Consequences of climate-induced range shifts for shared fish stocks: Insights from game theory and Northeast Atlantic fisheries

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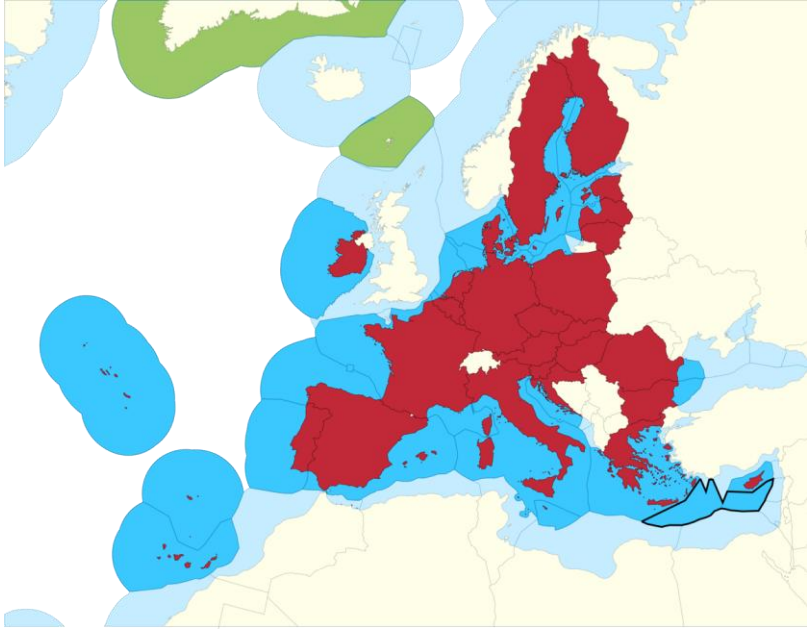
Shared stocks

- ✓Fish stocks that occur in the exclusive economic zone (EEZ) of more than one country (+possibly the high seas)
- EEZs have their legal basis in the United Nations Convention on the Law of the Sea (UNCLOS)



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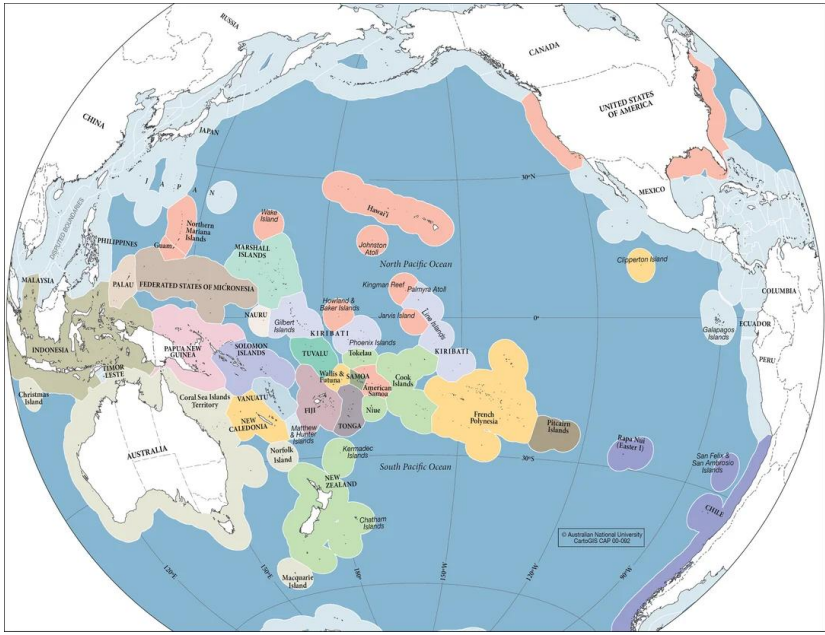

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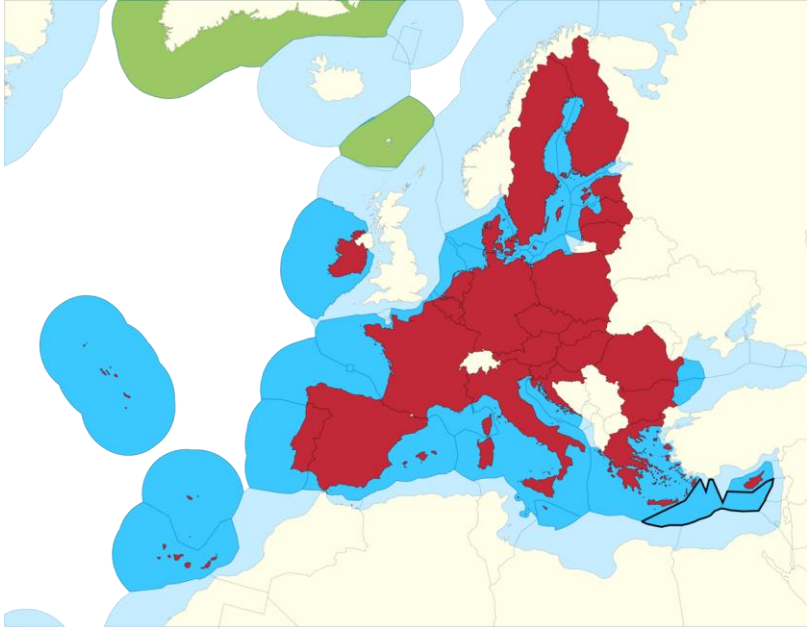
Shared stocks

- UNCLOS obligates states to co-operate in order to conserve and develop shared stocks
- UNCLOS does not state how such co-operation should work
  - In particular, how catch quotas of the shared stocks should be shared



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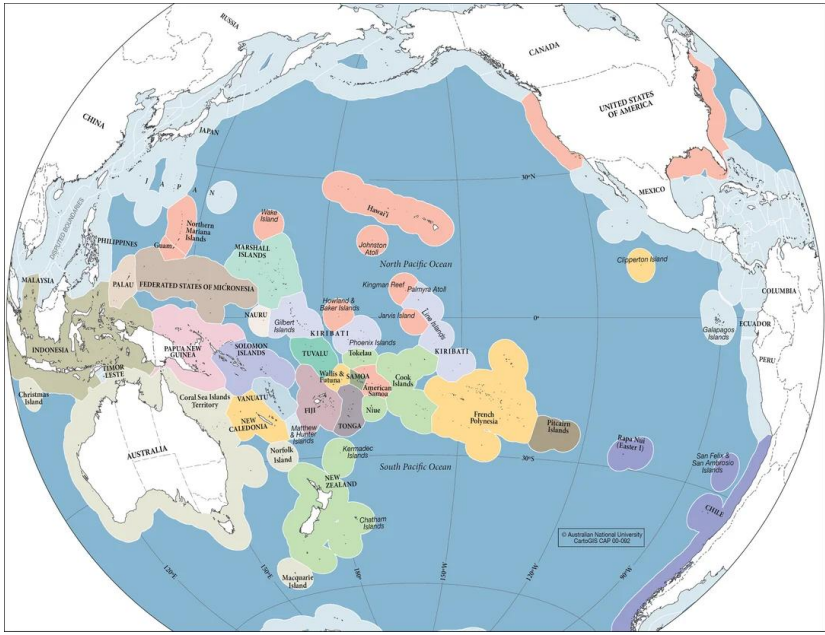


Dallor/reddit.com

Sharing shared stocks

- Main principle: **zonal attachment**
  = ownership is proportional to the fish biomass in the EEZ of each state
  - Arguably fair and seemingly objective
  - Requires good data
  - States may not agree how to calculate the shares
    - Which time period? Which season(s)?
    - Which data sources?
    - Extra weight given to spawning, body mass gain?
- Should historic catches or dependence on a fishery count? Can create perverse incentives…

