ADAPTATION OF FOREST TREES TO CLIMATE

HOW MUCH CAN WE LEARN FROM THE PAST TO ADDRESS THE FUTURE ?

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biogeco
INRA
SCIENCE & IMPACT

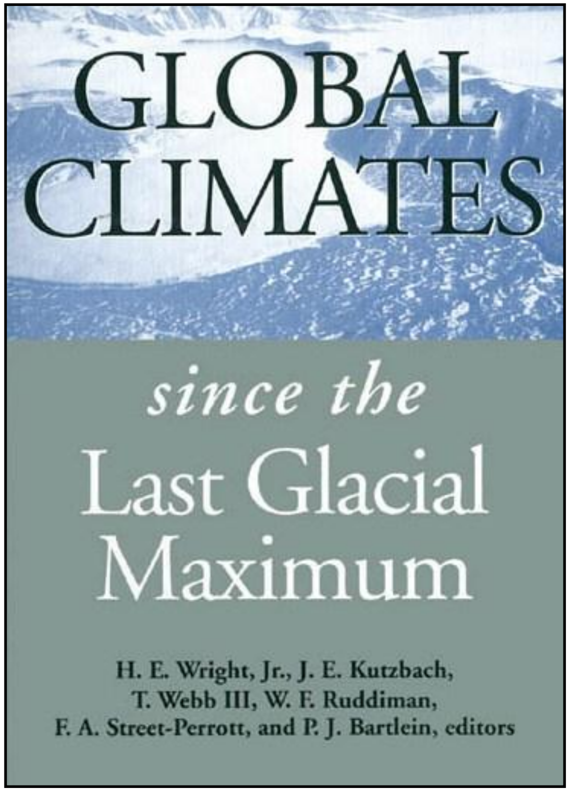
oaks & vineyard

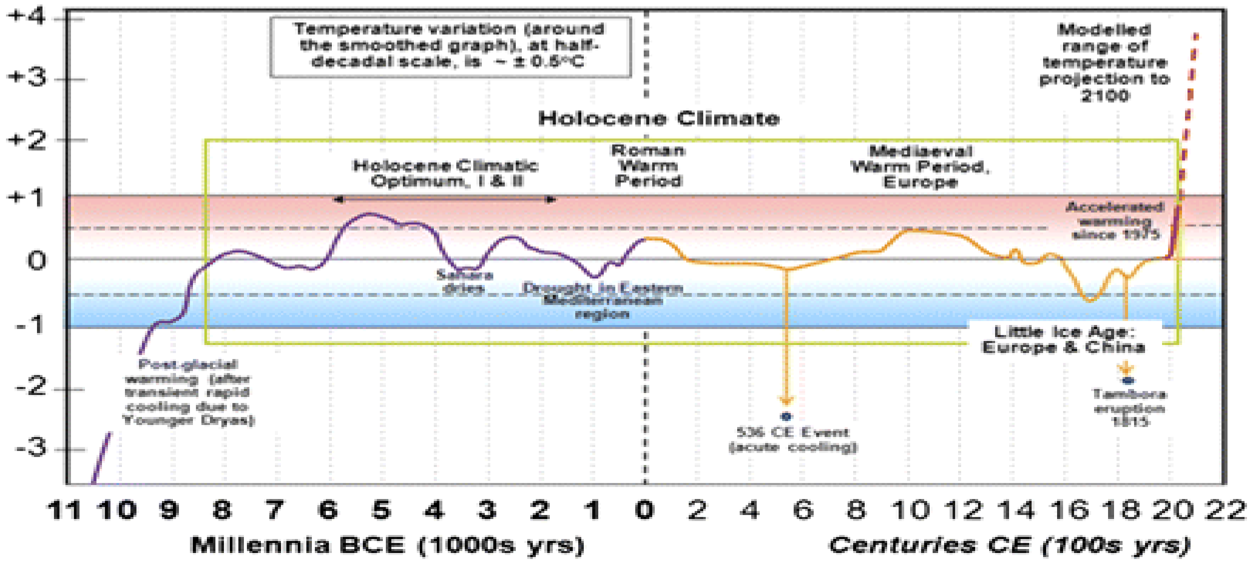


GENUS *QUERCUS*




CLIMATE CHANGE DURING ***THE HOLOCENE***

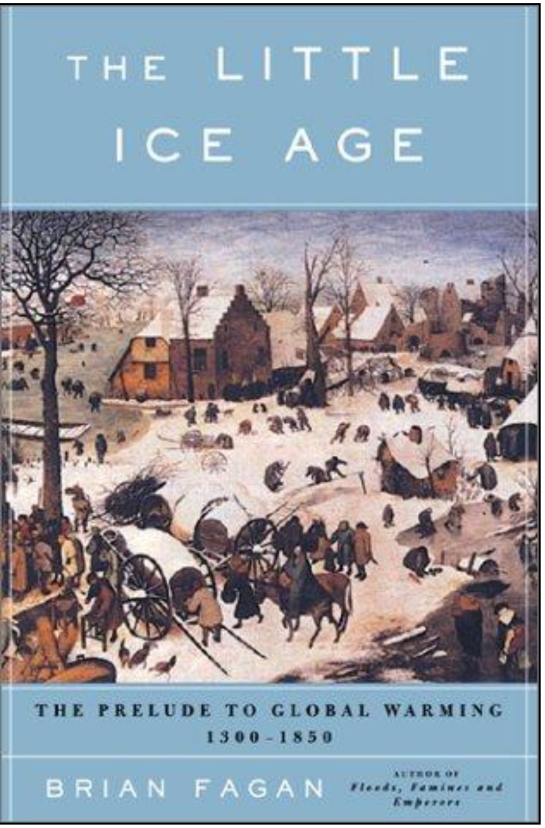


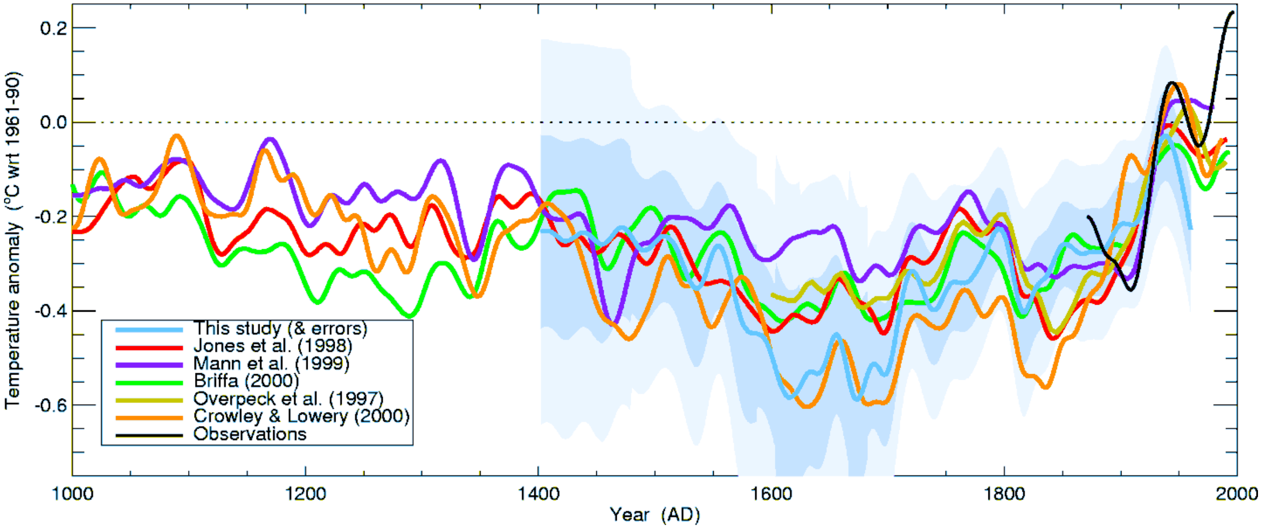


Variations in northern hemisphere temperature, °C (relative to mean temperature during 1960–1980), averaged from multiple sources published since 2007.

McMichael AJ 2012 *PNAS* 109 4730-4737

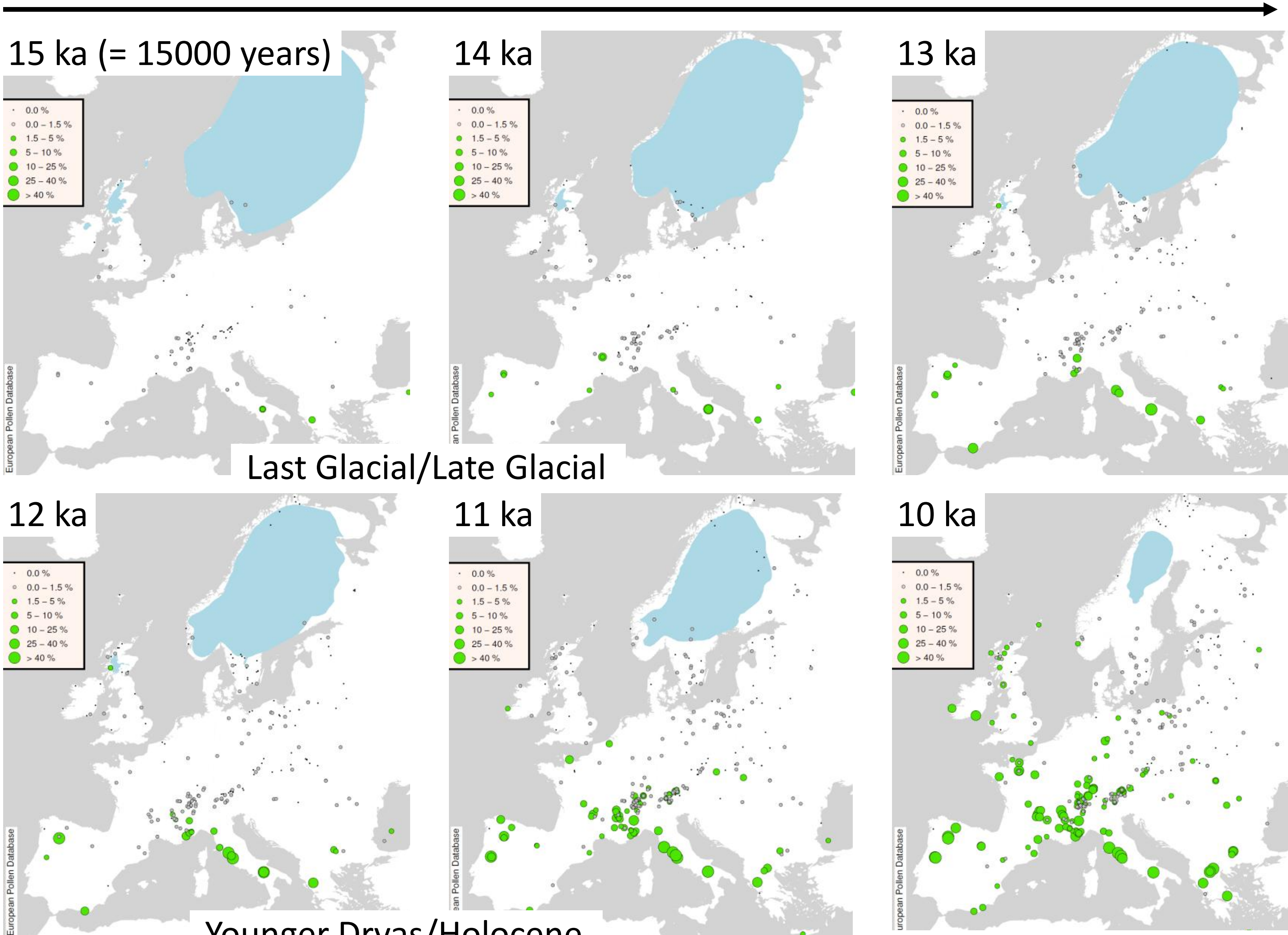
CLIMATE CHANGE DURING THE ***ANTHROPOCENE***





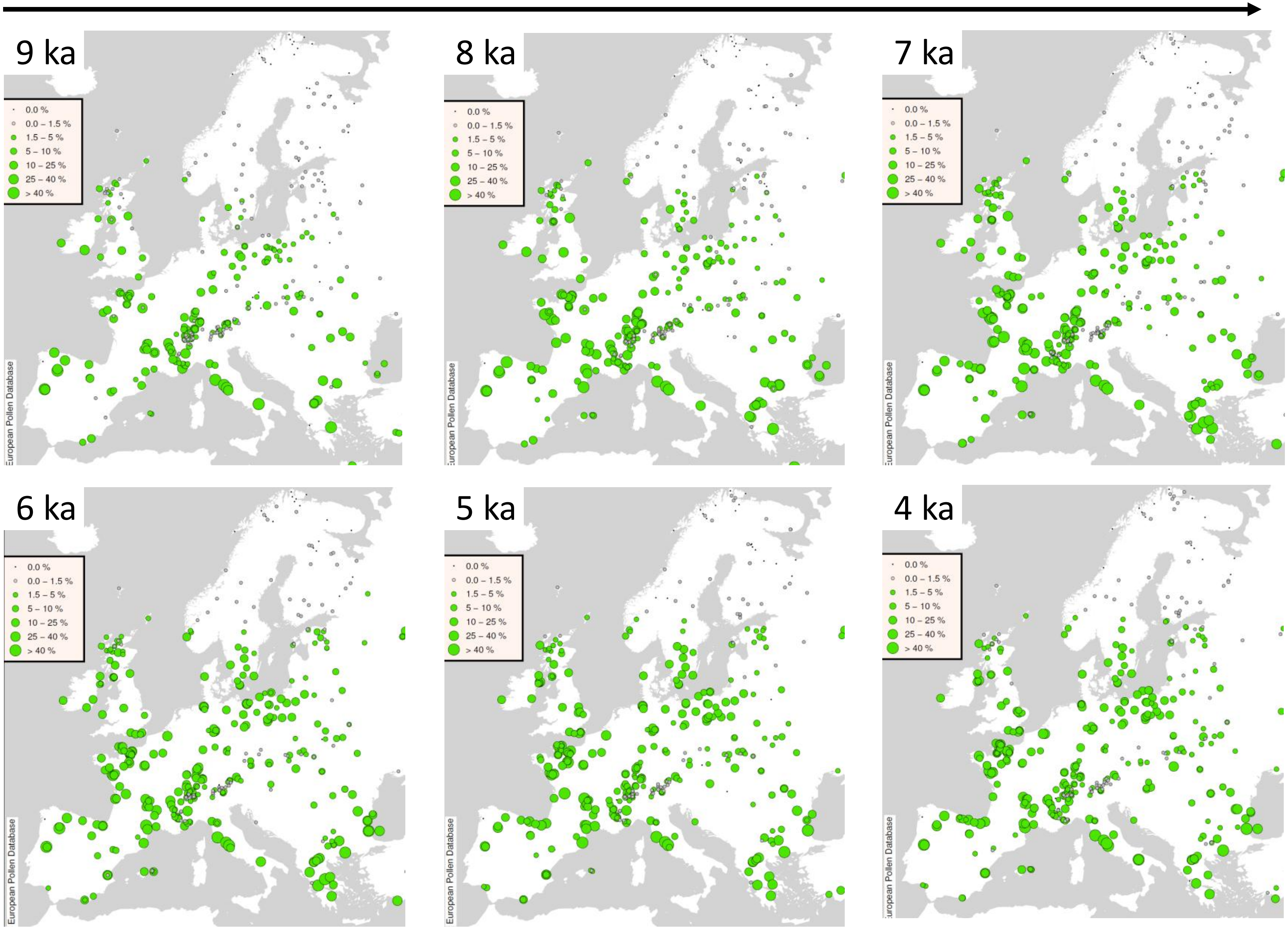
Briffa K.R. et al. 2001 *Journal of Geophysical Research* 106 2929-2941

Postglacial oak recolonisation documented by pollen deposits



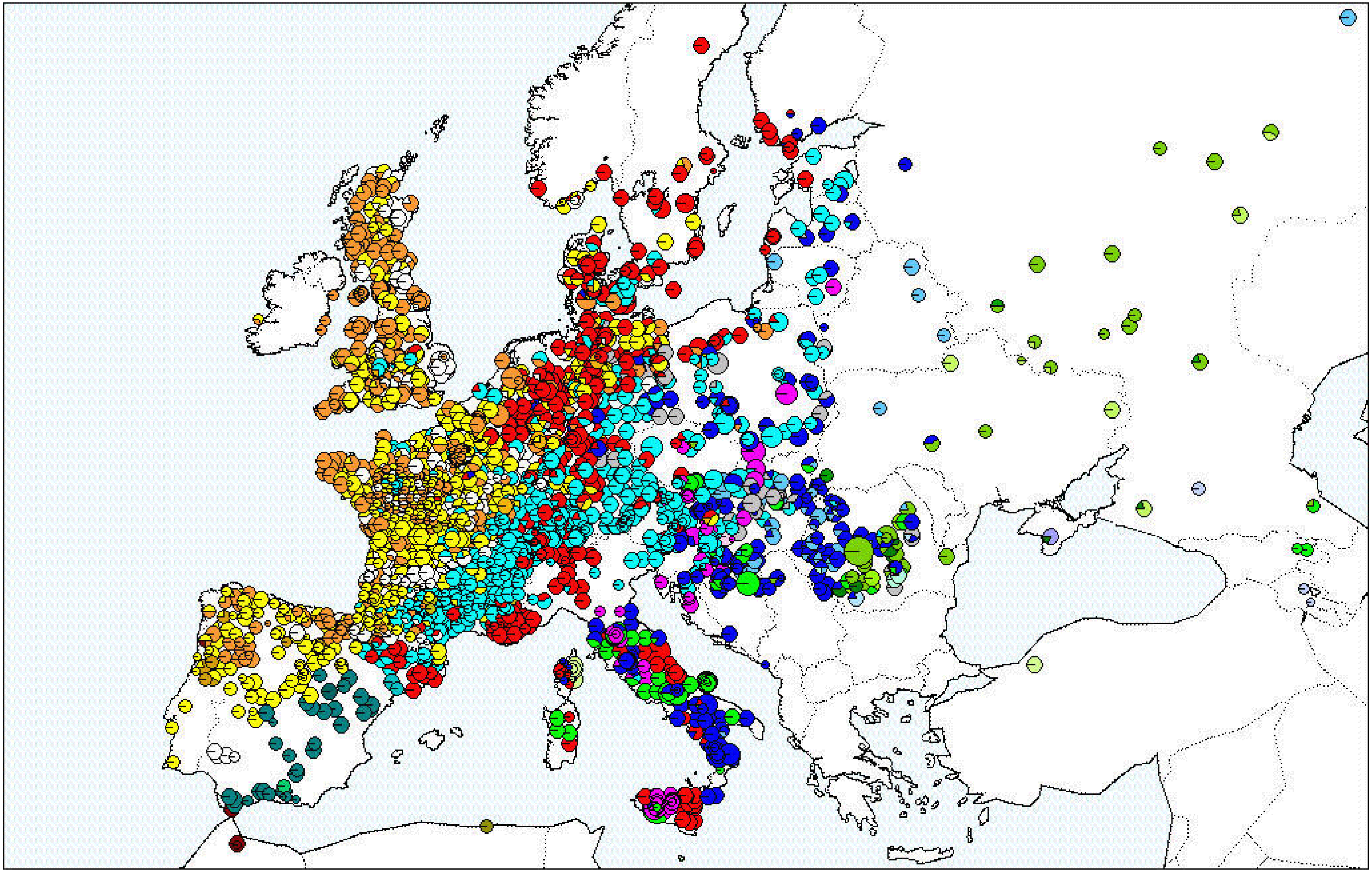
Giesecke *et al*. 2017 *J.Biogeography* 44: 1441-1456

