Self-Governance in the North Sea Brown Shrimp (*Crangon crangon*) Fishery: Potentials, Perceptions, and Challenges

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Summary

Effective fisheries management increasingly relies on science-based harvest strategies that prioritize long-term ecosystem and stock sustainability over short-term yields. For short-lived and data-limited species like the North Sea Brown Shrimp (*Crangon crangon*), the use of traditional stock assessments is hampered by high natural mortality, rapid population turnover, and incomplete or inconsistent data on fishing effort. At the core of the harvest strategies for such species are thus harvest control rules (HCRs)—predefined protocols that regulate fishing opportunities based on real-time or near-real-time indicators of stock status.

Despite being one of Europe's most valuable fisheries, the North Sea Brown Shrimp has lacked regular stock assessment and population-based management measures, relying instead on technical measures. However, advances in growth rate modelling and integrated international datasets have revealed evidence of growth overfishing, highlighting the need for formal management. In response, a collaborative management framework was established, culminating in Marine Stewardship Council (MSC) certification of the main fleets and the adoption of a self-regulatory management plan based on Landings per Unit Effort (LPUE) thresholds, effort restrictions and gear modifications to reduce growth overfishing and delimit the risk of potential recruitment overfishing.

This dissertation provides a comprehensive analysis of the recent dynamics in the Brown shrimp stock, the effectiveness of current management approaches, and the challenges faced in implementing effective and accepted management measures.

In **Chapter I**, monthly VMS and logbook data of the North Sea Brown shrimp fleets of Denmark, Netherlands and Germany from 2009 to 2018 were analysed for trends and regional patterns in five subareas. Effort increased by 12% while landings decreased by 9% from the first five to the second five years of the time series. All areas showed a significant decreasing trend of LPUE in the fishery of the first quarter of the year from 2009 to 2018. Fishing effort in Dutch and East Frisian waters during winter was negatively correlated with LPUE in the same and adjacent areas in March – April. Furthermore, highly significant negative correlations were found between fishing effort in January and February in Dutch waters and LPUE in July and August in areas further north, explaining up to 86% of the variance. Together our results support the hypothesis that early recruitment in the Northern areas partially depends on a new cohort coming from the south and that reduced recruitment in Northern areas may be a consequence of previous local depletion of egg-bearing females further south. Egg bearing shrimp appear to concentrate in southern areas in January and February and migrate to adjacent northern areas for larval release in March and April. The findings demonstrate that neither environmental drivers nor predation pressure alone can fully explain the recent decline in stock abundance. Instead,

fishing pressure—especially during critical winter months when the stock appears most vulnerable—emerges as a key factor influencing population trends. To prevent economic and ecological consequences for the shrimp stock and the fishery, transboundary management measures need to be considered and implemented. Further investigations of migration and drift patterns of brown shrimp are recommended.

In **Chapter II**, the effectiveness of the current HCR is quantified and alternative, more stringent HCR designs are tested under two plausible scenarios: a general reduction in stock abundance and a recruitment failure event, both representing common risks for short-lived stocks. A comprehensive shrimp population simulation model, parameterized with recent fisheries and biological data from the German Exclusive Economic Zone, replicates the seasonal patterns of growth, mortality, and fishery removals. The performance of HCR designs was evaluated in terms of their effects on shrimp biomass, egg production, landings, and total fishing effort. Results demonstrate that all HCR variants yield modest improvements in LPUE, biomass, and egg production relative to unmanaged scenarios, while annual landings remain largely unchanged. Importantly, the magnitude and speed of stock recovery depend considerably on the stringency of the effort reduction. The currently implemented approach, which employs stepwise weekly effort limits when LPUE reference points are breached, achieves only moderate effort reductions (averaging 12–19%), with limited capacity to rebuild biomass after major declines. In contrast, simulated approaches involving greater reductions in weekly fishing time or short complete fishery closures (up to 99% effort cut for two weeks) trigger much faster LPUE recovery and higher increases in spawning biomass and egg production, especially following recruitment failure scenarios. However, such drastic measures could pose operational difficulties and may be less acceptable to stakeholders due to increased variability in landings and disruption to fleet activities.

The current harvest control rule, based on empirical LPUE thresholds, provides a necessary foundation, but simulation results indicate that this mechanism may be insufficiently responsive under serious stock declines. More drastic, short-term reductions in effort, informed by timely and accurate abundance indices, are likely needed to prevent stock and fishery collapse, and could even result in increased future yields without compromising market supply.

In **Chapter III**, the self-management regime of the North Sea Brown Shrimp fishery was analyzed, drawing on Ostrom's design principles for robust self-governance of common-pool resources. The study employs a quantitative survey of shrimp fishers, complemented by qualitative insights, to examine user perceptions of the self-governance system. Fishermen's attitudes toward management efficacy, enforcement, participation, and adaptation to local conditions were assessed across three clusters of fishers.

Results indicate limited perceived need for management among fishers, with only a minority recognizing stock decline despite scientific evidence of increased fishing mortality and growth overfishing. While the fishery's biological and institutional characteristics—restricted user group, monopolistic market structure, and homogeneity in economic interests—are conducive to self-governance, significant challenges remain. Notably, trust is lacking in the fairness and effectiveness of monitoring and enforcement, particularly across national producer organizations (POs). Many fishers express skepticism about the impact of measures such as increased mesh size, viewing technical adjustments as easily circumvented. Effort reduction is more widely accepted, especially during periods of low stock, but regionalization of management is resoundingly rejected in favor of equal treatment for all fleet segments.

Fishermen report feeling insufficiently involved in the development and ongoing adaptation of management measures, leading to perceptions of remote, top-down decision-making—potentially undermining legitimacy and compliance. Nevertheless, there is strong interest, especially among less mobile, home-port-based fishers, for increased participatory roles in management design and rule-making.

The North Sea Brown Shrimp fishery illustrates both the potential and limitations of self-management frameworks. While user-led regulation can stabilize and add value to the fishery, persistent gaps exist between scientific advice, institutional frameworks, and user perceptions. Addressing these gaps will require enhanced communication of scientific findings, fostering trust among user groups and POs, broader stakeholder engagement, and greater transparency in enforcement.

Zusammenfassung

Erfolgreiches Fischereimanagement stützt sich zunehmend auf wissenschaftsbasierte Bewirtschaftungsstrategien, die langfristige Erträge sowie gesunde Ökosysteme und Bestände über kurzfristige Gewinne stellen. Für kurzlebige und daten-arme Arten wie die Nordseegarnele (*Crangon crangon*) werden konventionelle Bestandsbewertungen durch eine hohe natürliche Sterblichkeit, ein schnelles Populationswachstum und unvollständige oder inkonsistente Daten zum Fischereiaufwand erschwert. Im Zentrum der Bewirtschaftungsstrategien für solche Arten stehen daher Harvest Control Rules (HCRs) – vordefinierte Regelwerke, die Fangmöglichkeiten auf Basis von Echtzeit- oder nahezu Echtzeit-Indikatoren des Bestandsstatus festlegen. Obwohl die Nordseegarnele zu den umsatzstärksten Fischereien Europas zählt, gab es lange Zeit weder regelmäßige Bestandsbewertungen noch populationsbezogene Managementmaßnahmen, abgesehen von wenigen technischen Vorgaben. Fortschritte in der Bestimmung von Wachstumsraten sowie die Analyse internationaler Datensätze haben jedoch Hinweise auf Wachstumsüberfischung geliefert und somit auch die Notwendigkeit eines formalen Managements verstärkt betont. Nach mehreren Anläufen zur Einführung eines kooperativen Managements führte schließlich die Zertifizierung der wichtigsten Flotten nach den Kriterien des Marine Stewardship Council (MSC) zu der Einführung eines selbstverwalteten Bewirtschaftungsplans. Dieser kombiniert vom Einheitsfang (LPUE) abgeleitete Schwellenwerte mit Aufwandsbeschränkungen sowie mit Änderungen des Fanggeräts, um die festgestellte Wachstumsüberfischung zu verringern und das Risiko einer möglichen Rekrutierungsüberfischung zu begrenzen.

Die vorliegende Dissertation bietet eine umfassende Analyse der aktuellen Entwicklung des Bestands der Nordseegarnele, der Wirksamkeit aktueller Managementansätze sowie der Herausforderungen bei der Implementierung des Managementplans.

In **Kapitel I** wurden monatliche VMS- und Logbuchdaten der Nordseegarnelenflotten Dänemarks, der Niederlande und Deutschlands von 2009 bis 2018 hinsichtlich Trends und regionaler Muster in fünf Teilgebieten analysiert. Der Aufwand nahm von den ersten fünf auf die zweiten fünf Jahre der Zeitreihe um 12 % zu, während die Anlandungen um 9 % sanken. In allen Gebieten zeigte der LPUE im ersten Quartal deutlich negative Trends. Der Fischereiaufwand in niederländischen und ostfriesischen Gewässern im Winter stand in negativem Zusammenhang zum LPUE in denselben und angrenzenden Gebieten im März und April. Zudem wurden hochsignifikante negative Korrelationen zwischen dem Aufwand im Januar und Februar in niederländischen Gewässern und dem LPUE im Juli und August in weiter nördlich gelegenen Gebieten festgestellt, welche bis zu 86 % der Varianz erklären können. Die Ergebnisse stützen die Hypothese, dass Rekrutierungserfolge im Norden teilweise von neuen Kohorten aus dem Süden abhängen und somit eine geringere Rekrutierung teilweise durch vorangegangenen

Entnahme von eitragenden Weibchen weiter südlich erklärbar ist. Die eiertragenden Garnelen konzentrieren sich offenbar im Januar und Februar im Süden und wandern im März und April zum Schlupf der Larven auch in angrenzende Gebiete weiter nördlich. Die Ergebnisse zeigen, dass allein Umweltfaktoren und Fraßdruck den Bestandsrückgang nicht erklären können. Vielmehr erweist sich der Fischereiaufwand, insbesondere in den kritischen Wintermonaten, als Schlüsselfaktor für den Bestandstrend. Um wirtschaftliche und ökologische Folgen zu vermeiden, sind internationale Management-Maßnahmen, sowie weitere Untersuchungen zum Migrations- und Driftverhalten erforderlich.

In **Kapitel II** wird die Effektivität der derzeitigen HCR quantifiziert. Alternativ werden strengere HCR-Modelle unter zwei realistischen Szenarien getestet: allgemeiner Bestandsrückgang sowie ein Rekrutierungsausfall, beide typische Risikoszenarien für Bestände kurzlebiger Arten. Mit einem aktuellen Bestandsmodell werden saisonale Wachstums-, Mortalitäts- und Fischereimuster abgebildet. Die Bewertung der HCR-Varianten erfolgte anhand ihrer Effekte auf Biomasse, Eiablage, Anlandungen und Gesamtaufwand. Alle getesteten HCR-Varianten führten zu moderaten Verbesserungen bei LPUE, Biomasse und Eiablage im Vergleich zu nicht regulierten Szenarien; die jährlichen Anlandungen ändern sich kaum. Ausmaß und Geschwindigkeit der Bestandserholung hängen maßgeblich von der Stärke der Aufwandreduktion ab. Das aktuell implementierte Stufenmodell begrenzt den Aufwand im Mittel nur um 12–19 % und erlaubt nur begrenzte Bestandserholung nach starken Rückgängen. Im Gegensatz dazu führen deutlichere Beschränkungen der Fangzeit oder zeitlich befristete Fischereischließungen (z.B. 99 % Aufwandskürzung für zwei Wochen) zu schnellerer Erholung, insbesondere im Falle eines Rekrutierungsausfalls. Solche drastischen Ansätze bringen jedoch operative Herausforderungen mit sich und stoßen wegen erhöhter Ertragsvariabilität und Fischereiunterbrechungen auf geringe Akzeptanz. Die aktuelle empirische HCR auf Basis von LPUE-Schwellen bietet einen guten Ansatz, ist aber laut Simulationsergebnissen bei starkem Bestandsrückgang nicht reaktionsschnell genug. Deutlichere, kurzfristige Einschränkungen, gestützt auf aktuelle Bestandsindikatoren, werden wahrscheinlich benötigt, um im Risikofall einen Kollaps von Bestand und Fischerei zu verhindern und könnten sogar mittelfristig höhere Erträge ermöglichen.

In **Kapitel III** wurde das Selbstmanagement-Regime der Nordseegarnele auf Basis der von Ostrom vorgeschlagenen Prinzipien für erfolgreiche Selbstverwaltung von Gemeinschaftsgütern analysiert. Mit einer quantitativen Umfrage unter Fischern, ergänzt durch qualitative Einsichten wurde die Wahrnehmung zu Wirksamkeit, Kontrolle, Partizipation und Anpassung des Managementsystems in drei Gruppen von Fischern untersucht. Die Ergebnisse zeigen einen nur gering wahrgenommenen Managementbedarf bei Fischern; nur eine Minderheit erkennt einen Bestandsrückgang, trotz wissenschaftlicher Hinweise auf gestiegene fischereiliche Mortalität und Überfischung. Herausforderungen bestehen insbesondere durch das mangelnde Vertrauen in Fairness und Kontrolle, vor allem zwischen den nationalen Erzeugerorganisationen, trotz generell günstiger Rahmenbedingungen. Viele Fischer äußern Zweifel an der Wirksamkeit technischer Maßnahmen wie den größeren Maschenweiten, die als leicht umgehbar gesehen werden. Die Aufwandreduktion findet größere Akzeptanz, eine Regionalisierung des Managements wird jedoch abgelehnt, da gleiche Bedingungen für alle Flottenteile bevorzugt werden. Viele Fischer fühlen sich bei der Entwicklung und Anpassung von Managementmaßnahmen nicht ausreichend einbezogen – diese werden als distanzierte, von oben bestimmte Entscheidungsprozesse mit wenig Legitimität und Akzeptanz wahrgenommen. Dennoch besteht speziell bei weniger mobilen Fischern ein großes Interesse an stärkerer Mitbestimmung. Die Nordseegarnelenfischerei zeigt somit beispielhaft sowohl Potenziale als auch Grenzen selbstverwalteter Managementansätze. Selbstverwaltete Bewirtschaftung kann Stabilität und Ertrag der Fischerei erhöhen, doch besteht hier eine Kluft zwischen wissenschaftlichen Erkenntnissen, der Umsetzung im institutionellen Rahmen und der Wahrnehmungen der Fischer. Um diese zu überwinden, bedarf es einer breiteren Einbindung aller Fischer zur Förderung von Vertrauen und Transparenz sowie besserer Kommunikation wissenschaftlicher Erkenntnisse.

General Introduction

The management of global fisheries has been under increasing pressure since the 1990s due to stagnant catch volumes and many stocks lying outside safe biological limits (FAO, 2025). In particular, the debate over the concept of "fishing down the food web" has sparked controversy within the scientific community. While some researchers fear that fishing depletes the upper trophic levels (Pauly et al., 1998; Pauly and Palomares, 2005), others argue that this concept may be misleading (Branch et al., 2010; Caddy et al., 1998). However, a significant portion of global fish catches already consists of short-lived, fast-growing species typical of lower trophic levels. For instance, herrings, sardines, and anchovies accounted for 20% of all marine capture landings in 2022 (FAO, 2025). Invertebrate catches, such as cephalopods have also increased over recent decades (Anderson et al., 2011; Arkhipkin et al., 2021) and in heavily fished areas, like the Wadden sea, replaced many high-level target species (Lotze, 2007). Most of these species share common life-history traits: they often exhibit a short life span, mature early, and show highly variable, environmentally-driven recruitment (ICES, 2017; Sánchez-Maroño et al., 2021). The chaotic relationship between spawning stock and recruitment have made assessments, aiming at projecting future biomass, challenging (Punt et al., 2013). Missing information on fisheries impact on stock dynamics frequently led to the assumption that stock management is unnecessary or even not possible, resulting in many invertebrate stock unmanaged (Anderson et al., 2011).

One example of a target species where the need for a stock management has long been overlooked is the North Sea Brown Shrimp (*Crangon crangon*), a key species supporting one of Europe’s most valuable fisheries with landings of 25 000 tons, worth €69 million in 2021 (European Commission: Joint Research Centre et al., 2023; ICES, 2023).

Despite the high value of the fishery, for long time no target species specific management measures were implemented other than a minimum opening of the sieve of initially 6.5mm (Addison et al., 2017; Steenbergen et al., 2015). The carapace width of 6.5mm corresponds to individuals approximately equal or larger than 50 mm in total length (Sharawy, 2012). Additionally, the minimum mesh size is limited by EU regulations to 16mm and engine power is limited to 221kw inside a specific area (the plaice box) (Addison et al., 2017).

Similar as in other short-lived species, assessing the status of brown shrimp has been a challenge for decades. Biological characteristics such as the impossibility of age determination, the short life cycle and high predation mortality have complicated analytical assessments, despite major advances in knowledge of the life cycle of *C. crangon* in recent decades. Due to the lack of coherent effort data from international fisheries, estimates of abundance could not be derived from catch and effort based proxies such as LPUE. As a result, previous stock status studies have had to rely on a comparison of estimated predation and commercial landings. These studies often concluded that there was no need to manage the stock and that overfishing of *C. crangon* was not occurring, given that predation mortality far exceeded fishing mortality (Neudecker et al., 2011; Tiews, 1978; Welleman and Daan, 2001). However, some early studies already revealed a doubling of total mortality between the periods 1974–78 and 1984–88 (Temming et al., 1993), confirming the observation of decreasing shares of large shrimp in commercial catches related to increasing fishing effort (Boddeke, 1978). A main obstacle in the estimation of fishing and natural mortality has been for years the difficulty to produce reliable growth rates for shrimp. The reported growth rates from both, laboratory and field studies, showed large variations, resulting also in different hypotheses assigning the autumn peak in adult density to a parental cohort. A comparison of results from a simulation approach with field field observations on the seasonal occurrence of juvenile recruits in the German and Dutch Wadden Sea (Temming and Damm, 2002) together with laboratory experiments (Hufnagl M and Temming A, 2011a) resulted finally in reliable growth rates which were condensed into a temperature-, length- and gender-dependent growth rate model for *Crangon crangon* (Hufnagl M and Temming A, 2011b). Those growth rates made possible a separation of natural and fishing mortality and concluded, that growth overfishing of brown shrimp is occurring at the current levels of fishing and natural mortality (Temming and Hufnagl, 2015). This result shed also the light on the need for a stock management (ICES, 2014).

Reliable growth rates are also important to link recruitment to a parental cohort in invertebrate stocks. The lack of hard structures in invertebrate species such as crustaceans and cephalopods make it difficult to determine the age of the individuals. Without age, there is no link between spawning stock size and the size of recruitment at a certain time (Punt et al., 2013). Growth rates can be used to give a hint to the time of hatching of an incoming recruitment wave. While high growth rates would link the autumn peak to the same year's summer recruitment (Boddeke, 1978), lower growth rates would link the peak to the same year's spring recruitment (Kuipers and Dapper, 1984) or even the previous year's summer recruitment (Campos et al., 2009). (Temming et al., 2017; Temming and Damm, 2002) finally linked the incoming main recruitment wave in autumn to the spawning stock in winter. Those new insights into C. crangon's life cycle emphasize the critical role of winter egg production for late spring and late summer recruitment peaks (Temming et al., 2017; Temming and Damm, 2002). The anticipated intensification of the winter fishery off Sylt islands, driven by a shift of vessels from Dutch flatfish fisheries to shrimp fisheries since 1990, has already sparked debate over potential negative impacts, particularly in northern regions (Berghahn, 1991; Salz and de Wilde, 1990).

For a detailed analysis of the winter fishery and its spatial linkages along the North Sea coast, an integrated dataset on landings and effort from the Netherlands, Germany, and Denmark was necessary. Initial effort data, collected as fishing days, suffered from incompatible definitions and changes within national time series (ICES, 2005). Since 2007, a satellite-based vessel monitoring system (VMS) has provided fine spatial resolution of fishing activity. These VMS data, combined with effort and landings data from logbooks (Bastardie et al., 2010; Pedersen et al., 2009), allow estimating effort, landings, and landings per unit effort (LPUE) on a finer scale. It was not until the WGCRAN meeting in 2019 that an integrated dataset of VMS and logbook data for the main shrimp fishing fleets from Denmark, Germany, and the Netherlands became accessible (ICES, 2022), which was used in the current work to analyze the stock status of C. crangon.

The North Sea Brown Shrimp – a short-lived, highly variable target species

The North Sea Brown Shrimp, *Crangon crangon*, spans a wide geographic range from the Mediterranean to the Finnish fjords (Campos and van der Veer, 2008; Ehrenbaum, 1890). In the Wadden Sea, its densities are high enough to support a substantial commercial fishery. As a clear r-strategist species, *C. crangon* is characterized by high growth rates, a short lifespan, and a high recruitment potential (Tiews, 1970).

C. crangon produces eggs throughout the year, with the proportion of egg-bearing females peak in late winter and reaching its lowest levels in late autumn (Hünerlage et al., 2019). High densities of egg-bearing females are found at depths of 20-40m during winter months (Schulte et al., 2020). In contrast to other short-lived species which quickly release their eggs, female Brown shrimp carry their eggs until larval hatching, with the release of the larvae is likely connected to moulting (Temming et al., 2017). Especially in winter at low temperatures, egg development times could add up to more than 160 days (Saborowski and Hünerlage, 2022), which increases the vulnerability of the future recruitment to fishing (Schulte et al., 2020). Once hatched, the pelagic larvae drift with currents before settling as juveniles around 5mm in length (Hufnagl M and Temming A, 2011a). These juveniles likely migrate to shallower Wadden Sea areas as they grow (Boddeke, 1976; Temming and Damm, 2002), entering the fishery at lengths around 45mm (Hufnagl et al., 2010). In autumn, adult shrimps move to deeper waters again.

The primary fishing season begins in July and August with the first wave of recruits, mainly originating from winter eggs produced in November and December and hatching in February and March (Temming et al., 2017). A second recruitment wave follows in September and October, with a higher contribution from shrimp produced as eggs earlier in the summer. There is ongoing debate about the extent to which the first wave of recruitment is supported by larvae migrating from other areas, connecting *C. crangon* sub-populations along the coast (Daewel et al., 2011; Hufnagl et al., 2014).

Due to low winter temperatures and associated longer larval development phase, larvae hatching in March may travel with currents from the Dutch coast to the Northern German Bight. Conversely, higher summer temperatures accelerate larval development, suggesting that juveniles likely settle close to their hatching point, supporting local recruitment (Daewel et al., 2011). It remains unknown whether similar migration patterns support the high shrimp abundances off the Dutch coast from more southern areas, or if they rely solely on local recruitment (Hufnagl et al., 2014). Some shrimp from summer eggs may not enter the fishery in the same year but likely grow throughout winter, entering in the following spring. As adults grow larger and autumn temperatures fall, they return to deeper waters, up to 40m. The lowest landings per unit effort (LPUE), often used as a proxy for target species abundance, generally occur in February, with levels rising again in March (ICES, 2023).

The North Sea Brown shrimp fishery

The fishery on Brown shrimp in the North Sea follows the life cycle of the target species, showing a clear seasonal pattern. The fishery starts to target the new incoming cohort in July with increasing effort, with a peak in effort in September in Germany, Belgium and the Netherlands (ICES, 2023). The fishing continues in October and November, with decreasing effort as adult shrimp move further offshore and frequent strong winds substantially reduce the fishing activity during winter (ICES, 2023). Only some larger vessels continue fishing through December to February, until the effort is increasing again in March, targeting adult survivors of the spring and early summer cohorts (Hufnagl M and Temming A, 2011a). The winter fishery is traditionally most pronounced in Denmark and Germany, with the spring peak in effort less visible in the Dutch and Belgian fleets (ICES, 2023).

In the main fishing countries Denmark, Belgium, Germany and the Netherlands, Brown Shrimp are fished deploying beam trawls. The fishing gear is lighter than in the flatfish fishery, using bobbin ropes instead of tickler chains. Most vessels are owner-operated, with the skipper and one or two deckhands on board (Goti-Aralucea et al., 2021). At the time of the MSC certification, the fleets consisted of 28 Danish, 198 Dutch and 213 German vessels (Addison et al., 2017). Most of the German vessels were below 20m, while 60% of the Dutch fleet were above 20m and with more than 200kw engine power. Fishing trips are mainly between one and three days, often limited due to storage capabilities, although some vessels stay at sea longer, up to 9 days (Aviat et al., 2011; Respondek et al., 2014). The catch is first sieved on board to sort out undersized shrimp. Those shrimp are directly given over board, on the modern vessels the rotating sieve is flushed with sea water constantly to improve survival. However, while previous studies did state survival rates of up to 90% (Lancaster and Frid, 2002), more recent research revealed unexpected low long-term survival rates of below 30% in certain situations(Temming et al., 2022a). The remaining catch is boiled on board with sea water. Once landed, the shrimp are sieved again into at least two fractions: those shrimp falling through a sieve of at least

6.5mm (EU regulations) respective 6.8mm width (MSC requirements) are not marketable for human consumption and not allowed to be sold (Addison et al., 2017). The larger shrimp are often sieved further into fractions of different size, quality and value. The bulk of the catch is then going to Morocco for peeling (Goti-Aralucea et al., 2021). The market has been dominated by mainly three, now one large companies for the last decades (Aviat et al., 2011; Steenbergen et al., 2017), with very little alternatives for the fishers for marketing their catch.

The Brown shrimp population model

In an attempt to disentangle the different cohorts contributing to the main recruitment event in autumn, a first growth model was developed by (Temming and Damm, 2002). Soon the initial model grow in complexity to include mortality and improved growth estimates (Rückert, 2011; Temming et al., 2017), the latest version trying to close the life cycle (Temming et al., 2022b).

The modelling approach is based on a numerical simulation model. Individual *C. crangon* start every day as egg, then develop and grow, depending on the daily temperature. The mortality of the daily cohorts depends on size of the shrimp and season of the year, to reflect both, the fishing and the predation mortality. The seasonality of the fishing mortality is deviated from the seasonal fishing effort, assuming that effort translates into mortality directly. The seasonal landings pattern generated by the model can be compared to the real observation on landings from the shrimp fishery. The number of eggs, derived from an index, that start daily in the model can be adjusted, to match the observed landing values of the commercial fishery (Yield-per-Recruit). Once the model has been running for two years and all cohorts and size classes are present in the system, the egg index is replaced in the third year by the internally produced eggs, which then produce subsequent generations. Up to date, the model is fitted to the average situation of the stock fished in German waters from 2013 to 2020. Nevertheless, the outcomes can be used to compare options for the management of the stock, such as effort reductions (Temming et al., 2013) or mesh size increases (Günther et al., 2021).

The management history

Efforts to manage stock date back to the late 1990s when maximum landings per vessel were agreed upon by POs and wholesalers in response to overcapacity, despite scant stock status information (Aviat et al., 2011). However, these agreements were deemed price manipulation and thus illegal, resulting in fines (ACM, 2011). A second attempt in 2011 arose amid a fishery crisis from extremely low shrimp prices due to high catches. The discussion about a management plan to stabilize the market (ICES, 2011) ended without resolution. Eventually, Producer Organizations in the Netherlands, Germany, and Denmark initiated a Marine Stewardship Council (MSC) assessment process in 2007. An effective management requirement for MSC certification led to the development of a self-regulatory system using a harvest control rule (HCR) based on LPUE to manage shrimp populations (Temming et al., 2013). The certification of the majority of the Dutch, German and Danish fleets against the criteria of the MSC was finally successful in 2016, after officially adopting the management plan on 1st December 2015. The main regulations, starting from 1st of January 2016 on, are the stepwise increase of the mesh size from 16 to 26mm to reduce growth overfishing and the limit of the fishing effort whenever the landings per unit effort (LPUE), as a proxy for the abundance of the stock, falls below a pre-defined threshold (Addison et al., 2017). In absence of any national management authority, the fishery itself is responsible for the implementation of the management plan. The involved POs send representatives to the steering committee, which takes decisions by vote and is the main management authority. The administrative tasks, such as comparing the monthly LPUE values from the fishery with the threshold, are mainly delegated to the project group, which consists of a Dutch, Danish and German member.

Soon after the start of the management regime, it was tested for the first time. In April and May 2016, the LPUE of the fishery fell below the 1st Reference value. The fishery struggled to get the LPUE values calculated in time, so that the effort restriction to 72 hours at sea per week and vessel was implemented in the first two weeks of June. In the main season in 2016, the LPUE in the northern parts of the fishing area was again very low, but higher catches in the southern areas did help to lift the overall LPUE above the reference values. The question arose whether the HCR was able to protect low local abundances from additional fishing effort (ICES, 2022). After three years without effort restriction, the LPUE March 2021 fell below the second reference value. In Juli 2021 and March 2022, and again in June, August and the first two weeks of September 2023, the LPUE fell below the 1st reference value. In January 2024, the LPUE fell below the 2nd reference value, in February below the 4th reference value, restricting the fishery to 36 hours at sea per week and vessel. After restrictions to 72 hours at sea per week and vessel in October, November 2024, and January 2025, the LPUE fell again below the 4th reference value in February 2025.

Meanwhile, the fishery had already decided that in cases when the effort is limited to less than 48 hours at sea per week and vessel, the allowed maximum effort can be combined to 66 hours at sea per vessel and two weeks. The main measurement to reduce growth overfishing, the mesh size increase from initially 16 to 26mm has also already been modified. The amended management plan combines the mesh size increase with weekly closures for the fishery, to reduce overall effort. The mesh size for Dutch and German fleet members is fixed to 25mm minimum, for Danish members to either 24 or 25mm, depending on the effort reduction scheme. Each of the fleets has a specific effort reduction scheme, resulting approximately in a two-weeks closure in January and February and another one in mid-June to August (Addison et al., 2024).

As reaction to the fishing restrictions due to low stock levels, some fishers did already leave the MSC certified fleet and thus did also quit the self-management scheme, although the majority of the fleet still participates (as of May 2025). Actually, some parts of the fleet are requesting a new HCR approach, which takes into account also socio-economic considerations and thus reduces the economic consequences of the HCR for the remaining fishers (pers. Comment Philipp Oberdörffer).

Aim of the Study

This dissertation investigates three key aspects of the North Sea Brown shrimp fishery management – the current development of the target species, the evaluation of the harvest regulations and the setting with regard of the managed entity, the fishery.

First, the actual need for a stock management of Brown Shrimp is investigated. At the annual meeting of the working group on Crangon fisheries and life history (WGCRAN) in 2019, an integrated dataset on VMS derived effort and log book derived landings data of the main shrimp fishing fleets from Denmark, Germany and the Netherlands became accessible for the first time. Based on this dataset, 1) trends in effort (as proxy for fishing mortality) and of LPUE (as proxy for shrimp abundance) on a spatial scale with special focus on the winter fishery were investigated, and 2) the effects of varying winter effort in different areas on the resource availability in summer and autumn were tested.

Second, the HCR as a main element of the management plan was tested by simulating two scenarios of low abundance with the shrimp population model. The first scenario simulates an overall low shrimp abundance with the initial starting shrimp reduced by 30%. The second scenario simulates a recruitment failure of the first recruitment wave in late summer. Different HCR approaches are tested for their efficiency in bringing the LPUE back above the reference level.

Third, the circumstances of the self-management were analyzed. Based on previous works on requirements for successful self-management, the latest scientific findings but also the perception of the fishery with regard to the self-management were investigated.

The results give a comprehensive view on the strengths and weaknesses of one of the few self-designed management schemes in a valuable, well-developed European fishery.

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Chapter I. Connectivity of local sub-stocks of *Crangon crangon* in the North Sea and the risk of local recruitment overfishing

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Abstract

Monthly VMS and logbook data of the North Sea Brown shrimp (*Crangon crangon*) fleets of Denmark, Netherlands and Germany from 2009 to 2018 were analysed for trends and regional patterns in five subareas. Effort increased by 12% while landings decreased by 9% from the first five to the second five years of the time series. All areas showed a significant decreasing trend of LPUE in the fishery of the first quarter of the year from 2009 to 2018. Fishing effort in Dutch and East Frisian waters during winter was negatively correlated with LPUE in the same and adjacent areas in March – April. Furthermore, highly significant negative correlations were found between fishing effort in January and February in Dutch waters and LPUE in July and August in areas further north, explaining up to 86% of the variance. Together our results support the hypothesis that early recruitment in the Northern areas partially depends on a new cohort coming from the south and that reduced recruitment in Northern areas may be a consequence of previous local depletion of egg-bearing females further south. Egg bearing shrimp appear to concentrate in southern areas in January and February and migrate to adjacent northern areas for egg release in March and April. To prevent economic and ecological consequences for the shrimp stock and the fishery, transboundary management measures need to be considered and implemented. Further investigations of migration and drift patterns of brown shrimp are recommended.