Northeast Atlantic perspective, as seen from Norway

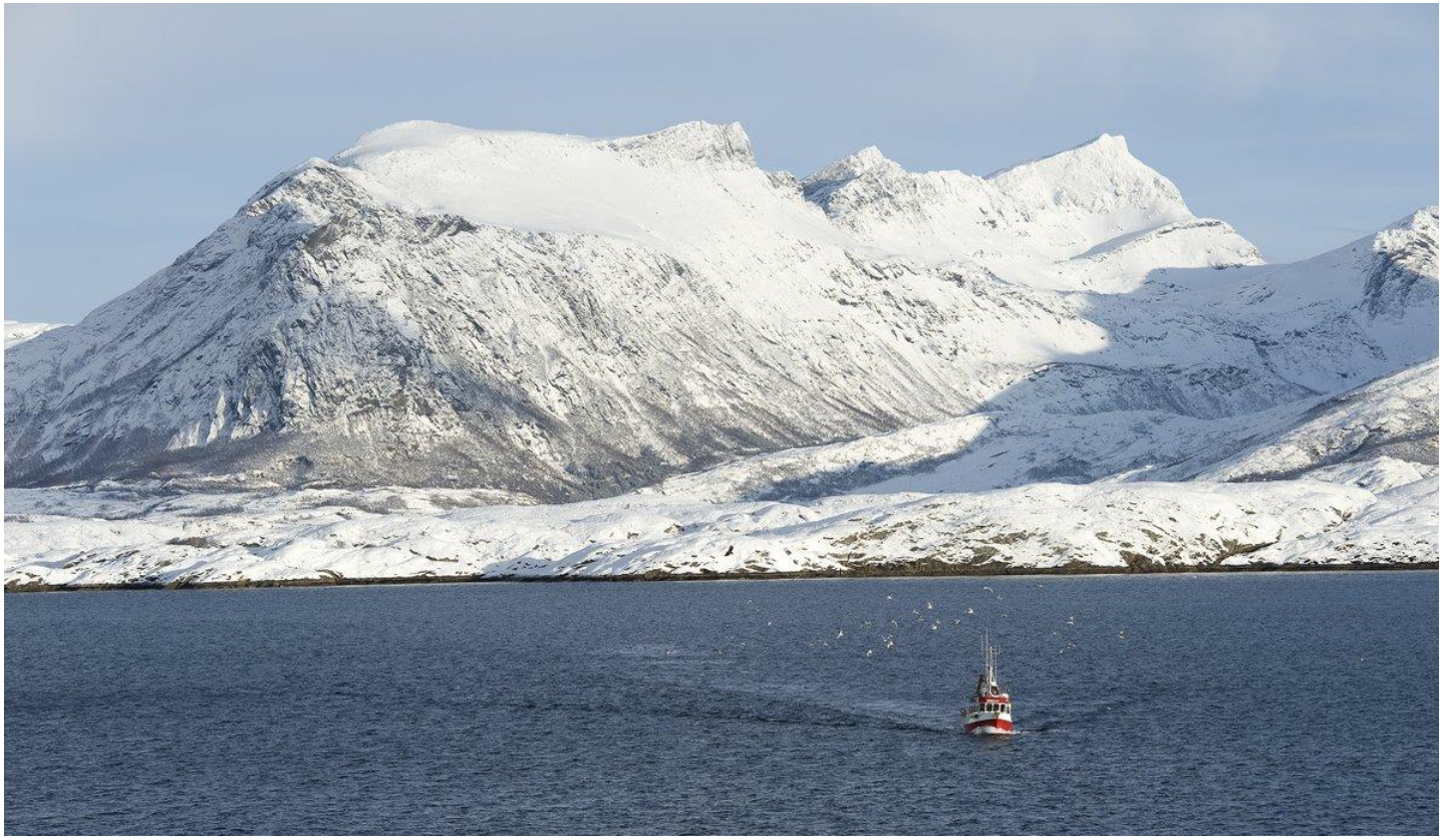


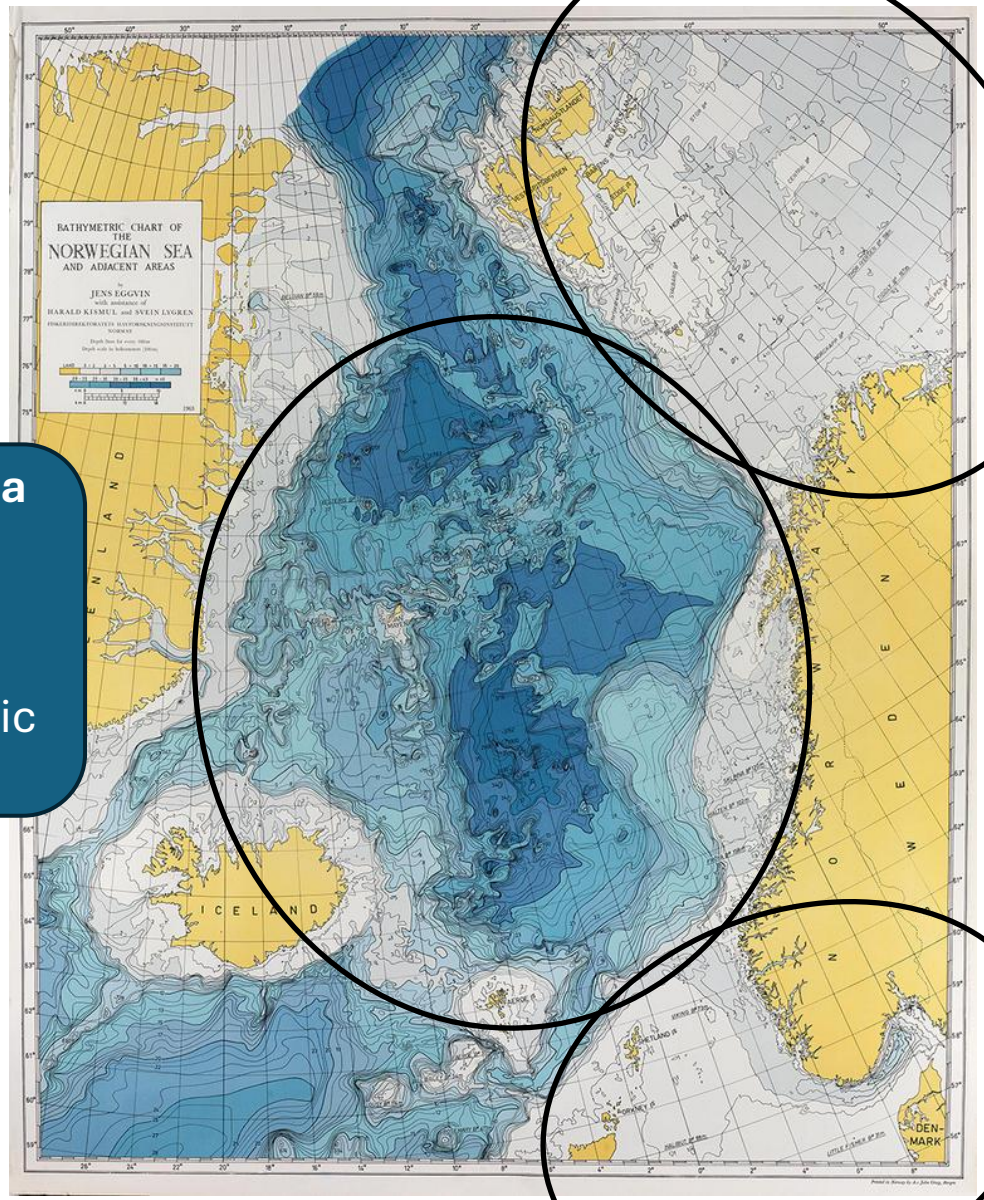
Photo: Jan Helge Fosså, IMR

Barents Sea

- Shelf sea
- Mostly demersal fisheries

Norwegian Sea

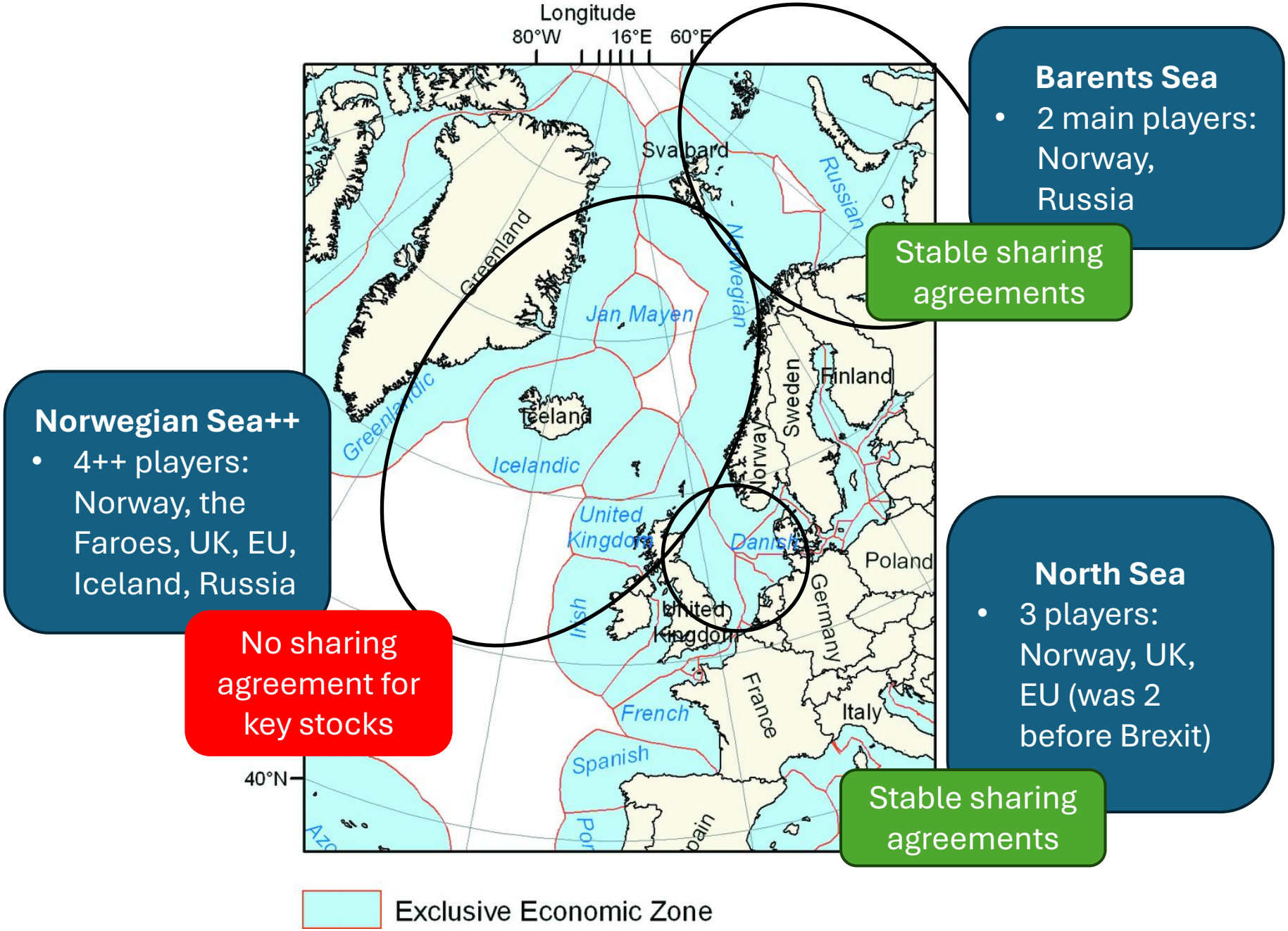
- Deep sea basin with a narrow shelf
- Mostly pelagic fisheries



Jens Eggvin (1899–1989)

North Sea

- Shelf sea
- Demersal & pelagic fisheries



Barents Sea

- 2 main players: Norway, Russia

Stable sharing agreements

Norwegian Sea++

- 4++ players: Norway, the Faroes, UK, EU, Iceland, Russia

No sharing agreement for key stocks

North Sea

- 3 players: Norway, UK, EU (was 2 before Brexit)

Stable sharing agreements

Map: Ekerhovd, N.-A. (2010). *Can. J. Fish. Aquat. Sci. 67*:534–552. doi:10.1139/F09-195

Fisheries

Coastal states agree mackerel catch limit for 2027

Sharing >100% of the cake leads to overfishing

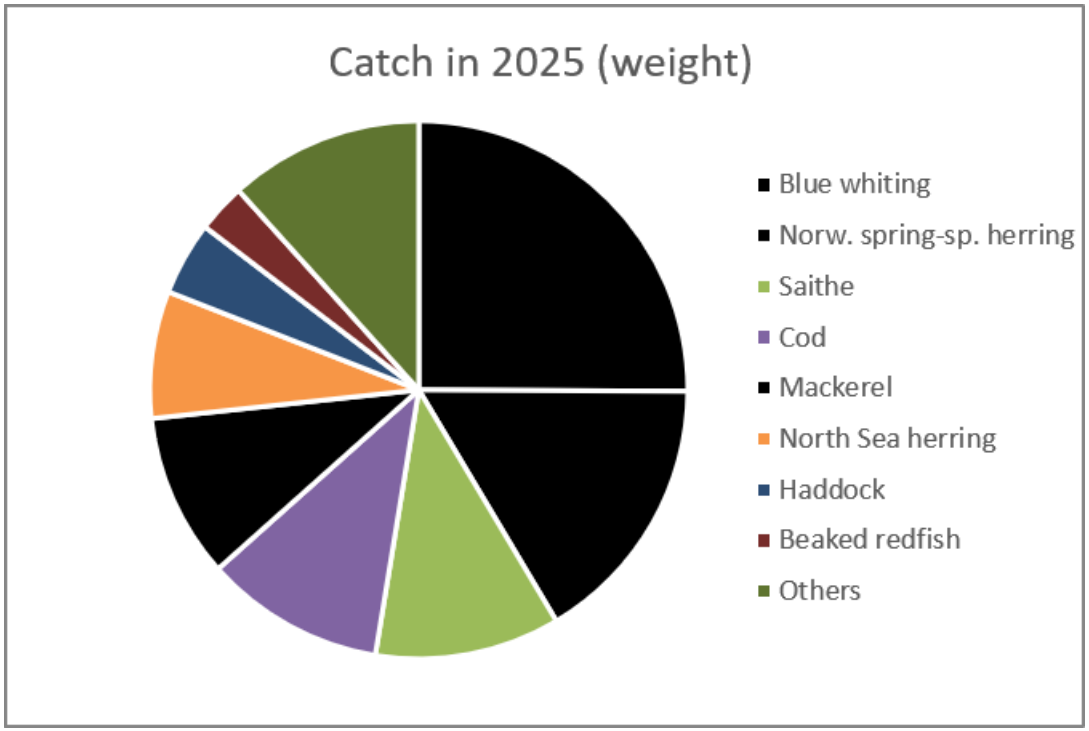
Russia is not part of the negotiations, meaning total catches could still significantly exceed the recommended level in 2027.



The coastal states have agreed on a total allowable catch (TAC) of 352,938 metric tons for 2027 after three days of negotiations, in line with the recommendation from the International Council for the Exploration of the Sea (ICES).

Westberg said she sees the new agreement as a positive sign ahead of the December meeting, when discussions on how to allocate quotas among the coastal states will continue. She cautioned, however, that reaching an agreement on allocation would be difficult.

- At present, about half of the Norwegian catch comes from shared stocks without a complete sharing agreement



Blue whiting
(*Micromesistius poutassou*)



Herring
(*Clupea harengus*)



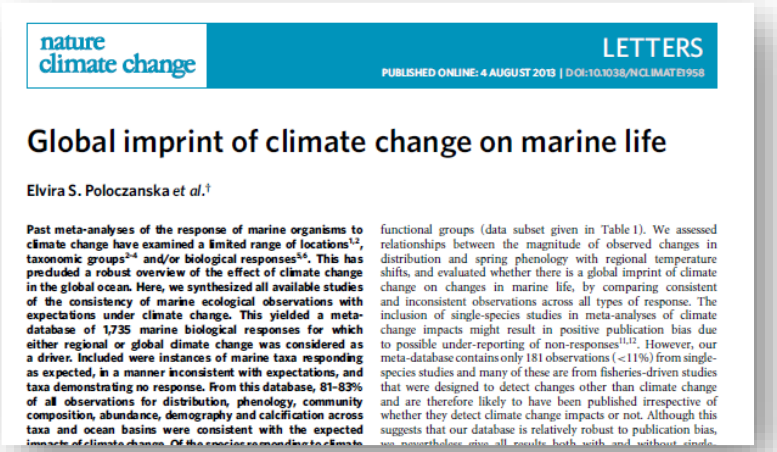
Mackerel
(*Scomber scombrus*)



Fish images: © Scandinavian Fishing Year Book
via fish-commercial-names.ec.europa.eu

Sharing shared stocks

- Additional challenge: Climate-change induced range shifts
  - ✓Among best-documented responses for marine fish



nature climate change

LETTERS

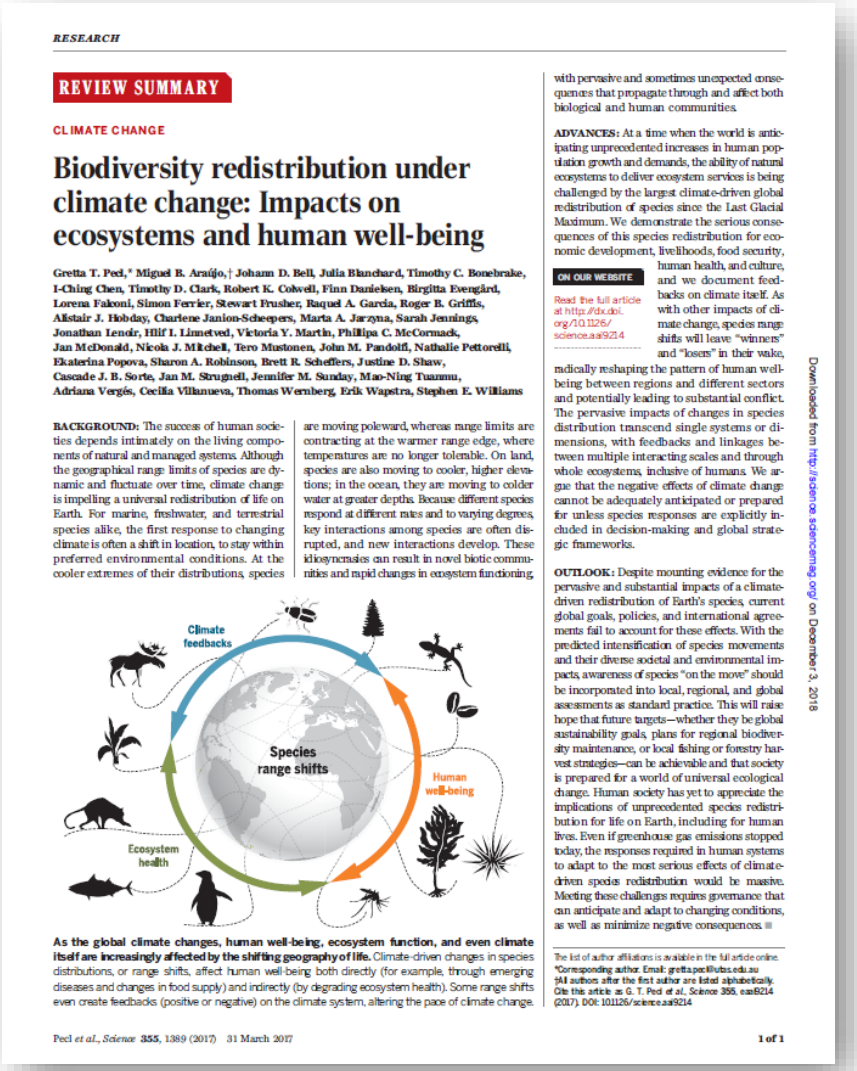
PUBLISHED ONLINE: 4 AUGUST 2013 | DOI:10.1038/NCLIMATE1958

Global imprint of climate change on marine life

Elvira S. Poloczanska *et al.*†

Past meta-analyses of the response of marine organisms to climate change have examined a limited range of locations[1,2], taxonomic groups[3,4] and/or biological responses[5,6]. This has precluded a robust overview of the effect of climate change in the global ocean. Here, we synthesized all available studies of the consistency of marine ecological observations with expectations under climate change. This yielded a meta-database of 1,735 marine biological responses for which either regional or global climate change was considered as a driver. Included were instances of marine taxa responding as expected, in a manner inconsistent with expectations, and taxa demonstrating no response. From this database, 81–83% of all observations for distribution, phenology, community composition, abundance, demography and calcification across taxa and ocean basins were consistent with the expected

functional groups (data subset given in Table 1). We assessed relationships between the magnitude of observed changes in distribution and spring phenology with regional temperature shifts, and evaluated whether there is a global imprint of climate change on changes in marine life, by comparing consistent and inconsistent observations across all types of response. The inclusion of single-species studies in meta-analyses of climate change impacts might result in positive publication bias due to possible under-reporting of non-responses[11,12]. However, our meta-database contains only 181 observations (<11%) from single-species studies and many of these are from fisheries-driven studies that were designed to detect changes other than climate change and are therefore likely to have been published irrespective of whether they detect climate change impacts or not. Although this suggests that our database is relatively robust to publication bias,



