Climate change impact on the seaweed *Fucus serratus*, a key foundational species on North Atlantic rocky shores

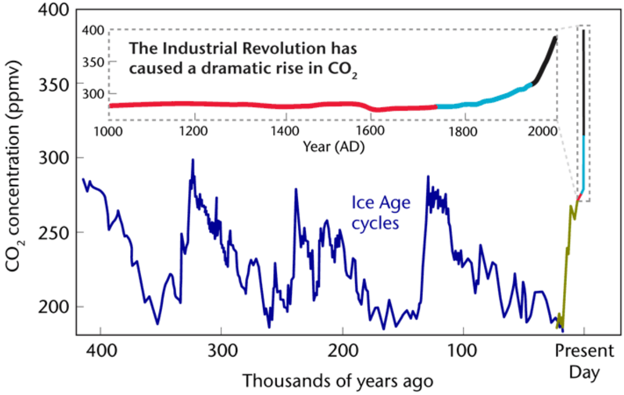
Alexander Jüterbock
Alexander.Juterbock@uin.no

Faculty of Biosciences and Aquaculture
University of Nordland

PhD Thesis, 01.06.2010–12.08.2013

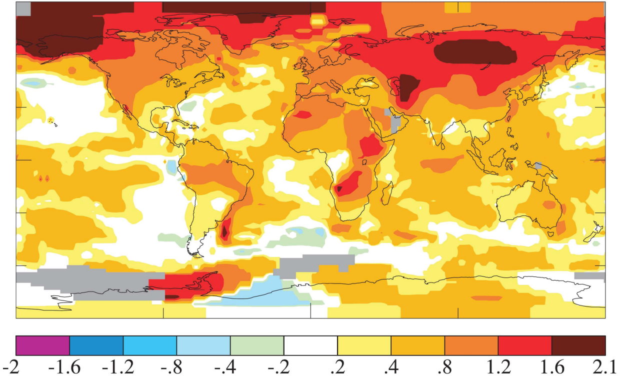
CO_2 increase since the industrial revolution

Variations in CO_2 concentrations from ice core records



Recent climate change

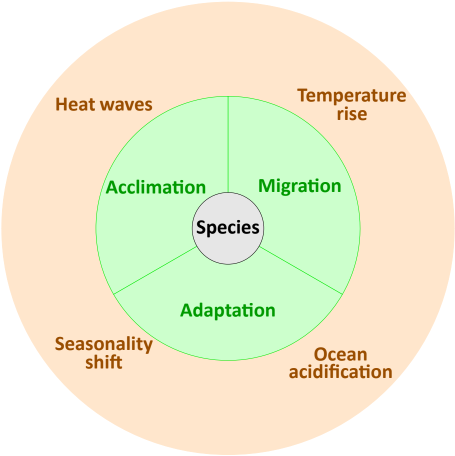
2001–2005 mean surface temperature anomaly
(Base Period = 1951–1981)
Global mean = 0.54



[Hansen et al., 2006; PNAS]

UNIVERSITETET I NORDLAND

Climate change responses



High sensitivity of intertidal species

UNIVERSITETET I NORDLAND

Seaweeds are key species in temperate North Atlantic regions

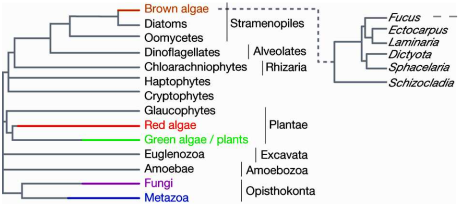
Between the 10°C summer and the 20°C winter isotherm

UNIVERSITETET I NORDLAND

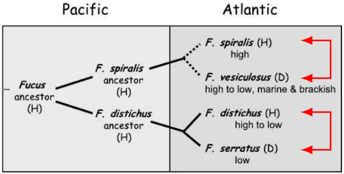

© Hoarau, G., 2010

The focal species *Fucus serratus*

Fucus in the tree of life



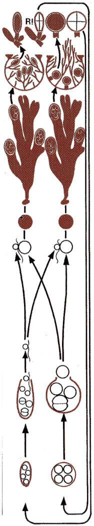
[Cock et al., 2010; Nature]



[Coyer et al., 2006; Mol. Phylogenet. Evol.]

Hybridization

Life cycle and dispersal of *Fucus serratus*

♂  ♀

Fucus

dioecious

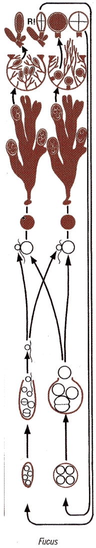
Fecundity: 10^6 eggs per female

[Braune, 2008; Meeresalgen]

UNIVERSITETET I NORDLAND

Life cycle and dispersal of *Fucus serratus*

♂



♀

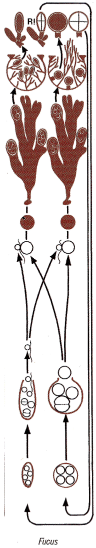
dioecious

zygote dispersal: <10m

Fecundity: 10^6 eggs per female

[Braune, 2008; Meeresalgen]

Life cycle and dispersal of *Fucus serratus*



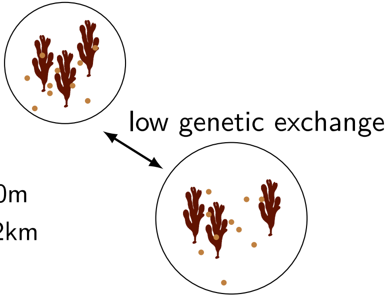
♂ ♀

dioecious

zygote dispersal: <10m

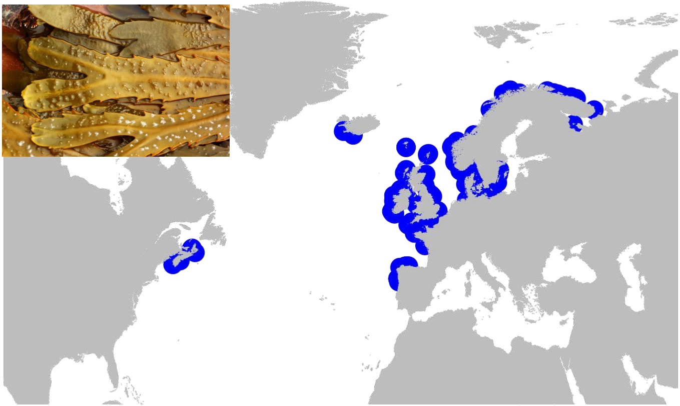
panmictic unit: 0.5–2km

Fecundity: 10^6 eggs per female



[Braune, 2008; Meeresalgen]

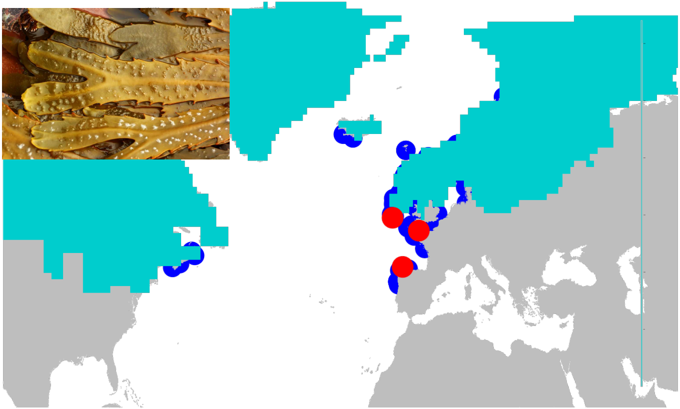
Distribution of *F. serratus* in the North Atlantic



● Occurrence records

Distribution of *F. serratus* in the North Atlantic

Last Glacial Maximum 18-20,000 years ago

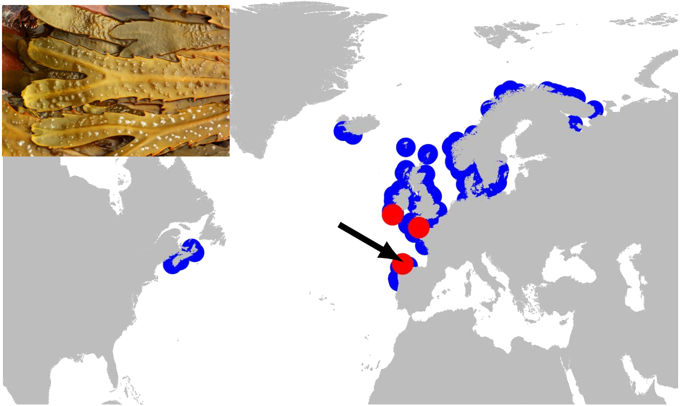


● Occurrence records ● Glacial Refugia

[Hoarau et al., 2007; Mol. Ecol.]

UNIVERSITETET I NORDLAND

Distribution of *F. serratus* in the North Atlantic



● Occurrence records ● Glacial Refugia

[Hoarau et al., 2007; Mol. Ecol.]

UNIVERSITETET I NORDLAND

Recent changes in southern edge populations of *F. serratus*

1999

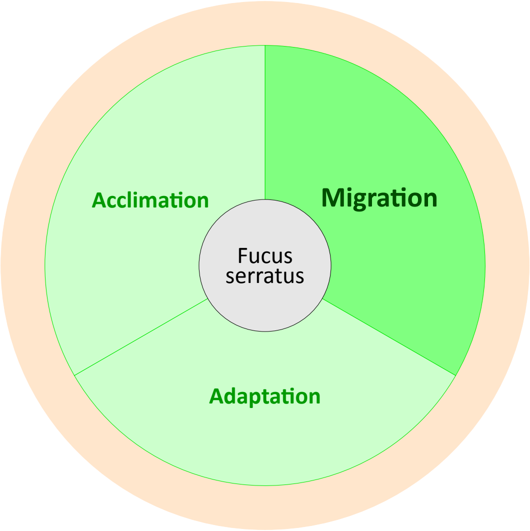
2010

- 90% abundance decline
- Reduced reproductive capacity

[Viejo et al., 2011; Ecography]

UNIVERSITETET I NORDLAND

Objectives



Paper I - Distributional shift

Ecology and Evolution

Open Access

Climate change impact on seaweed meadow distribution in the North Atlantic rocky intertidal

Alexander Jueterbock[1], Lennert Tyberghein[2,3], Heroen Verbruggen[4], James A. Coyer[5], Jeanine L. Olsen[6] & Galice Hoarau[1]

UNIVERSITETET I NORDLAND

Specific aims

Predominant seaweeds in the North-Atlantic

Fucus serratus

Fucus vesiculosus

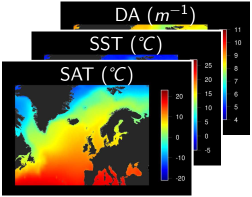
Ascophyllum nodosum

- Shores with biggest ecological change?
- Shift as an assemblage?