Introduction

The Brown Shrimp, *C. crangon* supports one of the most valuable European fisheries in the North Sea. The fishing fleets of Germany, the Netherlands and Denmark are responsible for over 90% of the yearly landings of Brown Shrimp from the North Sea (ICES, 2019b). The most recent years, however, were characterized by very large variations in the annual landings, especially in the northern regions. Both 2016 and 2017 were very poor years for northern Germany and Denmark, and while 2018 brought record landings, 2019 was again a very poor year in these northern regions. Despite the large advances in the understanding of the life cycle, the assessment of the stock status of the brown shrimp (*C. crangon*) has been a challenge for decades. This is to a large part due to the lack of coherent effort data from the international fishery. In addition, biological traits such as the impossibility of age determination, the short life cycle and high predation mortality rates have impaired or complicated analytical assessments. Earlier studies concluded that overfishing of *C. crangon* is not occurring or even impossible given a predation mortality that exceeds by far the fishing mortality (Tiews, 1978; Redant, 1980; Wellemann and Daan, 2001). This view was supported by increasing landings over long time periods along with apparently constant or even decreasing effort (Neudecker et al., 2011).

Difficulties to integrate fishing data from different countries

It was previously not possible to integrate the data of the three main fishing nations, the Netherlands, Germany and Denmark because the different measures of fishing effort. Even in the simplest form of fishing days data were incompatible and even changed within the national time series (e.g. ICES, 2005). In some cases fishing days were counted as full days regardless of the number of hours at sea, in other cases days were derived from the number of hours at sea divided by 24 and in other cases one day was subtracted to account for travel time. During decades, fishing effort of the German fleet was only recorded as the number of fishing trips, regardless of the duration of a trip. For some fleets the effort was also available in hp-days or hp-hours, but also here the definitions of the time component varied.

Fishing effort and efficiency have likely increased

In those fleets where hp-day were available, the data indicated increasing fishing effort over time, e.g. in the Dutch fleet the number of hp-days in the 200–300 hp. class approximately doubled between 1979 and 1989. Salz and de Wilde (1990) predicted that many large beam trawlers of the flatfish fisheries would switch to shrimp fishery due to lack of fish quotas. Their prediction became reality as there were 159 vessels in the hp-class 260–300 in 2019 compared to only 75 in 1988. Most of these vessels (140) are so called Euro cutters of >22 m length. In the German fleet the total engine power has increased by a factor of 1.57 between 1964 and 1989 despite a reduction in the number of vessels from 422 to 266 over the same period. In addition a Danish fleet started from scratch as late as in 1970, with landings increasing from 69 t to 2908 t between 1970 and 1999. Fishing effort in hp-days has increased between 1987 and 1999 by approx. 36% (mean of first half period compared to mean of second half) and remained on a high level since. Taken together these considerations already suggest a likely increase of the effective fishing effort of the total fleet. However, fishing days or even hp-fishing days are only a poor approximation of the fishing mortality, as many other factors influence the catchability of Brown shrimp. Increasing mortality, however, could theoretically be detected in changing size distributions of the target species. Boddeke (1978) related decreasing shares of large shrimp in the Dutch commercial catches with increasing fishing effort. Temming et al. (1993) analysed the time series of size distributions from commercial bycatch and detected a doubling of total mortality between the periods 1974–78 and 1984–88, confirming Boddeke's observation. However, a relation between size distributions and increased fishing effort could only be hypothesized. Temming and Hufnagl (2015) extended the time series of total mortality using size compositions from survey data and combined these with estimates of total predation of shrimp in relation to commercial landings. This made possible a separation of natural mortality and fishing mortality which revealed a doubling of fishing mortality over the period 1971 to 2010, and suggested growth overfishing of brown shrimp at the current levels of fishing and natural mortality.

Effect of the winter fishery on recruitment

The demonstration of growth overfishing leads to the question if also fishing effort which targets adult, egg-bearing shrimp in winter and spring has a negative impact on recruiting shrimp in the subsequent summer and autumn. The work of Temming and Hufnagl (2015) showed that much of the increase in landings was likely a consequence of the decreasing predation on brown shrimp and hence not necessarily an indication of improved recruitment. Brown shrimp females carry their fertilized eggs attached to the body until the larvae hatch. Boddeke and Becker (1979) highlighted that this coupling of the fate of the eggs and the adults presents a risk of recruitment overfishing especially in winter, when due to very long development times of the eggs the risk is largest. The most visible winter fishery takes place off Sylt islands, where groups of large vessels fish in a relatively restricted area. The prediction of the intensification of this fishery due to the shift of even more large vessels from the Dutch flatfish fishery into the shrimp fishery since 1990 has provoked discussions about potential negative effects of the fishery in the Sylt area during winter, at least for the northern regions (Berghahn, 1991). However, since overall landings increased from an average of about 20,000 t before 1990 to about 30,000 t in the subsequent decade, this discussion faded subsequently. With the findings of Temming and Hufnagl (2015) of a steady increase in fishing mortality and the recent strong fluctuations in landings in the northern regions, the issue is worth a second look. Added relevance to this research question comes from new results on the life cycle, which highlight the importance of the winter egg production for the late spring peak in recruits on the tidal flats (Temming and Damm, 2002) and the first peak in late summer of adult shrimp (Temming et al., 2017). Since 2007 a satellite-based vessel monitoring system (VMS) became mandatory also in the shrimp fishery, providing a fine spatial resolution of the fishing activity. These VMS data can be combined with effort and landings data from logbooks (e.g. Pedersen et al., 2009; Bastardie et al., 2010; Lee et al., 2010; Gerritsen and Lordan, 2011) allowing also the estimation of landings per unit effort (LPUE) on a finer spatial scale. Schulte et al. (2020) used these VMS data of the German fleet in combination with logbook data and data on size categories of landed shrimp from landing declarations to map the locations of high concentrations of large adult shrimp in winter. The analysis revealed relatively distinct distribution patterns of these mostly egg bearing females visible as two diagonal bands in NW directions: a southern one near Helgoland and a northern one starting off Sylt. Such stable structures pose risk of marked local depletion, if fishers are able to aggregate on these structures. However, since most of the winter fishery is carried out by Dutch and Danish vessels, a unique opportunity for an analysis of the North Sea wide situation arose at the annual meeting of the working group on Crangon fisheries and life history (WGCRAN) in 2019, when an integrated dataset on VMS derived effort and log book derived landings data of the main shrimp fishing fleets from Denmark, Germany and the Netherlands which are responsible for more than 90% of the annual landings in the North Sea became accessible for the first time. Based on this dataset we 1) investigate trends in effort (as proxy for fishing mortality) and of LPUE (as proxy for shrimp abundance) on a spatial scale with special focus on the winter fishery and 2) test for effects of varying winter effort in different areas on the resource availability in summer and autumn.

Material and methods

Aggregation of VMS/logbook data

VSM based effort and landings data of fishing fleets by m´etier and per month are requested yearly by ICES from the national authorities of the member states (ICES 2019a) in a spatial resolution of 0.05 ◦c-squares (Rees, 2003). In this study we use a subset of data of the Dutch, German and Danish fleets and is restricted to vessels with registered landings of *C. crangon* for the years 2009–2018. According to the proposed workflow of the ICES data call, the VMS data were filtered by VMS pings recognized as “fishing” and the landings of a fishing trip were evenly distributed between the VMS pings using VMStools routines (Hintzen et al., 2012) and then aggregated per month and per c-square. For this study, the ICES data were further aggregated to ten larger fishing areas (Fig. I-1). Five regions which follow the coastline are further split into an area close to the coast which contains the islands (inshore) and an offshore component, with the separating line roughly following the coastline. LPUE was calculated as landings in kg per hours fishing for each area. For an initial descriptive analysis landings and effort of the two separate time periods 2009–2013 and 2014–2018 are compared for the first and the second half of the year separately. With each of the time periods and half years having only five data points, no further statistical analysis was made. For this comparison, all 10 subareas are considered explicitly. Since in all but one off-shore area (G-N) less than 5% of the effort respective landings were located, the in- and offshore areas were combined for the subsequent correlation analysis. In addition, no significant effect on results of the following correlation analysis could be observed with data separated into in- and offshore areas. Thus, for each of fishing effort and landings, the data of each inshore area was combined with that for the associated offshore area before the subsequent analyses to reduce the number of area combinations substantially.

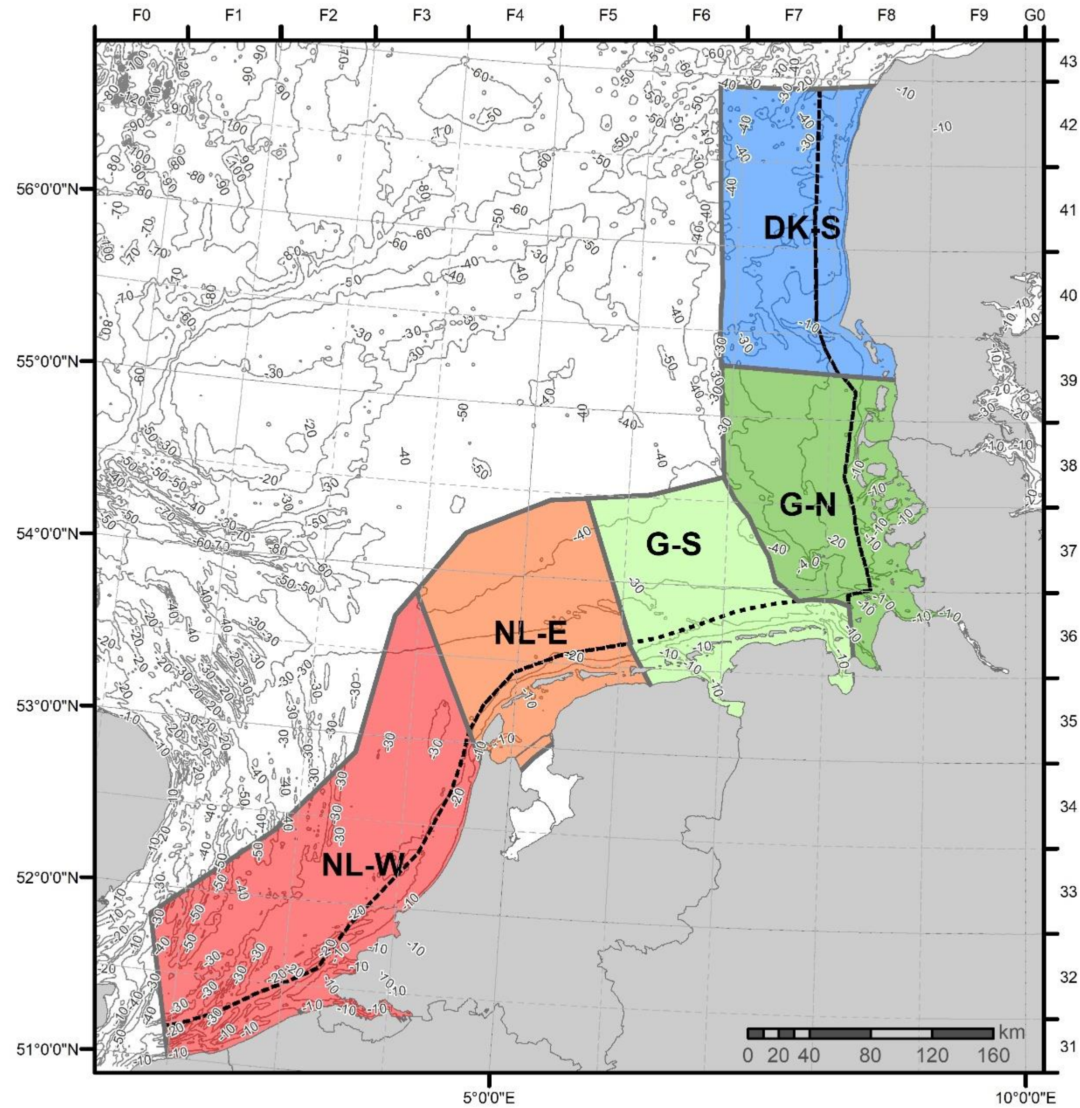

Fig. I-1. Fishing areas used for data aggregation. NL-W Netherlands West; NL-E: Netherlands East; G-S: Germany South, G-N: Germany North; DK-S: Denmark South. Each area is separated in an offshore and inshore component as marked by the dashed line. X- and Y-axes show latitude and longitude. The combination of 31-42 on the right and F1 – F8 on the upper side stands for the ICES statistical rectangles 31F1 – 42F8. Thin black lines show the bathymetry in 10 meter steps.

For the seasonal analyses the data of two adjacent month was aggregated: January and February, March and April etc. resulting in 6 effort and LPUE values per year and area. To test for possible effects of fishing effort on shrimp abundance, we correlated bimonthly averaged effort and bimonthly averaged LPUE as in all area combinations. Based on our understanding of the life cycle (Temming et al., 2017), significant negative correlations of effort with the LPUE in adjacent months within the first half year are consistent with a depletion of the same cohort. Significant negative correlations of fishing effort in the first half year with the LPUE in months after July would be expected if the effects of fishing effort on spawning stock are reflected in subsequent recruitment. Linear regression equations using fishing effort as the explanatory variable and the LPUE as the response variable were fitted to the data for selected data sets with highly significant correlations. If the size of the spawning stock in winter is expected to influence the subsequent recruitment in late summer and autumn, then winter LPUE – referring mostly to large egg bearing females – should reveal a positive correlation with LPUE in autumn – being dominated by small fast growing recruits of the new cohort. For this investigation also all area combinations were tested. Correlations were described with the Pearson correlation coefficient. For significant correlations we also performed a linear regression analysis. All statistical analysis and the processing of the logbook and VMS data were conducted with the statistical language R, version 3.6.1 (2019-07-05).

Additional long-term effort and landings data

To put the winter fishery of VMS/logbook data starting in 2009 into perspective with earlier periods, we extracted additional data from different sources and plotted the resulting extended time series of annual landings and fishing effort in the first quarter of the year. Yearly landings and effort data for the fleets fishing for *C. crangon* in the North Sea were used (ICES, 2019b). For the German fleet, effort data start in 2000, while for the Dutch fleet the years 1995–2003 are available. For the Danish fleet, a full dataset is available since 1987. No spatial information is given for the German and Danish data. The Dutch data from 1995 to 2003 from the VIRIS logbook system was available in an aggregated anonymized format from a previous EU-project. In those records, spatial reference for catch and effort is given per ICES rectangle. For the comparison of historical and recent effort in the winter fishery, it was assumed that the German and the Danish fleet fish in waters off the Northern German and the Danish coast in the first quarter of the year. For the Dutch fleet, effort and landings from the ICES rectangles 37F-40F were assigned to the Northern areas, effort and landings from the ICES rectangles 29F-36F were assigned to the Southern areas. Effort from VIRIS logbooks was calculated in hours at sea as the difference between leaving and returning to port. Effort from the German and Danish fleet are available in days at sea and were back-calculated to hours at sea by multiplication with 24. For the long term LPUE trend in the Danish fishery, also a homogeneous data set in kg landings per hp-hour-at-sea was used (ICES, 2019b). The number of new vessels per year was deducted from the building year of the vessels listed in the fleet inventory of the fishery.

Results

General effort and landings pattern

The mean annual effort between 2009 and 2013 was 612,155 h fishing in all areas combined. This value increased by 12% in the following time period from 2014 to 2018. The corresponding landings decreased by 9% from 33,074 to 29,952 t. The differences between both time periods were more pronounced in the first half of the year: the mean landings decreased by 34% (Table I-1), while the effort increased by 10% (Table I-2), simultaneously. In the second half of the year the landings increased slightly by 2% with a corresponding effort increase of 14%. With the exception of G-N, offshore subareas account for less than 3% of the annual landings or effort (Table I-1, I-2, Fig. I-2). However, G-N offshore is an important fishing area in the first half of the year accounting for 24% of the total effort. From the first to the second time period, landings and effort (Jan-Jun) in G-N offshore decreased by 53% and 17%, respectively (Table I-1, I-2, Fig. I-2). If in- and offshore areas are combined, the ranking according to effort increase from the first to the second period for the whole year is NL-W (28%), G-N (21%), G-S (16%), NL-E (11%), and DK-S (6%). The greatest increase in effort for separate seasons was observed in NL-E (70% in July-Dec.), DK-S (60% in Jan.-Jun.) and G-N (40% in Jan.- Jun.), while the strongest decrease occurred in DK-S (30% Jul.-Dec., inshore) (Table I-1, I-2, Fig. I-2). The ranking in landings is identical to the ranking in effort, if in- and offshore areas are combined. However, the pattern changes in the inshore areas between the two periods: some subareas show considerable declines (DK-S: - 50% Jul.-Dec., G-S: - 50% Jan.-Jun., NL-W: - 30% Jan.-Jun.), while other areas exhibit increases (NL-W: + 90% Jul.-Dec., DK-S: +20% Jan.-Jun. and NL-E: +10% Jul.-Dec.) (Table I-1, I-2, Fig. I-2). In the first period, German regions (G-N and G-S) are most important with 55% of all effort and 57% of all landings compared to 37% of all effort and 36% of all landings in the Dutch regions NL-E and NL-W. However, in the second period, there is a clear shift towards the Dutch coast. The effort in G-N and G-S remains nearly stable (5% increase), while the effort off the Dutch coast (NL-E and NL-W) increased by 24%. At the same time the landings from the German regions decreased by 25%, now contributing 47% to the overall landings. The landings from the Dutch coast increased by 20% and contribute 47% to all landings in the second period. A general pattern of half-year effort between both periods is an increase in inshore regions and a decrease in offshore regions. This effort increase is greater in the northern regions in the first half-year and greater in the southern regions in the second half-year. The increase in effort does not lead to similar increasing landings. Landings in most regions in the first half-year except DK-S declines. However, a 20% increase in landings in the first half year in inshore DK-S is accompanied by a 60% increase in effort. In the second half year, the gap between effort and landings is not that strong, but still the landings do not keep up with effort or decrease more than the effort. The only exemption is NL-W inshore, where a 70% increase in effort in the second half year leads to a 90% increase in landings.^

Table I-1. Mean annual landings per half-year (t) by subarea for two 5 year periods

Period		2009-2013				2014-2018				Factor of change	
	in/off	Jan-Jun		Jul-Dec		Jan-Jun		Jul-Dec		(2014-18/2009-13)	
Region	shore	tons	%	tons	%	tons	%	tons	%	Jan-Jun	Jul-Dec
DK-S	in	628	5.6	1149	5.3	785	10.3	618	2.8	1.2	0.5
G-N	in	2267	20.2	5295	24.2	1744	22.9	4558	20.4	0.8	0.9
G-S	in	1964	17.5	4043	18.5	1030	13.5	3840	17.2	0.5	0.9
NL-E	in	2171	19.3	6203	28.4	1882	24.7	7103	31.8	0.9	1.1
NL-W	in	616	5.5	2390	10.9	443	5.8	4438	19.9	0.7	1.9
DK-S	off	356	3.2	211	1.0	224	2.9	57	0.3	0.6	0.3
G-N	off	3005	26.8	2282	10.4	1420	18.6	1574	7.0	0.5	0.7
G-S	off	58	0.5	51	0.2	14	0.2	12	0.1	0.2	0.2
NL-E	off	94	0.8	169	0.8	52	0.7	112	0.5	0.6	0.7
NL-W	off	65	0.6	56	0.3	23	0.3	23	0.1	0.4	0.4
Total		11226	100	21848	100	7617	100	22336	100	0.7	1.0

Table I-2. Mean effort per half-year (fishing hours) by subarea for two 5 year periods

Period		2009-2013				2014-2018				Factor of change	
	in/off	Jan-Jun		Jul-Dec		Jan-Jun		Jul-Dec		(2014-18/2009-13)	
Region	shore	hours	%	hours	%	hours	%	hours	%	Jan-Jun	Jul-Dec
DK-S	in	14873	5.1	19631	6.1	23448	7.3	14538	4.0	1.6	0.7
G-N	in	51469	17.8	69623	21.6	69700	21.8	79750	21.7	1.4	1.1
G-S	in	46755	16.1	55632	17.3	47413	14.9	63823	17.4	1.0	1.1
NL-E	in	63915	22.0	100026	31.0	80232	25.1	115550	31.4	1.3	1.2
NL-W	in	19014	6.6	36048	11.2	21433	6.7	60426	16.4	1.1	1.7

DK-S	off	7839	2.7	2676	0.8	7724	2.4	1174	0.3	1.0	0.4
G-N	off	78602	27.1	34263	10.6	65238	20.4	30499	8.3	0.8	0.9
G-S	off	1543	0.5	852	0.3	673	0.2	236	0.1	0.4	0.3
NL-E	off	3410	1.2	2605	0.8	2246	0.7	1591	0.4	0.7	0.6
NL-W	off	2478	0.9	902	0.3	1001	0.3	248	0.1	0.4	0.3
Total		289898	100.0	322258	100	319106	100	367836	100	1.1	1.1

Trends in LPUE

The previously described increase in effort in combination with decreasing landings leads to significant negative trends in LPUE in the first quarter in all regions (Fig. I-3) with steeper slopes in Danish and German subareas (DK-S: -2.47, G-N: - 2.85 and G-S: - 3.51) than in the Dutch regions (NL-E: - 1.58 and NL-W: - 1.73). While the LPUE in the traditional winter fishing areas in the North and also in G-S is nearly 10 kg/h higher than in the Dutch regions at the beginning of our time series, it reaches the same level at around 20 kg/h in the end of the time series. In the second Quarter, only weak significant negative trends ($p < 0.1$) are observed in Southern areas (NL-E, NL-W and G-S), while the northern areas show less pronounced declines which are not significant. This is mainly caused by the high LPUEs in 2011. When the value for 2011 is left out, all trends except DK-S are significant in Q2 (not shown here). In Q3 and Q4, declining although not significant trends can be seen in the North while the southern regions show neutral or positive trends. When the year 2018 with exceptional high LPUE is taken out, the negative trends in Q3 for G-N and G-S, and in Q4 for G-N all become significant on $p < 0.05$ level (not shown here). Furthermore, the stable or slightly positive trend in Q3 and Q4 for NL-E and NL-W turn negative although not significant.

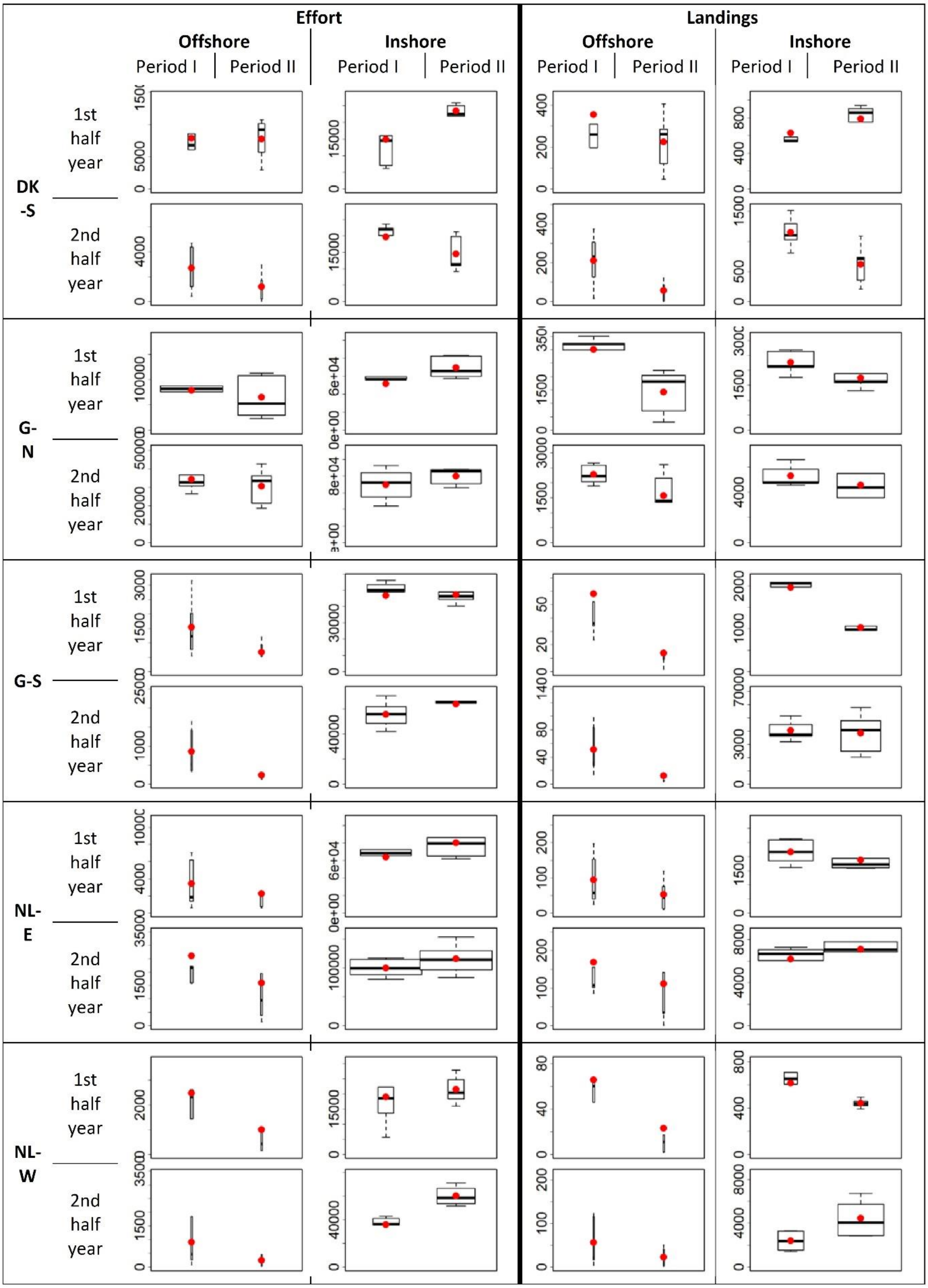

Fig. I-2. Boxplots for each area, half-year and time period (for values see table 1 -2). The width of the boxes is proportional to the contribution of the respective area to the overall effort per time period and season. The black lines of the boxplots show the median, the red dot show the mean value.

Long-term trends in the winter fishery in the North

A combination of the VMS-based data set (here G-N and DK-S) starting in 2009 with earlier data on landings and effort reveals a strong increase of the winter fishery with landings increasing from about 1000 t to about 3000 t in the years 2009–2012 (Fig. I-4). Thereafter landings decrease again to about 1500 t. Fishing effort has almost doubled from about 50,000 h (2000- 2003) to around 70–80,000 h (2009–2018) with peak values of 95,000 h (2018).

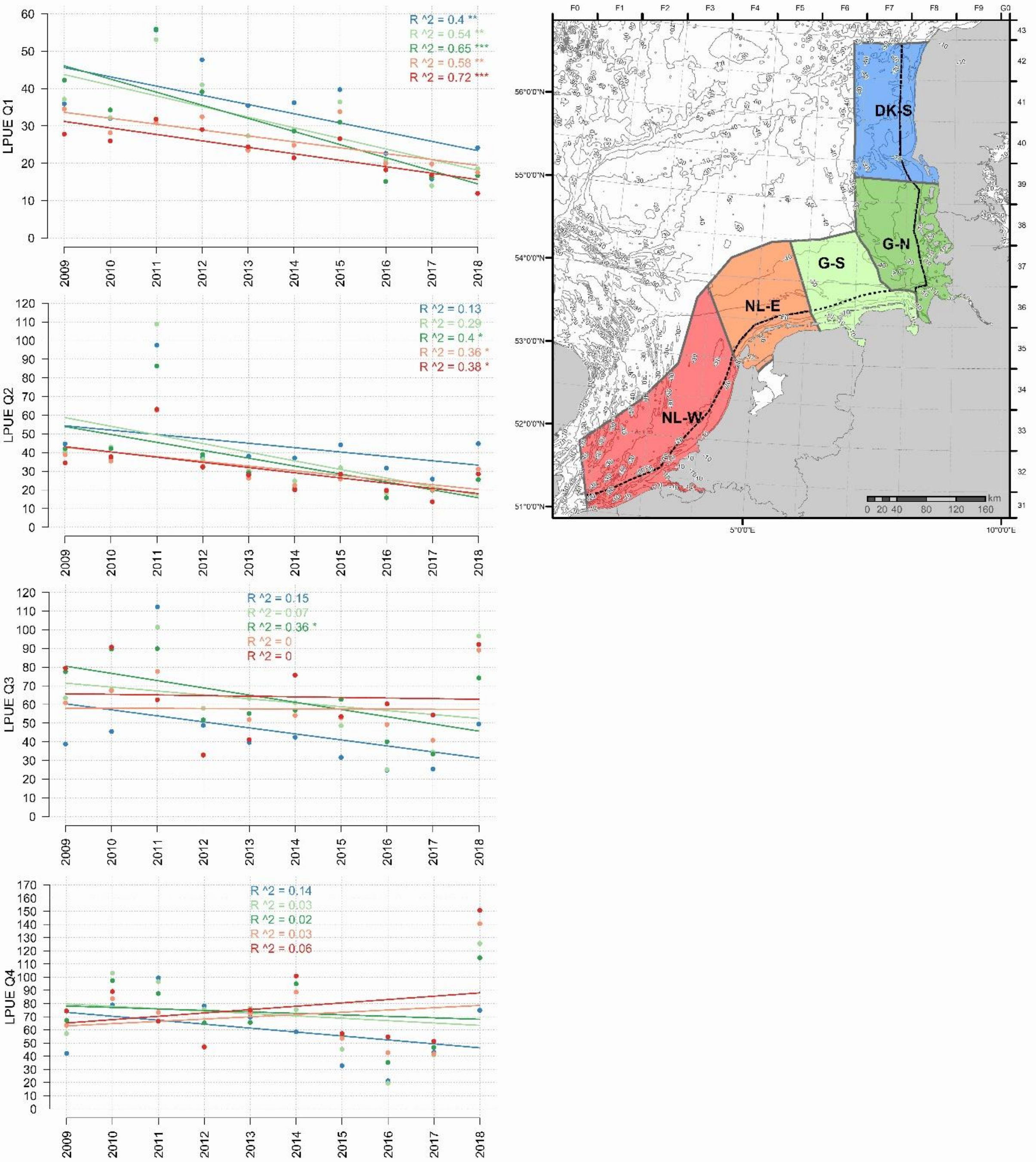

*Fig. I-3. Landings per unit effort (LPUE in kg/h) per quarter of the year. Color code for subareas corresponds to the colors Fig. 1, with red colors for Dutch areas, green for German areas and blue for Danish area. The stars mark the significance level with p<0.01 ***, p<0.05 **, p<0.1 *.*

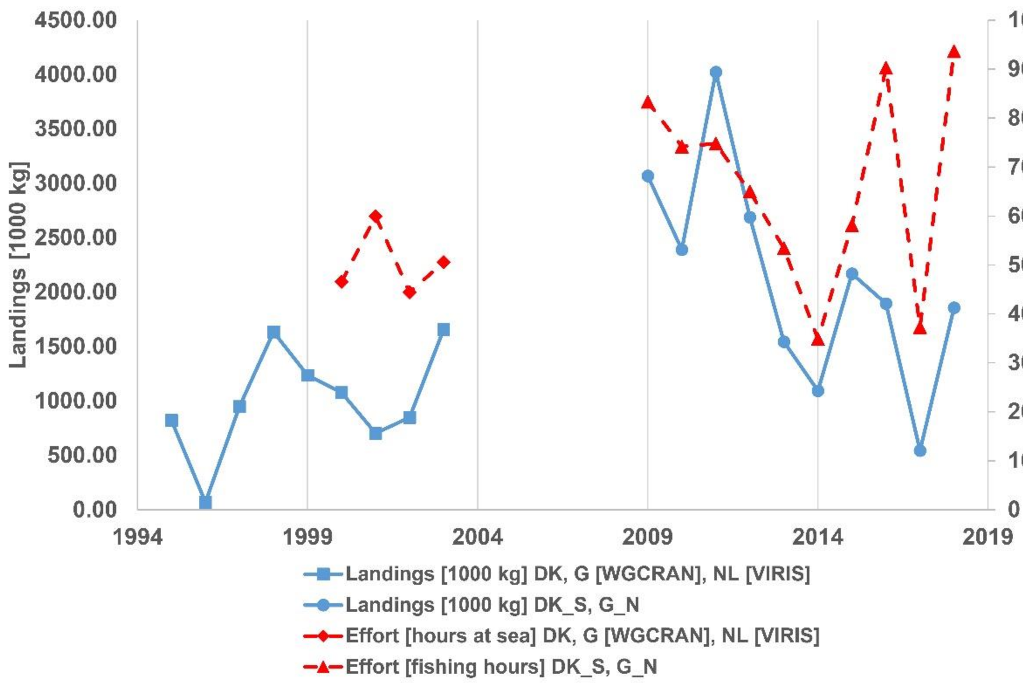

Fig. I-4. Effort and landings for the first quarter of the year off the Northern German and Danish coast, reconstructed from WGCRAN data (1995-2003) and from the combined VMS-Logbook data (2009-2018). Effort data from WGCRAN data (1995-2003) are in hours at sea for the full German and Danish fleet and those Dutch vessels fishing in ICES rectangles 37F-40F.

