting information for foresters concerned by regeneration capacity and seedling stress tolerance. The 5 species that we can identify as presenting the highest risk (confidence interval contains the threshold of 0,1 survival probability loss) for the long-term effects of RCP 8.5 are *Ceratonia siliqua*, *Eucalyptus globulus*, *Eucalyptus gundal*, *Castanea sativa*, and *Quercus suber*. The increase of the annual precipitation distance between establishment site and provenance of the material is expected to be higher on the long term under the more extreme scenario, revealing an impact even on Mediterranean more drought resistant species like *Quercus suber*. This exposes the importance of considering this distance when selecting the material for afforestation.

Quercus suber survives the summer drought of the Mediterranean climate. In spite of the drought resistance there is a reported lower water use efficiency than other evergreen oaks, like *Quercus ilex* (David et al. 2007). That is shown by its distribution along more wetter western coastal areas (David et al. 2007). There is a significant provenance effect on the response to climate conditions (Sampaio et al. 2016), which is also considered under the predictor variable used for the estimation. Nevertheless, on the statistical models in Correia et al. (2018), there was no significant variation detected within the species, for the 3 provenances tested. The low risk observed at the most northern point, comparing to the highest risk on the most southern one, is clearly due to the effect of the current low productivity expressed by the species in the north.

For the conifers, we identify 3 species that present a higher risk in the short and long-term: *Cunninghamia lanceolata*, *Calocedrus decurrens*, and *Pinus taeda*. A 4th species also present a very high risk for the long-term RCP 8.5 scenario: *Pinus nigra*.

Pinus taeda's performance depends highly on growing season's temperature and accumulated temperature (Nedlo et al. 2009; Correia et al. 2018), and particularly the survival depends on summer temperature, growing season, annual maximum and mean, and growing degree days (Thapa 2014). So, the expected long-term temperature increase will constrain the species future survival, increasing the risk of mortality. For *Cunninghamia lanceolata*, it has also been identified temperature as positively related to tree mortality (Zhang et al. 2017), and the increase of accumulated temperature will promote higher risk for mortality. *Calocedrus decurrens*' performance depends on cool temperatures in the latest summer (Johnson et al. 2017), so under higher temperature for growing season, growth and survival will decrease (Aubry-Kientz and Moran 2017; Correia et al. 2018).

There are 4 species presenting a negative risk: *Cedrus libani*, *Pinus ponderosa*, *Pinus brutia* and *Pinus pinaster*. *Pinus ponderosa* productivity and the likelihood of survival have been observed as equally dependent on elevation-driven variation in temperature and precipitation (Tague et al. 2013).

Pinus brutia is stated as very resilient to drought and thermal stress (Spencer et al. 2001), and thus survival is high under warmer climates.

For *Pinus pinaster*, although temperature plays an important role, precipitation is presented as the main climate factor for performance (Bogino and Bravo 2008). Nevertheless, population differentiation and within-population genetic variation for drought resistance follow different patterns (Gaspar et al. 2013). Along the studied gradient, this species presented a stable survival probability (Correia et al. 2018), and thus, a low risk, even for the long-term RCP 8.5 scenario.

4.2. Growth

Overall, we estimate that conifer species are subjected to a higher risk of growth losses, under climate change. In concordance with González-Muñoz et al. (2014), we found that broadleaf species present a lower risk for predicted scenarios. Even so, we identify 2 broadleaf species with a higher risk for growth, *Betula pendula*, and *Fagus orientalis*. *Betula pendula* is an important forest species on Northern and Eastern Europe, less for central and south (Hynynen et al. 2010), representing around 4% of national volume stock for Spain, France, and UK, and we should point out that one of the establishment methods for this species is natural regeneration. So, at establishment stage, if we face a risk for growth that not just constrains future growth, but also makes difficult for this shade intolerant species to surpass competition from ground vegetation, conducing to constraints on the later stand productivity (Hynynen et al. 2010). As for Fagus orientalis, the natural distribution range includes the south-eastern regions of Europe (e.g., Turkey) and the northern Caucasus (e.g., northern Iran and Syria) (Kara 2018). We see that on this shade-tolerant species' natural distribution, the optimum growth conditions are present on the north-facing slopes (Ertekin et al. 2015), so constraints are expected under a higher temperature, and drier climate, as projected for both scenarios, consequently leading to high risk under future climate.

As for species that succeed under the expected conditions, we observe 3 that are expected to present negative risk: *Eucalyptus gundal*, *Ceratonia siliqua*, and *Eucalyptus globulus*. The species with positive lower risk is *Acer pseudoplatanus*. This species presents a high intraspecific variability, and the presented phenotypical plasticity allows lower growth variation in response to the arboreta range climatic conditions (Correia et al. 2018), supporting higher variation. Being a pioneer fast growing species, it can present a valid replacement for *Betula pendula* for timber materials supply whenever the risk is found to be high. Obviously, we should point out that *Betula pendula* presents a superior growth rate, even when subjected to higher ADI values, is similar to *Acer pseudoplatanus* (Correia et al. 2018).

Eucalyptus globulus shows a small variation for growth along the gradient, with best responses for higher ADI values (Correia et al. 2018), and this explains that under a future warmer and drier climate it will present a lower overall risk. Nevertheless, even under a warming climate, the risk for the northern region tends to be high, as temperatures will not be warm enough to provide conditions for this cold susceptible species. For northern usage, *Eucalyptus gundal*, being a hybrid of two frost resistant species (Melun 2011), presents higher growth potential, as long as there is sufficient water availability.

Ceratonia siliqua shows the highest increase for growth under increasing ADI values, so the increment achieved under any climate change scenario is expected to improve the current performance, thus the negative risk value under any climate change scenario.

Eucalyptus gundal presents expressively higher growth potential under current conditions, increasing for higher temperature, limited only by very low precipitation (Correia et al. 2018). So, under an expected slight lower precipitation and higher temperature, it is expected that this species will present a growth increase for most locations.

For conifers, we find that there are 2 species presenting a higher level of risk, mainly for long-term scenarios: *Pinus pinaster* and *Larix decidua*.

As for *Larix decidua*, a light-demanding species, the high growth risk will promote the same constraints as for *Betula pendula*, making difficult to surpass competition from ground vegetation (Matras and Pãques 2008). We can observe in the previous study (Correia et al. 2018) that this species suffers a steep growth drop with the increase of ADI values.

On the conifer group, *Pinus pinaster* is the species with higher growth potential, under optimal conditions (low ADI), but with a steep growth loss for higher values of ADI (Correia et al. 2018). So the risk for predicted scenarios is quite high. As this is a very important species in central and southern Atlantic Europe, as a multifunctional species (Viñas et al. 2016), especially for this region, alternative more resilient species should be considered.

We identified 3 species with lower risk, *Cedrus libani*, *Pinus ponderosa* e *Pinus brutia*. Although *Cedrus libani* did not present an exceptional growth for the studied climatic range, compared to other conifers (Correia et al.

2018), nevertheless this species is capable of maintaining a slow but continuous growth even during the dry summer period, confirming its exceptional drought tolerance (Messinger et al. 2015). Thus an increase in temperature and decrease in precipitation under climate change will not bring significant changes to growth potential, and the risk is considerably low.

Pinus ponderosa growth is positively correlated with previous October, January, June, and July precipitation and temperature is not correlated with growth (KUSNIERCZYK and ETTL 2002). So, under expected lower precipitation, or mainly the extension of the dry season, there is still a considerable amount of precipitation on fall, winter and spring, so the impact of climate change will be reduced.

Pinus brutia is recognized as a very drought tolerant species (Gezer 1986), with constraints to growth from water-logging conditions, or high air moisture and rain values, which complies with our results, under more dry and warm predicted conditions.

4.3. Risk distribution

Considering the Risk maps for each species presented in supplementary material S, a noticeable effect of using this methodology is the low risk presented at arboreta sites where we would expect higher performance constraints, due to a higher temperature or lower precipitation, comparatively with other locations. This occurs at sites where species are already under a high constraint for growth or survival, so vulnerability (C), calculated as the loss between the present and hazardous conditions, assumes low values. As an example, we can consider the risk distribution for *Pinus elliotti* (S24), where we find low-risk projection for most of the range, deriving from a current very poor performance (growth and survival) on the range, except for more northern locations. In that way, we observe the highest risk where currently the species finds sufficient climatic conditions to thrive, but future scenarios indicate constraints for performance.

When interpreting the risk analysis, we need to consider if a species presenting a low risk for a given scenario presents an adequate performance, or if the high risk indicates a performance impact of sufficient magnitude to weight the future usage.

4.4. Trade-off

When considering the risk for plan-material selection in order to promote a more resilient Forest, what should be the most relevant trait? In most cases, forest managers will refer to secure the health of its stands, even while losing productivity. Some species present low-risk values for both traits, like *Pinus ponderosa* and *Pinus brutia* (S34), and can present a viable alternative for maintaining or improving wood products supply under climate change. But should this alternative be considered for replacing, for example, *Pinus pinaster*, that present high risk for growth? If we look at the results in Correia et al. (2018), we see that *Pinus pinaster* does present a considerable drop in growth for high ADI values (warmer/drier), but is only surpassed in growth by *Pinus brutia* around 0.14 ADI value. So this could be an important solution if we considered the higher risk scenario.

Species with current high growth potential like *Betula pendula* and *Eucalyptus gundal* present distinct risk values. *Betula pendula* are estimated to present very high growth loss, yet low impact on survival is expected.

Eucalyptus gundal will experience an increase in growth under all predicted scenarios, and significant loss for survival.

For broadleaf species, *Acer pseudoplatanus* represent lower trade-off (S35) since the risk for growth and survival are quite low. It can be a viable alternative for wood supply under climate change, although presenting a lower growth potential than *Betula pendula*, only overtaking the last in growth for 0.18 ADI values. So, even for long-term RCP 8.5, we should weight if the loss in growth potential will sufficiently impact *Betula pendula* forest productivity, to consider other species that present far lower growth.

As for *Eucalyptus gundal*, the high growth capacity expressed under dry conditions (high temperature and low precipitation) could compensate a small risk for survival.

5. Conclusion

Climate change is in some areas prompting forest stress and the increase in uncertainty. Risk analysis could represent an important reference for decision support on forest management as it shows comparatively the risk inherent in selecting species for forest production, the risk evolution along time, for 2 different scenarios. For future conditions, northern latitudes will originate an overall lower risk, and southern productive species can be considered for usage. This will be mediated by higher temperature and sufficient water availability. For southern latitudes, the risk will become higher.

These results are based on the early stage of stand growth and development (4 year trees). Although this is an important phase to access stand success, the correlation of these results with more mature stands should be confirmed with future stand age data analysis.

References

Allen R, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration. Guidlines for computing crop water requirements. {FAO} Irrigation and drainage paper n. 56

Aubry-Kientz M, Moran EV (2017) Climate Impacts on Tree Growth in the Sierra Nevada. Forests 8:414. doi: 10.3390/f8110414

Berrisford P, Dee D, Fielding K, et al (2009) The ERA-Interim Archive. ERA report series 1:1–16

Bogino SM, Bravo F (2008) Growth response of Pinus pinaster Ait. to climatic variables in central Spanish forests. Annals of Forest Science 65:506–506. doi: 10.1051/forest:2008025

Capellán-Pérez I, Arto I, Polanco-Martínez JM, et al (2016) Likelihood of climate change pathways under uncertainty on fossil fuel resource availability. Energy & Environmental Science 9:2482–2496. doi: 10.1039/C6EE01008C

Correia AH, Almeida MH, Branco M, et al (2018) Early Survival and Growth Plasticity of 33 Species Planted in 38 Arboreta across the European Atlantic Area. Forests 9:630. doi: 10.3390/f9100630

David TS, Henriques MO, Kurz-Besson C, et al (2007) Water-use strategies in two co-occurring Mediterranean evergreen oaks: surviving the summer drought. Tree Physiology 27:793–803. doi: 10.1093/treephys/27.6.793

Dee DP, Uppala SM, Simmons AJ, et al (2011) The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society 137:553–597. doi: 10.1002/qj.828

Ertekin M, Kırdar E, Ayan S (2015) The Effects of Exposure, Elevation and Tree Age on Seed Characteristics of Fagus orientalis Lipsky. South-east European forestry 6:. doi: 10.15177/seefor.15-03

Fick SE, Hijmans RJ (2017) WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. International Journal of Climatology 37:4302–4315. doi: 10.1002/joc.5086

Food and Agriculture Organization of the United Nations (ed) (2013) Climate change guidelines for forest managers. Food and Agriculture Organization of the United Nations, Rome

Gaspar MJ, Velasco T, Feito I, et al (2013) Genetic Variation of Drought Tolerance in Pinus pinaster at Three Hierarchical Levels: A Comparison of Induced Osmotic Stress and Field Testing. PLoS One 8:. doi: 10.1371/journal.pone.0079094

Gezer A (1986) The Sylviculture of Pinus brutia in Turkey. CIHEAM 13

González-Muñoz N, Linares JC, Castro-Díez P, Sass-Klaassen U (2014) Predicting climate change impacts on native and invasive tree species using radial growth and twenty-first century climate scenarios. Eur J Forest Res 133:1073–1086. doi: 10.1007/s10342-014-0823-5

Hamann A, Wang T, Spittlehouse DL, Murdock TQ (2013) A Comprehensive, High-Resolution Database of Historical and Projected Climate Surfaces for Western North America. Bulletin of the American Meteorological Society 94:1307–1309. doi: 10.1175/BAMS-D-12-00145.1

Hynard J, Rodger T David King, Daniel Schrag, Zhou Dadi, Qi Ye and Arunabha Ghosh. CLIMATE CHANGE 79

Hynynen J, Niemistö P, Viherä-Aarnio A, et al (2010) Silviculture of birch (Betula pendula Roth and Betula pubescens Ehrh.) in northern Europe. Forestry (Lond) 83:103–119. doi: 10.1093/forestry/cpp035

IPCC (2014) Summary for Policymakers. Climate Change 2014: Impacts, Adaptation and Vulnerability - Contributions of the Working Group II to the Fifth Assessment Report 1–32. doi: 10.1016/j.renene.2009.11.012

Johnson C, Chhin S, Zhang J (2017) Effects of climate on competitive dynamics in mixed conifer forests of the Sierra Nevada. Forest Ecology and Management 394:1–12. doi: 10.1016/j.foreco.2017.03.017

Kara F (2018) A silvicultural management tool for the Oriental beech (Fagus orientalis Lipsky) forests. Journal of Sustainable Forestry 37:403–413. doi: 10.1080/10549811.2017.1422271

Kirilenko AP, Sedjo RA (2007) Climate change impacts on forestry. Proceedings of the National Academy of Sciences 104:19697–19702. doi: 10.1073/pnas.0701424104

KUSNIERCZYK ER, ETTL GJ (2002) Growth response of ponderosa pine (Pinus ponderosa) to climate in the eastern Cascade Mountains, Washington, U.S.A.: Implications for climatic change. Écoscience 9:544–551

Lindner M, Garcia-Gonzalo J, Kolström M, et al (2008) Impacts of Climate Change on European Forests and Options for Adaptation. Development 173

Matras J, Pãques LE (2008) Larix decidua - Technical guidelines for genetic conservation and use for European larch. EUFORGEN

Melun F (2011) Dans le monde entier, les eucalyptus présentent un intérêt croissant pour la production renouvelable de biomasse ligneuse. Cet article est consacré à l’espèce Gundal, dont les performances de croissance restent inégalées à ce jour dans les conditions françaises. 7

Messinger J, Güney A, Zimmermann R, et al (2015) Cedrus libani: A promising tree species for Central European forestry facing climate change? Eur J Forest Res 134:1005–1017. doi: 10.1007/s10342-015-0905-z

Nedlo JE, Martin TA, Vose JM, Teskey RO (2009) Growing season temperatures limit growth of loblolly pine (Pinus taeda L.) seedlings across a wide geographic transect. Trees 23:751–759. doi: 10.1007/s00468-009-0317-0

Orazio C, Debets RC, Cantero LDLA, et al (2013) Arboretum and demonstration site catalogue REINFFORCE (REsource INFrastructures for monitoring, adapting and protecting European Atlantic FORests under Changing climate). IEFC-EFIATLANTIC. Site de recherche forêt-bois 69, route d’Arcachon, 33612 CESTAS. France.

Sáenz-Romero C, Lamy JB, Ducousso A, et al (2017) Adaptive and plastic responses of Quercus petraea populations to climate across Europe. Global Change Biology 23:2831–2847. doi: 10.1111/gcb.13576

Sampaio T, Branco M, Guichoux E, et al (2016) Does the geography of cork oak origin influence budburst and leaf pest damage? Forest Ecology and Management 373:33–43. doi: 10.1016/j.foreco.2016.04.019

Santos, F.D., Miranda, P. (eds) (2006) ALTERAÇÕES CLIMATICAS EM PORTUGAL CENÁRIOS, IMPACTOS E MEDIDAS DE ADAPTAÇÃO - PROJECTO SIAM II, F.D. Santos, P. Miranda. Gradiva, Lisboa

Spencer D, RIRDC/LWRRDC/FWPRDC Joint Venture Agroforestry Program, Rural Industries Research and Development Corporation (2001) Conifers in the dry country. Rural Industries Research and Development Corp., Barton, ACT

Tague CL, McDowell NG, Allen CD (2013) An Integrated Model of Environmental Effects on Growth, Carbohydrate Balance, and Mortality of Pinus ponderosa Forests in the Southern Rocky Mountains. PLOS ONE 8:e80286. doi: 10.1371/journal.pone.0080286

Thapa R (2014) Modeling Mortality of Loblolly Pine (Pinus taeda L.) Plantations. Faculty of the Virginia Polytechnic Institute and State University

van Oijen M, Beer C, Cramer W, et al (2013) A novel probabilistic risk analysis to determine the vulnerability of ecosystems to extreme climatic events. Environmental Research Letters 8:015032. doi: 10.1088/1748-9326/8/1/015032

Viñas RA, Caudullo G, Oliveira S, de Rigo D (2016) Pinus pinaster in Europe: distribution, habitat, usage and threats. In: San-Miguel-Ayans J, Caudullo G, Houston Durrant T, Mauri A (eds) European Atlas of Forest Tree Species. European Union, Luxemburg

Wang T, O’Neill GA, Aitken SN (2010) Integrating environmental and genetic effects to predict responses of tree populations to climate. Ecological Applications 20:153–163. doi: 10.1890/08-2257.1

Zhang X, Cao QV, Duan A, Zhang J (2017) Modeling tree mortality in relation to climate, initial planting density and competition in Chinese fir plantations using a Bayesian logistic multilevel method. Canadian Journal of Forest Research 47:

Chapter III – Conclusions

Conclusion

The key message emerging across the three articles is the need for selecting the correct Forest Regeneration Material for each propose, and the present intent is to establish a productive forest capable of adapting to different future conditions. Although it is expected that Forest ecosystems will present some resilience to climate change (and we can observe that resistance, to some extent, in Article II), it is estimated that the natural ability to adapt will be exceeded by 2100. It is imperative to identify the material able to reduce the estimated risk under changing climate conditions. Forest Regeneration Material origin needs to be considered with caution, as well as the traits plasticity under climate variation. Article I gives a first insight into the potential for exploring the data, using 2 arboreta from the network. The first results reveal that in a short climatic distance between sites, species maintain their phenological differences, without provenance presenting a significant influence. The plants from species that are native, present a higher risk for pest damage. Nevertheless, even for a short climatic distance, the site effect is significant for explaining growth, but most of all, survival.

In Article II, the climate variables representing higher expression in growth and survival are identified: Annual Dryness Index as the variable with higher impact for growth; Growing Season Degree days above 5ºC for Conifer survival; and Precipitation Climatic Distance from the origin for Broadleaf survival. Under these variables, the fitted models identify the species with the higher and the lower trait variability under the climatic variation. Using that information in Article III, the risk is estimated using a probabilistic methodology, for RCP4.5 and 8.5. The results predict a lower risk for broadleaf species survival under climate change scenarios. Species with high relevance for European Forestry production, like *Pinus pinaster*, *Larix decidua* and *Betula pendula* are among those presenting higher risk for growth loss.There is the suggestion of using species that present lower risk, like *Pinus ponderosa* and *Pinus brutia*, in alternative to those presenting higher risk, like *Pinus pinaster*. A higher risk is observed particularly in species with currently high productive capability, and in sites where they are found to be best performing.

Alternative species provide an overall lower performance under present conditions, but they will potentially surpass in growth and survival the currently used species under future conditions, at mid- or long-term. Determining when and whether it will be necessary to change currently used material depends on the accuracy of information, from climate predictions to material estimated response.

The enhancement of Forest resilience through the use of better adapted Forest Regeneration Material will not only impact directly on the supply of Forest products, but also on the adaptability of Forest ecosystems, influencing the potential of Forests as carbon sink and compensating the expected increase in atmospheric CO2 concentration.

Originality and value of the research goals

The current study presents a side-by-side comparison of the same genetic materials, subjected to an extended climate gradient, in a collection of 33 species. This allows not only to acquire information for each individual species, but mostly the added value is the comparison of species currently used with alternative species. With the inclusion of within species variability, the proposed estimates overcome the uncertainty associated with considering a single species' response, providing indication on the possibility of exploring the variation in order to improve the adaptation of some species. This indication of species more susceptible to climate change, including those relevant to European Forest production, and the suggestion of alternative Forest Regeneration Material, carries significance in forest adaptation planning under climate change.

The importance of the present work conveys the ability to transfer the results to the managers and policy-makers. Thus, the resulting information generated by the original contributions for this study were arranged in order to provide the most explicit and easy access to information for stakeholders, so that it could be promptly used as a basis for a better adapted forest, capable of maintaining or improving its productive value under future climate conditions.

Outcomes at a glance

For the Forest Regeneration Material under test, there are some species needing additional attention, like *Pinus pinaster*, *Larix decidua* and *Betula pendula* (Article I, Article II and Article III), which represent important species in European Forestry, and this is by itself a very important indication for future reference. Alternative species that provide survival and growth risk reduction under climate change are identified, like *Pinus ponderosa*, *Pinus brutia*, *Eucalyptus gundal* and *Acer pseudoplatanus* (Article II and Article III). The survival and growth risk in southern-most locations will be higher than in northern sites, where an increase in growth potential is expected (Article III).

Dissemination of the results – Smartphone application “Forest advisor”

In order to promote the dissemination of this work’s results among stakeholders, an Android^{TM} Smartphone application has been developed. It focuses on species selection for the location identified by the user, providing information on survival and growth, under the climate change scenarios addressed along the work. The application can be downloaded in “apk” installer format at the url https://project-nature.outsystemscloud.com/NativeAppBuilder/App?Name=Forest+Advisor&AppKey=e20bff12-1658-48bd-848b-62345e649ac7, and will be available in the future at the Google play app store, and REINFFORCE project website.

Research implication and future directions

Analyzing the data from this Forest Regeneration Material establishment under the same climate gradient allowed to directly compare performance between currently used important species for forest products supply, and alternative species/provenances that represent a viable solution to promote a better adapted forest. This leads into providing a sustainable supply for the expected increasing demand of these materials, and reduces the inherent risk under climate change.

A complementary assessment is required in order to determine the economic viability in changing Forest Regeneration Material within Forest Industry. The impact of processing different wood materials, optimizing the production of alternative seedlings’ stock and updating production models and practices can be overwhelming and presents a barrier to the required actions for promoting an adapted Forest in a short- to mid-term horizon. Thus, a careful analysis of the economic return behind each alternative is in order, as well as the inclusion of non-economical revenues emerging from the adaptation to Climate Change.

The REINFFORCE network will remain an important structure for generating data leading to a better selection of material and for the identification of the increasing constraints to the productivity and health of current forest. The subsequent analysis of this material will maintain an up-to-date information system, and will allow to link the present results for establishment period to mature age trees, and to assess the climate effect on the forest products characteristics. Further studies need to address the variability in phenology along the climate gradient, as well as the resulting susceptibility to pest damage and to late frost, and to estimate growing season alterations under each of the climate conditions.

Final remarks

One of the constraints felt along the present work, expressed by most of the research partners, is the typology of current available funding for Forest research. The REINFFORCE project was supported by INTERREG Atlantic Space, for the establishment period, finalized in 2013. The posterior lack of funding revealed to be an impediment to proceed the work from Article I (phenology, pest damage, frost tolerance) in all of the arboreta from the network. There seems to be a lack of knowledge about the long-standing nature of forest studies, since the main funding Programs present a maximum time horizon of 4 years. The matter of climate change is definitely urgent, given that the material we are planting today needs to present some resilience to conditions right until the harvest (from 40 to 120 years henceforward). So the short time we have to gather some consistent information to allow for a productive response, is somewhat challenged by the time-span needed for conducting these studies. But it is imperative to maintain a continuous supply of data plus results that will ensure the reduction of uncertainty, and a fine adjustment for adaptation purpose. This is clearly evident when regarding the emergence of new pests and diseases, and the intensification of biotic and abiotic damages. The long term nature of forest studies need to be addressed by specific funding that can secure continuity.

References

Bréda N, Peiffer M (2014) Vulnerability to forest decline in a context of climate changes: new prospects about an old question in forest ecology. Annals of Forest Science 71:627–631. doi: 10.1007/s13595-014-0411-3

Edwards JE, Hirsch KG, Canadian Council of Forest Ministers, et al (2012) Adapting sustainable forest management to climate change: preparing for the future. Canadian Council of Forest Ministers, Ottawa

Eriksson G, Ekberg I, Clapham D (2013) Genetics applied to forestry. Uppsala

IEFC (2011) Reinfforce arboretum field manual-Version 17

IPCC (2014) Summary for Policymakers. Climate Change 2014: Impacts, Adaptation and Vulnerability - Contributions of the Working Group II to the Fifth Assessment Report 1–32. doi: 10.1016/j.renene.2009.11.012

Lindner M, Fitzgerald JB, Zimmermann NE, et al (2014) Climate change and European forests: What do we know, what are the uncertainties, and what are the implications for forest management? Journal of Environmental Management 146:69–83. doi: 10.1016/j.jenvman.2014.07.030

Lindner M, Garcia-Gonzalo J, Kolström M, et al (2008) Impacts of Climate Change on European Forests and Options for Adaptation. Development 173

Orazio C, Debets RC, Cantero LDLA, et al (2013) Arboretum and demonstration site catalogue REINFFORCE (REsource INFrastructures for monitoring, adapting and protecting European Atlantic FORests under Changing climate). IEFC-EFIATLANTIC. Site de recherche forêt-bois 69, route d'Arcachon, 33612 CESTAS. France.

Payn T, Carnus JM, Freer-Smith P, et al (2015) Changes in planted forests and future global implications. Forest Ecology and Management 352:57–67. doi: 10.1016/j.foreco.2015.06.021

Rigby JR, Porporato A (2008) Spring frost risk in a changing climate. Geophysical Research Letters 35:1–5. doi: 10.1029/2008GL033955

Santos, F.D., Miranda, P. (eds) (2006) ALTERAÇÕES CLIMATICAS EM PORTUGAL CENÁRIOS, IMPACTOS E MEDIDAS DE ADAPTAÇÃO - PROJECTO SIAM II, F.D. Santos, P. Miranda. Gradiva, Lisboa

van Oijen M, Beer C, Cramer W, et al (2013) A novel probabilistic risk analysis to determine the vulnerability of ecosystems to extreme climatic events. Environmental Research Letters 8:015032. doi: 10.1088/1748-9326/8/1/015032

Annex

Funding

The present work was mainly funded via a Ph.D. grant, attributed to the candidate by the Portuguese Science Foundation (FCT grant *PD/BD/52405/2013*).

The research operationalization benefitted from the REINFFORCE project, funded by the INTERREG Atlantic Space program. Within the REINFFORCE frame, there was collaborative work from the partners: EFI/IEFC, Neiker, HAZI, Xunta de Galicia, iuFOR, GAV, Azorina, DRRF, FPF, INRA, Forest Research and ISA.

IEFC/EFI Atlantic provided facilities for a short-term mission, allowing the direct interaction with the project Database.

The resulting outcomes of these interactions were disseminated as oral presentations and posters in Portuguese and International conferences, supported by ISA and FCT funding.

Presentations

- Orazio, C., Correia, A.H. et al “The potential of non-native tree species to mitigate climate change effects of European forests”. 4th International Conference on Planted Forests, September 2018. Beijing, China.
- Correia, A.H. et al “Selecting Forest Reproductive Material in the context of Climate Change: Improving Forest adaptation.” Adaptação da Agricultura ás Alterações Climáticas: França, Portugal e Região Mediterrânica, September 2018. Rome.
- Correia, A.H. et al “Identifying Forest genetic material tolerance to Climate Change through analysis of performance using REINFFORCE arboreta network climate gradient.” WC Climate Change Impact and Response, September 2018. Rome.
- Orazio, C., Correia, A.H. et al “Comparing the potential of exotic species as defined by NNEXT with native species in REINFFORCE arboreta”. COST Action FP1403 NNEXT International Conference NON-NATIVE TREE SPECIES for EUROPEAN FOREST, September 2018. Vienna.