RESEARCH

REVIEW SUMMARY

CLIMATE CHANGE

Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being

Gretta T. Pecl,* Miguel B. Araújo,† Johann D. Bell, Julia Blanchard, Timothy C. Bonebrake, I-Ching Chen, Timothy D. Clark, Robert K. Colwell, Finn Danielsen, Birgitta Evengård, Lorena Falconi, Simon Ferrier, Stewart Frusher, Raquel A. Garcia, Roger B. Griffis, Alistair J. Hobday, Charlene Janion-Scheepers, Marta A. Jarzyna, Sarah Jennings, Jonathan Lenoir, Hlif I. Linnetved, Victoria Y. Martin, Phillipa C. McCormack, Jan McDonald, Nicola J. Mitchell, Tero Mustonen, John M. Pandolfi, Nathalie Pettorelli, Ekaterina Popova, Sharon A. Robinson, Brett R. Scheffers, Justine D. Shaw, Cascade J. B. Sorte, Jan M. Strugnell, Jennifer M. Sunday, Mao-Ning Tuanmu, Adriana Vergés, Cecilia Villanueva, Thomas Wernberg, Erik Wapstra, Stephen E. Williams

BACKGROUND: The success of human societies depends intimately on the living components of natural and managed systems. Although the geographical range limits of species are dynamic and fluctuate over time, climate change is impelling a universal redistribution of life on Earth. For marine, freshwater, and terrestrial species alike, the first response to changing climate is often a shift in location, to stay within preferred environmental conditions. At the cooler extremes of their distributions, species are moving poleward, whereas range limits are contracting at the warmer range edge, where temperatures are no longer tolerable. On land, species are also moving to cooler, higher elevations; in the ocean, they are moving to colder water at greater depths. Because different species respond at different rates and to varying degrees, key interactions among species are often disrupted, and new interactions develop. These idiosyncrasies can result in novel biotic communities and rapid changes in ecosystem functioning, with pervasive and sometimes unexpected consequences that propagate through and affect both biological and human communities.

ADVANCES: At a time when the world is anticipating unprecedented increases in human population growth and demands, the ability of natural ecosystems to deliver ecosystem services is being challenged by the largest climate-driven global redistribution of species since the Last Glacial Maximum. We demonstrate the serious consequences of this species redistribution for economic development, livelihoods, food security, human health, and culture, and we document feedbacks on climate itself. As with other impacts of climate change, species range shifts will leave "winners" and "losers" in their wake, radically reshaping the pattern of human well-being between regions and different sectors and potentially leading to substantial conflict. The pervasive impacts of changes in species distribution transcend single systems or dimensions, with feedbacks and linkages between multiple interacting scales and through whole ecosystems, inclusive of humans. We argue that the negative effects of climate change cannot be adequately anticipated or prepared for unless species responses are explicitly included in decision-making and global strategic frameworks.

ON OUR WEBSITE

Read the full article at http://dx.doi.org/10.1126/science.aai9214

OUTLOOK: Despite mounting evidence for the pervasive and substantial impacts of a climate-driven redistribution of Earth's species, current global goals, policies, and international agreements fail to account for these effects. With the predicted intensification of species movements and their diverse societal and environmental impacts, awareness of species "on the move" should be incorporated into local, regional, and global assessments as standard practice. This will raise hope that future targets—whether they be global sustainability goals, plans for regional biodiversity maintenance, or local fishing or forestry harvest strategies—can be achievable and that society is prepared for a world of universal ecological change. Human society has yet to appreciate the implications of unprecedented species redistribution for life on Earth, including for human lives. Even if greenhouse gas emissions stopped today, the responses required in human systems to adapt to the most serious effects of climate-driven species redistribution would be massive. Meeting these challenges requires governance that can anticipate and adapt to changing conditions, as well as minimize negative consequences. ■

As the global climate changes, human well-being, ecosystem function, and even climate itself are increasingly affected by the shifting geography of life. Climate-driven changes in species distributions, or range shifts, affect human well-being both directly (for example, through emerging diseases and changes in food supply) and indirectly (by degrading ecosystem health). Some range shifts even create feedbacks (positive or negative) on the climate system, altering the pace of climate change.

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Sharing shared stocks

- Additional challenge:
  Climate-change induced range shifts

  → “Fair” shares will change over time

    ✓Collapse of the mackerel agreement was triggered by the range expansion – caused by larger stock size and warming climate

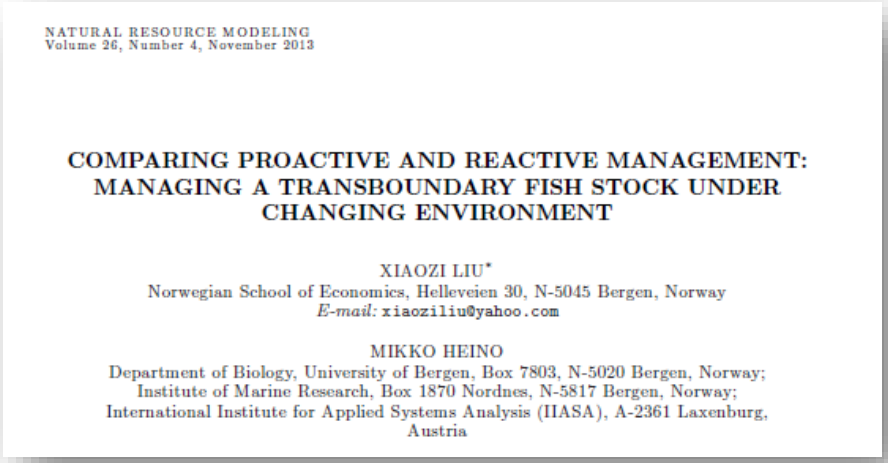
Sharing shared stocks

- The stage – political geography – is beyond our control
- We can try to understand the underlying dynamics of cooperation and non-cooperation
- We can try to use this understanding to develop smarter ways of sharing stocks in the dynamic world

  ➢Game theory

Research questions

- How do range shifts affect non-cooperative exploitation of shared fish stocks?
- How do range shifts affect stability of stock sharing agreements?
- How to formulate more robust sharing rules?



NATURAL RESOURCE MODELING
Volume 26, Number 4, November 2013

COMPARING PROACTIVE AND REACTIVE MANAGEMENT: MANAGING A TRANSBOUNDARY FISH STOCK UNDER CHANGING ENVIRONMENT

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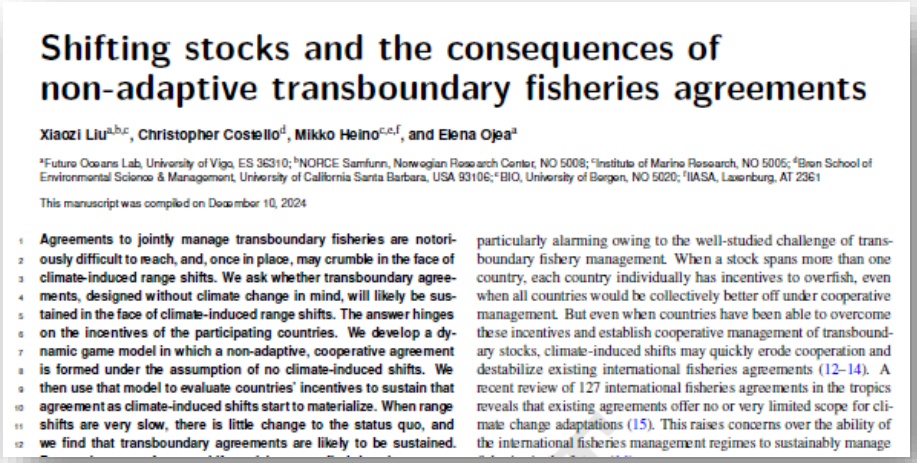

Shifting stocks and the consequences of non-adaptive transboundary fisheries agreements

Xiaozi Liu[a,b,c], Christopher Costello[d], Mikko Heino[c,e,f], and Elena Ojea[a]

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This manuscript was compiled on December 10, 2024

Agreements to jointly manage transboundary fisheries are notoriously difficult to reach, and, once in place, may crumble in the face of climate-induced range shifts. We ask whether transboundary agreements, designed without climate change in mind, will likely be sustained in the face of climate-induced range shifts. The answer hinges on the incentives of the participating countries. We develop a dynamic game model in which a non-adaptive, cooperative agreement is formed under the assumption of no climate-induced shifts. We then use that model to evaluate countries' incentives to sustain that agreement as climate-induced shifts start to materialize. When range shifts are very slow, there is little change to the status quo, and we find that transboundary agreements are likely to be sustained.

particularly alarming owing to the well-studied challenge of transboundary fishery management. When a stock spans more than one country, each country individually has incentives to overfish, even when all countries would be collectively better off under cooperative management. But even when countries have been able to overcome these incentives and establish cooperative management of transboundary stocks, climate-induced shifts may quickly erode cooperation and destabilize existing international fisheries agreements (12–14). A recent review of 127 international fisheries agreements in the tropics reveals that existing agreements offer no or very limited scope for climate change adaptations (15). This raises concerns over the ability of the international fisheries management regimes to sustainably manage

Co-operative exploitation

- Co-operation is optional:
  - Whether to initially enter an agreement
    - Our model: always, unless very uneven ownership
  - Whether to exit the agreement
    - “Grim trigger” – re-entry not permitted
  - Under co-operation, benefits are shared based on fixed proportions
- If players do not co-operate, then they choose the best option from their individual perspectives → Nash strategy

Game structure

- Objective: maximize own Net Present Value (NPV)
- Repeated game over a fixed 50-yr time horizon
  - Solved through backward iteration
  - Each year, both players choose the strategy that maximizes NPV of the stock in their zone, given the choice of the other player
- Strategy of each player has **two** components:
  1. Choose to play Co-operative or play Nash
  2. Escapement (separately for Co-op and Nash)

Biological–economic model

- «Split stream» model of Golubtsov & McKelvey[1]
  - ✓Simple bioeconomic population model
  - The fishable stock is split between two players (countries), no mixing during the fishing season
  - Price is constant
  - Cost per unit catch is density-dependent and increases over the course of a fishing season
  - Reproduction is based on what is left after the fishing season – in both zones combined

  +stochastic reproduction

[1] Golubtsov & McKelvey 2007. The incomplete-information split-stream fish war: examining the implications of competing risks. *Natural Resource Modeling*, 20: 263–300.