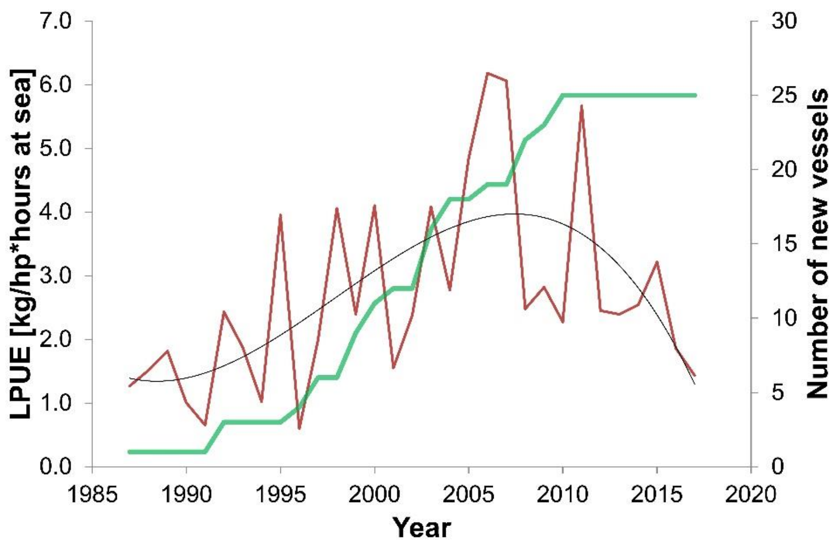

Fig. I-5. Danish LPUE in kg/hp-h and number of new vessels. Red line: mean LPUE of the months January – June. Thin black line: polynom 3rd degree fitted to the mean LPUE of the months January-June. Fat green line: number of Danish vessels replaced with a new construction of a total fleet of 28 vessels.

Long term LPUE trend in the Danish fishery

For the Danish fleet a consistent data set of landings and fishing effort since 1987 shows a steady increase in LPUE between 1987 and 2005 and a likewise clear decline thereafter (Fig. I-5). Over the same period (1987–2010) 25 of 28 vessels in the Danish fleet were replaced with modern new constructions.

Correlations of effort and LPUE

Intra-cohort correlations

Correlations of winter (February–January) and spring (March–April and May–June) effort with LPUE in adjacent months within the first half year are consistent with a depletion of the same cohort. The significant negative correlation of winter effort (January–February) in the region G-S and LPUE of the regions located to the east and north (G-S, G-N, DK-S) is greatest in the same period (January–February), while the winter effort in the region NL-E correlates significantly negative with LPUE in the subsequent months of all regions (Fig. I-6). In contrast, correlations with effort from other sub-areas are weak. No significant correlations were found between effort in March–April and the LPUE values in the first half year.

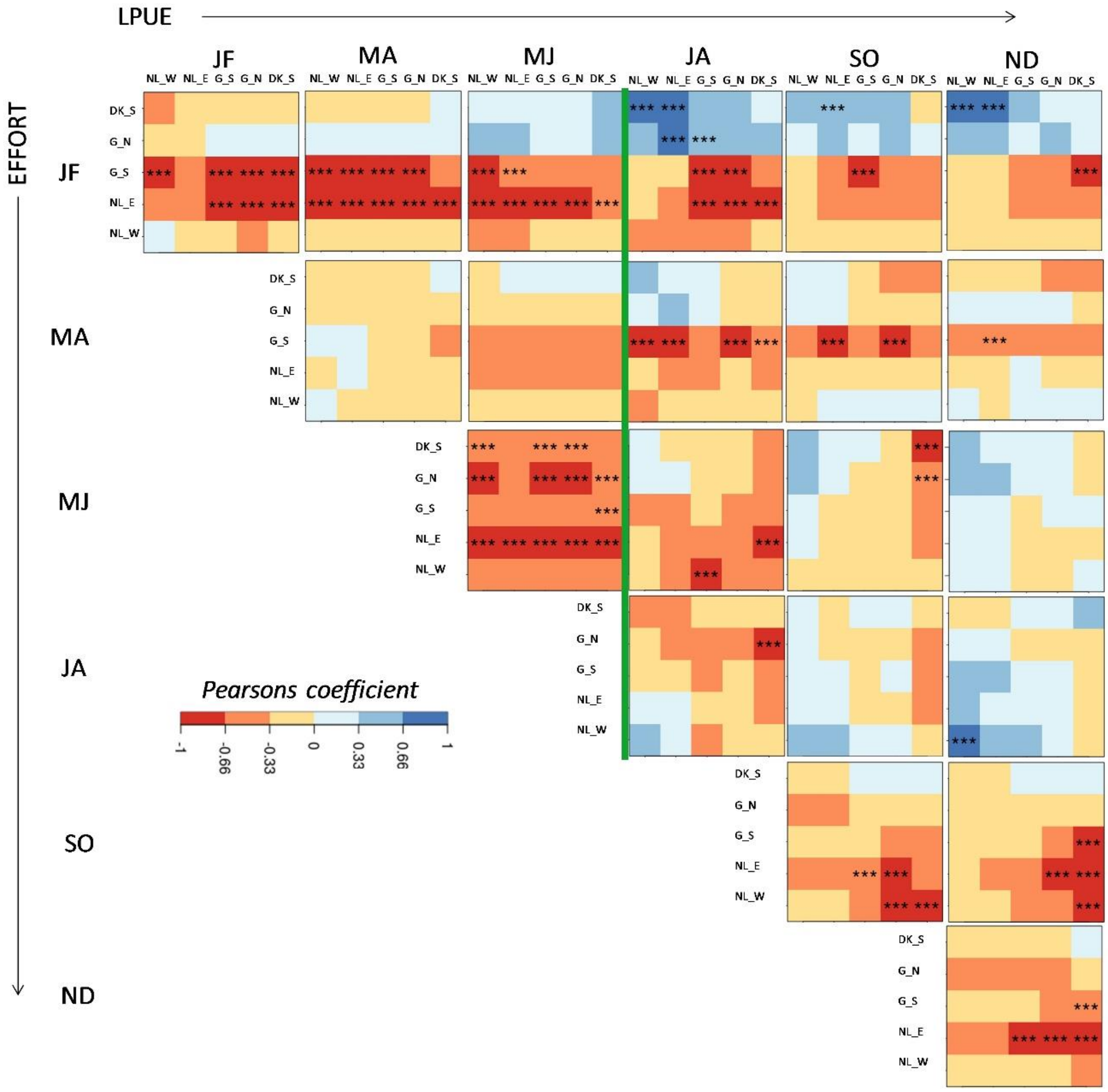

Fig. I-6. Colored contour plot for Pearson's correlation coefficients of fishing effort versus LPUE for bimonthly intervals (JF = January-February, MA = March-April, MJ = May-June, JA = July-August, SO = September-October, ND = November-December). Each rectangle stands for a correlation between two areas (DK-S, G-N, G-S, NL-E, NL-W). Three stars indicate a 5% probability of error. The thick green line displays the change from the "old" to the "new" cohort as indicated by modelling work.

Inter-cohort effects

Out of all correlations performed, we found strong and significant effects of winter (January–February) and spring (March–April) effort on LPUE in the following summer season (July – August; Fig. I-6). Note that these between season effects suggest recruitment effects on the subsequent cohort caused by reductions of the spawning stock (Temming et al., 2017). Specifically significant negative correlations were found for winter effort in NL-E and summer LPUE in all regions east and north of NL-E (Fig. I-6). Likewise two significant negative correlations were found for winter effort in G-S and summer LPUE in G-S and G-N and an additional one with LPUE in September–October within the same area (G-S). Effort in early spring (March–April) in G-S is likewise negatively and significantly correlated with LPUE in July–

August in NL-W, NL-E, G-N and DK-S (Fig. I-6). The same effect can be seen with LPUE in September–October in NL-E and G-N (Fig. I-6). The highly significant negative correlations of winter effort and summer LPUE ($p < 0.01$) are illustrated in linear regressions (Fig. I-8). The strongest linear model in terms of significance is the effect of effort in January–February in NL-E on the LPUE in July–August in the German regions G-S and G-N. Next to this South-North pattern, there is also a strong relationship of effort in G-S in January–February on LPUE more south in NL-E from July to August. Effort in late spring (May–June) has mainly negative effects in the same season but there are some isolated negative correlations in later seasons. Quite surprisingly, four significant positive correlations were found for winter effort and LPUE in July–August (Fig. I-6). These correlations can be better interpreted, when taking the correlation between winter effort in different regions into account (Fig. I-7). Effort in January and February correlated significantly negative between G-N and NL-W (R2 = - 0.88, $p < 0.01$) and between G-N and NL-E (R2 = - 0.67, $p < 0.05$). Effort in January and February correlated significantly positive between G- and NL-E (R2 = 0.91, p < 0.01). The linear regression plot for the most interesting combination of areas for our analysis, G-N and NL-E is shown in Fig. I-7.

Effect of winter and spring LPUE on the LPUE of the following months

Intra cohort effects

Most of the positive correlations are found between all regions in the period January – June, suggesting that the same good or bad year classes are dominating the catches in all regions. Interestingly in the regions NL-W the correlations disappear first, followed by NL-W and G-N.

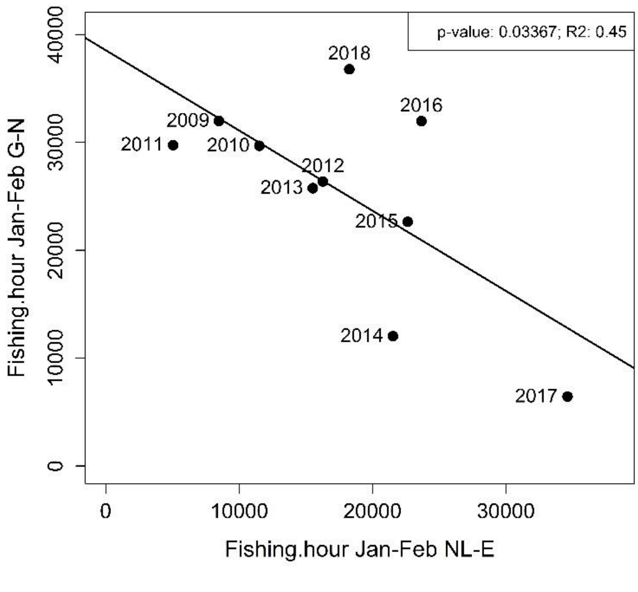

Fig. I-7. Linear Regression of Effort in NL-E (x-Axis) and Effort in G-N (Y-Axis) in January and February. The significance – levels are p-<0.01 and p<0.05. R2 values display the variance explained by the linear model.

Inter cohort effects

The logic for these tests is complementary to the tests of negative effects of winter effort on the subsequent LPUE of the new cohort. If such a relation exists, one would also expect high LPUE in winter and early spring as a proxy of the spawning stock to correlate positively with the subsequent recruitment which manifests in summer/autumn LPUE. However, the LPUE in January and February was not significantly correlated with the LPUE in July and August or September and October in any region except for the combination DK-S (Jan-Feb) – DK-S (Sep- Oct) (Fig. I-9). In contrast, LPUE in March–April correlated positively and significantly with the LPUE in July–August for all combinations of G-S, G-N and DK-S (Fig. I-9). For LPUE in September–October only the region DK-S correlates significantly with LPUE in March–April of southern regions (NL-W, G-S, G-N (Fig. I-9).

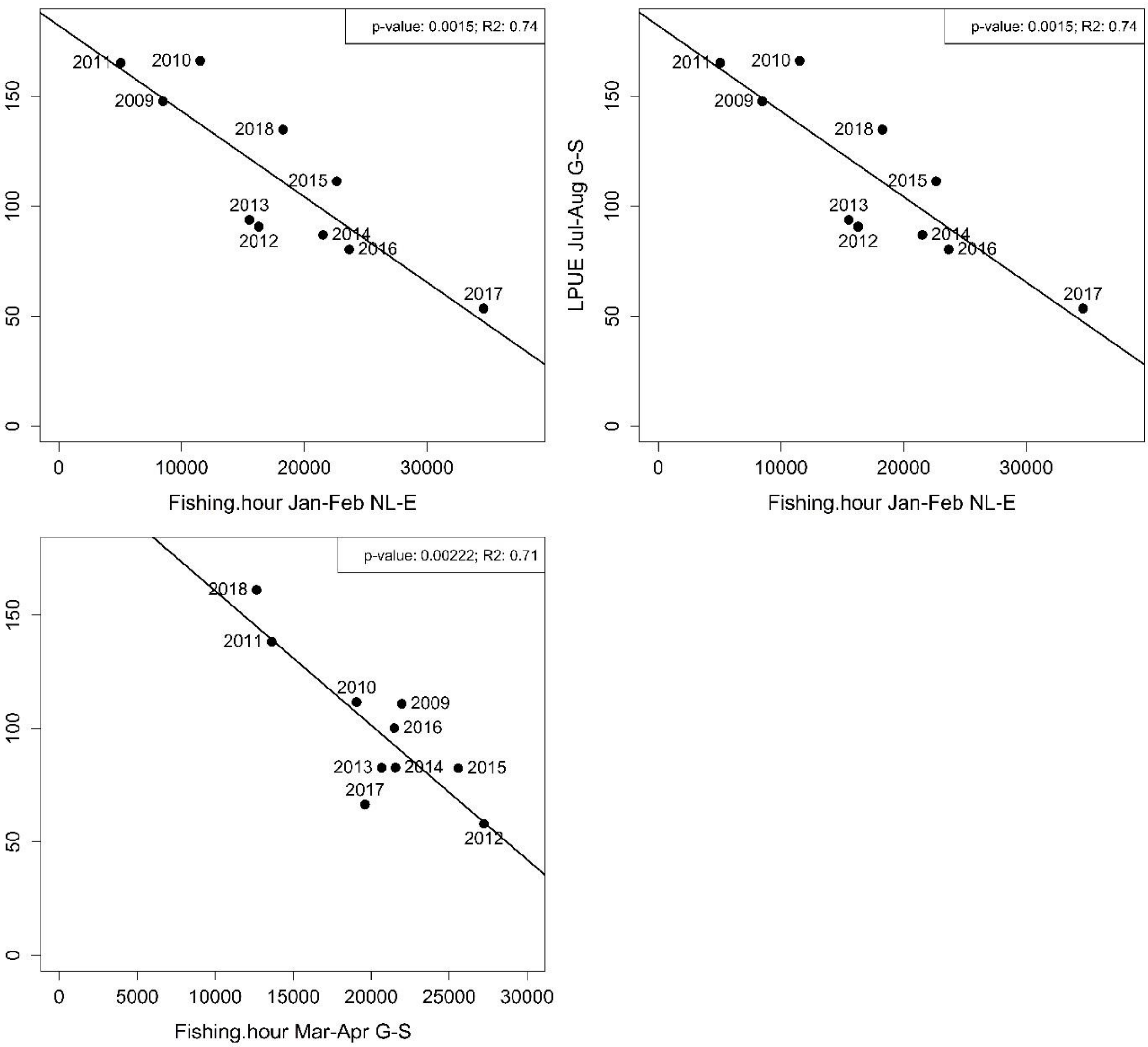

Fig. I-8. Linear Regression of effort (x-axis) in winter/spring and LPUE in the following season (y-axis). The significance – levels are p<0.01 and p<0.05.

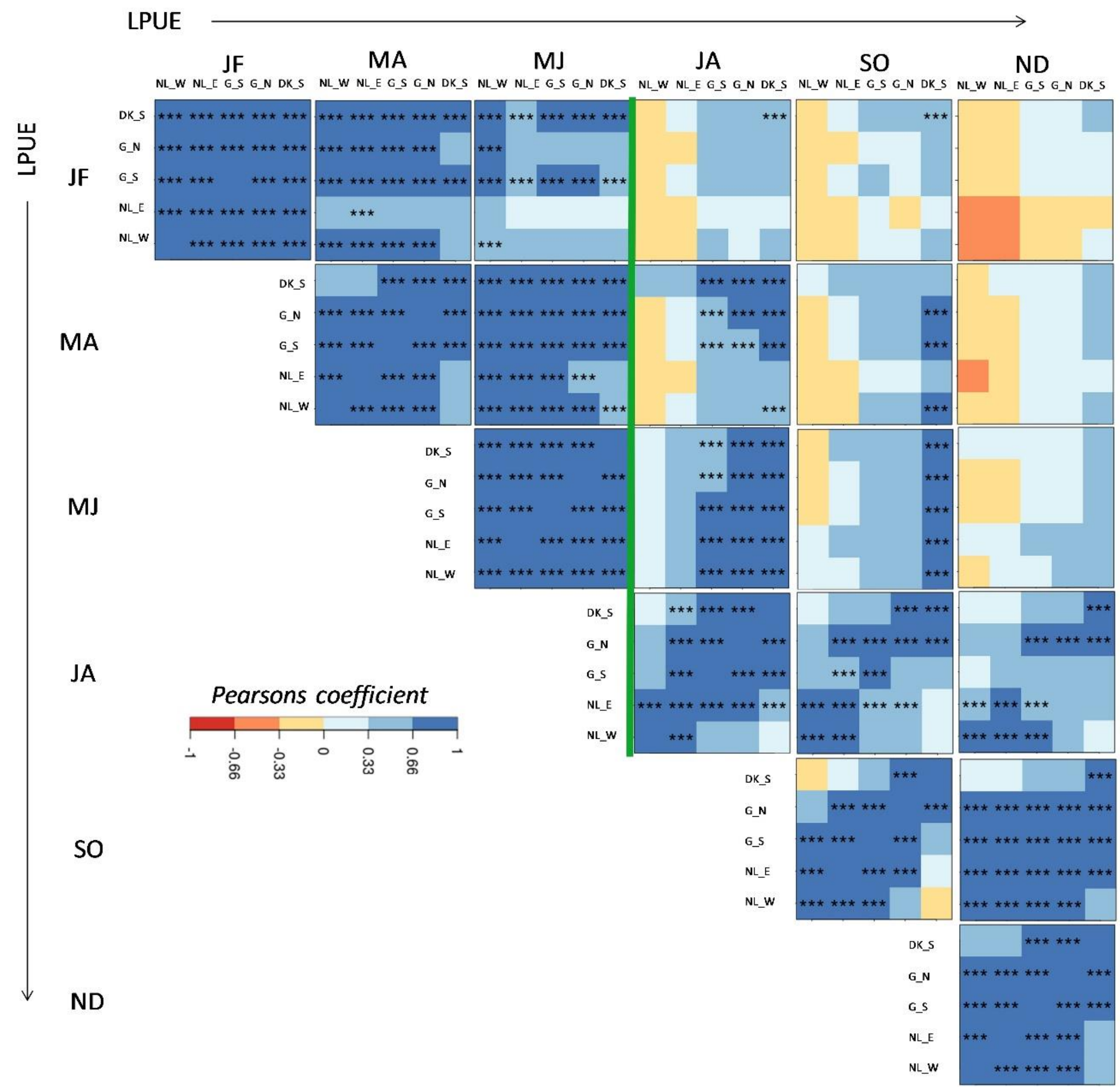

Fig. I-9. Colored contour plot for Pearson's correlation coefficients of LPUE versus LPUE for bimonthly intervals (JF = January-February, MA = March-April, MJ = May-June, JA = July-August, SO = September-October, ND = November-December). Each rectangle stands for a correlation between two areas (DK-S, G-N, G-S, NL-E, NL-W). Three stars indicate a 5% probability of error. The thick green line displays the change from the "old" to the "new" cohort as indicated by modelling work.

Discussion

Trends in effort, landings and LPUE

Effort increase of 12% over the 10 year period

Mean effort in fishing hours showed an increase of about 12% from 2009 to 2013 to 2014–2018 while mean landings decreased by 9% (Table I-1 and I-2). However, due to the limited time series and strong annual variations, no significant trend over the full period and all areas could be detected in effort. The estimated effort increase confirms indications from previous analysis (ICES, 2005), which however suffered from non-comparable effort measures. Estimations of the swept area (Neudecker et al., 1999) demonstrated a likely small effort increase in the German fleet in spite of a reduction of the number of vessels by a factor of 2.5 between the 1956 and 1996. This was mainly due to larger vessels operating larger gear with increasing numbers of fishing hours per day. The entrance of large beam trawlers which previously fished for flatfish (Dutch) and of newly build shrimpers likewise accelerated this trend even after the mid-1990s. The estimation of fishing hours from VMS data may still lead to under- or overestimation of the actual time spend fishing due to the ping frequency of only 2 h (Schulte, 2015) and the since activity is estimated from the observed speed (Hintzen et al., 2012; ICES 2019a) and not a recorded status. A haul in the Brown shrimp fishery may be anything from 15 min to four hours depending on the catch and fishers preference. Thus, the VMS ping does only give a snapshot of the activity at a single moment and does not contain information on the activity between two pings. Nevertheless, throughout the time series considered here it is unlikely that this bias has changed and hence the observed trends are considered accurate. However, even if accurate, fishing hours will underestimate the effective fishing effort – being proportional to fishing mortality –, because the corresponding information on vessel dimensions, technical installations and skipper skills is missing. New vessels with new technical designs of gear, hull and propulsion system catch more per fishing hour with the same engine power than traditional ones. New automatic boilers and sorting devices reduce the processing time and hence increases the haul frequency. Effective fishing effort is also strongly influenced by the degree of overlap between fishing tracks and shrimp concentrations. Here information is the crucial point, which is not entering any measure of nominal effort. The necessary information is gathered from experience, digitally stored successful tracks of the own vessel or "copied" tracks of other successful vessels. Also automatic steering equipment and radio communication contribute to fishing effort becoming more effective. Schulte et al. (2020) estimated a factor of four in LPUE under comparable conditions between the most and the least effective German vessel of similar size, age and engine power. Hence it is likely that the fishing pressure on the Crangon stock increased even stronger than the estimated 12% from VMS/logbook data during the last decade. This so far undocumented increase in fishing pressure has been deduced before from indirect methods. By comparing increased landings with stable total biomass estimates Tulp et al. (2016) assumed increasing fishing mortality as main factor behind increasing landings. The same conclusion was reached by Temming and Hufnagl (2015) from the analysis of a time series of total mortality and total predation in relation to total landings.

North – South shift

Both Northern offshore areas show a 20% decline in effort over the 10 year period. These areas are well known as "traditional" winter fishing areas. The retraction of the fishery from these areas is likely explained by strongly decreased landings with reductions between 40% (G-N) and 50% (DK-S) between the first and the second half of the 10- year period (Table I-1 and I-2, Fig. I-2). While the northern off-shore regions have seen a decline in effort and landings the westernmost inshore region (NL-W) has seen a strong increase in effort with 50% plus between periods, now representing 12% of all effort. The increase in effort corresponds to an even stronger increase in landings (+ 60%). This shift in importance to south-western waters contradicts the apparent shift of the Crangon population to the north as discussed earlier (ICES, 2005). The earlier statement was based on high Crangon densities found along the Danish coast, increasing commercial LPUE values from the Danish fishery on the one side and steadily decreasing LPUE values of the Belgian fleet. However, the negative trend in the northern regions has even continued after 2018: In 2019 the landings from Schleswig Holstein were well below average with 3560.379 t compared to the mean of the previous decade 2009–2018 (5495.988 t) (LLUR, 2019).

Hydrography and predation as explaining factors?

It was speculated that the Crangon population was shifted towards colder waters driven by increasing North Sea water temperatures (ICES, 2005). This interpretation is, however, not compatible with the recent trend demonstrated here. Furthermore the multi-decadal downward trend in Belgian LPUE has been reversed since late 1998 with again increasing landings (ICES, 2019b). Extensive studies on temperature preference of adult and juvenile *C. Crangon* did also not provide evidence for a narrow range of preferred temperatures (Reiser et al., 2014, 2016) while growth studies indicate that juvenile C.crangon exhibit the highest growth rates at the highest temperatures tested (25 ◦C, Hufnagl and Temming, 2011). At temperatures above 27 ◦C juveniles leave the tidal flats towards deeper waters (Berghahn, 1983, 1984), but on the other hand adult shrimp are found in locations with up to 30 ◦C (Havinga, 1930; Tiews, 1970). These results make a temperature related shift in the distribution pattern unlikely. Based on survey data from 1974 to 2002, Siegel et al. (2005) did not detect any significant trend in Crangon abundance in spring or autumn and failed to detect any influence of biotic or abiotic factors on spring Crangon abundance. Also investigation on temperature trends in the North Sea only revealed a long-term increase from 1982 to 2012, but no specific trend which corresponds to our time series starting in 2009 (Høyer and Karagali, 2016). Furthermore investigations in the Dutch Wadden Sea from 1970 to 2010 did find neither salinity nor temperature to be critical in structuring brown shrimp population densities in autumn (Tulp et al., 2012). Studies of adult Crangon temperature preference also found no evidence of such preferences as mentioned above (Reiser et al., 2014, 2016). Since we did pool the data over three months, also possible artefacts like delayed migratory patterns are unlikely as cause for the trend. In the last decades, a de-eutrophication process, detectable in the reduction of nutrient river loads to the sea, caused a decrease of nutrient concentrations in coastal waters under riverine influence in the Wadden Sea (Desmit et al., 2020). This process is linked to decreasing chlorophyll *a* concentrations in those waters (Desmit et al., 2020; van Beusekom et al., 2019) and is discussed to have caused a decline in copepod densities at Helgoland stations (Boersma et al., 2015). The decline in nutrient loads but also in copepod densities is most pronounced until the beginning of the 2000s, then levelling off on a low level. During this period, we rather observe strongly increasing landings in the Crangon fishery which are most likely related to decreased predation (Temming and Hufnagl, 2015). However, no decline in macrozoobenthos linked to this de-eutrophication could be detected. In contrast, macrozoobethos densities are increasing in recent years in the Wadden Sea, particularly in the north-eastern parts (Drent et al., 2017). Given that our data indicate the strongest negative trend in Crangon abundance in the northern parts, a bottom-up effect of decreasing nutrient loads on the egg-bearing shrimp in winter or on the subsequent life stages is unlikely. In his long-term analysis in 2005, Siegel already assumed an unknown predatory effect as mechanism behind the variation in spring Crangon abundance. Known predators of large adult shrimp are mainly gadoids. However, although the impact of 0-group gadoids on shrimp stock in autumn is widely assumed (Tulp et al., 2016; Siegel et al., 2005), a significant negative effect in spring has not yet been detected. In contrary, the stocks of the main gadoid predators, namely cod and whiting, are still at very levels. The mortality of Brown shrimp from predation is reported to have decreased in the last decades, leading to the fishery taking over the role as main source of mortality (Temming and Hufnagl, 2015; ICES, 2019b; Tulp et al., 2012).

The role of increased fishing effort on Q1 LPUE

The negative trend in LPUE is most pronounced in the first quarter and for all regions, with the northern regions showing the steepest decrease (Fig 3). The positive or stable trend in the southern regions in Q3 and Q4 is only held up by the exceptional high LPUE in 2018. A general increase in effort levels, specifically in summer and autumn on the incoming cohort increases the landings and simultaneously reduces the number of shrimp surviving into the winter period. The landings in the beginning of the year are composed of individuals from the same cohort that is fished as smaller adults in autumn. Only later in spring the contributions from the late summer recruitment of the previous year are growing into the fishery (Temming et al., 2017; Schulte et al., 2020). Such a shift with increasing fishing mortality to more autumn landings and less winter and spring landings has also been demonstrated with an earlier version of the life cycle simulation model by Rückert (2011).

The impact of the winter fishery in northern areas

A comparison of the VMS-based data set from 2009 to 2018 with earlier data on landings and fishing hours for the period 1995–2003 (Fig. I-4) reveals a strong increase of the winter fishery with landings tripling from about 1000 t (1995–2003) to about 3000 t in the years 2009–2012. Thereafter landings decrease again to about 1500 t. Fishing effort has approximately doubled from about 5000 h (2000–2003) to above 8500 h (2009–2018) with peak values of 12,000 h (2018) and since stayed at a high level. The mortality effect on the overwintering shrimp stock is probably stronger than these effort data suggest, as vessel size and effectiveness are not taken into account. Especially in the Danish fleet a complete modernization has taken place over the same period with 25 out of 28 vessels being newly built between 1987 and 2010. This modernization together with learning effects of new captains could theoretically also explain the initial increase in the LPUE. Likewise the Dutch winter fishery in northern areas is carried out by the largest boat class, often switching from flatfish to shrimp fishing. These captains have also local information on fishable grounds further off-shore, where egg bearing shrimp were previously undisturbed in winter. While this is the first time that a significant decreasing trend in LPUE has been detected, concerns about the potentially negative effect of the winter fishery on the shrimp stock arose before (Boddeke and Becker, 1979; Berghahn, 1991) based on the fact that the catch consists mostly of large egg bearing females. Generally, landings of *C. crangon* used for human consumption as recorded in logbooks refer to shrimp with a carapax width (CW) of at least 6.5 mm (minimal sieve width for commercially used shrimps). This corresponds to a total length of 50 mm (Sharawy, 2012). The proportion of females at this size is already between 60 and 80%, and further increases to 100% at around 60 mm total length (Siegel et al., 2008). While the onset of sexual maturity in males can only be estimated since they have no external feature revealing this status, it is clear that they become mature at a smaller size than females. The minimum size of maturity for males is reported as 22 mm (Boddeke, 1966), while Tiews (1954) observed a range of 38–42 mm total length as size of maturity. It is thus clear that male Crangon mature before they recruit into the fishery. Due the size and the habit of carrying the eggs under the abdomen until hatching, the fishing pressure on females is the most likely link to possible recruitment effects of fishing. The northern winter fishery has been shown to concentrate actively on spatially restricted aggregations of these large shrimp (Schulte et al., 2020) which are mostly egg bearing females (Hünerlage et al., 2019; Siegel et al., 2008). These winter eggs in turn, are responsible for the first massive wave of recruits and the first increase in late summer and autumn catches at least in the German Bight (Kuipers and Dapper, 1984; Temming and Damm, 2002; Temming et al., 2017)). Furthermore a study linking larval drift from spawning grounds and adult migration patterns suggested that sub-populations could be regionally self-sustained (Hufnagl et al., 2014). Hence, theoretically a local northern spawning stock component could have been decimated by too high fishing effort in winter, leading over time to reduced recruitment and a subsequent gradual decline in abundance these areas.