Postglacial oak recolonisation documented by pollen deposits



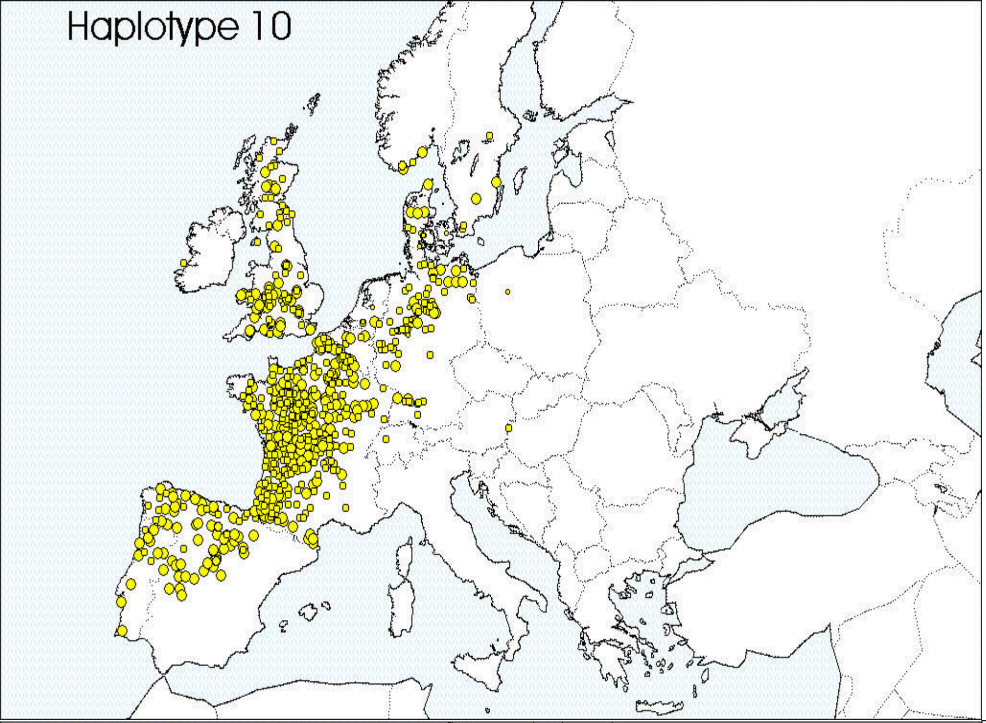
Giesecke *et al*. 2017 *J.Biogeography* 44: 1441-1456

DISTRIBUTION OF CpDNA HAPLOTYPES IN EUROPEAN WHITE OAKS



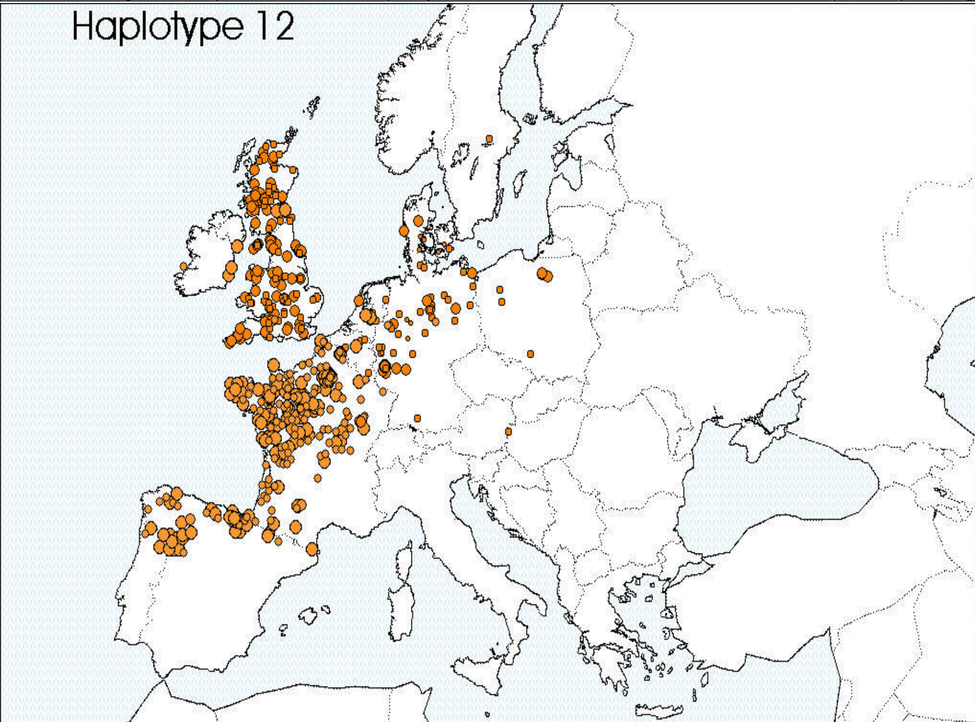
> 3000 populations, 42 haplotypes

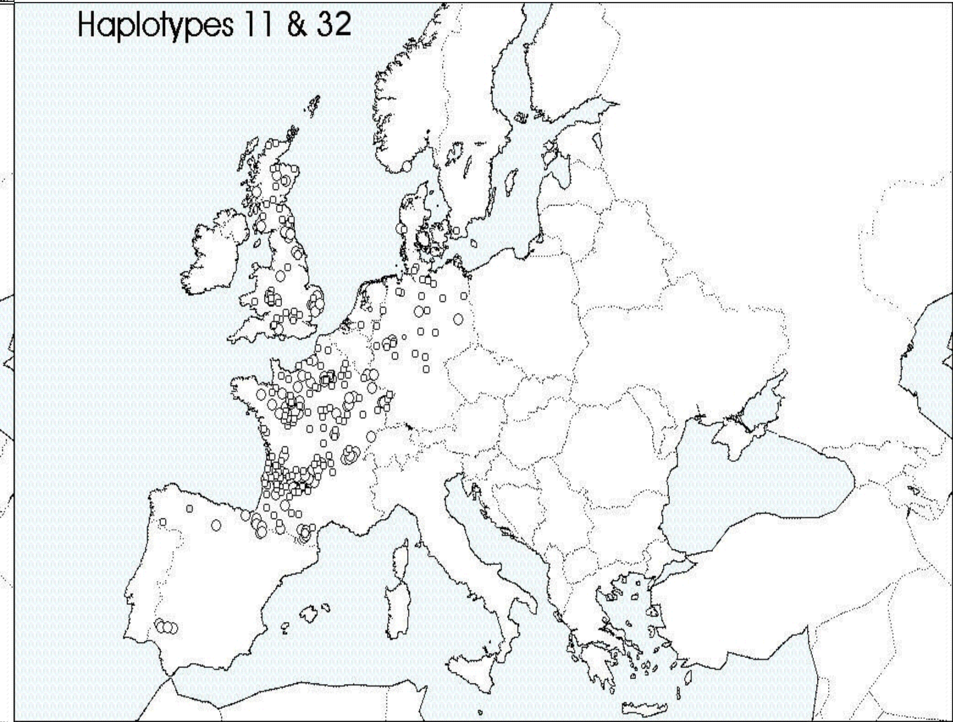
Petit et al 2002. *Forest Ecology and Management 156: 5-26*
http://gd2.pierroton.inra.fr/

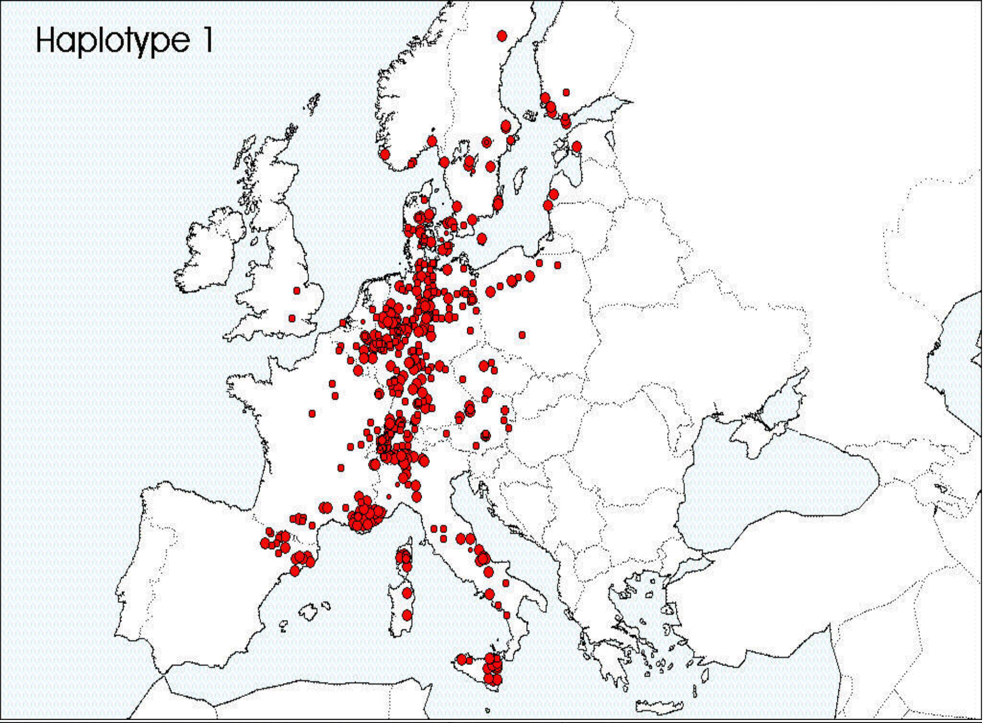


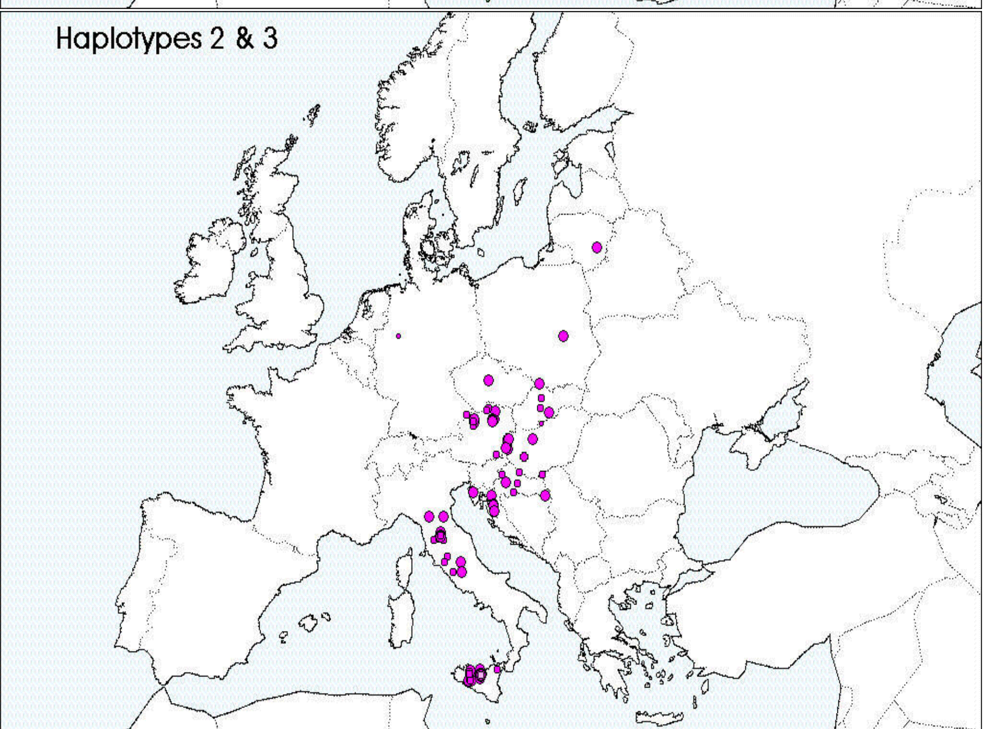
DISTRIBUTION OF HAPLOTYPES OF THE **ATLANTIC (B)** LINEAGE

Petit et al 2002. *Forest Ecology and Management 156: 5-26*
http://gd2.pierroton.inra.fr/



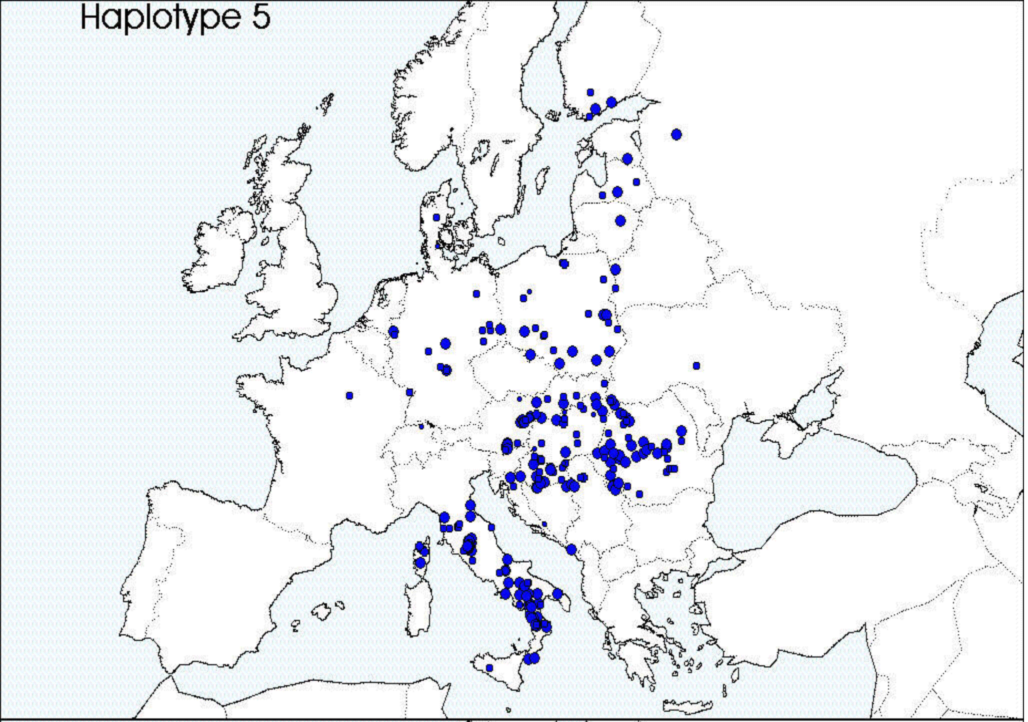


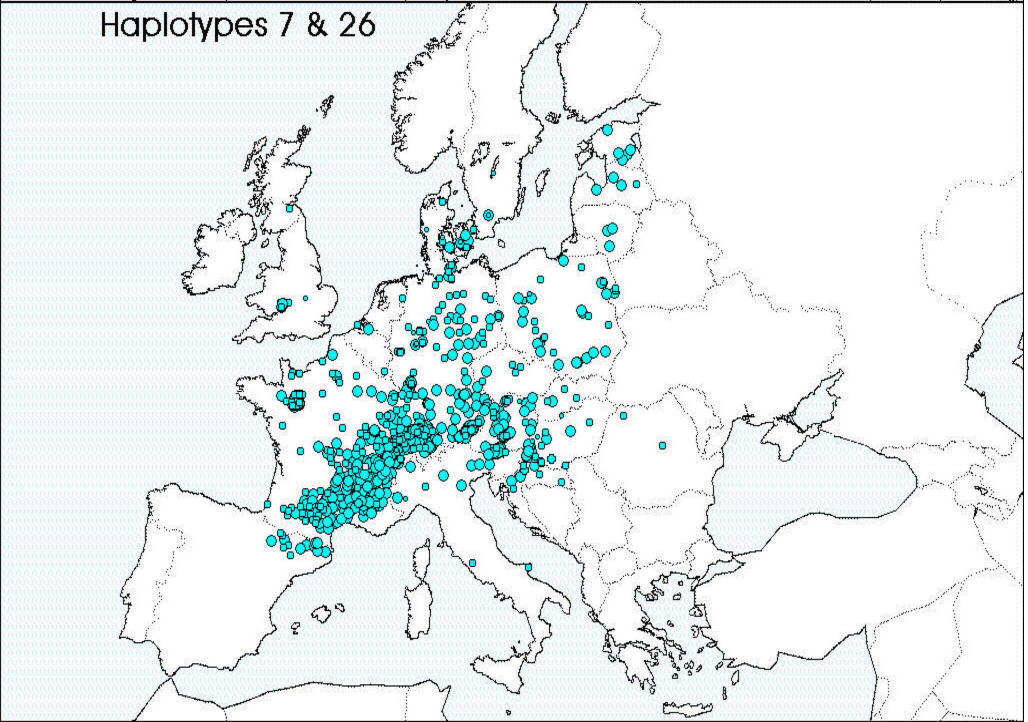




DISTRIBUTION OF HAPLOTYPES OF THE CENTRAL (C) LINEAGE

Petit et al 2002. *Forest Ecology and Management 156: 5-26*
http://gd2.pierroton.inra.fr/