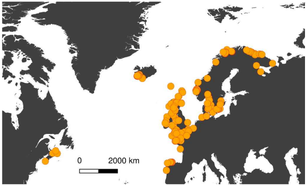
UNIVERSITETET I NORDLAND

Ecological Niche Modelling

Present-day conditions
Bio-ORACLE database
[Tyberghein et al., 2011; Global Ecol. Biogeogr.].



Georeferenced Occurrences



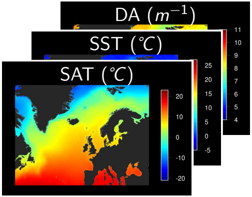
Ecological Niche Model (Maxent [Phillips et al., 2006; Ecol. Model.])

2000 2100 ? 2200 ?

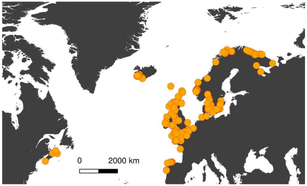
UNIVERSITETET I NORDLAND

Ecological Niche Modelling

Present-day conditions
Bio-ORACLE database
[Tyberghein et al., 2011; Global Ecol. Biogeogr.].

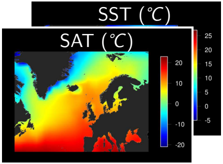


Georeferenced Occurrences

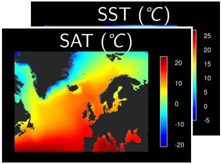


Ecological Niche Model (Maxent [Phillips et al., 2006; Ecol. Model.])

2000



2100 ?



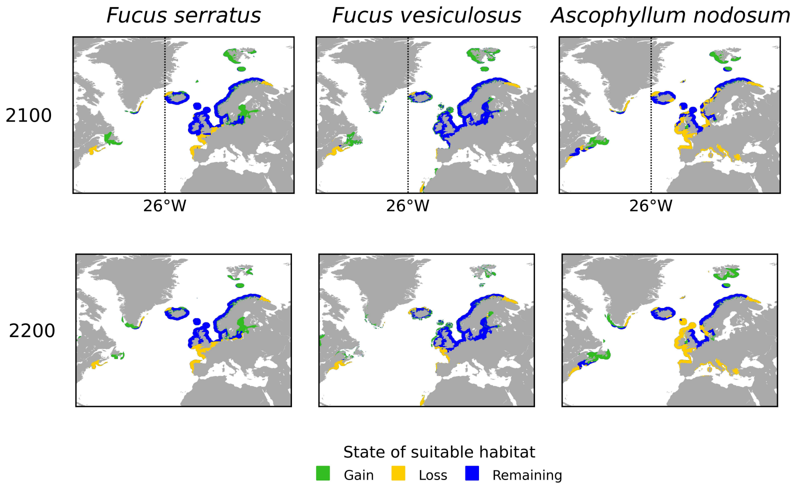
2200 ?

CO_2 emission scenario changes

UNIVERSITETET I NORDLAND

Predicted Niche Shifts

Based on the intermediate IPCC scenario A1B



UNIVERSITETET I NORDLAND

Conclusions
Distribution

- Shores with biggest ecological change?
  - **Disappearance** from shores south of **Brittany** and from **Nova Scotia**
  - Suitable habitat in the **southern Arctic**
- Shift as an assemblage?

UNIVERSITETET I NORDLAND

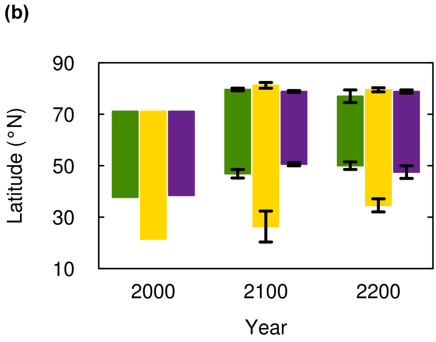
Conclusions
Distribution

- Shores with biggest ecological change?
  - **Disappearance** from shores south of **Brittany** and from **Nova Scotia**
  - Suitable habitat in the **southern Arctic**
- Shift as an assemblage?

UNIVERSITETET I NORDLAND

Predominant seaweeds shift northward as an assemblage

East-Atlantic



F. serratus *F. vesiculosus* *A. nodosum*

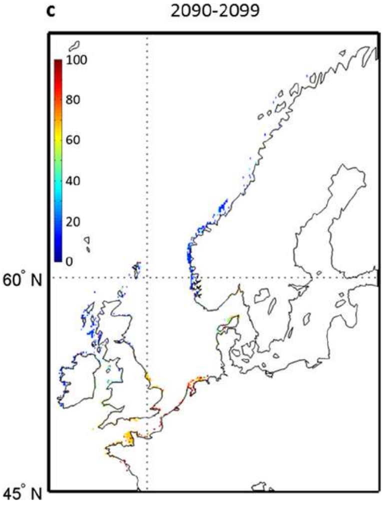
UNIVERSITETET I NORDLAND

Conclusions
Distribution

- Shores with biggest ecological change?
  - **Disappearance** from shores south of **Brittany** and from **Nova Scotia**
  - Suitable habitat in the **southern Arctic**
- Shift as an assemblage?
  - **Yes**

UNIVERSITETET I NORDLAND

Climate change impact also on subtidal kelp



Percentage of models forecasting a disappearance of *Laminaria digitata*

[Raybaud et al., 2013; PLOS ONE]

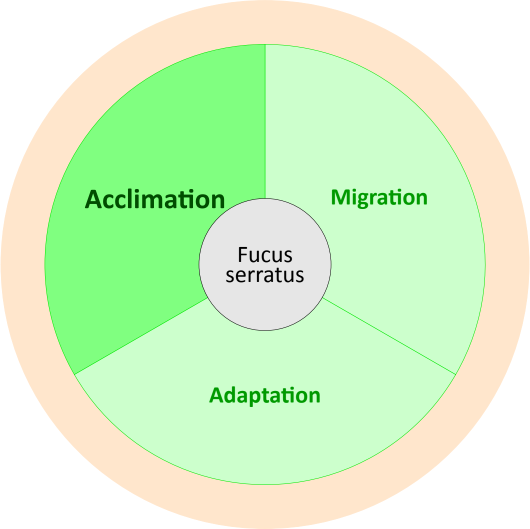
UNIVERSITETET I NORDLAND

Conclusions
Distribution

- Shores with biggest ecological change?
  - **Disappearance** from shores south of **Brittany** and from **Nova Scotia**
  - Suitable habitat in the **southern Arctic**
- Shift as an assemblage?
  - **Yes**
- **Mitigation by plasticity and adaptation?**

UNIVERSITETET I NORDLAND

Objectives



UNIVERSITETET I NORDLAND

Paper II - Phenotypic plasticity

Thermal stress resistance of the brown alga *Fucus serratus* along the North-Atlantic coast: acclimatization potential to climate change

Alexander Jueterbock, Spyros Kollias, Irina Smolina,
Jorge M.O. Fernandes, James A. Coyer, Jeanine L. Olsen, Galice Hoarau

Marine Genomics. Submitted

Specific aims
Plasticity

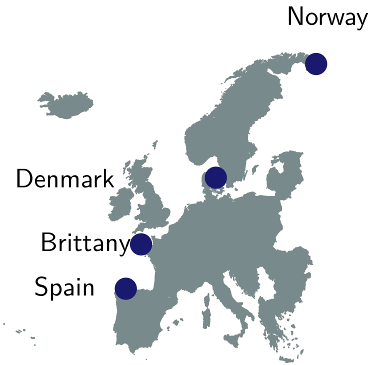
Plasticity along the entire E-Atlantic range of distribution

Local adaptation Population-specific stress response?

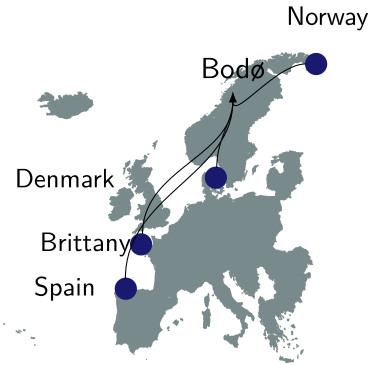
Extinction risk Where will temperatures exceeed the species' thermal tolerance?