- Orazio, C., Correia, A.H. et al “Growth, Survival, and risk analysis of tree species in Atlantic Europe based upon the results from REINFFORCE arboreta network”. EFI Planted Forests Facility & IEFC 2018 Annual Meeting, June 2018. Porto.
- Correia, A., Orazio, C., Cordero, R., Tomé, M., Branco, M., Almeida, M. H. “Evaluating forest species response to different climate conditions using REINFFORCE arboreta network.” 125th IUFRO Anniversary Congress, 2017. Freiburg.
- Orazio, C., Correia, A.H. “Alternative tree species in Atlantic Europe: early results from the REINFFORCE project.” EFIATLANTIC & IEFC 2017 Annual Meeting, Edinburgh

Posters

- Correia, A.H., Almeida, M.H., Arias González, A., Bravo, F., Cantero, A., Castro, A., Cordero-Debets, R., Di Lucchio, L., Diez Casero, J., Ferreira, M., Gartzia-Bengoetxea, N., Jinks, R., Nóbrega, C., Paillassa, E., Pastuszka, P., Prieto Recio, C., Rodrigues, A., Rozados Lorenzo, M.J., Silva Pando, F., Traver, M.C., Zabalza, S., Orazio, C."Simulating climate change effect on forest species using spatial gradient: The Arboreta network at work”, Natural and human-assisted adaptation of forests to climatic constraints: the relevance of interdisciplinary approaches, international conference, Le Studium, Orléans, 2014
- Almeida, M.H., Arias González, A., Bravo, F., Cantero, A., Castro, A., Cordero-Debets, R., Correia, A., Di Lucchio, L., Diez Casero, J., Ferreira, M., Gartzia-Bengoetxea, N., Jinks, R., Nóbrega, C., Paillassa, E., Pastuszka, P., Prieto Recio, C., Rodrigues, A., Rozados Lorenzo, M.J., Silva Pando, F., Traver, M.C., Zabalza, S., Orazio, C. “REINFFORCE ARBORETA NETWORK: A TRANSNATIONAL TOOL OF ATLANTIC FOREST ADAPTATION TO CLIMATE CHANGE.” CIRCLE-2 International Conference "Adaptation Frontiers: European Climate Change Adaptation Research and Practice", Lisboa 2014.

During the present work, the candidate felt the need for improvement of knowledge beyond what was available in the Ph.D. curricular first year. The following course was attended:

“Phylogeography”, promoted by the Applied Biology Centre, from the Lisbon University, 2014. 36 hours.

Supplementary material for Article I

Supporting supplementary material for "Monitoring two REINFFORCE Network Arboreta:

First result on site, climate and genetic interaction showing impact on phenology and biotic damages" article

Supplementary S1- Characteristics of the study sites.

Supplementary S2 - The distribution of the provenances for the studied species in the arboreta.

Supplementary S3 - Survival multiple comparison test for interaction

Supplementary S4 Analysis of Variance table (type III test) for growth
Supplementary S5 Growth multiple comparison test for interaction
Supplementary S6 Temperature that causes death to 50 % of plants TL50 ranking (°C) per provenance

Supplementary S1- Characteristics of the study sites. Climatic variables correspond to the mean of the 1971-2000 periods (Source: IPMA)

site variables	**Lisbon**	**Sintra**
altitude (m)	106	400
Climatic classification (Köppen)	Mediterranean Csa	Mediterranean Csb
Soil type	loam-Sandy clay loam	sandy-loam
Ph	6.4	4.3
maximum temperature (°C)	20.0	18.2
minimum temperature (°C)	12.5	12.3
mean precipitation (mm)	725	786
mean temperature (°C)	14.9	13.9

Supplementary S2 - The distribution of the provenances for the studied species in the arboreta. Climate data period 1961-1990 generated with the ClimateEU v4.63 software package, available at ***http://tinyurl.com/ClimateEU***, based on methodology described by Hamann et al. (2013)

Species	**provenances identification - Codes**	**latitude**	**longitude**	**altitude (m)**	**mean temperature ºC**	**annual precipitation mm**
Q. rubra	Auberive, France - FEST	47.79	5.10	400	9.2	972
	Litoral Vasco, Spain -VANA	43.30	-2.03	210	13.5	1338
Q. robur	Ruisseau de Tiolet, France-FRAN	46.21	2.20	380	10.1	828
	New forest, Hampsphire-UK - UNIT	43.2	-2.43	140	13.8	1192
	Navarro-Spain-Pago	50.85	-1.62	45	10	782
	Posavina-Croatia -POSA	44.47	16.46	1200	5.6	1184
Betula pendula	Nord Est et Montagne France - NORD	48.39	5.98	470	8.2	918
	Kralova-Slovakia -KRAL	48.352	17.32	240	9	697
	Wales-UK -UNIT	52.405	-4.03	15	9.5	1112

Supplementary S3 - Survival multiple comparison test for interaction using Wald Chi-square statistic. *Pval* significance code (“***” < 0.0001 < ”**” < 0.001 < “*” < 0.05 < “.” < 0.1 < “ “ < 1).

Species	**Fixed**	**Pairwise**	**Value**	**Df**	***Chisq***	***Pval***
BEPE	KRAL	Lisbon-Sintra	0.044776	1	77.306	***
	NORD	Lisbon-Sintra	0.019802	1	83.675	***
	UNIT	Lisbon-Sintra	0.042254	1	33.759	***
	Lisbon	KRAL-NORD	0.60000	1	2.0710	
	Lisbon	KRAL-UNIT	0.50000	1	0.0000	
	Lisbon	NORD-UNIT	0.40000	1	1.0503	
	Sintra	KRAL-NORD	0.39264	1	0.8506	
	Sintra	KRAL-UNIT	0.48485	1	0.0135	
	Sintra	NORD-UNIT	0.59281	1	0.4494	
	Residuals			209		
QURO	FRAN	Lisbon-Sintra	0.27778	1	3.6583	.
	PAGO	Lisbon-Sintra	0.23077	1	9.4229	**
	POSA	Lisbon-Sintra	0.25000	1	7.9000	*
	UNIT	Lisbon-Sintra	0.33333	1	4.7565	.
	Lisbon	FRAN-PAGO	0.44444	1	0.2227	
	Lisbon	FRAN-POSA	0.50000	1	0.0000	
	Lisbon	FRAN-UNIT	0.50000	1	0.0000	
	Lisbon	PAGO-POSA	0.55556	1	0.2227	
	Lisbon	PAGO-UNIT	0.55556	1	0.2963	
	Lisbon	POSA-UNIT	0.50000	1	0.0000	
	Sintra	FRAN-PAGO	0.38424	1	1.2370	
	Sintra	FRAN-POSA	0.46429	1	0.1137	
	Sintra	FRAN-UNIT	0.56522	1	0.3743	
	Sintra	PAGO-POSA	0.58140	1	1.3002	
	Sintra	PAGO-UNIT	0.67568	1	6.2073	
	Sintra	POSA-UNIT	0.60000	1	1.8870	
	Residuals			268		
QURU	FEST	Lisbon-Sintra	0.26316	1	1.4768	
	VANA	Lisbon-Sintra	0.00000	1	0.0001	
	Lisbon	FEST-VANA	0.6	1	0.2006	
	Sintra	FEST-VANA	0.0	1	0.0001	
	Residuals			44		
All	BEPE	Lisbon-Sintra	0.034428	1	207.777	***
	QURO	Lisbon-Sintra	0.266504	1	63.120	***

	QURU	Lisbon-Sintra	0.097765	1	97.859	***
	Lisbon	BEPE-QURO	0.29939	1	35.2023	***
	Lisbon	BEPE-QURU	0.52208	1	0.2271	
	Lisbon	QURO-QURU	0.71882	1	28.4535	***
	Sintra	BEPE-QURO	0.81324	1	43.9947	***
	Sintra	BEPE-QURU	0.76851	1	20.6962	***
	Sintra	QURO-QURU	0.43259	1	2.0588	
	Residuals			533		

Supplementary S4 Analysis of Variance table (type III test) for growth. *Pval* significance code (“***” < 0.0001 < ”**” < 0.001 < “*” < 0.05 < “.” < 0.1 < “ “ < 1).

Species	**Variance source**	**Height**			**Diameter**		
		SS	**Df**	**F(Pval)**	**SS**	**Df**	**F(Pval)**
BEPE	provenance	567.9	2	2.781(.)	7.58	2	0.352
	Site	2515.4	1	24.641(***)	631.21	1	58.656(***)
	provenance:Site	334.4	2	1.638	5.76	2	0.268
	Residuals	9800.0	96		1194.50	111	
QURO	provenance	82.9	3	0.410	42.32	3	2.066
	Site	49.8	1	0.739	114.97	1	16.836(***)
	provenance:Site	314.2	3	1.554	43.47	3	2.122
	Residuals	7481.9	111		976.58	143	
QURU	provenance	44.98	1	1.279	50.781	1	15.121(**)
	Site	86.48	1	2.458	18.070	1	5.381(*)
	provenance:Site	21.03	1	0.5977	8.020	1	2.388
	Residuals	633.27	18		60.448	18	
All	Species	561.4	2	12.079(***)	9.80	2	1.795
	Site	718.7	1	30.924(***)	156.78	1	57.429(***)
	Species:Site	328.7	2	7.072(**)	43.39	2	7.947(***)
	Residuals	5508.0	237		775.33	284	

Supplementary S5 Growth multiple comparison test for interaction using Wald Chi-square statistic. *Pval* significance code (“***” < 0.0001 < ”**” < 0.001 < “*” < 0.05 < “.” < 0.1 < “ “ < 1)

Species	**Fixed**	**pairwise**	**Height**			**Diameter**		
			Value	**Df**	**Chisq(Pval)**	**Value**	**Df**	**Chisq(Pval)**
BEPE	KRAL	Lisbon-Sintra	-23.392	1	18.760	-6.532	1	23.209(***)
	NORD	Lisbon-Sintra	-10.625	1	3.871 (*)	-5.211	1	12.114(***)
	UNIT	Lisbon-Sintra	-12.417	1	5.286 (*)	-6.484	1	23.869(***)
	Residuals			96			111	
	Lisbon	KRAL-NORD	-13.607	1	6.348 (.)	-0.901	1	0.255
	Lisbon	KRAL-UNIT	-4.441	1	0.676	-0.560	1	0.116
	Lisbon	NORD-UNIT	9.167	1	2.881	0.341	1	0.037
	Sintra	KRAL-NORD	-0.841	1	0.024	0.420	1	0.197
	Sintra	KRAL-UNIT	6.535	1	1.464	-0.512	1	0.292
	Sintra	NORD-UNIT	7.375	1	1.865	-0.932	1	0.969
	Residuals			96			111	
QURO	FRAN	Lisbon-Sintra	-6.989	1	3.261	-2.614	1	6.0046(*)
	PAGO	Lisbon-Sintra	-4.375	1	1.278	-2.017	1	3.775
	POSA	Lisbon-Sintra	1.400	1	0.131	-3.905	1	13.397 (**)
	UNIT	Lisbon-Sintra	3.3088	1	0.731	-0.167	1	0.024
	Residuals			111			143	
	Lisbon	FRAN-PAGO	-1.347	1	0.121	-0.011	1	0.0001
	Lisbon	FRAN-POSA	-2.122	1	0.301	2.401	1	3.798
	Lisbon	FRAN-UNIT	-2.972	1	0.590	-0.383	1	0.097
	Lisbon	PAGO-POSA	-0.775	1	0.040	2.412	1	3.992
	Lisbon	PAGO-UNIT	-1.625	1	0.176	-0.372	1	0.095
	Lisbon	POSA-UNIT	-0.850	1	0.048	-2.784	1	5.107
	Sintra	FRAN-PAGO	1.267	1	0.107	0.585	1	0.452
	Sintra	FRAN-POSA	6.267	1	2.622	1.110	1	1.624
	Sintra	FRAN-UNIT	7.326	1	0.445	2.064	1	5.616
	Sintra	PAGO-POSA	5.000	1	1.669	0.525	1	0.363
	Sintra	PAGO-UNIT	6.059	1	2.451	1.479	1	2.883
	Sintra	POSA-UNIT	1.059	1	0.075	0.954	1	1.200
	Residuals			111			143	
QURU	FEST	Lisbon-Sintra	-3.333	1	0.316	-4.958	1	7.318 (**)
	VANA	Lisbon-Sintra	-9.818	1	2.740	-1.123	1	0.451
	Residuals			18			18	
	Lisbon	FEST-VANA	-1.500	1	0.064	0.584	1	0.068

	Sintra	FEST-VANA	-7.985	1	1.812	4.419	1	17.442(***)
	Residuals			18			18	
All	BEPE	Lisbon-Sintra	-15.478	1	30.924 (***)	-6.107	1	57.429 (***)
	QURO	Lisbon-Sintra	-1.664	1	0.476	-2.165	1	13.932(***)
	QURU	Lisbon-Sintra	-6.576	1	3.721	-3.073	1	7.623 (**)
		Residuals		237			237	
	Lisbon	BEPE-QURO	10.771	1	17.114 (***)	-0.830	1	0.956
	Lisbon	BEPE-QURU	13.409	1	18.567 (***)	1.1785	1	0.920
	Lisbon	QURO-QURU	2.638	1	0.799	2.008	1	3.269
	Sintra	BEPE-QURO	24.585	1	89.165 (***)	3.112	1	36.491(***)
	Sintra	BEPE-QURU	22.311	1	51.404 (***)	4.213	1	46.811(***)
	Sintra	QURO-QURU	-2.274	1	0.593	1.101	1	3.551
	Residuals			237			237	

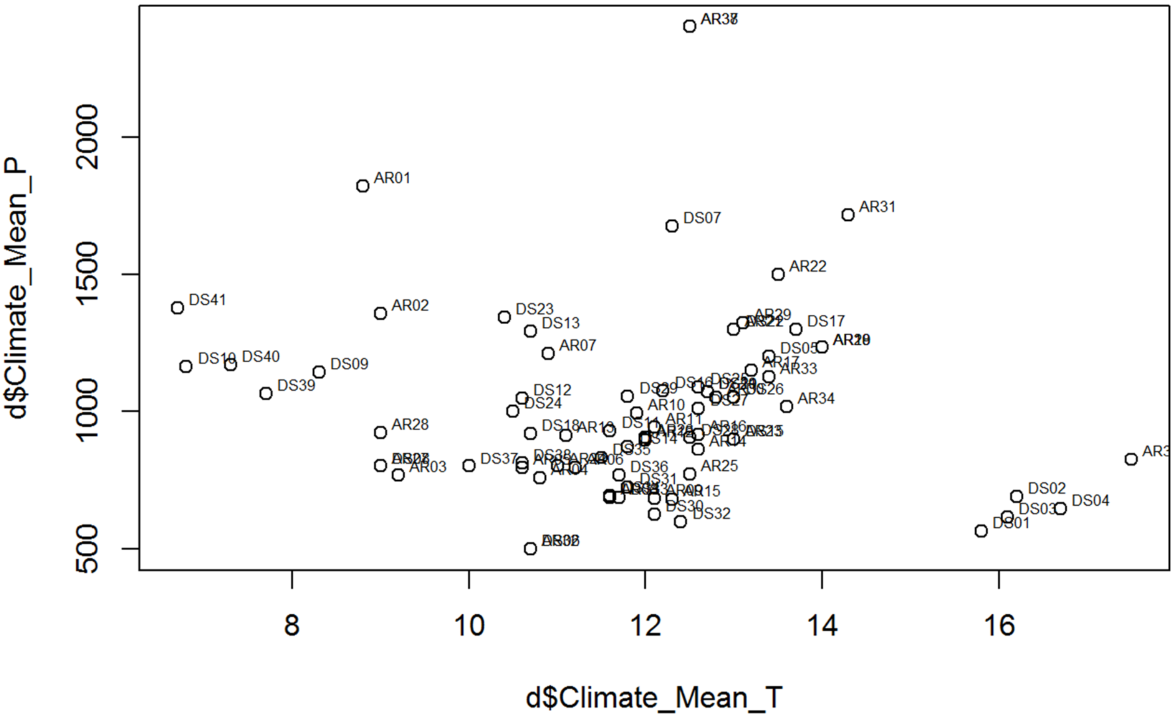
Supplementary S6 Temperature that causes death to 50 % of plants TL50 ranking (°C) per provenance

Provenance	**TL50 (°C)**
QURO-UNIT	-7,26
BEPE-NORD	-7,18
BEPE-KRAL	-7,15
QURO-POSA	-7,15
QURO-PAGO	-7,12
BEPE-UNIT	-6,82

Supplementary material for Article II

Supplementary material for the article "Early survival and growth plasticity of 33 species planted in 38 arboreta across Europe Atlantic Area" by Correia et al. (2018)

S1- Climate gradient along REINFFORCE network (1971-2000 normal). Graphic shows annual precipitation (mm) on y axis, and average monthly air temperature (ºC) on X axis. Arboreta are coded with AR, followed by arboreta number (from 01 to 38). DS coded data points refer to demonstration sites, not part of current work, but integral part of the full network.



Source: Christophe Orazio/IEFC - EFI planted Forests facility

S2- Species and provenance description, with coding used in this work

Species code	Species	Provenance location	Provenance code
ACPS	Acer pseudoplatanus	ALPS JURA, Switzerland	ACPS-ALPS
		France, Origine APS101 NORD	ACPS-NORD
		4 VERTIENTE SEPTENTRIONAL CANTABRICA, Spain	ACPS-VANA
		30, WALES, UK	ACPS-WALE
BEPE	Betula pendula	1, KRALOVA, Slovakia	BEPE-KRAL
		NORD EST ET MONTAGNE, France	BEPE-NORD
		30, WALES, UK	BEPE-UNIT
CADE	Calocedrus decurrens	CENTRAL CALIFORNIA - USA	CADE-CECA
		NORTHERN CALIFORNIA - USA	CADE-NOCA
		SOUTHERN CALIFORNIA - USA	CADE-SOCA
CASA	Castanea sativa	ES19 - SIERRA DE GREDOS - Spain	CASA-CORD
		MEDITERRANEE 741, France	CASA-MEDI
		BASSIN PARISIEN, France	CASA-PARI
CEAT	Cedrus atlantica	DJURDJURA, Algeria	CEAT-ALGE
		LUBERON CR TE, France	CEAT-LUBE
		CAT-PP-01 MENERBES, France	CEAT-MENE
CELI	Cedrus libani subsp. libani	MERSIN-ASLANKOY, Turkey	CELI-ADAN
		ADANAN-POZANTI, Turkey	CELI-POZA
		Turkey	CELI-TURK
CESI	Ceratonia siliqua	HVAR ISLAND, Croatia	CESI-HVAR
		Italy	CESI-ITAL
CULA	Cunninghamia lanceolata	LISHU - China	CULA-LISH
		SHAN XI, China	CULA-SHAN
		YUNNAN, China	CULA-YUNN
CUSE	Cupressus sempervirens	KOPRULU KANYON, Turkey	CUSE-ANTA
		France	CUSE-FRAN
		Var. Pyramidalis - Italy	CUSE-ITAL
EUGO	Eucalyptus globulus	E.globulus - WIELANGTA (18894), Tasmania - Australia	EUGO-WIEL
EUGU	Eucalyptus gundal	E.gundal I => France (plants)	EUGU-GUN1
EUNI	Eucalyptus nitens	E.nitens - RUBICON (18075), Victoria - Australia	EUNI-RUBI
FAOR	Fagus sylvatica subsp. orientalis	BURSA M.K.PASA, Marmara region, Turkey	FAOR-MARM
		ORDU MESUDIYE - BACKWARD BLACK SEA REGION - Turkey	FAOR-ORDU
		VEZIRKOPRU GOLKOY - BACKWARD BLACK SEA REGION - Turkey	FAOR-SINO
LADE	Larix decidua	ALPES INTERNES SUD, France	LADE-ALPE
		STRAZA, Slovenia	LADE-STRA
		LE THEIL, France	LADE-THEI
LIST	Liquidambar styraciflua	ARKANSAS - USA	LIST-ARKA
		Castelleone, Lombardie, Italy	LIST-ITAL
		Maryland, USA	LIST-MARY
		Missouri, USA	LIST-MISS
PIBU	Pinus brutia	Variety eldarica Crimea	PIBU-ELDA
		MARMARIS, Turkey	PIBU-MARM
		TAURUS, Turkey	PIBU-TAUO
PIEL	Pinus elliottii	GEORGIA - USA	PIEL-GEO
		LOUISIANA, USA	PIEL-LOU
		SOUTH CAROLINA - USA	PIEL-SOUT
PINI	Pinus nigra subsp. salzmannii	salzmannii - ES07b - SISTEMA IBERICO MERIDIONAL, SUR DE CUENCA - Spain	PINI-CUEN
	Pinus nigra subsp. laricio	Laricio variety calabrian LES BARNES-SIVENS, France	PINI-SIVE
		Laricio variety corsican SOLOGNE VAYRI_RES, France	PINI-VAYR
PIPI	Pinus pinea	2 VALLES DEL TIETAR Y DEL ALBERCHE, Spain	PIPI-CAST
		REGION MEDITERRANEENNE, France	PIPI-FRAN
		Italy	PIPI-ITAL
PIPO	Pinus ponderosa	CENTRAL CALIFORNIA - USA	PIPO-CALI
		Southern rockies (New Mexico)	PIPO-MEXI
		OREGON - USA	PIPO-OREG
PIPT	Pinus pinaster	PICARD (Lande Corse), France	PIPT-LACO
		MIMIZAN LANDES, France	PIPT-LAND
		TAMJOUT (COLLOBRIERE), Morocco - French seeds orchard	PIPT-TAMJ
PISY	Pinus sylvestris	5, SEVEROZAPADNA, Slovakia	PISY-SLOV
		Turkey	PISY-TURK
		ES10 - SIERRA DE GUADARRAMA - Spain	PISY-VALS
PITA	Pinus taeda	Hardiness zone Georgia seed orchard	PITA-GEOR
		SOUTHERN CALIFORNIA - USA	PITA-SOUT
		VIRGINIA - USA	PITA-VIRG
PSME	Pseudotsuga menziesii	CENTRAL CALIFORNIA - USA	PSME-CECA
		LUZETTE, France	PSME-LUZE
		WASHINGTON CASCADE, USA	PSME-WASH
QUIL	Quercus ilex subsp. rotundifolia	Ilex - CROATIA	QUIL-CROA
		ES11a - REGION EXTREMADURIENSE - Spain	QUIL-EXTR
		Spain	QUIL-SPAN
QUPE	Quercus petraea subsp. petraea	CHARENTES POITOU, France	QUPE-CHAR
		GASCOGNE, France	QUPE-GASC
		GRESIGNE - GASCOGNE, France	QUPE-GRES
		BRISTOL, UK	QUPE-UNIT
QURO	Quercus robur	France	QURO-FRAN
		LITORAL VASCO-NAVARRO (E 05)	QURO-PAGO
		SZLICHTYNGOWA, Pologne	QURO-SZLI
		New Forest, Hampshire, UK	QURO-UNIT
QURU	Quercus rubra	Rubra- EST 902, France	QURU-FEST
		ES06 - LITORAL VASCO - Spain	QURU-VANA
QUSH	Quercus shumardii	shumardii - Texas, USA	QUSH-TEXA
QUSU	Quercus suber	ALCACER DO SAL, Portugal	QUSU-ALCA
		PYRENEES ORIENTALES, France	QUSU-PYRE
		ES03 - MONTES DE TOLEDO VILLUERCAS - Spain	QUSU-VILL
ROPS	Robinia pseudoacacia	NOVI PAZAR -KULEVCHA, Bulgary	ROPS-KULE
		PUSZTAVACS,Hungary	ROPS-PUZT
SESE	Sequoia sempervirens	CALIFORNIA - USA	SESE-CAL2
		COAST CALIFORNIA - USA	SESE-COCA
		NORTHERN CALIFORNIA - USA	SESE-NOCA
THPL	Thuja plicata	IDAHO - USA	THPL-IDAH
		PORT ANGELES, Washington - USA	THPL-OLYM
		262 LEBANON, Oregon - USA	THPL-OREG

S3- Fitted model results table and plot for Eucalyptus 'Gundal' growth

Yearly Height Growth (Log) for Eucalyptus gundal			
Fixed part	**Estimate**	**% Variance**	**pval**
Intercept	1,775		0,1113
Site Mean Temperature	0,162		0,051
Site Precipitation	0,001		0,0308
Random part			
Site(Intercept)		52,498	
Residual		47,502	
AIC	627,760		
R² marginal	0,137		

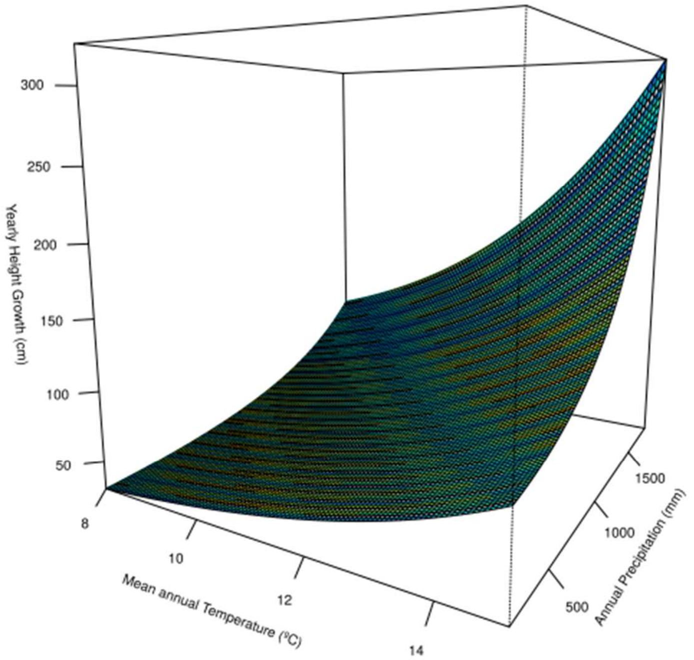
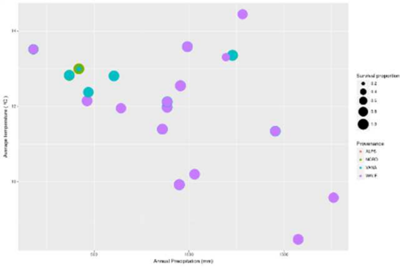
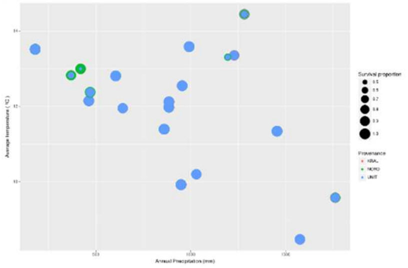
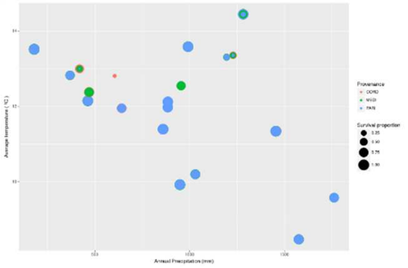
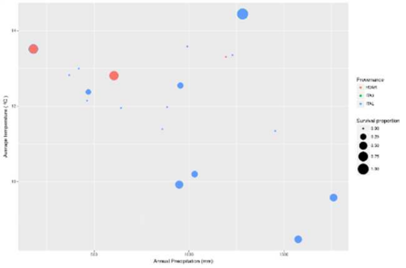
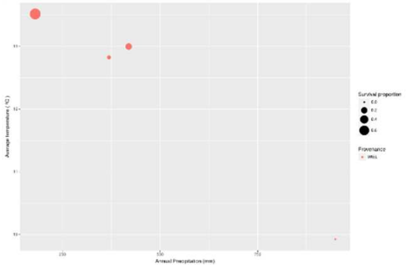
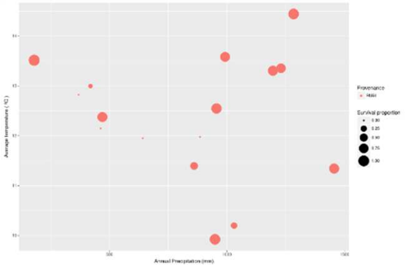
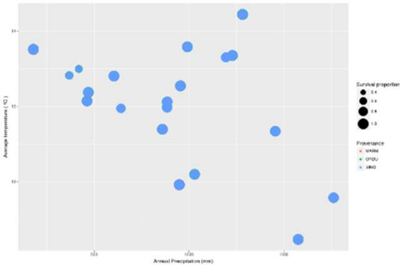
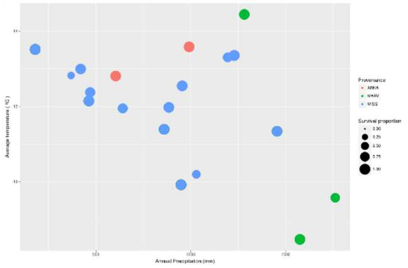
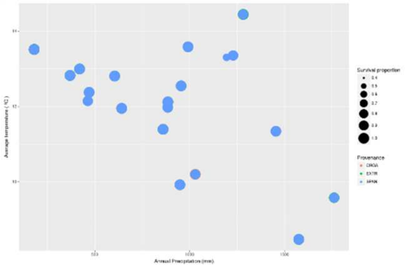
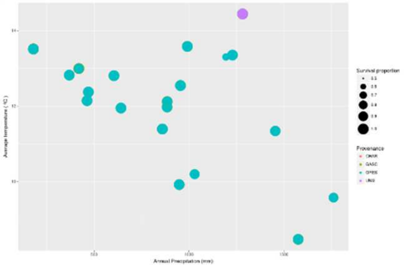
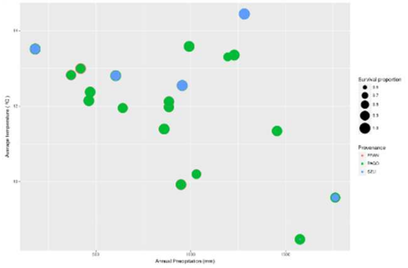
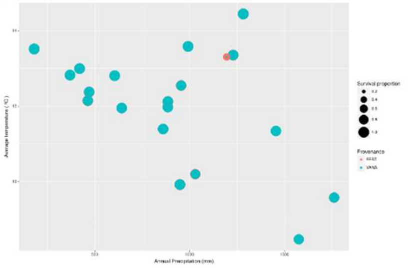
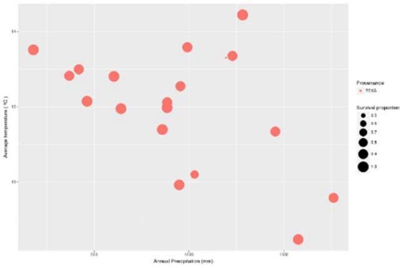