Connectivity between regions: remote effects of fishing effort

Winter effort in southern regions explains 86% of LPUE in late summer in the northern regions

In our results, a single variable, winter effort, explained up to 86% of the variability of the following summer landings in various regions (Fig. I-6). The linear model does still explain more than 70% of the variance for the combinations with the highest correlation coefficient (Fig. I-8). This is clearly more than previous attempts trying to explain variability in survey abundance of shrimp in German waters with the NAO index of the previous year, winter temperature, river run-off and a predator index leading to 57% explained variance (Siegel et al., 2005). Based on previous work (Temming et al., 2017; Siegel et al., 2005) we can assume that LPUE in July–August is dominated by the new incoming cohort and not by survivors of the previous year. This is also supported by the lack of significant LPUE – LPUE correlations (Fig. I-9) between January–February and July–August. This excludes a hypothetical explanation of the correlation resulting from fisher's behavior. If fishers would investigate the areas for high abundance early in the year, they may in years with poor abundance in the North decide to put all effort in the South. This would then lead to the same negative correlation if the abundance in summer would be related with that in winter. However, the abundance of Crangon in July–August is simply independent of the abundance in January–February, as described before by Siegel et al. (2005).

Predation pressure

For 2016, high predation pressure by whiting has been suggested as an explanation of low abundance of Crangon in autumn in the German Bight and in Danish waters. Effects of extreme gadoid predator abundance and autumn Crangon abundance have been documented by Siegel et al. (2005), but they did not consider fishing effort as a variable at all. It may be speculated, that the correlation between high whiting abundance and low landings in autumn may actually result from an indirect effect: In years with average or good recruitment, juvenile Crangon settle over a large area were they are accessible to predators. In years with weak recruitment, whiting are forced to search for shrimp closer to the coast, thus appearing in larger numbers in those surveys which sample juvenile fish and Crangon in the Wadden areas. This interpretation is consistent with the observation that high whiting abundance in the Wadden area does not correspond well with strong year classes of whiting. The most extreme occurrence of whiting in the Wadden Sea in 1990 came from a below average year class while the year classes 2001 and 2016 – both with high densities in the Wadden Sea - were not stronger than those of adjacent years with no whiting invasions, namely 1998–2000 and 2014–2015.

Possible recruitment overfishing?

The strongest correlations and regressions involve the effort in January and February (Fig. I-6); hence the months before the eggs of the winter period are released. Schulte et al. (2020) showed that standardized LPUEs for large shrimp (TL ca. > 69 mm) are considerably higher than for the smaller size class (TL ca. 48–69 mm) in January and February. It can thus be assumed that the fishery in these months targets mostly large, egg-carrying females. These large females are concentrated in characteristic areas in those month (Schulte et al., 2020), showing a certain depth preference of 10–20 m of the females. Along the Dutch and East Frisian coasts the relevant depth range is compressed into a narrow area, making potential aggregations quite vulnerable. Hence the mechanism behind our correlation is most likely a reduced spawning stock impacting negatively the subsequent recruitment, as landings in July–August stem from eggs of the previous winter which were released as larvae in March–April (Temming et al., 2017). The correlations are still negative, but no longer significant if the months September and October are considered. In these months increasing contributions from the summer egg production are arriving, which are to a lesser degree depending on mere biomass as egg numbers increase exponentially with female size and spawning frequency increases with temperature. With increasing temperature in spring and summer development times become short and larval drift occurs only over short distances (Daewel et al., 2011; Temming et al., 2017). This leads to a closer spatial connection between egg production and recruitment (Daewel et al., 2011). The fact that no correlations with similar explanatory power are found here suggests a stronger impact of environmental factors on the autumn landings and a smaller role of fishing effort. Most surprisingly, the correlations and linear regression of effort in NL-E in winter and LPUE in the following season in Northern Regions are highly significant even though three years with extreme LPUE values are included: 2011, 2016 and 2018. The plots of the linear regression do clearly show those years well within the range of the linear trend (Fig. I-8).

The winter fishery affects local recruitment only in remote regions

Contrary to our expectations, the detected strong effect of effort on subsequent recruitment works across regions rather than within regions. The sole exception is G-S, where the effort in Jan/Feb also impacts the LPUE in the same region in July to October (Fig. I-6). The correlations between remote areas suggest that at least the early recruitment in July–August of the Northern regions originates from the South, with no or very little local northern recruitment. Larval drift or juvenile migration involving selective tidal stream transport (STST) from southern areas towards the North has been suggested before based on a temporal mis-match of simulated and observed patterns of young recruits entering the tidal flats in Germany, when German water temperatures were used in the simulations (Temming and Damm, 2002). This mis-match could only be resolved with Dutch water temperatures. Subsequent studies with 3 D ocean models confirmed the long drift routes of winter larvae and the import into German waters (Daewel et al., 2011; Hufnagl et al., 2014). Due to higher temperatures in the Southern areas, egg and larval development is accelerated and could lead to an early wave of recruits in the North originating from southern-hatched larvae. The larvae from local northern recruitment would then be expected to reach the juvenile stage later in the year and contribute to the landings beginning in September.

Spring LPUE as a proxy for spawning stock size

Given the strong negative effects of winter effort in NL-E and G-S on the subsequent summer LPUE of the new cohort in eastern and northern areas, one would also expect high LPUE in winter to correlate positively with respective summer/autumn LPUEs. Contrary to expectations, the LPUE in that region and period, where the winter fishery impacts the recruitment most, namely NL-E in January–February, did not correlate significantly with summer/autumn LPUE. However, there are several significant positive relationships of the LPUE in March–April in G-S and the summer/autumn LPUE in the northern regions (Fig. I-9). The region G-S is somewhat special with negative effects of effort in both periods (January–February and March–April). From the current state of knowledge regarding the lifecycle of brown shrimp in the North Sea, it is clear that correlations between LPUE in March–April and July–August can only be caused via recruitment rather than reflecting an intra-cohort correlation. A complex simulation model of the *C. crangon* life cycle (Temming et al., 2017) reveals that commercial landings in July and August originate mostly from winter eggs fertilized in the months November and December, which will hatch in March–April as larvae. Interestingly corresponding positive correlations exist also for the regions G-N and DK-S. Since the March–April LPUE in all regions is strongly negatively influenced by the winter effort in regions NL-E and G-S (Fig. I-6) it must be concluded, that those shrimp that release larvae in March–April in all regions must have concentrated during winter - as egg bearing females - in the two regions NL-E and G-S. In this area they are under the influence of the local winter fishery which determines the size of the surviving fraction of this spawning stock component that subsequently spreads out to adjacent regions where the larvae are released (see schematic drawing in Fig. I-10). Such a migration pattern of the adults has been proposed in a more general form by Boddeke (1976), however, he did not refer to regions but rather postulated that the adult shrimp would target warmer regions, which means in winter also deeper regions. Since the southern North Sea is on average warmer this may also explain a possible migration of shrimp from the North German and Danish coast into the regions off East Frisia and the Netherlands. This migratory behavior of *C. crangon* seems likely unrelated to size or sexual category (Boddeke, 1976). This finding has been supported by the work of Siegel et al. (2008), who observed the same pattern of sex ratio of migrating shrimp in each year as well as in the different seasons (Winter, Spring and autumn) (Fig. I-1, Siegel et al., 2008), but with high fluctuations between years.

Why does the winter effort in Northern regions not have any negative effects?

For these regions we could only demonstrate a positive effect of winter fishery on subsequent LPUE in summer/autumn, which appears rather paradoxical at first glance. However, the likely explanation is that the same fleet components fish during winter either in Northern or in Southern regions. This is indicated by a significant negative correlation of effort in the North (G-N) and effort in the South (NL-E) (Fig. I-7). Hence high effort in the North indicates low effort in the South, which is then causing the benefits indirectly. Nevertheless the winter fishery in the North targets large concentrations of mostly egg bearing shrimp and lands often at least the same amounts as is caught in southern regions during winter. Unless one assumes that the fishery is so effective, that most of the spawning stock is wiped out, there must be a recruitment contribution from these regions. The question is, why we do not see any related signal. In our data there are indications of decreasing LPUEs in the first quarter especially in the northern regions (Fig. I-3). This may indicate that the winter fishery in northern areas has increased over longer periods substantially and may have reached a point where local recruitment overfishing leads to a steady decline of this stock component. This may at least partly be a factor, but the picture is more complex. In the northern regions the seasonal temperature development is somewhat delayed compared to the Dutch coast waters as Temming and Damm (2002) demonstrated in a comparison between temperatures from Büsum harbor and Texel lightship. The resulting longer egg development has also the negative side effect of a longer exposure of egg bearing shrimp to the winter and spring fishery. At the same time the longer development leads to recruits occurring later in the fishery and hence correlations between winter effort and LPUE in July–August do not show a signal, but are rather influenced by the southern recruitment component. In the subsequent months, however, the recruitment components from the northern spawning grounds might get mixed with migrating recruits from both the winter- and summer-egg production of southern regions.

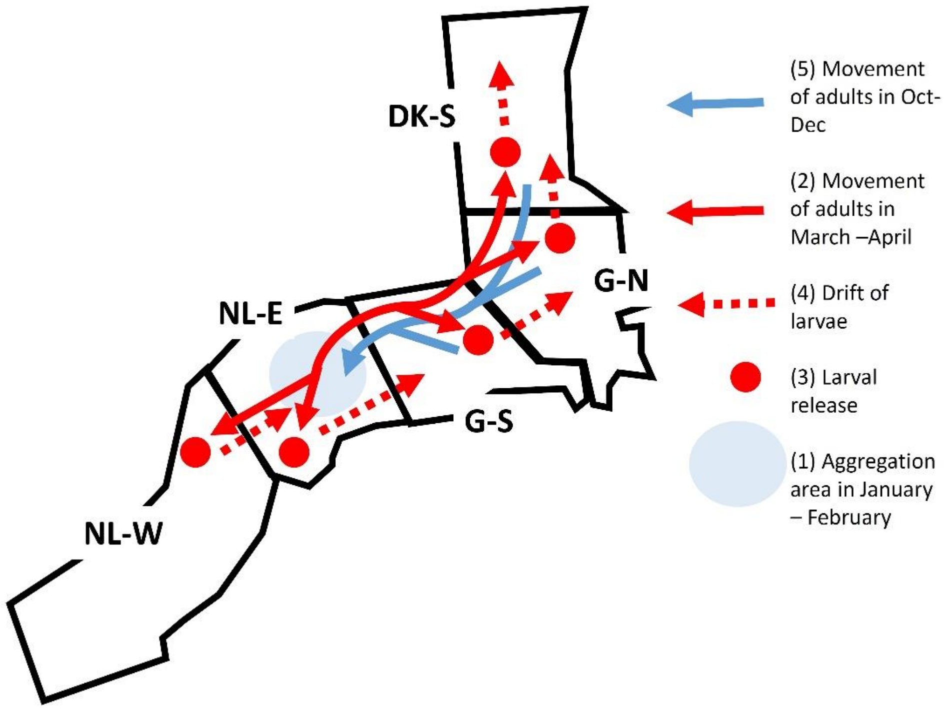

Fig. I-10. Schematic drawing of the assumed underlying mechanism regarding the impact of the winter fishery on recruitment. The fishery targets large female shrimp in January and February (1), part of the surviving shrimp migrates to adjacent areas (2), the larvae hatch from winter eggs in March-April (3) and are distributed by currents and drift along the coast (4). It is likely that adult shrimp move back along the coast with decreasing temperatures again in October-December (5). The recruitment mechanism on the east and south Netherlands coast is still unknown.

Any recruitment contribution of larvae from the northern areas to the same region requires specific behavioral patterns of either larvae, juveniles or both to remain in the same region. In simulations conducted by Hufnagl et al. (2014) larvae from the zoea stage 3 on were assumed to perform selective flood stream transport, which brings larvae rapidly to shallow coastal waters. If this assumption is not accurate, larvae without this behavior will drift much further north into areas with an even more delayed temperature pattern. These areas are not fished normally. However experimental fishing with RV Solea in 2008 and 2009 revealed considerable densities of *C. crangon* along the Danish coast up to the Limfjord (Neudecker, internal cruise reports). While growing shrimp may then gradually return south to the spawning stocks and hence not contribute to the increasing LPUE in summer but rather later in the season.

Conclusion and outlook

The analysis of the first integrated dataset covering the main fishing areas and –fleets for Brown shrimp *C. crangon* did reveal. a) An overall increase in effort of 12% in terms of fishing hours over a decade. b) a general depletion of local spawning stock components in the first quarter. c) a stronger decline in landings in northern off shore areas and an increase in landings in southern inshore areas. d) a strong negative impact of the winter fishery in southern areas on summer LPUE in northern areas. e) indications for a concentration of egg bearing shrimp in southern areas in January and February and a subsequent migration to adjacent northern areas. f) increasing effort in the northern winter fishery in the past as a possible explanation for decreasing LPUEs in northern areas. Our results suggest that intensive fishing in one area might influence LPUE in other areas by means of indirect effects, i.e. decreased recruitment. Hence the precautionary inclusion of limitations on the winter fishing effort into the current management plan operated for the MSC certification might be a strategy counter these negative effects. To better understand the across-region effects demonstrated here more research is needed with regard to migratory behavior of adults and drift of larvae. Furthermore, information on shrimp fishery from regions even further south could help understanding the effects on the stock in the southern regions in the present study.

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Chapter II. Investigating the effectiveness of the harvest control rule of the North Sea brown shrimp fishery using shrimp specific Y/R simulation model

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Abstract

Harvest control rules (HCRs) are central to science-based fisheries management, especially for data-limited or short-lived stocks where traditional stock assessments are unavailable. The North Sea Brown Shrimp (*Crangon crangon*) fishery, among the most valuable in Europe, adopted a self-regulatory management plan based on landings per unit effort (LPUE) HCRs to meet Marine Stewardship Council (MSC) certification. However, assessing stock status remains challenging due to uncertain effort data and biological traits such as high natural mortality and short lifespan. This study evaluates the effectiveness of the current HCR, which triggers progressive effort reductions when LPUE falls below defined reference points, and compares it to alternative, more stringent designs. Using a numerical population model simulating two scenarios—general stock reduction and severe recruitment failure—we quantified the effects of different HCRs on stock biomass, egg production, and landings. Results indicate that all HCR implementations led to higher LPUE and slight gains in stock biomass and egg production compared to unmanaged scenarios, whereas impacts on annual landings were minimal. The most robust improvements occurred with more aggressive strategies, such as temporary closures, which prompted faster and larger stock recovery but may present operational and social challenges. Current HCR designs deliver only moderate effort reductions, insufficient for major biomass rebuilding following sharp stock declines. These findings underscore the need to revisit HCR reference levels and involve the fishing sector in co-developing responsive management measures. Future research should explore extended simulations and more adaptive HCR frameworks to enhance the resilience and sustainability of short-lived, data-limited fisheries such as the one for Brown shrimp.

Introduction

Harvest strategies are a science-based approach in fisheries management that shift the perspective from short-term, reactive decision-making to longer-term objectives. They are increasingly being implemented in fisheries around the world. Harvest control rules (HCRs), pre-agreed procedures for determining how much fishing can take place based on indicators of the status of the target stock, are the core of these strategies (Kvamsdal et al., 2016). In many cases, the status of the stock in relation to overfishing is not known. Therefore, the objective is to maintain current stock levels (Geromont and Butterworth, 2015). Without stock assessments, many HCRs operate by adjusting recommended catches or effort according to trends in an index such as abundance or calculations of how much effort is needed to fish a certain quantity, known as catch per unit effort (CPUE). Within the International Council for the Exploration of the Sea (ICES), such an approach has been implemented as a trend-based "2-over-3" catch rule (ICES, 2021), an empirical harvest control rule used for data-limited stocks which adjusts the most recent advised catch according to the ratio of average stock size indices over the last years. However, this approach works very poorly for stocks with rapid growth and limited maximum age typical of short-lived species (Fischer et al., 2021, 2020). Due to their short lifespan and the delays between survey and management, a large proportion of these populations will have declined by the time management is implemented, adding to the already high uncertainties about the state of the stock at the time of fishing (Walker et al., 2023). The solution is to use in-season assessment data, which are typically based on CPUE data of commercial fisheries or pre-season surveys (Sánchez-Maroño et al., 2021).

Such in-season assessments are used, for example, for the most commercially important cephalopod fisheries, e.g. the Falkland Islands Illex fishery (Arkhipkin et al., 2013) due to the highly migratory and adaptive nature of these species. The CPUE, as in-season information on abundance, allows fishery managers, for example in the Japanese T. pacificus fishery, to forecast catches and abundances in specific fishing grounds (Kidokoro et al., 2014). Several published examples have used analyses of commercial CPUE or catch data instead of formal assessments to provide information on abundance trends, e.g. for whiting (Verdoit et al., 2003) or in the Portuguese mixed fisheries (Leitão et al., 2022).

In Europe, such an approach has only recently been implemented as a harvest control rule in the brown shrimp (*Crangon crangon*) fishery. The brown shrimp supports one of the most valuable European fisheries in the North Sea (€69 million in 2021 (European Commission: Joint Research Centre et al., 2023)). The fishing fleets of Germany, the Netherlands and Denmark are responsible for more than 90% of the annual landings (ICES, 2023). Despite the high value of the fishery, there is no regular advice, no dedicated survey and no regular stock assessments. There are no quotas or effort limitations, and national and international legislation and fisheries policies do not provide for population-based management measures.

In particular, assessing the status of brown shrimp (*Crangon crangon*) has been a challenge for decades. This is largely due to the lack of coherent effort data from international fisheries. In addition, biological characteristics such as the impossibility of age determination, the short life cycle and high predation mortality have complicated analytical assessments, despite major advances in knowledge of the life cycle of *C. crangon* in recent decades. As a result, previous stock status studies have had to rely on a comparison of predation and commercial landings. These studies often concluded that there was no need to manage the stock and that overfishing of *C. crangon* was not occurring, or was even impossible, given that predation mortality far exceeded fishing mortality (Tiews, 1978; Welleman and Daan, 2001).

Fishermen's organisations in the Netherlands, Germany and Denmark started a Marine Stewardship Council (MSC) assessment process in 2007 in order to be certified according to MSC criteria. An important requirement for MSC certification is that effective management of the target stock is in place. In order to meet this criterion, the industry started to develop a self-regulatory system based on landings per unit effort (LPUE) as a harvest control rule (HCR) to manage the population of the fished species (Temming et al., 2013).

Finally, POs in the Netherlands (Coöperatieve Visserij Organisatie (CVO)), Germany (MSC-GbR) and Denmark (Danish Fishermen Producer Organisation (DFPO)) developed and officially adopted the shrimp management plan, which came into force on 1 January 2016. A cap on the number of vessels and the combined kW power of the fleet should freeze fishing effort at the level recorded by the authorities in the Netherlands, Germany and Denmark on 1 January 2015. Vessels will be limited to 200 days at sea per year. The management plan details the harvesting strategy, including a set of HCRs and a set of additional regulations for shrimp trawl fisheries. It focuses on two main issues: reducing growth overfishing and preventing recruitment from being impaired by a declining stock. Growth overfishing was first diagnosed by Temming & Hufnagl (2015) based on a Y/R model, while indications for a possible recruitment overfishing were presented in (Respondek et al., 2022).

The CRANNET project has shown that growth overfishing of shrimp stocks can be reduced by increasing the mesh size of trawl nets so that smaller shrimp escape and continue to grow (Günther et al., 2021). As larger shrimp produce more eggs, such a strategy would also reduce the risk of recruitment overfishing. The initial management plan therefore aimed to increase mesh size in the cod end from the current 20mm to 26mm by 1 May 2020.

In order to minimise the non-target by-catch, the trawl must be equipped with a sieve net with a maximum mesh size of 70 mm or a sorting grid with a maximum bar spacing of 20 mm. Catches must be sorted mechanically on board using a mesh size adapted to commercial shrimp size and later also on land at the sorting station using a sieve with a minimum mesh size of 6.8 mm. The undersized shrimp, resulting from the sorting process, referred to as "sievage", must not exceed 15% of a vessel's total landings over a period of two calendar weeks.

LPUE data (expressed in kg per hour at sea) are used as an indicator of the state of the stock. In years when the recruitment is low, such that the LPUE falls below a pre-determined precautionary level, fishing effort is reduced to protect the stock. For this the monthly average LPUE data for all vessels, collected from electronic logbooks and auction data, are compared with the pre-determined monthly reference levels of LPUE.

The harvest control rule was tested in an earlier version by Temming et al. (2013). However, the design has changed since then. Deviating from the originally recommended harvest strategy, the predefined reference values were set to 70% of the mean LPUE for the German fleet in 2002 and 2007. This resulted in a very low probability of falling below the reference points (ICES, 2019). The LPUE is calculated by the MSC Steering Committee at the end of each month and compared with the reference values. If one of the reference points is reached, the corresponding effort restriction is applied. The LPUE is then monitored and calculated every two weeks until it is back above the first reference level. The aim of this study is to test the effectiveness of this harvest control rule in its current form and to compare it with an alternative approach.

Two scenarios will be tested. In scenario A), the size of the Crangon stock in the population model was reduced to 70% of its initial size. This scenario has been chosen according to an earlier investigation into the robustness of a HCR design for the shrimp fishery (Temming et al., 2013). This scenario simulates a year with an overall decreased shrimp stock throughout the year. In scenario B), a simulated recruitment failure reduced the number of eggs starting to develop in November and December, leading to a recruitment failure in the following summer. This scenario, leading to very low shrimp abundance in the second part of the year, could be caused by massive invasion of predators, a mismatch of the shrimp larvae and their prey (Hünerlage et al., 2019) or an increase in the winter fishery, leading to high mortalities of egg-bearing females (Respondek et al., 2022).

The aim of the study was to 1) quantify the effect of the HCR-induced effort reduction on the stock in two different scenarios and 2) test alternative HCR designs with regard on this effect.

Material and Methods

Adjustment of the shrimp population model

For the simulations, the yield-per-recruit model as described in (Günther et al., 2021; Temming et al., 2017) was used in an updated version (Temming et al., 2022). In simplified terms, this is a numerical simulation model in which shrimp eggs start their development every day and grow depending on the prevailing temperature conditions. The daily starting shrimp cohorts are subject to a mortality that varies both size-dependently and seasonally and thus reflects the influence of predators and fishing on the population. To validate the performance of the model, the seasonal landing patterns generated by fishing mortality can be compared with the real observations. Similarly, observations of the timing of the mass occurrence of small shrimps on the tidal flats can be used to validate the model. Lastly the distribution of the monthly simulated catch in two commercial size classes can be compared to corresponding observations from the sieving stations. The absolute number of eggs that start daily in the model is adjusted such that the sum of the annual landings after three simulation years match the observed values of the commercial fishery. In a first version, the model simulated the average situation of the German fleet in the 1980s, mainly outstanding due to a high level of natural mortality compared to fishing mortality, in what was named as standard run I in a follow-up study by (Temming et al., 2017). In that study, the authors developed a model version which they called standard-run II, representing the situation of the stock fished in the years 2002 to 2012. The newly developed model run used here represents the average situation of the stock fished in German waters in the years 2013 to 2020 and takes into account changes in the fishery as well as the latest knowledge of the population dynamics resulting from the CRANMAN project (Temming et al., 2022)(see Table II-1 and 2 for details). To investigate the influence of the fishery on the spawning stock, the life-cycle in the model was closed: the egg index from (Temming et al., 2017) was initially used in the first two years to start the model ("spin-off"). Once the model has been running for two years and all cohorts and size classes are present in the system, the index is replaced in the third year by the internally produced eggs, which then produce subsequent generations.

Although the model runs on a daily basis, some input data (effort) and output variables (e.g. landings) are calculated on a monthly basis. The values for landings, biomass and egg-production after reaching a stable state in the fourth year of the simulation were then used for the evaluation of the HCR.

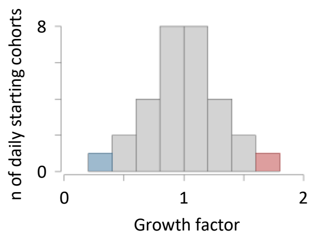
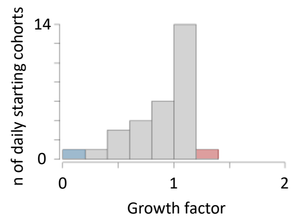
Table II-1: Model settings for mortality compared to Temming et al 2017.

		Basic model		**Updated model**	
		Equation or numbers of setting	***Reference***	***Equation or numbers of setting***	***Reference***
1	Larval M (year^{-1})	$y = 1.22 \times 1.5758 \times DW_{ZS}^{-0.25}$	Peterson & Wroblewski 1984	Not changed	-
2	Dry weight larvae (g)	$y = e^{2.7+0.222 \times ZS} \times 10^6$	Criales & Anger 1986	Not changed	-
3	Juvenile M (year^{-1})	$y = e^{\ln(M_6)+(\ln(L)-\ln(6)) \times \frac{\ln(M)-\ln(M_6)}{\ln(50)-\ln(6)}}$	Temming et al 2017	Not changed	-
4	M (year^{-1})	1.5	Temming & Hufnagl 2015,	1.1	Temming et al 2022
5	Larvae M-monthly index	0.23; 0.23; 0.27; 0.28; 0.56; 1.13; 1.69; 2.26; 2.26; 1.69; 1.13; 0.28	Temming et al 2017	Not changed	
6	Juvenile 1 M monthly index	0.23; 0.23; 0.27; 0.28; 0.56; 1.13; 1.69; 2.26; 2.26; 1.69; 1.13; 0.28	Temming et al 2017	Not changed	

	(<20 mm)				
7	Juvenile 2 M monthly index (20-50mm)	0.22; 0.22; 0.27; 0.28; 0.57; 1.12; 1.69; 2.26; 2.26; 1.69; 1.12; 0.28	Temming et al 2017	Not changed	
8	Adult M monthly index (>=50 mm)	0.33; 0.33; 0.33; 0.33; 0.33; 0.95; 1.53, 2.01; 2.15; 2.01; 1.27; 0.44	Temming et al 2017	Not changed	
9	F (year-1)	3.8	Temming & Hufnagl 2015,	4.5	Temming et al 2022
10	Retention probability cod-end	$b = \frac{2 \times \log(3)}{SR}$ $a = -(b \times L_{50})$ $y = \frac{e^{a+b\times L}}{1 + e^{a+b\times L}}$ Mesh size 20 mm; L_{50}=26.9 mm TL; SR =7.5 mm TL	Santos et al 2019	See "Retention probability cod-end" for formula; Mesh size 21 mm; L_{50}=38.6 mm TL; SR =7.8 mm TL	Santos et al 2019
11	Retention probability "alive-sieving" (%)	See "Retention probability cod-end" for formula; L_{50}=38.5 mm TL, SR=20.5 mm TL	Günther et al. 2021	See "Retention probability cod-end" for formula; L_{50}=51.5 mm TL, SR=7.8 mm TL	Temming et al 2022
12	Discard survival (anuual or monthly %)	80	Lancaster & Frid 2000	80, 90, 90, 80, 70, 60, 55, 50, 50, 55, 65, 80	Temming et al 2022
13	Retention probability "sieving station", Consumption size (%)	Knife-edge, 45.7 mm	Sharawy et al 2019	See "Retention probability cod-end" for formula; L_{50}=52.8 mm TL, SR=3.1 mm TL	Friese et al (in prep)
14	Retention probability "sieving station", Consumption size fractions (%)	-	-	See "Retention probability cod-end" L_{50}=62.5 mm TL, SR=4.3 mm TL for formula	Friese et al (in prep)
15	F monthly index	0.19; 0.20; 0.86; 1.60; 1.39; 1.26; 1.19; 1.25; 1.27; 1.26; 1.09; 0.40	Temming et al 2017	0.39, 0.48, 1.08, 1.66, 1.52, 1.12, 1.04, 1.11, 1.12, 1.00, 1.00, 0.46	Temming et al 2022

Table II-2: Model setting for growth compared to Temming et al 2017.

		Basic model		**Updated model**	
		Equation or numbers of setting	***Reference***	***Equation or numbers of setting***	***Reference***
1	Spawning index (monthly)	0.62, 0.38, 0.41, 0.98, 1.61, 2.2, 2.51, 1.37, 0.41, 0.29, 0.62, 0.61	Temming & Damm 2002, Temming et al 2017	0.37, 0.28, 0.23, 0.65, 1.17, 2.22, 3.04, 2.40, 0.64, 0.33, 0.50, 0.18; (only spin-off year if life-cycle is closed)	-

2	Egg development (days)	$y = 1031.44 \times T^{-1.354}$	Redant 1978	Not changed	-
3	Larval development (days)	$y = (5.5/0.00584) \times T^{-1.347}$	Criales & Anger 1986	Not changed	-
4	Length Growth females ($mm*day^{-1}$)	$y = 0.03964 \times T - 0.00177 \times e^{0.0951 \times T} \times L$	Hufnagl & Temming 2011, Günther et al. 2021	Not changed	-
5	Length Growth males ($mm*day^{-1}$)	$y = 0.03964 \times T - 0.00177 \times e^{0.0951 \times T} \times L$	Hufnagl & Temming 2011, Günther et al. 2021	Not changed	-
6	Length Growth with variability ($mm*day^{-1}$)	$y = Length\ Growth \times Growth\ Factor$ 	Temming et al. 2017	$y = Length\ Growth \times Growth\ Factor$ 	-
7	Length growth with cohort effect ($month^{-1}$)	n.a.	-	$y = Length\ Growth \times Growth\ Factor \times Cohort\ Factor$ (1, 0.65, 0.65, 0.65, 0.65, 0.65, 0.65, 0.65, 0.85, 1, 1, 1)	-
8	Size at female maturity (mm)	$y = 45.7 + \frac{1}{0.244} \times \ln\left(\frac{P_{mat}}{99.5 \times 0.076 - 0.076 \times P_{mat}}\right)$ P_{mat} is randomly chosen between 0 and 100	Inverted function of Neudecker & Damm 1992	Not changed	-
9	Age at female maturity (days)	-		Not changed	-
10	Eggs attached to female (n)	$y = 0.01878 \times L^{3.0}$	Havinga 1930	Julian Day 1-46 & 305-365: $y = 0.09295 \times L^{2.52145}$ Julian Day 47-90 & 259-304: $y = 0.08139 \times L^{2.61757}$ Julian Day 91-258: $y = 0.07837 \times L^{2.67729}$	Boddeke 1982
11	Intermoulting period - IMP (days)	$y = 5.7066 \times L^{0.7364} \times e^{-0.09363 \times T}$	Hufnagl & Temming 2011,	$y = 0.423 \times L^{1.512} \times e^{-0.133 \times T}$	Sharawy et al 2019

			Günther et al 2021		
12	Seasonality of egg-bearing females (% all females)			34.5, 50.5, 69.8, 58.9, 47.9, 38.4, 39, 28.3, 10.2, 0.7, 39.9, 37.2	Hünerlage et al 2019
13	Egg production (n)	$y = n_{mature\ fem} \times Eggs\ at\ female \times \frac{1}{IMP}$	Temming & Damm 2002	Estimated on the basis of daily cohorts	

LPUE values from the simulation

Mortality in the model is implemented using two different sources; on the one hand, the average annual share of fishing (F) and natural (M) mortality in total mortality (Z) was estimated using the approach of Temming & Hufnagl (Temming and Hufnagl, 2015) updated by (ICES, 2023). To take into account seasonal variations in fishing mortality, the absolute seasonal pattern of fishing effort was used on the other hand to distribute annual fishing mortality over the season. The fishing effort used here reflects the effort in the German Exclusive Economic Zone (EEZ), derived from combined VMS and logbook data for the years 2013-2020 (Temming et al., 2022).

The starting number of eggs is adjusted so that the model produces landings equivalent to the average landings in the German EEZ, as indicated by the VMS and logbook data. To test the Harvest Control Rule (HCR), LPUE values from the simulation are required. However, the model itself does not produce LPUE values since the fishing effort is only used to generate the seasonal fishing mortality pattern. We assume here that the fishing mortality pattern in the simulation matches the real-world pattern resulting from fishing effort. Therefore, it follows that the fishing effort in the simulation, generating landings equal to the average landings in the German EEZ from 2013-2020, must be the same as the average fishing effort in the German EEZ during that period. The simulated LPUE is thus calculated by dividing the landings from the model by the mean fishing effort from the combined VMS and logbook data for the German EEZ from 2013-2020.