UNIVERSITETET I NORDLAND

Common-garden heat stress experiments



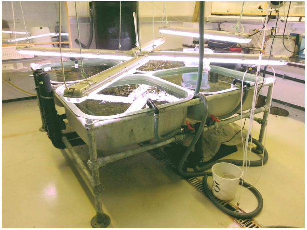
Common-garden heat stress experiments

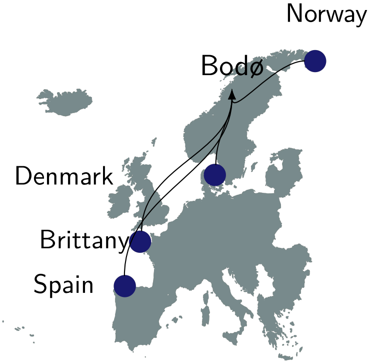


UNIVERSITETET I NORDLAND

Common-garden heat stress experiments

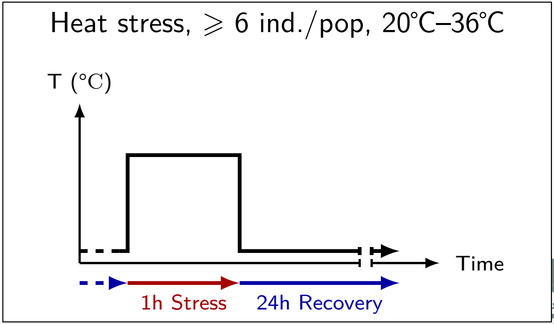
Acclimation at 9°C

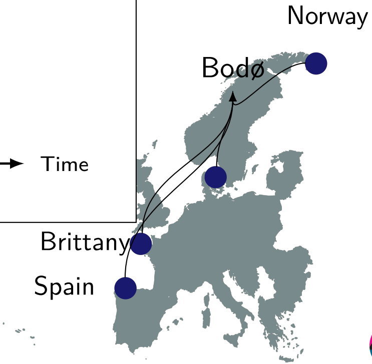




UNIVERSITETET I NORDLAND

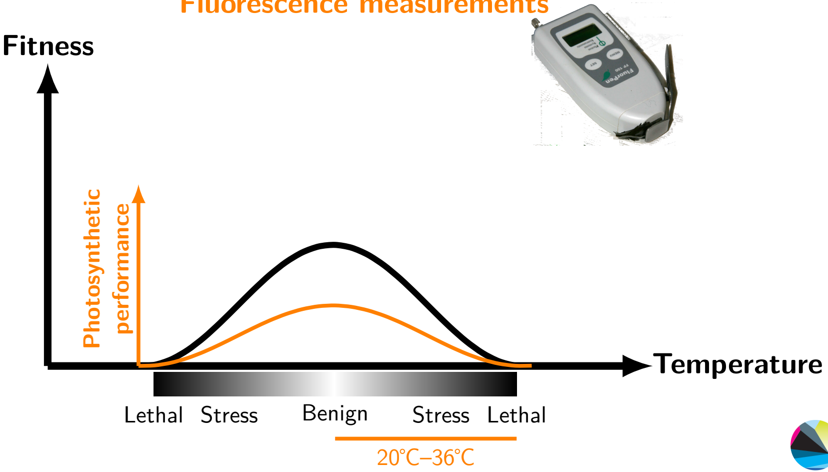
Common-garden heat stress experiments





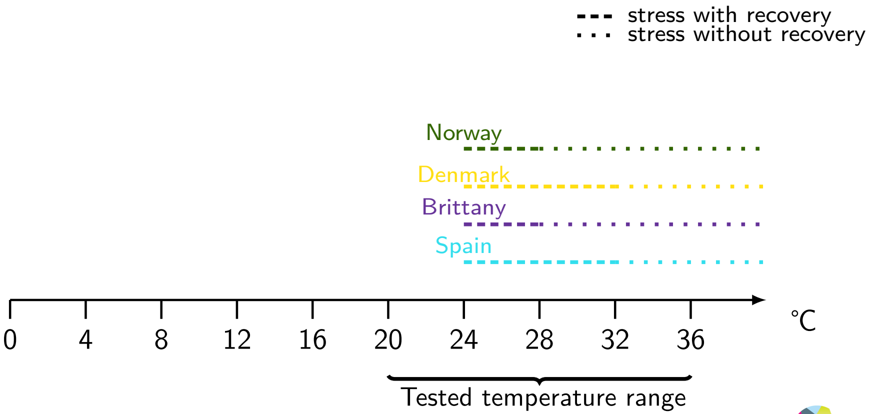
Measuring the physiological stress response

Fluorescence measurements



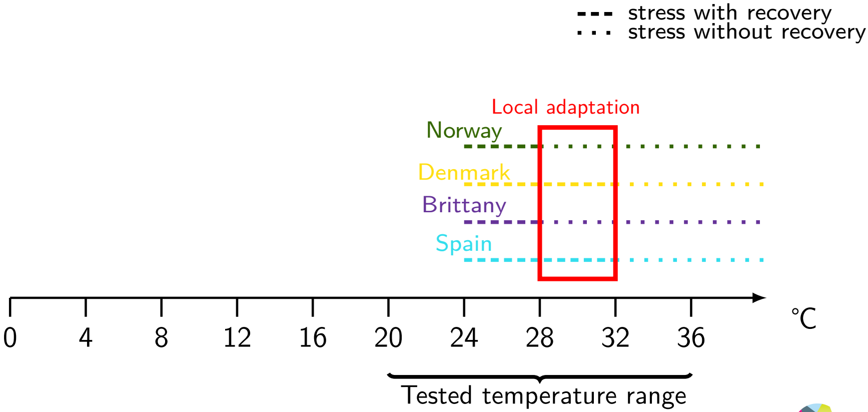
UNIVERSITETET I NORDLAND

Photosynthetic response



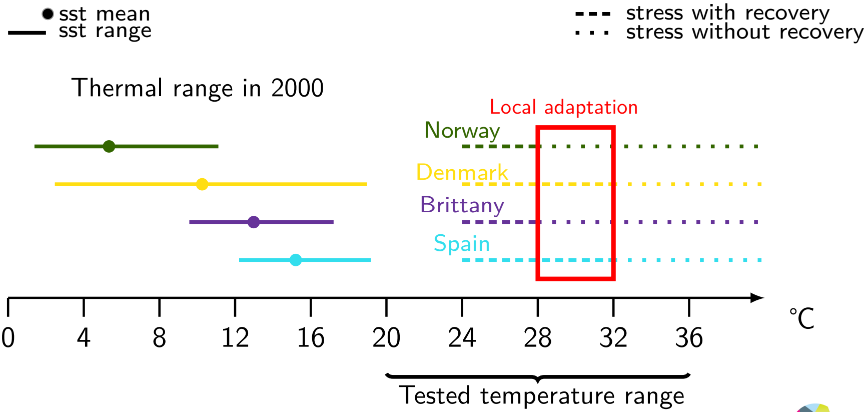
UNIVERSITETET I NORDLAND

Photosynthetic response



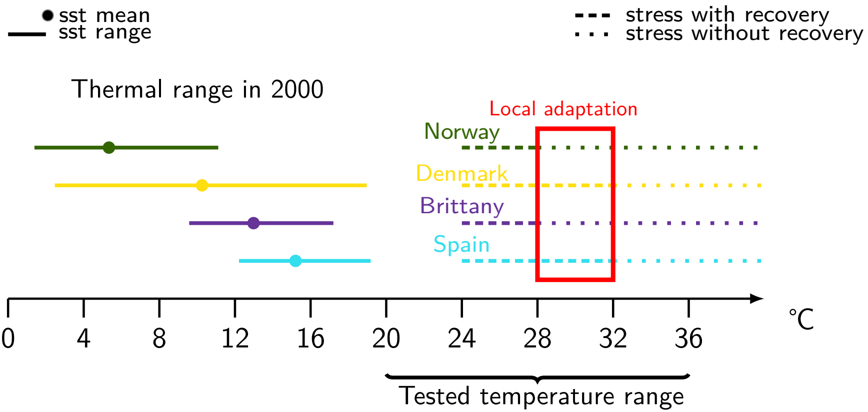
UNIVERSITETET I NORDLAND

Photosynthetic response



UNIVERSITETET I NORDLAND

Photosynthetic response

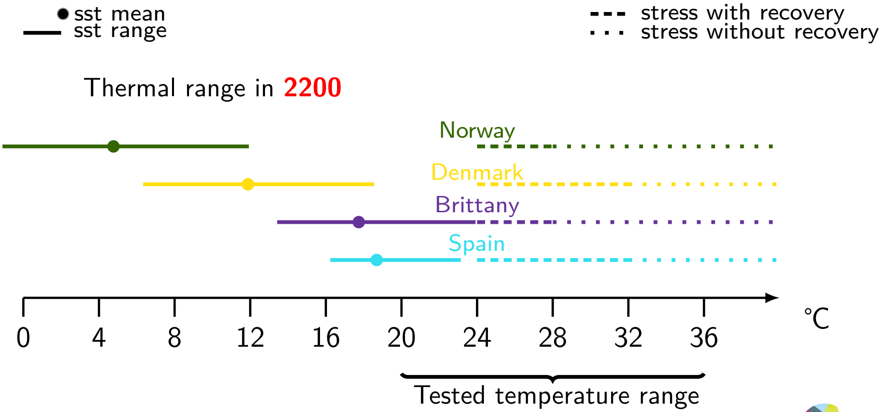


highest upper temperature

highest tolerance limit

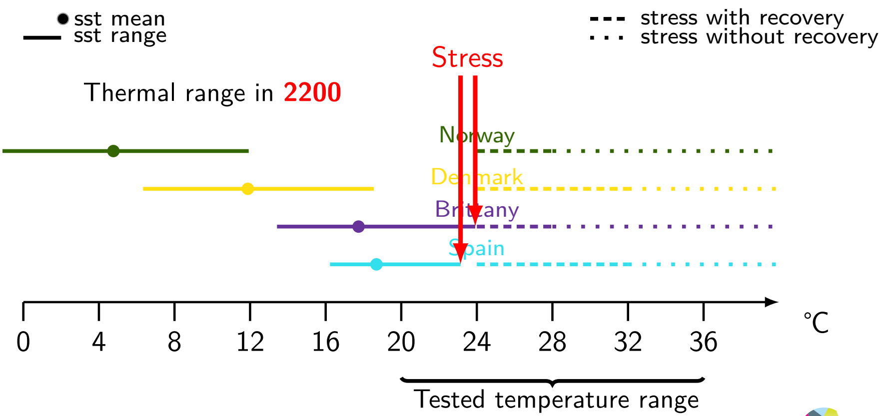
UNIVERSITETET I NORDLAND

Photosynthetic response



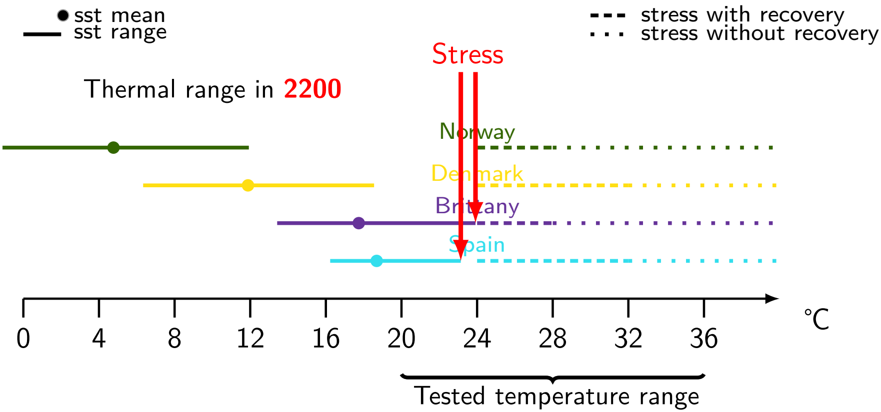
UNIVERSITETET I NORDLAND

Photosynthetic response



UNIVERSITETET I NORDLAND

Photosynthetic response



Stress limit reached at the southern range

Conclusions
Plasticity

Plasticity along the entire E-Atlantic range of distribution

Local adaptation Population-specific stress response?

Extinction risk Where will temperatures exceeed the species' thermal tolerance?

UNIVERSITETET I NORDLAND

Conclusions
Plasticity

Plasticity along the entire E-Atlantic range of distribution

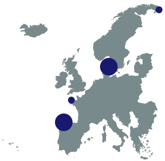
Local adaptation Population-specific stress response?

- Highest resilience in **Denmark and Spain**

Extinction risk Where will temperatures exceeed the species' thermal tolerance?

Photosynthetic performance

Resilience



UNIVERSITETET I NORDLAND

Conclusions

Plasticity

Plasticity along the entire E-Atlantic range of distribution

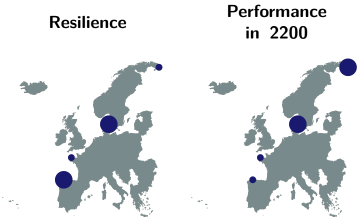
Local adaptation Population-specific stress response?