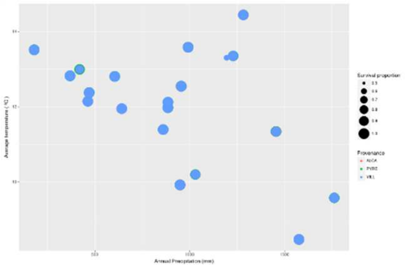
Figure 1 – Estimated Yearly Height Growth for explanatory variables "Mean annual Temperature" and "Annual Precipitation" for *Eucalyptus* 'Gundal'. Plotted surface expresses the model's estimated response

S4- Plotting survival vs. Mean annual temperature and annual accumulated precipitation for Broadleaf group. Point size reflects survival proportion (alive/total). Color represents provenance within species

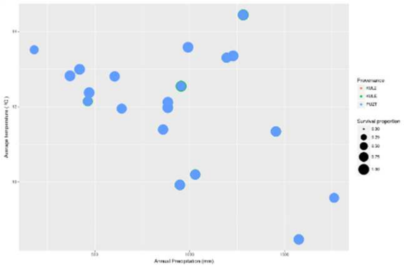
 Acer pseudoplatanus	 Betula pendula	 Castanea sativa
 Ceratonia siliqua	 Eucaliptus globulus	 Eucaliptus nitens
 Fagus orientalis	 Liquidambar styraciflua	 Quercus ilex
 Quercus petrea	 Quercus robur	 Quercus rubra



Quercus shumardii

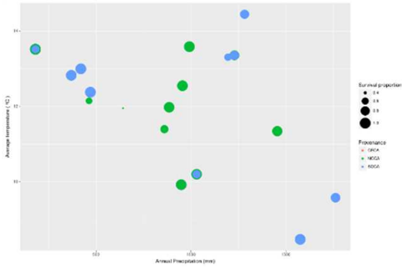
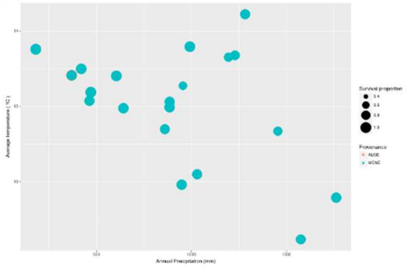
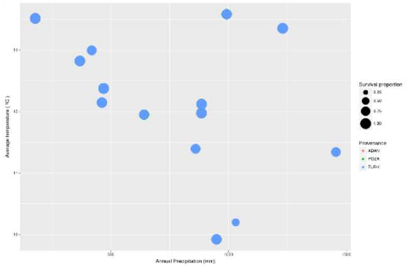
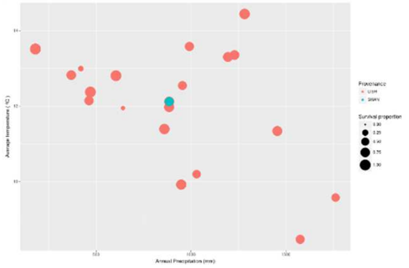
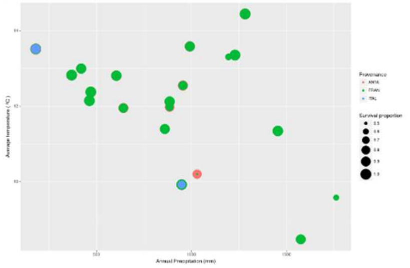
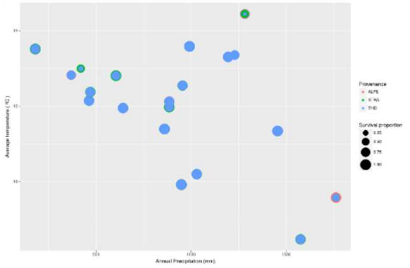
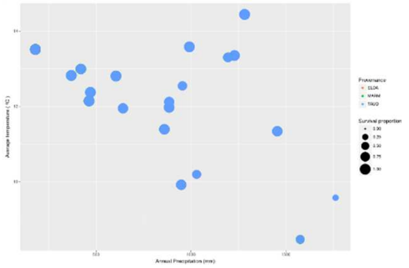
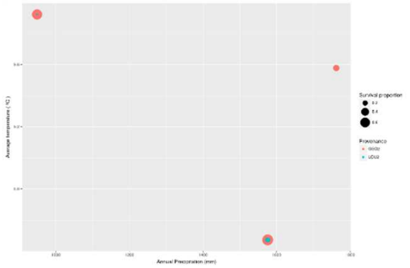
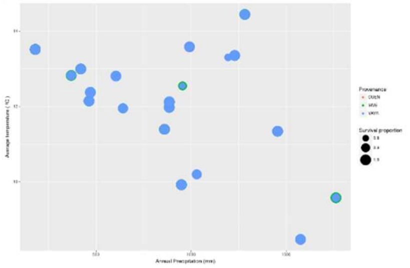
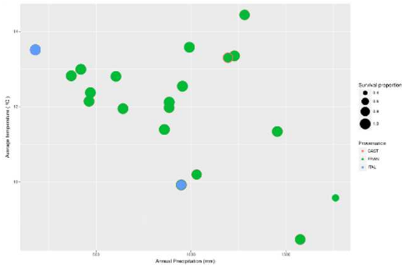
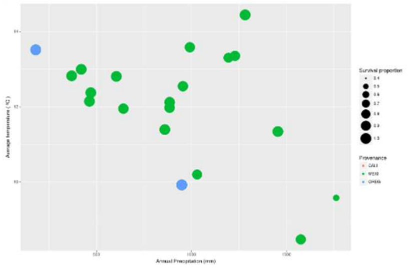
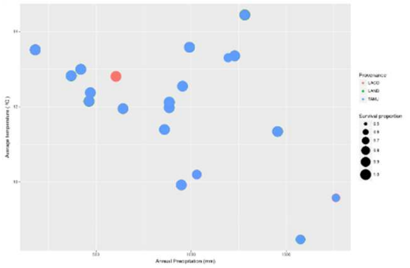


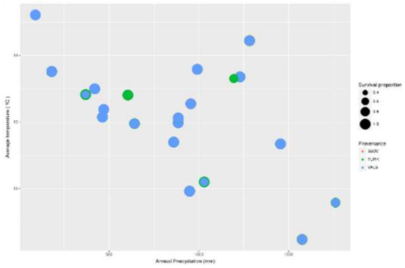
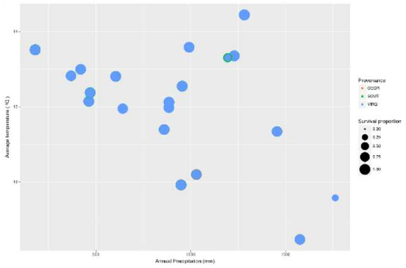
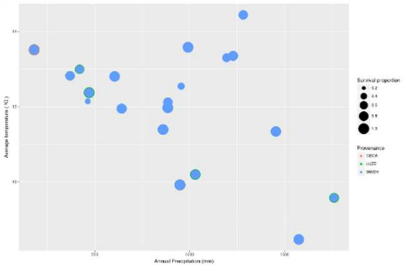
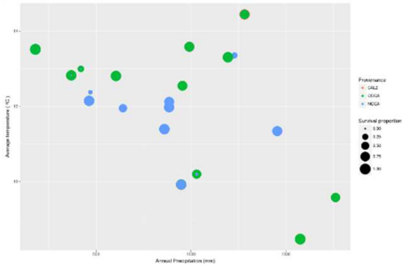
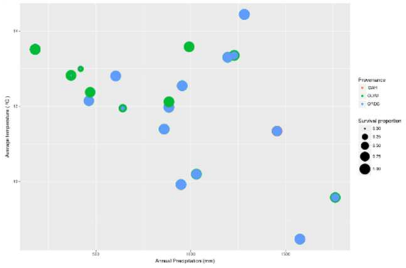
Quercus suber



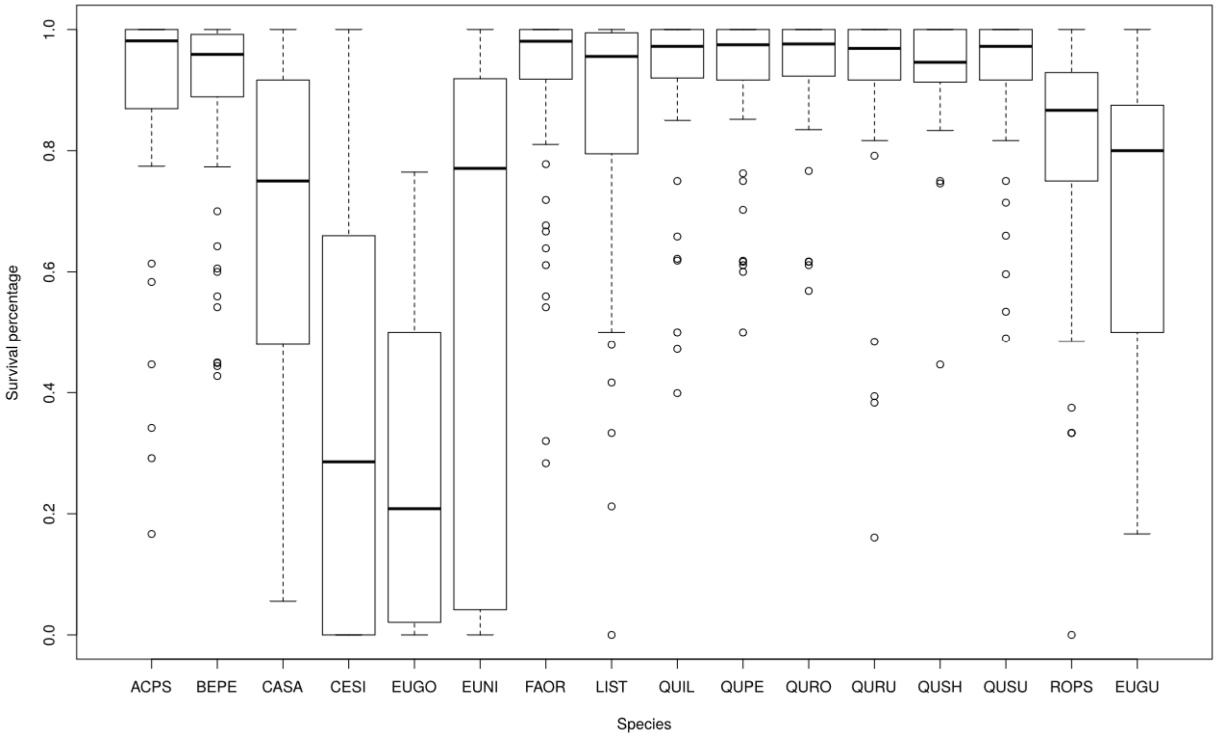
Robinia pseudoacacia

S5 - Plotting survival vs. Mean annual temperature and annual accumulated precipitation for Conifer group. Point size reflects survival proportion (alive/total). Different colors represent provenance within species.

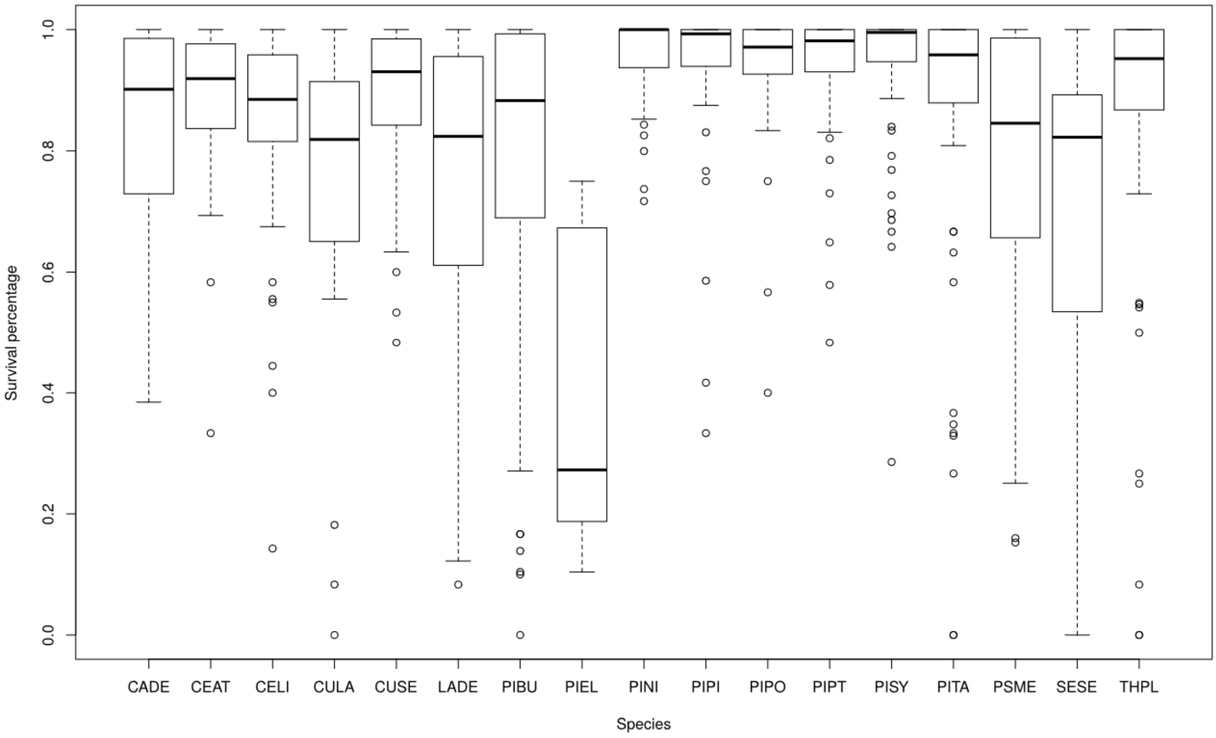
 Calocedrus decurens	 Cedrus atlantica	 Cedrus libani
 Cunninghamia lanceolata	 Cupressus sempervirens	 Larix decidua
 Pinus brutia	 Pinus elliotti	 Pinus nigra
 Pinus pinea	 Pinus ponderosa	 Pinus pinaster

 Pinus sylvestris	 Pinus taeda	 Pseudotsuga mensiesii
 Sequoia sempervirens	 Thuja plicata	

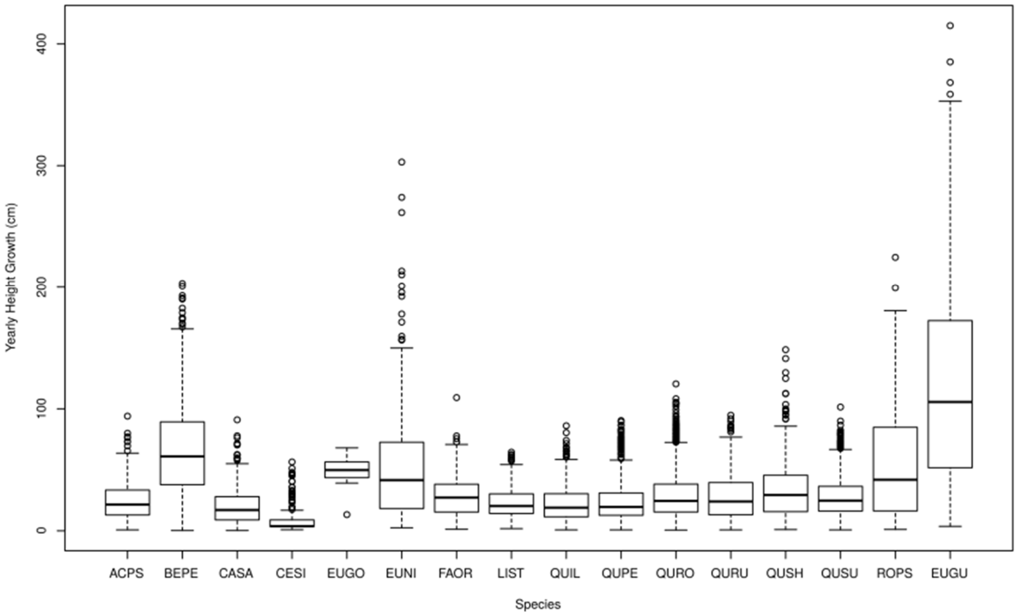
S6- Survival percentage for broadleaf species. The boxplot shows 50% of scores in the middle box. The bold horizontal line is the scores median.



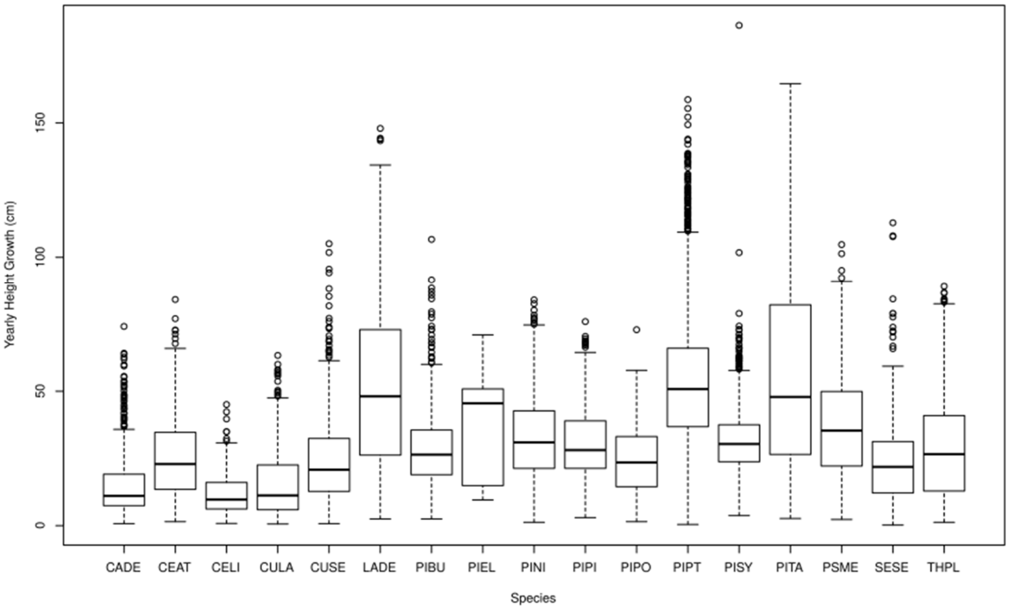
S7- Survival percentage for conifer species. The boxplot shows 50% of scores in the middle box. The bold horizontal line is the scores median.



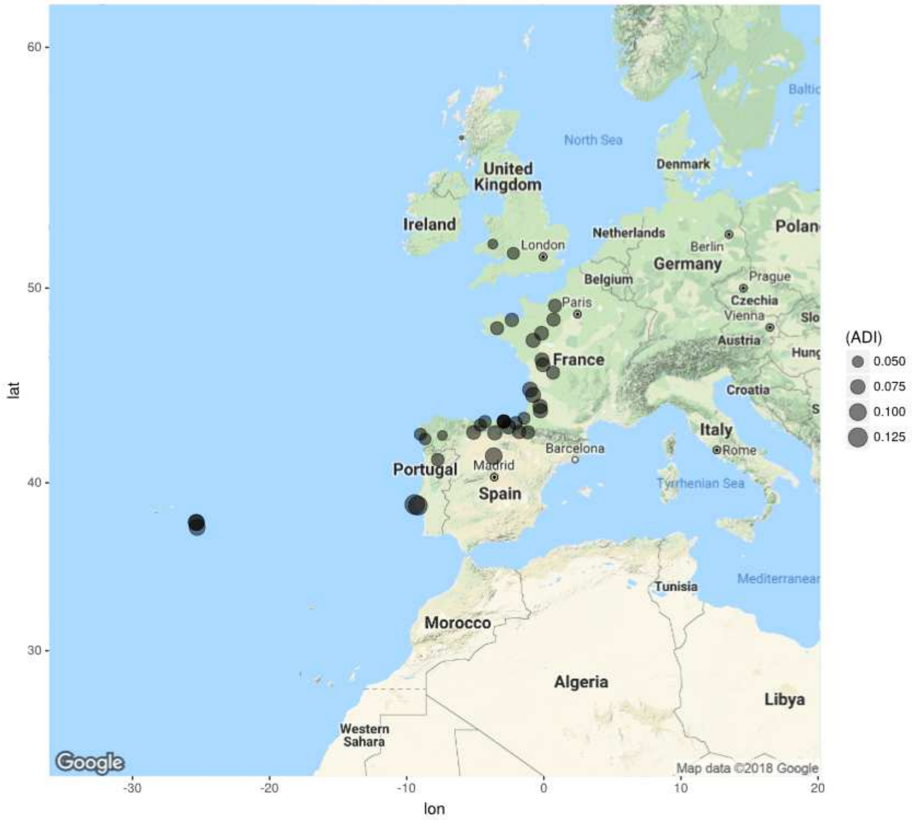
S8- Boxplot for Yearly Height Growth per broadleaf species along REINFFORCE arboreta gradient. Middle Box indicate inter-quartile range (50% of scores). Middle line indicates the median.

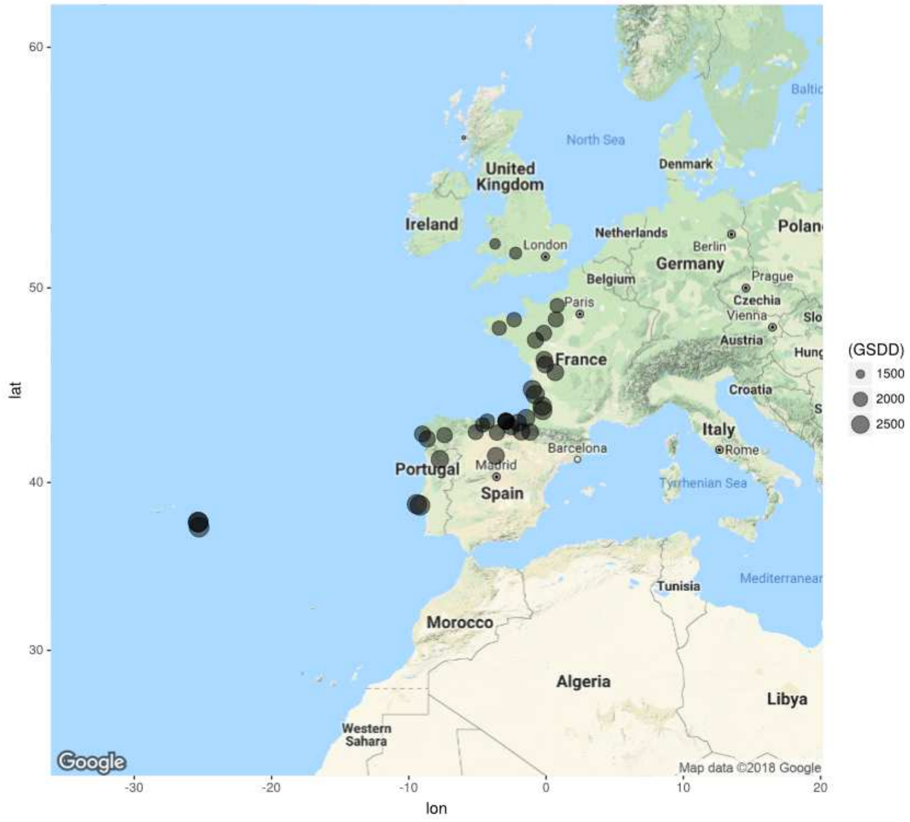


S9- Boxplot for Yearly Height Growth per conifer species, along REINFFORCE arboreta gradient. Middle Box indicate inter-quartile range (50% of scores). Middle line indicates the median.