Conversion of reference values for the simulation

The input effort for the model is measured in fishing hours at sea (fihas). As a result, the LPUE (Landings Per Unit Effort) from the simulation is expressed in kilograms per fihas. However, the reference values used in the management of the Brown shrimp fishery are based on LPUE expressed in kilograms per HAS (hours at sea, Table II-1). To ensure comparability, these reference values must be converted from kilograms per HAS to kilograms per fihas. The reference values rely on the average German landings (in kg) and effort (measured in HAS) from the years 2002 and 2007. Unfortunately, fihas are determined using combined VMS (Vessel Monitoring System) and logbook data, which are unavailable for the years 2002 and 2007, making direct comparisons impossible. Furthermore, the combined VMS and logbook data provide information on the location rather than the nationality of the fleet, further complicating the situation. Additionally, the logbook data that the Harvest Control Rule (HCR) relies on lacks detailed and reliable spatial information and is available only for the years 2013 to 2018 for the Dutch, German, and Danish fleets. To address this issue, we calculated conversion factors by dividing the monthly LPUE in kg/fihas, as derived from the combined VMS and logbook data for the Dutch, German, and Danish Exclusive Economic Zones (EEZ), by the LPUE in kg/HAS from the logbook data for the same fleets over each month from 2013 to 2018. The monthly mean of these conversion factors was then used to adjust the reference values from the management plan for the modeling exercise. The reference values 4 and 5 from the management plan were not converted as there was no need for them in the simulation.

Potential effort reduction of the fleet(s)

The HCR imposes a restriction on the fishing effort, measured in hours at sea per week and vessel, to a certain limit when the average LPUE of the fleet drops below a specified threshold. When e.g. the LPUE falls below the first reference value, the effort is restricted to 72 HAS per week and vessel. To simulate the impact of the HCR on the shrimp stock, we needed to evaluate the fishing effort under effort restrictions compared to the effort without such restrictions. To take the example above, to test the effect of an effort restriction to 72HAS per week and vessel in week 1, we need to know much effort the fleet would have generated in this week with and without effort restriction. In practice, there is no scenario where both states exist simultaneously within a given year – it's either effort-restricted or not. Therefore, we calculated the potential reduction in effort for each of the effort limit values using logbook data for the German fleet from years without restrictions. Only vessels exceeding the effort limit would need to reduce their effort. The year 2016 marked the introduction of effort restrictions. It is assumed that during the years 2002-2015, all vessels fished without limitations as they did historically. For each week and vessel, starting from Monday 0am to Sunday 24pm, the total effort was calculated. Vessels that exceeded the weekly effort limits of 72, 60, 48, and 36 HAS were identified for each week. Their effort was adjusted to match the respective effort limit. Then, the sum of weekly effort including all vessels was calculated, once for the fleet with the maximum weekly effort set to the limit and once without any restrictions. The difference between the sums of the unrestricted and restricted effort represents the potential effort reduction for each week from 2002 to 2015. The average potential effort reduction per calendar week was then calculated for each effort limit (Lim 1-4, as shown in Table II-1). As mentioned before, the simulations does not use the value of fishing effort other than for shaping the pattern of the fishing mortality. Thus, to analyze the effect of reduced fishing effort on the population in the simulation, we assume that the reduced effort directly leads to equally reduced fishing mortality. When e.g. the effort restriction to 72HAS per vessel and weeks results in an effort reduction of 10% in week 1 (Fig. II-2), we reduced the fishing mortality in the simulation by 10% in week 1.

Four different HCR designs were tested in the simulation (Table II-4). The first design (no HCR) presumes that no effort restrictions are placed on the fleet, regardless of the LPUE values. The second design (HCR72) is similar to the actually implemented HCR, with an effort reduction to 72 hours at sea when the first reference value is breached. When the LPUE falls below the second reference value, the effort is restricted to 60 hours at sea per week and vessel (Table II-1) and 48 hours at sea below the reference value 3. The third design (HCR60) starts with an effort reduction to 60 hours at sea per week and vessel when the LPUE falls below the first reference value, with 48 and 36 hours as next steps. The fourth design (HCR48) starts with 48 hours at sea directly and 36 and 24 hours are the effort limitations for the reference values 2 and 3. The last design (HCR99) exerts a complete two-weeks closure when the first reference value is breached (HCR99). Only a small test-fishing would be allowed in this case, to get current LPUE values. This approach was simulated by reducing the effort by 99% for two weeks. In this case, the model could still produce some landings for LPUE calculation.

Table II-1. Effort limitations in hours at sea for the HCR designs.

Reference value	Maximum hours at sea per week and vessel and potential effort reduction (in brackets)				
	noHCR	HCR72	HCR60	HCR48	HCR99
< Ref1	-	72 (Lim1)	60 (Lim2)	48 (Lim3)	0 (99%)
< Ref2	-	60 (Lim2)	48 (Lim3)	36 (Lim4)	0 (99%)
< Ref3	-	48 (Lim3)	36 (Lim4)	24	0 (99%)

Decision building in the simulation model

The LPUE from the simulation is calculated on a monthly basis. If the LPUE falls below the (adjusted) reference value, the effort is limited in the first two full weeks of the following month, depending on the reference value and the maximum allowed hours at sea per week and vessel (Fig. II-1, Table II-2). The LPUE of this month is calculated again, and if it is still below the reference value, the restriction is extended by another two weeks. If at least the last week with effort limitation is in a month with an LPUE above the reference value, the restriction is withdrawn.

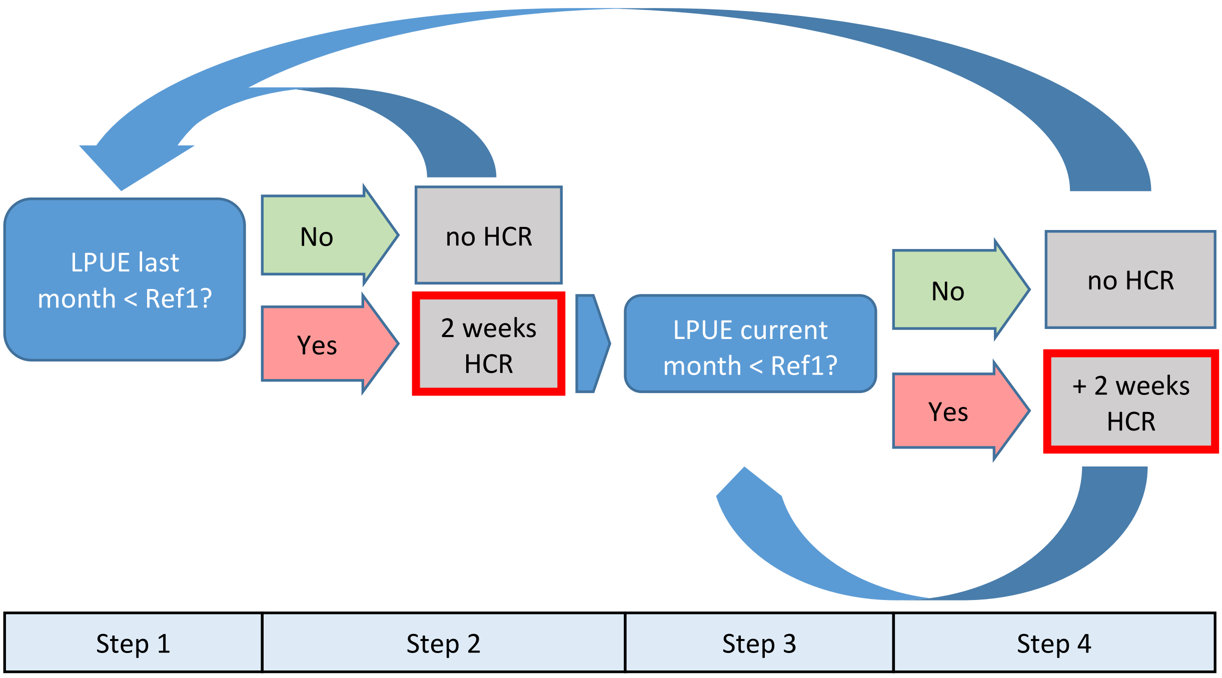


Fig. II-1: Decision model used for the HCR simulation. Each Month, the LPUE is calculated (Step 1). When the LPUE is below the reference value (Table II-1), the effort of the next two weeks is restricted (Step 2). After the simulation of the actual month is finished, the LPUE of the actual month is calculated (Step 3). When the LPUE of the actual month is still below the reference value (Step 4), the effort is restricted for additional 2 weeks and the LPUE of the actual month is calculated again (Step 3). Otherwise the effort is not restricted and the simulation continues (Step 1).

Creation of low stock scenarios

Two low abundance scenarios were simulated:

1) Stock reduction to 70% due to reduced recruitment
2) Egg-loss in November-December

For a stock reduction to 70%, the initial number of starters in the spin-off phase were reduced by 30% compared to the standard run values. For Egg-loss in November-December, the number of eggs starting to develop were reduced by 50% in the calendar days 206 to 365 (November and December) in year 3 of the simulation by introducing an “egg-loss”-factor. This factor reduces the number of newly spawned eggs per female in this period.

For the quantification of the effects of the different HCR approaches, the landings of consumption shrimps, the total biomass, egg production and effort of the final simulation runs in the fourth year of the simulation are compared.

Results

Conversion of reference values for the simulation

The monthly conversion factor to translate the reference values from the management in kg per HAS to reference values in kg per fihas shows a seasonal pattern (Table II-2). The largest difference is found In May with one kg per HAS being equivalent to 1.642 kg per fihas, the lowest value in January with 1.378. The standard deviation was highest in March with 0.3424 and lower in the main season with the lowest value in October (0.0480) (Table II-4). On average, the LPUE in kg/fihas, which does not take into account the steaming time, is 1.5 times larger than the LPUE in kg/HAS which is based on the total effort including the steaming time.

When applied to the reference values 1-3 of the management plan, the calculation results in higher reference values Ref 1, Ref 2 and Ref 3 (Table II-4).

Table II-4. Conversion factor from LPUE in kg/HAS to kg/fihas (column "Mean 2013-2018") and standard deviation ("SD"). Adjusted reference values for the simulation in kg/fihas are shown in columns 5 - 7(Ref1-Ref3). For comparison the official reference values for Ref 1 in kg/HAS are added in column 4. The reference values 2-5 from the official Management plan are not shown for readability.

Month	Conversion factor LPUE VMS/LPUE Logbook		Management plan Reference value 1	Ref 1	Ref 2	Ref 3
	Mean 2013-2018	SD				
1	1.378	0.2256	16.36	22.55	20.93	19.32
2	1.420	0.2773	12.39	17.60	16.34	15.08
3	1.527	0.3424	14.12	21.56	20.02	18.49
4	1.585	0.1693	14.20	22.51	20.89	19.29
5	1.642	0.1182	13.50	22.17	20.59	19.00
6	1.605	0.1052	12.17	19.54	18.14	16.74
7	1.525	0.0803	16.98	25.90	24.05	22.19
8	1.529	0.0720	22.27	34.04	31.62	29.19
9	1.538	0.0739	26.20	40.29	37.42	34.54
10	1.528	0.0480	26.52	40.53	37.63	34.73
11	1.494	0.0682	20.75	30.99	28.79	26.56
12	1.389	0.0598	16.78	23.31	21.64	19.97

Potential effort reduction of the fleet(s)

When the LPUE falls below the first reference value, the effort is restricted to 72 hours at sea (HAS) per week and vessel. This results in an average potential effort reduction of 12% (Fig. II-2). The potential reduction is more significant during the first half of the year compared to the second half. Specifically, the reduction is approximately 15% during weeks 1 to 25 and around 10% during weeks

26 to 51. The highest potential reduction occurs in week 17, exceeding 20%. As the limit values are further decreased—first to 60, then to 48, and finally to 36 HAS per week and vessel—the potential effort reduction increases, since more vessels are subject to the effort restriction. For a limitation of 60 HAS, the average potential reduction is 19%, for 48 HAS it is 29%, and for 36 HAS it reaches 42%. The lowest potential reduction values are observed in the last two weeks of the year, with around 10% when the effort is restricted to 36 HAS per week and vessel during weeks 52 and 53. In contrast, the potential effort reduction is highest in weeks 15 and 17, exceeding 50% when the limit is set to 36 HAS per week and vessel (Fig. II-2).

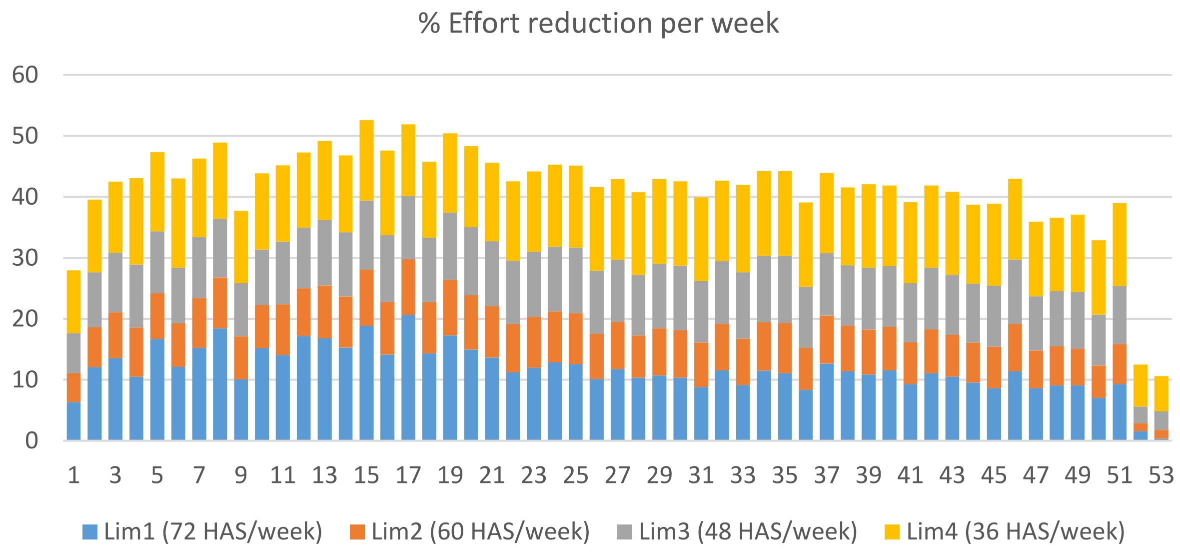


Fig. II-2: Percentage of effort reduction per week when different limits in hours at sea apply to the German reference fleet. Only the potential reduction for the limits of 72, 60, 48 and 36 HAS per vessel and week are displayed, as only those have been used in the simulation.

Standard run

The run of the model with no effort restrictions, no stock reduction and no egg loss is used as baseline (hereafter "standard run"). It is the first version with a closed life-cycle. It produces a stable output in the third and fourth year after two years of spin-off phase (Fig. II-3). The simulated landings in the third and fourth year in June are lower than the observed landings. The landings and biomass in the fourth year are 6% respective 7% lower than in the third year (Fig. II-3). The number of juvenile shrimp of 10mm peaks in June in the first year, in May in the following years (Fig. II-3). The egg production of the model is 2.75 times the initial number of eggs when the simulation started. To reach an equilibrium and a stable state, the number of eggs for the closed life cycle is reduced by this factor.

For the purpose of this study, the 4th year of the simulation is used (Fig. II-4). The seasonal landings and LPUE patterns can be compared to observed values. Landings and LPUE of the simulation are higher than the mean of the observed values of 2013 to 2020 from January to May. From June to December, the landings and LPUE are lower than the mean of the observed values (Fig. II-4). For both, LPUE and landings, the simulated values are within the range of the observed values, which show higher variation in the second half of the year (Fig. II-4). The mean of the adjusted reference value 1 is 64% of the mean LPUE calculated from landings and the corresponding effort of the standard run, with the lowest value of 53% in September, the highest with 80% in June (Fig. II-4). The limit reference value of the management plan is on average 46% of the LPUE of the standard run, with the lowest value in February with 36% and the highest value in June with 57%.

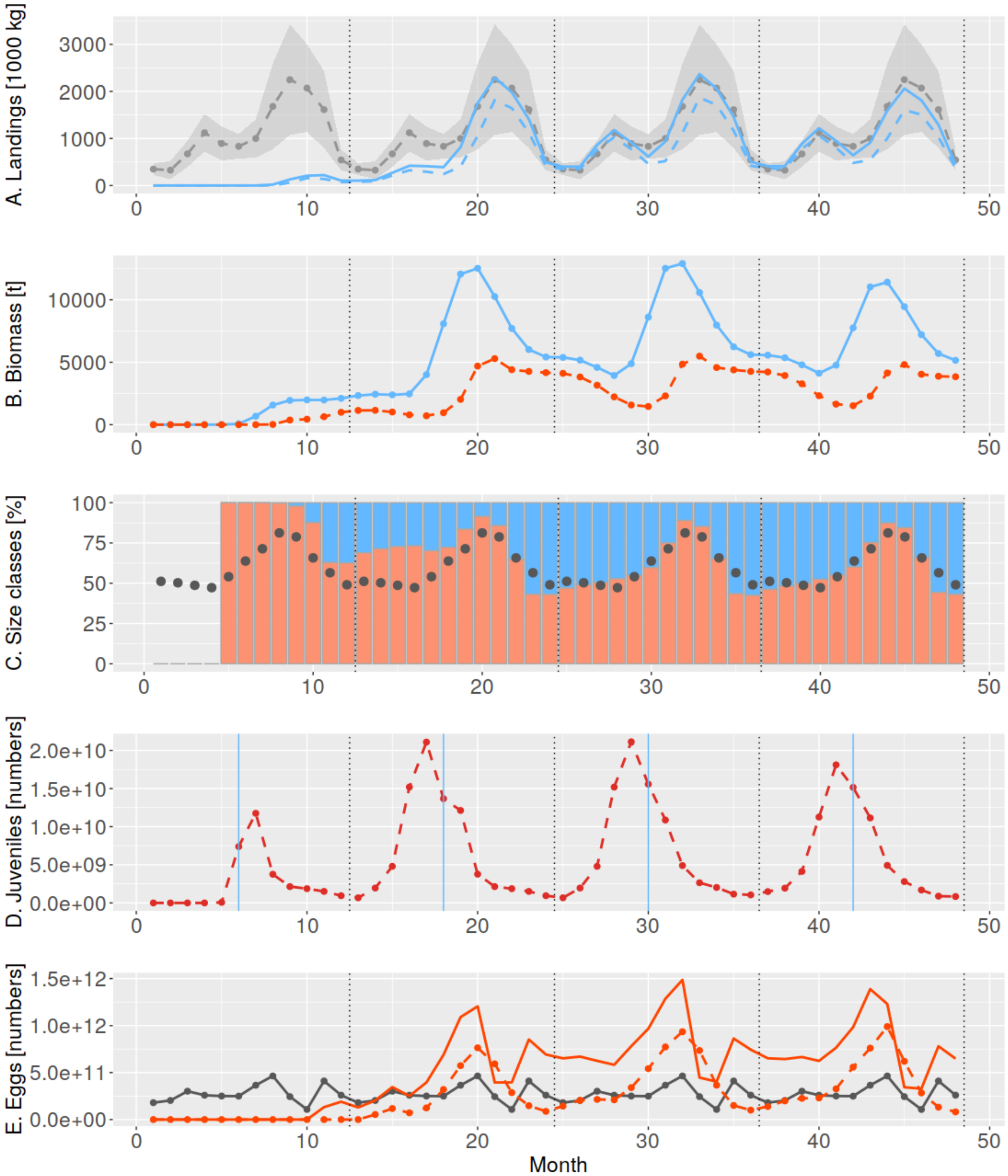


Fig. II-3: Model output. From top to bottom:

A. Observed landings (dashed grey line) for the years 2013 to 2020 and simulated values for LPUE and landings (blue solid line: all srimp landings, blue dashed line: consumption size only). The grey shaded area displays the range of the observed values.

B. Biomass (blue solid line: all sizes, dashed orange line: commercial sized shrimps).

C. Size structure of the landings: The orange bars display the percentage of shrimp between 6.8mm and 8.5mm carapax width, the blue bars the shrimp larger than 8.5mm carapax width from the simulation output. The grey points display the relation between the shrimp larger than 8.5mm *carapax and shrimp between 6.8mm and 8.5mm carapax width from landing declaration data for the years 2002 – 2016 and 2018. 2017 was excluded due to low data quality.*

D. Number of juvenile shrimp in the simulation: the orange line represents the number of juvenile shrimp of 10mm length. The blue vertical line mark the peak of juvenile shrimp of 10mm size in June as observed in the field by (Temming and Damm, 2002).

E. Eggs: The black line shows the number of eggs as initially starting in the model. The orange solid line shows the number of eggs as produced by the model, the orange dashed line shows the number of actually hatched eggs.

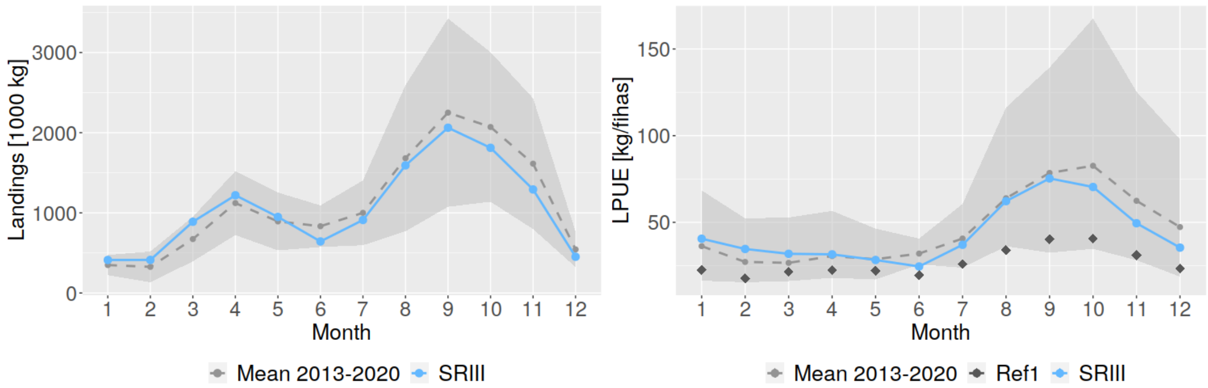


Fig. II-4: Landings (left) and LPUE (right) from the standard run, year 4 of the simulation. Mean observed values for LPUE and landings from VMS and logbook data (dashed grey line) for the years 2013 to 2020 and simulated values for LPUE and landings (blue solid line). The grey shaded area displays the range of the observed values. The dark grey diamonds in the right plot display the adjusted reference values Ref1 from Table II-4.

Stock reduction to 70%

In the scenario with the stock reduction to 70%, the landings in the last year were consequently lower (Fig. II-5). The LPUE fell below the first reference Ref 1 in April and below the second reference value Ref 2 in May and June (Fig. II-5 and Table II-5).

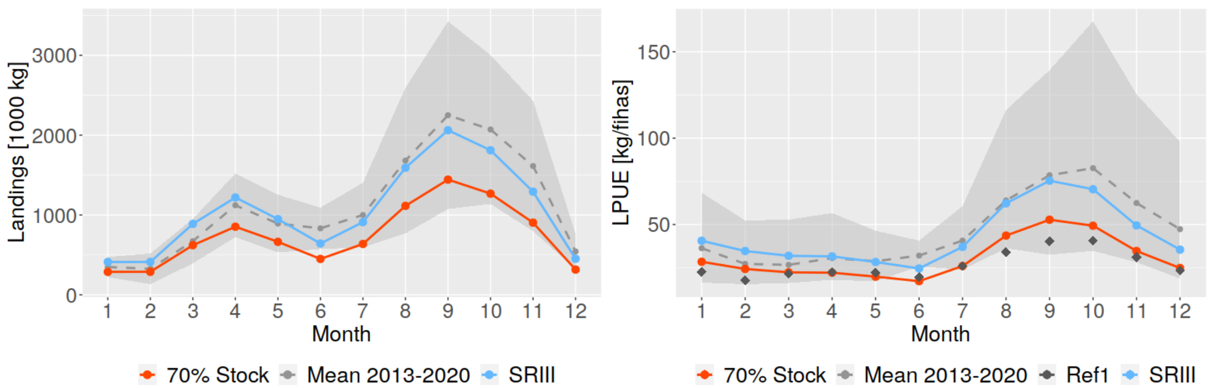


Fig. II-5: Landings (left) and LPUE (right) of year 4 of the simulation. The mean of the observational values from 2013-2020 for landings and LPUE from VMS and logbook data is displayed as dashed grey line, the range of the observed value sis displayed as grey shaded area. The values for the standard run are displayed in blue, the values for the run with the initial stock reduced to 70% in *orange. The dark grey diamonds in the right plot display the adjusted reference values Ref1 from Table II-4.*

HCR72

As the first reference value was undercut in April, this resulted in a first effort reduction to 72 hours at sea per week and vessel in the first two weeks of May (18 and 19) in the HCR72 approach (Table II-5). After applying this reduction, the LPUE in May was still below the second reference value. As result, the effort was restricted to 48 hours at sea per week and vessel in the next two weeks of May (weeks 20 and 21). After that, the LPUE did increase above the second but remained below the first reference value in May, leading to an additional restriction of the effort to 72 hours at sea in the weeks 22 and 23. The following restriction of the effort to 72 hours at sea for the weeks 24-25 did not result in raising the LPUE above the reference values. After the first two weeks of July (26 and 27), the effort restriction was lifted (Table II-5). The LPUE stays above the LPUE of the “no HCR” approach for the rest of the year, with in September and October being the highest LPUE of all approaches with 53.8 and 49.97 kg/fihas.

HCR60

When the effort was reduced to 60 hours at sea per week and vessel in the first two weeks of May in the HCR60 approach (Table II-5), the LPUE in May did not increase above the second reference value. Accordingly, the effort was reduced to 48 hours at sea per week and vessel in the next two weeks, 20 and 21. This did result in an increase in LPUE in May above the second reference value. After two additional weeks (22 and 23) of effort reduction to 60 hours at sea per week and vessel, the LPUE in June did increase above the first reference value and no further effort limitation did apply (Table II-5).

HCR48

In the HCR design with an effort reduction at the first reference value of 48 hours at sea per week and vessel, already the first effort reduction in weeks 18 and 19 did lead to an increase of the LPUE in May (Table II-5 and Fig. II-6). As the LPUE was still below the first reference value, another two weeks of effort limitation to 48 hours did apply. This did result in the June LPUE being above the first reference value. Subsequently, after two additional weeks of effort limitation to 48 hours, the effort restrictions were lifted. In this approach, the highest LPUEs of all approaches in July and August were reached with 28.72 and 45.34 kg/fihas.

HCR99

In the HCR 99 approach, breaching the first reference value results in a reduction of the effort by 99% in weeks 18 and 19 (Table II-5). Afterwards, the LPUE in May did already rise above the first reference value, such that the effort restriction is lifted. The LPUE in May is nearly 4 kg/fihas higher than that of the no HCR approach and still nearly 2 kg/fihas higher than that of the second highest LPUE of the HCR 48 approach. The LPUE of June, November and December is the highest of all approaches with 20.82, 35.21 and 25.53 kg/fihas.

Table II-5. Effort restrictions and resulting LPUE values as implemented by the decision model. The effort was reduced to 72, 60 and 48 hours at sea per week and vessel or by 99% per week when the first reference value was undercut depending on the HCR. The column name displays the name of the HCR approach and those weeks where an effort reduction has been applied. The colour of the cell refers to the reference value that has been breached, with green indicating the LPUE is above all reference values, light red indication below the first reference value and deep red indicating a LPUE below the second reference value. Values marked in bold are the highest values of all approaches in those months after the effort restriction. The 30th April is the first day in week 18, the first week with effort reduction.

Month	no HCR	**HCR72** Weeks 18 to 27: 72 HAS	**HCR60** Weeks 18 to 23: 60 HAS	**HCR48** Weeks 18 to 23: 42 HAS	**HCR99** Weeks 18 to 19: 99%
1	28.37	28.37	28.37	28.37	28.37
2	24.23	24.23	24.23	24.23	24.23
3	22.29	22.29	22.29	22.29	22.29
4	22.07	22.09	22.10	22.11	22.19
5	19.78	20.81	21.37	21.81	**23.71**
6	17.16	19.13	19.98	20.79	**20.82**
7	25.92	28.29	28.08	**28.72**	28.43
8	43.56	45.23	44.93	**45.34**	45.01
9	52.73	**53.80**	53.50	53.73	53.50
10	49.27	**49.97**	49.75	49.90	49.79
11	34.63	35.07	35.00	35.12	**35.21**
12	24.79	25.18	25.20	25.32	**25.53**

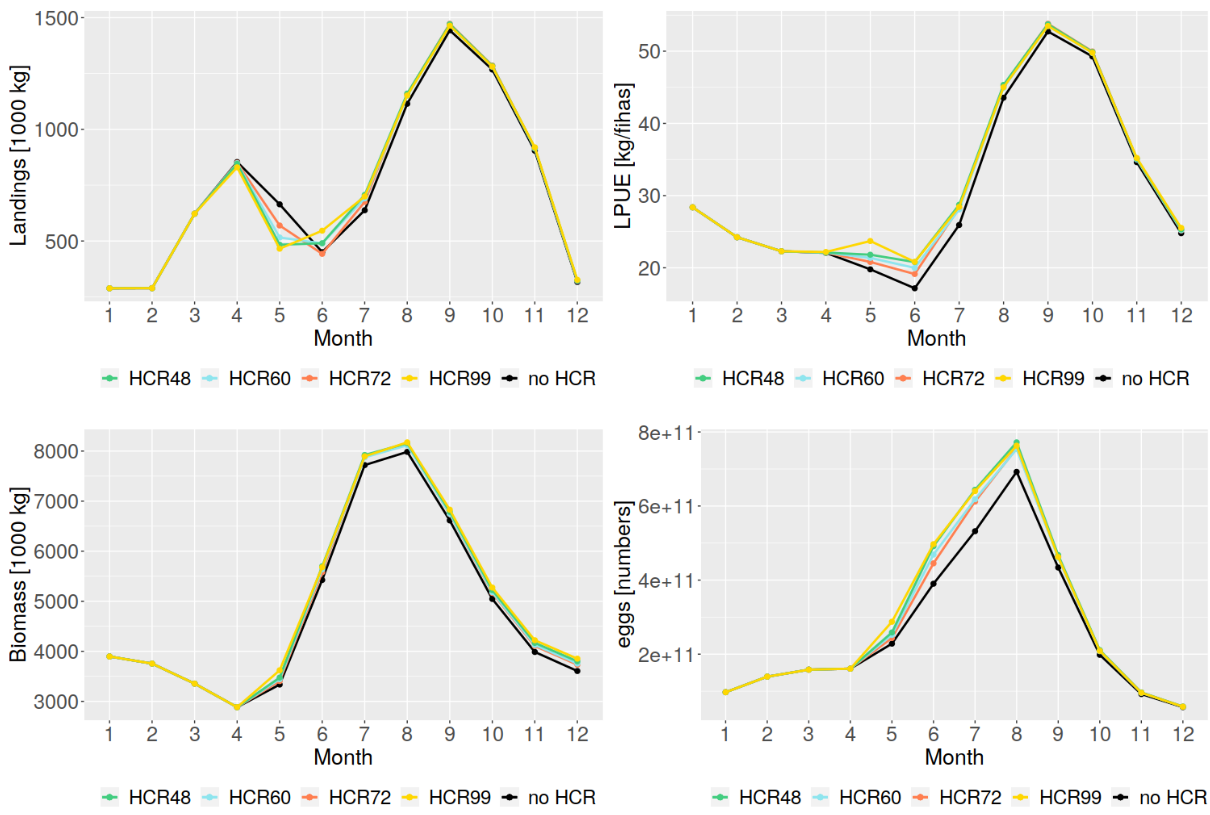


Fig. II-6: Final runs of the model with different HCR approaches according to table 3, montly values of the 4th year of the simulation. Upper left: Landings in 1000kg, upper right: LPUE in kg/fihas. Lower left: biomass in 1000kg, lower right: produced eggs in numbers.