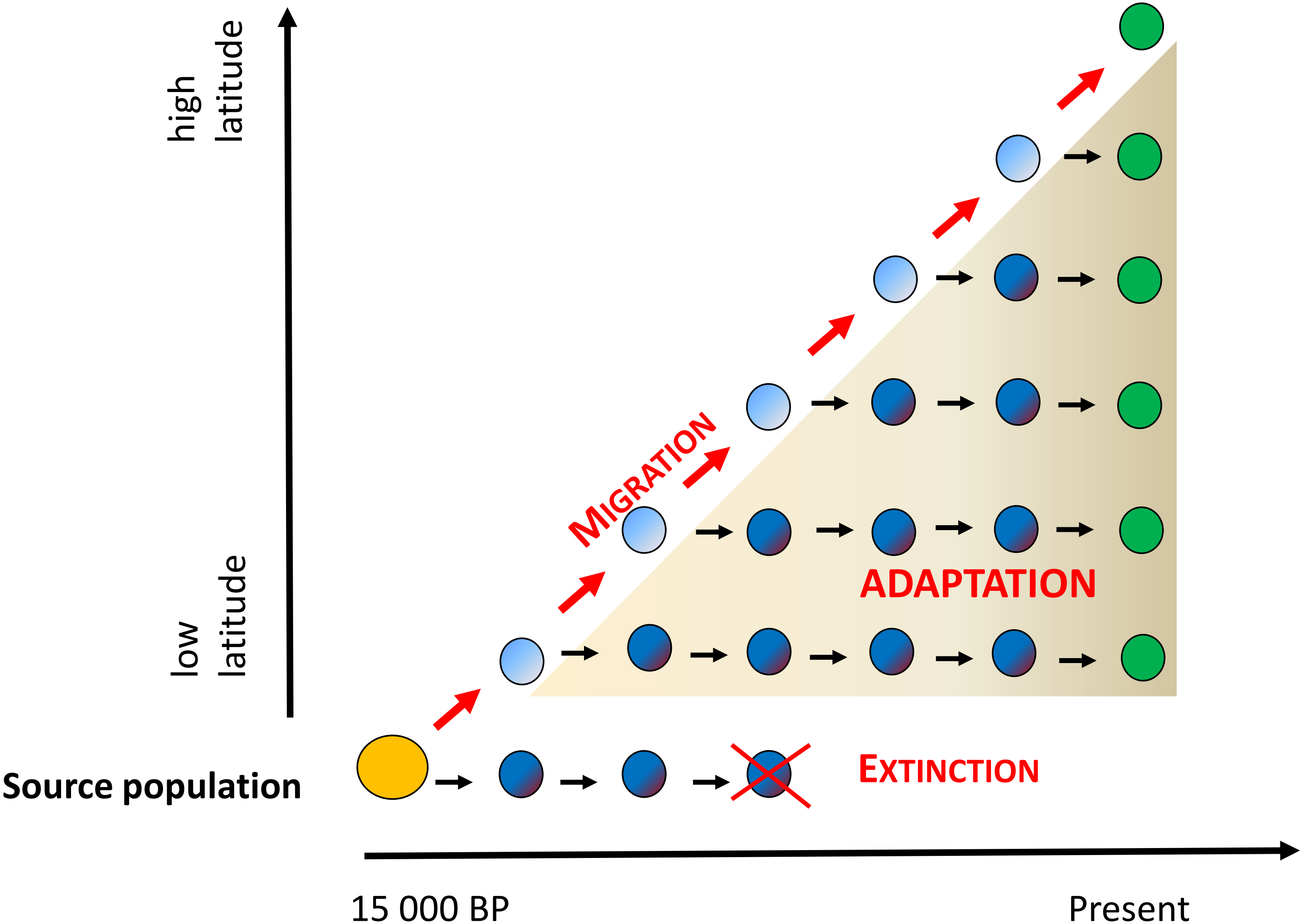




DISTRIBUTION OF HAPLOTYPES OF THE EASTERN (A) LINEAGE

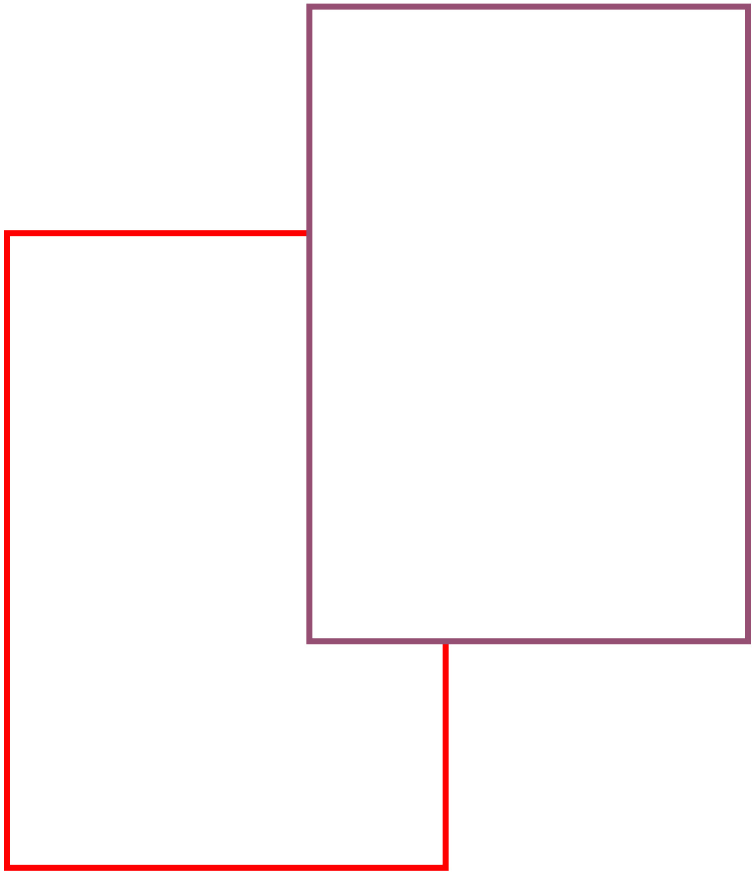
Petit et al 2002. *Forest Ecology and Management 156: 5-26*
http://gd2.pierroton.inra.fr/

EVOLUTIONARY TRAJECTORIES DURING THE HOLOCENE

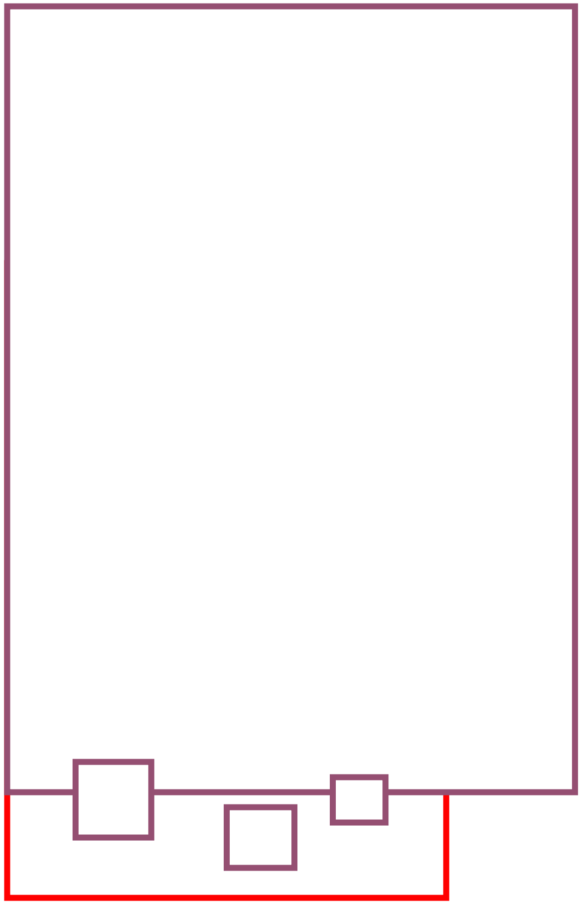


Kremer A. 2016 CR Biologies 339: 263-267

CHANGES OF RANGE DISTRIBUTION DUE TO CLIMATE CHANGE

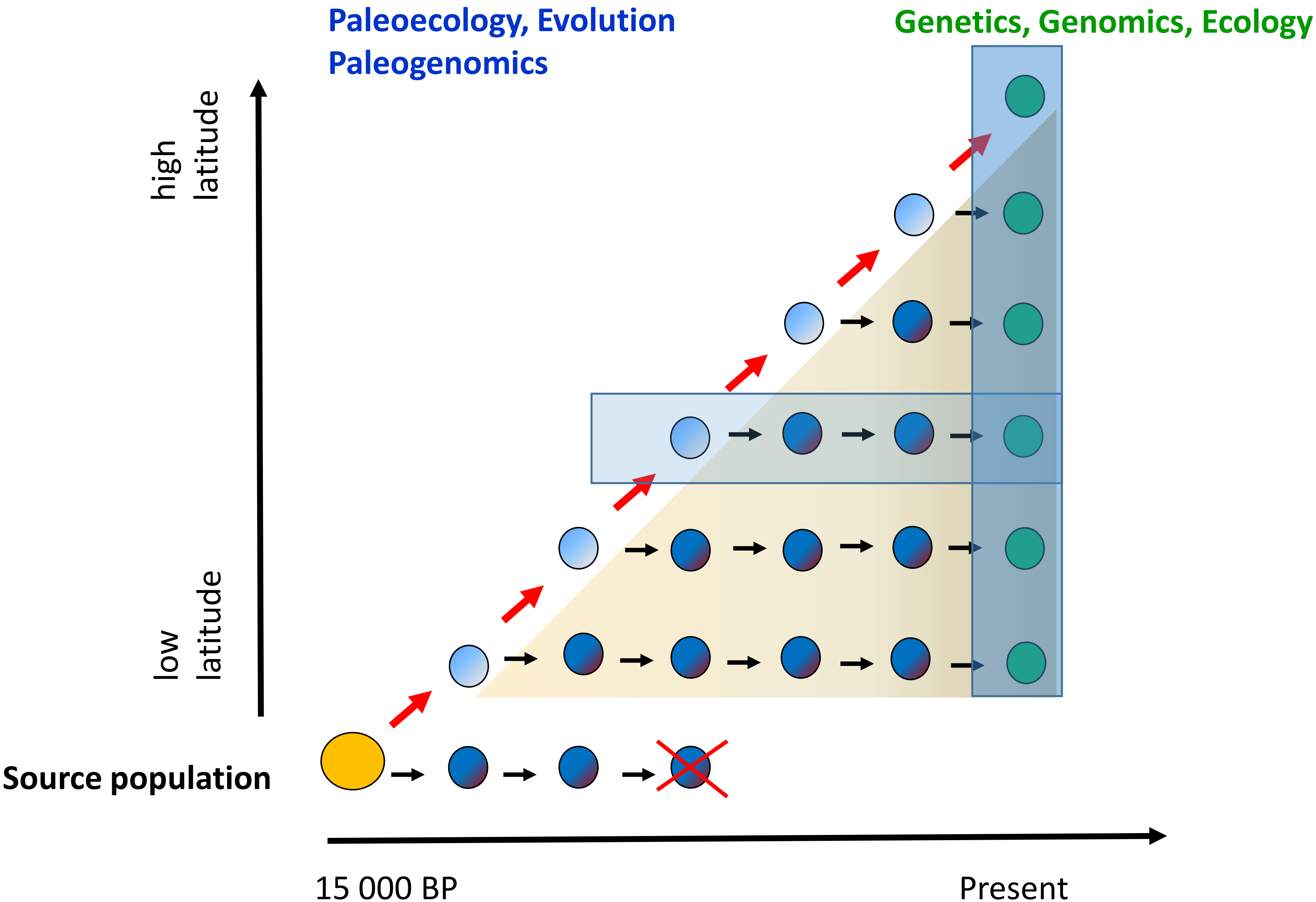


RANGE SHIFT



EXPANSION

SYNCHRONIC vs ALLOCHRONIC EVOLUTIONARY RECONSTRUCTIONS



Kremer A. 2016 CR Biologies 339: 263-267

1 EXPANSION-RAPID MIGRATION

2 INTROGRESSION

3 LOCAL ADAPTATION

4 MAINTENANCE OF DIVERSITY



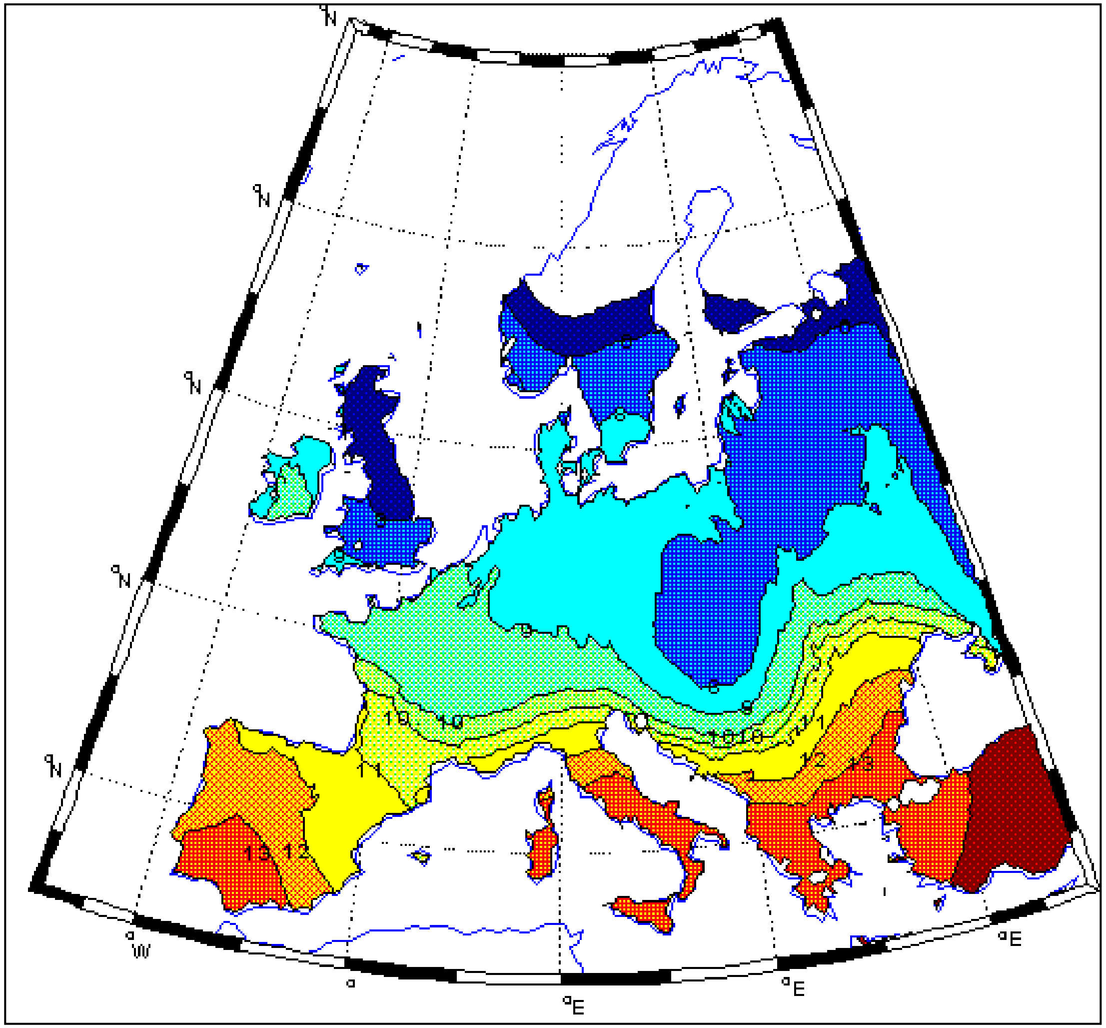

1 **EXPANSION-RAPID MIGRATION**

2 INTROGRESSION

3 LOCAL ADAPTATION

4 MAINTENANCE OF DIVERSITY

OAK POLLEN ISOCHRONE MAP (1000 years intervals)