- Highest resilience in **Denmark and Spain**

Extinction risk Where will temperatures exceeed the species' thermal tolerance?

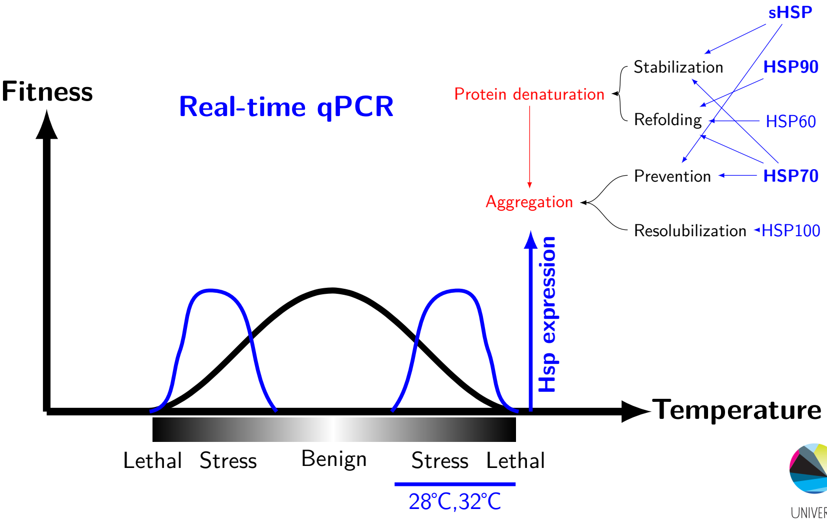
- In **Brittany and Spain**

Photosynthetic performance



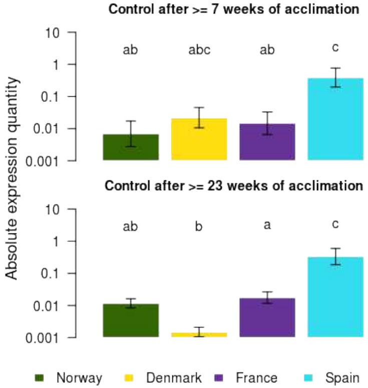
UNIVERSITETET I NORDLAND

Measuring the physiological stress response

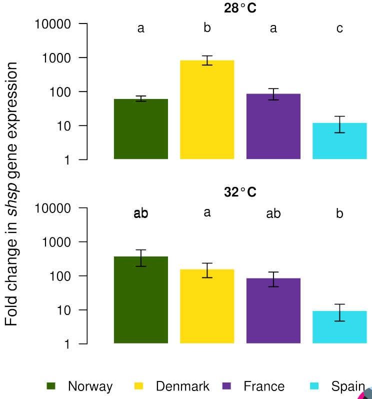


sHsp gene expression

Before heat shock exposure



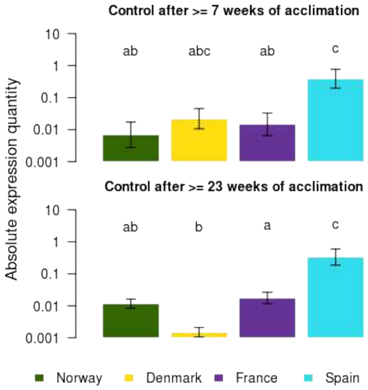
After 24h recovery



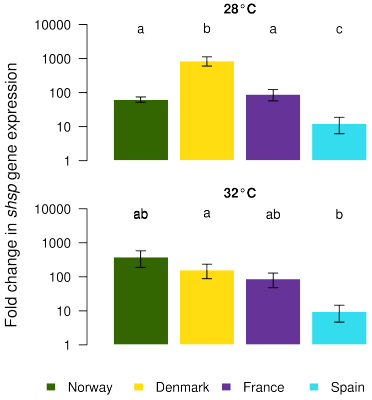
UNIVERSITETET I NORDLAND

sHsp gene expression

Before heat shock exposure



After 24h recovery

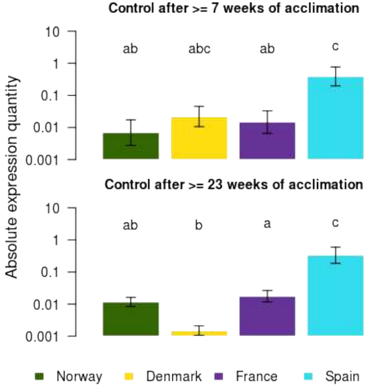


High constitutive expression

UNIVERSITETET I NORDLAND

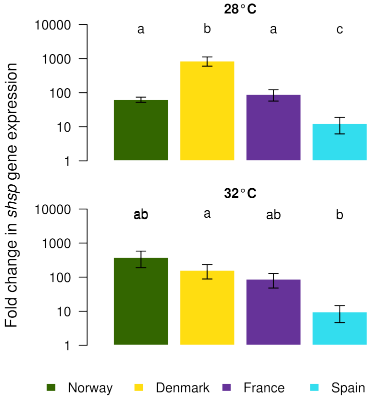
sHsp gene expression

Before heat shock exposure



High constitutive expression

After 24h recovery



Reduced responsiveness

UNIVERSITETET I NORDLAND

Conclusions
Plasticity

Plasticity along the entire E-Atlantic range of distribution

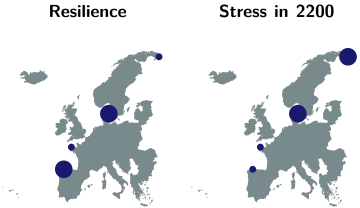
Local adaptation Population-specific stress response?

- Highest resilience in **Denmark and Spain**

Extinction risk Where will temperatures exceeed the species' thermal tolerance?

- In **Brittany and Spain**

Photosynthetic performance



UNIVERSITETET I NORDLAND

Conclusions
Plasticity

Plasticity along the entire E-Atlantic range of distribution

Local adaptation Population-specific stress response?

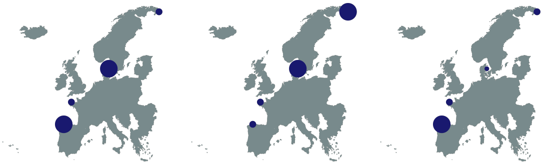
- Highest resilience in **Denmark and Spain**

Extinction risk Where will temperatures exceeed the species' thermal tolerance?

- In **Brittany and Spain**

Photosynthetic performance *hsp* expression

Resilience **Stress in 2200** **Constitutive expression**



UNIVERSITETET I NORDLAND

Conclusions
Plasticity

Plasticity along the entire E-Atlantic range of distribution

Local adaptation Population-specific stress response?

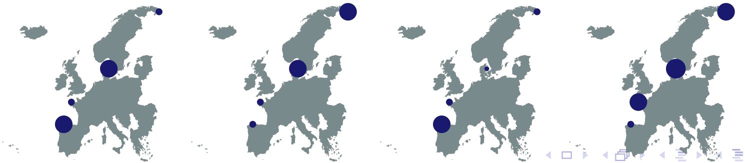
- Highest resilience in **Denmark and Spain**
- **Spain** of reduced responsiveness

Extinction risk Where will temperatures exceeed the species' thermal tolerance?

- In **Brittany and Spain**
- **lowest responsiveness** in **Spain**

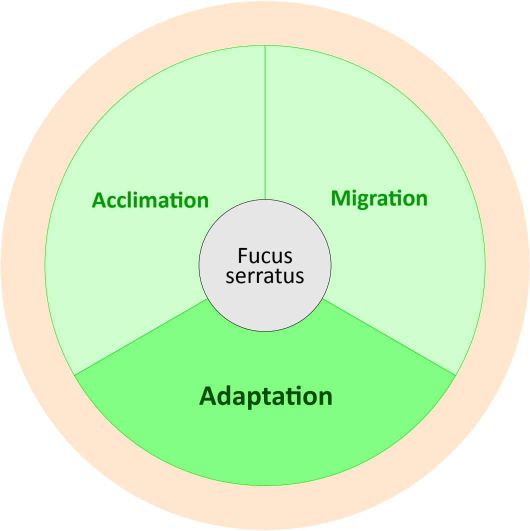
Photosynthetic performance | *hsp* expression

Resilience | **Stress in 2200** | **Constitutive expression** | **Heat shock response**



UNIVERSITETET I NORDLAND

Objectives



UNIVERSITETET I NORDLAND

Paper III - Genetic changes

A decade of climate change on North Atlantic rocky shores - can the seaweed *Fucus serratus* adapt to rising temperatures?

Alexander Jueterbock, Spyros Kollias, James A. Coyer, Jeanine L. Olsen, Galice Hoarau

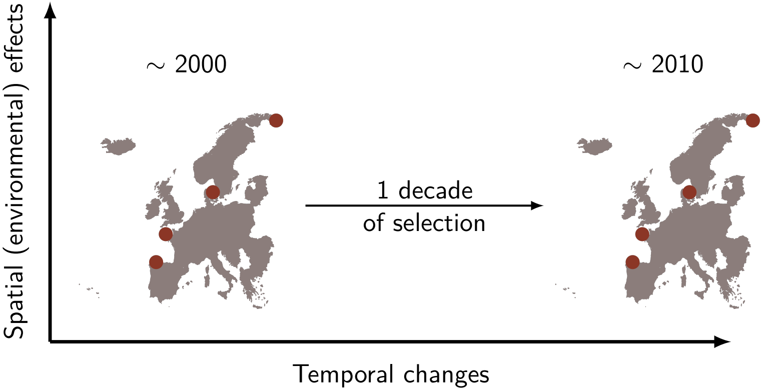
Manuscript

UNIVERSITETET I NORDLAND

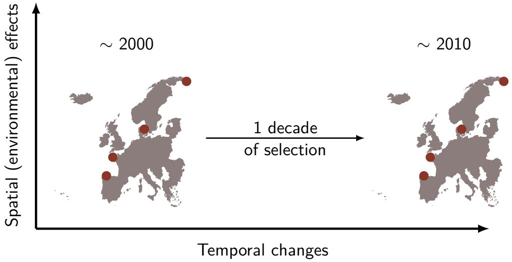
Specific aims
Genetic changes

- Assess the **effective population size** N_e of *F. serratus* along its distributional range
- Identify **genetic changes** of *F. serratus* in the NE-Atlantic over the past 10 years

Sampling scheme (50–75 ind./pop)