The landings off all approaches with HCR are lower in May than without HCR (Fig. II-6), but increase above the no HCR approach in the following months (Fig. II-6). From July to August, the highest landings are achieved by the HCR48 approach, in June, November and December the highest landings are achieved with the HCR99 approach. The highest biomass is achieved in May and from August to December with the HCR99 approach, in June and July with the HCR48 approach. The egg production is highest with the HCR48 approach from July to October and with the HCR99 approach in May, June, November and December.

Recruitment failure: Egg-loss November-December

A possible recruitment failure, simulated by reduced egg numbers in November and December in year 3, leads to lower landings in the autumn of year 4. The LPUE and Landings are at the level of standard run from January to May and start to decline in June (Fig. II-7). The autumn season starts directly with the second reference value breached in July (Table II-6, Fig. II-7). The LPUE undercuts the second reference value from July to August and October to December and the first reference value in September (Table II-6).

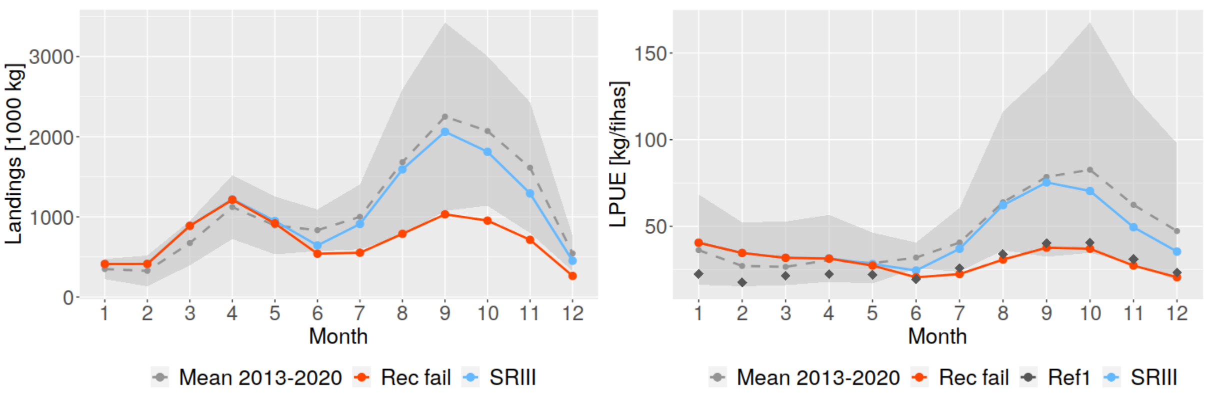


Fig. II-7: Landings (left) and LPUE (right) of year 4 of the simulation. The mean of the observational values from 2013-2020 for landings and LPUE from VMS and logbook data is displayed as dashed grey line, the range of the observed value sis displayed as grey shaded area. The values for the standard run are displayed in blue, the values for the run with the simulated recruitment failure in orange. The dark grey diamonds in the right plot display the adjusted reference values Ref1 from table 4.

HCR72

In the HCR 72 approach, the effort was reduced to 60 HAS per week and vessel from the first week of August (week 32) to the second week in the beginning of September (week 37). This finally led to an increase in September LPUE above Ref1. In October, the LPUE did fall below Ref1 again, resulting in an effort reduction from November on to 72 HAS per week and vessel. The LPUE did stay below Ref1 until the end of the year, resulting in the weeks 45-52 staying restricted to 72 HAS per week and vessel. This approach resulted in 14 weeks with effort restrictions.

HCR60

When HCR60 is applied and the effort is restricted to 48 HAS per week and vessel in weeks 32 and 33, the LPUE in August increases above Ref2 but is still below Ref1. Thus, the effort is restricted to 60 HAS per week and vessel in the weeks 34 and 35, leading to a further increase in LPUE above Ref1 in September. In October, the LPUE falls below Ref1 again, and the effort is restricted to 60 HAS per week and vessel in the first two weeks of November (45 and 46) again. The LPUE did not rise above Ref1 until the end of the year again, so the effort restriction is not lifted until the end of the year, with 12 weeks with effort restriction overall.

HCR48

In the HCR48 design the breaching of Ref2 in August leads to an effort restriction to 36 HAS per week and vessel in the weeks 32 to 33. In course of this effort reduction, the LPUE rises above Ref2, but stays below Ref1 in August. After two more weeks (weeks 34 and 35) with effort restricted to 48 HAS per week and vessel, the LPUE of September is above Ref1 and the effort limits are lifted. In November, the LPUE falls below Ref1 again and the effort in the first weeks of December (49 and 50) is restricted to 48 HAS per week and vessel. This limitation does not result in increasing the LPUE above Ref1, and the effort restriction stays in place until the end of the year. Overall, in 8 weeks effort restrictions have been applied.

HCR99

In the HCR99 approach, the reduction of the effort by 99% in weeks 32 and 33 let the LPUE increase from below Ref2 to above Ref1 in August. The LPUE stays above Ref1 in September and October. In November, the LPUE falls below Ref1 again. An additional reduction of the effort by 99% in the weeks 49 and 50 results in an increase above Ref1 in December, leading to 4 weeks with effort restriction in total.

Table II-6. Effort restrictions and resulting LPUE values as implemented by the decision model. The effort was reduced to 72, 60 and 48 hours at sea per week and vessel or by 99% per week when the first reference value was undercut depending on the HCR approach. The column name displays the name of the HCR approach and those weeks where an effort reduction has been applied. The colour of the cell refers to the reference value that has been breached, with green indicating the LPUE is above all reference values, light red indication below the first reference value and deep red indicating a LPUE below the second reference value. Values marked in bold are the highest values of all approachs in those months after the effort restriction.

Month	**no HCR**	**HCR72** Weeks 32 to 37: 60 HAS, Weeks 45 to 52: 72 HAS	**HCR60** Weeks 32 to 33: 48 HAS, Weeks 34 to 35: 60 HAS, Weeks 45 to 52: 60 HAS	**HCR48** Weeks 32 to 33: 36 HAS, Weeks 34 to 35: 48 HAS, Weeks 49 to 52: 48 HAS	**HCR99** Weeks 32 to 33: 99%, Weeks 49 to 50: 99%
1	40,53	40,53	40,53	40,53	40,53
2	34,60	34,60	34,60	34,60	34,60
3	31,80	31,80	31,80	31,80	31,80
4	31,37	31,37	31,37	31,37	31,37
5	27,34	27,34	27,34	27,34	27,34
6	20,58	20,58	20,58	20,58	20,58
7	22,44	22,44	22,44	22,44	22,44
8	30,81	31,45	31,90	32,36	**36,15**
9	37,66	40,92	40,48	42,04	**43,27**
10	37,04	40,07	39,32	40,58	**41,52**
11	27,31	29,50	29,27	29,41	**29,93**
12	20,61	22,45	22,65	22,18	**23,65**

The Landings off all approaches with HCR are lower in August than without HCR (Fig. II-8), but increase above the no HCR approach in September and October, except for the HCR72 approach, where the landings in September are lower than in the no HCR approach. In September, the landings of the HCR72 approach are lower than from the no HCR approach. In December, the landings of all approaches with HCR are lower than from the no HCR approach. The HCR99 approach produces the highest landings, except for August and December, where is produces the lowest landings of all approaches (Fig. II-8). The HCR99 approach produces the highest values for LPUE, biomass and egg production. The lowest values for LPUE, biomass and egg production are produced by the no HCR approach.

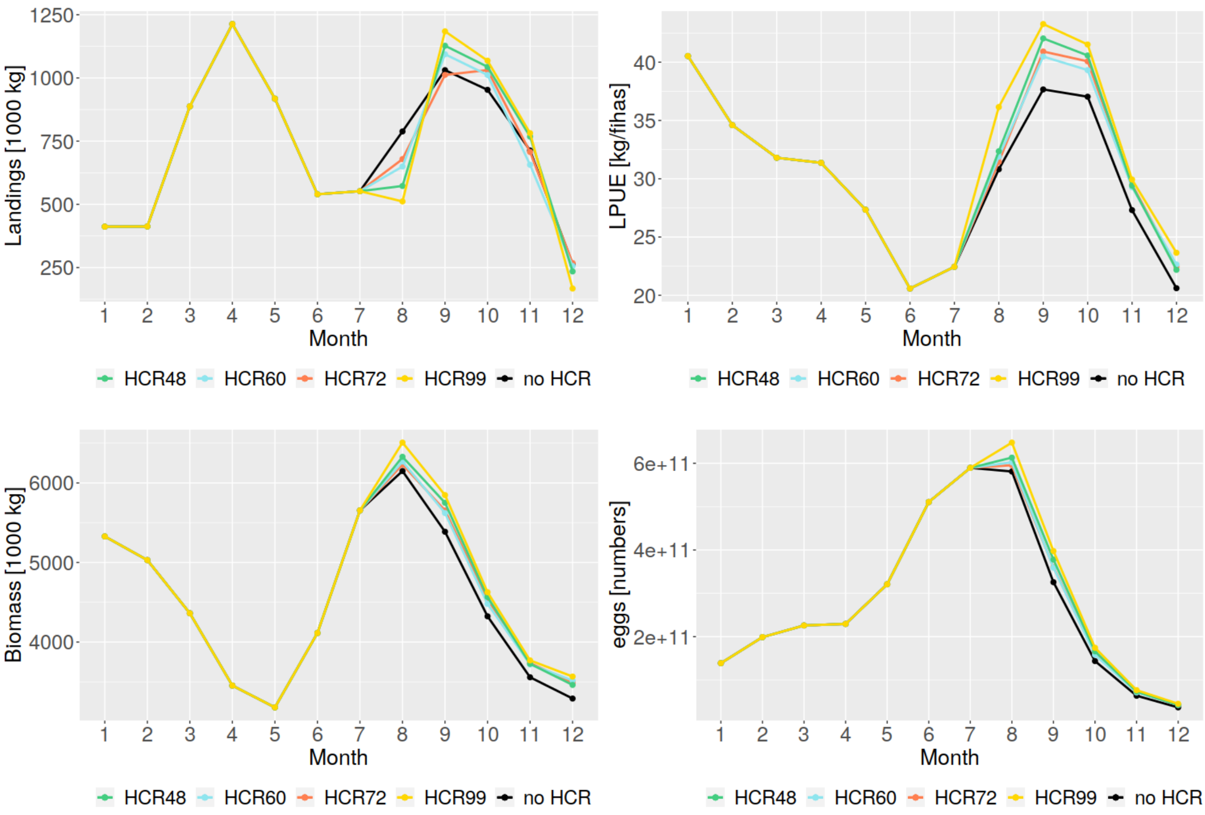


Fig. II-8: Final runs of the model with different HCR approaches according to Table II-3, montly values of the 4th year of the simulation. Upper left: Landings in 1000kg, upper right: LPUE in kg/fihas. Lower left: biomass in 1000kg, lower right: produced eggs in numbers.

When the results of the different approaches for the full year are compared, the effect on the landings is below 1% for all approaches. The effect on the biomass is the largest for the HCR99 approach, with an increase in biomass of 3.17% for the stock reduction to 70% case and 2.99% for the recruitment failure case. The increase in the yearly egg production is also largest for the HCR99 approach with 12.23% respective 5.66% more eggs compared to the no HCR approach. The effort reduction for the full year is largest for the HCR99 approach, too; with 5.23% respective 5.9% less effort than in the no HCR approach (Table II-7).

Table II-7. Results of year 4 of all runs and approaches. The percentage in the columns refers to the value of the approaches compared to the "no HCR" approach.

1) Stock reduction to 70%	**standard run**	**no HCR**		**HCR72**		**HCR60**		**HCR48**		**HCR99**	
Landings [1000 kg]	12646	8852	70%	8890	+0.43%	8874	+0.24%	8881	+0.32%	8884	+0.36%
Landings consumption [1000 kg]	9907	6935	70%	6981	+0.66%	6963	+0.40%	6971	+0.52%	6969	+0.49%
Effort [fihas]	290684	290684	100%	280437	-3.53%	279201	-3.95%	276165	-4.99%	275467	-5.23%
Biomass [1000 kg]	82297	57608	70%	58659	+1.82%	58774	+2.02%	59119	+2.62%	59436	+3.17%
Egg-production [1 Mio.]	4542355	3179648	70%	3439933	+8.19%	3470091	+9.13%	3555266	+11.81%	3568552	+12.23%

2) Egg-loss November-December	**standard run**	**no HCR**		**HCR72**		**HCR60**		**HCR48**		**HCR99**	
Landings [1000 kg]	12646	8684	69%	8633	-0.59%	8604	-0.93%	8683	-0.02%	8649	-0.41%
Landings consumption [1000 kg]	9907	7005	71%	7009	+0.07%	6984	-0.30%	7064	+0.85%	7062	+0.82%
Effort [fihas]	290684	290684	100%	281066	-3.31%	279971	-3.69%	280048	-3.66%	273532	-5.90%
Biomass [1000 kg]	82297	53828	65%	54771	+1.75%	54727	+1.67%	54954	+2.09%	55438	+2.99%
Egg-production [1 Mio.]	4542355	3365405	74%	3446032	+2.40%	3447925	+2.45%	3487004	+3.61%	3555733	+5.66%

Discussion

General limitations of the used VMS-Logbook data and the simulation model

The model output of the various seasonal patterns is generally close to available observational data (Fig. II-3). The deviations from the observed values are considered to be of minor importance regarding the conclusions drawn from the simulations, which focus on the differences between baseline and the specific scenarios. The fit of the model is not discussed here further in detail, for full discussion see (Temming et al., 2017).The yield per recruit model used in this analysis can only display a stable state of the stock and simulate effects of specific changes, such as e.g. effort reductions per month, against the baseline scenario. It cannot yet be used to forecast recruitment, or long-term stock development (Temming et al., 2017).

The data used as basis for landings and effort have several limitations, as described in detail by (ICES, 2023) and (Respondek et al., 2022). Specifically, minor landings of other species than *C. crangon* cannot be ruled out totally, and the estimation of the effort based on fishing pings and logbook entries may lead to some estimation bias of the "real" fishing effort. However, those limitations are well-known and the data is the best available up to date.

Translating the reference values into VMS-based values

The conversion factor shows higher fluctuations in the first half of the year, especially in January to March (Table II-4). It can be speculated that the reason behind is differences in steaming times to fishing grounds, which are usually farer from the coast in those months (Respondek et al., 2014). As the steaming time is included in the logbook effort, but not in the VMS-based effort, the LPUE conversion factor is higher in months when more steaming is included.

Calculating the potential effort reduction

In general, any avoidance-behavior by the fleet cannot be tested by this approach. It is assumed that all fishers have a very stable effort pattern which does not change too much over the years. They would just reduce the effort to the maximum allowed in the weeks with effort restrictions. Although previous investigations did reveal that overall the most fishers stick to their behavior (Respondek et al., 2014), examples from other fisheries show that e.g. when an MPA is planned, the fishers likely react with a fishing effort increase (McDermott et al., 2019). This behavior, called "preemptive overfishing", would reduce the effect from effort limitations due to the fact that the fishers know the limitation is likely coming. It has been observed in the logbook data, that the first time the fishing effort was limited by the HCR, the fishers responded by fishing closer to the coast, essentially decreasing steaming time and leaving more fishing time (ICES, 2022).

Another effect which has not been taken into account here is based on price development. In times with low shrimp densities and landings, prices can show a considerable increase, as it happened in spring 2016. Stimulated by the high prices, some fishers did increase their hours at sea and did work around the clock (pers. Comment). If this increase refers to vessels that normally do not fish 72 hours per week, it could even increase the effort if the first level of restrictions is enforced. Driven by variability of the shrimp population, shrimp price, weather and personal circumstances the annual patterns in effort may vary largely, so that a comparison between a "normal year" without effort restriction and a year where effort restrictions were put in place is difficult. As fishers generally complain about the effort reductions, it can be assumed that only those fishers decrease their effort which were above the critical level. As such, the calculated potential effort reduction can be seen as a good indicator for the effect of the HCR on the total fishing effort.

Management decision model

The decision model used here deviates from the way the effort restrictions are put in place in the real world. The fishery is calculating the LPUE values based on the first three weeks of each month, to decide whether the effort will be restricted from the beginning of the next month or not. When an effort restriction is put in place, the fishery calculates the LPUE every two weeks. This was not possible to simulate with the population model setup, as it – despite its daily time step – works with monthly average effort values. Instead, the LPUE is calculated after the actual month is finished (Fig. II-1). The effort is then reduced by the value given in Fig. II-2 for the respective weeks. The reduced effort value for the month is fed back into the model and the simulation is run again. In the simulation, the LPUE of the full month must be above the reference value, and this must be achieved by reducing the effort of only the two last weeks. In the real world, the LPUE of the last two weeks only must be above the reference value. Thus, the increase in landings in the simulation must be larger compared to the real world fishery to result in a similar increase in LPUE. However, compared with the uncertainties resulting from the fishermen's possible response to the effort restriction, the deviation of this setup from the real world was considered of minor importance.

Selection of scenarios

The first scenario of a stock reduction of 30% was selected to compare with the initial test of the harvest control rule (Temming et al., 2013), where a similar scenario was used to test the HCR. Hence as in this previous study, the number of initial starting eggs was reduced by 30%. This approach results in an equally lower stock throughout all simulated years, including the last year (Fig. II-5). The landings from this reduced stock are still well within the observed range, although on the lower edge (Fig. II-5). The Brown shrimp stock as observed in field surveys is highly variable. The total commercial-size shrimp biomass varied between 4000 and 21 000 tons over the years 1970-2015 (Tulp et al., 2016), hence such a scenario can be considered realistic. The mechanism behind the reduced stock must not necessarily be related to the fishery; however, it would be wise to reduce the fishing pressure in such case to allow that a larger share of shrimp to grow to maturity and contribute to the recovery of the stock.

The second scenario simulates a recruitment failure, which could be triggered by effects outside the fishery. Similar effects have been described by (Neudecker and Damm, 1992), which observed very low numbers of egg bearing females in 1992. A phenomenon known as “egg loss” has been described in the literature, possibly caused by the burrowing behavior of *C. crangon* (Oh and Hartnoll, 2004). Alternatively, the winter-fishery could be responsible very directly for removing large females together with the eggs attached (Respondek et al., 2022), or the larval mortality could be increased for a specific batch of larvae by an unknown factor. However, the egg loss was the most straightforward way to realize the recruitment failure in the model, without changing more code as necessary. In the case simulated here, the recruitment failure had to be a drastic case, otherwise the reference values in the second half year would not have been breached. Although the loss of half of all eggs for nearly two months may appear unrealistic, a combination of both, a low initial stock and a somewhat reduced recruitment could have a likewise strong effect on the LPUEs. However, a simulation of this combination would have resulted in possible effort reductions already in the first half year which should be avoided in this scenario to explicitly test the HCR in the main fishing season in contrast to the other scenario that lead to a triggered HCR in the first half of the year.

Selection of HCRs

The first approach tested, the HCR72, is very similar to the one currently implemented in the fishery. The limitations of the current design of the HCR have been discussed at repeatedly (ICES, 2022, 2019). The lack of any spatial element in the HCR does hinder the effective protection of local low abundances of shrimp from excess fishing effort, as has happened the main season in 2016 (ICES, 2022) when high catches in the southern areas did prevent effort limitations, while the LPUE in the northern parts of the fishing area was very low.

The reference values of the current HCR are calculated exclusively from two selected years of only German landings and effort data, whereas the current LPUE values which are used to be compared with the reference values in the management are calculated from all fleets which are member of the MSC group. When more years and all fleets would have been taken into account, the reference values would have been considerably higher (ICES, 2019). This led to challenges in designing the scenario with the recruitment failure, as the reduction of the stock by 30% as in the first scenario did not trigger the

HCR in the second half year. A quite drastic approach was needed to breach the relatively low references values in autumn, which resulted in only half of the landings in August to October compared to the standard run landings (Fig. II-7).

The potential effort reduction resulting from the limitation of the hours at sea to 72 per vessel and week is on average only 12% after the first reference value is breached. It is higher in the first half of the year, with values mainly between 10 and 20% effort reduction per week than in the second half. This can easily be explained by the longer trips to more offshore fishing grounds in the first half of the year (Respondek et al., 2014), which result in higher weekly effort for those larger vessels which are fishing. In the second half of the year, smaller boats are involved undertaking more short trips. These are not staying at sea more than 72 hours per week and are thus not affected by the effort reduction. The potential effort reduction is higher in the other approaches which would result in a mean 19% respectively 29% reduction after the first reference value is breached for HCR60 and HCR48.

Impact on the fishery

With the stepwise effort reduction, the currently implemented HCR, as well as the simulated approaches HCR60 and HCR48, follow a "proportional threshold harvesting" approach (Engen et al., 1997). In these systems, fishing effort is reduced stepwise whenever the abundance index falls below a reference point. In contrast, the "threshold harvesting" approach, such as the HCR99 approach, has a different design and results in a 99% reduction of effort right away, just allowing for some test-fishing (Lande et al., 1997). As such, the potential effort reduction is far higher than in the other approaches, a strategy which could be beneficial in rebuilding the biomass to a higher level (Hightower and Grossman, 1987) and thus increasing the resilience of the stock . On the other hand, this approach leads to higher variability in the landings than the stepwise reduction of the effort, and could result in a "stop-and-go fishery" (Evans, 1981), both which could reduce the acceptance of the fishers for such a drastic approach.

It is difficult to draw conclusions on the economic effects of the HCR approaches on the fishery in the real world from the simulations. When only the landings weights are compared, the impact of any HCR approach on the overall landings of consumption sized shrimp is minimal with less than 1% (Table II-7). It could be more interesting to look at the effort, which shows the largest decrease in the HCR99 approach in both scenarios, while still producing a small increase in landings (Table II-7). Each hour at sea less means less expenses for fuel and crew, which would be beneficial for the revenue. The HCR99 approach results in less weeks with effort restriction for the fishery. After two weeks closure, in both scenarios all restrictions are lifted (Table II-5, 6). However, it must be taken into account that a possible compensatory increase in weekly fishing hours after the closure may minimize the positive effects on the stock. It should also be taken into account that the current HCR approach as well as the HCR60 and HCR48 have the largest impact on the most active fishers. A considerable part of the fleet may not be impacted at all, at least when the hours at sea per week and vessel are restricted to 72. Additionally, the shrimp price is highly variable, and can - but must not – increase in times with low abundances. This has been the case in 2016, when high fishing effort did pay off for the fishers, regardless of the low catch volumes.

Performance of the HCR approaches

In both stock scenarios, the HCR in its different designs has a positive impact on the stock compared to the no HCR approach. After some weeks of effort reduction, the LPUE rises and stays generally higher up to the end of the year when an effort limitation is applied (Fig. II-6,8). In both scenarios, the HCR99 approach has the largest and most immediate effect on the LPUE (Table II-5 and 6). In both cases, after two weeks fishing closure, the LPUE rises above the reference value 1. In both cases, but more remarkable in the recruitment failure scenario, the closure prevents the LPUE from falling below the reference value again in the next months. In general, those HCR approaches with higher effort reductions lead to a faster increase in LPUE (Table II-5 and 6). This is very clear in the recruitment failure scenario, where the HCR99 approach results in the highest values for LPUE, biomass and egg production throughout the year (Fig. II-8). In the stock reduction scenario, the HCR99 approach results also in the highest values for biomass and egg production when looking at the annual values. However, in September and October, the LPUE from the HCR72 approach is higher and in July and August, the LPUE from the HCR48 approach is higher (Table II-5). This could be due to the longer effort reduction in those approaches, which results in a later increase in LPUE, when the effect of the initial higher effort reduction of the HCR99 approach is already fading away.

In our case, the effect of the HCR is monitored within one cohort. That said, the increase in LPUE following a reduction in effort is mainly based on the growth of the shrimp. Within the short timeframe in which the LPUE did increase again, no recruitment effects can be monitored. However, the model output shows that the number of eggs did increase in all scenarios with HCR compared to those without, because the female shrimp continue to produce eggs and thus contribute to the stock. More simulated years are necessary to predict in which timeframe the increased number of eggs could lead to a full recovery of the population to the 2013-2020 mean.

In a previous study, the performance of a different HCR design was tested with an earlier version of the population model (Temming et al., 2013). Analogous to our approach, the stock was reduced by 30% of the standard run. An effort reduction of approx. 35% was needed to rebuild the baseline biomass and of 30% to generate an egg production comparable to that of the baseline run (Temming et al., 2013). The effort reductions in this case study are by far lower, as only in single weeks the effort is reduced (Fig. II-2). For an approximate effort reduction of 30%, the effort would have to be restricted to 48h at sea per vessel and week throughout the year (Fig. II-2). In all simulated scenarios, the largest annual effort reduction was 5.9% (Table II-7). Consequently, the egg production even for the HCR99 approach in the stock reduction scenario reaches only 79% of the standard run value (Table II-7).

In any case, the aim of the HCR is not to bring the population back to a “standard” level immediately, but to prevent a further decline and increase the abundance above the critical level. In short lived species with unknown or weak stock-recruit relationships, the effect of any decrease in fishing mortality may not necessarily result in a proportional stock increase in the following generation (Deroba and Bence, 2008). In Brown shrimp, however, a first hint towards a stock-recruit relationship has been shown in a recent study (Respondek et al., 2022). Thus, preventing the stock from falling below the reference values can be recommended as a management target, which is apparently achieved fastest with a sharp cut in fishing activity as by the HCR99 approach.

The increase in LPUE after applying HCR measures is higher in the recruitment failure scenario than in the stock reduction scenario. This may be explained by the larger number of small shrimps in the second half of the year (Fig. II-3), when the HCR is applied in this scenario. Shrimps smaller than 6.8mm carapax width are subject to considerable discard mortality in the model (Temming et al., 2017) and show higher growth rates than larger shrimps. Decreasing effort reduces the mortality of undersized shrimps which can then grow into commercial size and add to the landings. The high growth rates of small shrimps does also lead to an increase in landings when the shrimps have more time to grow. In contrast, in the stock reduction scenario the HCR is applied in the first half of the year, when the simulated landings are mainly larger shrimps (Fig. II-3). This results in large females staying longer in the water before being caught. The large shrimps, which dominate the catches in spring, produce more eggs per female. As a result, the increase in egg production is more than twice as high in the stock reduction scenario as in the recruitment failure scenario (Table II-7). This could lead to a faster recovery of the stock to standard levels when the model would be allowed to run for several years.

For small pelagic fish species, which are mostly short-lived r-strategists as is Brown shrimp, a threshold of 25% of the long-term average biomass was often observed before the stocks collapsed (Essington et al., 2015). In this simulation, the lowest biomass was observed in the recruitment failure scenario, with 51% of the biomass of the standard run in July. The lowest LPUE was observed in the same scenario in August and September with approximately 50% of the standard scenario LPUE. The effort in August was reduced by only 16% in the HCR72 approach respective by 45% in the HCR99 approach compared to the no HCR approach. Even the limit reference value, which at the lowest point is reached at 36% of the standard run LPUE, does not lead to a closure of the fishery, but to a limit of 24 hours at sea per week and vessel (Addison et al., 2017). It must be concluded, that the effort reduction of the HCR in its current design does not deliver the needed effort reduction to result in considerable effects on the stock.

Conclusion and outlook

Different designs of HCRs for the Brown shrimp fishery have been tested in two scenarios of reduced shrimp stock. This study did show that the HCR of the shrimp fishery in the current design (HCR72) did lead to an increase in LPUE after two weeks of effort restriction, although six weeks (recruitment failure scenario) or ten weeks (stock reduction scenario) of effort restrictions were needed to raise the LPUE above the first reference value. In general, the larger the initial effort decrease, the faster is the recovery of the stock, with the closure of the fishery for two weeks (HCR99) being the most effective HCR approach. This more radical approach could also lead to more acceptance by the fishers as all are equally impacted by the closure. In the other approaches, the most active fishers contribute the most to the effort reduction. Although the tested HCR designs had an effect on the population level, the effect on the fleet’s effort and thus on the biomass is quite low, compared to the drastic reduction in biomass needed to trigger the HCR action.

In a next step, other HCR approaches can be developed together with the fishers and tested for their effectiveness. The simulation should also be extended to include more years after the HCR implementation, so the effect over more than one shrimp generation can be tested.

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Chapter III. A paved road or a stony path? Investigation of the circumstantial settings and user perceptions in the Brown Shrimp Self-Management

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Abstract

The North Sea Brown Shrimp (*Crangon crangon*) fishery, primarily operated by fleets from Germany, the Netherlands, and Denmark, is a major European fishery historically managed with limited regulatory oversight. This study evaluates the self-management scheme introduced to fulfill Marine Stewardship Council (MSC) certification requirements in 2016. Applying Ostrom's principles for resource self-governance, we surveyed shrimp fishers to assess their perceptions of management effectiveness, enforcement, participation, and adaptation to fishery conditions.

Results show limited recognition among fishers of stock decline or the ecological need for management, despite scientific evidence of increased fishing mortality and growth overfishing. While the fishery's fleet structure and market characteristics favor self-management, key challenges remain. Trust in equal enforcement and monitoring across producer organizations is low, and technical measures such as mesh size increases are viewed as only marginally effective. Effort limitation is more accepted, but there is strong resistance to regionalized regulation, with fishers preferring uniform rules.

Importantly, many fishers feel insufficiently involved in management decision-making, perceiving the process as top-down and disconnected from their daily realities, which may undermine compliance and effectiveness. Nonetheless, there is strong support for increased participation in future management—a potential lever for improving legitimacy and sustainability.

Our findings highlight as well favorable biological and institutional conditions, but also the need for more active engagement and trust across fishers. Improved communication, transparent enforcement, and participatory processes are recommended to bridge gaps between scientific advice, management measures, and fishermen's perceptions.

Introduction

The history of non-management

The fishing fleets of Germany, the Netherlands and Denmark are responsible for over 90% of the yearly landings of the Brown Shrimp, *Crangon crangon* in the North Sea. The fishery is among the most valuable in the EU, with peak landings of 45.206 tonnes at a total value of EUR 171 million in 2018 (EUMOFA, 2020).
Despite the high value of the fishery, no regular advice is published and no regular stock assessments for this species are carried out. Neither quotas nor effort restrictions are in place and no population-aimed management measures are defined by national or international legislation and fishing policy. The European legislation relevant to brown shrimp fisheries is defining technical measures as the use of a sieve net in certain times and a minimum mesh size. Local management regulations include licences and vessel size and power restrictions to fish in the national waters, closed areas and a weekend fishing stop in the Netherlands. However, none of these measures aims at the target species stock.

In specific, the attempts to estimate biomass and determine the status of the stock of the brown shrimp (*Crangon crangon*) have been a challenge for decades. One of the main reasons is the lack of coherent effort data from the international fishery. In addition, biological characteristics of this short-lived species, such as the impossibility of age determination and the high natural mortality have complicated analytical assessments, despite the large advances in the knowledge of the life cycle of *C. crangon* in the last decades. Thus, earlier studies on the stock status had to be based on a comparison of estimated predation and commercial landings. Those studies often concluded that it was not necessary to manage this stock and overfishing of *C. crangon* is not occurring or even impossible, given a predation mortality that exceeds by far the fishing mortality (Redant, 1980; Tiews, 1978; Welleman and Daan, 2001). Over many years, there was little doubt that this conclusion remained valid. Commercial landings have constantly increased since the 1970s along with effort believed to be constant or even decreasing (Neudecker et al., 2011). The suspected robustness to overfishing was supported by observations that a single year with very low recruitment (1990) was followed again by a somewhat normal year, suggesting that the spawning potential even in a bad year is sufficient to recover the population within one generation. This resilience to fishing of the stock was observed at a time when no precautionary measures in response to decreasing population densities were in place. Rather on the contrary, often effort was increased to compensate for reduced landings, especially when prices increased simultaneously. The overall stable situation has subsequently led to a decreasing interest in research about this species, especially in the national fisheries research centres. Consequently, both the Netherlands and Denmark did not employ a single scientist working primarily with this species or the fishery. Hence, the governments of the North Sea brown shrimp fisheries (Netherlands, Germany, Denmark, Belgium, and United Kingdom) have also shown little interest in the management of the shrimp fisheries, which lead to a similar lack of action on the EU level to establish a management system for shrimp, as well as little resources for research and monitoring.