Game structure

- Two versions of cooperative gameplay
  1. **Sidepayment is present**
  - Players agree on catch shares when the cooperation starts
    - Currently, catch share = initial owership («zonal attachment»)
  - Players choose escaments that maximize their joint NPV
  - Sidepayment: player catching more than their catch share transfers the value of the excess catch to the other player
  2. No sidepayment
  - Players choose escaments that maximize their joint NPV
  - Each player gets the benefits of the harvest in their own zone

Game structure

- Phase 1:
  - Players choose whether to play Co-op or Nash
  - If they play Co-op, they set the catch shares (=initial ownership) and move to Phase 2:
- Phase 2:
  - Players choose whether to play Co-op or Nash
  - If they play Nash, they move to Phase 3 («grim trigger»)
- Phase 3:
  - Players play Nash to the end of the game

Strategic options

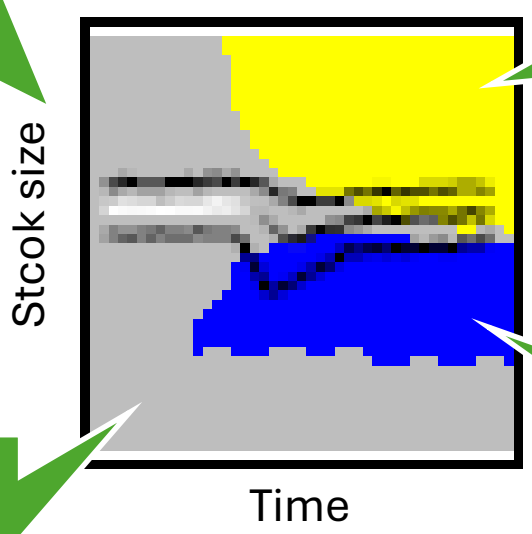
- ➢There is always a trade-off between short-term and long-term benefits
- Cooperation allows players sacrifice to some short-term benefits in favor of long-term benefits
  - Cooperation is associated with
    - more conservative harvest
    - higher stock size
    - higher joint long-term benefits

    than the competitive (Nash) solution
- Lack of cooperation (Nash) encourages short-termism
  - If ownership is asymmetric:
    - Freeriding: minor owner has less conservation interest than the major one
    - Bargaining power shrinks with shrinking ownership

Game dynamics over time

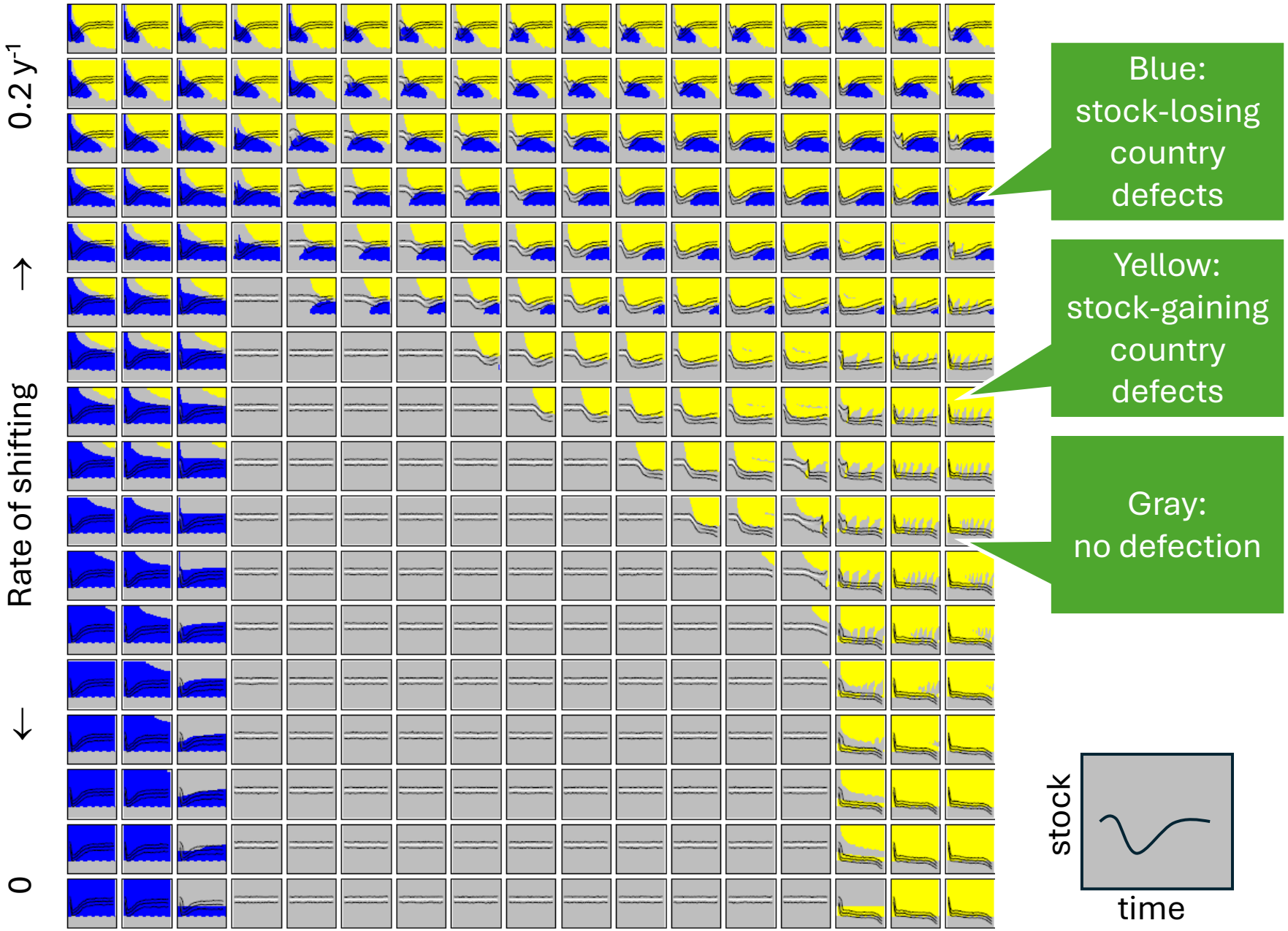
Stock trajectory with quartiles
- White→black curve: mean stock (white=100% co-op, black =100% Nash)