S10- *up*: Arboreta classification for Annual Dryness Index - ADI (√Degree-days>5ºC/annual precipitation); *bottom*: growing season degree days- GSDD (degree-days above 5°C, for the April-September period). Circumference size indicates the value of the variable




60
50
40
30
lat
-30
-20
-10
0
10
20
lon
(GSDD)
1500
2000
2500
North Sea
Baltic
United Kingdom
Ireland
London
Denmark
Netherlands
Berlin
Poland
Germany
Belgium
Prague
Czechia
Paris
Vienna
Slo
Austria
Hung
France
Croatia
Italy
Rome
Barcelona
Portugal
Madrid
Spain
Tyrrhenian Sea
Tunisia
Mediterranean
Morocco
Algeria
Libya
Western Sahara
Google
Map data ©2018 Google

Supplementary material for Article III

Supplementary material for Risk analysis on 33 forest species performance along a 9 °C mean temperature gradient for RCP 4.5 and 8.5 scenarios using REINFFORCE arboreta network results

Mapping risk analysis results for Broadleaf species:

S1 to S16

Mapping risk analysis results for Conifer species:

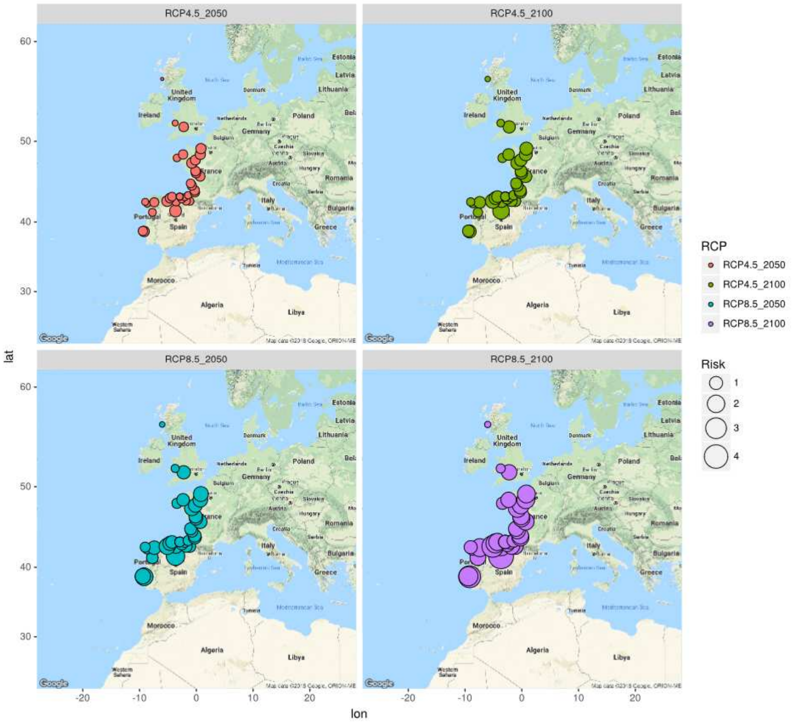
S17 to S33

Bi-dimensional Trade-off plotting, growth-survival, per scenario:

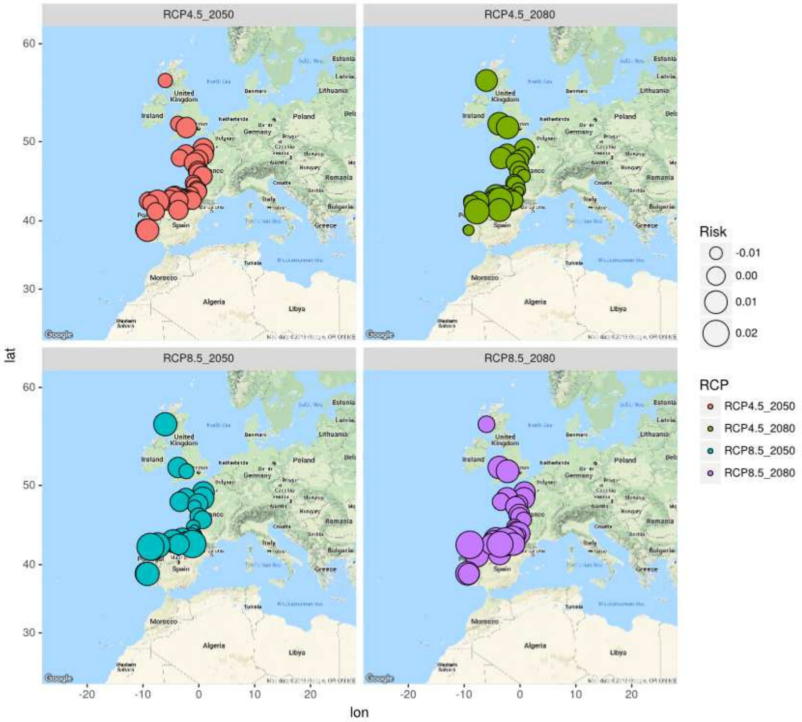
S34, S35

S1- Risk analysis results for *Acer pseudoplatanus*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a) *Acer pseudoplatanus*, yearly growth Risk in cm

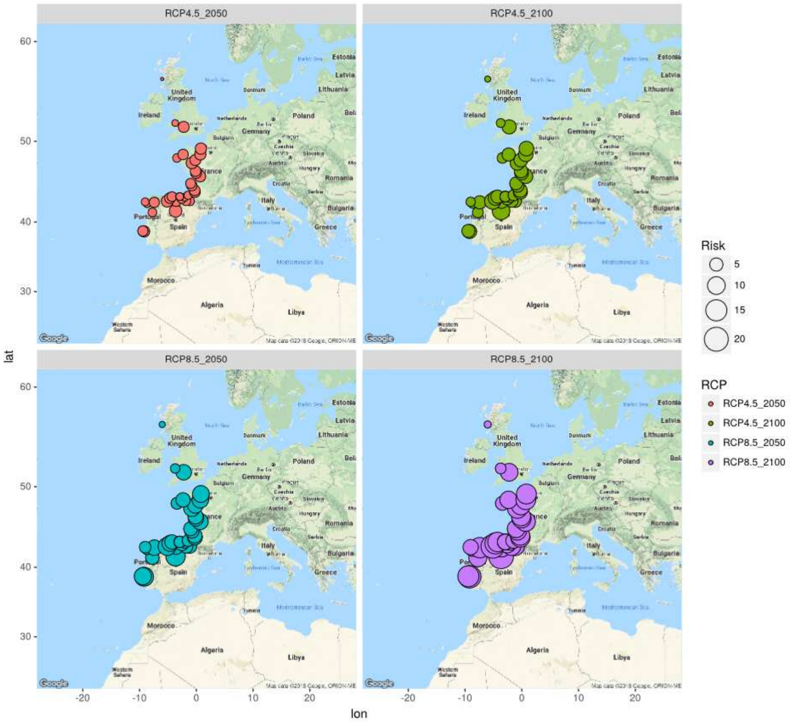


b) *Acer pseudoplatanus*, survival Risk in probability

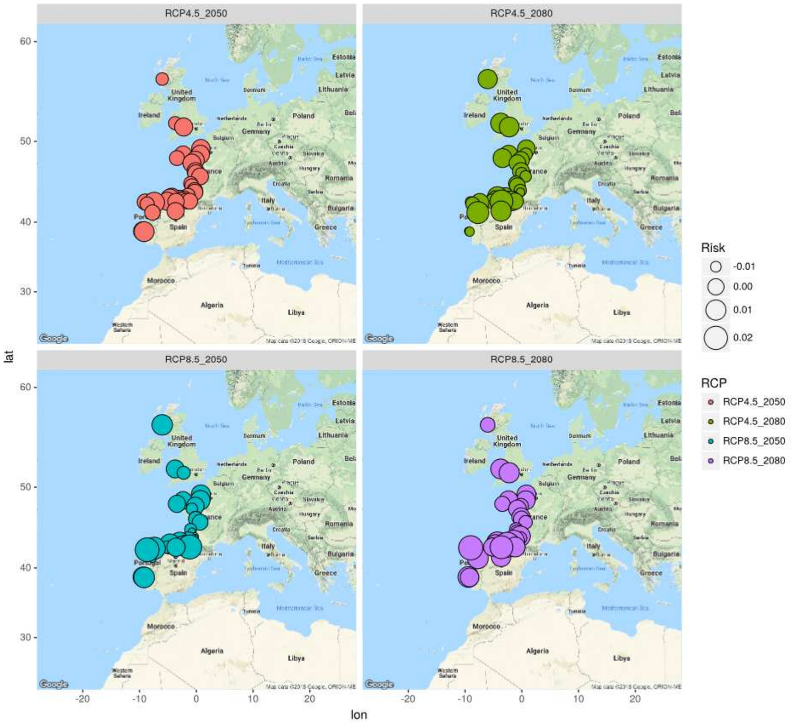


S2- Risk analysis results for *Betula pendula*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

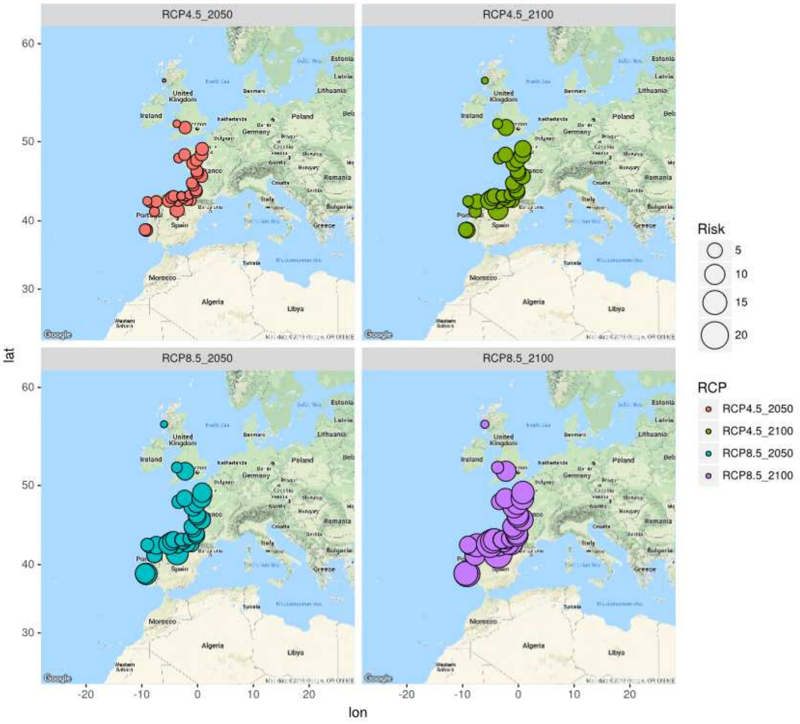


b)

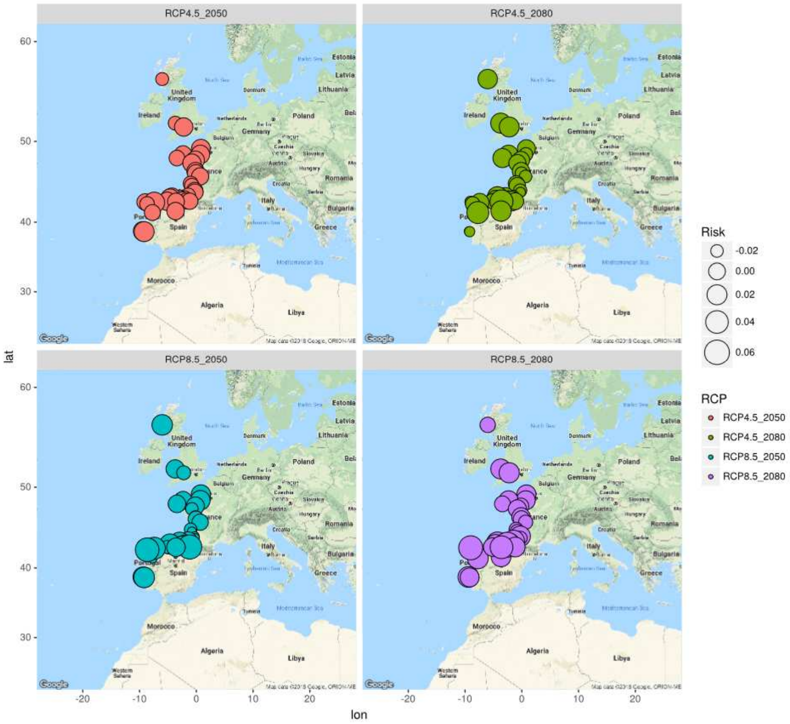

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
60
50
40
30
lon
-20
-10
0
10
20
Risk
-0.01
0.00
0.01
0.02
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080

S3- Risk analysis results for *Castanea sativa*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

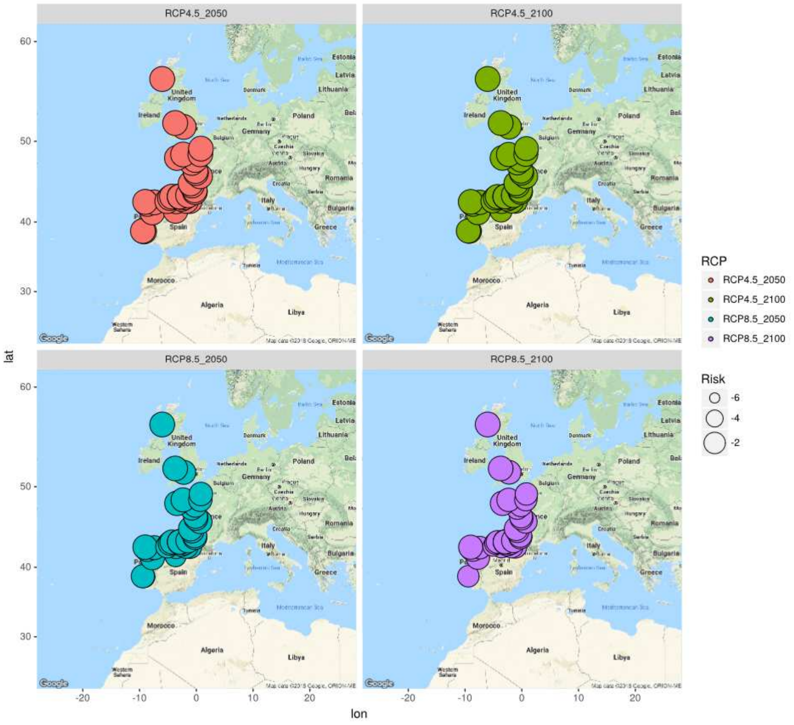


b)

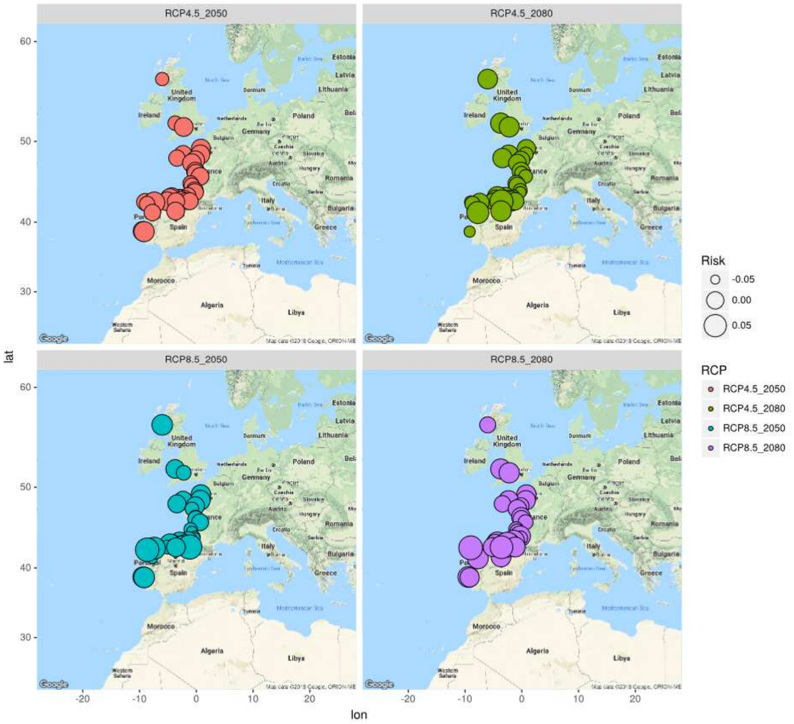

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
lon
60
50
40
30
-20
-10
0
10
20
Risk
-0.02
0.00
0.02
0.04
0.06
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080

S4- Risk analysis results for *Ceratonia siliqua*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

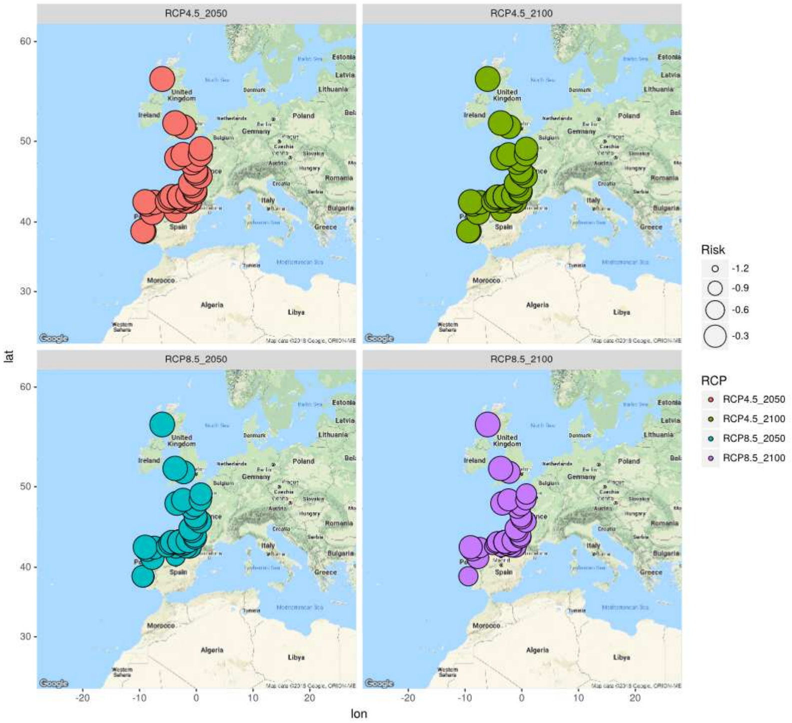


b)

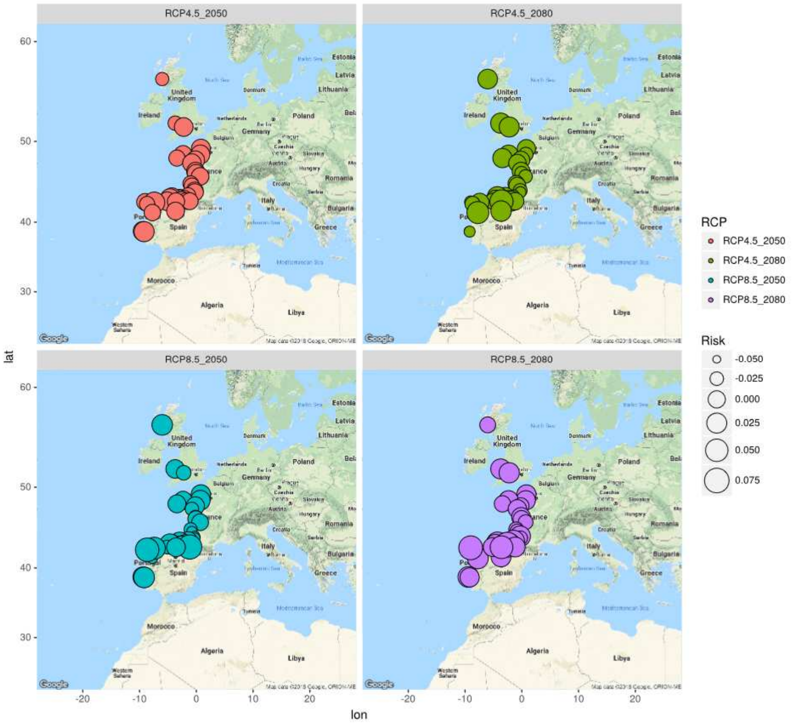

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
lon
60
50
40
30
-20
-10
0
10
20
Risk
-0.05
0.00
0.05
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080

S5- Risk analysis results for *Eucalyptus globulus*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

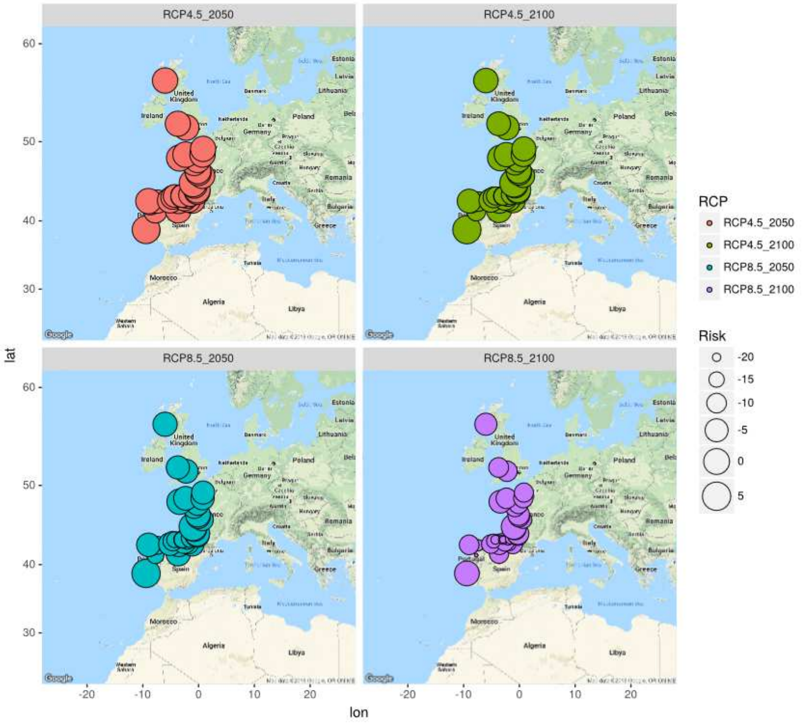


b)

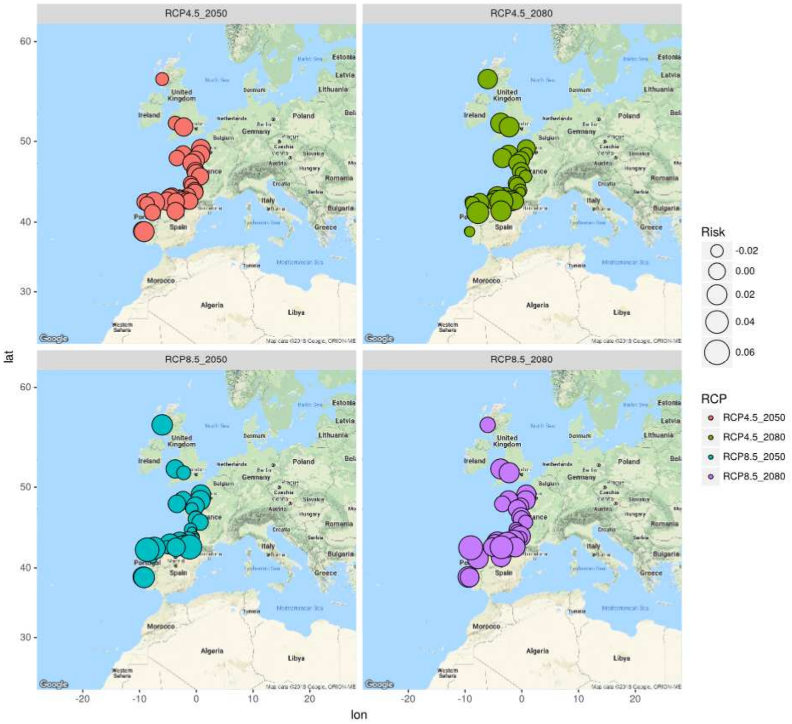

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
60
50
40
30
lon
-20
-10
0
10
20
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
Risk
-0.050
-0.025
0.000
0.025
0.050
0.075

S6- Risk analysis results for *Eucalyptus gundal* (*E. gunni x dalrympleana* hybrid), for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

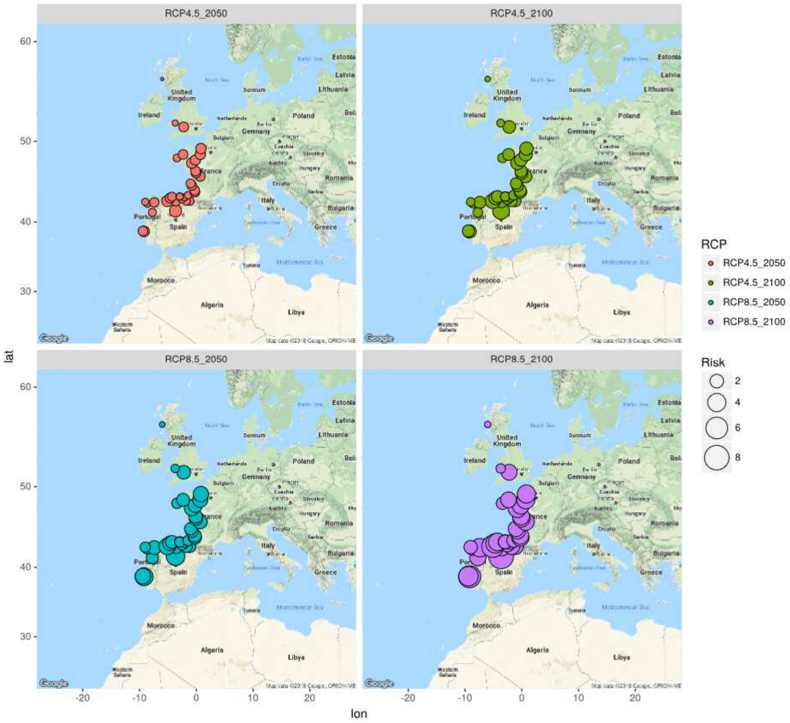


b)

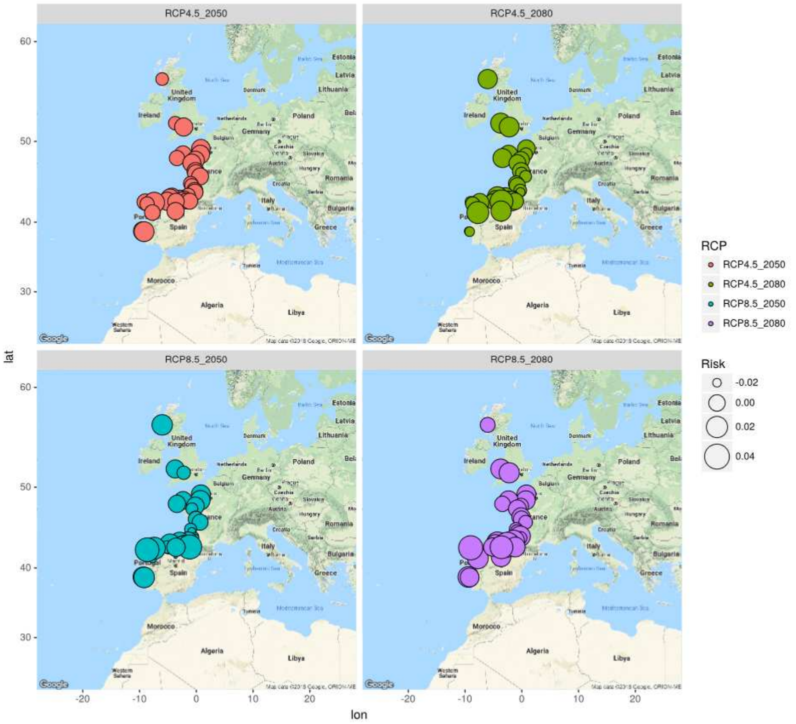

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
60
50
40
30
lon
-20
-10
0
10
20
Risk
-0.02
0.00
0.02
0.04
0.06
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080

S7- Risk analysis results for *Eucalyptus nitens*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

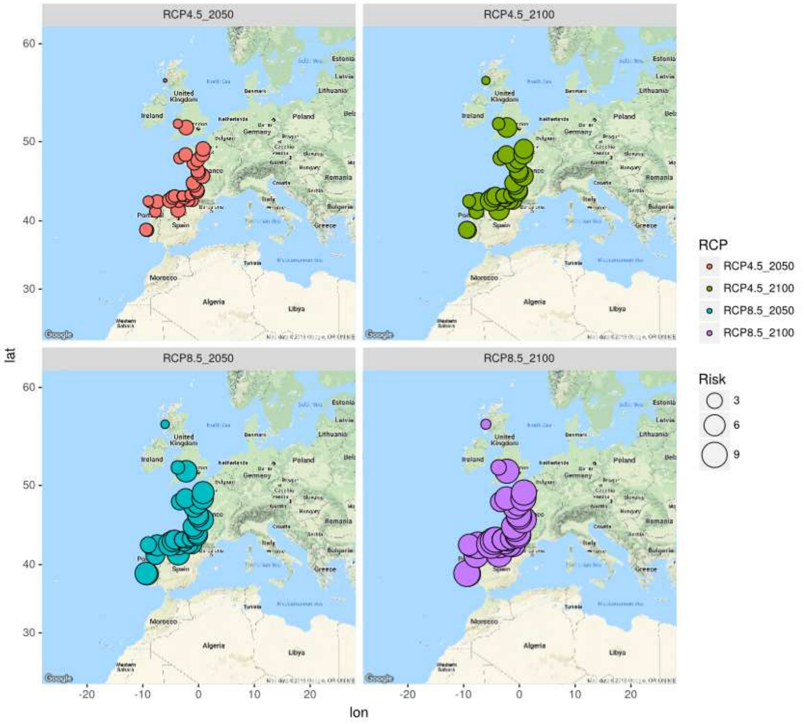


b)

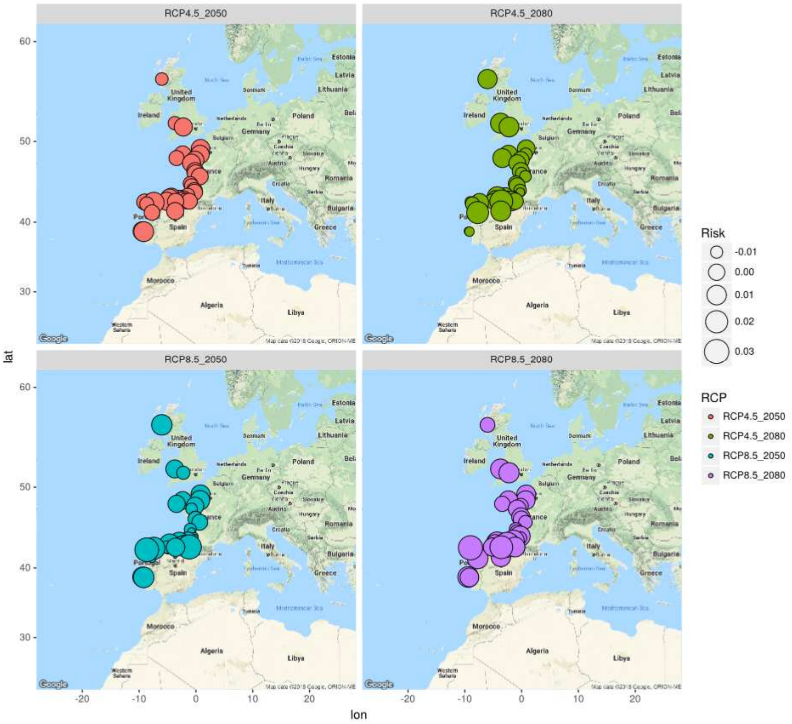

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
60
50
40
30
lon
-20
-10
0
10
20
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
Risk
-0.02
0.00
0.02
0.04

S8- Risk analysis results for *Fagus orientalis*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

