

# Table of contents

Abstract .....	
Resumen .....	
Resum .....	
Acknowledgements .....	
Table of contents.....	
Liste of figures .....	
Liste of tables .....	

## **1. Background of the Thesis**

1.1. Global changes in climate.....	1
1.2. Forests in a changing climate .....	2
1.2.1. Ecophysiological responses.....	2
- To temperature and water availability .....	2
- To increased CO <sub>2</sub> concentration.....	3
- To carbon storage and nutrient availability .....	3
1.2.2. Species distributions .....	4
1.2.3. Transient responses in species compositions .....	4
1.2.4. Potential biome distributions .....	5
1.2.5. Biodiversity .....	5
- Effects at the edge of the range of distribution .....	6
- Effects within the range of distribution .....	7
- Effects on small ranges of distribution .....	7

1.3. Climate change in the Mediterranean region .....	8
1.3.1. Temperature .....	8
1.3.2. Precipitation.....	9
1.4. Climate change impacts on Mediterranean forests .....	10
1.5. Forest-species responses towards climate change.....	13
1.5.1. Phenotypic plasticity.....	13
1.5.2. Adaptation through natural selection .....	14
1.5.3. Natural migration.....	16
1.6. Selected forest pine species .....	18
1.6.1. Aleppo pine ( <i>Pinus halepensis</i> ) .....	18
1.6.2. Black pine ( <i>Pinus nigra</i> ) .....	18
1.7. Intraspecific variability and climate changes.....	20
1.8. Neutral vs. adaptive genetic variation under climate change.....	21
1.9. Proactive vs. reactive adaptation strategies to climate change .....	23
1.10. Assisted populations migration as an adaptation strategy for climate change .....	26
1.10.1. Assisted populations migration for species conservation.....	28
1.10.2. Assisted populations migration for forest management.....	29
1.11. Forest tree genomics .....	30
1.12. Forest tree proteomics .....	32
1.13. Proteomics in the genus <i>Pinus</i> .....	34
1.14. References.....	36
<b>2. Synopsis of the Thesis</b>	
2.1. Problem statement.....	49
2.2. General objectives and approach.....	49
2.3. References.....	53

**3. Chapter one: Testing Aleppo pine seed sources response to climate change by using trial sites reflecting future conditions**

Abstract..... 55

3.1. Introduction..... 56

3.2. Material and methods..... 60

    - Plant material ..... 60

    - Site selection and characterization ..... 63

    - Site preparation, planting works and experimental layout..... 64

    - Plant monitoring and measurments..... 65

    - Statistical analysis..... 66

3.3. Results..... 68

3.3.1. Climatic variation among sites ..... 68

3.3.2. Plantation performance..... 69

    - Survival response ..... 71

    - Growth response ..... 72

    - Physiological response ..... 76

3.3.3. Multivariate screening of seed sources ..... 77

3.4. Discussion..... 81

3.5. Conclusion ..... 88

3.6. References..... 91

**4. Chapter two: Addressing Genotype by Environment Interaction in *Pinus halepensis* towards assisted population migration programmes in response to climate change**

Abstract..... 97

4.1. Introduction..... 98

4.2. Material and methods..... 102

4.2.1. Plant material and trial sites..... 102

4.2.2. Phenotypic plasticity and reaction norms ..... 105

---

4.2.3. Genotype by environment interaction and adaptation .....	106
- Analysis of variance.....	106
- Joint regression analysis.....	107
- Additive main effects and multiplicative interaction.....	108
4.3. Results.....	109
4.3.1. General performance .....	109
4.3.2. Phenotypic plasticity.....	110
4.3.3. Norms of reaction .....	112
4.3.4. Genotype by environment interaction.....	113
4.3.5. Adaptation analysis.....	117
4.4. Discussion.....	121
4.5. Conclusion .....	128
4.6. References.....	131

**5. Chapter three: On the assisted population migration in *Pinus nigra* ssp. *salzmannii*: early plantation performance and genotype by environment interaction of different seed sources in contrasting ecological sites**

Abstract.....	136
5.1. Introduction.....	137
5.2. Experimental methodology .....	140
5.2.1. Plant material.....	140
5.2.2. Trial sites selection and characterization .....	143
5.2.3. Sites preparation, planting works and experimental layout .....	145
5.2.4. Plantation monitoring and measurments .....	145
5.2.5. Data analysis .....	146
5.3. Results.....	151
5.3.1. Survival response .....	151
5.3.2. Growth response .....	152

---

5.3.3. Phenotypic plasticity.....	156
5.3.4. Genotype by environment interaction.....	157
5.3.5. Adaptation analysis.....	159
5.4. Discussion.....	162
5.5. Conclusion.....	169
5.6. References.....	171

**6. Chapter four: Physiological, biochemical and proteomic response of Aleppo pine seed sources to water and cold stress as a contribution for assisted population migration in the species**

Abstract.....	178
6.1. Introduction.....	179
6.2. Material and methods.....	182
6.2.1. Plant material.....	182
6.2.2. Experimental conditions and treatments.....	184
6.2.3. Measurements.....	185
6.2.3.1. Water potential.....	185
6.2.3.2. Photosynthetic gas exchange.....	185
6.2.3.3. Chlorophyll fluorescence.....	186
6.2.3.4. Photosynthetic pigments.....	186
6.2.3.5. Soluble sugars.....	187
6.2.3.6. Extraction, separation and determination of proteins.....	187
6.2.4. Statistical analysis.....	188
6.3. Results.....	189
6.3.1. Water potential.....	191
6.3.2. Photosynthetic gas exchange and water use efficiency.....	192
6.3.3. Chlorophyll fluorescence.....	192
6.3.4. Photosynthetic pigments.....	196
6.3.5. Soluble sugars.....	198

6.3.6. Multivariate screening of seed sources .....	200
6.3.7. Proteins.....	204
6.4. Discussion.....	207
6.5. Conclusion .....	213
6.6. References.....	215
<b>7. General discussion</b>	
7.1. Survival.....	224
7.2. Growth .....	227
7.3. Phenotypique plasticity .....	231
7.3. Genotype by environment interaction.....	232
7.4. Physiological response.....	236
7.5. Molecular response .....	238
<b>8. Main findings and conclusion.....</b>	<b>243</b>
<b>9. Limitations and challenges .....</b>	<b>248</b>
References .....	251