EPD, European Pollen Data base, Université de Marseille

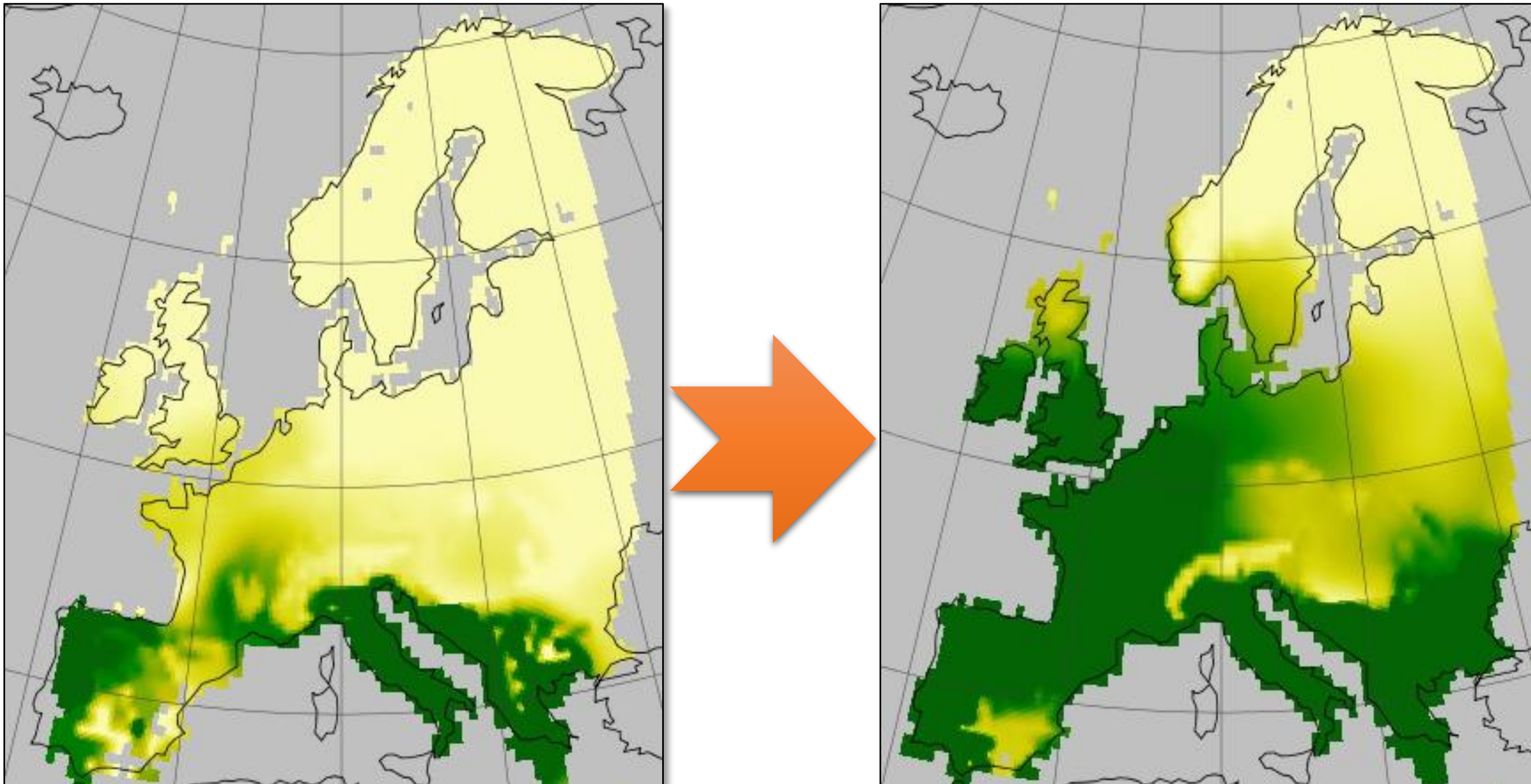
ON AVERAGE THE MIGRATION OF OAKS WAS EXTREMELY RAPID: 400 METERS PER YEAR

Brewer et al 2002 *Forest Ecology & Management* 161: 27-48

Giesecke et al. 2017, *J.Biogeography* 44: 1441-1456

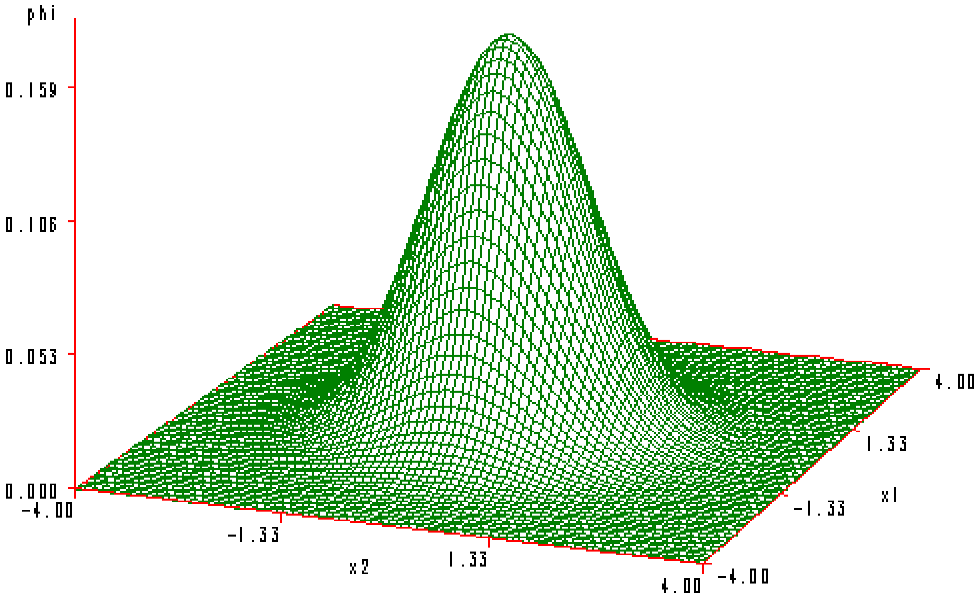
Quercus 11000 cal. BP

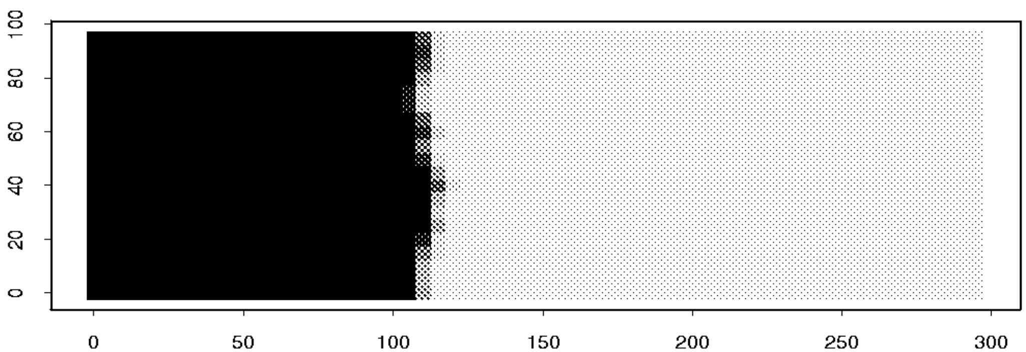
Quercus 8000 cal. BP



Giesecke T. 2016 *New Phytologist* 212:15-18

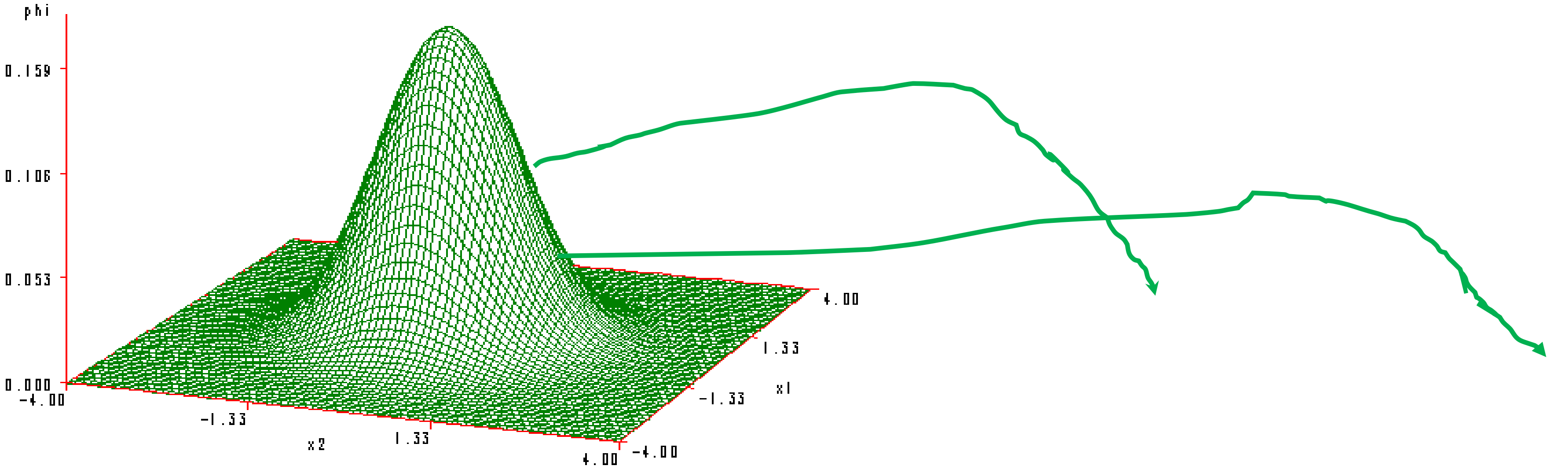
DISPERSION BY DIFFUSION

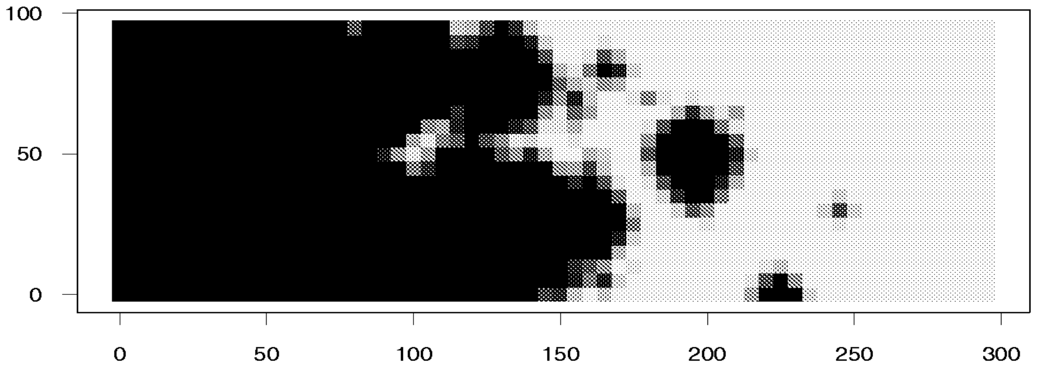




Le Corre et al, 1997 *Genet. Res.* 69 : 117-125

DIFFUSION + RARE LONG DISTANCE DISPERSION (LDD)

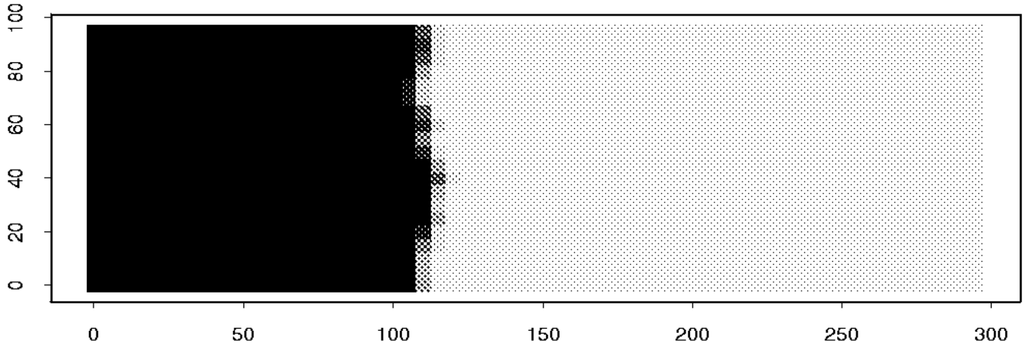




Le Corre et al, 1997 *Genet. Res.* 69 : 117-125

COMPARATIVE RATES OF DISPERSION

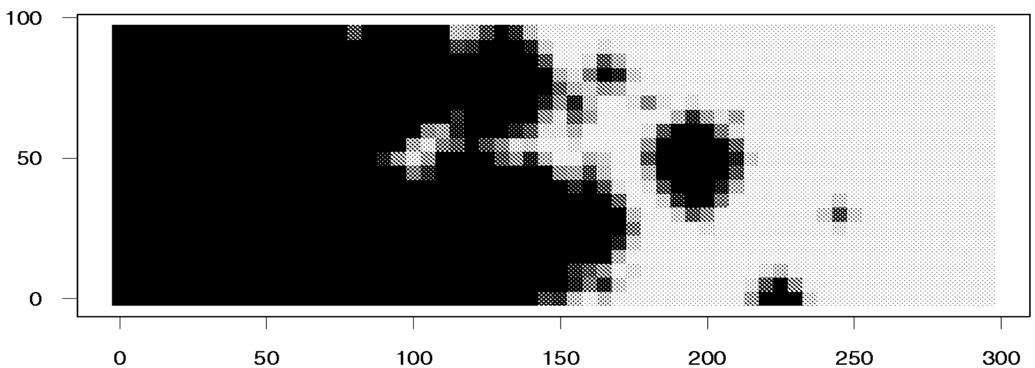
100 m/year



Diffusion

Dispersion law = N(0, sd1 = 250 m)

400 m/year



Diffusion + LDD

Dispersion law =

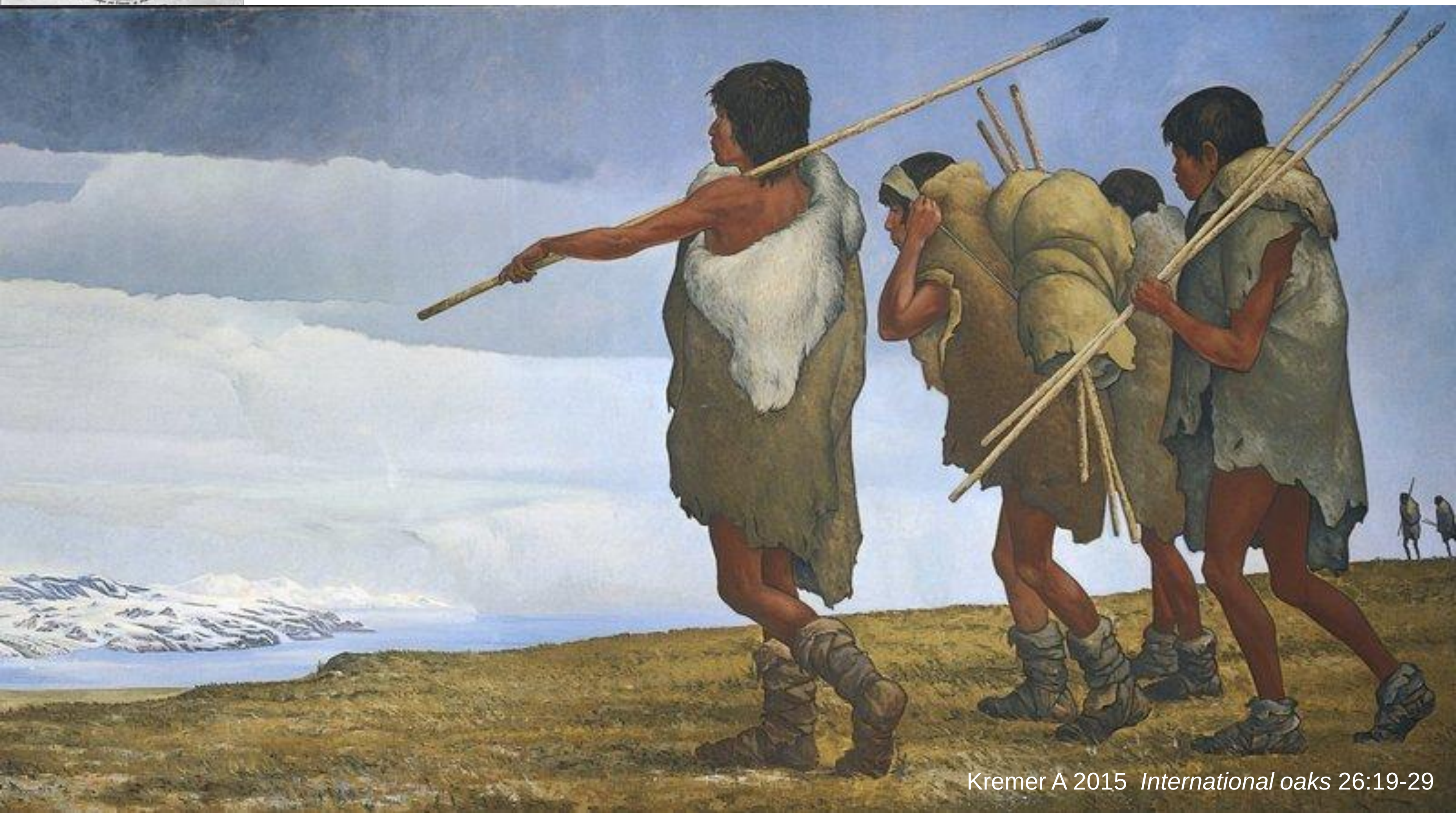
N (0, sd1= 250 m)

+ $5*10^{-6}$ N(0, sd2=50 km)

Le Corre et al, 1997 *Genet. Res.* 69 : 117-125

Pliny the Elder (23-79)

« When the cereals become rare, they dry the acorns, they shell them and grind them to make a flour and finally to produce bread. Today, even in the Hispanias, acorns are also part of desserts.»   Naturalis Historia



Kremer A 2015 *International oaks* 26:19-29

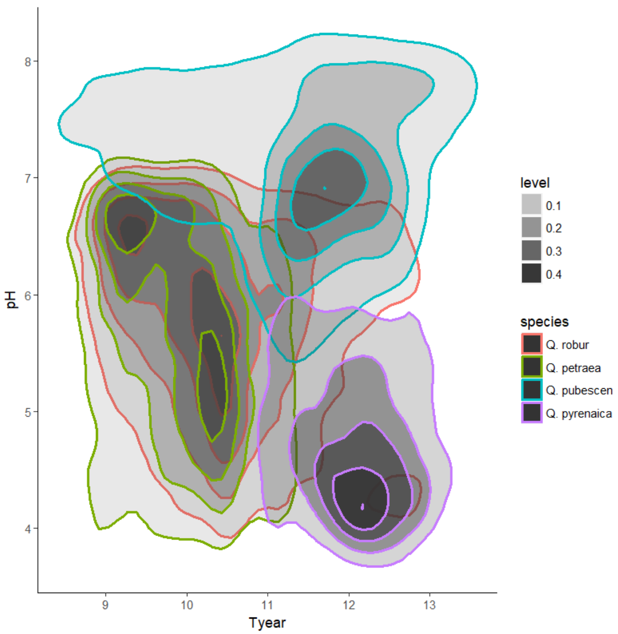
1 EXPANSION-RAPID MIGRATION

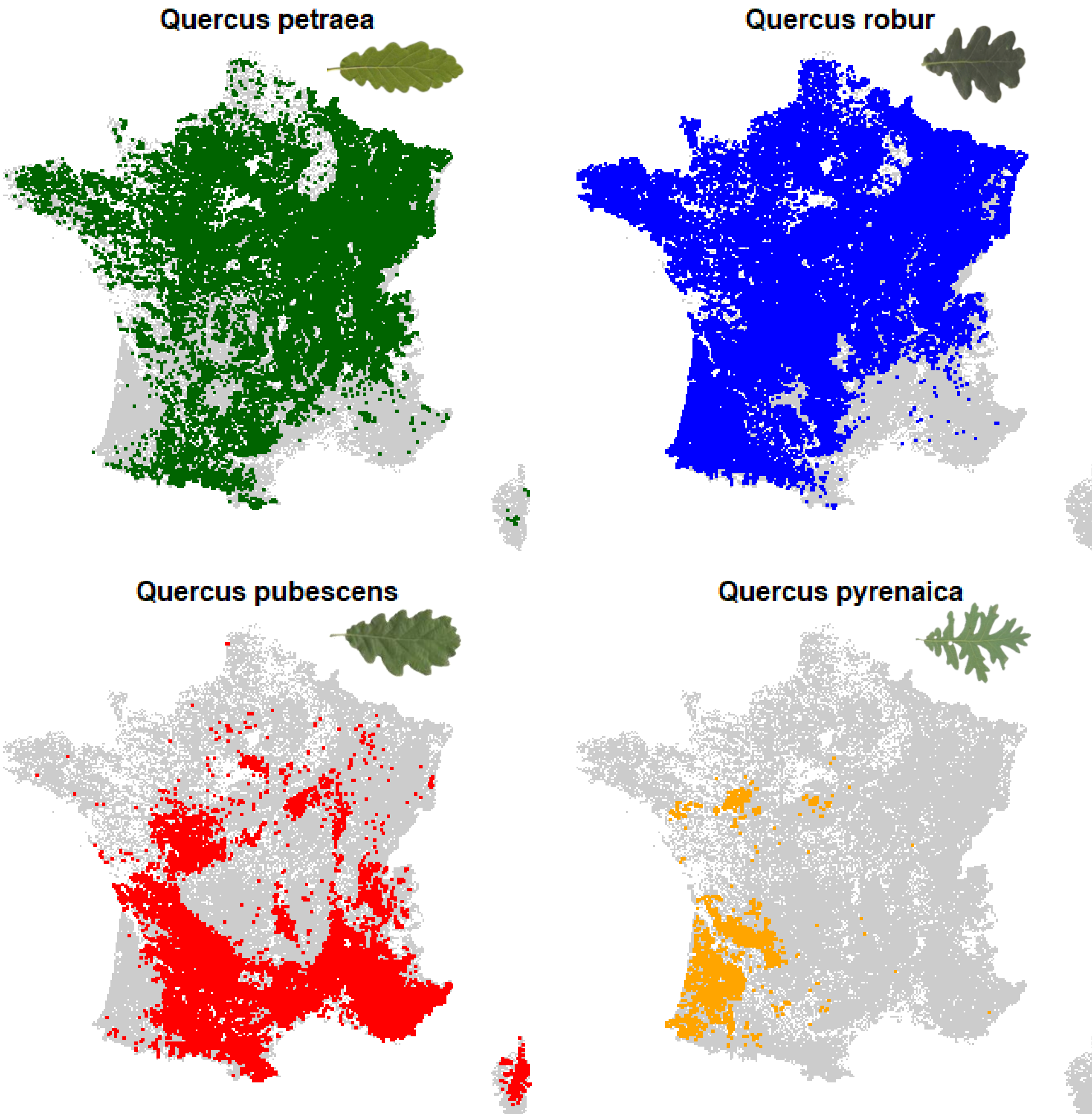
2 **INTROGRESSION**

3 LOCAL ADAPTATION

4 MAINTENANCE OF DIVERSITY

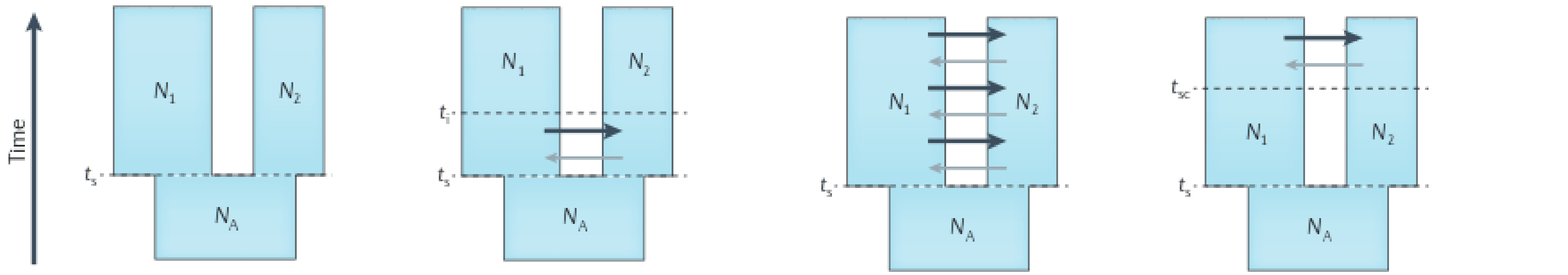
WHITE OAKS IN FRANCE





TIMING AND PATTERNS OF CONTACTS IN EUROPEAN WHITE OAKS

STRICT ISOLATION (SI) | **ANCIENT MIGRATION (AM)** | **CONSTANT MIGRATION (CM)** | **SECONDARY CONTACTS (SC)**



Approximate Bayesian Computation (ABC) and Diffusion Approximation to the joint frequency spectrum (∂a∂i)