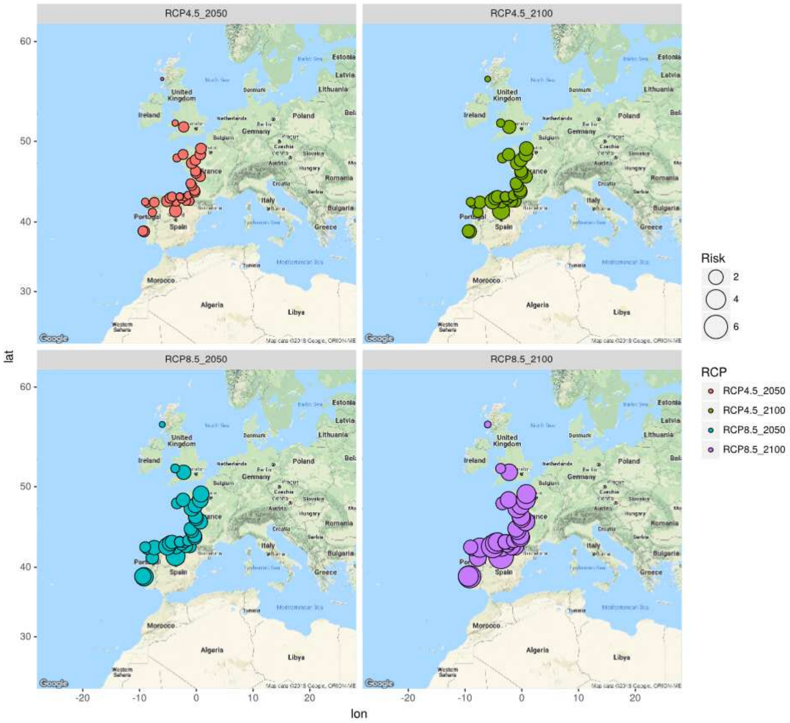


b)

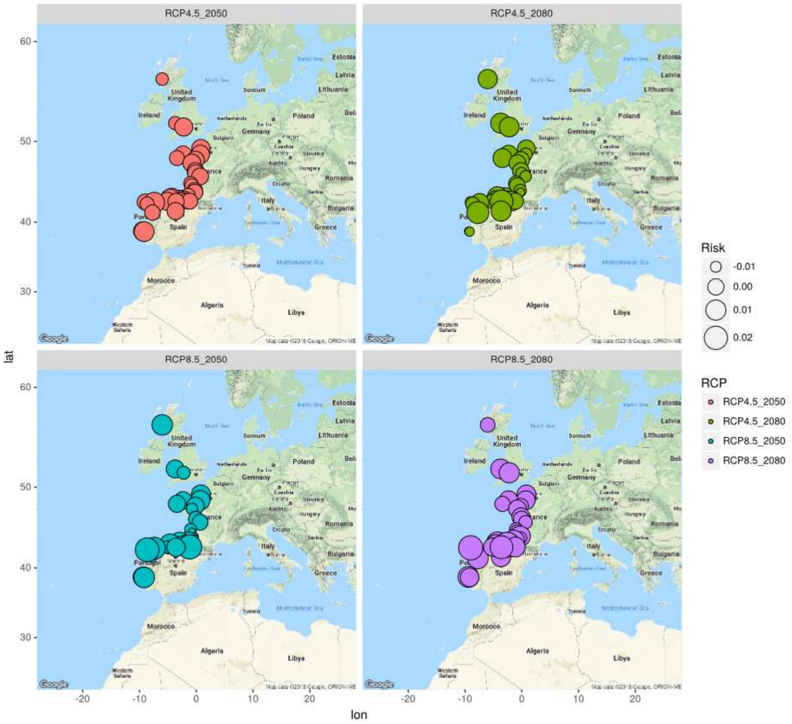

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
60
50
40
30
lon
-20
-10
0
10
20
Risk
-0.01
0.00
0.01
0.02
0.03
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
United Kingdom
Ireland
Spain
Portugal
France
Germany
Poland
Italy
Greece
Morocco
Algeria
Libya
Western Sahara
Denmark
Lithuania
Latvia
Estonia
Romania
Bulgaria
Hungary
Serbia
Croatia
Austria
Belgium
Netherlands
Google
Map data ©2018 Google, ORION-ME

S9- Risk analysis results for *Liquidambar styraciflua*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

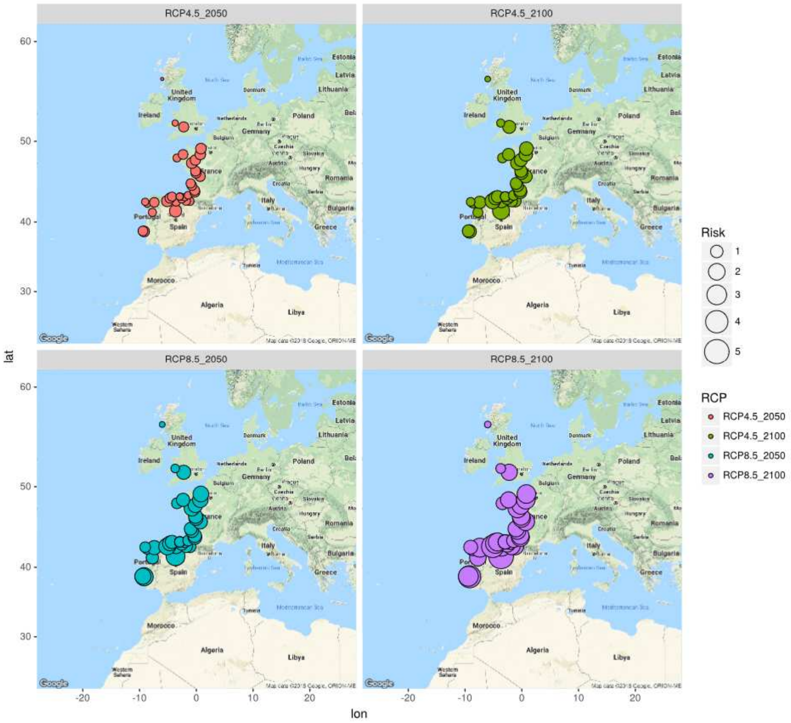


b)

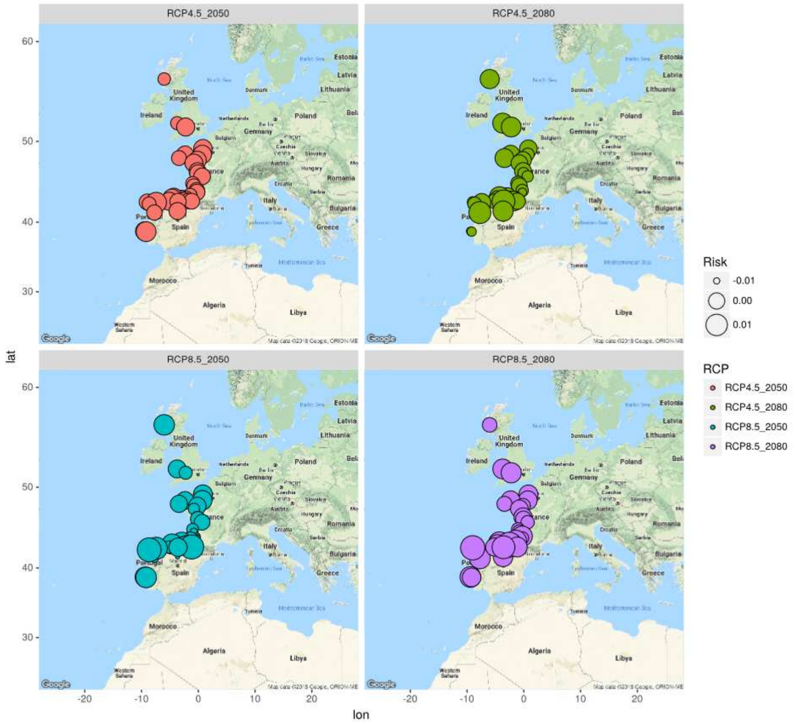

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
60
50
40
30
lon
-20
-10
0
10
20
Risk
-0.01
0.00
0.01
0.02
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080

S10- Risk analysis results for *Quercus ilex*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

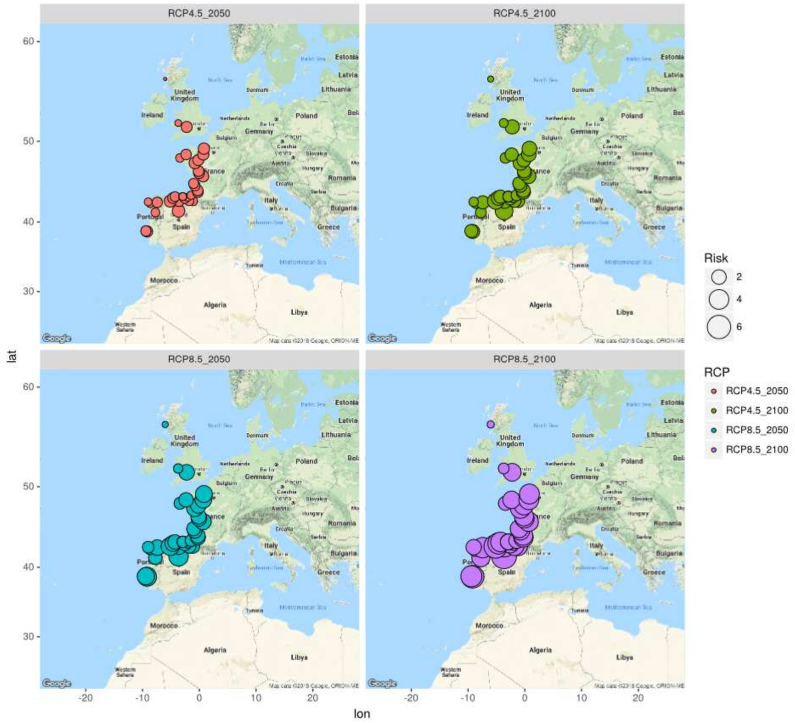


b)

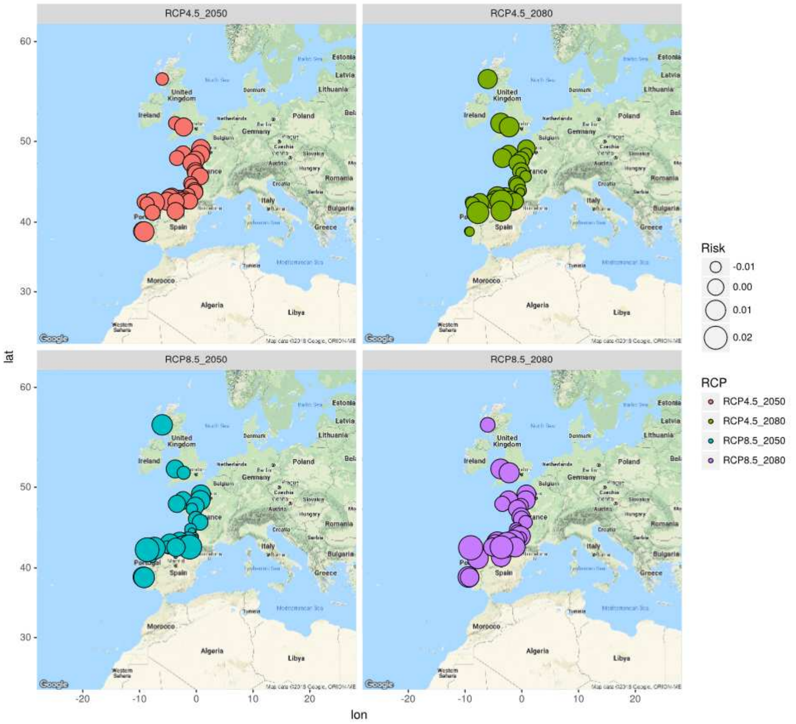

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
lon
60
50
40
30
-20
-10
0
10
20
Risk
-0.01
0.00
0.01
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
United Kingdom
Ireland
Germany
Poland
Spain
Italy
Greece
Morocco
Algeria
Libya
Estonia
Latvia
Lithuania
Romania
Bulgaria
Western Sahara

S11- Risk analysis results for *Quercus petrea*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

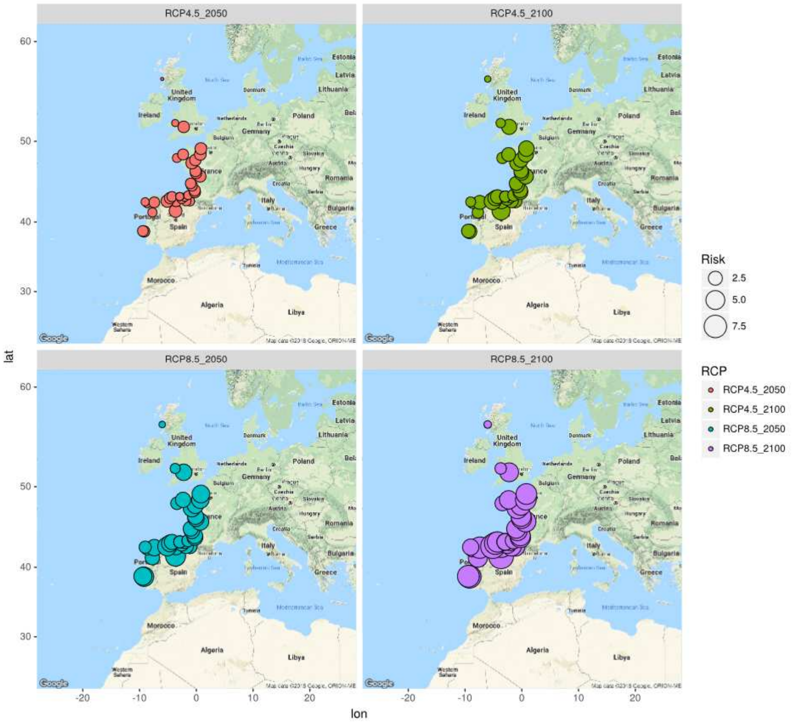


b)

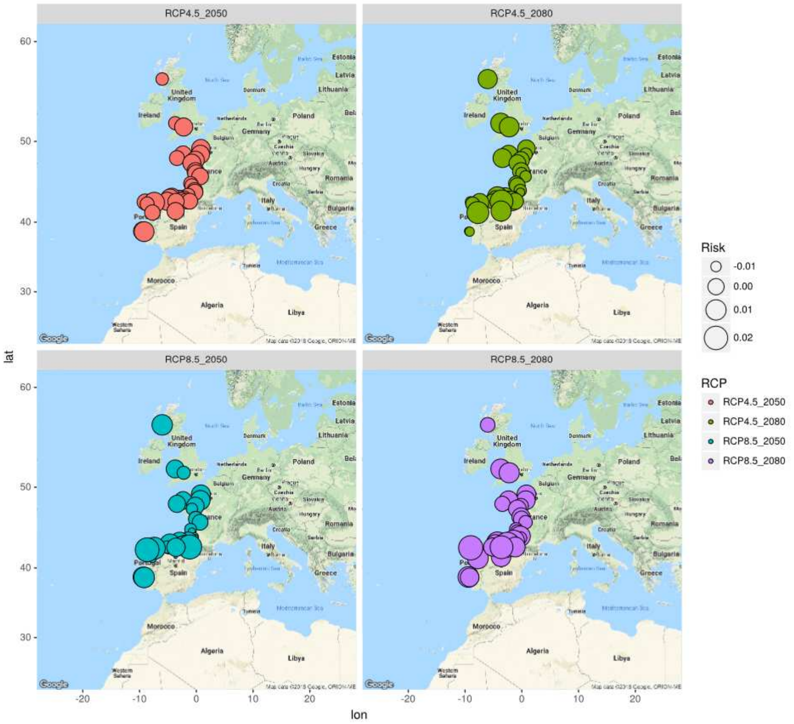

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
lon
60
50
40
30
-20
-10
0
10
20
Risk
-0.01
0.00
0.01
0.02
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080

S12- Risk analysis results for *Quercus robur*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

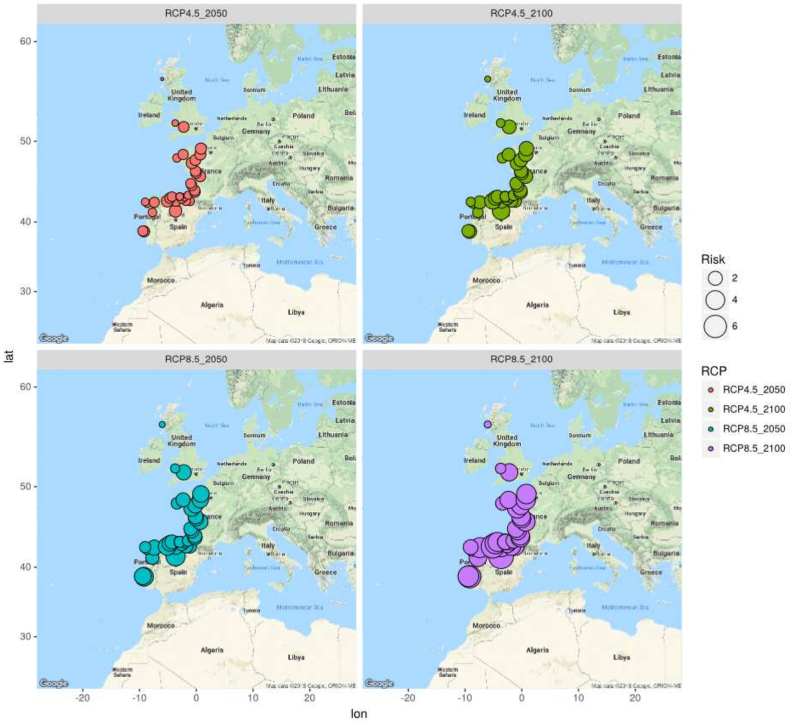


b)

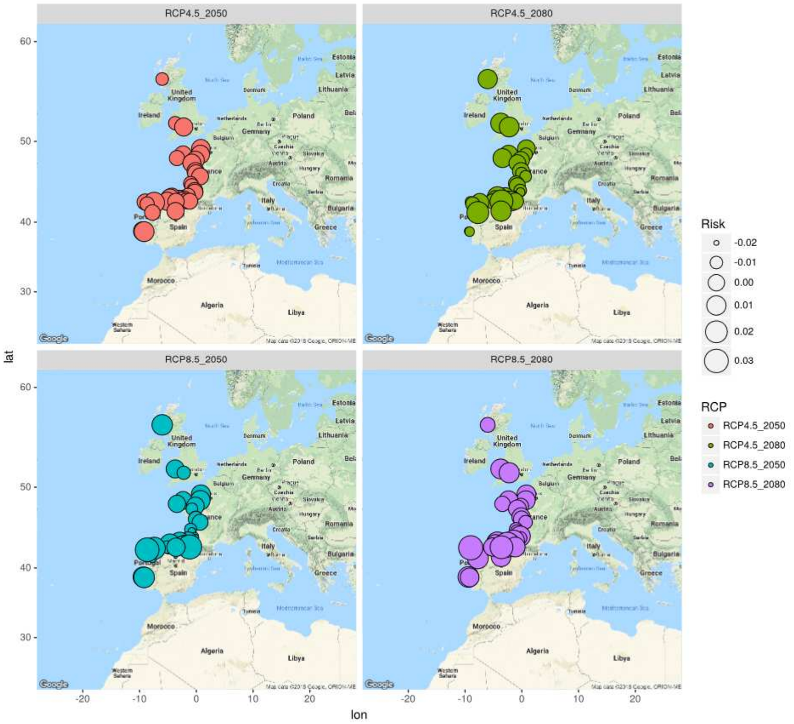

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
60
50
40
30
lon
-20
-10
0
10
20
Risk
-0.01
0.00
0.01
0.02
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080

S13- Risk analysis results for *Quercus rubra*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

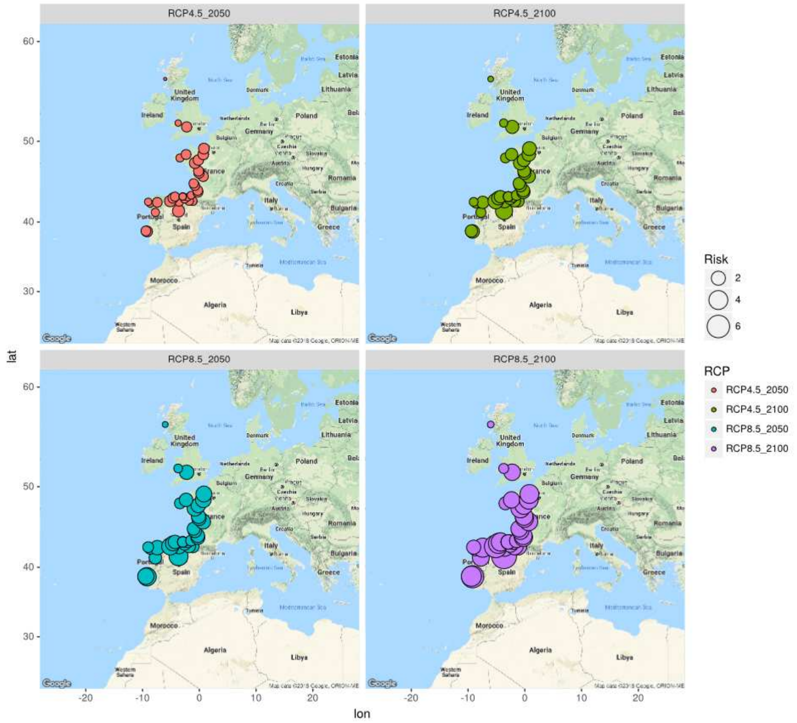


b)

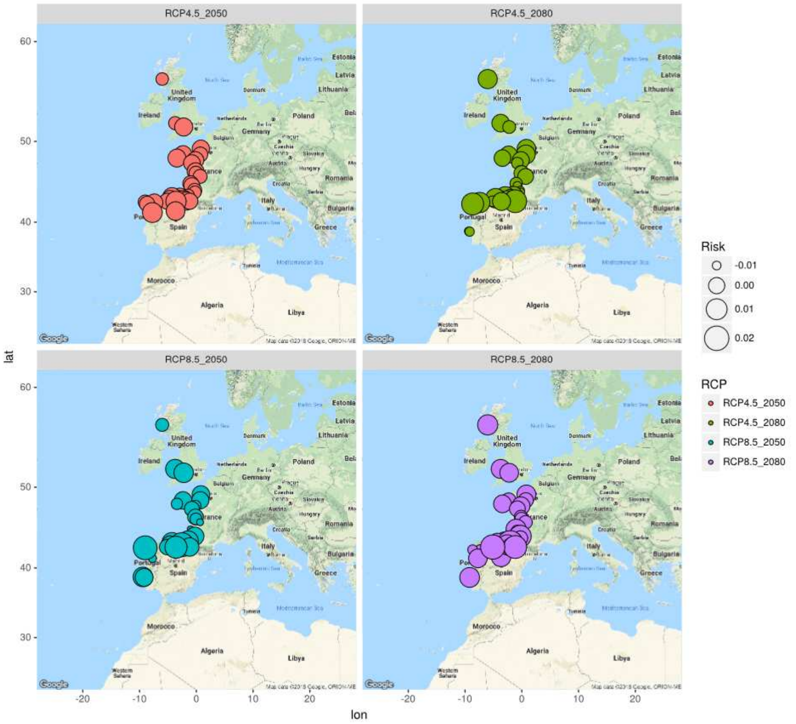

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
60
50
40
30
lon
-20
-10
0
10
20
Estonia
Latvia
Lithuania
United Kingdom
Ireland
Denmark
Poland
Germany
Netherlands
Belgium
France
Spain
Portugal
Italy
Austria
Hungary
Slovakia
Czechia
Croatia
Serbia
Romania
Bulgaria
Greece
Morocco
Algeria
Tunisia
Libya
Western Sahara
North Sea
Mediterranean Sea
Google
Map data ©2018 Google, ORION-ME
Risk
-0.02
-0.01
0.00
0.01
0.02
0.03
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080

S14- Risk analysis results for *Quercus schumardii*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

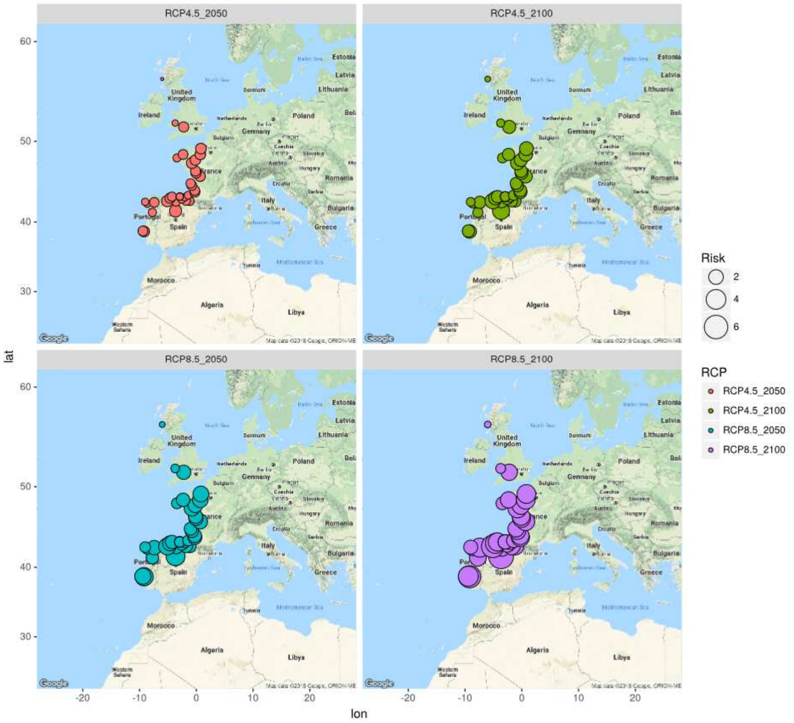


b)

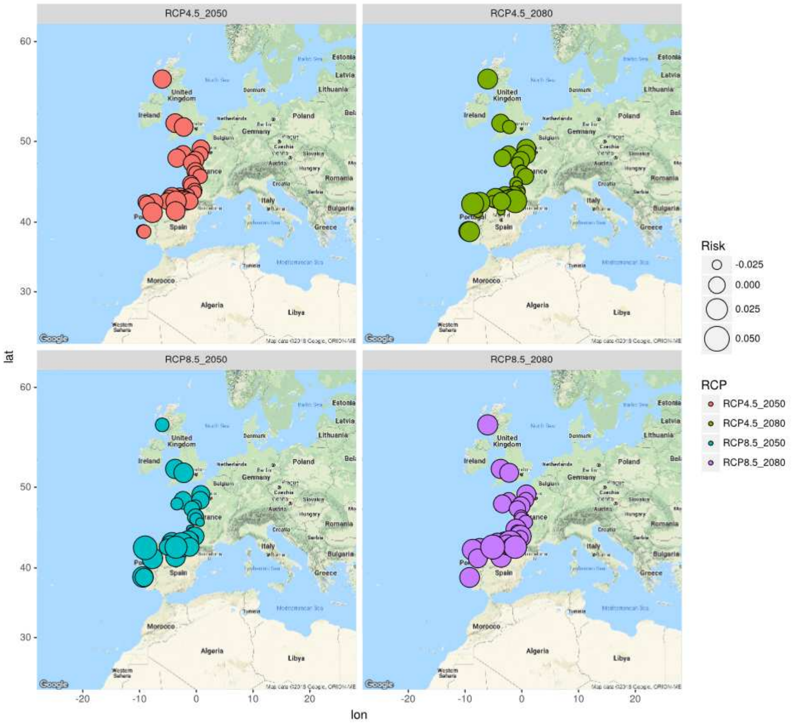

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
lon
60
50
40
30
-20
-10
0
10
20
Risk
-0.01
0.00
0.01
0.02
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080

S15- Risk analysis results for *Quercus suber*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

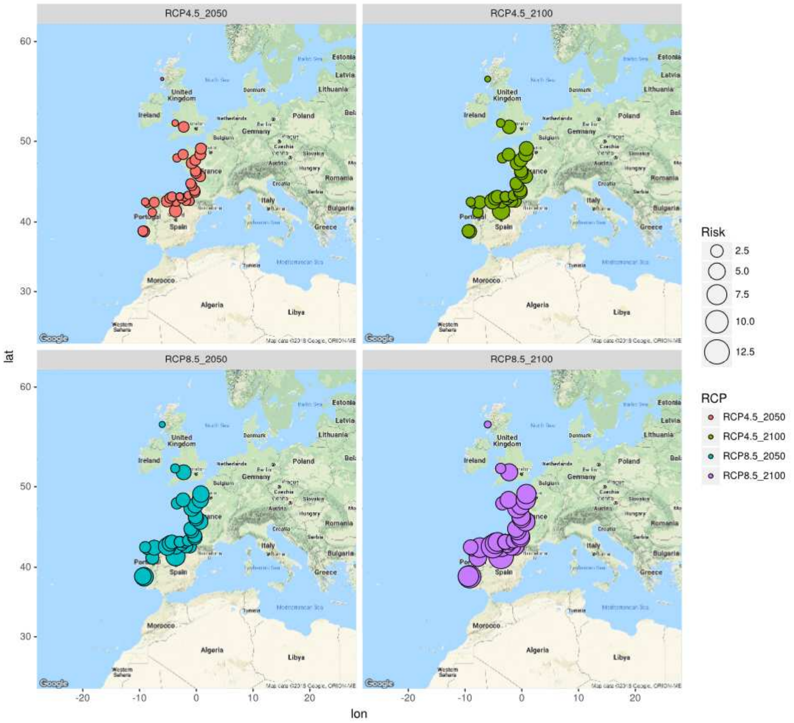


b)