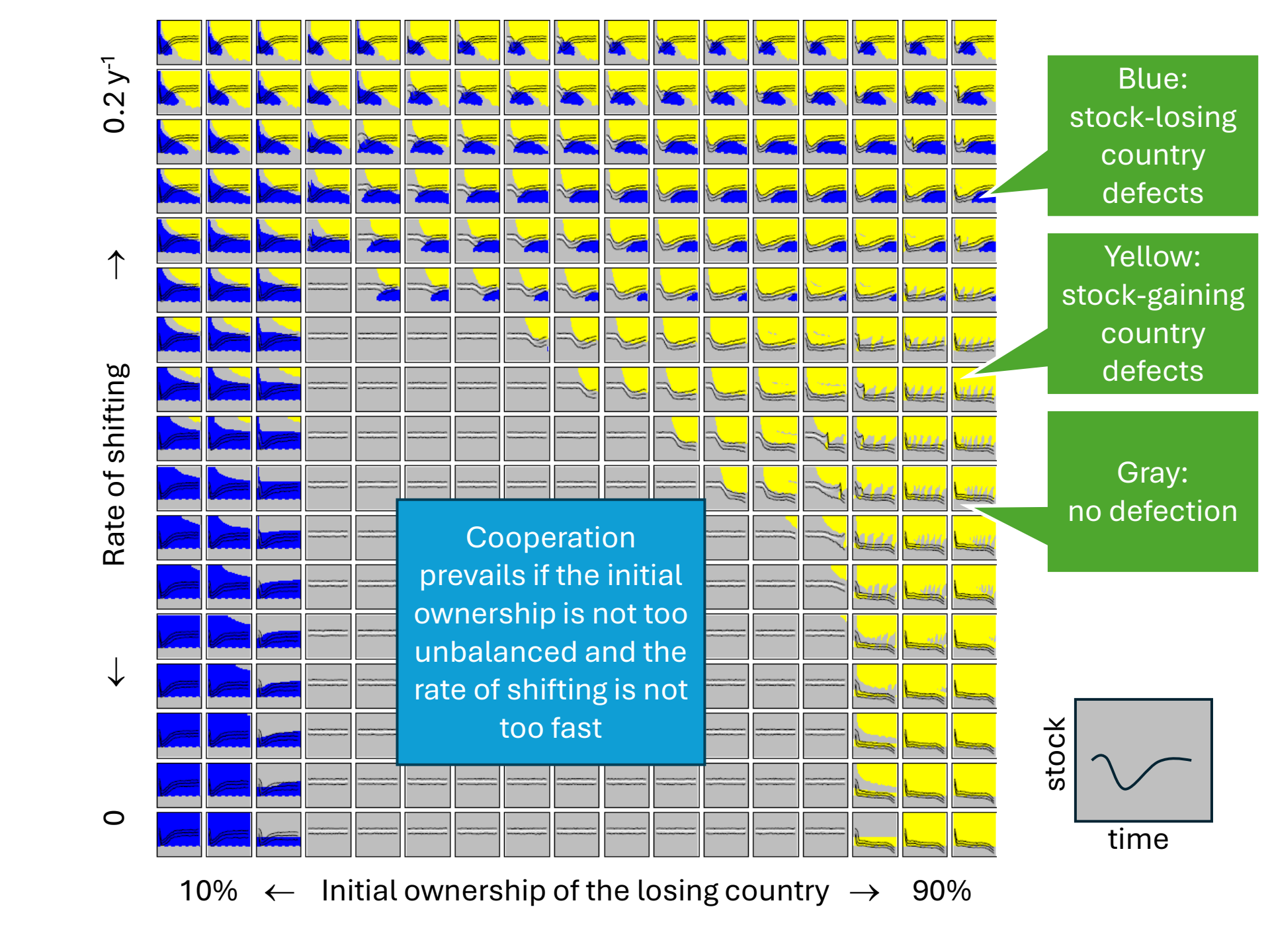
Yellow: stock-gaining country defects



Blue: stock-losing country defects

Gray: co-operation


0.2 y-1
Rate of shifting
0
10% ← Initial ownership of the losing country → 90%
Blue: stock-losing country defects
Yellow: stock-gaining country defects
Gray: no defection
stock
time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Rate of shifting
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10% ← Initial ownership of the losing country → 90%
Blue: stock-losing country defects
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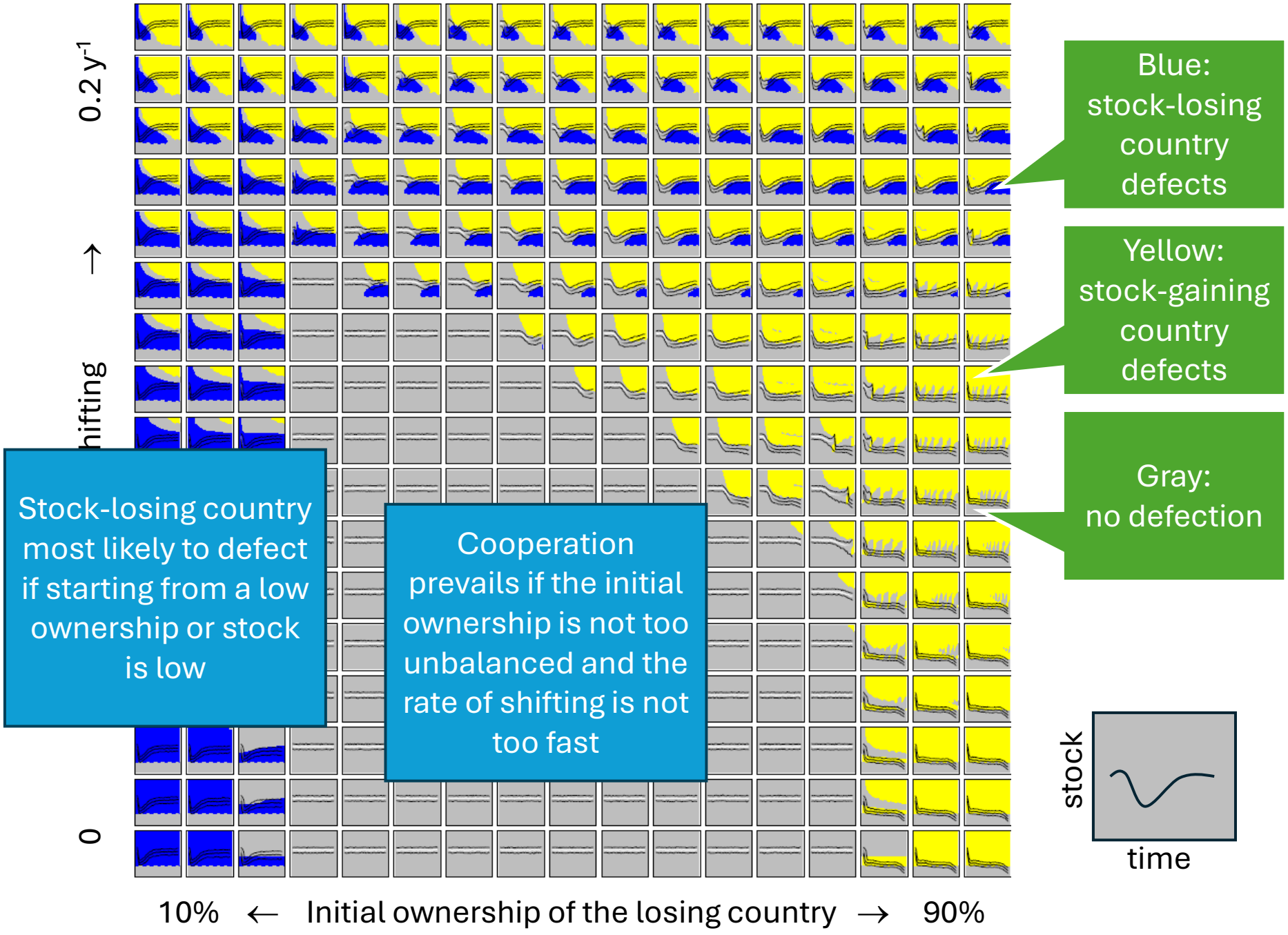
Gray: no defection
Cooperation prevails if the initial ownership is not too unbalanced and the rate of shifting is not too fast
stock
time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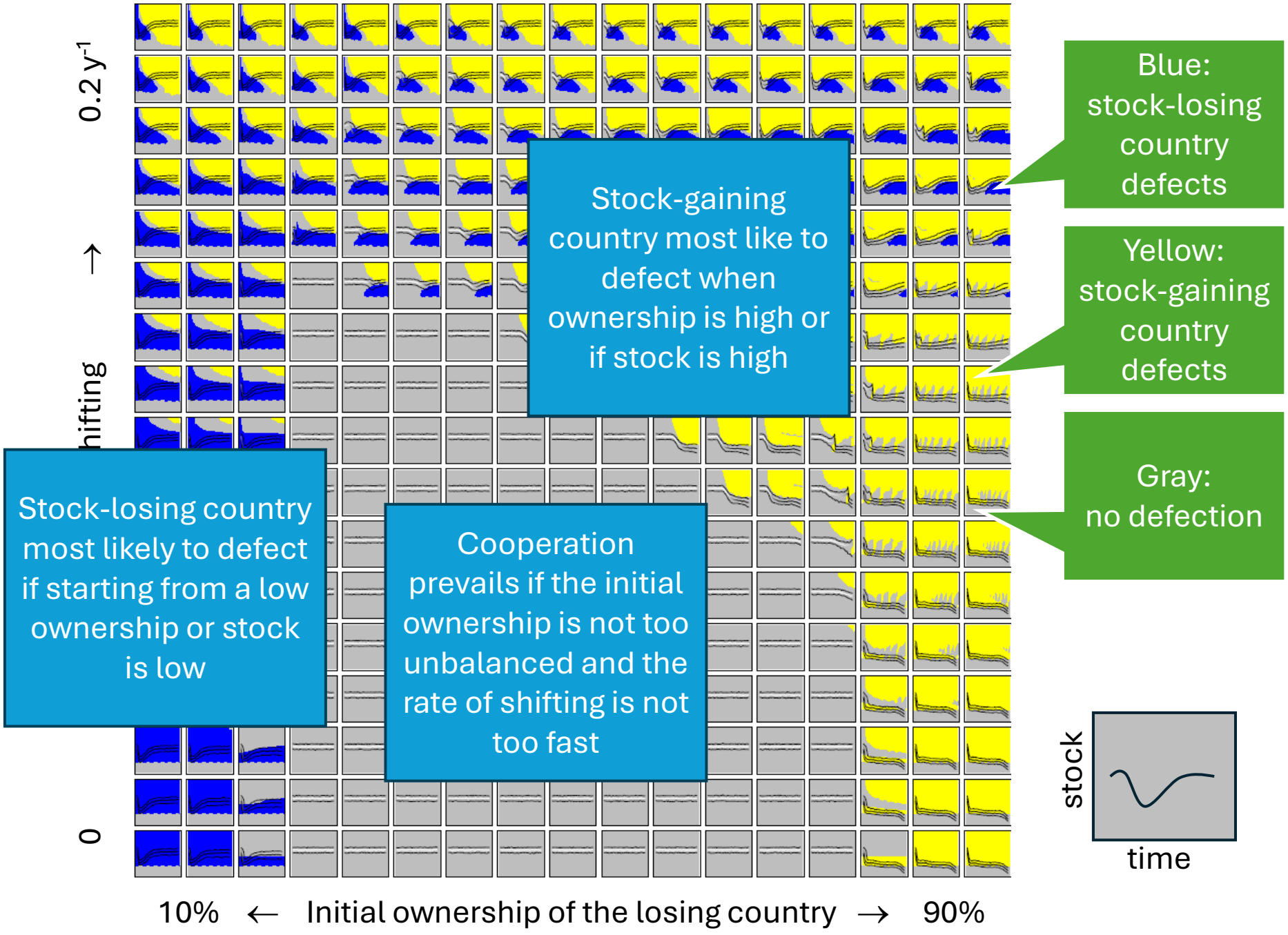
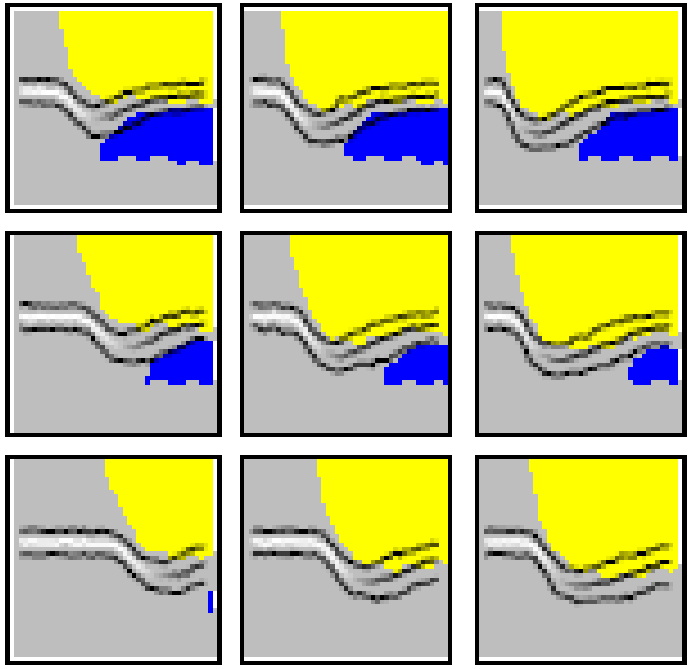
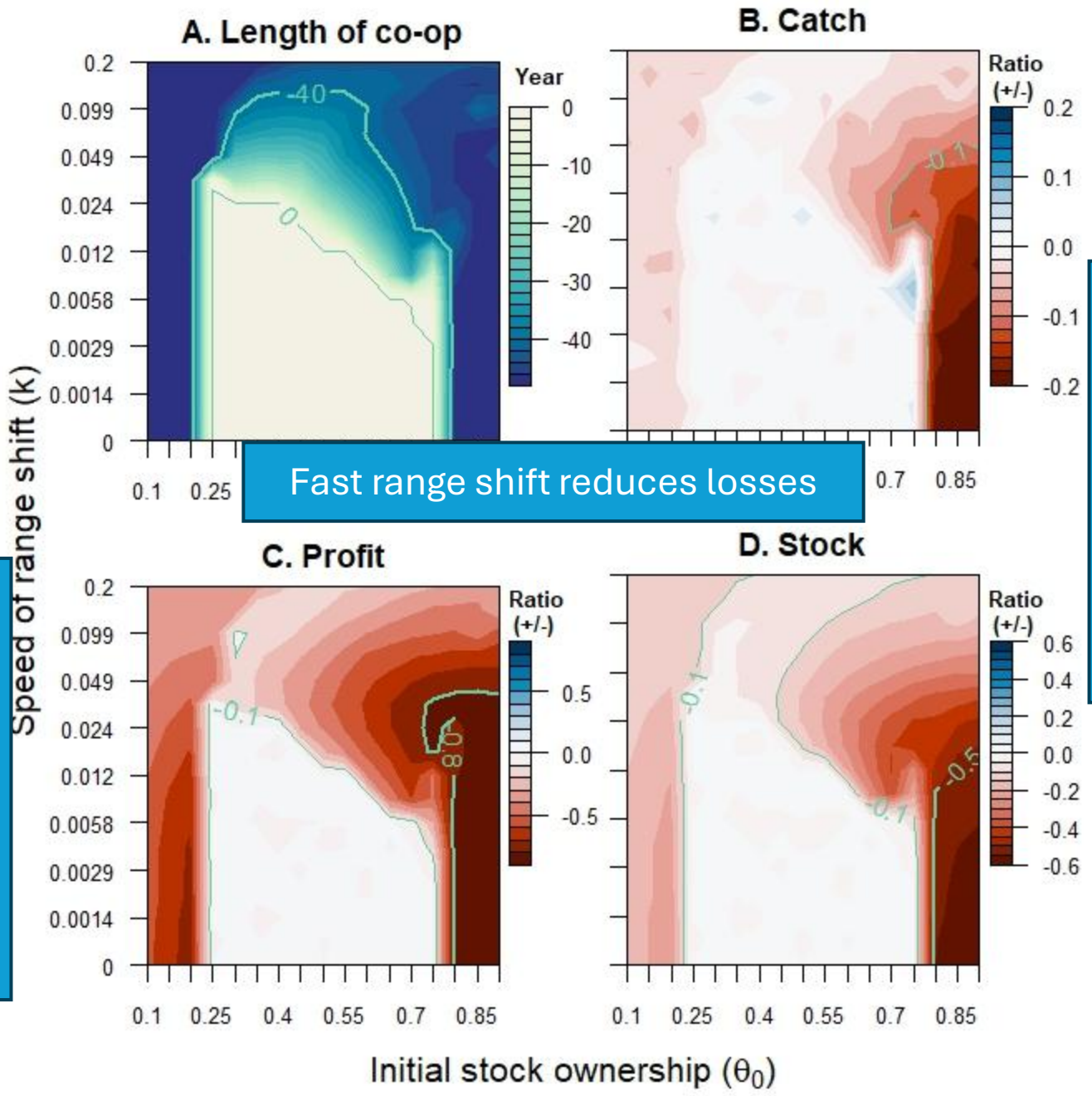
Blue: stock-losing country defects
Yellow: stock-gaining country defects
Gray: no defection
Stock-losing country most likely to defect if starting from a low ownership or stock is low
Cooperation prevails if the initial ownership is not too unbalanced and the rate of shifting is not too fast
stock
time
10% ← Initial ownership of the losing country → 90%


0.2 y-1
Rate of shifting
0
Blue: stock-losing country defects
Yellow: stock-gaining country defects
Gray: no defection
Stock-gaining country most like to defect when ownership is high or if stock is high
Stock-losing country most likely to defect if starting from a low ownership or stock is low
Cooperation prevails if the initial ownership is not too unbalanced and the rate of shifting is not too fast
stock
time
10% ← Initial ownership of the losing country → 90%

Strategic interactions

- Co-operative over-exploitation
  - Co-operation usually leads to “optimal” exploitation
  - But:
    - If the collapse of co-operation can be delayed by over-exploitation, **co-operative over-exploitation** can occur
    - In our model, this is frequent – and a warning sing of the approaching collapse





Fast range shift reduces losses

Large economic losses occur also when stock-losing country has low initial ownership

Largest biological losses occur when stock-losing country has high initial ownership

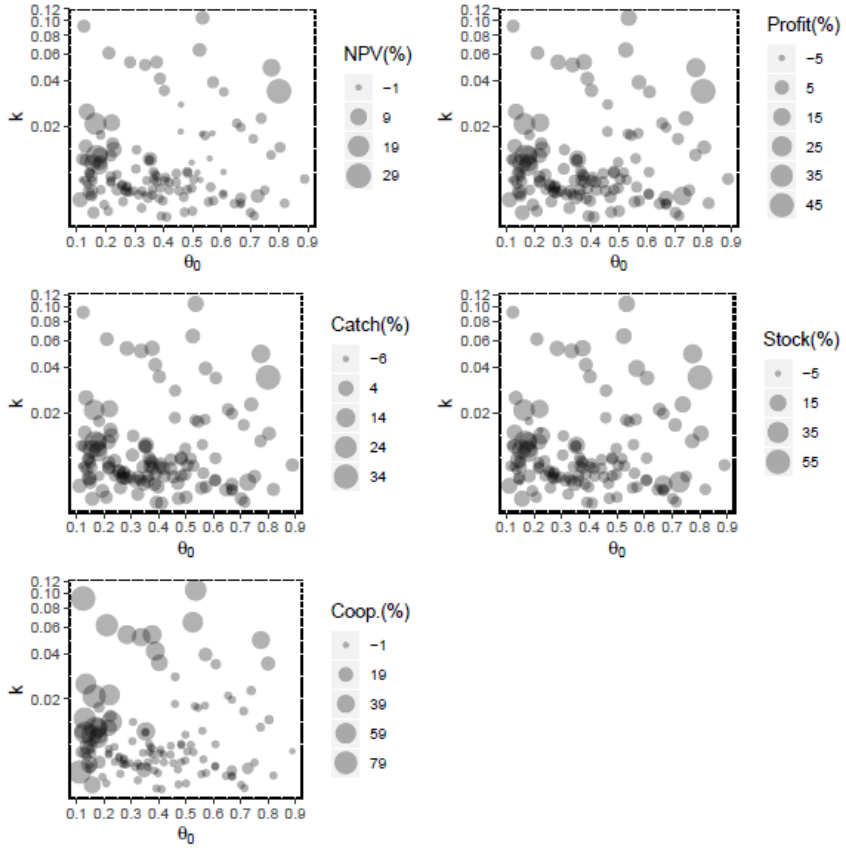


Fig. 3. Relative bio-economic losses measured in joint NPV (5% discount), profit (zero discount) and yield, mean stock, and length of cooperation for 126 shared stocks that are shifting under climate change projections. Y axis is in logarithm scale; the size of bubbles is proportional to the losses. Results are based on stochastic forward projections of 1000 replicates.

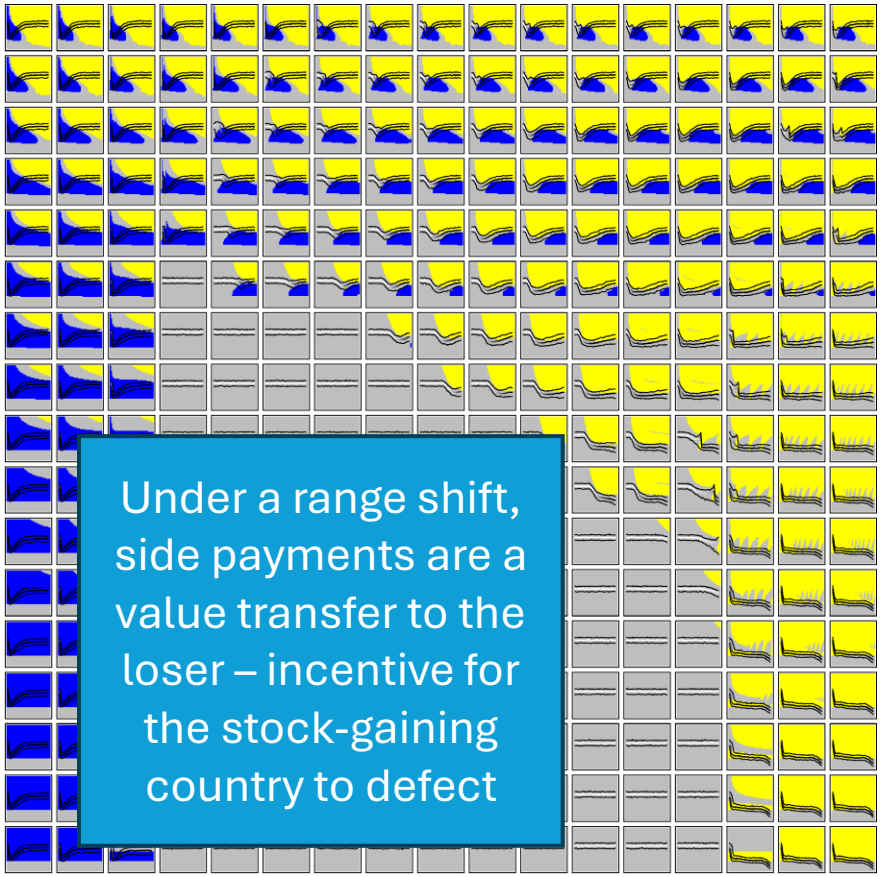
Expected range shifts of real fish stock mostly in the region without huge bioeconomic losses