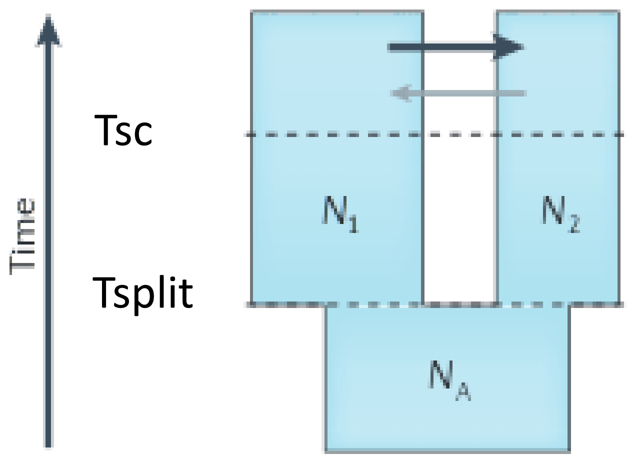
3524 SNPS + whole genome sequences

		Post. Proba. **(SI)**	*Post. Proba.* **(AM)**	*Post. Proba.* **(CM)**	*Post. Proba.* **(SC)**
	robur *vs* pyrenaica	<0.001	<0.001	0.067	**0.933**
	robur *vs* petraea	<0.001	<0.001	0.009	**0.991**
	petraea *vs* pubescens	<0.001	0.001	0.103	**0.896**

Leroy et al. 2017 *New Phytologist* 214: 865-878

TIMING OF SECONDARY CONTACTS IN EUROPEAN WHITE OAKS

SECONDARY CONTACTS (SC)

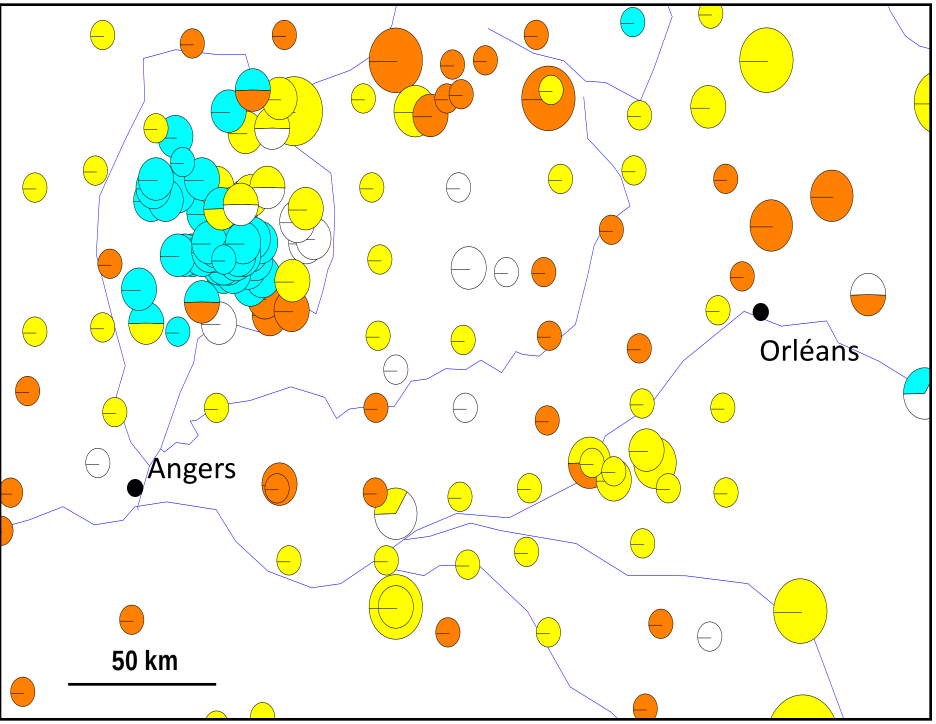


Timing of SC (Tsc)		Mean	CI95%
robur *vs* pyrenaica		11,970	[3,100-40,500]
robur *vs* petraea		14,870	[4,300-40,500]
petraea *vs* pubescens		21,760	[7,700-62,400]

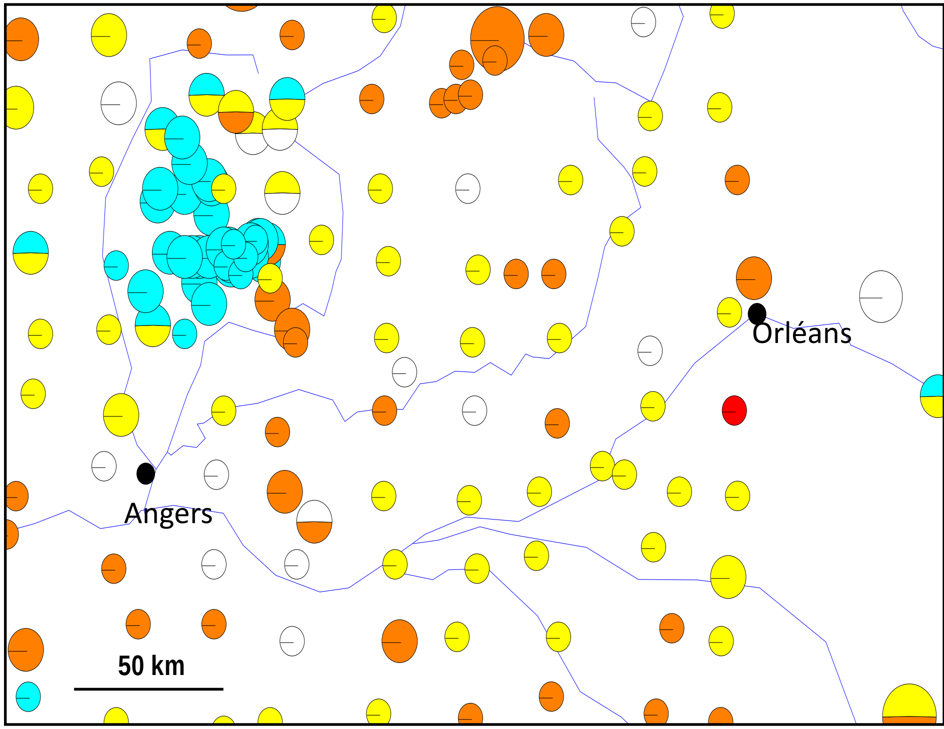
Hubert F et al. 2014 *Systematics and Biodiversity* 12 : 405-423
Leroy T et al. 2017 *New Phytologist* 214: 865-878

EVIDENCE OF INTROGRESSION : SHARING OF CHLOROPLAST HAPLOTYPES

Q. petraea (Sessile oak)



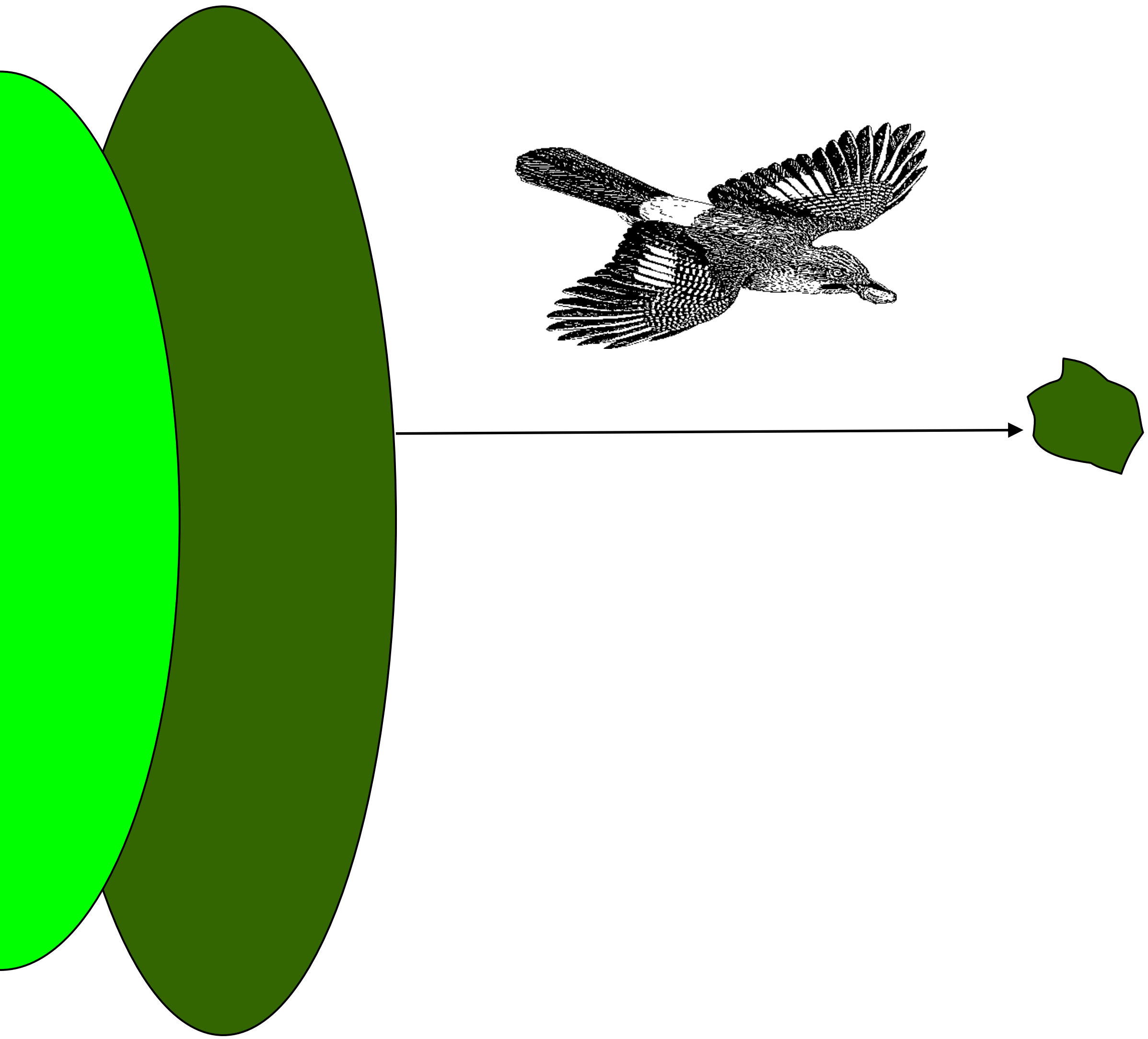
Q. robur (Pedunculate oak)



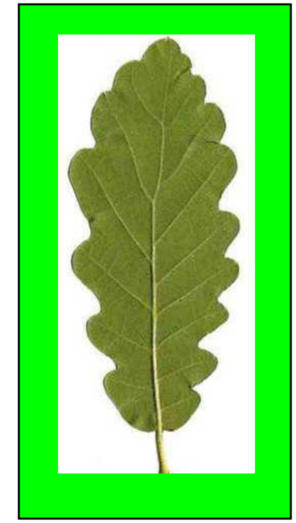
Two oak species share the same haplotypes when they cohabit in the same forest =
the outcome of repeated unidirectional backrossings

Petit et al. 1996 *PNAS* 94 : 9996-10001

DISPERSION OF *QUERCUS ROBUR*



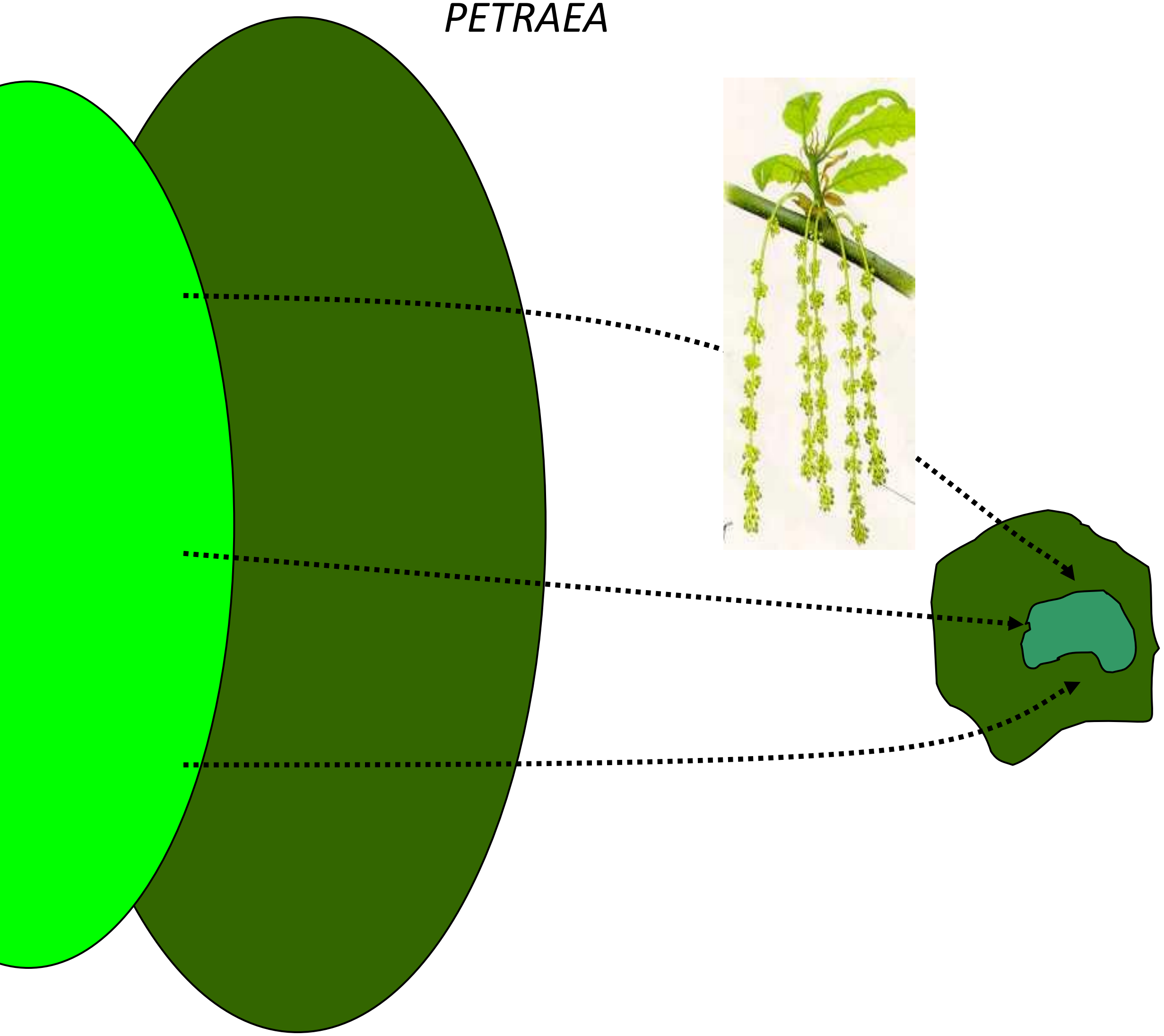
Q. petraea (Sessile oak)



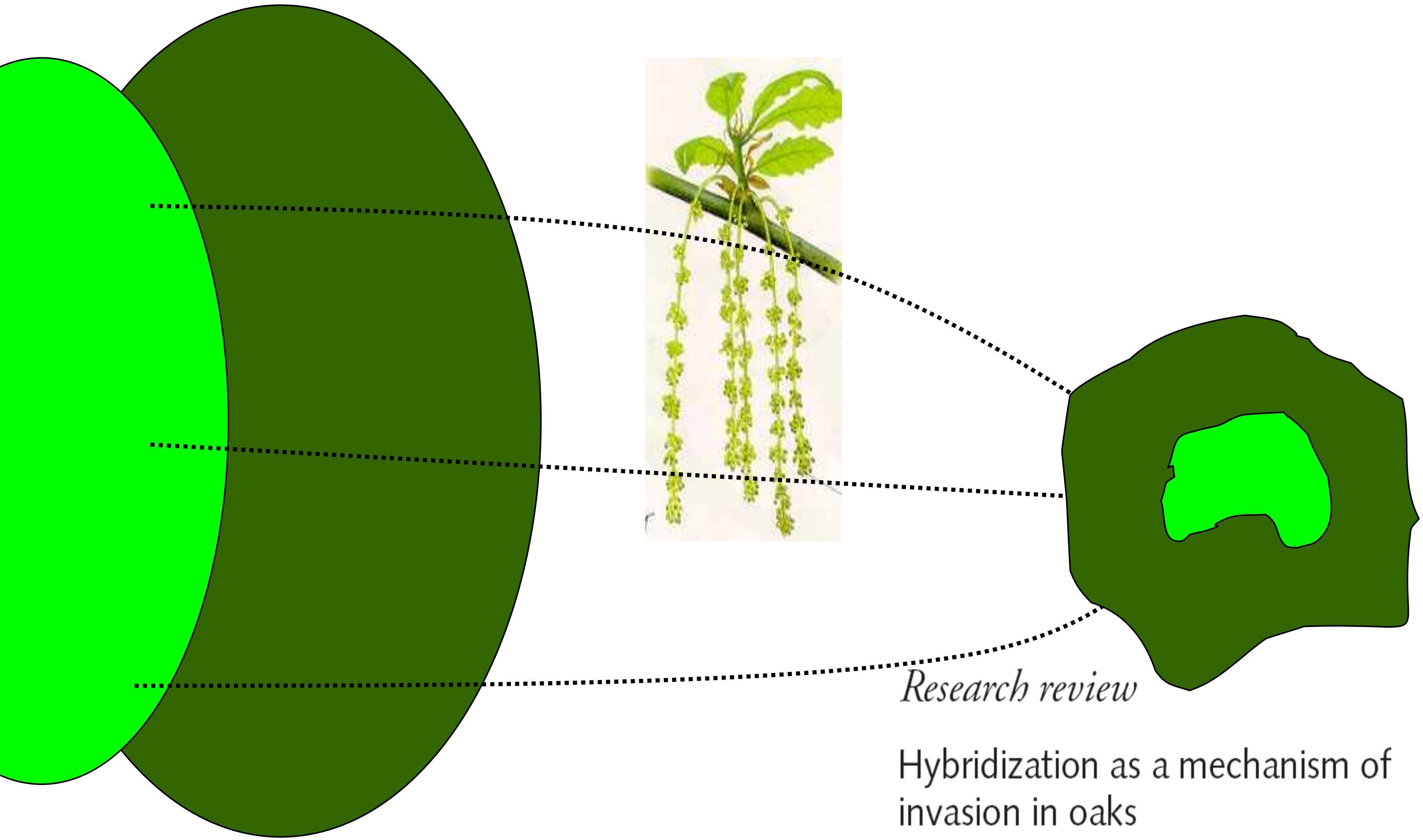
Q. robur (Pedunculate oak)

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

Petit RJ et al 2003 *New Phytologist* 161(1):151-164.