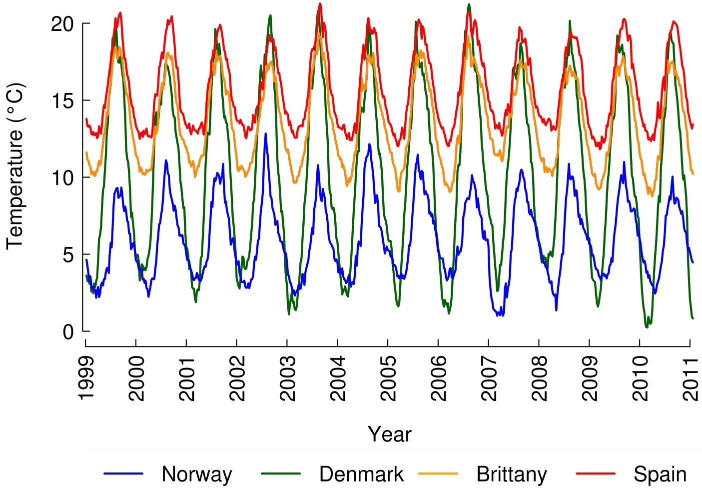
Methods and analysis



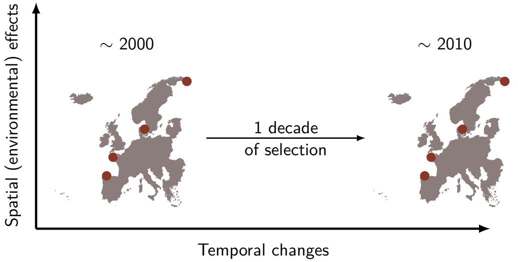
- **Temperature characterization**
- Genotyping
  - 31 microsatellite markers (20 EST-linked)
- Analysis
  - effective population size (N_e)
  - Allelic richness (α)
  - Temperature associated outlier loci

UNIVERSITETET I NORDLAND

Temperature conditions



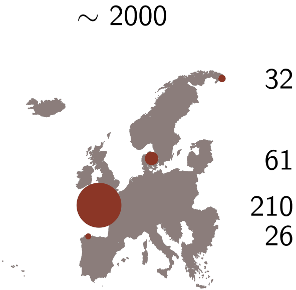
Methods and analysis

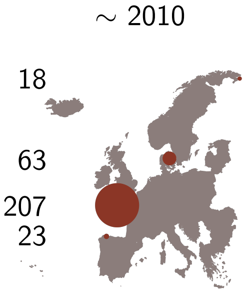


- Temperature characterization
- Genotyping
  - 31 microsatellite markers (20 EST-linked)
- analysis
  - **effective population size (N_e)**
  - Allelic richness (α)
  - Temperature associated outlier loci

Effective population size N_e

Reflecting adaptive capacity





Estimates excluding outlier loci

UNIVERSITETET I NORDLAND

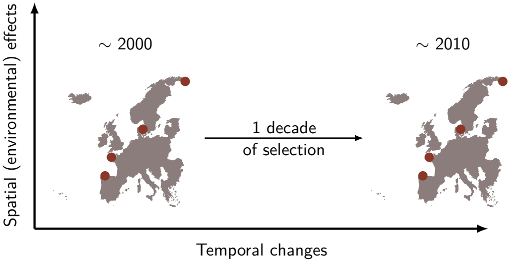
Conclusions
Genetic changes

- Assess the **effective population size** N_e of *F. serratus* along its distributional range
  - **Specifically low at the range limits**
  - **Highest in Brittany**
- Identify **genetic changes** of *F. serratus* in the NE-Atlantic over the past 10 years

N_e in 2010

UNIVERSITETET I NORDLAND

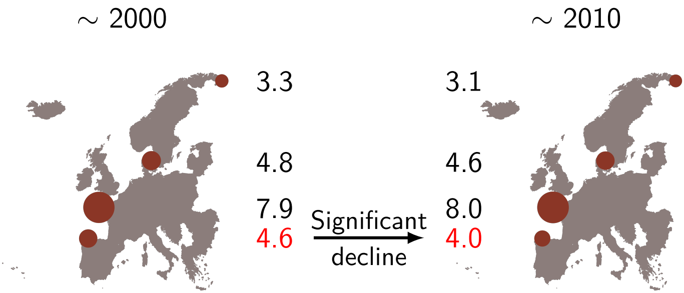
Methods



- Temperature characterization
- Genotyping
  - 31 microsatellite markers (20 EST-linked)
- analysis
  - effective population size (N_e)
  - **Allelic richness (α)**
  - Temperature associated outlier loci

UNIVERSITETET I NORDLAND

Changes in allelic richness



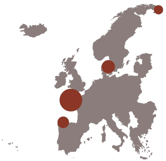
UNIVERSITETET I NORDLAND

Conclusions
Genetic changes

- Assess the **effective population size** N_e of *F. serratus* along its distributional range
  - Specifically low at the range limits
  - Highest in Brittany
- Identify **genetic changes** of *F. serratus* in the NE-Atlantic over the past 10 years
  - α: **significant decline in Spain**

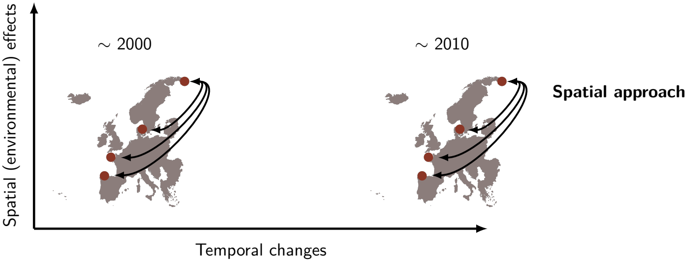
N_e **in 2010**

α **in 2010**



UNIVERSITETET I NORDLAND

Methods and analysis

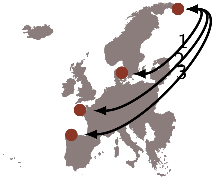


- Temperature characterization
- Genotyping
  - 31 microsatellite markers (20 EST-linked)
- analysis
  - effective population size (N_e)
  - Allelic richness (α)
  - **Temperature associated outlier loci**

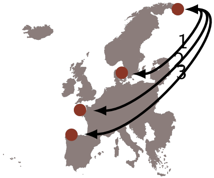
UNIVERSITETET I NORDLAND

Spatial outlier loci

∼ 2000



∼ 2010



1: E6, L58

2: F36, F49, L58

3: F19, L58

1: F19, L58

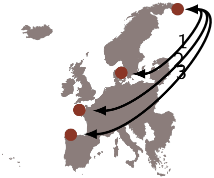
2: E9, F22, F49, L58

3: E9, F19, F60, L58

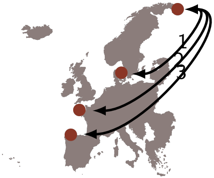
UNIVERSITETET I NORDLAND

Spatial outlier loci

∼ 2000



∼ 2010



Outliers in both years

∼ 2000	∼ 2010
1: E6, L58	1: F19, L58
2: F36, F49, L58	2: E9, F22, F49, L58
3: F19, L58	3: E9, F19, F60, L58

UNIVERSITETET I NORDLAND

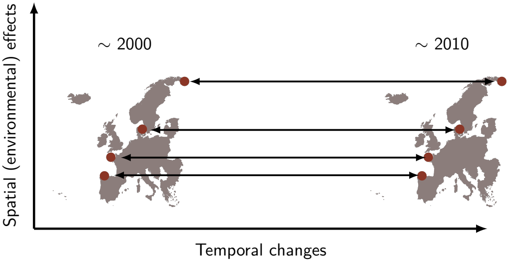
Local adaptation - or?

Examples fo alternative reasons for spatial outliers

- Genetic incompatibilities [Bierne et al., 2011; Mol. Ecol.]
- Isolation-by-distance pattern increases false positive rate [Fourcade et al. 2013; Mol. Ecol., Bierne et al., 2013; Mol. Ecol.]

UNIVERSITETET I NORDLAND

Methods and analysis

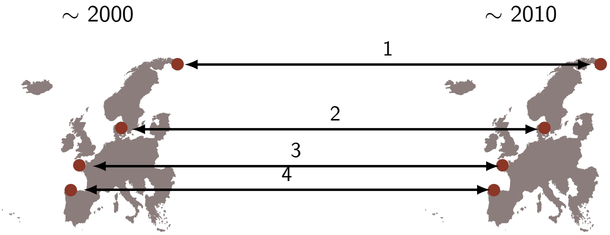


Temporal approach

- Temperature characterization
- Genotyping
  - 31 microsatellite markers (20 EST-linked)
- analysis
  - effective population size (N_e)
  - Allelic richness (α)
  - **Temperature associated outlier loci**

UNIVERSITETET I NORDLAND

Temporal outlier loci



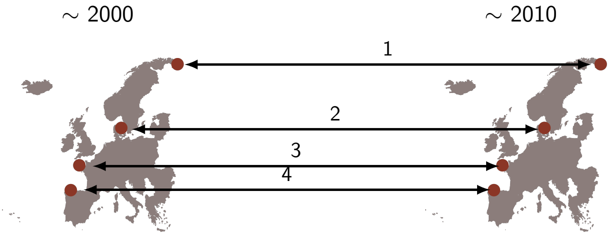
1:

2: F19, F36

3: B113, B128, E6, E9, F12, F72, L58

4: F19, F65, F69, F72

Temporal outlier loci



Highest proportion of outliers: strongest selection

1:

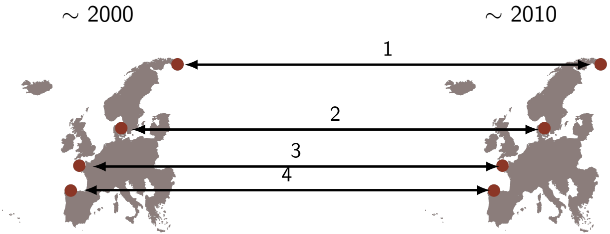
2: F19, F36

3: B113, B128, E6, E9, F12, F72, L58

4: F19, F65, F69, F72

UNIVERSITETET I NORDLAND

Temporal outlier loci



Highest proportion of outliers: strongest selection

Congruent outlier: broad-scale selection

1:

2: F19, F36

3: B113, B128, E6, E9, F12, F72, L58

4: F19, F65, F69, F72

UNIVERSITETET I NORDLAND

Spatio-temporal outlier loci

Spatial outliers

∼ 2000

1: E6, L58

2: F36, F49, L58

3: F19, L58

∼ 2010

1: F19, L58

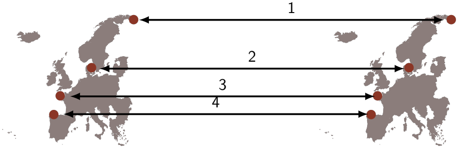
2: E9, F22, F49, L58

3: E9, F19, F60, L58

Outliers in both years

Temporal outliers

∼ 2000 ∼ 2010



1:

2: F19, F36

3: B113, B128, E6, E9, F12, F72, L58

4: F19, F65, F69, F72

Highest proportion of outliers: strongest selection

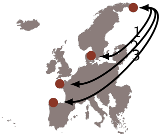
Congruent outlier: broad-scale selection

UNIVERSITETET I NORDLAND

Spatio-temporal outlier loci

Spatial outliers

∼ 2000



1: E6, L58

2: F36, F49, L58

3: F19, L58

∼ 2010

1: F19, L58

2: E9, F22, F49, L58

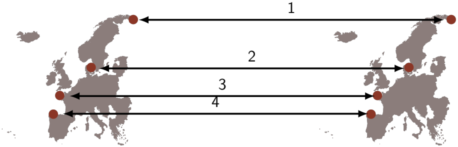
3: E9, F19, F60, L58

Outliers in both years

F19 - response to climate change?