[older model version]

- 126 shared stocks with estimates of current ownership, rate of shifting, and population growth rate from Gaines et al. 2018, «Improved fisheries management could offset many negative effects of climate change», *Science Advances*

Side payments dramatically affect the incentives

With



Without



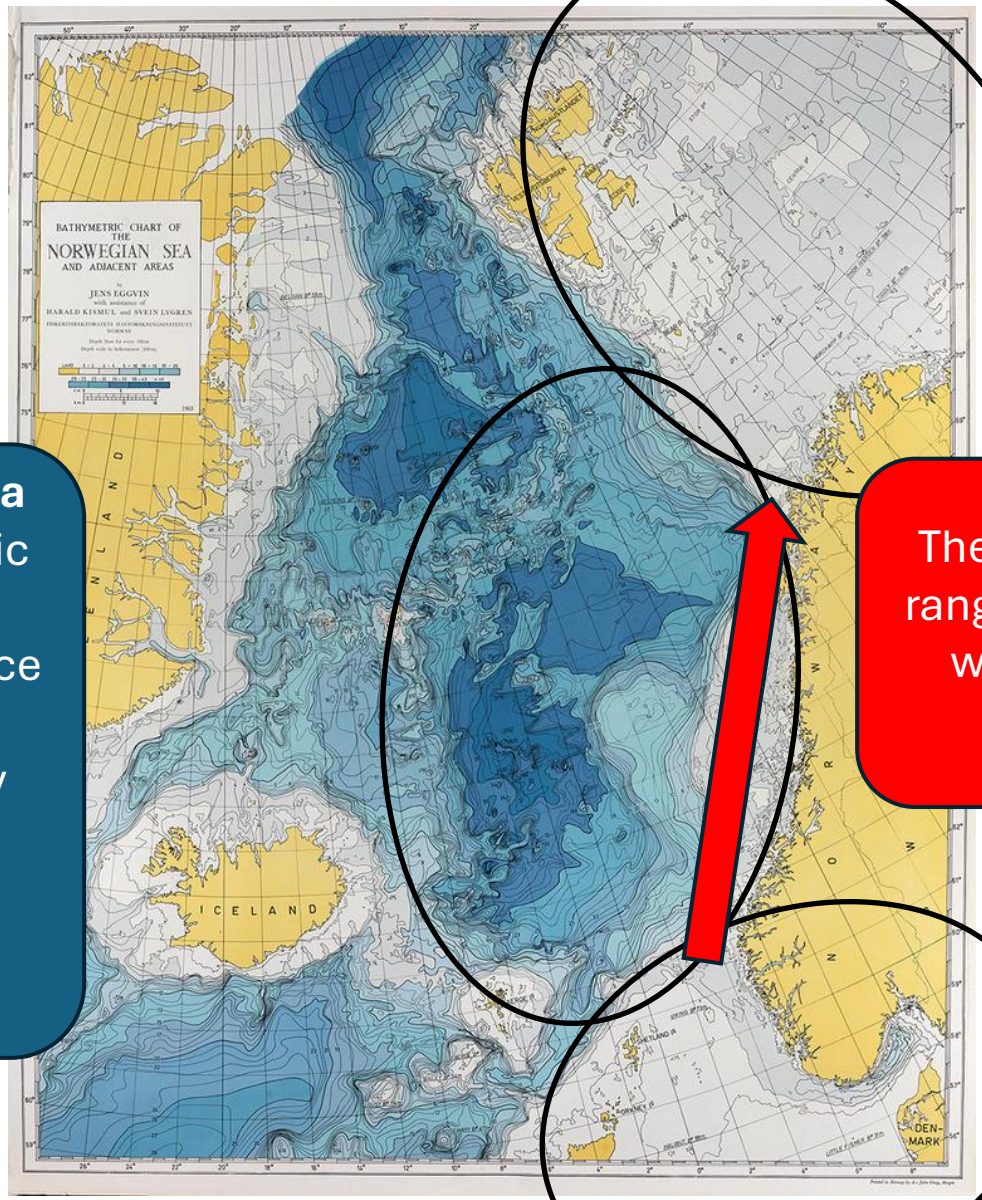
Conclusions

- Range shifts will destabilize sharing agreements that were “fair” pre-climate change – unless the shift is slow and initial ownership is relatively even
- Collapse of the sharing agreement leads to bioeconomic losses
- Over-exploitation during co-operative management is a signal of approaching the collapse of the sharing agreement
- Biggest losses when the stock-gaining country defects early and both countries maintain bargaining power
- Side payments can either increase or diminish stability

Detecting and documenting range shifts

- Survey data – the gold standard
  - Designed to sample large parts of communities
  - High taxonomic resolution
  - ✓Expensive – restricted coverage in space and within a year

- Fisheries-dependent data
  - More selective by design, changing all the time
  - Limited taxonomic resolution
  - ✓Often high frequency “sampling”, extensive spatial coverage



Jens Eggvin (1899–1989)

Barents Sea

- Very good survey coverage twice a year

Norwegian Sea

- Open, pelagic ocean: good coverage once a year
- Shelf: survey once a year with limited habitat coverage

The shelf is the corridor for range expansion of shallow-water species – yet it is poorly surveyed

North Sea

- Very good survey coverage twice a year

Using commercial catch data

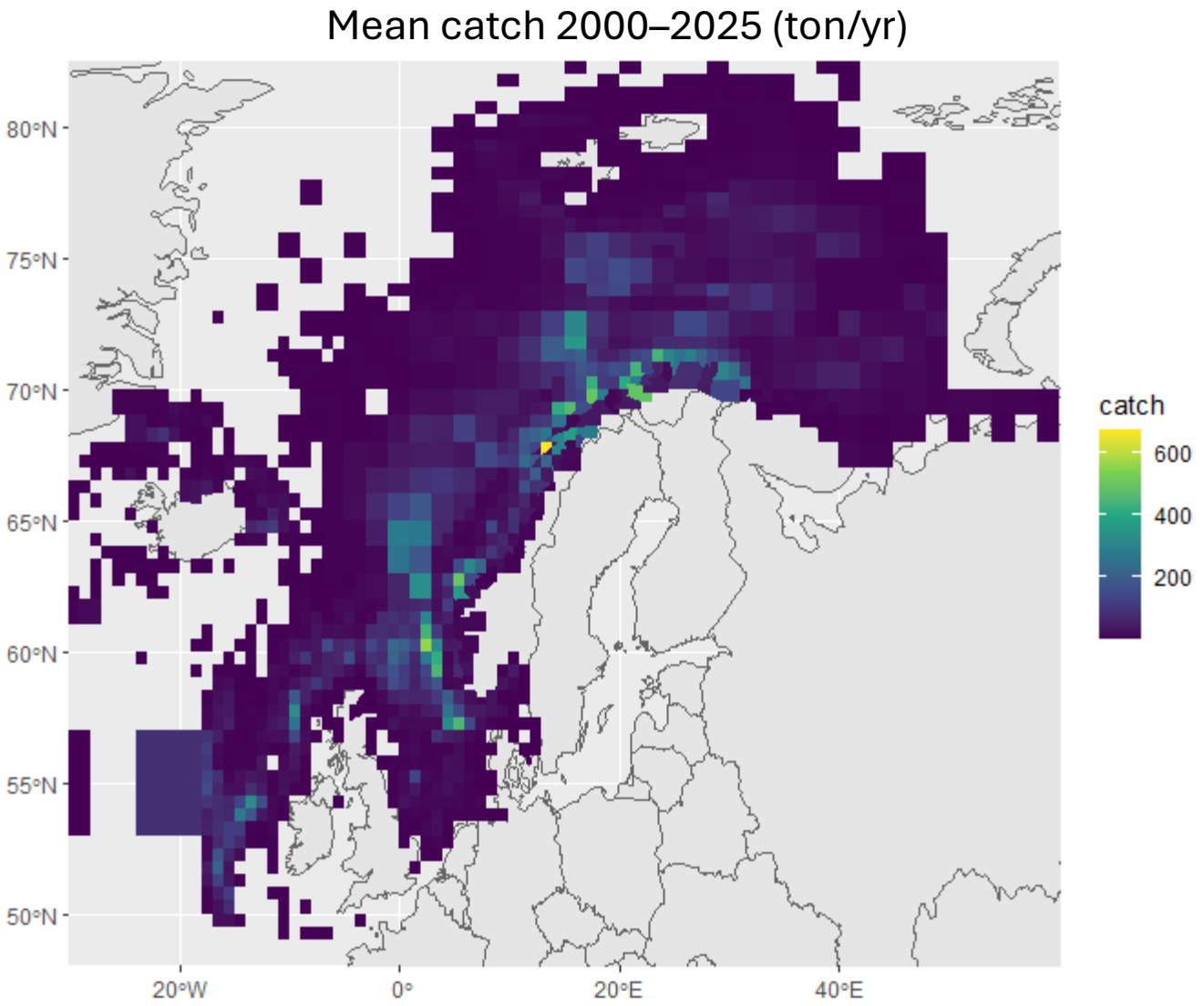
Norwegian sales slip data

- ➢ About 1 million single-species sales transactions, representing ~0.2 million fishing trips per year
- Landed value and quantity (weight) per species
- Location (mostly 0.5 ° lat ×1 ° lon, ~56 km×56 km at 60 °N)
- Gear; date of last catch (→ fishing effort = “trip”)
- Vessel characteristics

✓ Available electronically from 2000

Norwegian fisheries landings

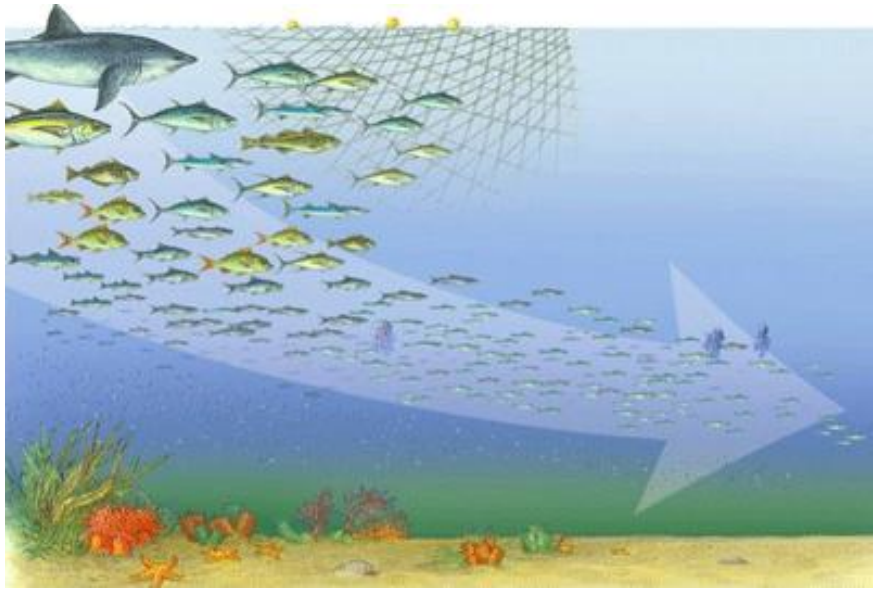
- Far-reaching footprint
- Intensive fisheries SW Barents Sea, S Norwegian Sea, near the shelf edge and the Norwegian Deep



Trophic level of Norwegian fish catches

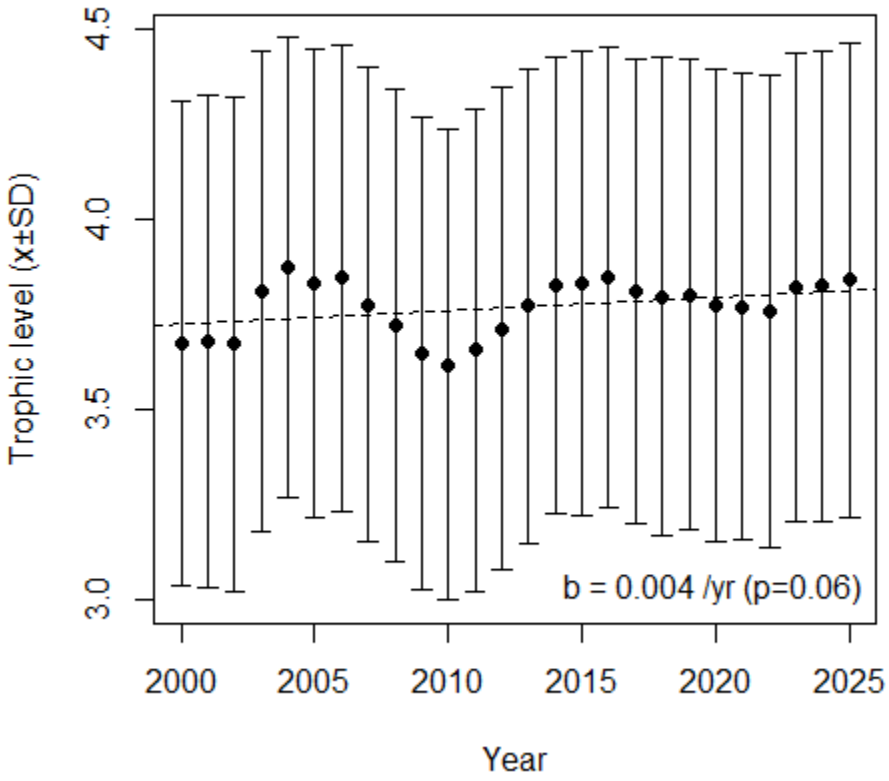
✓Trophic level for fishes available from FishBase

Fishing Down Marine Food Webs?