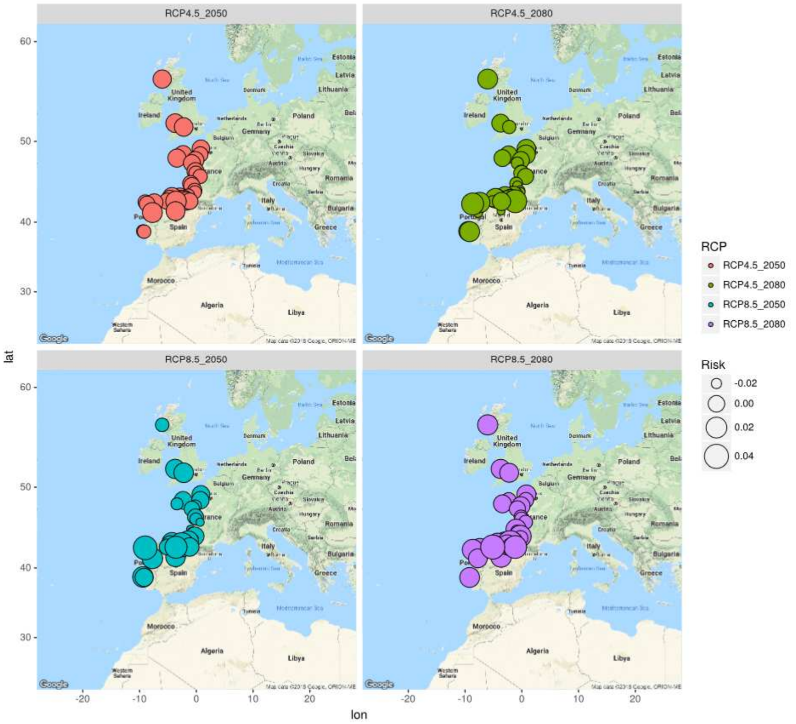

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
lon
60
50
40
30
-20
-10
0
10
20
Risk
-0.025
0.000
0.025
0.050
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080

S16- Risk analysis results for *Robinia pseudoacacia*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

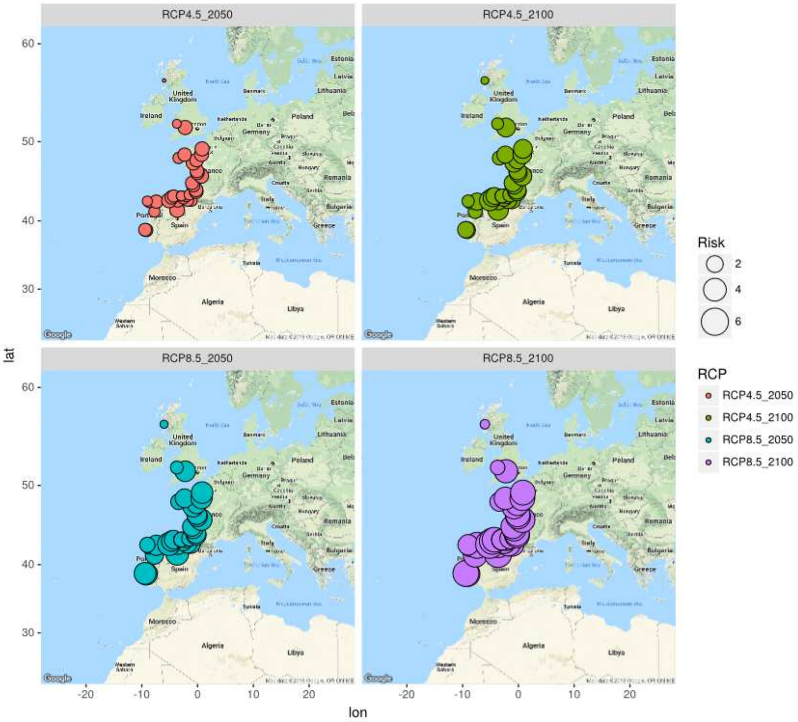


b)

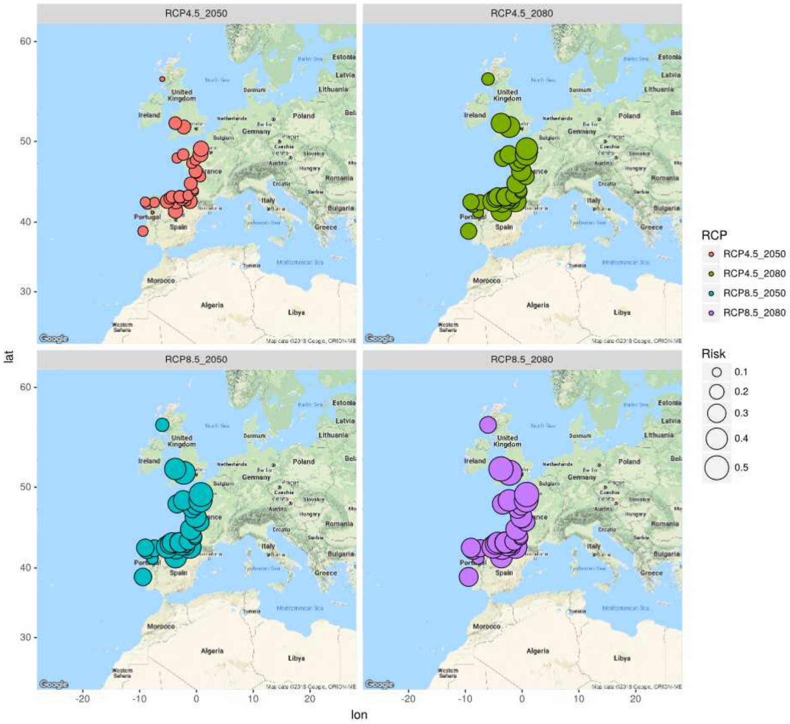

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
lon
60
50
40
30
-20
-10
0
10
20
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
Risk
-0.02
0.00
0.02
0.04

S17- Risk analysis results for *Calocedrus decurrens*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

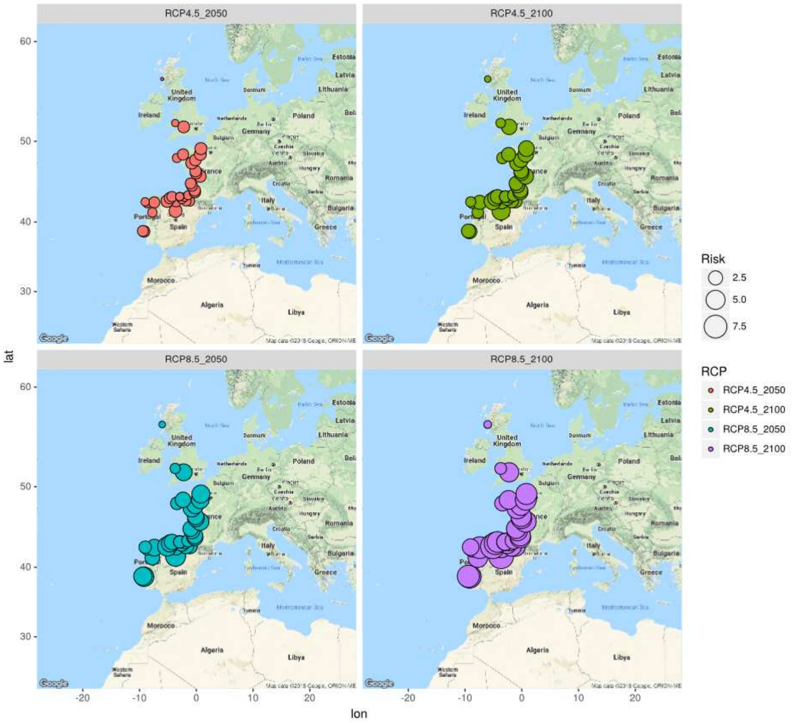


b)

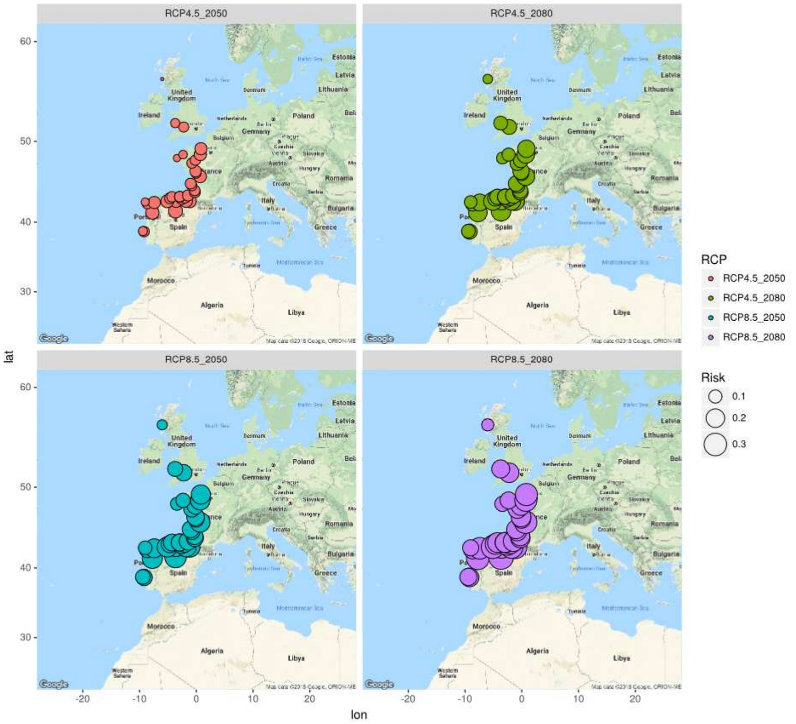

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
60
50
40
30
lon
-20
-10
0
10
20
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
Risk
0.1
0.2
0.3
0.4
0.5

S18- Risk analysis results for *Cedrus atlantica*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

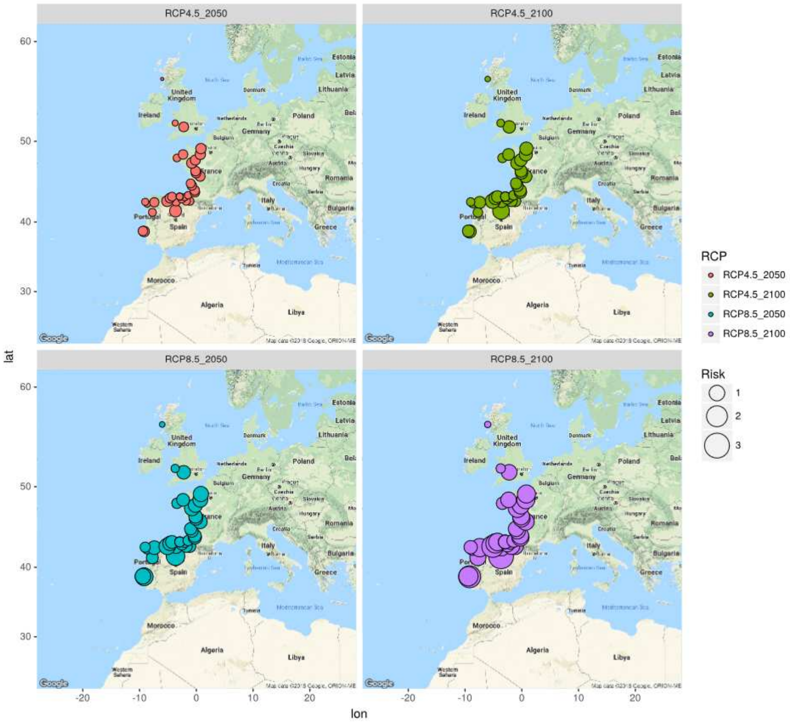


b)

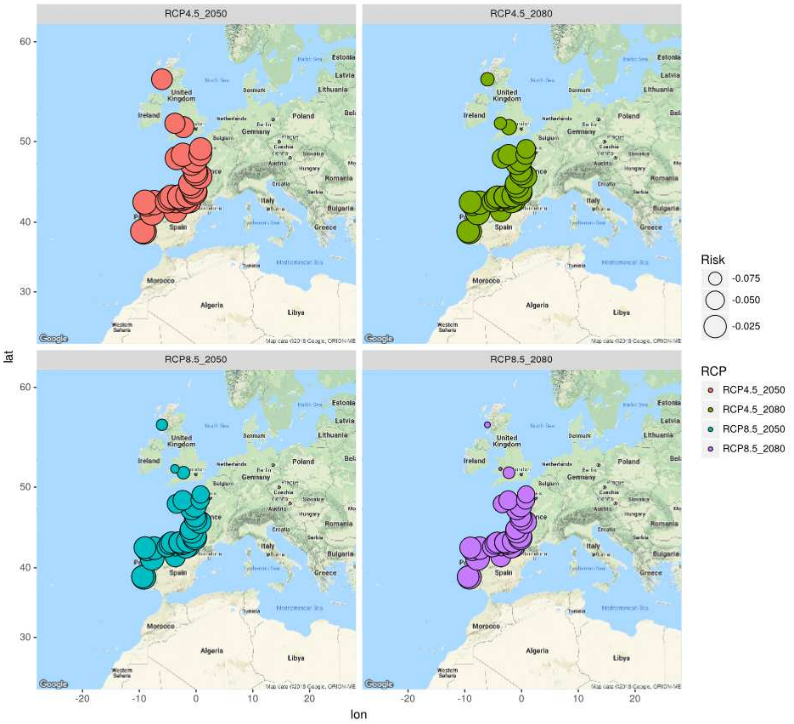

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
60
50
40
30
lon
-20
-10
0
10
20
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
Risk
0.1
0.2
0.3
Map data ©2018 Google, ORION-ME

S19- Risk analysis results for *Cedrus libani*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

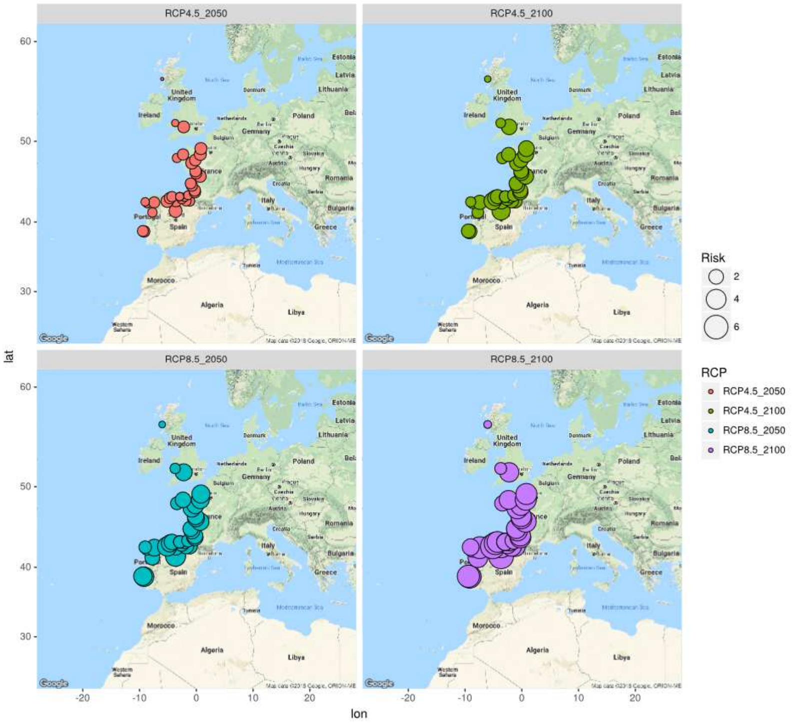


b)

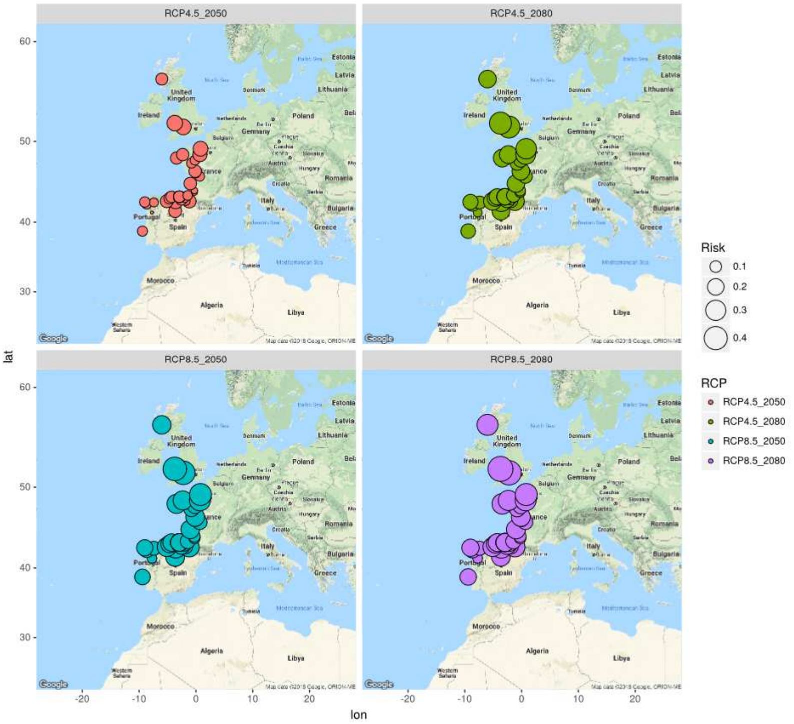

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
60
50
40
30
lon
-20
-10
0
10
20
Risk
-0.075
-0.050
-0.025
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080

S20- Risk analysis results for *cunninghamia lanceolata*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

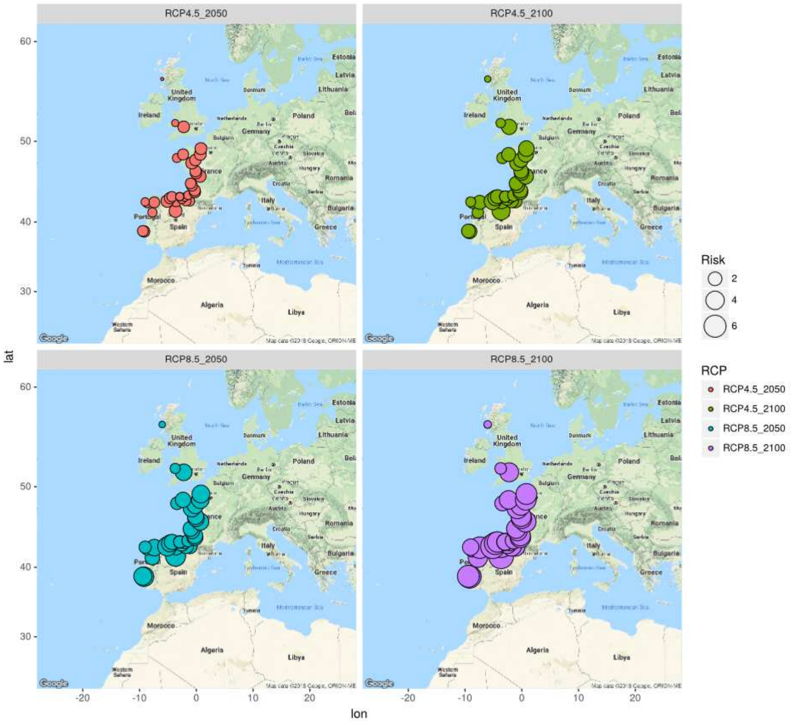


b)

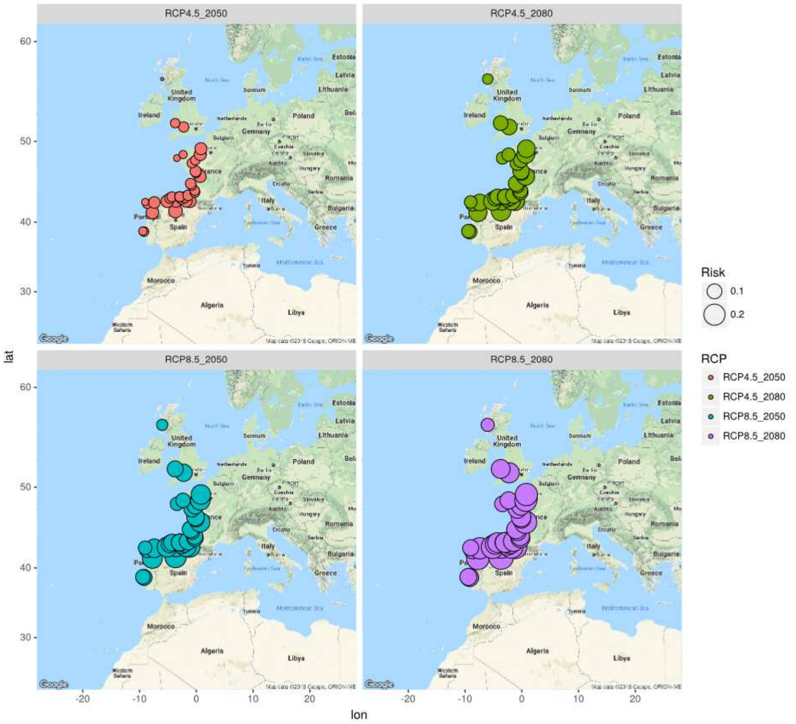

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
60
50
40
30
lon
-20
-10
0
10
20
Risk
0.1
0.2
0.3
0.4
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080

S21- Risk analysis results for *Cupressus sempervirens*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

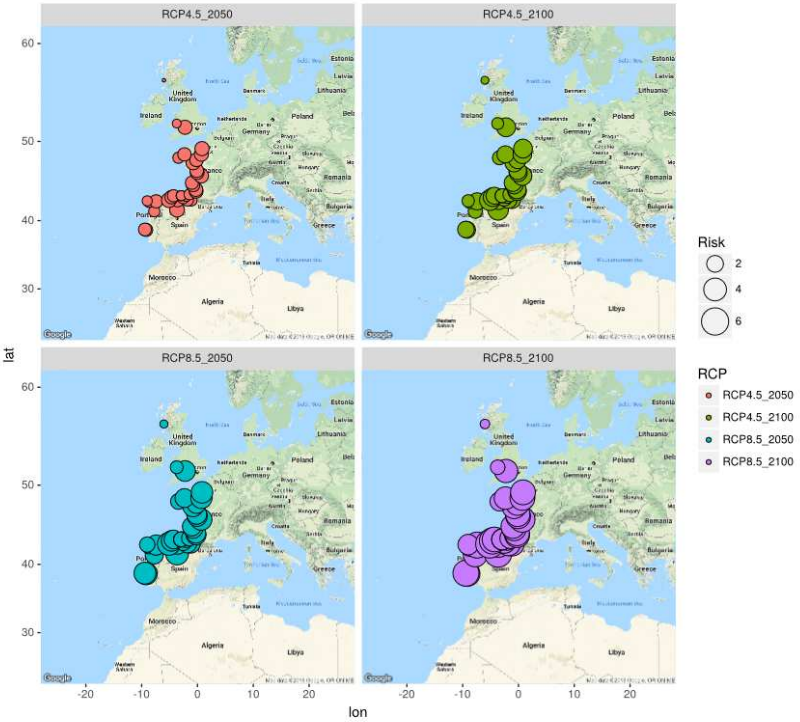


b)

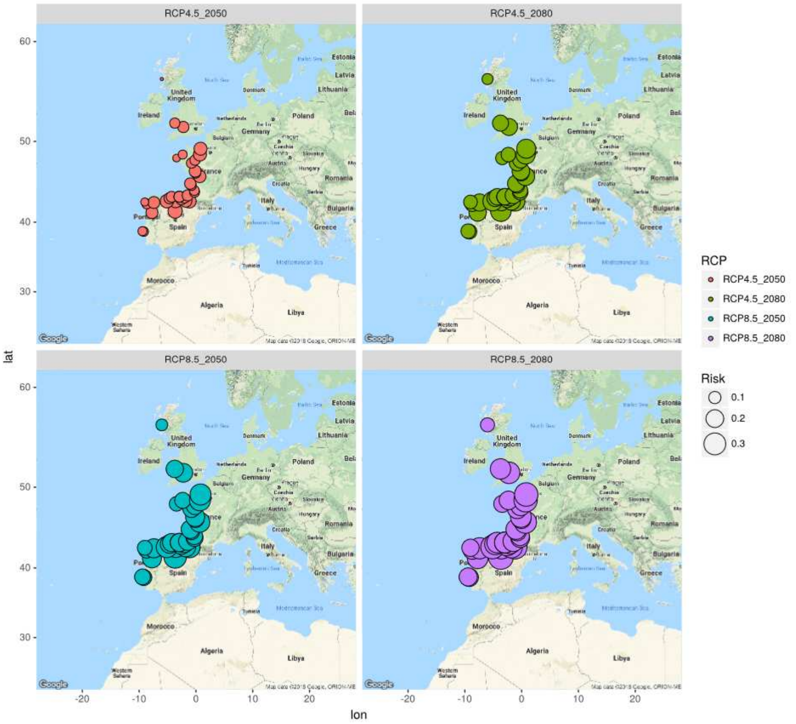

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
60
50
40
30
lon
-20
-10
0
10
20
Risk
0.1
0.2
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080

S22- Risk analysis results for *Larix decidua*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

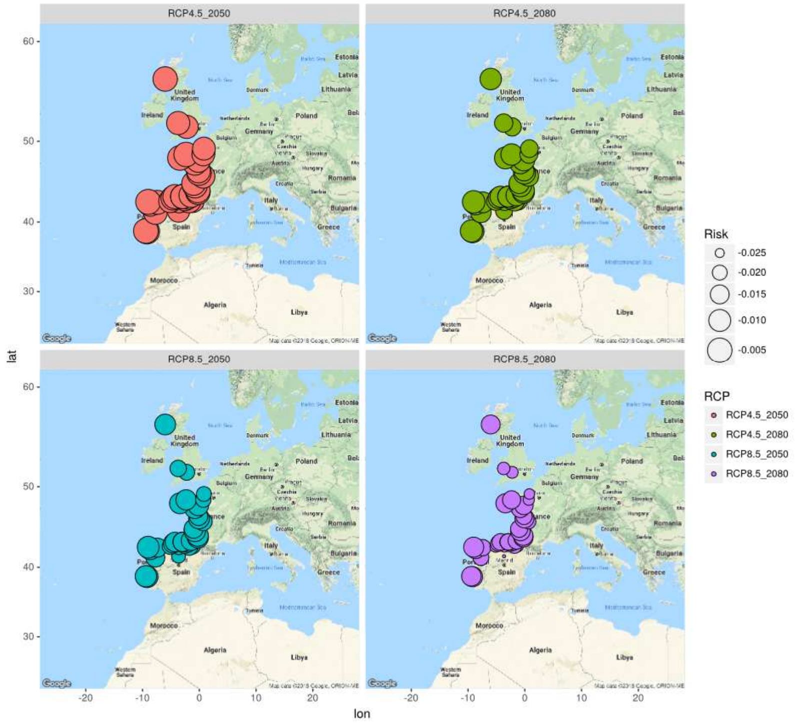


b)

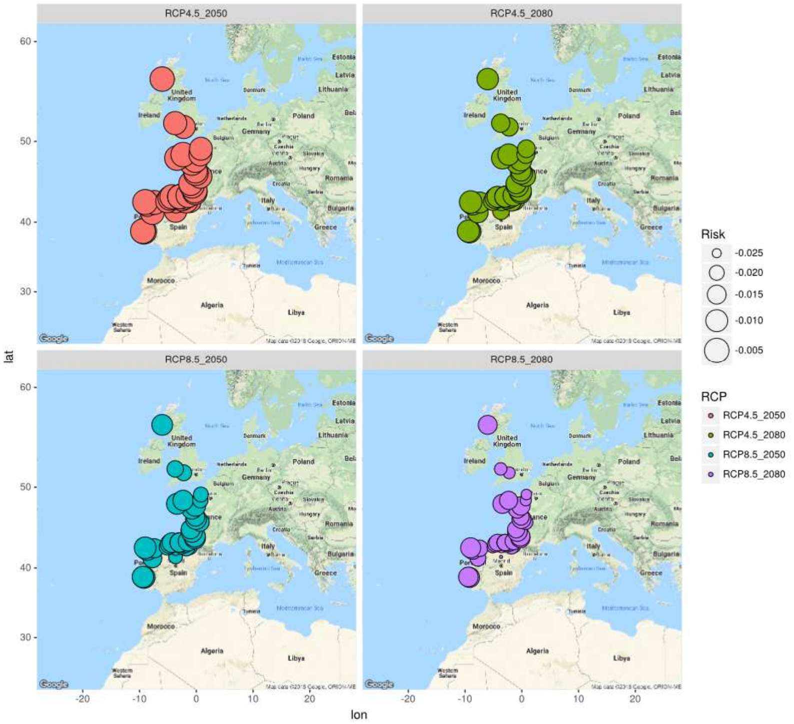

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
60
50
40
30
lon
-20
-10
0
10
20
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
Risk
0.1
0.2
0.3