In the late 1990s the POs and the Wholesalers agreed on maximum landings per vessel in response to the overcapacity in the shrimp sector. Without ecological arguments for the measures at that point, the agreements were classified as price manipulative measures and thus illegal and resulted in fines from the Authority for Consumers and Markets (ACM, 2011).

In 2011 again, the shrimp fisheries experienced severe difficulties because of extremely low prices offered by the processing and trading companies. The German, Danish and Dutch fleets stopped fishing for several weeks during spring. The fishery discussed whether the implementation of a management plan could help (ICES, 2011) to reduce the amount of shrimp on the market and stabilize the prices, but without result.

Independently of the price issue, fishermen organisations in the Netherlands, Germany and Denmark started a Marine Stewardship Council (MSC) assessment process to become certified against the criteria of the MSC in 2007. An important prerequisite for MSC certification is that effective management of the targeted stock is in place. To fulfil this criteria, the industry started to design a self-regulation system based on landings per unit effort (LPUE) as harvest control rule (HCR) to manage the fished species population (Temming et al., 2013).

However, due to a lack of data and research, no ecological arguments for effort limitation were available. Therefore any proposals by the industry to limit fishing effort and/or landings where deemed illegal by the ACM and could result in further fines for the industry. All attempts to introduce any management system were therefore doomed to failure by the role of the Dutch ACM (Steenbergen et al., 2017).

Things changed in recent years, when reliable growth and mortality rates have been produced (Hufnagl et al., 2013, 2010; Hufnagl M and Temming A, 2011). Increasing mortality could theoretically be detected in changing size distributions of the target species. Boddeke (Boddeke, 1978) related decreasing shares of large shrimp in the Dutch commercial catches with increasing fishing effort. (Temming et al., 1993) analysed the time series of size distributions from commercial bycatch and detected a doubling of total mortality between the periods 1974–78 and 1984–88, confirming Boddeke's observation. However, a relation between size distributions and increased fishing effort could not yet be proven. (Temming and Hufnagl, 2015) extended the time series of total mortality using size compositions from survey data and combined these with estimates of total predation of shrimp in relation to commercial landings. This made for the first time a separation of natural mortality and fishing mortality possible. The study revealed a doubling of fishing mortality over the period 1971 to 2010. Even more importantly, the analysis confirmed growth overfishing of brown shrimp occuring at the current levels of fishing and natural mortality.

These new insights into the current state of the stock acted as a "game changer," giving a consortium of the fisheries of the Netherlands, Germany and Denmark the scientific justification to limit fishing effort without opposing the Dutch ACM. The consortium successfully implemented a self-management scheme and subsequently achieved certification to MSC standards.

The self- management of the fishery

The initial attempts to self-manage the fishery resulted from the unwillingness of the relevant government agencies to introduce a management regulation. However, the interest of national authorities in introducing a management regime increased after the ICES WGCRAN advice that management would be beneficial to the fishery and the ecosystem (ICES, 2011). In 2011 the Dutch industry and ministry initiated the establishment of an NSAC focus group on shrimp to discuss the possibility of management of shrimp by member states or the EU. However, the NSAC shrimp focus group, the invited government representatives and other stakeholders could not agree to formulate a request for management at the EU level. They feared the irreversible implementation of an EU management scheme, which would result in unpopular TACs and could be too strict and overly bureaucratic. In general, EU common fisheries management is not popular within the fishing community, as documented in a March 2015 NSAC meeting document stating, "In terms of management we could improve on what we have and there was a general feel to stay away from Brussels management as much as possible” (Steenbergen et al., 2017).

POs in the Netherlands (Coöperatieve Visserij Organisatie (CVO)), Germany (MSC-GbR) and Denmark (Danish Fishermen Producer Organisation (DFPO)) finally began a new effort to achieve certification under the MSC criteria, which requires a management strategy for the species under assessment. The fishery with support from the scientific community developed and officially adopted the shrimp management plan on December 1, 2015, to be effective from January 1, 2016 on. The management plan describes in detail the harvest strategy, including the harvest control rules (HCR) and a set of regulations for trawls used in the shrimp fishery (Addison et al., 2017).

Successful self-management in fisheries

Since 1974, the number of fish stocks fished within their biologically sustainable limits has declined from 90% to 65.8% in 2017 (FAO, 2020), with declining yields and incomes in dependent industries as a result. Fisheries are therefore often cited as an example of the "tragedy of the commons." This "tragedy" refers to the decline of a commons resource due to unlimited extraction by its users as a result of a lack of management rules (Hardin, 1968). Most attempts to halt this decline with respect to fish stocks through management plans have not yielded the hoped-for success (Caddy and Cochrane, 2001; Pontecorvo and Schrank, 2006). The only thing researchers in this field agree on so far is that regulations and institutions are necessary for successful management (Acheson, 2006). In recent decades, cooperative or wholly self-managed management approaches have seen increasing progress and success in this regard (Townsend et al., 2008). The foundations of the success of self-managed management approaches have been extensively analyzed and described by Nobel Laureate Elinor Ostrom (Ostrom, 1990). Based on her extensive analysis of case studies, she developed eight design principles as prerequisites for "robust" or durable and stable self-management approaches:

1. Clearly defined boundaries: Individuals or households who have rights to withdraw resource units from the Common Pool Resource (CPR) must be clearly defined, as must the boundaries of the CPR itself.

2. Congruence between appropriation and provision rules and local conditions: Appropriation rules restricting time, place, technology, and/or quantity of resource units are related to local labor, material, and/or money.

3. Collective-choice arrangements: Most individuals affected by the operational rules can participate in modifying the operational rules.

4. Monitoring: Monitors, who actively audit CPR conditions and appropriator behavior, are accountable to the appropriators or are the appropriators.

5. Graduated sanctions: Appropriators who violate operational rules are likely to be assessed graduated sanctions (depending on the seriousness and context of the offense) by other appropriators, by officials accountable to these appropriators, or by both.

6. Conflict-resolution mechanisms: Appropriators and their officials have rapid access to low-cost local arenas to resolve conflicts among appropriators or between appropriators and officials.

7. Minimal recognition of rights to organize: The rights of appropriators to devise their own institutions are not challenged by external governmental authorities.

8. Nested enterprises: Appropriation, provision, monitoring, enforcement, conflict resolution, and governance activities are organized in multiple layers of nested enterprises.

The Brown shrimp management plan

The management plan of the Brown shrimp fishery can be regarded as self-governance according to the definition of Townend and Shutton (Townsend et al., 2008):

"Self-governance uses existing or new private institutions, rather than creating new political or government institutions or delegating authority to existing lower levels of government. […] Self-governance, in contrast, expands upon rights-based management by increasing the scope of decisions that are assumed by industry."

No decisions are delegated to institutions other than the POs of the industry. The management is coordinated by the "project group", consisting of members of the industry, which e.g. calculate the monthly LPUE values. All decisions are made by vote by members of the steering committee, which are representatives of the POs. The POs themselves are responsible for the enforcement of the decisions made against their members.

The management plan targets at two main topics: the reduction of growth overfishing and the prevention of recruitment impairment by a dwindling stock.

The CRANNET Project showed that an increase in mesh size, resulting in larger shrimps in the landings, can reduce growth overfishing in the shrimp stock (Günther et al., 2021). As larger shrimp produce larger numbers of eggs, such a strategy would also reduce the risk of recruitment overfishing. The Management Plan therefore aims to increase the mesh size in the cod end from the current mesh of 20 mm to 26 mm by 1 May 2020 (Addison et al., 2017).

Additional regulations require the use of a sieve net with a maximum opening of 70 mm or a sorting grid with a maximum bar spacing of 20 mm, to minimise the impact on undersized shrimp and catches of non-target bycatch species. Catches must be sorted on board and later on land at the sieving station with a bar spacing of 6.8mm, adjusted to commercial size shrimp carapax width. The undersized shrimp which are sorted out during the sieving process, termed the sievage, must not exceed 15% of the total landings from a vessel over a period of two calendar weeks.

A cap on the number of vessels, the combined kW power of the fleet and on maximum 200 days at sea per vessel should freeze the effort at the level registered by the authorities in the Netherlands, Germany and Denmark on 1 January 2015.

Landings per unit effort (LPUE) data (expressed as kg per hour at sea) are used as an indicator of the status of the stock. The key management strategy is that in years when the size of the recruiting shrimp cohort is low such that LPUE falls below a predetermined level, fishing effort is limited to 72 hours per week to first avoid the typical effort increase in response to the poor stock situation. With further decreasing stock densities the restrictions of the HCR become more substantial with 60, 48, 36 and 24 hours allowed per week (Addison et al., 2017). Observed monthly average LPUE data for all vessels collected from electronic log books and auction data are compared with the pre-determined reference values of LPUE. If observed LPUE in any month drops below a specific reference value, then the number of hours per week that each vessel may fish is reduced in line with the harvest control rules.

Aim of the study

After the first five years of management, the framework settings and the design of the management system should be investigated based on Ostroms design principles. A preview study by Steenbergen (Steenbergen et al., 2017) has already used those principles for analysing the favourability of the institutional settings of the Brown shrimp fishery for successful self-management. This study will focus on the user group and their perception of the self-governance system. In contrast to the fisheries described by Townsend and Shotton (Townsend et al., 2008), in case of the Brown shrimp fishery the main driver behind the establishment of the self-governance system has been the requirements of the MSC certification rather than the urgent need for resource regulation. We will thus focus on the following questions:

- Is North Sea shrimp a suitable target species for a self-management approach?
- Are the management plan and its implementation in its current form adapted to local and fishery conditions?
- Is management implementation effectively monitored and violations punished?
- Are fishermen sufficiently involved in development and implementation?

Methods

Based on Ostrom design principles, researchers of the commons have proposed the Social Ecological Systems (SES) framework as the state of the art approach for the analysis whether conditions in a specific case are in favour for successful common property regimes (Anderies et al., 2004; Ostrom, 2007). A variety of studies did apply since then the design principles of Ostrom and other, similar criteria deducted from her work to self-governance systems. Often, the focus lies on a specific part of the framework, as has been done by Steenbergen (2017) (Steenbergen et al., 2017) with focus on the institutional settings of the Brown shrimp fishery.

The main methods applied are literature review and interviews, both qualitative and quantitative.

Our study employed a quantitative research design utilizing an online survey. The survey was developed to gather data on the fishermen's perception of the management system. The questionnaire was structured in five distinct sections, each aimed at collecting comprehensive data related to the above mentioned aspects of our research objectives.

Survey Design and Distribution

The online questionnaire was designed using the Socisurvey online tool (Leiner, 2024) and optimized for smartphones. The questions were formulated in a clear and concise manner to minimize ambiguity and ensure accurate responses.

The questionnaire was developed in German and translated to Dutch. The rigid covid 19 regulations in Germany made it unfortunately impossible to visit industry meetings (which were, anyhow, often cancelled) to distribute the link to the survey and advertise for participation. Instead, the link to the questionnaire was distributed through the Dutch and German representative in the MSC project group.

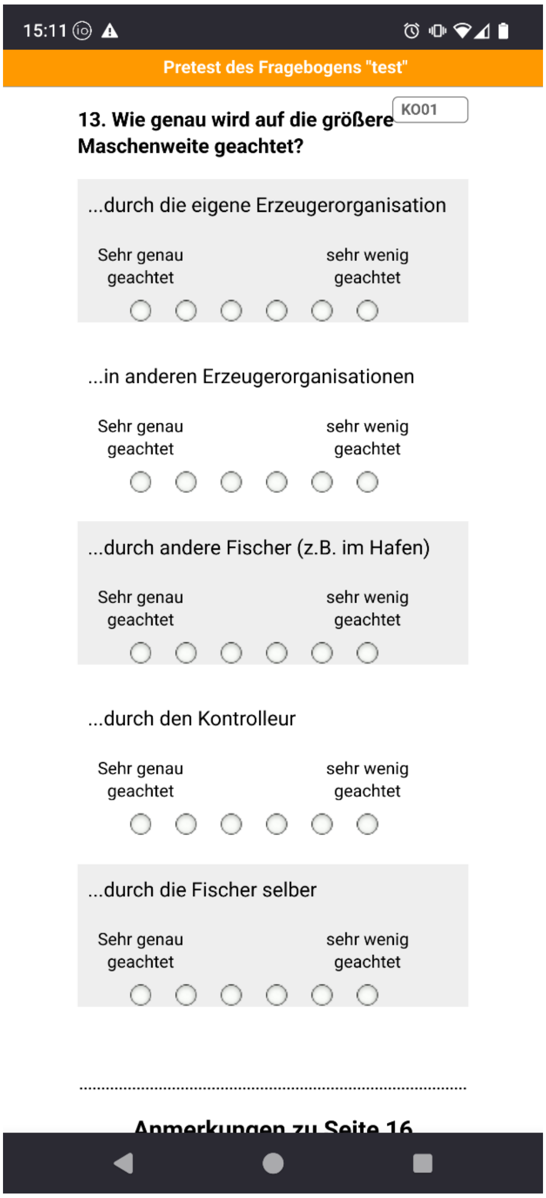

Fig. III-1: screenshot of the questionnaire in German on a mobile phone, here a question of section 5 with Likert scales to tick.

Ethical Considerations

The survey was completely anonymous, and no personally identifiable information was collected, ensuring that responses could not be traced back to individual participants. Participation was entirely voluntary, and respondents were informed of their right to withdraw at any stage without any consequences.

Structure and Content

The questionnaire comprised a mix of closed-ended questions, using Likert scales and multiple-choice formats, as well as open-ended questions where applicable, to enrich the quantitative data with qualitative insights (see Annex for full questionnaire). The questions were dived in 5 sections, each addressing a different topic:

1. “Mobility”: The first section asks about the mobility range of the fishers. Together with the language of the questionnaire, this section was used to identify different groups of fishers.

2. “Need for Management”: This section asks about the perception of the development of the stock and the fishing effort in the last decade, and how the fishery reacts to low abundances. This section is aimed to find out whether there is a perceived need for management from the fishermen’s view.

3. “Management efficiency”: The third section addresses the management efficiency. The questions in this section aim at the fishermen’s perception whether the management measures to reduce growth overfishing and to reduce fishing pressure in time with low shrimp abundances are appropriate or not. The option “free text” was made available to a) collect ideas on alternative measures and b) reduce the number of fishers which cancel the questionnaire because they do not agree with any of the listed options. A special focus was set with the question targeting at the localization of management measures, as WGCRAN (ICES, 2022) recommends adding a spatial element to the HCR. The justification for the acceptance/denial of the regionalization of the management was also asked for.

4. “Participation”: The questions in this section target the involvement of the fishers in the design of the management system and the influence on following decisions. It is also asked for the influence of the POs and other, external organizations on the design and decision making regarding the management.

5. “Control and Compliance”: This section contains questions about the monitoring of the mesh size and the effort limitation as stated in the management plan. The questions in this section also ask for the compliance with these rules, and which management authority would be suited best for the enforcement of the management regime.

Data Analysis

The aim of the statistical analysis was to define groups of fishers regarding differences in the perception of the management. A hierarchical cluster analysis was performed in R (R Core Team, 2020), based on the answers to the questions in the sections 3 – 5. The analysis was done by hierarchical clustering using Ward’s method and Euclidean distance (Ward, 1963). The clusters were identified using visual inspection of the dendrogram.

Results

Of all recipients, 133 questionnaires were filled out. However, only 78 participants completed the survey with all questions answered. Of those, 31 participants completed the German questionnaire and 47 the Dutch questionnaire.

The cluster analysis of all filled out questionnaires was based on the answers to the questions in the sections 3 – 5 in the survey. We decided to divide the participants into three different clusters by visual inspection of the dendrogram (Fig. III-2). 26 fishers were assigned to cluster 1 (C1), 41 fishers to cluster 2 (C2), and 11 fishers to cluster 3 (C3). The branches of the dendrogram show that cluster 2 and 3 have more in common in their answers in the sections 3 – 5 and cluster 1 has a more distinct opinion. While the two larger clusters consisted of roughly equal numbers of recipients of the Dutch and German questionnaires, the smaller cluster (3) consisted only of respondents to the Dutch questionnaire (Fig. III-2). This cluster also differs from the other two clusters in terms of the mobility of the fishers, with very mobile fishers who fish from different harbours and often stay at sea for longer than three days (Fig. III-3). The mobility in cluster 1 and 2 is nearly the same (Fig. III-3). Approximate half of the fishers are switching fishing locations to other places in times with little shrimp and staying at sea longer than 3 days, and the other half is almost always fishing from the home port. Only a few fishers are making only day trips, less than 24 hours at sea (Fig 3).

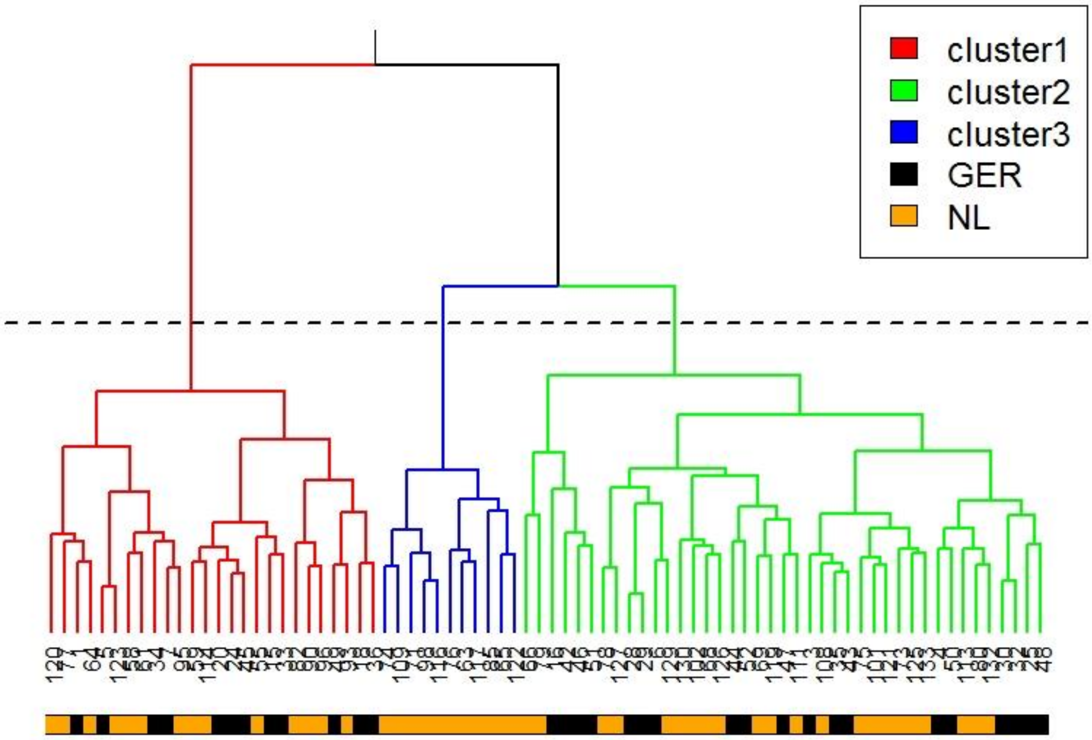

Fig. III-2: Dendrogram of the results of the cluster analysis based on answers to the management questions. The dashed black line indicates the selected division into three clusters (C1 – C3). The lower bar shows which version of the questionnaire was processed in the clusters (orange for the Dutch version, black for the German version). The length of the branches corresponds to the similarity of the answers of the groups.

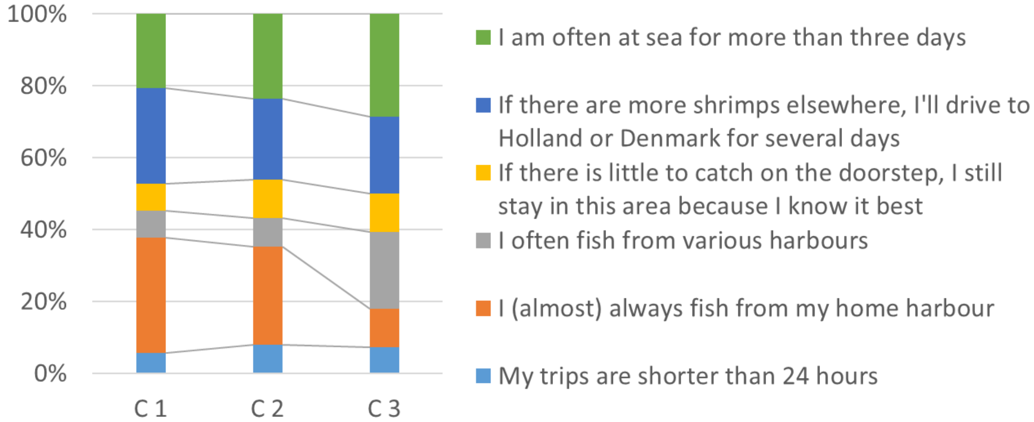

Fig. III-3: Agreement ('I agree') and disagreement ('I disagree') with statements on the mobility of fishermen. The percentage of positive agreements per cluster are shown, neutral statements were not possible.

According to our survey, only a minority of fishers see the shrimp stock as declining (Fig. III-4). Roughly above 40% in cluster 2 is the largest proportion of the fishers which experience a declining stock. The lowest proportion is in cluster 1 with less than 10%. In contrast, the overall effort is perceived as increasing in all clusters, with the highest value of nearly 100% in cluster 3. Only a minority of less than 10% in cluster 1 and 2 describe the effort as decreasing (Fig. III-4). Most fishers in all clusters would expect fishing to continue without changes when stocks are falling. Only in cluster 2 and 3, 32% respective 36% expect fishers to compensate for falling catches by increasing effort. In cluster 1, the fishers would rather expect decreasing effort in times with low shrimp abundance (19%).

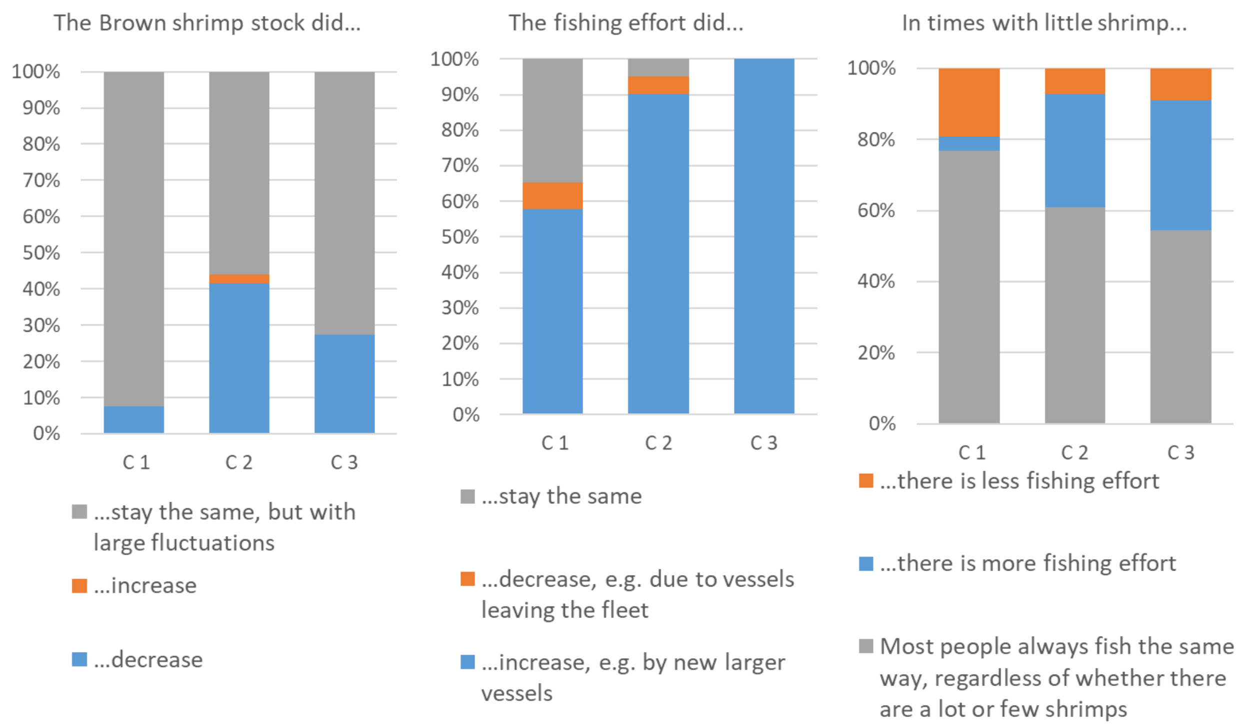

Fig. III-4: Perception of recent development in shrimp stock and fishery. The participants had to choose one of the statements. The graphs show the percentages per cluster which did agree to the statements.

Contrary to our assumptions and recommendations, the vast majority of fishers, between 78% (cluster 2) and 91% (cluster 3) are against regionalisation of management (Fig. III-5). The most common reason given for rejecting regionalisation is that all fishers should have the same conditions, with 38% in cluster 1, 42% and 43% in clusters 2 and 3.

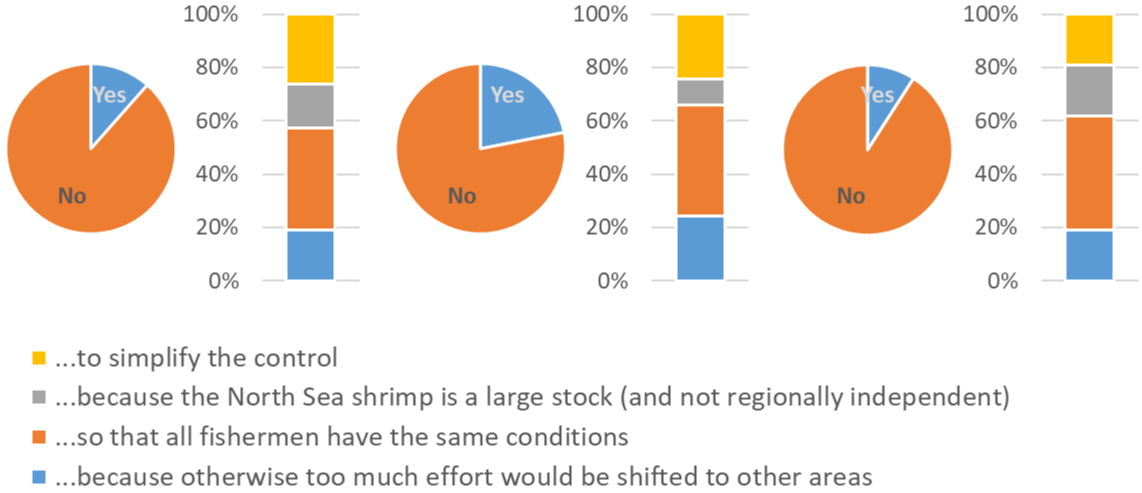

Fig. III-5: Approval or rejection of regionalization of management, separated by cluster. The bar chart on the right shows the reasons for the rejection of regionalization for each cluster. Only one answer could be given in each case. From left to right: Cluster 1-3.

When it comes to management measures, increasing the mesh sizes in the codend, which should actually reduce the amount of undersized shrimp in the catch and thus reduce overfishing, is not seen as effective (Fig 6). Around 50% of all fishers did also agree that by changing the net settings the mesh size effect can be fooled (Fig. III-6). However, more fishers would agree to stay at 26mm mesh size and leave the effort at the current level, than complement the mesh size of 24mm with a temporary fishing stop.

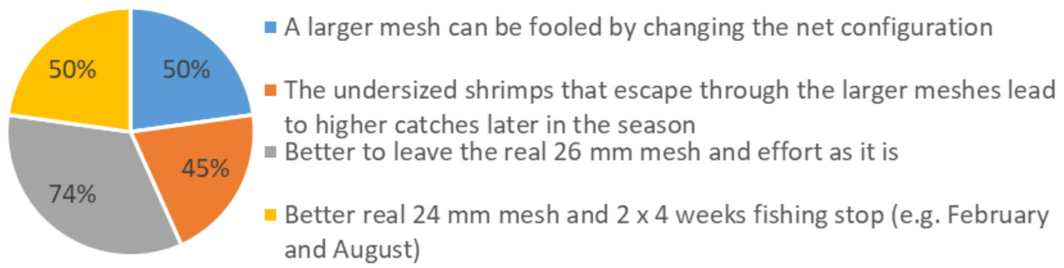

Fig. III-6: *Agreement ('I agree') and disagreement ('I disagree') with statements on the effectiveness of different management measures. The percentage of positive agreements are shown, neutral statements were not possible.*

The three groups of fishers differed in their ideas as to which measure would make sense instead. The majority of cluster 1 proposes a change in the screening process on board before cooking. Members of Cluster 3 preferred high penalties for undersized landings (Fig. III-7). The fishers in cluster 2 and cluster 3 would also support the idea of limiting the effort in weeks with small shrimp in the catches.

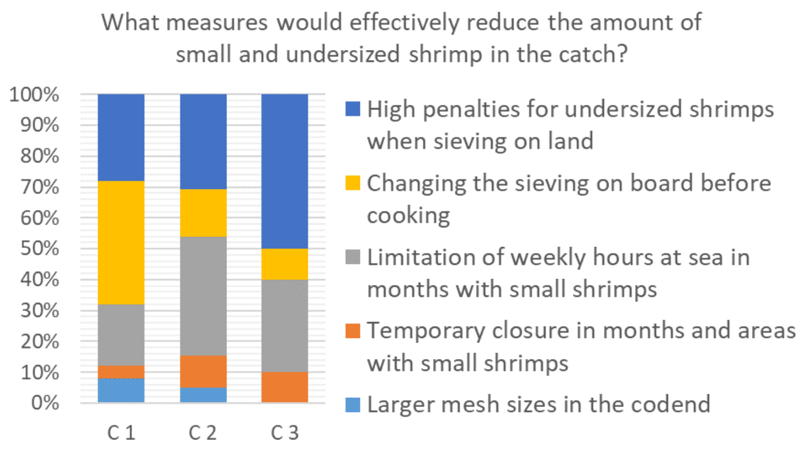

Fig. III-7: Acceptance of various measures to reduce growth overfishing. The option 'Larger mesh sizes in the codend' is currently being implemented in the management plan. In addition, there are penalties if the landings of undersized shrimp exceed a threshold value.

Compared to the mesh size increase, the effort reduction to reduce fishing pressure at very low stock densities is far more accepted (Fig. III-8). In clusters 2 and 3, a clear majority is in favour of this regulation. Only in cluster 1 is the attitude that fishing generally has no influence on the population predominant.

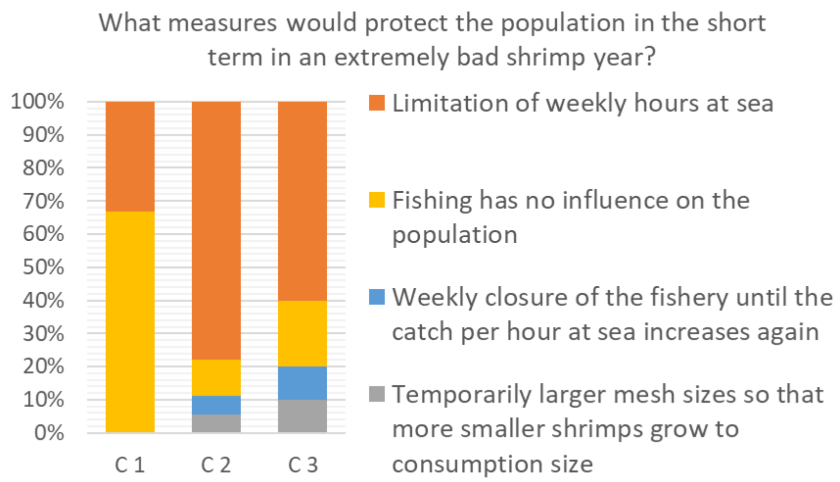

Fig. III-8: Acceptance of various measures to reduce fishing pressure at low stock sizes. The option 'Limitation of weekly hours at sea' is currently being implemented in the management plan.