Temporal outliers

∼ 2000 ∼ 2010



1:

2: F19, F36

3: B113, B128, E6, E9, F12, F72, L58

4: F19, F65, F69, F72

Highest proportion of outliers: strongest selection

Congruent outlier: broad-scale selection

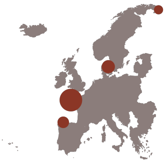
UNIVERSITETET I NORDLAND

Conclusions
Genetic changes

- Assess the **effective population size** N_e of *F. serratus* along its distributional range
  - Specifically low at the range limits
  - Highest in Brittany
- Identify **genetic changes** of *F. serratus* in the NE-Atlantic over the past 10 years
  - α: significant decline in Spain
  - **Strongest selective pressure in Brittany and Spain**
  - **Locus F19: Adaptive value under climate change?**

N_e in 2010

α in 2010



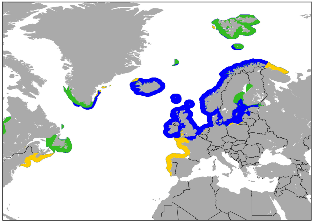
Temporal outliers

UNIVERSITETET I NORDLAND

Overall conclusions

- Predicted shift
  - Biggest changes: Arctic and warm-temperate regions
- Importance of populations
  - Norway: Colonization of the Arctic?
  - Denmark: Center of distribution
  - Brittany: Center of adaptability
  - Spain: Insufficient plasticity and adaptability

F. serratus, 2200, SRES A1B scenario

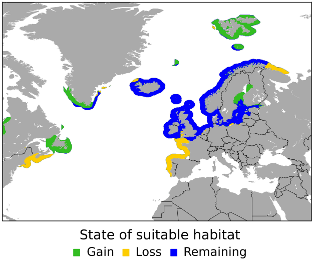


State of suitable habitat
Gain Loss Remaining

Overall conclusions

- Predicted shift
  - Biggest changes: Arctic and warm-temperate regions
- Importance of populations
  - Norway: Colonization of the Arctic?
  - Denmark: Center of distribution
  - Brittany: Center of adaptability
  - Spain: Insufficient plasticity and adaptability

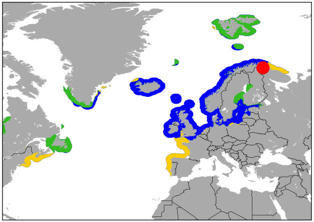
F. serratus, 2200, SRES A1B scenario



Overall conclusions

- Predicted shift
  - Biggest changes: Arctic and warm-temperate regions
- Importance of populations
  - Norway: Colonization of the Arctic?
  - Denmark: Center of distribution
  - Brittany: Center of adaptability
  - Spain: Insufficient plasticity and adaptability

F. serratus, 2200, SRES A1B scenario

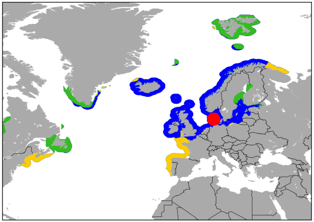


UNIVERSITETET I NORDLAND

Overall conclusions

- Predicted shift
  - Biggest changes: Arctic and warm-temperate regions
- Importance of populations
  - Norway: Colonization of the Arctic?
  - Denmark: Center of distribution
  - Brittany: Center of adaptability
  - Spain: Insufficient plasticity and adaptability

F. serratus, 2200, SRES A1B scenario

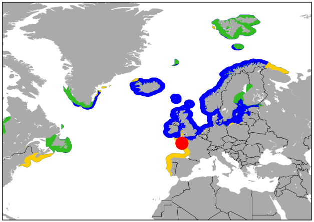


UNIVERSITETET I NORDLAND

Overall conclusions

- Predicted shift
  - Biggest changes: Arctic and warm-temperate regions
- Importance of populations
  - Norway: Colonization of the Arctic?
  - Denmark: Center of distribution
  - Brittany: Center of adaptability
  - Spain: Insufficient plasticity and adaptability

F. serratus, 2200, SRES A1B scenario



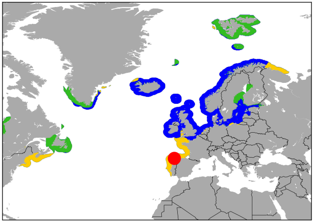
State of suitable habitat
Gain Loss Remaining

UNIVERSITETET I NORDLAND

Overall conclusions

- Predicted shift
  - Biggest changes: Arctic and warm-temperate regions
- Importance of populations
  - Norway: Colonization of the Arctic?
  - Denmark: Center of distribution
  - Brittany: Center of adaptability
  - Spain: Insufficient plasticity and adaptability

F. serratus, 2200, SRES A1B scenario



State of suitable habitat
Gain Loss Remaining

Acknowledgements

Supervisors:

Galice Hoarau
Jorge Fernandes
Jeanine L. Olsen

Spyros Kollias
Irina Smolina
Ketil Eiane
Kurt Tande
Mark Powell
Randi Restad Sjøvik
Steinar Johnson
All lab- and wetlab technicians
All administrative staff
All friends

Dissertation Committee:

Christine Maggs
Nicolas Bierne
Kurt Tande

Olivier De Clerck
Klaas Pauly

Heroen Verbruggen

Lennert Tyberghein

James A. Coyer

The Research Council of Norway

UNIVERSITETET I NORDLAND

References I

Balanya, J.; Oller, J.M.; Huey, R.B.; Gilchrist, G.W.; Serra, L. (2006)
Global genetic change tracks global climate warming in *Drosophila subobscura*.
Science 313(5794):1173–1175.

Berteaux, D.; Reale, D.; McAdam, A.G.; Boutin, S. (2004)
Keeping pace with fast climate change: can arctic life count on evolution?
Integrative and Comparative Biology 44(2):140–151.

Bierne, N. (2010)
The distinctive footprints of local hitchhiking in a varied environment and global hitchhiking in a subdivided population
Evolution 64(11):3254–3272.

Bierne, N.; Welch, J.; Loire E.; Bonhomme, F.; David, P. (2011)
The coupling hypothesis: why genome scans may fail to map local adaptation genes
Molecular Ecology 20(10):2044–2072.

Bierne, N.; Roze, D.; Welch, J. (2013)
Pervasive selection or is itâĂę? why are FST outliers sometimes so frequent?
Molecular Ecology 22(8):2061–2064.

Bradshaw, W. E. and Holzapfel, C. M. (2006)
Climate change - Evolutionary response to rapid climate change
Science 312(5779):1477–1478.

UNIVERSITETET I NORDLAND

References II

Braune, W. (2008)
Meeresalgen
Koeltz Scientific Books Königstein, Germany.

Bussotti, F.; Desotgiu, R; Pollastrini, M.; Cascio, C. (2010)
The JIP test: a tool to screen the capacity of plant adaptation to climate change
Scandinavian Journal of Forest Research 25(Suppl 8): 43–50.

Charlesworth, B.; Nordborg, M.; Charlesworth, D. (1997)
The effects of local selection, balanced polymorphism and background selection on equilibrium patterns of genetic diversity in subdivided populations
Genetic Research 70:155–174.

Coyer, J. A.; Peters, A.F.; Stam, W.T.; Olsen, J.L. (2003)
Post-ice age recolonization and differentiation of *Fucus serratus* L. (Phaeophyceae; Fucaceae) populations in Northern Europe
Molecular Ecology 12:1817–1829.

Coyer, J. A.; Hoarau, G.; Oudot-Le Secq, M.-P.; Stam, W.T. (2006)
A mtDNA-based phylogeny of the brown algal genus *Fucus* (Heterokontophyta; Phaeophyta)
Molecular Phylogenetics and Evolution 39:209–222.

Cock, J.M.; Sterck, L.; Rouzé, P. et al. (2010)
The *Ectocarpus* genome and the independent evolution of multicellularity in brown algae
Nature 465(3):617–621.

UNIVERSITETET I NORDLAND

References III

Excoffier, L.; Foll, M.; Petit, R.J. (2009)
Genetic Consequences of Range Expansions
Annual Review of Ecology, Evolution, and Systematics 40:481–501.

Excoffier, L.; Lischer, H.E.L. (2010)
Arlequin suite ver 3. 5: a new series of programs to perform population genetics analyses under Linux and Windows
Molecular Ecology Resources 10(3):564–567.

Fredriksen, S.; Christie, H.; Saethre, B.A. (2005)
Species richness in macroalgae and macrofauna assemblages on *Fucus serratus* L. (Phaeophyceae) and *Zostera marina* L. (Angiospermae) in Skagerrak, Norway.
Marine Biology Research 1(1):2–19.

Fourcade, Y.; Chaput-Bardy, A.; Secondi, J.; Fleurant, C.; Lemaire, C. (2013)
Is local selection so widespread in river organisms? Fractal geometry of river networks leads to high bias in outlier detection
Molecular Ecology 22(8):2065–2073.

Halpern, B.S.; Walbridge, S.; Selkoe, K.A.; Kappel, C.V.; Micheli, F.; D'Agrosa, C.; Bruno, J.F.; Casey, K.S.; Ebert, C.; Fox, H.E. and others (2010)
A global map of human impact on marine ecosystems
Science 319(5856):948–952.

Hansen, J.; Sato, M.; Ruedy, R.; Lo, K.; Lea, D.W.; Medina-Elizade, M. (2006)
Global temperature change
Proceedings of the National Academy of Sciences 103(39):14288–14293.

UNIVERSITETET I NORDLAND

References IV

Hoarau, G.; Coyer, J.A.; Veldsink, J.H.; Stam, W.T.; Olsen, J.L. (2007)
Glacial refugia and recolonization pathways in the brown seaweed *Fucus serratus*
Molecular Ecology 16(17):3606–3616.