S23- Risk analysis results for *Pinus brutia*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

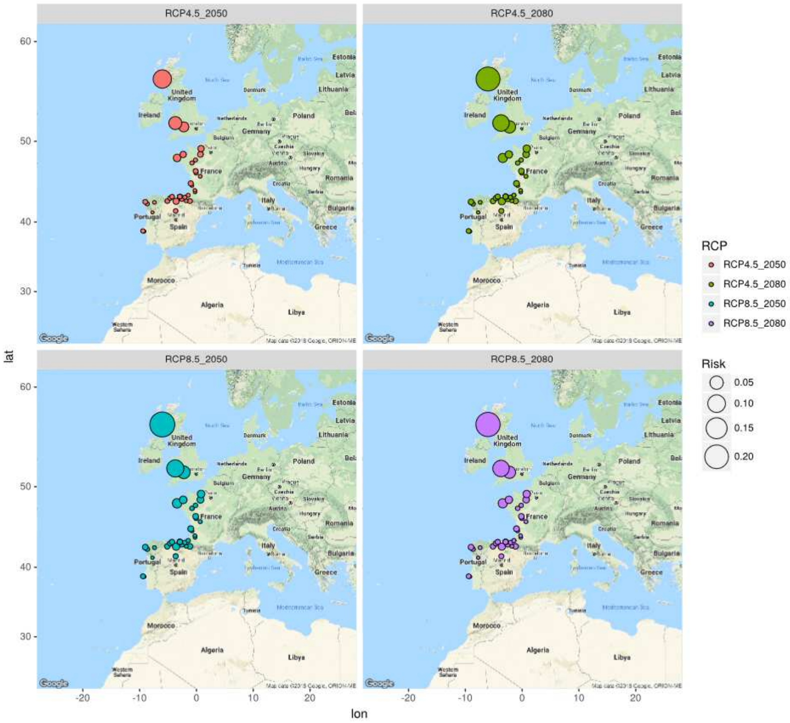


b)

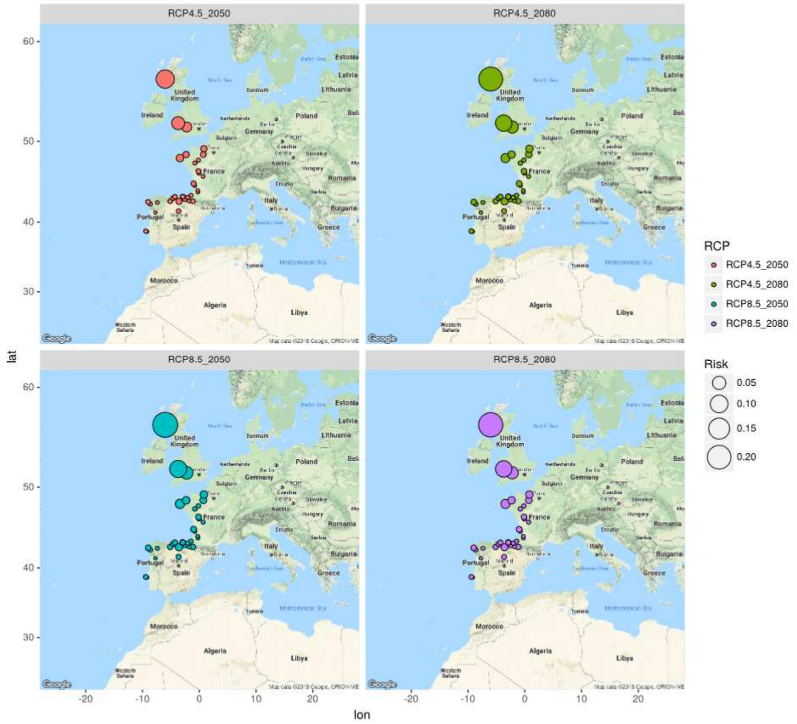

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
60
50
40
30
lon
-20
-10
0
10
20
Risk
-0.025
-0.020
-0.015
-0.010
-0.005
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
United Kingdom
Ireland
Spain
France
Germany
Poland
Italy
Morocco
Algeria
Libya
Greece
Tunisia
Western Sahara
Denmark
Lithuania
Latvia
Estonia
Romania
Bulgaria
Serbia
Hungary
Austria
Czechia
Slovakia
Croatia
Netherlands
Belgium
Mediterranean Sea
North Sea
Google
Map data ©2018 Google, ORION-ME

S24- Risk analysis results for *Pinus elliotti*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

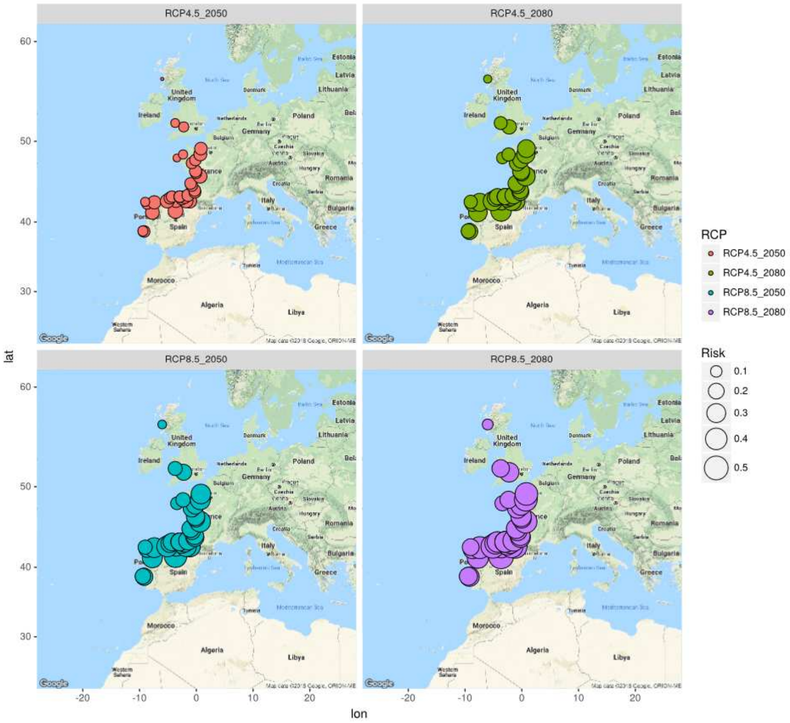


b)

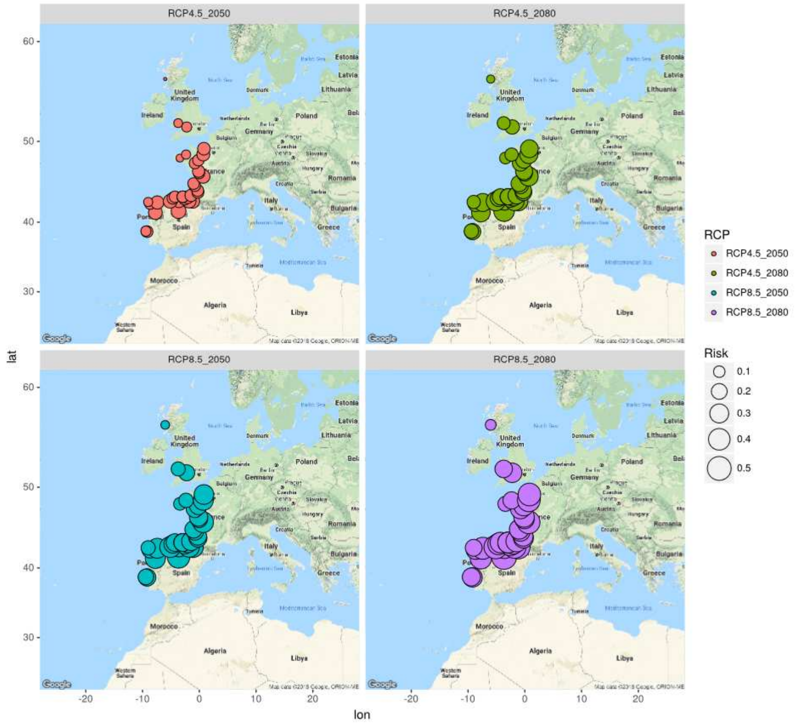

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
60
50
40
30
lon
-20
-10
0
10
20
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
Risk
0.05
0.10
0.15
0.20

S25- Risk analysis results for *Pinus nigra*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

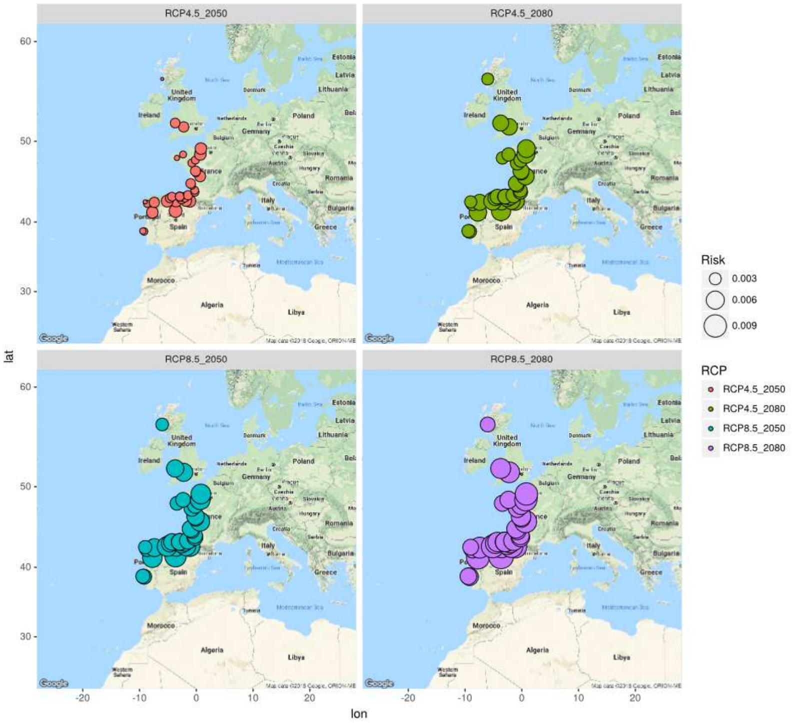


b)

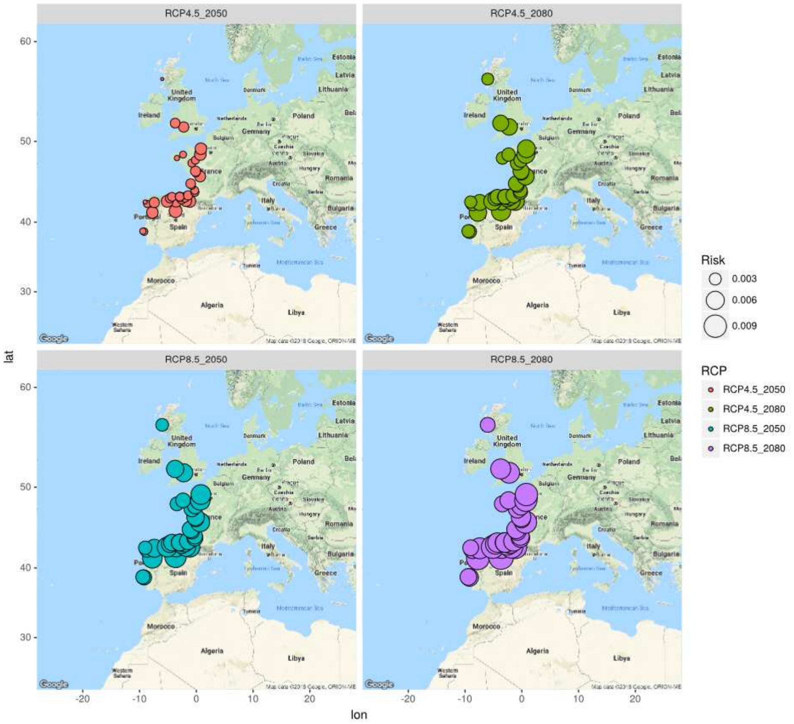

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
60
50
40
30
lon
-20
-10
0
10
20
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
Risk
0.1
0.2
0.3
0.4
0.5

S26- Risk analysis results for *Pinus pinea*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

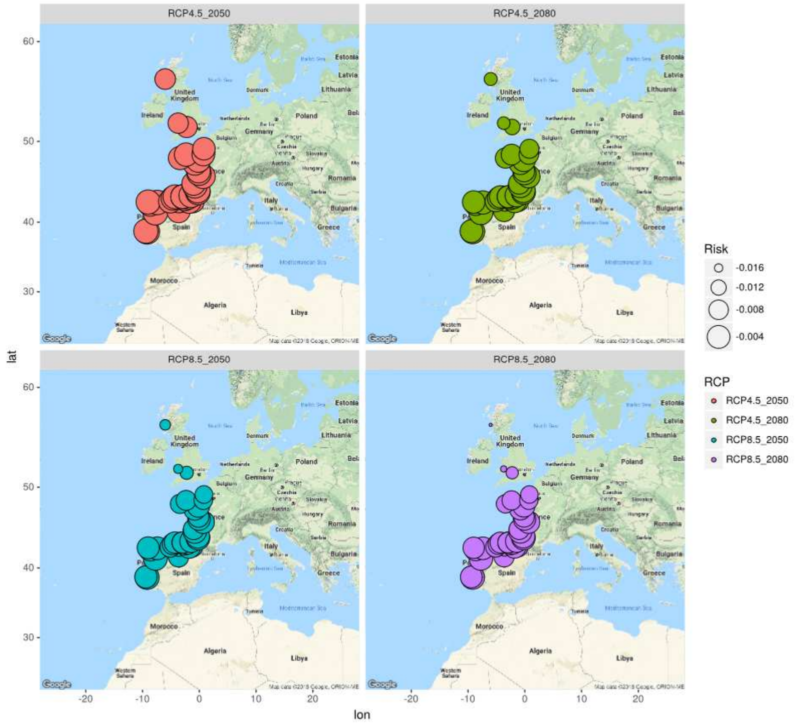
a)



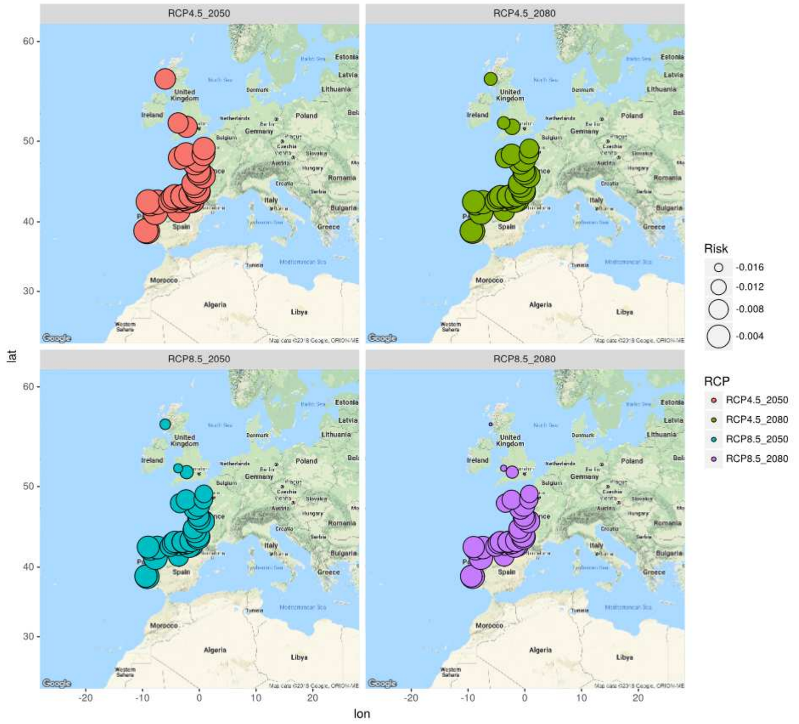
b)



S27- Risk analysis results for *Pinus ponderosa*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk a)

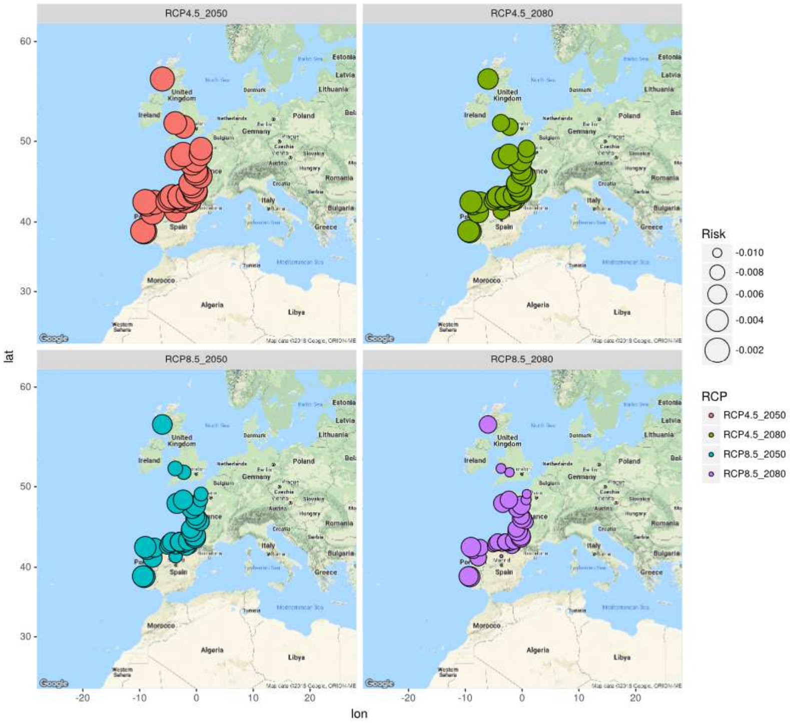

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
60
50
40
30
lon
-20
-10
0
10
20
Risk
-0.016
-0.012
-0.008
-0.004
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080

b)

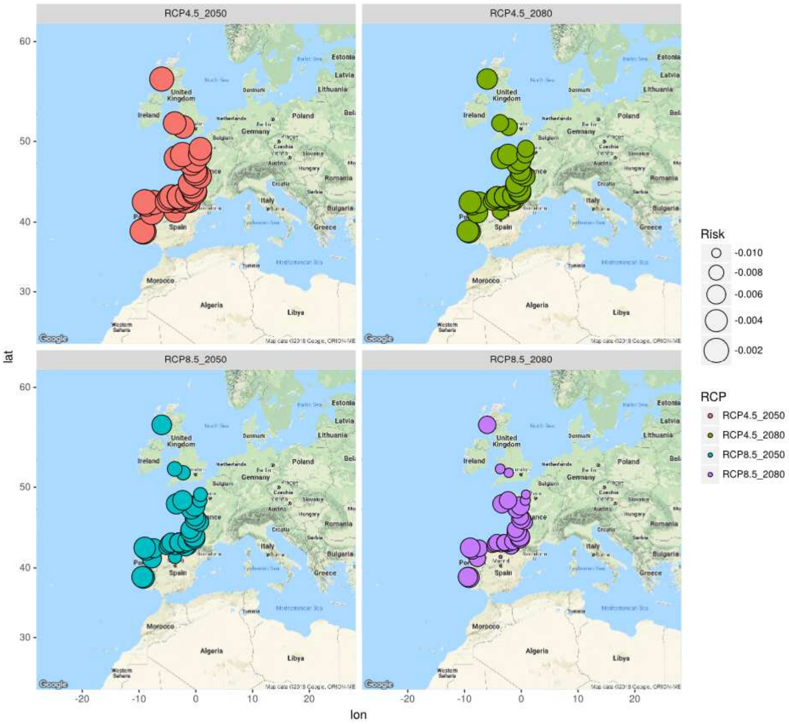

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
60
50
40
30
lon
-20
-10
0
10
20
Risk
-0.016
-0.012
-0.008
-0.004
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080

S28- Risk analysis results for *Pinus pinaster*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

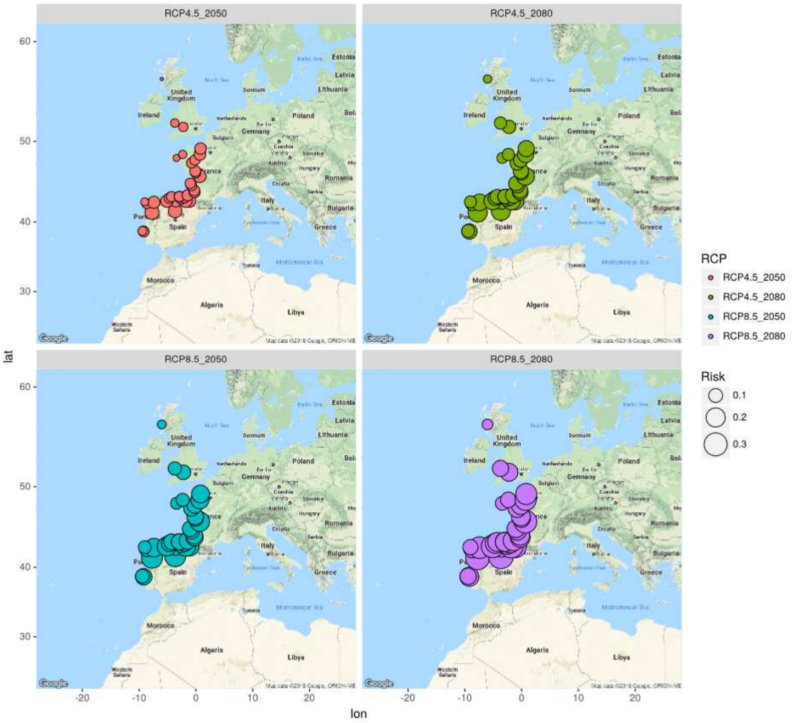


b)

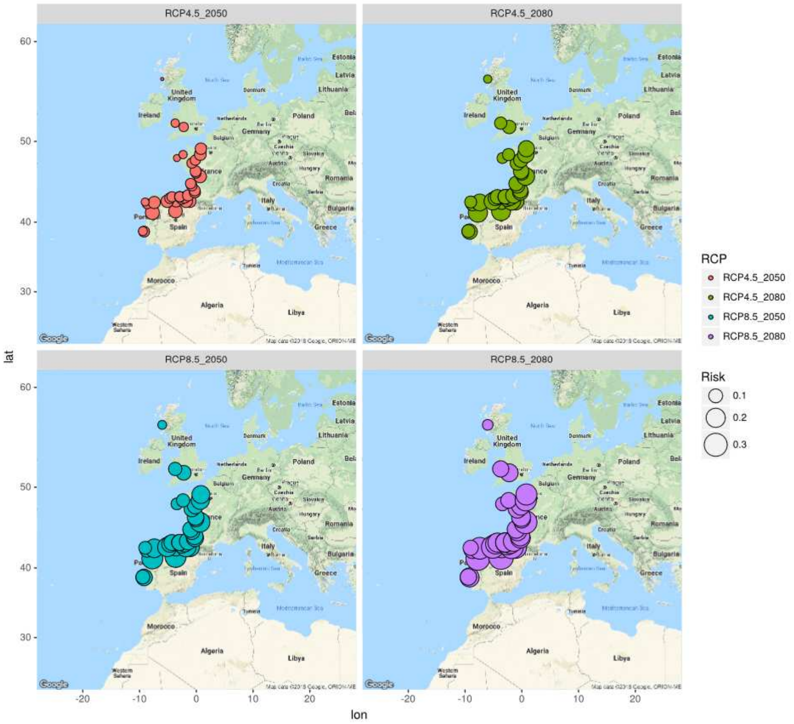

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
60
50
40
30
lon
-20
-10
0
10
20
Risk
-0.010
-0.008
-0.006
-0.004
-0.002
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080

S29- Risk analysis results for *Pinus sylvestris*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

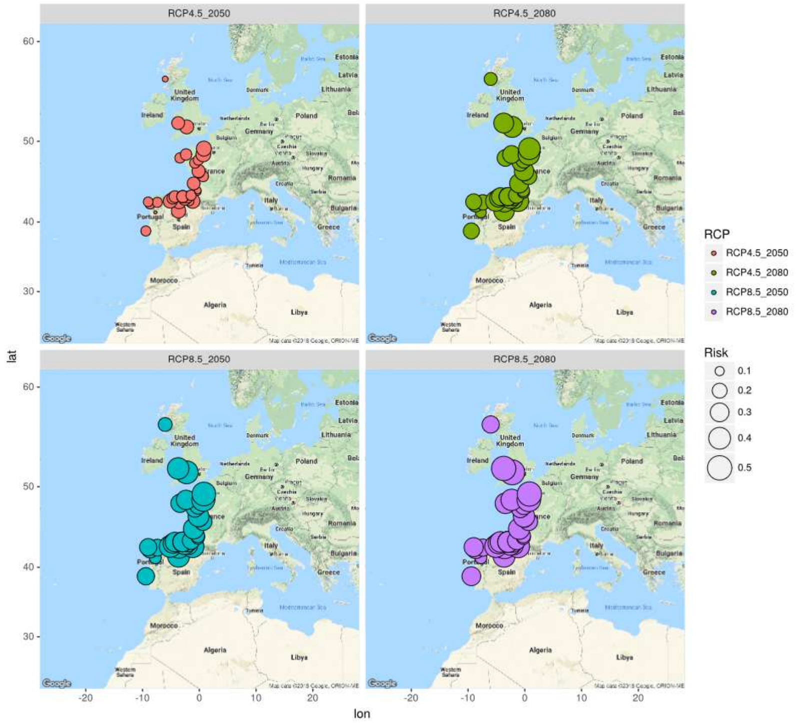


b)

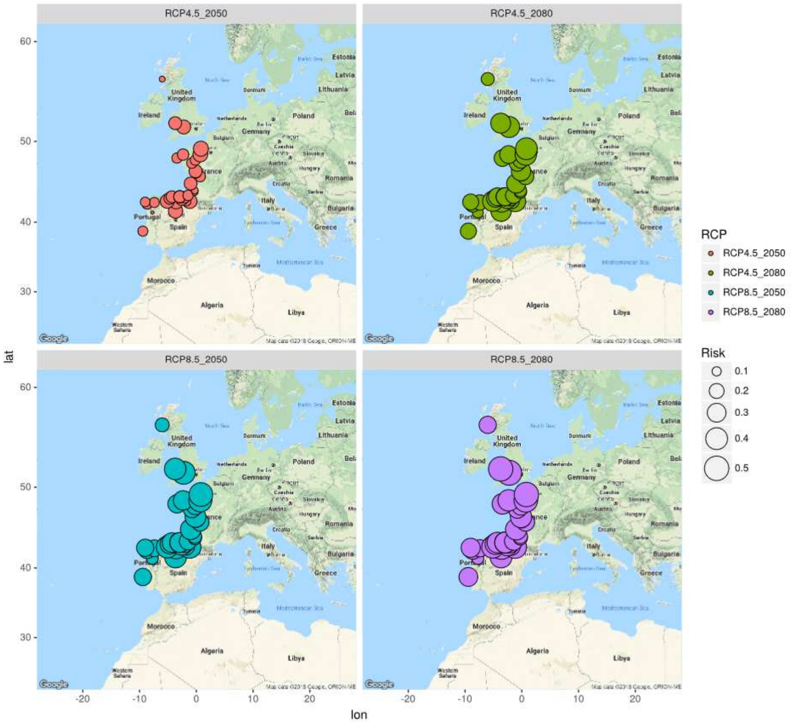

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
60
50
40
30
lon
-20
-10
0
10
20
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
Risk
0.1
0.2
0.3
United Kingdom
Ireland
Spain
Morocco
Algeria
Libya
Germany
Poland
Italy
Greece
Romania
Bulgaria
Estonia
Latvia
Lithuania
Denmark
Map data ©2018 Google, ORION-ME

S30- Risk analysis results for *Pinus taeda*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