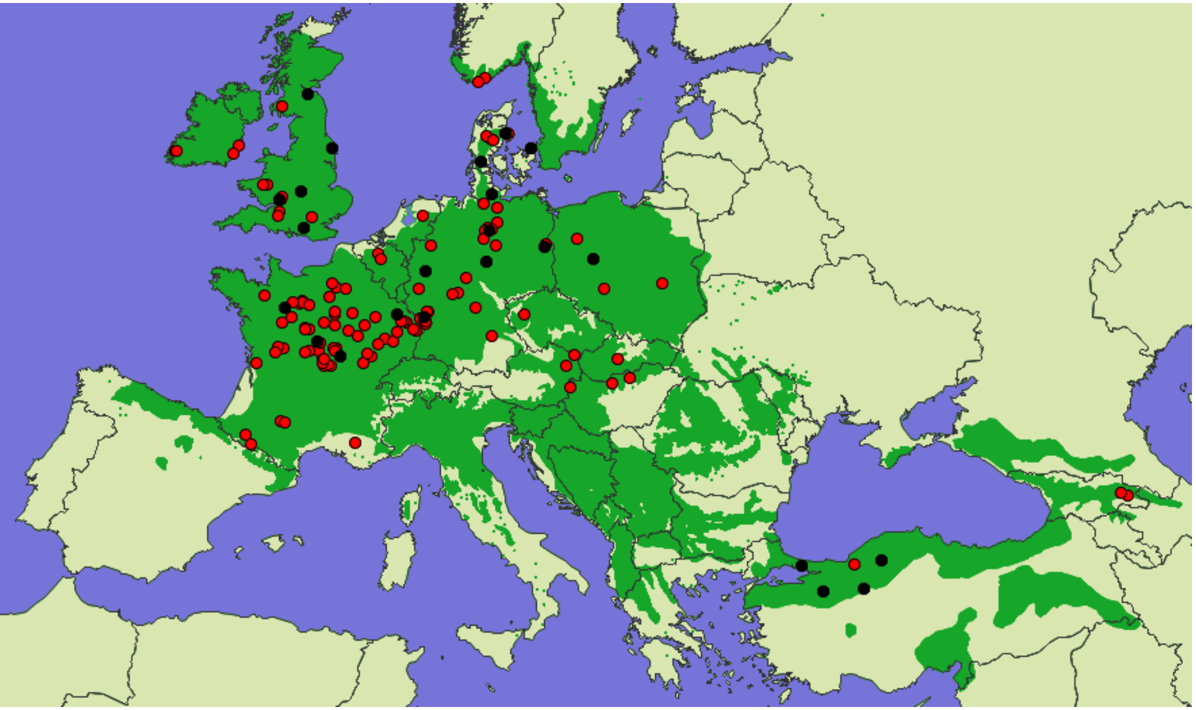

1 EXTINCTIONS

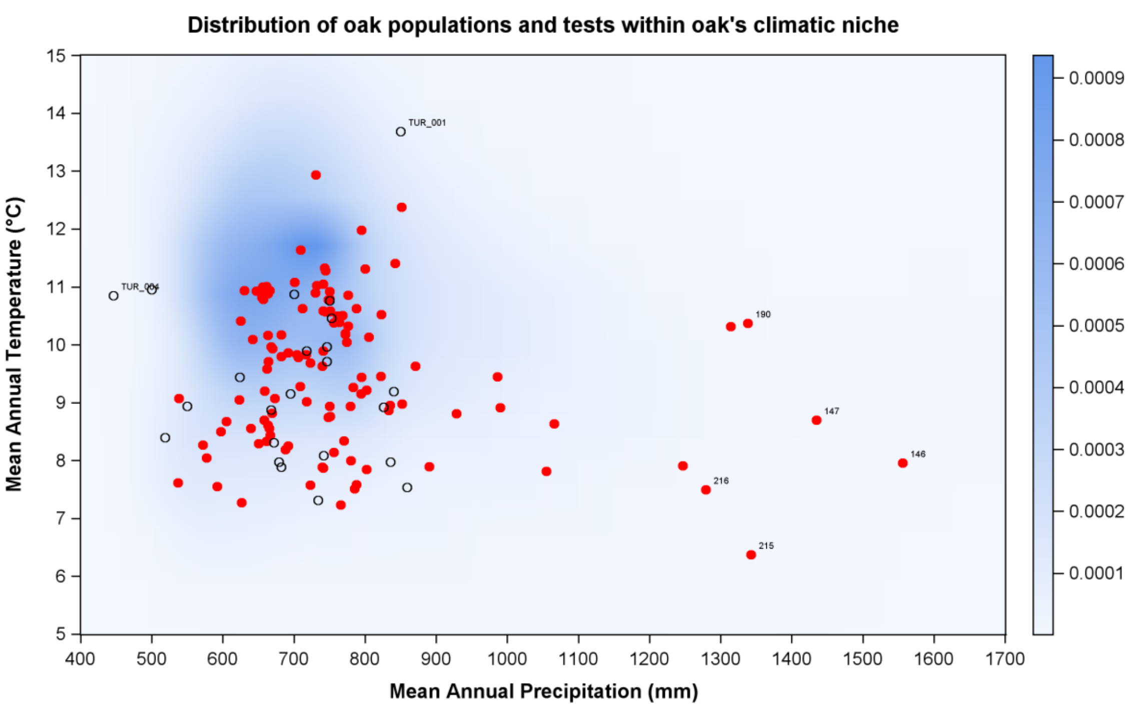
2 EXPANSION - MIGRATION

3 **LOCAL ADAPTATION**

4 MAINTENANCE OF DIVERSITY

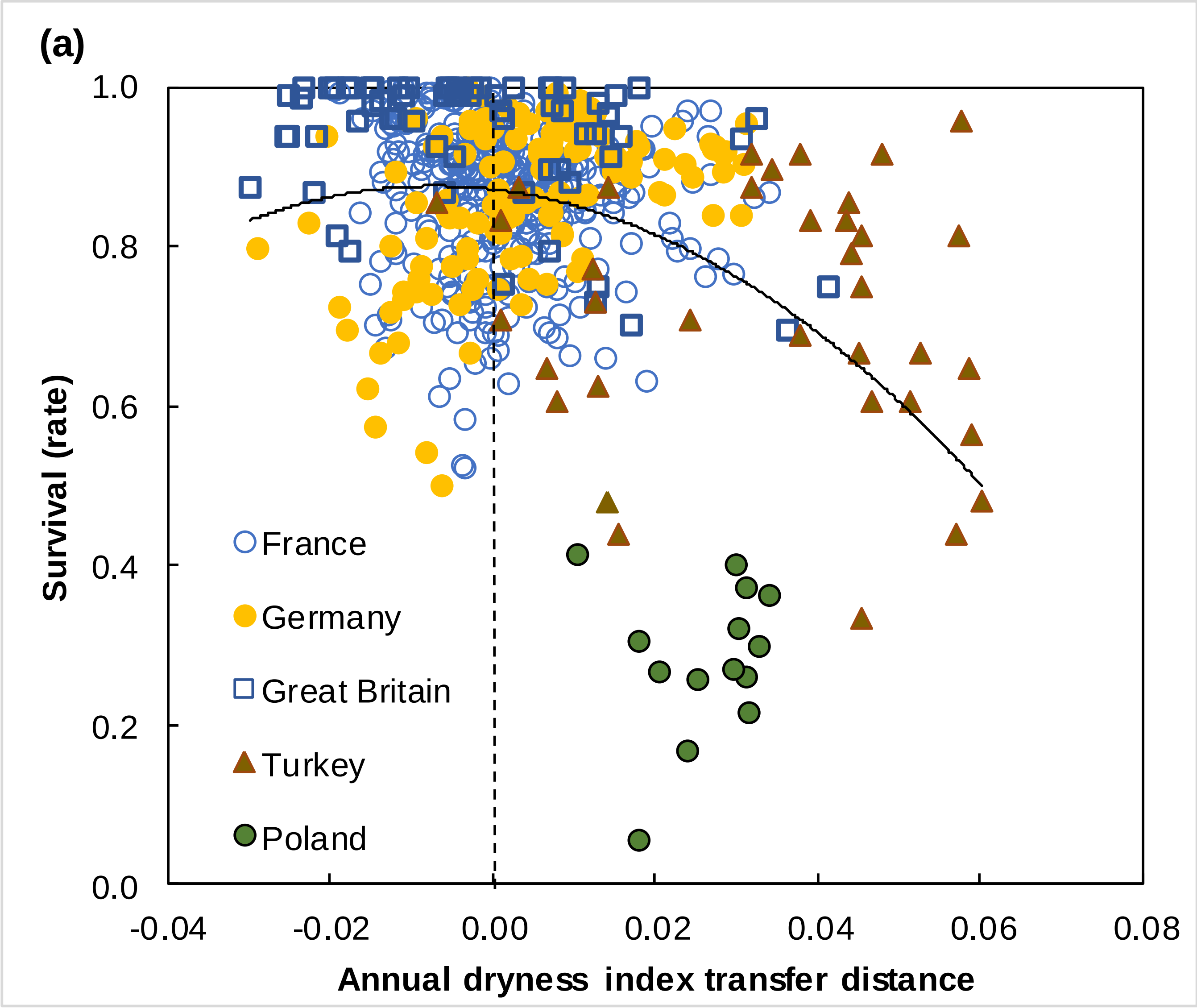
COMMON GARDEN EXPERIMENTS





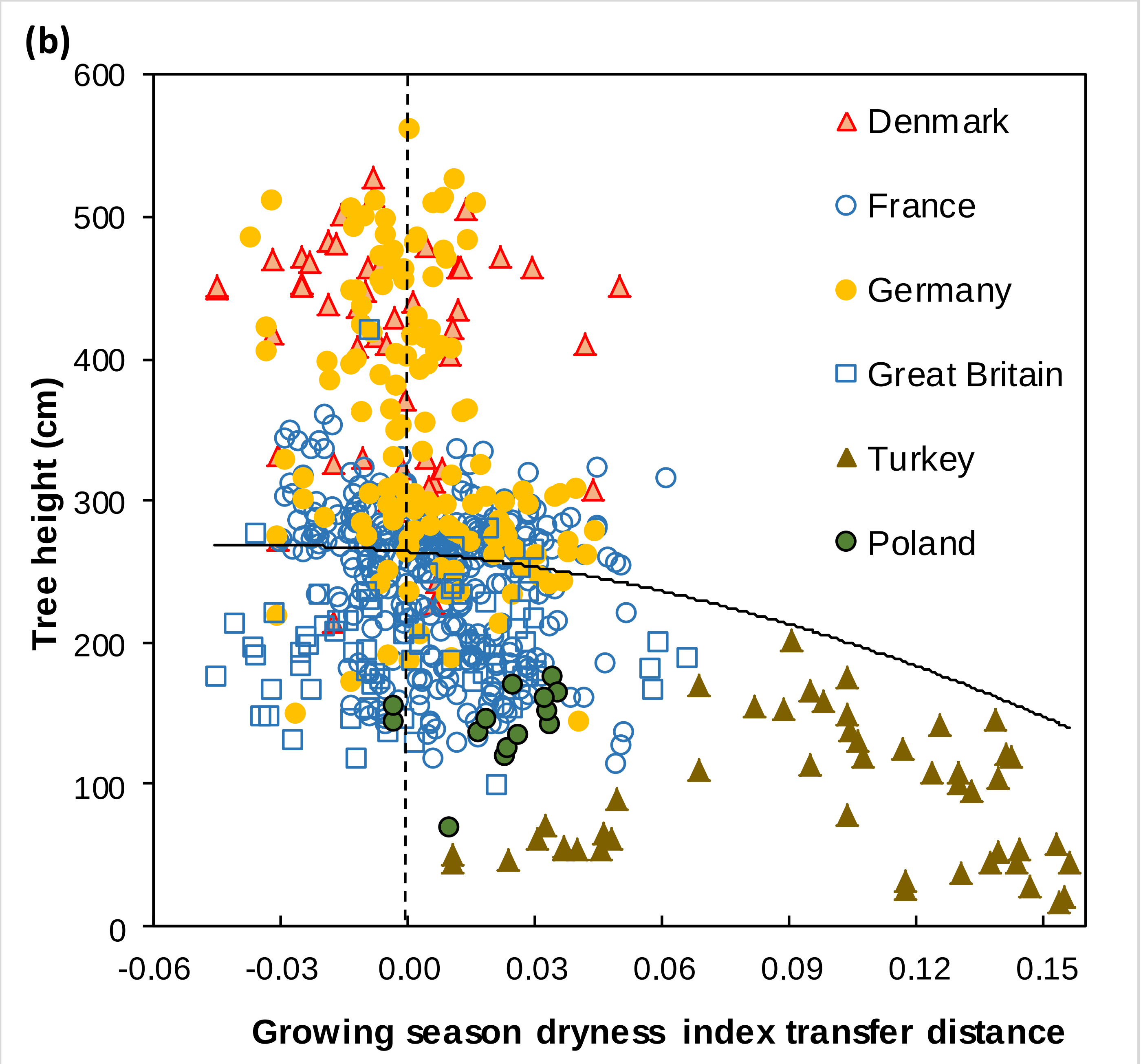
Provenance tests planted in the early 90s (23 tests and >100 provenances)

POPULATION VARIATION OF SURVIVAL IN RESPONSE TO THE TRANSFER



Saenz-Romero et al., 2017 *Global Change Biology* 23:2831-2847

POPULATION VARIATION OF GROWTH IN RESPONSE TO THE TRANSFER



Saenz-Romero et al., 2017 *Global Change Biology* 23:2831-2847

Kremer A. et al. 2002 Forest Ecology & Management 156: 75-87

62 TRAIT * TEST COMBINATIONS

Significant provenance variations observed for all traits

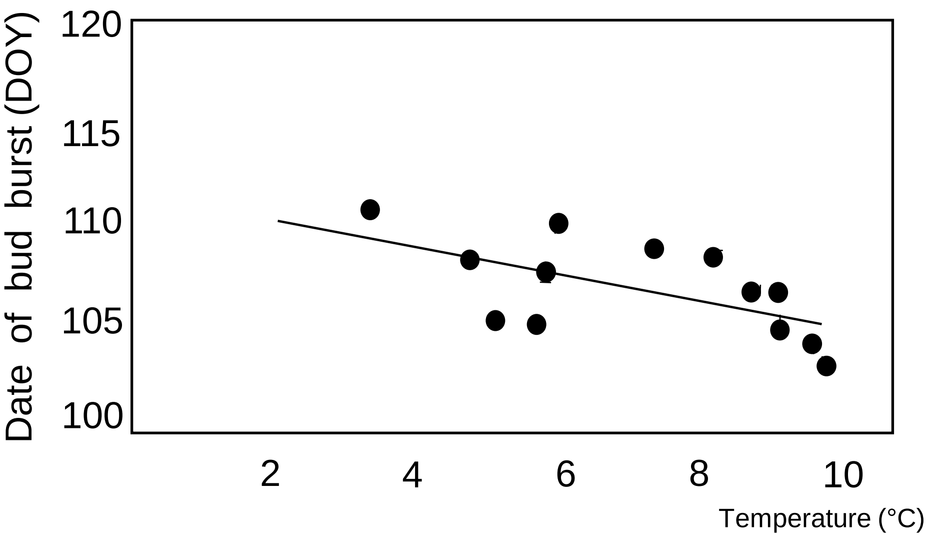
Qst ≈ 0.36 to 0.53


BUD BURST
0
1
2
3
4
5

GENETIC DIFFERENTIATION ALONG TEMPERATURE GRADIENTS

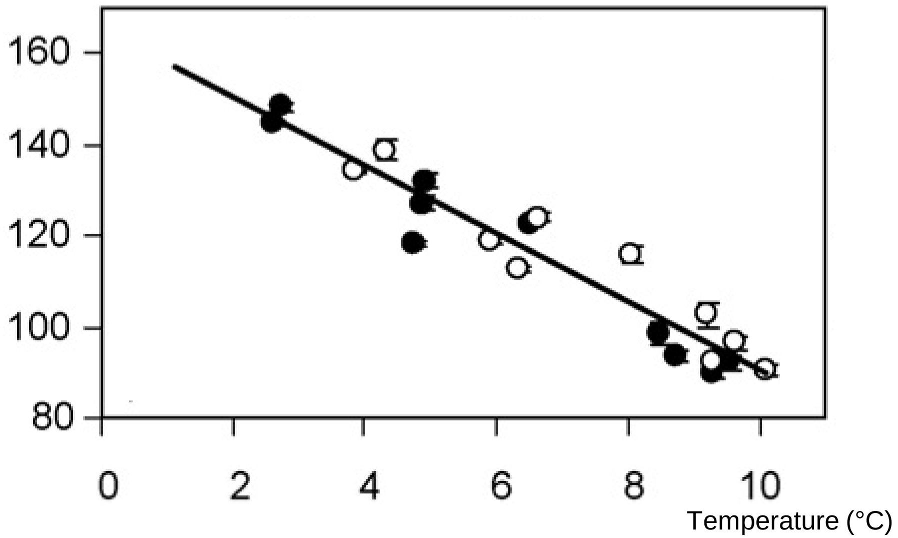
2°C to 12°C : range of mean spring temperatures

In common gardens



0.7 days/ °C

In situ



7.3 days/ °C

Vitasse et al. 2009, *Canadian Journal of Forest Research* 39**:** 1-11
Vitasse et al. 2009, *Agricultural & Forest Meteorology* 149: 735-744



