Adaptation of forest trees to climate: what can we learn from their evolutionary history?

Antoine Kremer
PREDICTED BIOCLIMATIC ENVELOPES OF Q. petraea IN 2080

GG emissions model – A2 Climate model – CSIRO2

GG emissions model – A1FI Climate model – CGCM2

Thuiller GCB 2003, Thuiller et al. PNAS 2005
RETROSPECTIVE NICHE MODELLING

Brewer et al, FEM 2002
Pedunculate oak
*Quercus robur*

Sessile oak
*Quercus petraea*
RANGE SHIFT VS RANGE EXPANSION

SHIFT

EXPANSION
GENUS QUERCUS
FAGACEAE

Aimée CAMUS (1879-1965)

Fagaceae

Fagoideae

Fagus (beech) 13
Castanea (chestnut) 12
Castanopsis 100 à 200
Lithocarpus 300

Castaneoideae

Quercus (oaks) 450 à 600
Trigonobalanus 3

Quercoideae
1. Extinctions
2. Expansion - Migration
3. Local Adaptation
4. Maintenance of Diversity
65 Million Years of Climate Change
EXTINCTION OF FAGACEAE GENERA AT THE BEGINNING OF THE MILANKOVITCH CYCLES
1. Extinctions
2. Expansion - Migration
3. Local Adaptation
4. Maintenance of Diversity
HOLOCENE RECONSTRUCTION
RAPID MIGRATION

Brewer et al, FEM 2002
ON AVERAGE THE MIGRATION OF OAKS WAS EXTREMELY RAPID: 400 METERS PER YEAR

Brewer et al, FEM 2002
SEED DISPERSION VELOCITY

1. Diffusion  100 meters/year

2. Diffusion + rare long distance  400 meters/year

HYBRIDIZATION ENHANCES MIGRATION

Curtu, A. L. et al. BMC Evolutionary Biology 2007
Lepais et al., TGG 2013
DISPERSION OF *QUERCUS ROBUR*

*Q. petraea* (Sessile oak)

*Q. robur* (Pedunculate oak)
HYBRIDIZATION

POLLEN OF QUERCUS PETRAEA
RECURRENT ASSYMETRIC BACKCROSSINGS

Research review

Hybridization as a mechanism of invasion in oaks

Rémy J. Petit, Catherine Bodénès, Alexis Ducousso, Guy Roussel and Antoine Kremer

UMR Biodiversity, Genes & Ecosystems, INRA, 69 Route d’Arcachon, F-33612 Cestas Cedex, France
Two oak species share the same haplotypes when they cohabit in the same forest

Petit et al, PNAS, 1996
1. Extinctions

2. Expansion - Migration

3. Local Adaptation

4. Maintenance of Diversity
PROVENANCE TESTS (16)

ORIGINS OF PROVENANCES (20 to 94)
<table>
<thead>
<tr>
<th>Trait</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEIGHT</td>
<td></td>
</tr>
<tr>
<td>BUD</td>
<td>Burst</td>
</tr>
<tr>
<td>CROWN ARCHITECTURE</td>
<td></td>
</tr>
<tr>
<td>SURVIVAL</td>
<td></td>
</tr>
</tbody>
</table>

Significant provenance variations observed for all traits

\[ Qst \approx 0.36 \text{ to } 0.53 \]

Kremer et al, FEM 2002
Early flushing
Late flushing

PHENOLOGICAL DIFFERENTIATION versus Cp DNA DIFFERENTIATION

Kremer et al. Academic press 2010
DRIVERS OF LOCAL ADAPTATION

In situ

Provenance test
Experimental evidence of co-gradient variation in sessile oak

Alberto et al. 2011, Journal of Evolutionary Biology 24, 1442-1454
ASSORTATIVE MATING

POSITIVE ASSORTATIVE MATING WITHIN POPULATION
ASSORTATIVE MATING AT A LANDSCAPE SCALE

Gene flow introduces « late flushing genes » in populations at higher latitude

NEGATIVE ASSORTATIVE MATING BETWEEN POPS
- Pollen flow & assortative mating generate genetic clines
- Genetic clines are in the same direction than the environmental gradient