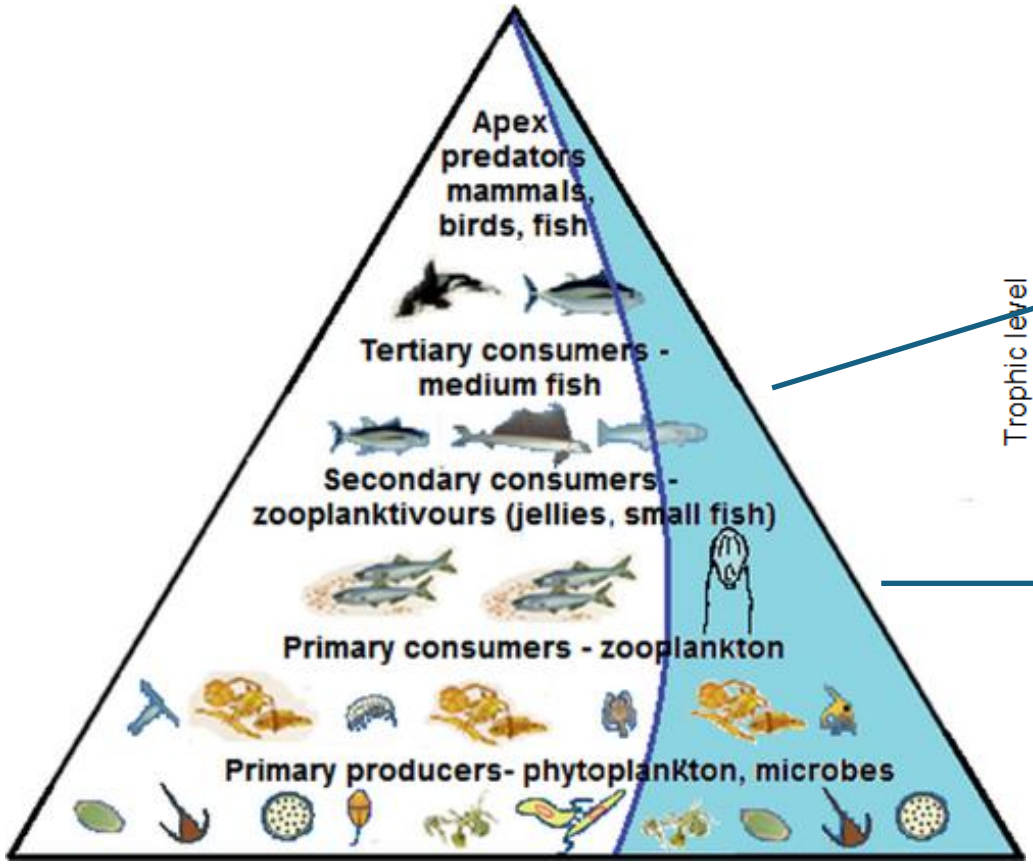
seaaroundus.org

Remarkably stable trophic level!

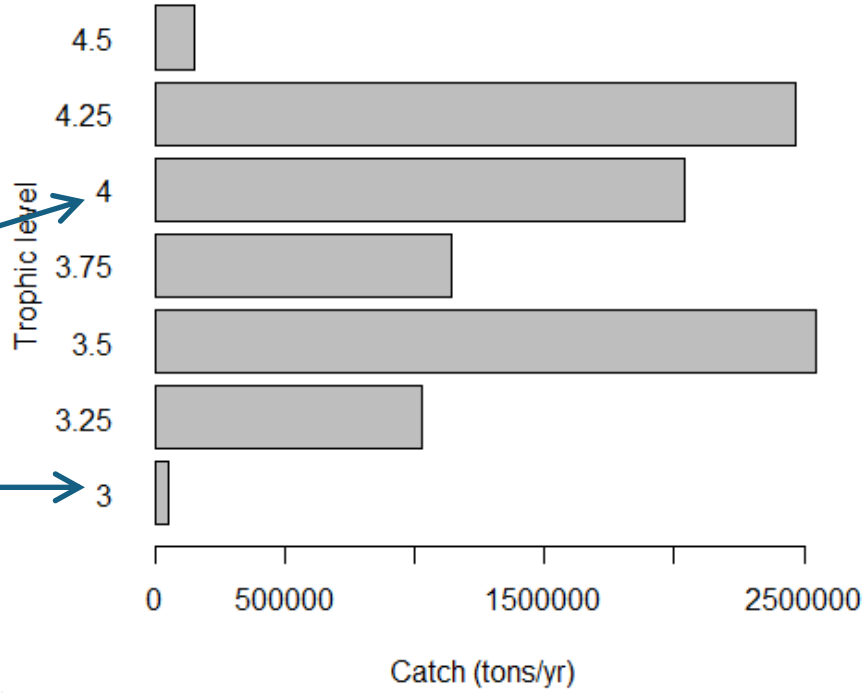


Trophic level of Norwegian fish catches

Balanced harvesting?

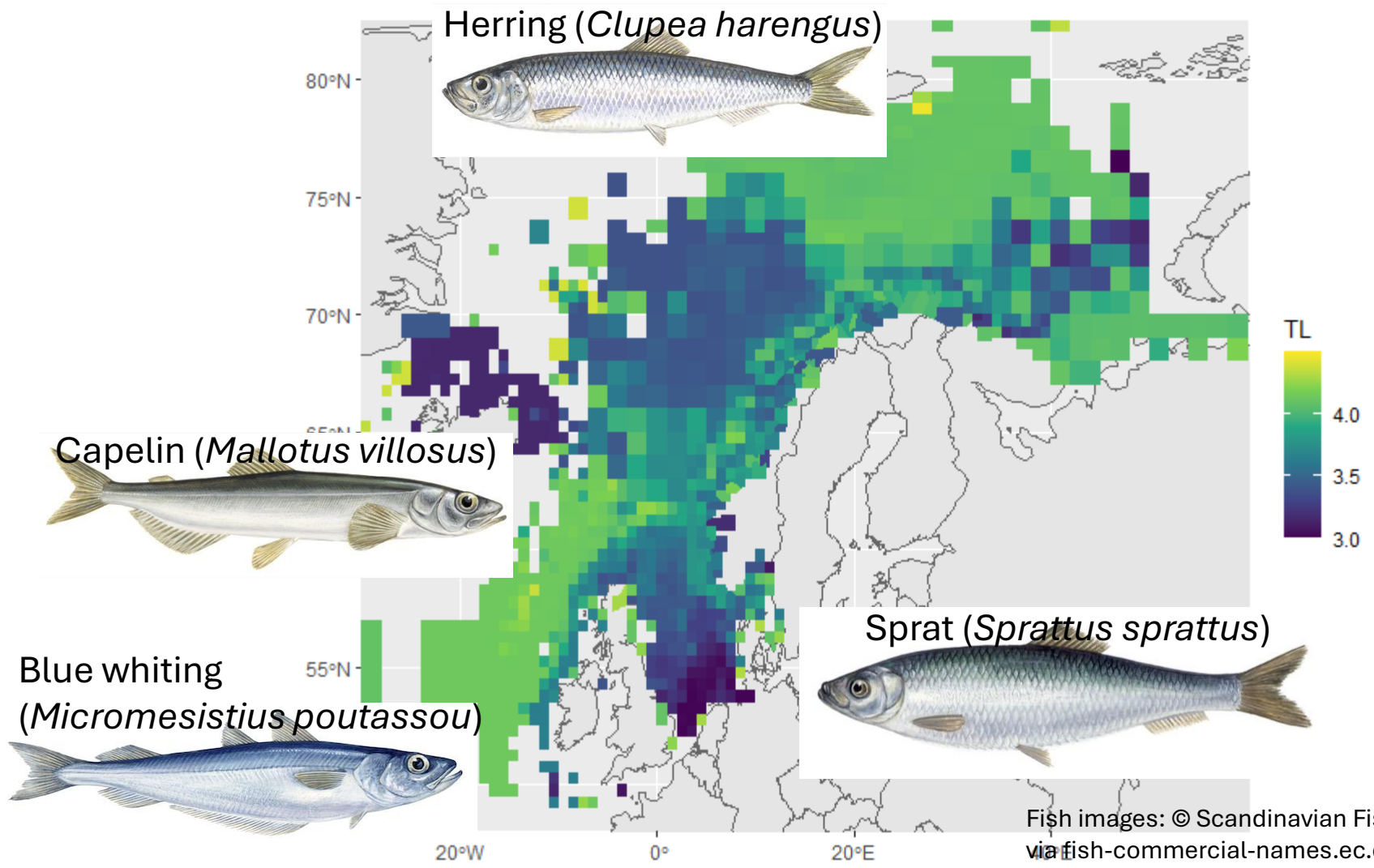


Fisheries catch is top-heavy! (non-fish catch excluded)



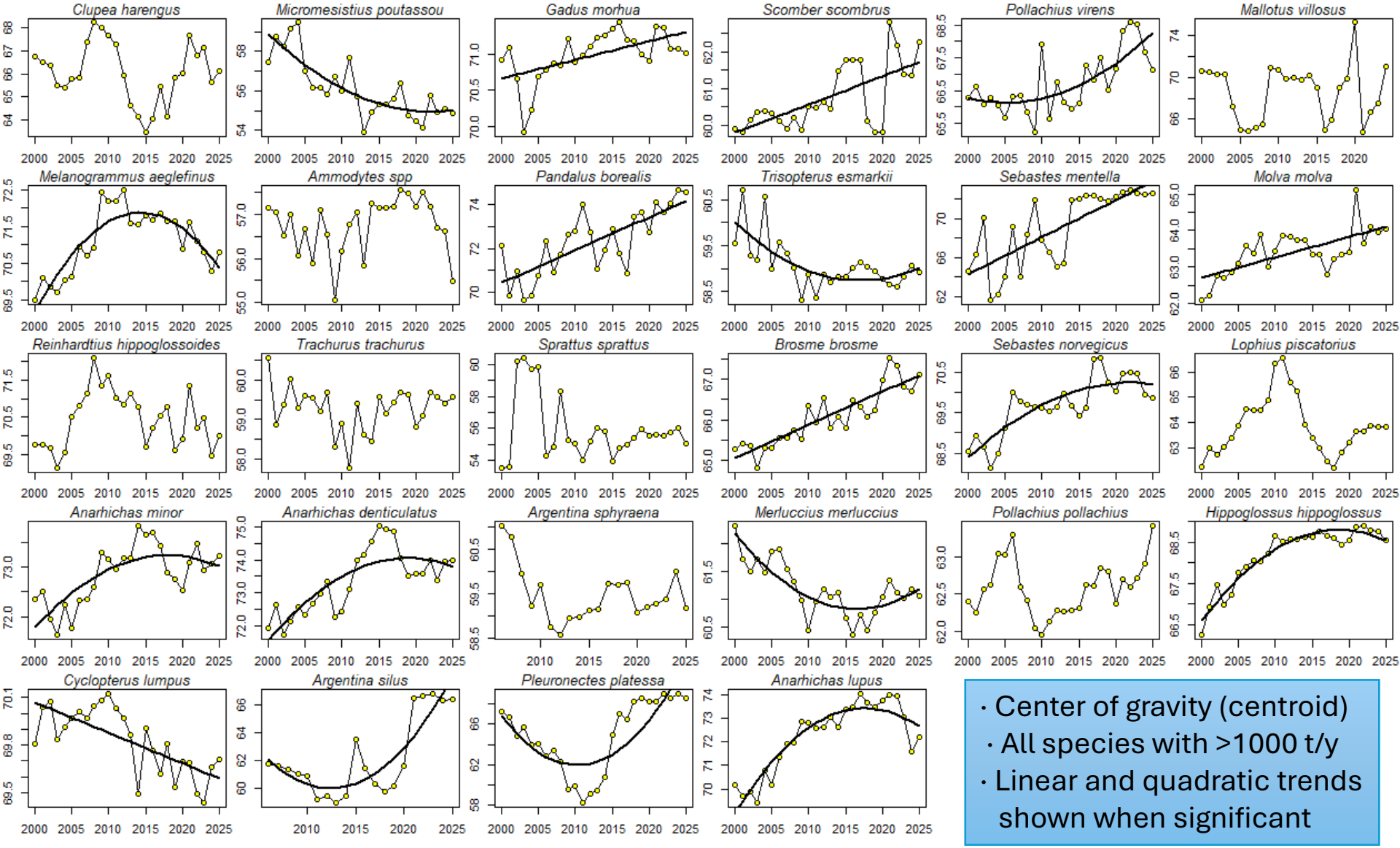
Gilman et al. (2014) *Fish and Fisheries 15*:327

Trophic level of Norwegian fish catches



Fish images: © Scandinavian Fishing Year Book via fish-commercial-names.ec.europa.eu