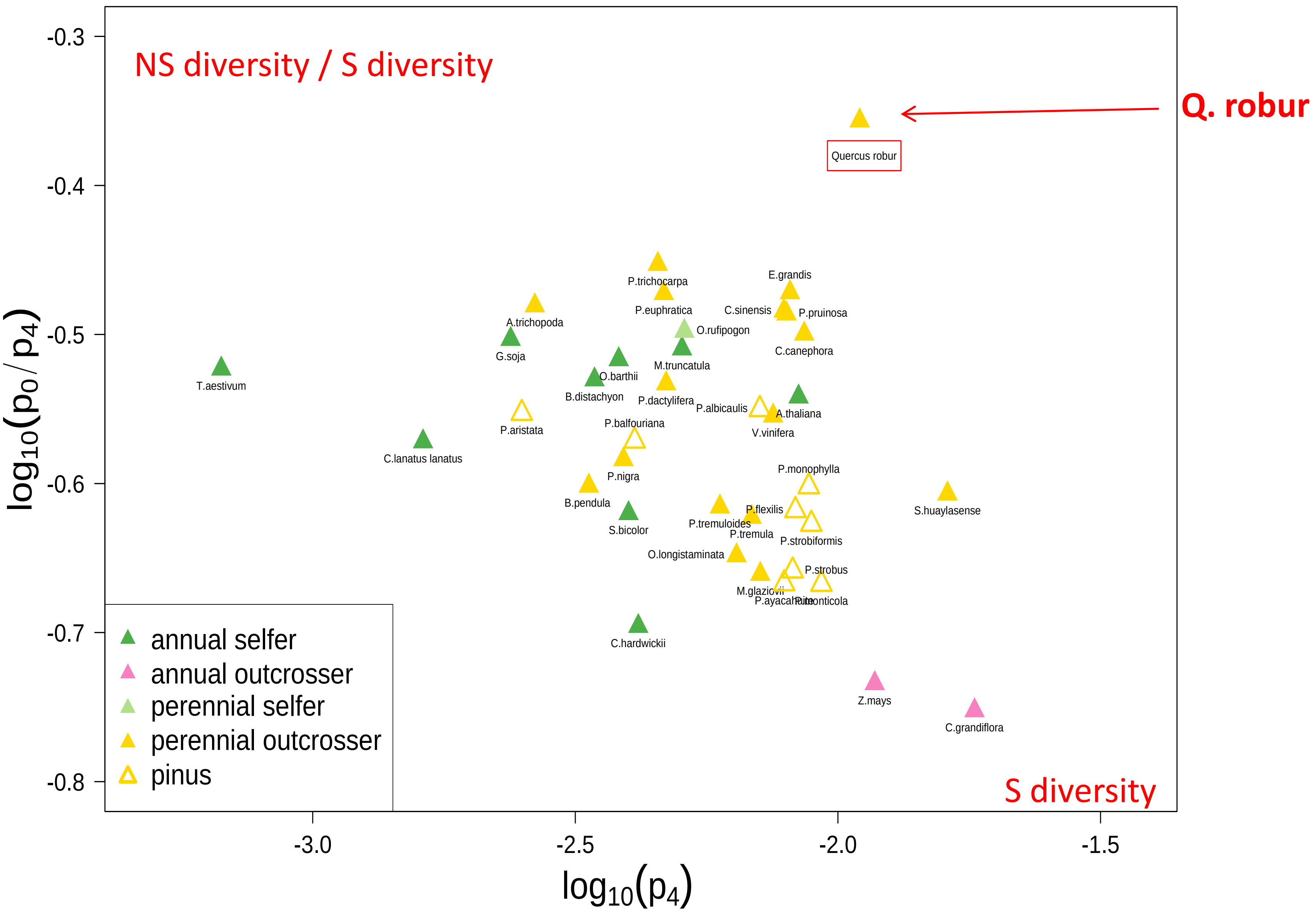

1 EXTINCTIONS

2 EXPANSION - MIGRATION

3 LOCAL ADAPTATION

4 **MAINTENANCE OF DIVERSITY**

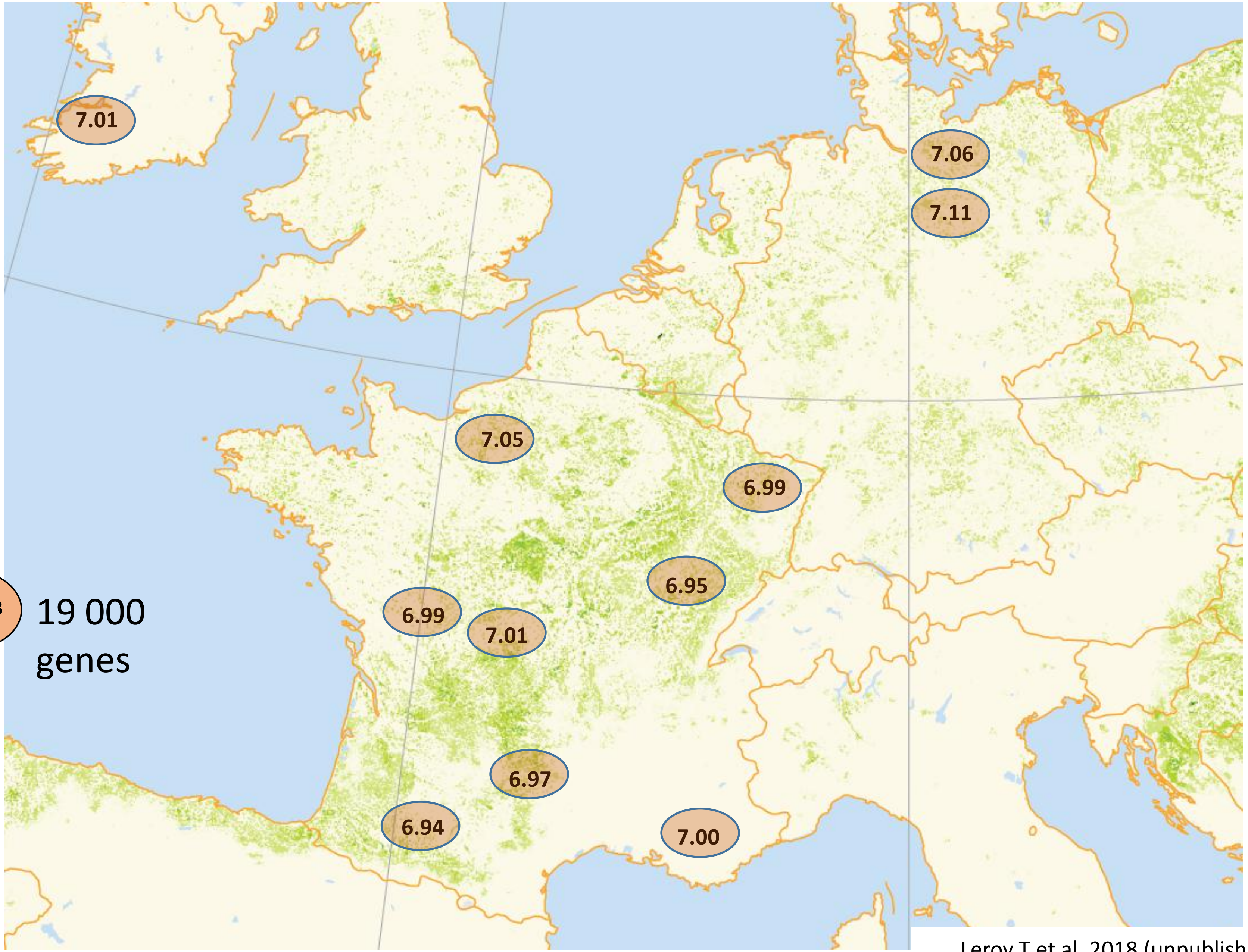
COMPARATIVE DIVERSITY SPECTRUM IN PLANTS



Plomion C et al. 2018 *Nature Plants* 4:440-452

GEOGRAPHIC DISTRIBUTION OF GENOME WIDE DIVERSITY IN Q. petraea

S Diversity



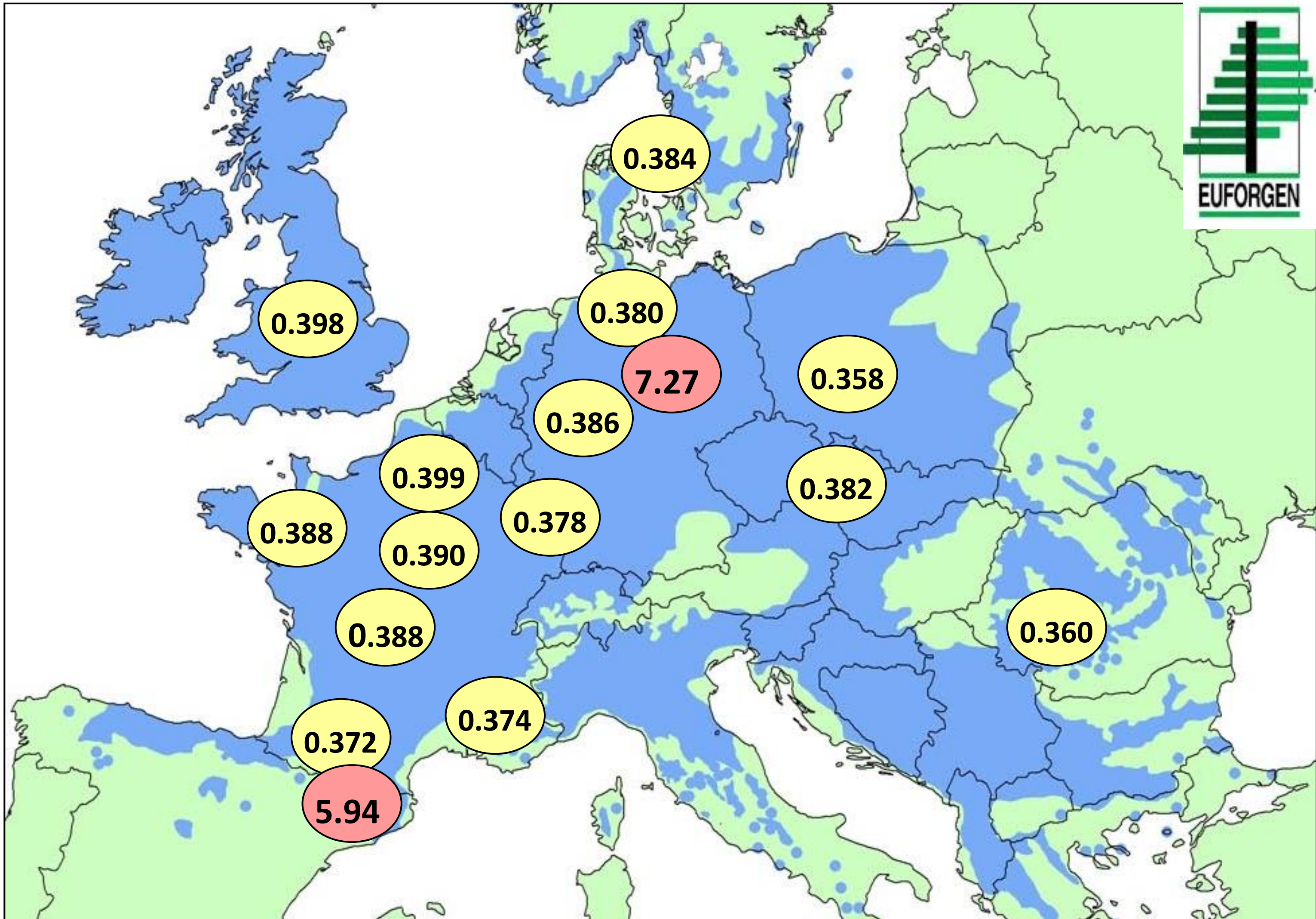
π 10^{-3} 19 000 genes

Leroy T et al. 2018 (unpublished data)

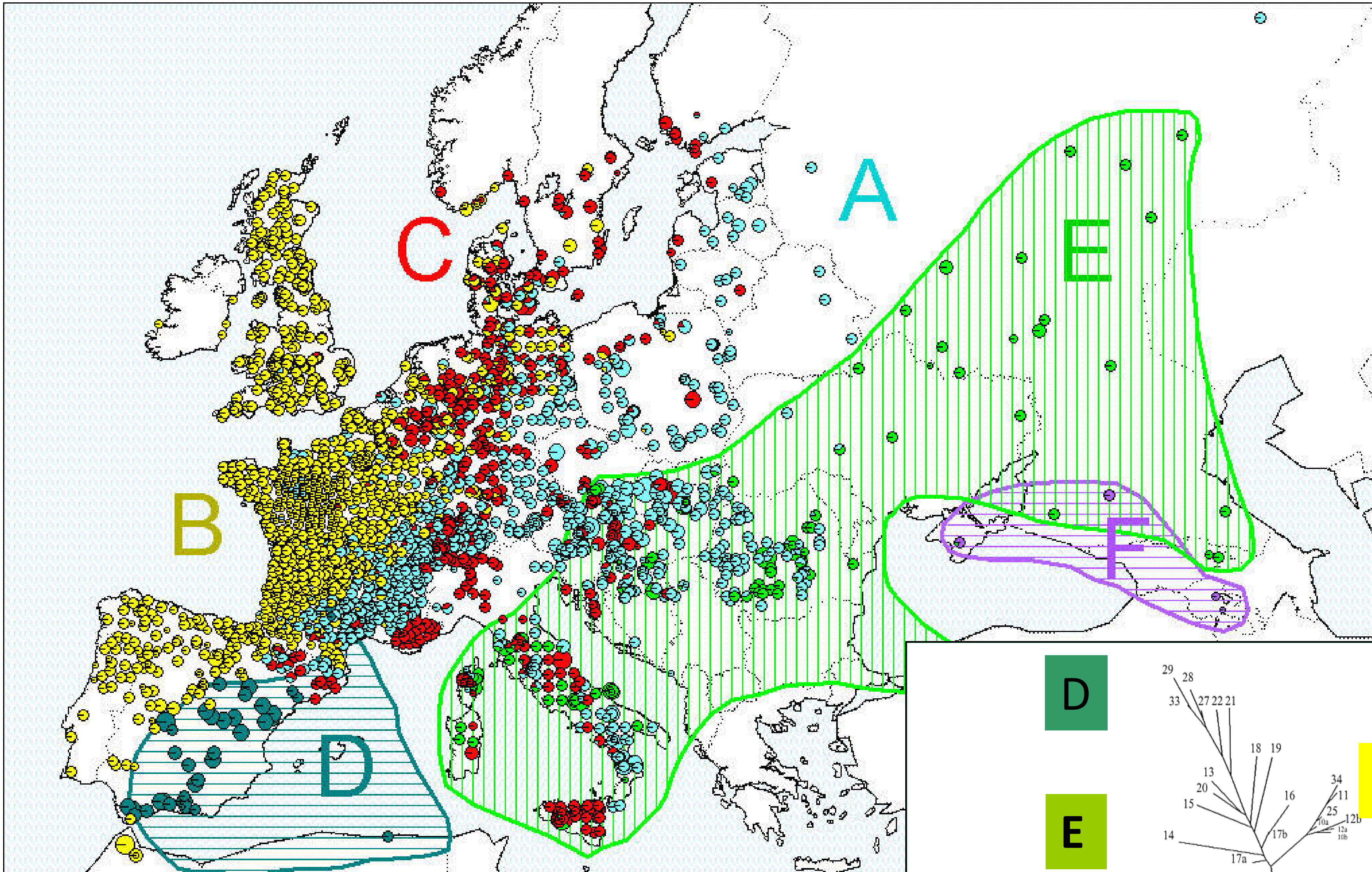
MAINTENANCE OF GENE DIVERSITY IN Quercus petraea

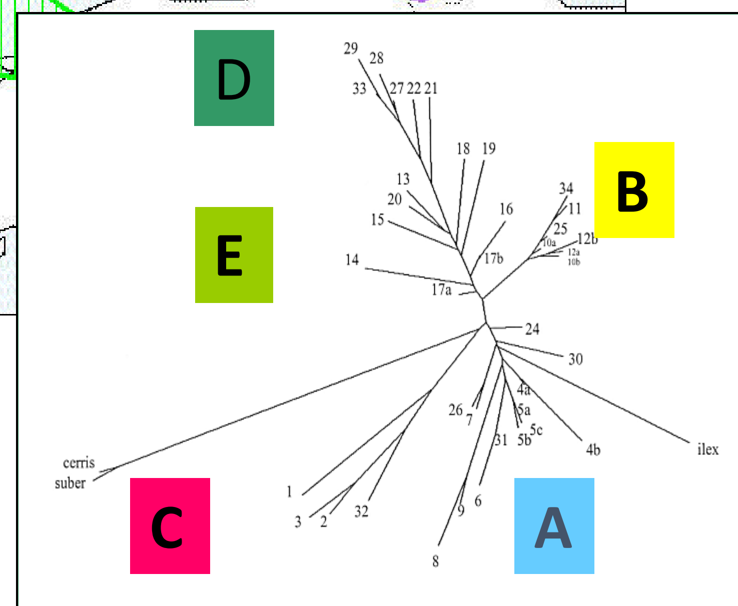
$\pi \ 10^{-3}$ Genes

H_e Proteins



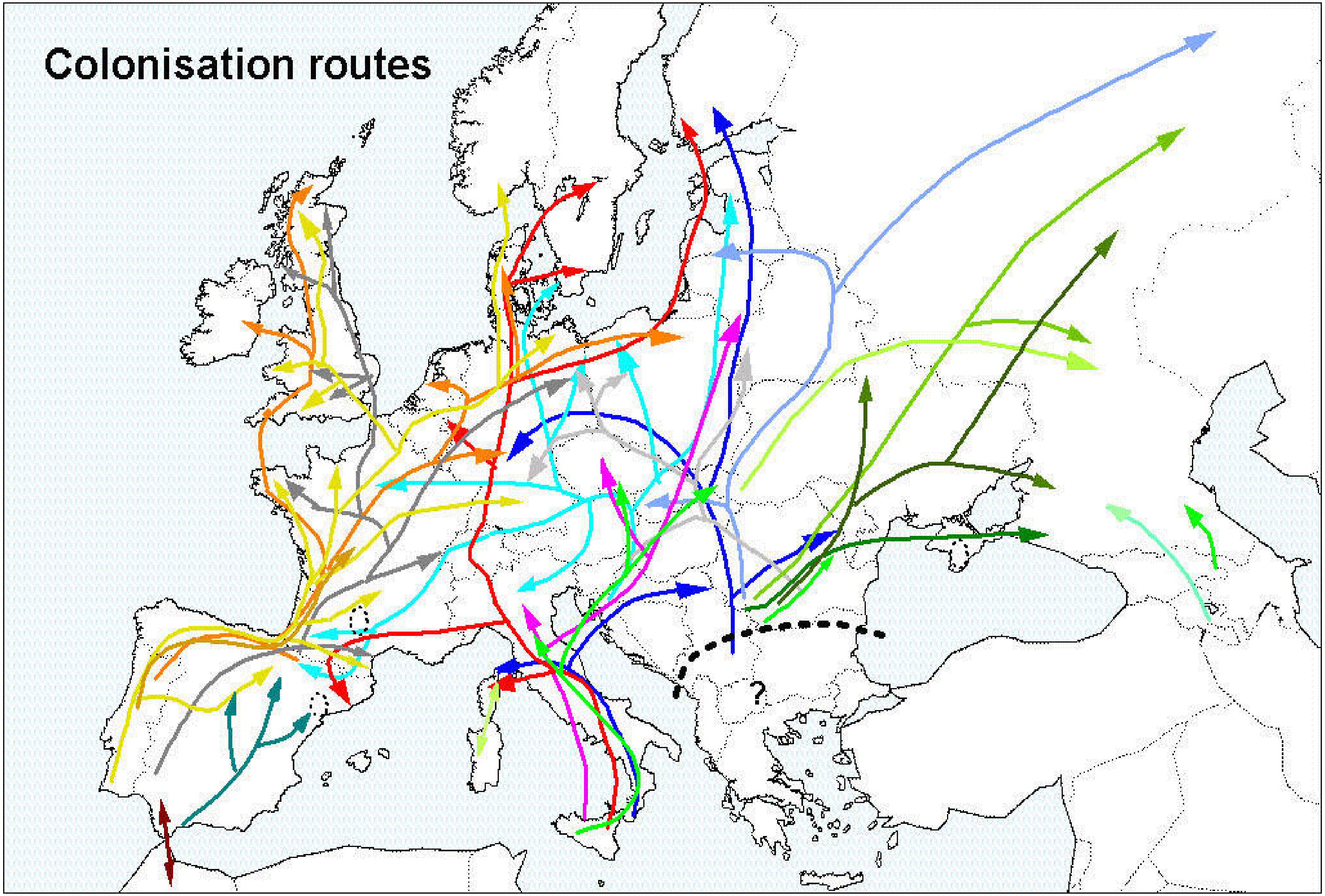
Zanetto A & Kremer A 1995 *Heredity* 75:506 - 517
Derory J et al, 2010 *Heredity* 104: 438 – 448
Alberto F et al. 2013 *Genetics* 195 : 495–512