Hofer, T.; Ray, N.; Wegmann, D.; Excoffier, L. (2009)
Large Allele Frequency Differences between Human Continental Groups are more Likely to have Occurred by Drift During range Expansions than by Selection
Annals of Human Genetics 73(1):95–108.

Jimenez-Valverde, Alberto (2012)
Insights into the area under the receiver operating characteristic curve (AUC) as a discrimination measure in species distribution modelling
Global Ecology and Biogeography 21:498–507.

Jueterbock, A.; Tyberghein, L.; Verbruggen, H.; Coyer, J.A.; Olsen, J.L.; Hoarau, G. (2013)
Climate change impact on seaweed meadow distribution in the North Atlantic rocky intertidal
Ecology and Evolution 3(5):1356–1373.

Knight, M.; Parke, M. (1950)
A biological study of *Fucus vesiculosus* L. and *F. serratus* L.
Journal of the Marine Biological Association of the UK 29:439–514.

Køie, M.; Kristiansen, A.; Weitemeyer, S. (2001)
Der große Kosmos Strandführer.
Kosmos.

UNIVERSITETET I NORDLAND

References V

Luikart, G.; England, P. R.; Tallmon, D.; Jordan, S.; Taberlet, P. (2003)
The power and promise of population genomics: from genotyping to genome typing
Nature Reviews Genetics 4(12):981–994.

McMahon, C.R. & Hays, G.C. (2006)
Thermal niche, large-scale movements and implications of climate change for a critically endangered marine vertebrate.
Global Change Biology 12(7):1330–1338.

Meehl, G.A.; Stocker, T.F.; Collins, W.D.; Friedlingstein, P.; Gaye, A.T.; Gregory, JM.; Kitoh, A.; Knutti, R.; Murphy, J.M.; Noda, A.; Raper, S.C.B.; Watterson, I.G and Weaver, A.J.; Zhao, Z.-C. (2007)
Global Climate Projections.
Climate Change 2007: the physical science basis: contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Eds: Solomon S. et al.

Nicastro, K.R.; Zardi, G.I.; Teixeira, S.; Neiva, J.; Serrao, E.A.; Pearson, G.A. (2013)
Shift happens: trailing edge contraction associated with recent warming trends threatens a distinct genetic lineage in the marine macroalga *Fucus vesiculosus*.
BMC Biology 11(6).

Nolan, T.; Hands, R.E.; Bustin, S.A. (2006)
Quantification of mRNA using realtime RT-PCR
Nature Protocols 1(3)1559–1582.

Pannell, J. R.; Charlesworth, B. (2000)
Effects of metapopulation processes on measures of genetic diversity
Philosophical Transactions of the Royal Society of London B 355(1404):1851-1864.

UNIVERSITETET I NORDLAND

References VI

Pearson, G.A.; Lago-Leston, A.; Mota, C. (2009)
Frayed at the edges: selective pressure and adaptive response to abiotic stressors are mismatched in low diversity edge populations.
Journal of Ecology 97(3):450–462.

Phillips, S.J.; Anderson, R.P.; Schapire, R.E. (2006)
Maximum entropy modeling of species geographic distributions.
Ecological Modelling 190(3-4):231–259.

Pounds, J. A.; Bustamante, M.R.; Coloma, L.A.; Consuegra, J.A.; Fogden, M.P.L.; Foster, P.N.; La Marca, E.; Masters, K.L.; Merino-Viteri, A.; Puschendorf, R.; Ron, S.R.; Sanchez-Azofeifa, G.A.; Still, C.J.; Young, B.E. (2006)
Widespread amphibian extinctions from epidemic disease driven by global warming
Nature 7073:161–167.

Raybaud, V.; Beaugrand, G.; Goberville, E.; Delebecq, G.; Destombe, C.; Valero, M.; Davoult, D.; Morin, P.; Gevaert, F. (2013)
Decline in Kelp in West Europe and Climate
PLOS ONE 8:e66044.

Sturm, M.; Schimel, J.; Michaelson, G.; Welker, J.M.; Oberbauer, S.F.; Liston, G.E.; Fahnestock, J.; Romanovsky, V. (2005)
Winter biological processes could help convert Arctic tundra to shrubland.
*Bioscience*55(1):17–26.

Tyberghein, L.; Verbruggen, H.; Pauly, K.; Troupin, C.; Mineur, F.; De Clerck, O. (2011)
Bio-ORACLE: a global environmental dataset for marine species distribution modelling.
Global Ecology and Biogeography.

UNIVERSITETET I NORDLAND

References VII

van Asch, M.; Salis, L.; Holleman, L.J.M.; van Lith, B.; Visser, M.E. (2013)
Evolutionary response of the egg hatching date of a herbivorous insect under climate change.
Ecography 3:244–248.

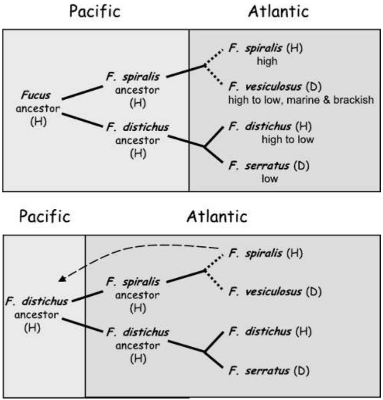
Viejo, R.M.; Martínez, B.; Arrontes, J.; Astudillo, C.; Hernández, L. (2011)
Reproductive patterns in central and marginal populations of a large brown seaweed: drastic changes at the southern range limit.
Ecography 34(1):75–84.

Walther, G.-R.; Post, E.; Convey, P.; Menzel, A.; Parmesan, C.; Beebee, T.J.C.; Fromentin, J.-M.; Hoegh-Guldberg, O.; Bairlein, F. (2002)
Ecological responses to recent climate change.
Nature 416(6879):389–395.

Wernberg, T.; Russell, B.D.; Thomsen, M.S.; Gurgel, F.D.; Bradshaw, C.J.A.; Poloczanska, E.S., Connell, S.D. (2011)
Seaweed Communities in Retreat from Ocean Warming.
Current Biology 21(21):1828–1832.

UNIVERSITETET I NORDLAND

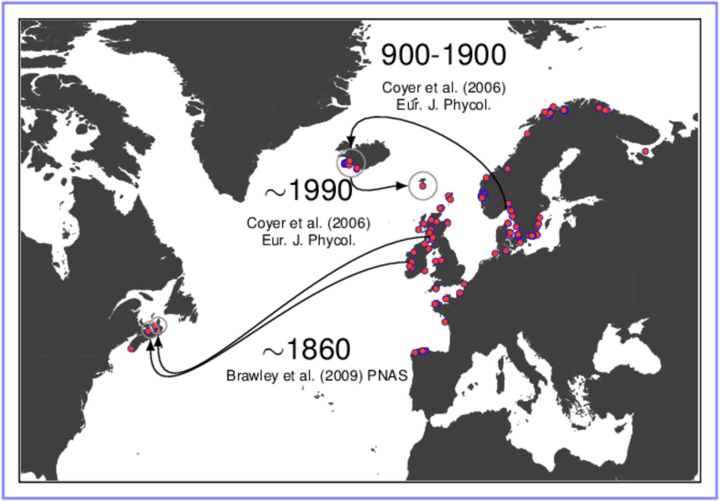
mtDNA based Phylogeny



[Coyer et al., 2006; Mol. Phylogenet. Evol.]

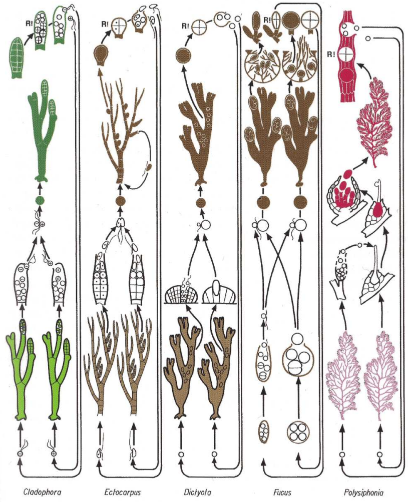
UNIVERSITETET I NORDLAND

Human introduction



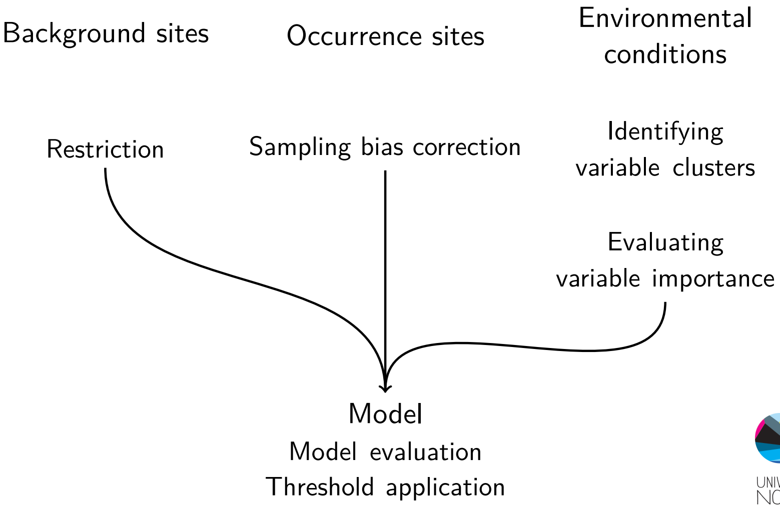
UNIVERSITETET I NORDLAND

Life cycles of algae

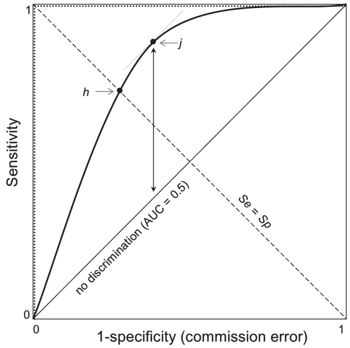


[Braune, 2008; Meeresalgen]

Choices in Ecological Niche Modeling



The AUC value



[Jimenez-Valverde, 2012; Global Ecol. Biogeogr.]