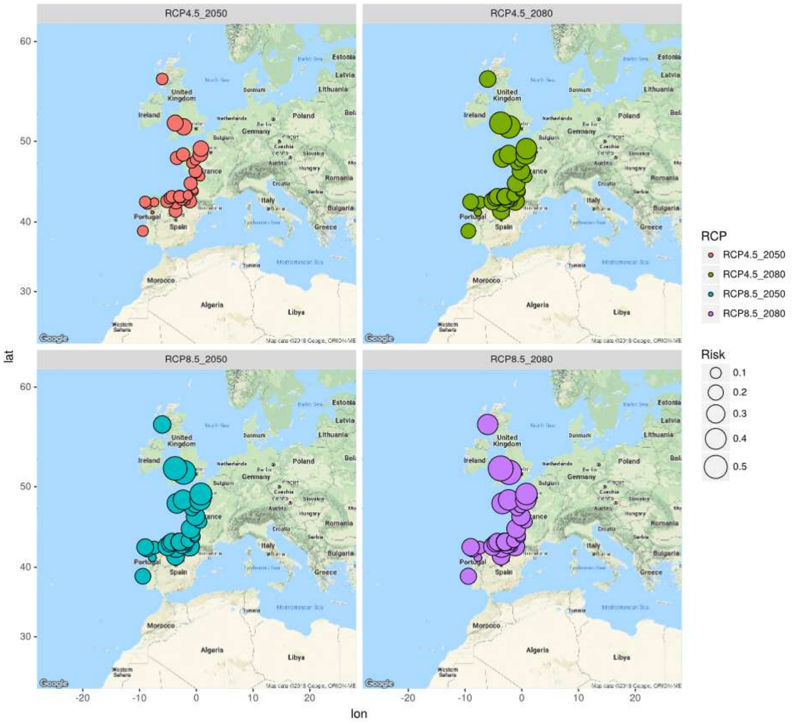


b)

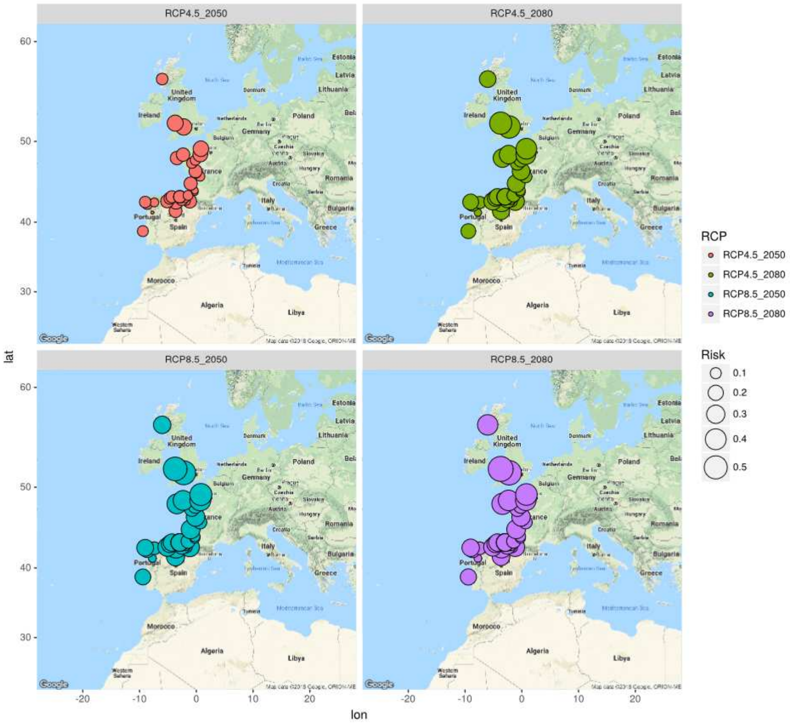

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
lon
60
50
40
30
-20
-10
0
10
20
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
Risk
0.1
0.2
0.3
0.4
0.5

S31- Risk analysis results for *Pseudotsuga menziesii*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

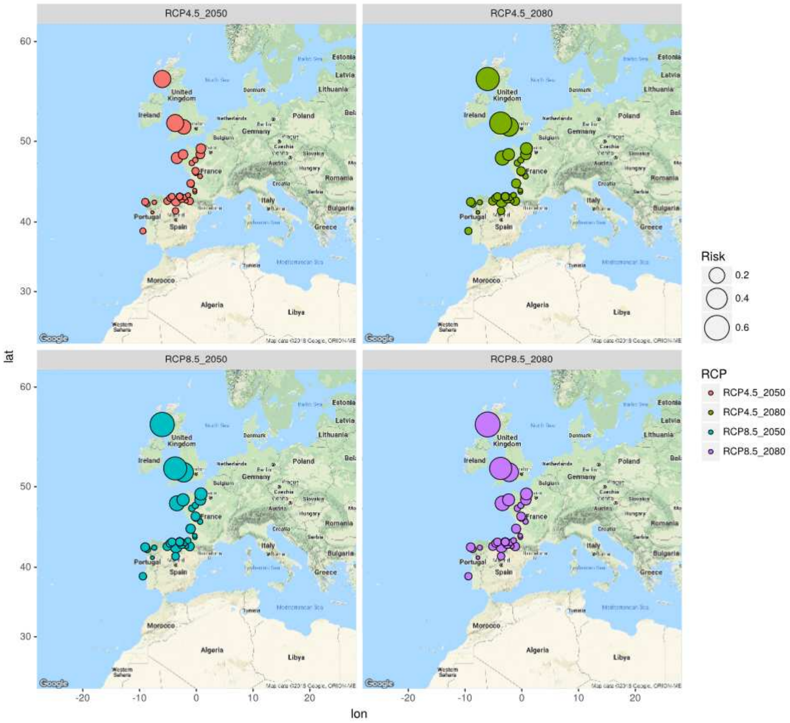


b)

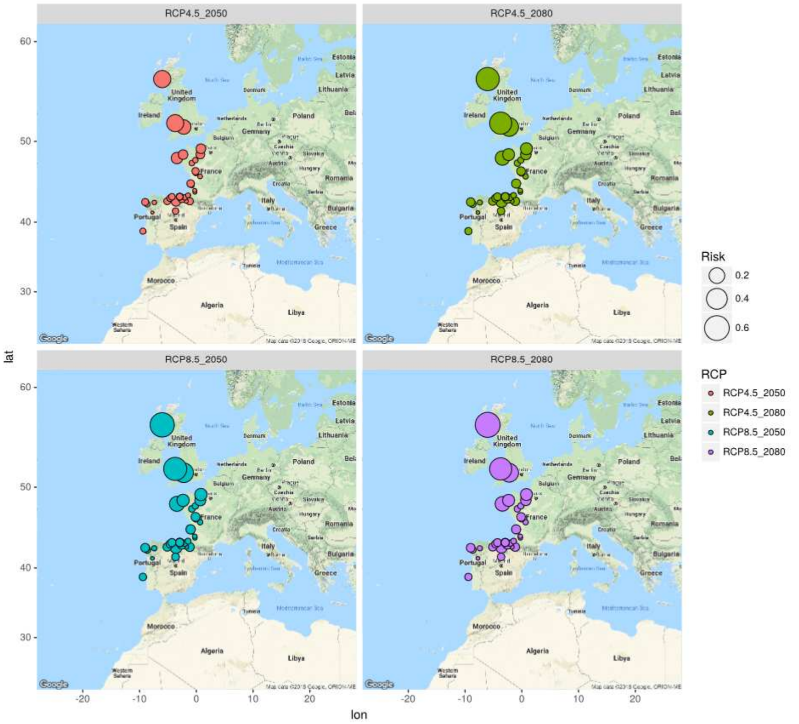

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
60
50
40
30
lon
-20
-10
0
10
20
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
Risk
0.1
0.2
0.3
0.4
0.5

S32- Risk analysis results for *Sequoia sempervirens*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

a)

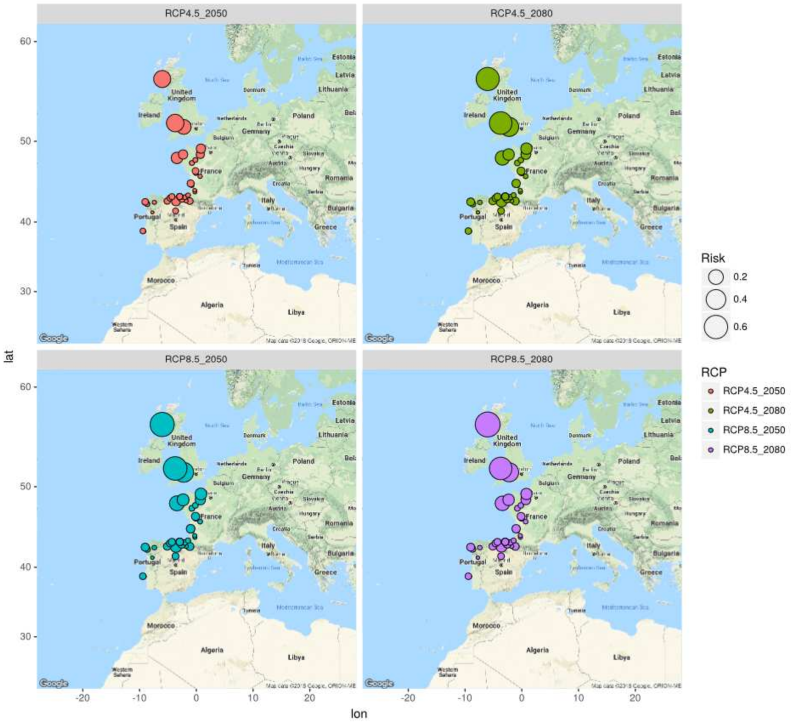


b)

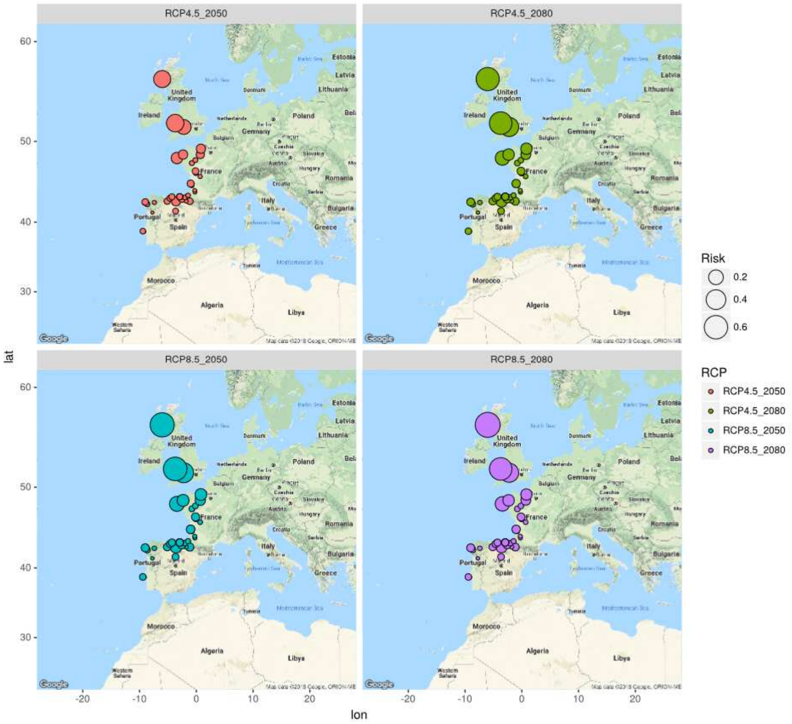

RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
lat
60
50
40
30
lon
-20
-10
0
10
20
Risk
0.2
0.4
0.6
RCP
RCP4.5_2050
RCP4.5_2080
RCP8.5_2050
RCP8.5_2080
United Kingdom
Ireland
France
Spain
Portugal
Germany
Poland
Italy
Morocco
Algeria
Libya
Map data ©2018 Google, ORION-ME

S33- Risk analysis results for *Thuja plicata*, for a) yearly growth (cm) and b) survival (probability). The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models. Dot size represents variation on risk

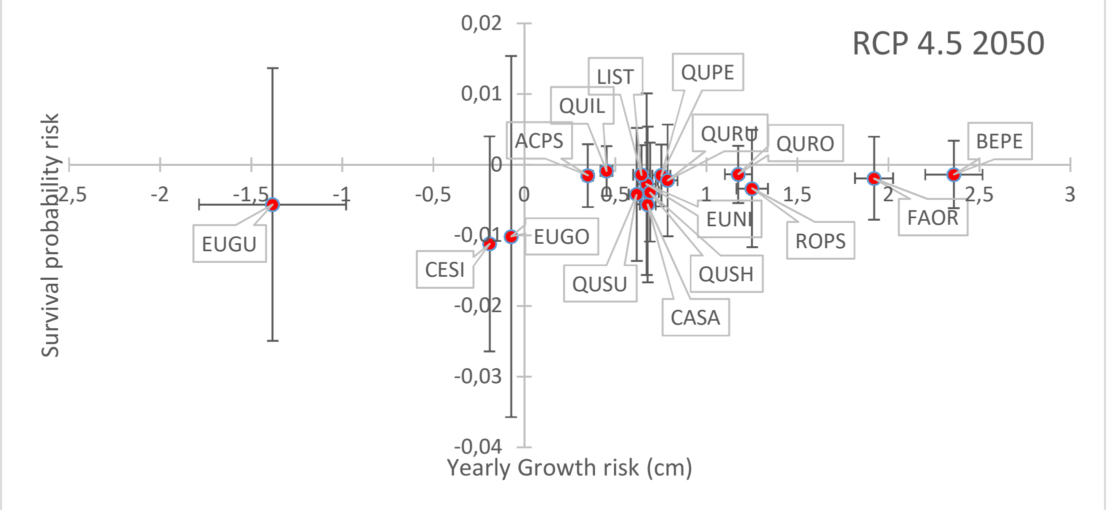
a)

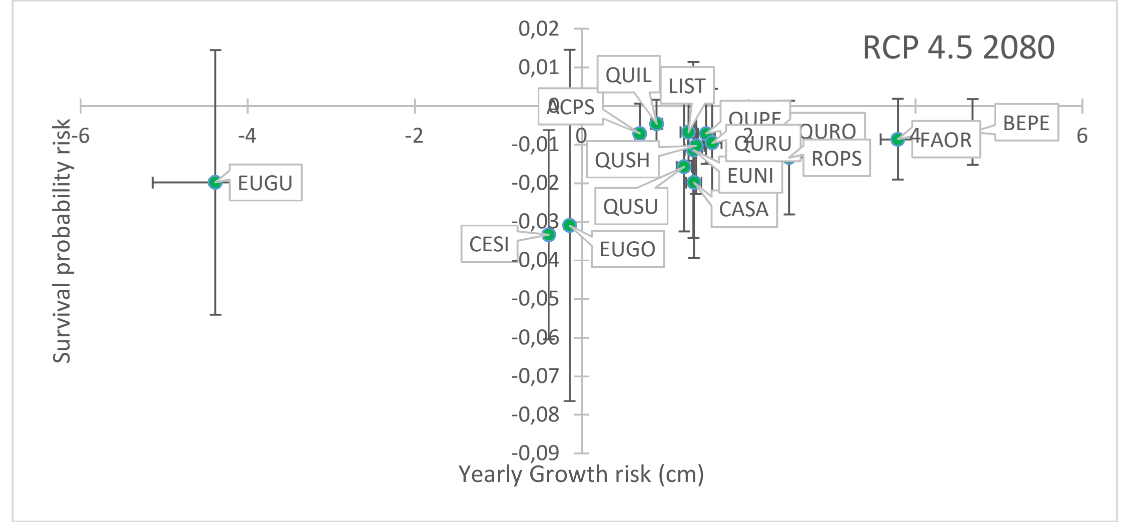


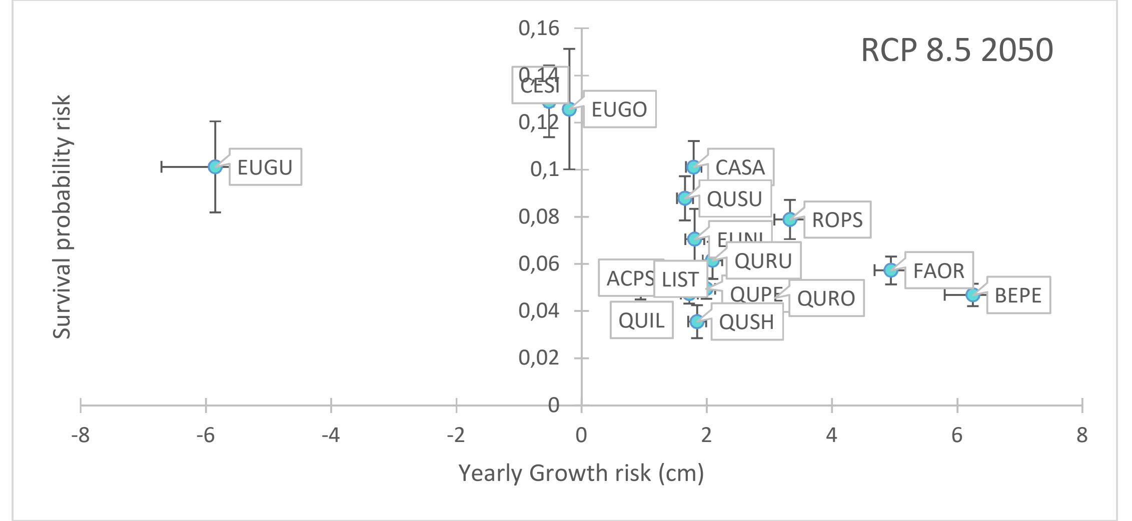
b)

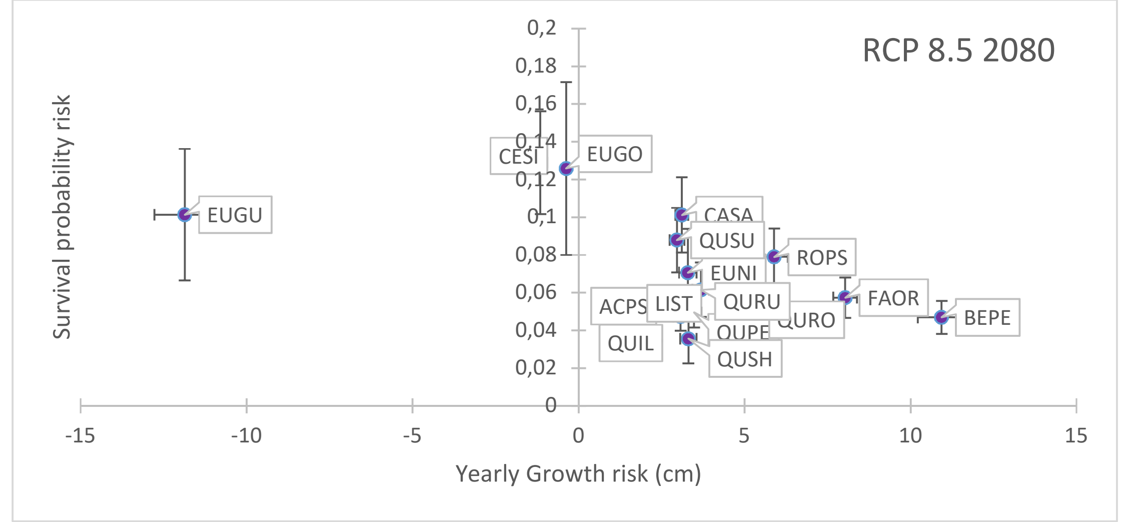


S34- Bi-dimensional plot of growth and survival for broadleaf species. The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models.

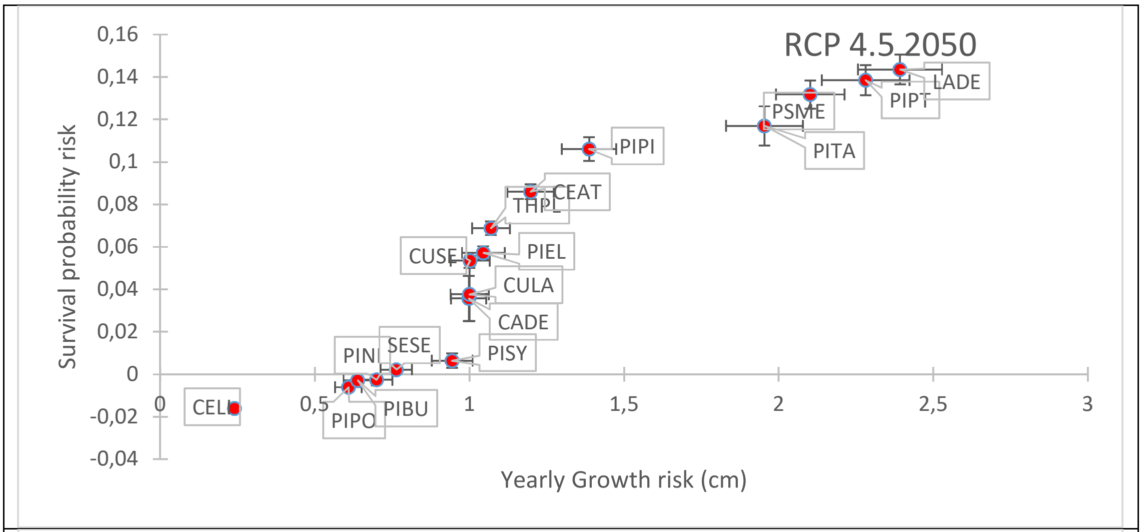


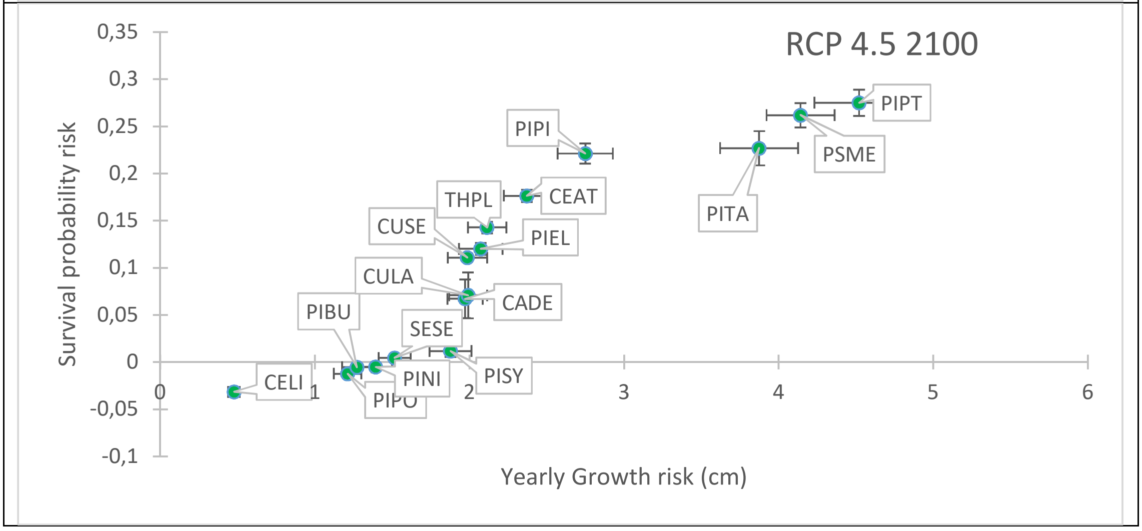

RCP 4.5 2080
Survival probability risk
Yearly Growth risk (cm)
0,02
0,01
0
-0,01
-0,02
-0,03
-0,04
-0,05
-0,06
-0,07
-0,08
-0,09
-6
-4
-2
0
2
4
6
EUGU
QUIL
LIST
ACPS
QUPE
QURO
QURU
QUSH
ROPS
EUNI
QUSU
CASA
CESI
EUGO
FAOR
BEPE

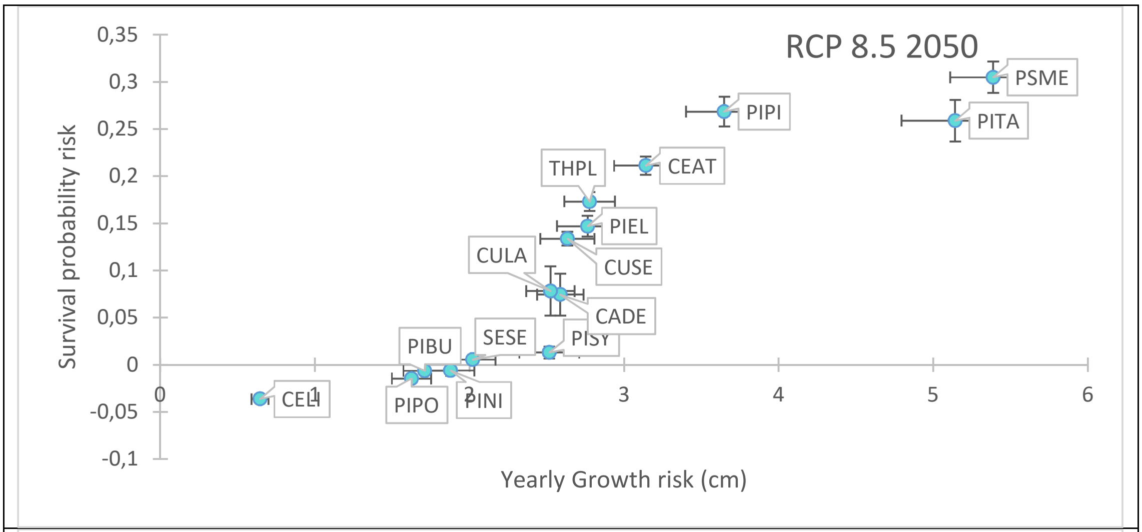

RCP 8.5 2050
Survival probability risk
Yearly Growth risk (cm)
0,16
0,14
0,12
0,1
0,08
0,06
0,04
0,02
0
-8
-6
-4
-2
0
2
4
6
8
CESI
EUGO
EUGU
CASA
QUSU
ROPS
EUNI
QURU
FAOR
ACPS
LIST
QUPE
QURO
BEPE
QUIL
QUSH

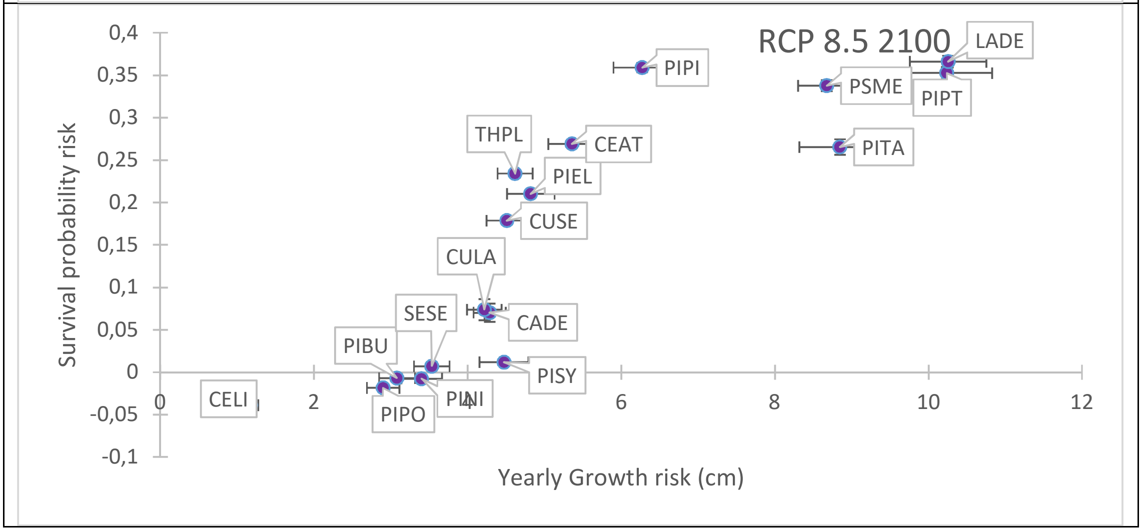

RCP 8.5 2080
Survival probability risk
Yearly Growth risk (cm)
0,2
0,18
0,16
0,14
0,12
0,1
0,08
0,06
0,04
0,02
0
-15
-10
-5
0
5
10
15
CESI
EUGO
EUGU
CASA
QUSU
ROPS
EUNI
ACPS
LIST
QURU
FAOR
QURO
QUPE
BEPE
QUIL
QUSH

S35- Bi-dimensional plot of growth and survival for conifer species. The represented scenarios are RCP 4.5 and 8.5 w/m2, for 2050 and 2080-time perspective. Risk is calculated as the difference between present and expected trait values (loss) multiplied by the probability of occurrence of predicted scenario. Trait prediction were done using Correia et al (2018) fitted models.






RCP 8.5 2050
Survival probability risk
Yearly Growth risk (cm)
0,35
0,3
0,25
0,2
0,15
0,1
0,05
0
-0,05
-0,1
0
1
2
3
4
5
6
PSME
PIPI
PITA
THPL
CEAT
PIEL
CULA
CUSE
CADE
PIBU
SESE
PISY
CELI
PIPO
PINI


RCP 8.5 2100
Survival probability risk
Yearly Growth risk (cm)
0,4
0,35
0,3
0,25
0,2
0,15
0,1
0,05
0
-0,05
-0,1
0
2
4
6
8
10
12
LADE
PIPI
PSME
PIPT
THPL
CEAT
PITA
PIEL
CUSE
CULA
SESE
CADE
PIBU
PISY
CELI
PINI
PIPO