PHYLOGEOGRAPHIC STRUCTURE OF EUROPEAN WHITE OAKS

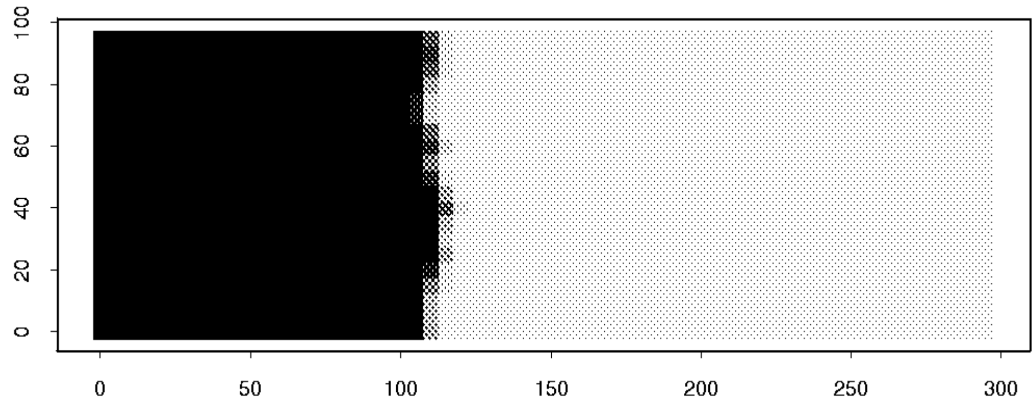
Petit et al 2002. *Forest Ecology and Management 156(1-3):5-26*.



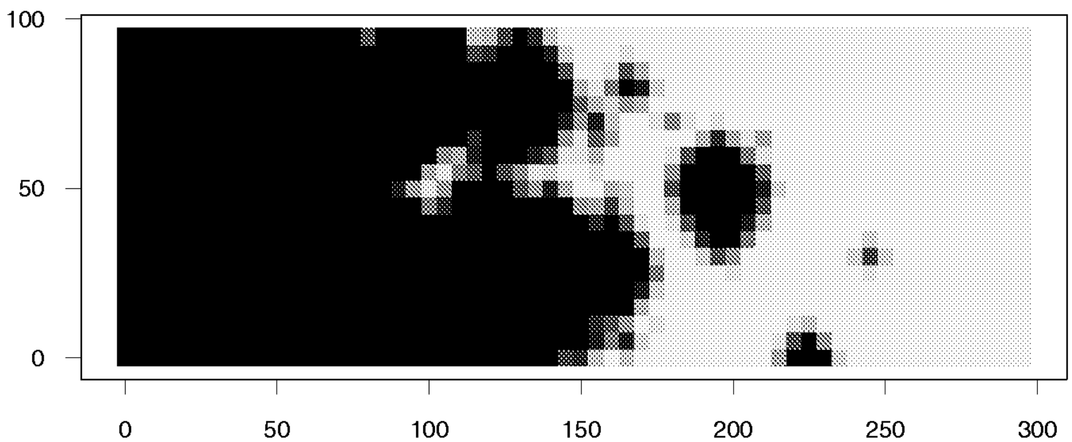
Petit et al, *2002 Forest Ecology and Management 156(1-3):5-26*.

PATTERNS OF COLONIZATION

1. Diffusion



2. Diffusion + LDD

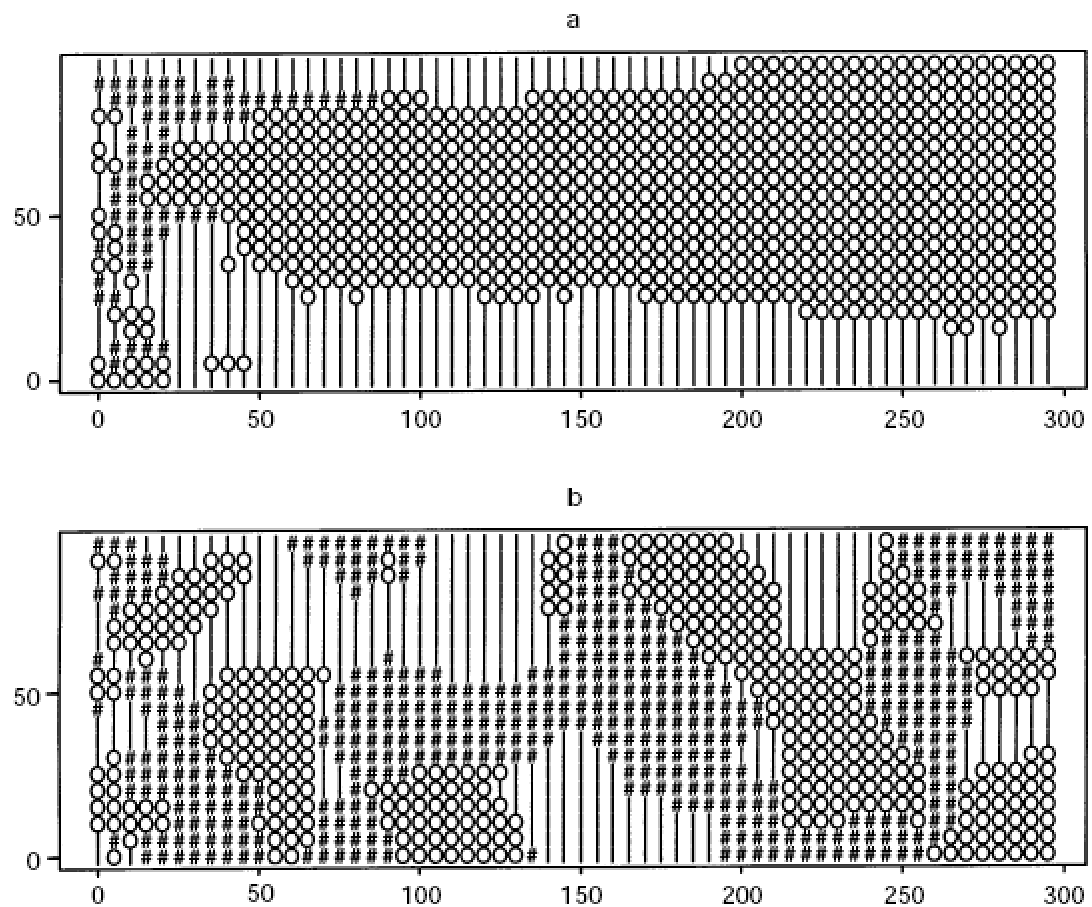


Le Corre et al. 1997 *Genetical Research* 69:117-125

PATTERNS OF COLONIZATION AND MAINTENANCE OF DIVERSITY

DIFFUSION

DIFFUSION + LDD

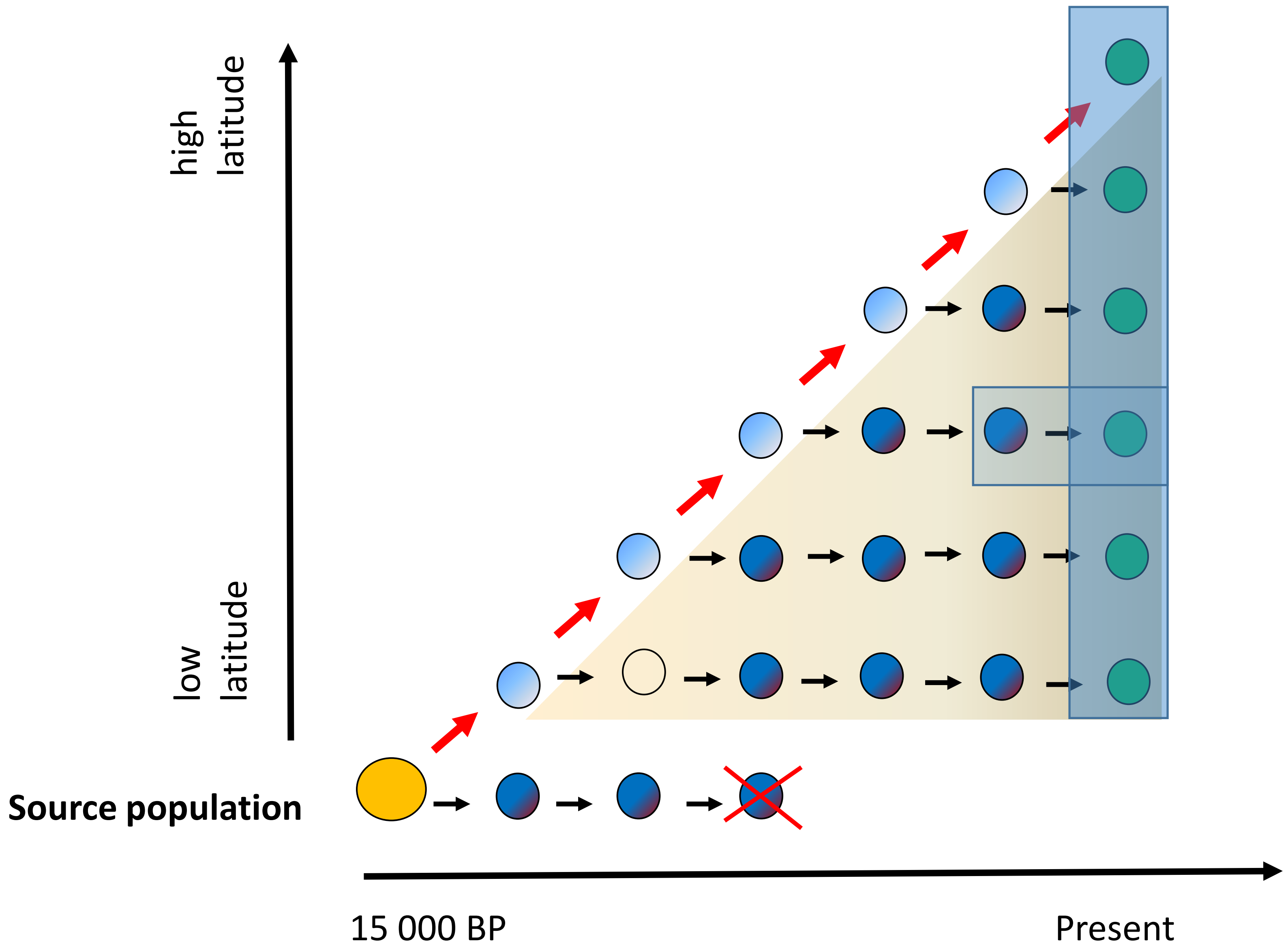


Le Corre et al. 1997 *Genetical Research* 69:117-125

IN CONCLUSION

IS THERE AN ADAPTIVE SYNDROME ?

ADAPTIVE SYNDROME : PHENOTYPIC AND GENOMIC IMPRINTS OF PAST AND CONTEMPORARY ADAPTIVE EVOLUTION



PAST IMPRINTS : DETECTED IN COMMON GARDEN EXPERIMENTS

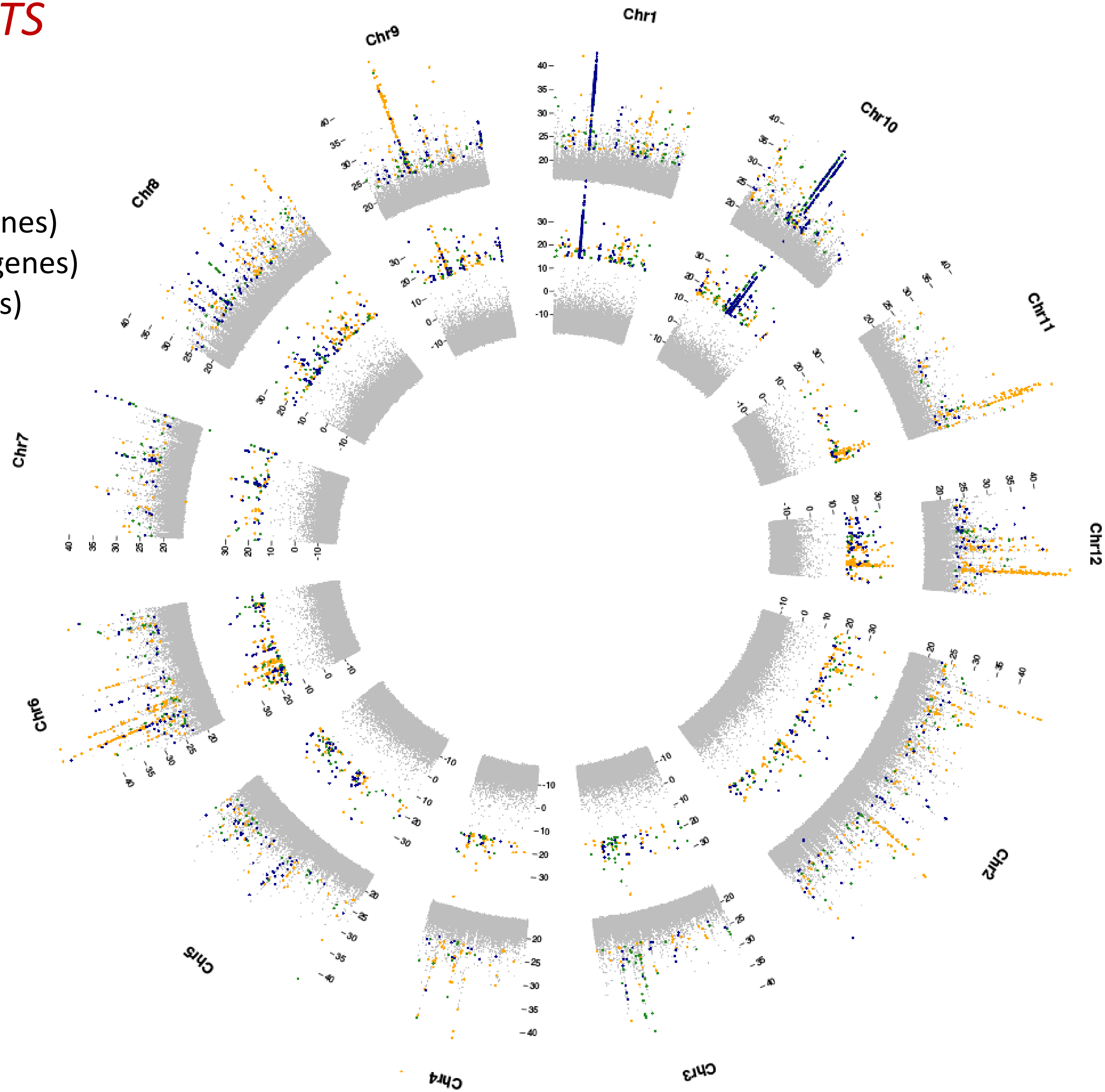
TRAIT	DIFFERENTIATION	GENETIC CLINES
GROWTH Height, Diameter, Tree rings	**+ +**	+ temperature, precipitation
PHENOLOGY Bud burst	**+ + +**	+ temperature
REPRODUCTION Seed crops, reproductive success	**+ +**	- temperature (altitude)
STRUCTURE Wood density	**0**	none
PHYSIOLOGY-WATER METABOLISM Stomatal density, WUE, Δ13c	**+**	none
HYDRAULICS Water potential, P50 , Vulnerability to embolism	**0**	none

Lobo A. 2017 *Forest Ecology and Management* 424: 53-61
Kremer A et al. 2016 *Functional Ecology* 28: 22-36
Firmat et al. 2017 *Journal of Evolutionary Biology* 30: 2116-2131
Torrez-Ruiz JM et al. 2017 (unpublished data)

GENOMIC IMPRINTS

Outer circle : differentiation
Inner circle : clinal variation

Blue : precipitation (1077 genes)
Yellow : temperature (848 genes)
Green : bud burst (531 genes)



Leroy T et al. (unpublished data)

CONTEMPORARY IMPRINTS : In situ MONITORING OF SELECTION

TRAIT	HERITABILITY, EVOLVABILITY	SELECTION GRADIENTS CORRELATION WITH FITNESS
GROWTH Height, Diameter, Tree rings	**+**	**+ + +**
PHENOLOGY Bud burst	**+ + +**	**+**
REPRODUCTION Seed crops, Reproductive success	**+**	Not available
STRUCTURE Wood density	**+ + +**	none
PHYSIOLOGY-WATER METABOLISM Stomatal density, WUE, Δ13c	**+**	**+**
HYDRAULICS Water potential, P50 , Vulnerability to embolism	**Not available**	**Not available**

Alexandre H et al., Treepeace project (unpublished data)

TAKE HOME MESSAGES

Evolutionary trajectories (migration, pace of adaptation) faster than expected

Peculiar mechanisms (LDD, introgression) drive evolution during environmental change

Adaptive imprints limited to very integrative traits (growth, phenology..)

ACKNOWLEDGEMENTS

European Research Council

From Holocene to Anthropocene: the pace of microevolution in trees

TREEPEACE

SEVENTH FRAMEWORK PROGRAMME

Evolution of trees as drivers of terrestrial biodiversity

evoltree

Models for adaptive forest management

MOTIVE

Towards the Sustainable Management of Forest Genetic Resources in Europe

forgeR

AGENCE NATIONALE DE LA RECHERCHE ANR

Mechanisms of adaptation to climate change: how will phenotypic plasticity, microevolution and migration affect forest tree phenology.

Special Thanks

Sylvain Delzon

Alexis Ducousso

Rémy Petit

Christophe Plomion


Cuauhtemoc Saenz Romero


Thibault Leroy


Hermine Alexandre


Laura Truffaut


Jean Baptiste Lamy


Valérie Le Corre


Yann Vitasse


Florian Alberto