Sensitivity: Present, predicted as present

1-Specificity: Absence, predicted as present

UNIVERSITETET I NORDLAND

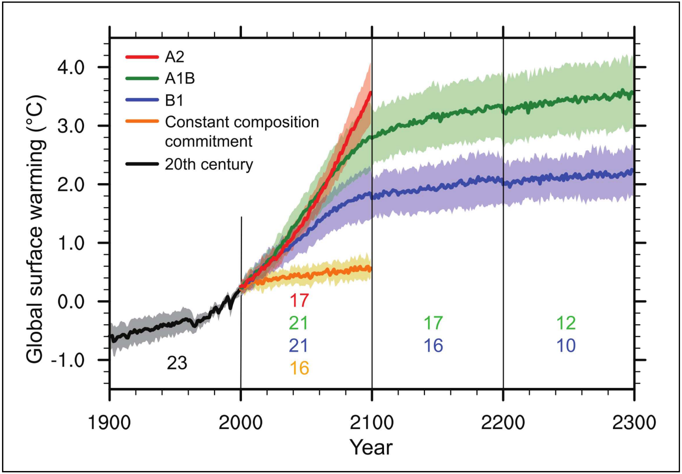
Importance of temperature for algal distribution

			Contribution (%)		
Variable	Derivative	Unit	*Fucus serratus*	*Fucus vesiculosus*	*Ascophyllum nodosum*
SST	Minimum	°C	66	46.4	82.3
SST	Maximum	°C	24.7	42.8	
SST	Mean	°C	9.3		
SAT	Minimum	°C			7.3
Salinity	Mean	PSS			10.4
DA	Minimum	m^{-1}		10.8	

[Jueterbock et al., 2013; Ecol. Evol.]

UNIVERSITETET I NORDLAND

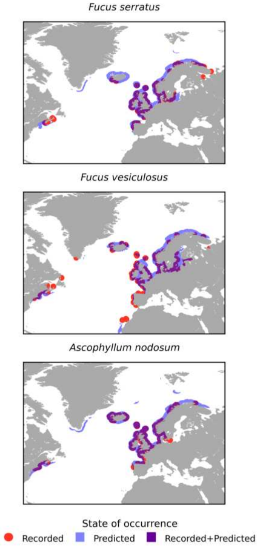
SRES CO2 emission scenarios



[Meehl et al., 2007; Climate Change 2007]

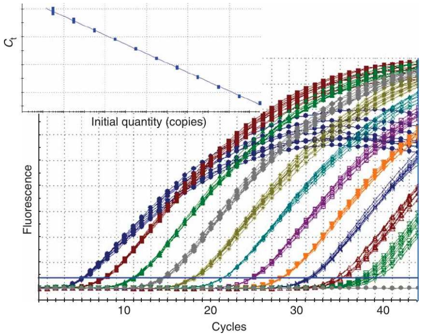
UNIVERSITETET I NORDLAND

Present-day habitat suitability and occurrence sites



[Jueterbock et al., 2013; Ecol. Evol.]

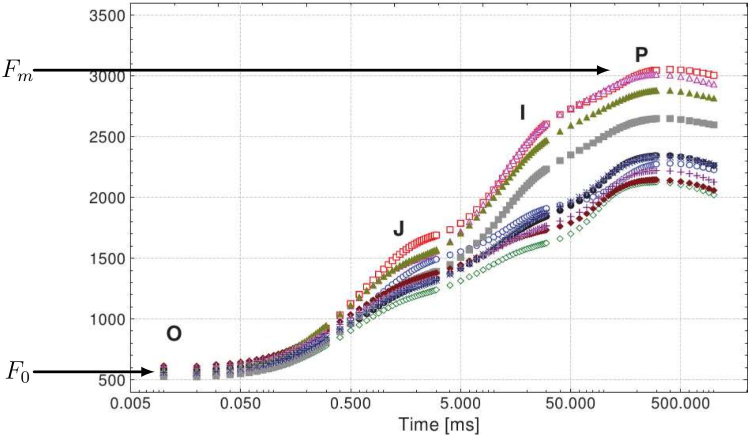
Quantification of gene products



[Nolan et al., 2006; Nature Protocols]

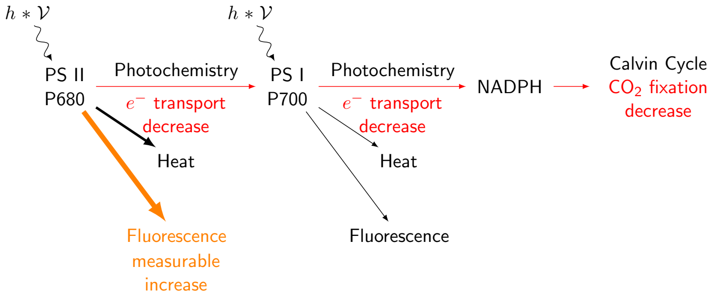
$$Efficiency = 10^{-1/slope}$$
$$quantity = 10^{\frac{Ct-b}{slope}}$$

OJIP curve

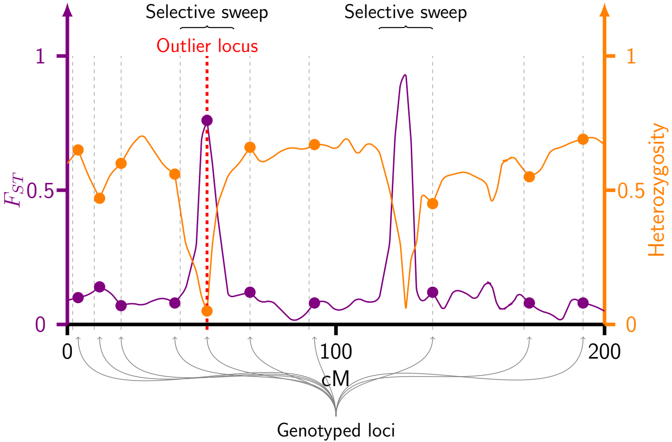


[Bussotti et al., 2010; Scand. J. Forest Res.]

Heat stress effect on photosynthesis

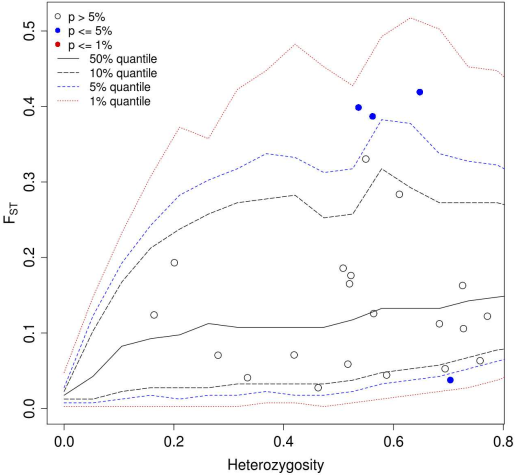


Genome scan for outlier loci



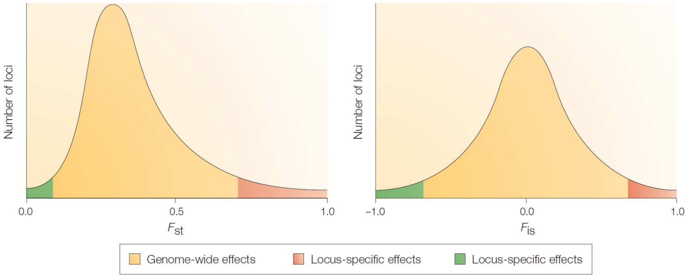
UNIVERSITETET I NORDLAND

Arlequin - test for outlier loci



[Excoffier & Lischer, 2010; Mol. Ecol. Res.]

Identification of outlier loci



[?]

Potential reasons for low N_e values

- Unequal sex ratios
- Variance in family size (individual gametic contribution)
- Fluctuations of population size (potential reason for the low N_e in Spain
- Reduced gene flow between populations
- Inbreeding

UNIVERSITETET I NORDLAND

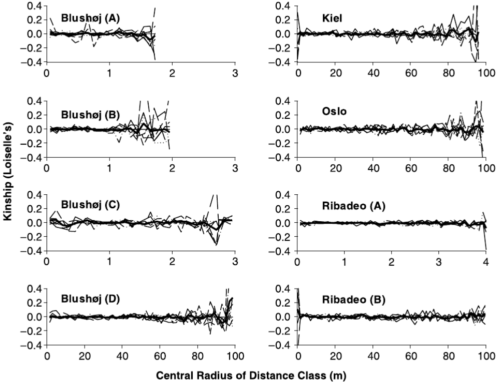
N_e indicates

- The rate of genetic change due to genetic drift is proportional to $\frac{1}{2N_e}$
- The effectiveness of selection over genetic drift (drift dominates if selection $< \frac{1}{2N_e}$
- Nucleotide diversity $4Nu$ with u being the mutation rate
- In a closed population, N_e can indicate MLH. Gene flow uncouples N_e from genetic stochasticity

UNIVERSITETET I NORDLAND

Significant F_{IS} values can not be explained by a small-scale family structure

Genetic correlations among individuals



[Coyer et al., 2003; Mol. Ecol.]

Local adaptation - or?

Alternative reasons for spatial outliers

- Geographic distribution that creates correlations in population structure [Fourcade et al. 2013; Mol. Ecol., Bierne et al., 2013; Mol. Ecol.]

Rivers

Oceanic ridges

Coastlines

Local adaptation - or?

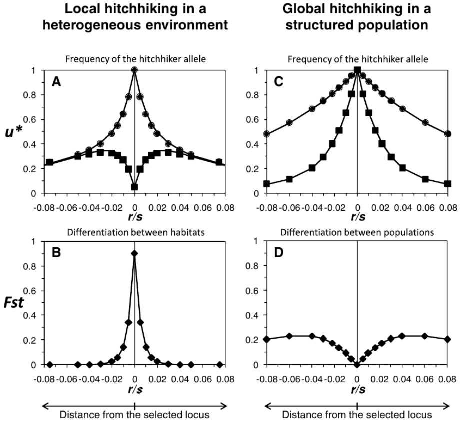
Alternative reasons for spatial outliers

- Background selection against deleterious mutations
  [Charlesworth et al., 1997; Genet. Res.]

Local adaptation - or?

Alternative reasons for spatial outliers

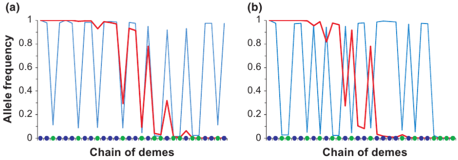
- Species-wide selective sweeps [Bierne, 2010; Evolution]



Local adaptation - or?

Alternative reasons for spatial outliers

- Coupling of endogenous with exogenous gene flow barriers
  [Bierne et al., 2011; Mol. Ecol.]

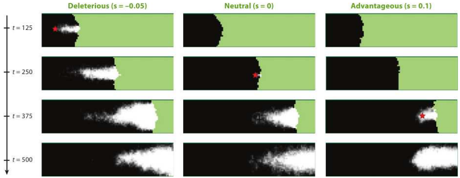


red: endogenous, blue: exogenous alleles

UNIVERSITETET I NORDLAND

Local adaptation - or?
Alternative reasons for spatial outliers

- Stochastic effects at the wave edge of an expanding population [Excoffier et al., 2009; Annu. Rev. Ecol. Evol. Syst.]



UNIVERSITETET I NORDLAND