Soularue JP & Kremer A 2012 *BMC Evolutionary Biology* 2012, 12:79
1. EXTINCTIONS
2. EXPANSION - MIGRATION
3. LOCAL ADAPTATION
4. MAINTENANCE OF DIVERSITY
MAINTENANCE OF GENE DIVERSITY IN Quercus petraea

Fst 1 to 2%

\[ \pi \times 10^{-3} \] Genes

\[ H_e \] Proteins

Zanetto & Kremer, 1995, Heredity, 75:506 - 517
Alberto et al. 2013, Genetics 195 : 495–512
PHYLOGEOGRAPHIC STRUCTURE OF EUROPEAN WHITE OAKS

Petit et al, FEM 2002
DISTRIBUTION OF HAPLOTYPES OF THE ATLANTIC (B) LINEAGE

http://www.pierroton.inra.fr/Fairoak/
DISTRIBUTION OF HAPLOTYPES
OF THE CENTRAL (C) LINEAGE

http://www.pierroton.inra.fr/Fairoak/
DISTRIBUTION OF HAPLOTYPES OF THE EASTERN (A) LINEAGE
VELOCITY OF SEED DISPERSION

1. Diffusion

2. Diffusion + rare long distance

VELOCITY OF SEED DISPERSION AND MAINTENANCE OF DIVERSITY

DIFFUSION

DIFFUSION + LDD

1. **EXTINCTIONS**
   - Selection for site capture

2. **EXPANSION - MIGRATION**
   - LDD + hybridization

3. **LOCAL ADAPTATION**
   - Assortative mating + LD gene flow

4. **MAINTENANCE OF DIVERSITY**
   - Migration history and dynamics
NICHE MODELLING OF HOLM OAK (Q. ilex)

Observed distribution

Extant distribution of holm oak (Quercus ilex), IFN data

Bioclimatic envelope predicted ARPEGE B2 (Carbofor project)

Extant

2050

2100
DISTRIBUTION OF HOLM OAK (Q. ilex)
MIGRATION OF HOLM OAK AT ITS NORTHERN LIMIT

Forêt domaniale d’Hourtin


Forêt domaniale d’Olonne sur mer

1891 1912 1953 1971 2004

Rate of migration : 30 m / year…. 3Km / 100 years

Delzon et al., 2013 Plos One e80443
OBSERVED AND PREDICTED MIGRATION

PREDICTED BY NICHE MODELLING: 100 TO 500 Kms

INFERRRED FROM POLLEN RECORDS: 40 Kms

OBSERVED: 3 Kms
LONG DISTANCE POLLEN MIGRATION (Pinus taeda)

Bohrerova et al. (2009) Ecology applications
Kremer et al. (2012), Ecology Letters
OVERALL CONCLUSIONS

1 HISTORICAL EVIDENCE OF EVOLUTIONARY ADAPTIVE RESPONSES TO CLIMATE CHANGE
OVERALL CONCLUSIONS

2

REPEATED COLD-WARM SEQUENCES SCREENED SPECIES AND POPULATIONS FOR RAPID MIGRATION & ADAPTATION
OVERALL CONCLUSIONS

Adaptive responses can be rapid in trees due to large gene diversity, extensive gene flow, hybridization.
OVERALL CONCLUSIONS

UNDER CONTEMPORARY CLIMATE CHANGE, THESE MECHANISMS MAY STIMULATE ADAPTIVE RESPONSES
OVERALL CONCLUSIONS

5

EVOLUTIONARY MECHANISMS MAY NOT BE SUFFICIENT. HUMAN ASSISTANCE MIGHT BE NEEDED
SPECIAL THANKS TO..

Rémy Petit  Florian Alberto  Jean Paul Soularue  Alexis Ducousso
FAIROAK  Synthetic maps of gene diversity and provenance performance for utilization and conservation of oak genetic resources

OAKFLOW  Intra and interspecific gene flow in oaks as mechanisms promoting genetic diversity and adaptive potential