Latitudinal trends in the catches

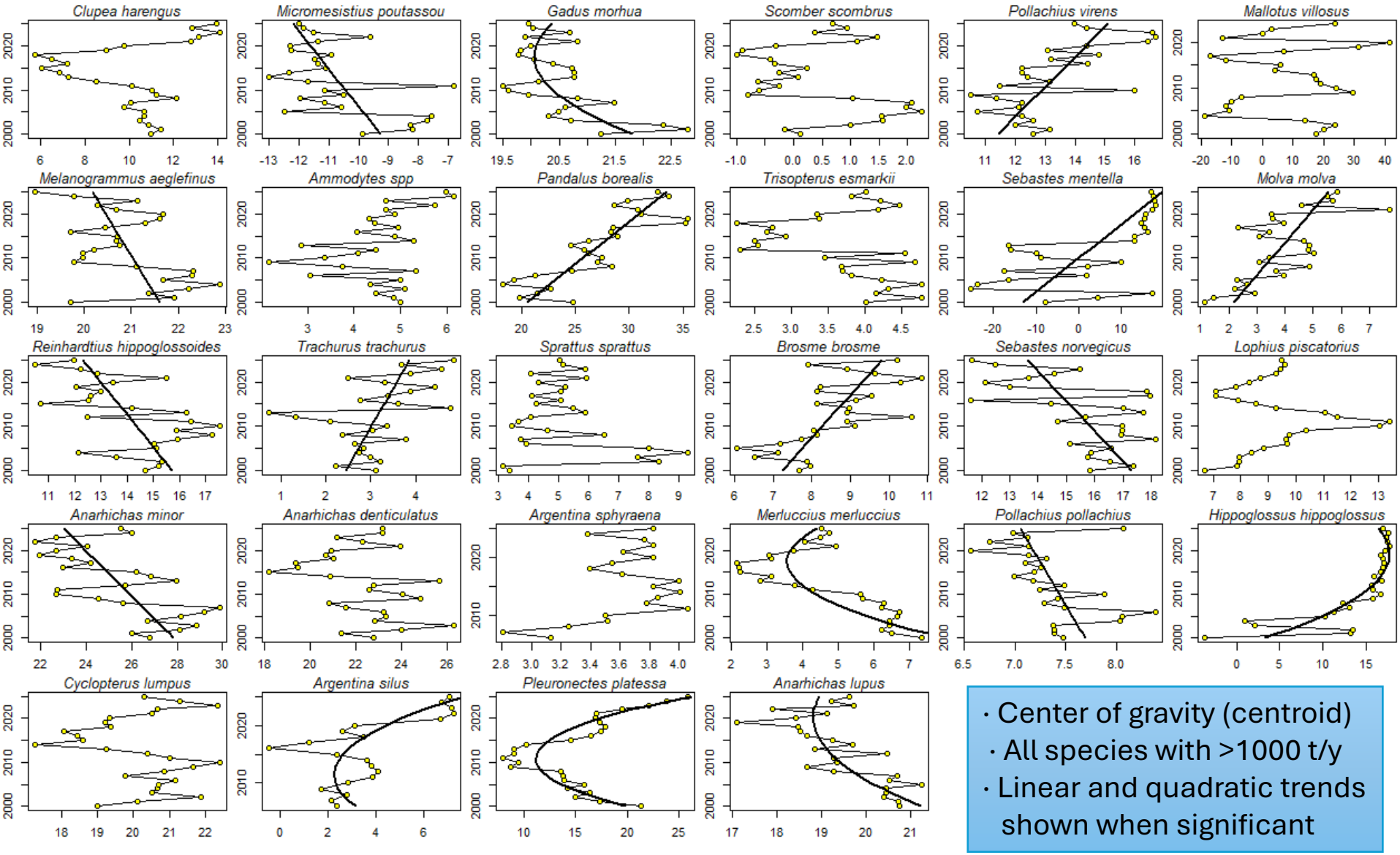


- Center of gravity (centroid)
- All species with >1000 t/y
- Linear and quadratic trends shown when significant

Latitudinal trends in the top-28

- 68% (19/28) of the species have a significant **linear** latitudinal catch trend
  - Among these,
    - 79% moved northward and 21% southward
    - Median and mean trend is 0.08 °/yr (1° in 13 years)
- 43% (12/28) of the species have a significant **quadratic** latitudinal catch trend (=reversal)
  - In half these, the initial northward trend reversed, but the overall northward trend always remained
  - In the other half, the initial southward trend reversed, but the overall southward trend remained (3/6), or the northward trend took over

Longitudinal trends in the catches



- Center of gravity (centroid)
- All species with >1000 t/y
- Linear and quadratic trends shown when significant

Longitudinal trends in the top-28

- 64% (18/28) of the species have a significant **linear** longitudinal catch trend
  - Among these,
    - Equal proportions of eastward and westward trends
    - Median trend is 0.015 °/yr (1° east in 65 years)
- 21% (6/28) of the species have a significant **quadratic** longitudinal catch trend (=reversal)
  - In one case, the initial eastward trend was reversed, but the overall eastward trend remained
  - In the remaining cases, the initial eastward trend was reversed, for an overall eastward or westward effect

Atlantic cod
(*Gadus morhua*)



Saithe
(*Pollachius virens*)



Mackerel
(*Scomber scombrus*)



Fish images: © Scandinavian Fishing Year Book
via fish-commercial-names.ec.europa.eu

Pollack (*Pollachius pollachius*)

- No trend in 2020 – 2025
- ✓Major trend 1914 – 2024



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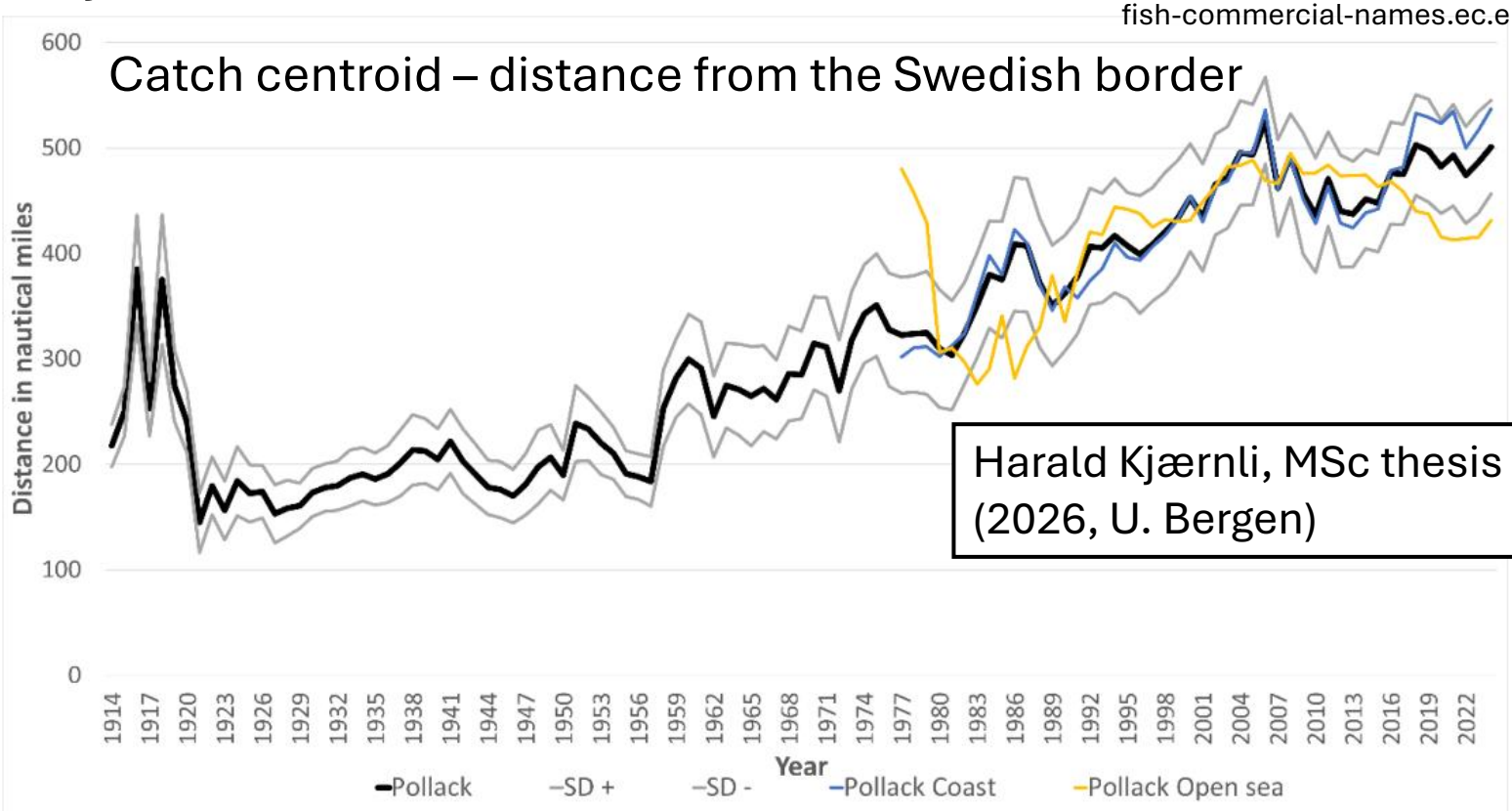


Harald Kjærnli, MSc thesis (2026, U. Bergen)

Emerging targeting tactics

- Clustering methods can be used to infer fisher behaviour

ICES Journal of Marine Science, 2022, **00**, 1–19
DOI: 10.1093/icesjms/fsac207
Original Article

ICES International Council for the Exploration of the Sea
CIEM Conseil International pour l'Exploration de la Mer

Gaussian mixture models reveal highly diverse targeting tactics in a coastal fishing fleet

Xiaozi Liu [1,*,†], Cecilie Hansen [1], Kjell Nedreaas [1], Hans Hagen Stockhausen [1] and Mikko Heino [2]

- Clustering of catch patterns using Gaussian mixture models
  - Restricted to cod-catching vessels in 2019
  - Interpreted as latent “targeting tactics”

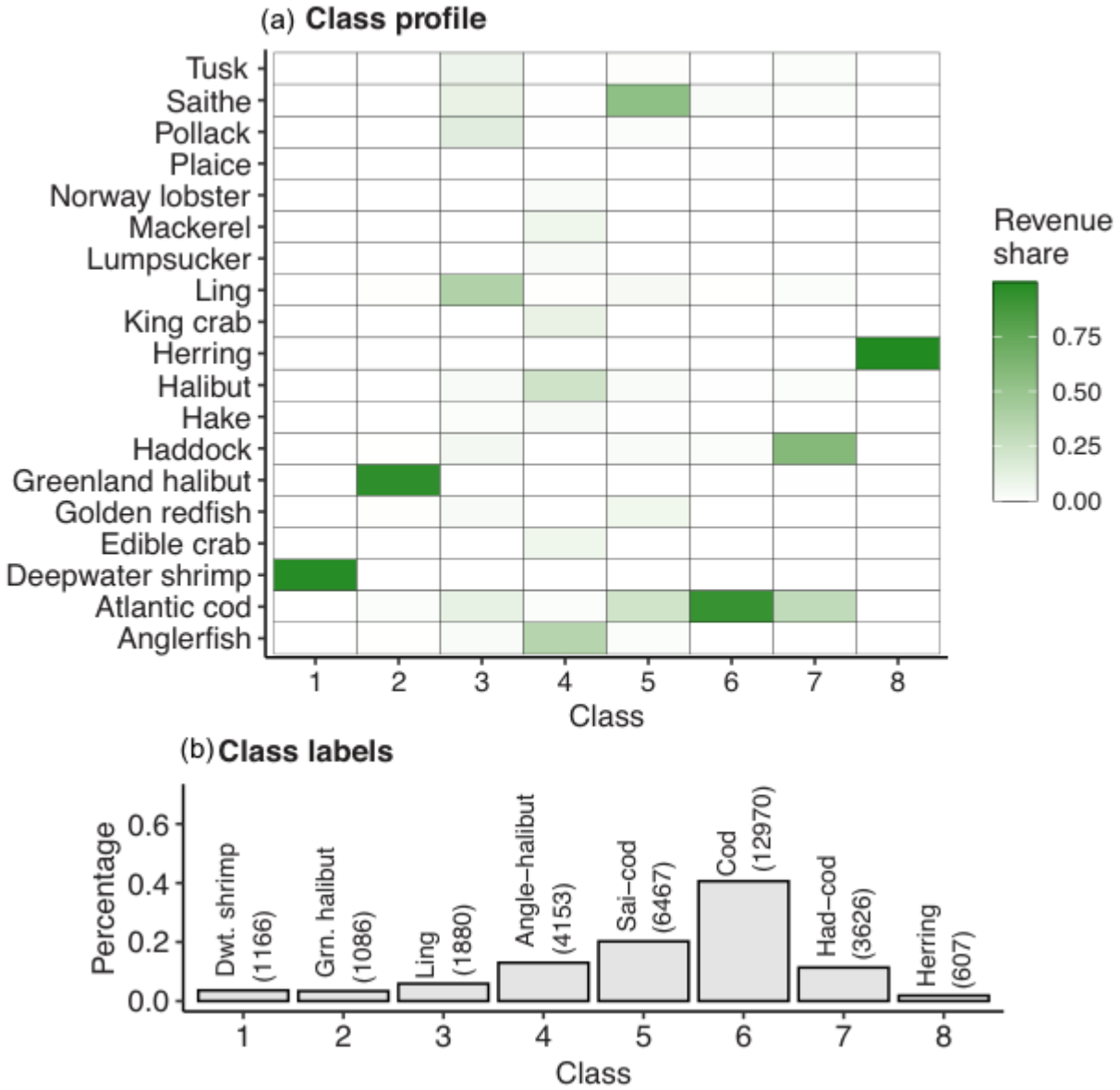
Atlantic cod
(*Gadus morhua*)



© Scandinavian Fishing Year Book via fish-commercial-names.ec.europa.eu

- Eight targeting tactics (métiers)

✓The most frequent ones involve cod as the main target, with or without one other gadid



Catch per unit effort?

- The only measure of effort is “trip” – means different amounts and types of fishing for different fleet segments and gears
  - Highly heterogeneous fleet in terms of size, gear, and available licenses

✓Standardization using mixed models

➢Can we use inferred métiers for CPUE standardization?

Concluding remarks

- Shared stocks are challenging to manage under all but the best conditions (two ~equal owners)
- Range shifts risk destabilizing existing sharing agreements
- We should better harness the power of fisheries-dependent data

The Research Council of Norway

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PICES