There is a general perception among the fishers surveyed that the POs do not monitor compliance with the larger mesh sizes, or do so only to a limited extent (Fig. III-9). The same picture emerges in all clusters: the mesh size is primarily observed by the inspector, followed by the fishers themselves. Other fishers and the POs show little interest in monitoring. The control by the fishers seems to be perceived as stricter across the board by members of the 1st cluster. The control of the regulations is generally perceived as at least strict among the very mobile fishers in the 3rd cluster.

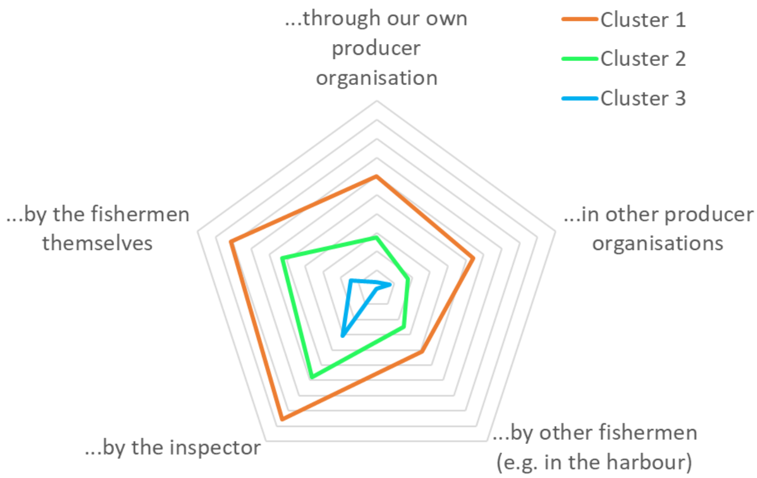

Fig. III-9: Control of mesh size increase by various institutions on a scale from very closely controlled (outside) to very little controlled (inside).

The monitoring of the compliance with the effort regulations is viewed as stricter in all clusters (Fig. III-10). Again, the perception differs between the clusters, with the strictest monitoring experienced in cluster 1 and followed by cluster 2. The fishers of cluster 3 did in contrast not experience strict monitoring of the effort limitations. The fishers of cluster 2 do suspect that other POs do not follow up the control of the effort reductions as much as their own PO does, a pattern which can be also seen in clusters 1 and 3. As a consequence, the fishers of other POs are suspected not to follow the rules regarding the effort reduction (Fig. III-11), with more 64% of the fishers of cluster 3 agreeing to the statement “The fishermen of some producer organisations/countries do not follow the rules because there is no monitoring”. Of the cluster 1 and 2, 50% and 46% agree to this statement. Fishermen of cluster 2 do show the highest voluntary compliance with the rules (39%), followed by cluster 3 (36%) and cluster 1 (27%). Only the fishers in cluster 1 did agree in a considerable numbers to the statement that nobody can ignore the effort regulations (23%).

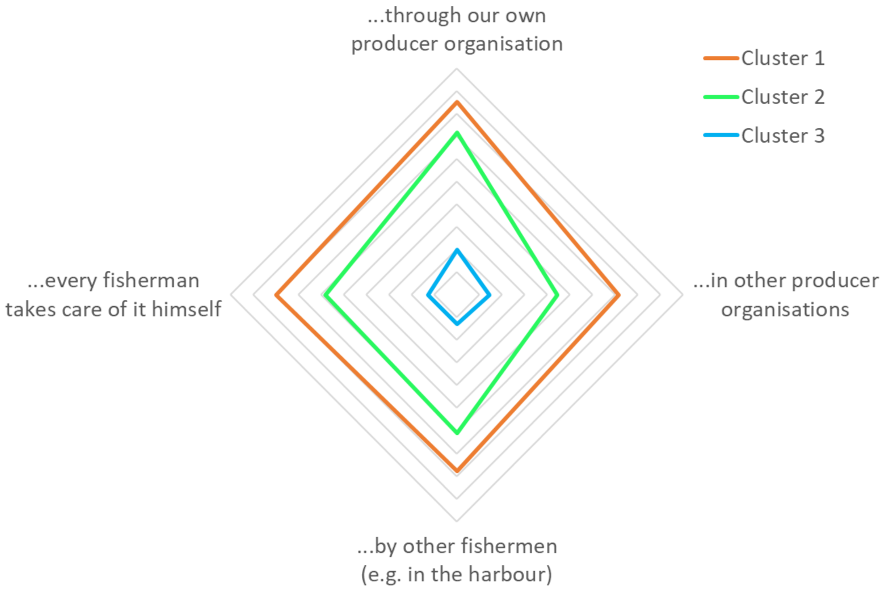

Fig. III-10: Monitoring of compliance with effort reduction by various institutions on a scale from very closely controlled (outside) to very little controlled (inside).

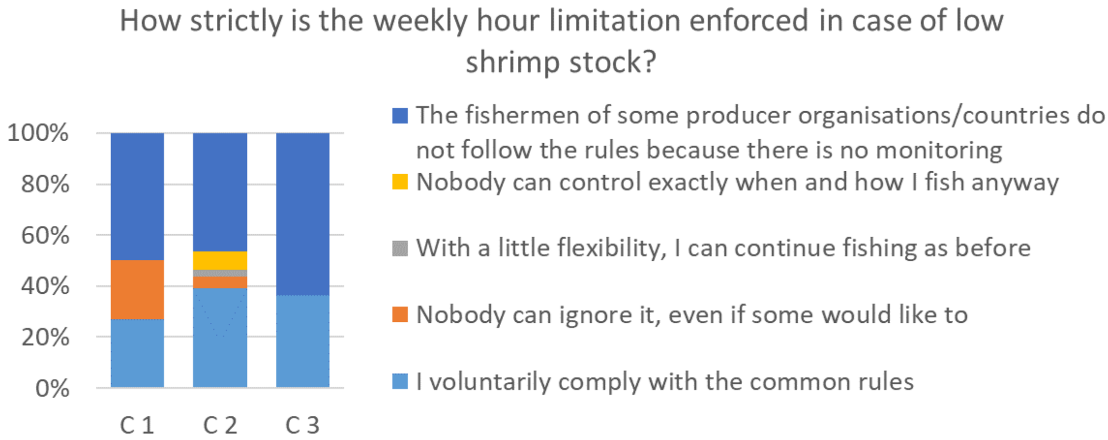

Fig. III-11: The participants were asked to select the statement which described the situation best, regarding the effort reduction as implemented in the management plan.

Asked what would be the preferred management institution responsible for ensuring compliance to the regulations, the fishers in cluster 2 (68%) and 3 (64%) did vote in the majority for an external institution (Fig. III-12). The PO, which is currently responsible for the implementation of the management, was preferred only by the majority of fishers of cluster 1 (54%). The fishers of cluster 3 did not mention the PO at all, and only 15% the fishers of cluster 2 did prefer the PO.

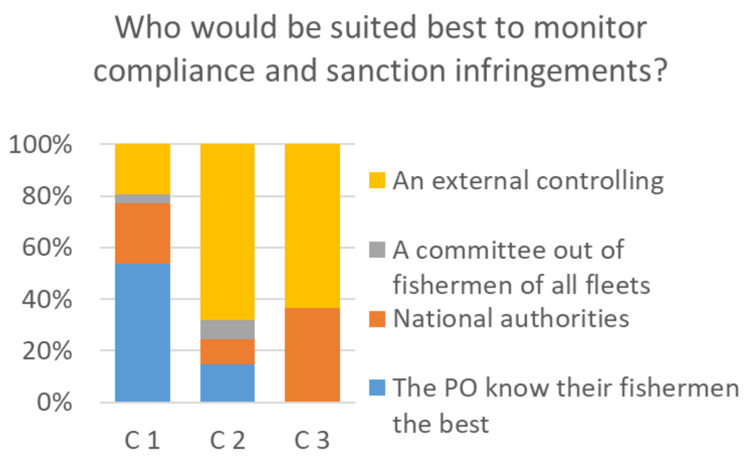

Fig. III-12: Effectiveness of different management institutions. One statement could be selected.

When it comes to the process of development and design of the management system, the fishers in cluster 2 felt more involved than those of the other two clusters (Fig 13). The largest differences are in the involvement of the own PO and the national fisheries. For the fishers of cluster 2 and 3, the own PO had the largest influence on the management design. For the fishers of cluster 1, the largest influence have been from external organisations. All fishers did state that they themselves had been less involved in the design of the management than the other actors mentioned here. The influence on following decisions is perceived as low by all fishers (Fig 13).

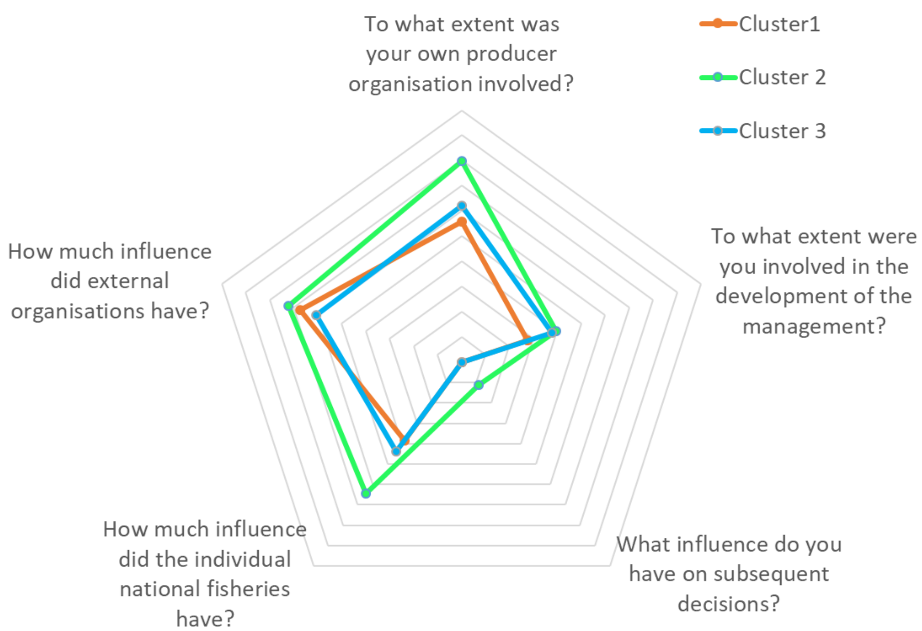

Fig. III-13: Involvement of various institutions into the design and development of the management scheme on a scale from very closely involved (outside) to very little involved (inside).

Nevertheless, a majority in all groups think that they should get more involved into management decisions in the future (Fig. III-14). The largest agreement is in cluster 1 with 85%, followed by cluster 2 with 81% and cluster 3 with 54%. In cluster 1 and 2, most of those agreeing argue with better acceptance of unpopular decisions, while in cluster 3 the argument prevails that "the fisheries and POs do not represent the interests of all fishermen". Of those rejecting the stronger involvement of the fishers, the majority in cluster 2 and 3 are stating that they are quite well represented organizations. Those of cluster 1 which are rejecting a stronger involvement are concerned that unpopular but necessary decisions will not be taken.

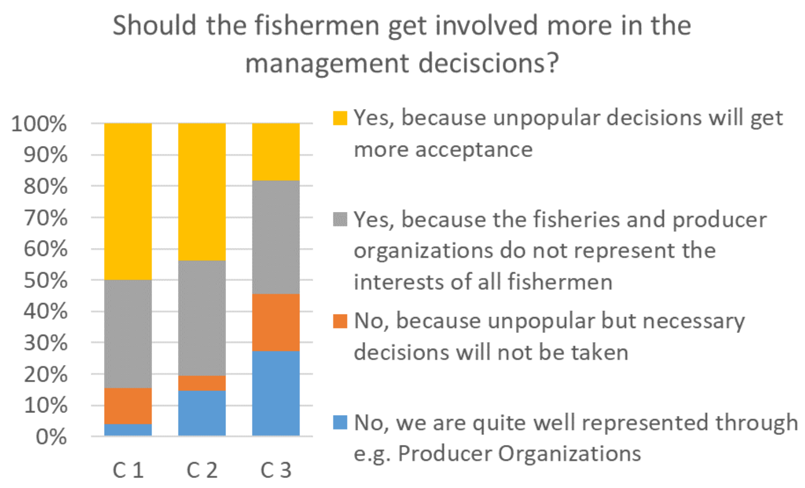

Fig. III-14: Desired participation of the fishermen in future decisions. The participants were asked to choose one statement.

Discussion

1. Is North Sea shrimp a suitable target species for a self-management approach?

Lobster, shrimp and crab fisheries are over-represented in the 32 cases of successful self-management reviewed by Townsend and Shotton (Townsend et al., 2008). This is probably not a coincidence. As these target species are restricted to inshore waters, it is not surprising that the group of users is also limited. This exclusion of external users is also cited by Ostrom (Ostrom, 1990) as the first criterion for successful self-management.

Other studies mention a perceived need or concern for resource condition as a prerequisite for effective self-management (Chuenpagdee and Jentoft, 2007; Hauck and Sowman, 2001; Ostrom, 1999). In the Norwegian Aquaculture industry, the perceived thread from parasites and diseases was found to be the main incentive for collaborating with other actors (Osmundsen et al., 2021). In a more recent modelling approach, the capacity to cooperate and the perceptions of the state of the stock were important for success of the management scheme (Gilmour et al., 2013).

Unlike the fisheries described above, in the North Sea shrimp fisheries, MSC certification requirements have been the main driver in setting up the self-management system, rather than the urgent need to regulate the resource. Nevertheless, there is a clear recommendation for stock management (ICES, 2014) based on the current state of knowledge for the shrimp fishery. (Temming and Hufnagl, 2015) have shown, using size composition from survey data and estimates of total landings and total predation, that fishing mortality is currently in excess of natural mortality and that growth overfishing occurs. In other words, Brown shrimp are removed from the fishery before they have reached their full growth potential. Research from a current project combining logbook and VMS data additionally showed an impact of winter fishing on subsequent recruitment (Respondek et al., 2022). The same study also showed a significant decline in spawner abundances in all areas surveyed while fishing effort increased by 12% between 2009 and 2018. These figures do not yet take into account the additional increase due to a hidden increase in fishing effort. Not only have many vessels become more efficient due to technological progress, but we also know that how fishers behave has changed. In general, although not reflected in the hours at sea, the time between hauls appears to have become shorter. Furthermore it can be deduced from AIS signal information that groups of fishers seem to inform each other about profiting fishing locations, leading to local aggregations of vessels for restricted periods (pers. Comment A. Temming). This information component of fishing behaviour leads to a higher fishing mortality per unit of nominal fishing effort, such as e.g. fishing hours. In view of these findings, there is a need for effective protection of the shrimp stock from fishing pressure and for regulation of the fishery.

However, the results of the above studies do not consistently correspond to fishermen's perceptions. According to our survey, only a minority of fishers perceive that the Brown shrimp stock is declining (Fig. III-3), even though effort is perceived to be increasing. It is striking that this perception is predominant among fishers classified in cluster 1. These fishers also only partially perceive the effort as increasing. Asked how fishers would react in times of low shrimp abundance, most fishers in all groups assume that the same amount of fishing will always take place regardless of the shrimp stock. This is in line with previous studies based on logbook data from the German shrimp fishery (Respondek et al., 2014).

A serious management challenge arises from this assessment. A shared goal, such as e.g. improving the stock situation, is a necessary prerequisite for the successful cooperation in resource management (Tu et al., 2023). If the stock of the target species is perceived by the fishers as being independent of fishing effort development, the acceptance of management measures aimed at protecting the stock tends to be low. This is reflected in their reluctance to support an increases in mesh size, with fewer than 10% of fishers considering this measure beneficial (Fig. III-7). In contrast, the latest scientific evidence suggests that increasing mesh size would also have a positive effect on the survival of undersized shrimp and could potentially lead to an increase in value later in the year (Günther et al., 2021). This also highlights a challenge for science. Despite repeated presentations in meetings with industry representatives, the results of previous studies have either not reached the fishers themselves or are not considered reliable. This could be explained with the practical knowledge of the fishers that small modifications of the net design can easily compensate for the effects of larger mesh sizes. Additionally, longer tows with higher catches may have a similar effect. These issues need to be addressed in future research.

More profit through participatory management

In shrimp fisheries, small-scale control of fishing within a season can have a significant impact on the average size of shrimp and thus on their weight and value. As a result, the potential benefits of management are higher, more visible and therefore more certain in these fisheries, where the costs of self-management are often lower (Townsend et al., 2008). In the Australian shrimp fisheries, the Western King Prawn Fishery and the Exmouth Gulf Prawn Fishery, management plans have been introduced as a result of declining catches due to overfishing of growth and recruitment. These include rules not only to protect the stocks, but also to concentrate the fishing effort in the most profitable areas and at the most profitable times. This has allowed the fisheries to survive in a global shrimp market which has been severely affected by falling prices (Townsend et al., 2008). In the Swedish fishery for *Pandalus borealis* in the Gulf of Gullmar, the establishment of self-management by the local coastal fishery has led to the regulation and reduction of the seasonal fishing effort and to a voluntary increase in the mesh size from 35 to 45 mm. As a result, the prices obtained by this fishery are about 50% higher than those obtained by the off shore marine fishery. These higher prices are largely due to increased and better product quality resulting from targeted effort management (Eggert and Ulmestrand, 2007). A comparison between fishers who are members of a self-management group and those who are not, across various Korean fisheries, found that membership in a self-management group positively impacts both the revenue and cost aspects of fishing for the member fishers (Uchida et al., 2010).

It can therefore be assumed that effective stock management can also lead to added value for the North Sea shrimp fishery. Those parts of the stock which are suitable for economic exploitation are limited. Only in parts of the North Sea, including the coast from Belgium to Denmark abundances of Brown shrimp are high enough for fishing, which increases the likelihood of successful self-management. Other locally fished conglomerations of Brown shrimp are spatially and perhaps biologically separated, e.g. in the Wash. Accordingly, the North Sea shrimp stock is suitable for a self-management approach, provided that the need for stock management and potential benefit from the management is experienced by the fishers.

Are the conditions in place to establish self-management in the structure of the fishing fleet?

A cap on the number of vessels and the combined kW power of the fleet are intended to freeze fishing effort at the level recorded by the authorities in the Netherlands, Germany and Denmark on 1 January 2015. Vessels are also limited to 200 days at sea per year. However, these measures do not effectively limit fishing effort in practice (ICES, 2022), as the regular effort of many fishers is below the 200 day limit. In addition, new fishers can still enter the fishery or old vessels can be replaced by new and more effective ones. The expansion of the fishery is currently limited by trade restrictions. As the major mass market retailers have voluntarily committed to stock only MSC-certified or otherwise ecologically safe products, the chances of success for a fishery outside the self-governing MSC consortium are rather slim. The first of Ostrom's criteria, the exclusion of unauthorised users from the resource (Ostrom, 1990), can therefore be seen as largely applicable here.

The behavioural incentive of the individual users of a common pool resource are subject to ongoing discussion. Instead of solely looking for maximizing economic profit from the resource, action of users may be triggered by e.g. by social norms in terms of values, attitudes and overall interdependence (Saunders, 2014). However, to maximize individual returns, irrespective of their nature, users should not only pursue their own interests, but also ensure that the resource as a whole is utilised efficiently and sustainably so that all users can benefit (Ostrom, 1990). Success in maximising joint returns is limited by transaction costs. Transaction costs refer to the effort required to reach agreement on the rules of use. These costs can include time, money or resources required for negotiation and coordination. If these costs are too high, it may become difficult or impossible to achieve the cooperation necessary to effectively maximise joint profits (Ayres et al., 2018).

It is often argued in the co-management literature that non-economic ties between participants, such as cultural, family or social ties, reduce transaction costs. However, most of the case studies examined by Townsend and Shotton (Townsend et al., 2008) are clearly motivated by economic self-interest and do not reveal clear evidence of pre-existing community ties. Legally enforceable contracts, often with specific provisions for compliance and sanctions, are present in about half of the cases. Long-term involvement in a larger community may facilitate self-governance, but it is clearly not a prerequisite. The transaction costs of negotiations depend not only on the number of participants, but also on their individual circumstances. Participants with similar ships, markets, interests and financial situations will face lower negotiation costs than those with very different ones.

This is clearly an advantageous situation in relation to the shrimp fishery. The shrimp fishery is almost exclusively in the hands of family enterprises. Due to the monopolistic market structure with only few processing companies, all fishers face a similar economic situation when selling their catch. The reasons given for rejecting regionalisation of management (Fig. III-4) and the results of the cluster analysis (Fig. III-1 and 2) also reveal a rather homogeneous picture of the fishers. Language barriers and cultural differences do not seem to be an obstacle compared to common interests. However, there are differences in the equipment and size of the vessels as well as in the economic background (Respondek et al., 2014). Fishermen of Cluster 3 are very mobile, and fish often from different ports, staying longer at sea than the other clusters (Fig. III-3). The clusters 2 and 3 are more stationary and less mobile. In the Dutch fleet, a previous study found 40% of the fleet often fishing from different ports, e.g. switching to the coast off the Sylt area in winter (Steenbergen et al., 2015). Those fishers did often invest in new vessels and equipment and are now under pressure to pay back their loans. The same study defined 60% of the fleet as “home bound”, which do not often switch their landing harbor. These are often fishers with older, smaller vessels. The German fleet, too, consists of older and smaller vessels (Aviat et al., 2011), which are likely already paid off and less capable of staying at sea for long fishing trips. The Danish fleet has the same average length than the German vessels, but consists of newer vessels (Respondek et al., 2022). While most fishers are solely targeting shrimp, a considerable part of the Dutch fleet of about 30% switches to other species such as sole and Nephrops when shrimp catches are low (Aviat et al., 2011). The fleet can thus be divided by the age and size of the vessel, the financial pressure and the ability of switching the target species rather than nationality or language. This divide repeatedly manifests in complaints about foreign fishers fishing with large

boats off the coast, leaving nothing for the local fishery – a statement which is made by Dutch as well as German fishers equally (Steenbergen et al., 2015) (pers. Comment P. Oberdoerffer).
The structure of the fleet is therefore only partly feasible for implementing a self-management system. While the language barrier and different nationality should not hinder a success, the differences in the fleet between large, mobile vessels with high economic pressure and small, home-port bound vessels which are relying on local shrimp abundance could present an obstacle for successful management.

2. Are the management plan and its implementation in its current form adapted to local and fishery conditions?

Contrary to our assumptions and recommendations, the vast majority of fishers are against regionalisation of management (Fig 4). This is surprising, as regionalisation would allow fishers to continue fishing in another area even when stocks are low in one area. The most common reason given for opposing regionalisation is that all fishers should have the same conditions for fishing. The importance of a level playing field for all was also repeatedly stressed in meetings with fishers. However, the shrimp density can vary greatly from one region to another in one season, which means especially for the less mobile fishers very different fishing conditions (ICES, 2022).

It is likely that the rejection of regionally specific management regulations is also based on the view that the stock is not affected by fishing. This view is also reflected in responses to the effectiveness of current regulations (Fig. III-5). Increasing mesh sizes in the codend, which should reduce the amount of undersized shrimp in the catch and thus reduce overfishing, is not considered useful or effective. The three groups of fishers differ in their views on what measures would be useful instead. Cluster 1, with a majority, suggests a change in on board inspection before boiling. Cluster 3, mainly suggesting high penalties for undersized landings, leaves it up to the fishers to decide what measures should be taken to reduce small shrimp landings (Fig. III-5).

Compared to increasing mesh size, reducing fishing effort to reduce fishing pressure in times with low stock densities is much more accepted (Fig. III-6). In clusters 2 and 3 there is a clear majority in favour of these measures. Only in cluster 1 does the attitude prevail that fishing in general has no effect on the population.

The current harvest control regime does not take account of these different regional developments of the shrimp stock, which may expose local low abundances to additional fishing effort (ICES, 2022). The current reference points also do not reflect the general population dynamics of the shrimp because they are set very low, based only on two years instead an average over more years , and are based on data from only the German part of the fleet (ICES, 2019). In addition, when shrimp stocks are low, effort limits are set at levels that do not constrain parts of the fleet (ICES, 2022). It is therefore concluded that the management rules are not adapted to local conditions, and thus Ostrom's second criterion is not met.

3. Is management implementation effectively monitored and violations punished?

Acceptance of the various measures against overfishing of growth and recruitment is reflected in the control of the regulations. For example, 50% of all fishers agree with the statement: "A larger mesh size can be cheated by changing the net settings". In general, there is a perception among the fishers interviewed that POs also have little or no control over compliance with larger mesh sizes (Fig. III-7). The same picture emerges in all clusters: mesh size is mainly controlled by the inspector, followed by the fishers themselves. Other fishers and POs show little interest in control.

The control of effort limitation is perceived by the fishers in clusters 1 and 2 as much stricter than the control of mesh size (Fig. III-8). POs in particular are very vigilant about compliance. Effort limitation is also much easier to control through logbooks than mesh size. Again, cluster 3 stands out strongly from the other two groups with the perception of very little control. For Cluster 2, it is noticeable that there is a predominant perception that other POs do not pay as much attention to compliance with effort limitations as their respective POs. This concludes in all groups in the perception that other fishers do not follow up the regulations because of weak control (Fig. III-9).

In all clusters, control seems to be perceived as stricter by the fishers in cluster 1. Control is generally perceived least strict among the highly mobile fishers in cluster 3. This can mainly be explained by differences in fishing behaviour. Cluster 1 fishers mostly fish from their home port and are less likely to spend several days at sea. They are therefore more likely to be controlled by the assigned inspector, observed by other fishers or the producer organisation. The highly mobile fleet in cluster 3, on the other hand, often fishes from different ports and is at sea for several days. The fleets have different agencies assigned for inspection of their member vessels, which are also responsible for control of member vessels in foreign ports (Addison et al., 2024). It is less likely that the inspector for the Dutch fleet shows up in German or Danish ports, as he is not responsible for controlling German or Danish vessels.

The time spent in port is likely to be shorter, as only loading and unloading takes place. This likely results also in lower perception of social control by other fishers. It is likely that in foreign ports there is less contact with other fishers, partly due to language barriers. Maybe this makes it less likely that infringements of the management regulations are reported to the fishers's PO, or that catches and days in harbour are closely observed. On the other hand, there has been strong competition between German and Dutch fishers for years, which could lead to closer monitoring of the “foreign” vessels.

When Cluster 2 is subdivided according to the language of the questionnaires, there is a difference in perceived social control and observance of the effort limitation by other fishers (Fig. III-9). Participants in the German survey perceive control and observation as very strict, while participants in the Dutch survey perceive control and observance by other fishers as considerably less strict. To what extent cultural differences influence these perceptions can only be speculated, although the German culture, which is known for its appreciation but also strict interpretation of structures and rules, could be the reason that control and compliance play an important role in the German fleet. It is also interesting that the current audit surveillance report lists by far more infringements of the Dutch part of the fleet than the other parts, with 69 overall infringements compared to 9 and 6 for the German and the Danish fleet (Addison et al., 2024). For all fleets, the level of inspections is the same with around 20% of the fleet. The perception of more efficient management control in cluster 1 is reflected in the fact that the fishers in this cluster also prefer the POs as the management authority (Fig. III-12). In contrast, the majority of fishers in the other clusters would prefer an external control authority, as they distrust specifically the enforcement of the management rules by other POs (Fig. III-9 and 10). This may have historical reasons as well, as it is reported that in the past the control in the Dutch sieving stations was less strict than in German or Danish sieving stations (Addison et al., 2021). However, since implementation of the MSC certification, the Dutch sieving stations are monitored by video surveillance or presence of an inspector, while the same measures have not been applied for German or Danish sieving stations (Addison et al., 2021). External control agencies do check on the follow up action of the POs when their members are cited for non-compliance, for monitoring of the mesh size and inspections for the sieving stations. Again, the fleets could not agree on one agency, leading to the Dutch POs, sieving stations and vessels being controlled by another company than the German and Danish ones (Addison et al., 2024). Bearing in mind the importance of a "level playing field" which is stressed by the fishers, it is likely that the assignment of separate control agencies adds to the distrust whether the same level of monitoring and control is applied among the fishers.

The overall impression is that most fishers voluntarily comply with the agreed rules, but there is a lack of trust in monitoring by other POs and compliance by other fishers. This is an important weakness for the success of the management, as trust and the ability to enforce rules and regulations are essential for successful co- und self-management (Agrawal, 2001; Gilmour et al., 2011; Gutiérrez et al., 2011; Pomeroy et al., 2001). Trust can be can be undermined by non-compliance and suspicion. There is room for improvement concerning trust among the fishers, especially as compliance by the fishers themselves appears to be high. This high level of compliance supports the findings of an earlier study, which recommended that greater involvement of fishers in decision-making in the CFP could increase compliance (Österblom et al., 2011). Given that the management system is rather new, the growing cooperation needs to build on previous successes, as benefits from the management are likely to take more time to materialize. The shrimp fishery has made several attempts to establish international cooperation of the fleets. The most successful may have been the 2011 fishing moratorium, which resulted in an agreement with the wholesalers to stabilize prizes (Steenbergen et al., 2017). Yet, this attempt was not successful in the long run and did obviously not increase trust between the fishers of the different fleets. .

In summary, it can be assumed that compliance is high, which would support the claim that management is effectively implemented and sanctions are effectively applied. However, the perception of the fishers is different and they suspect that other fishers are benefiting from the low level of control and monitoring levels, which may pose a serious challenge to the success of management.

4. Are fishermen sufficiently involved in development and implementation?

Fishermen in all three clusters are largely unanimous in their assessment of their own involvement in management development (Fig. III-13). POs and external organisations have been significantly involved in the development, while individual fishermen's involvement upstream of management development is rated lower. The involvement of the fishers from Cluster 2 seems to have worked slightly better than that of the fishers from the other two clusters. In Cluster 3, the design of the management was primarily driven by external organisations, even more than by the POs. It is questionable whether the fishers develop ownership of a self-management system perceived as designed without their participation. It is striking that the interviewed fishers see very little or no influence of their own on the further development of management, a perception which mimics the perceived involvement in the initial development of the management. In this aspect, the self-management is perceived similar to the management on the EU-level - of being remote, unresponsive and insensitive in relation to specific contexts (Österblom et al., 2011). Instead, the self-management approach to fisheries should include the participants, and not to repeat this mistake.

Maybe as a result, only a slight minority of the fishers in Cluster 1 and 2, and a quarter of the fishers in Cluster 3 feel well represented by POs (Fig 14). This perception is also independent from the questionnaires language. It can be speculated that the fishers of Cluster 3 have better access to the representatives of the POs, through more engagement in fishing, but also maybe simply through the higher economic pressure by higher investments in their businesses. This access could pay off in special regulations, such as the exception from the week-end closure in the Netherlands (Steenbergen et al., 2015). Decision making in the management needs to be perceived as fair and open by fishing industry members to build trust (Gilmour et al., 2013). This fair participation applies to all the processes within an industry. If such processes are not perceived to be open and fair, the legitimacy of industry-devised rules may suffer, along with levels of voluntary compliance (Hauck and Sowman, 2001; Pomeroy et al., 2001).

Nevertheless, the fishers from cluster 2, like those from cluster 1, are overwhelmingly in favour of more fishermen's involvement in management (Fig. III-14). For cluster 3, this is still slightly more than 50%. Strong leadership was identified as the most important attribute contributing to success of co-management approaches to fisheries by (Gutiérrez et al., 2011). This could be a role for the POs, trying to find a way of better engagement with their members when it comes to decision-making and further development of the management system. More than 50% of the fishers in cluster 1 and more than 40% in cluster 2 state that with more participation, the acceptance of unpopular decisions will also increase. Thus, it is unlikely that the fishers just desire more involvement to prevent unpopular measures, such as effort restrictions. It is more likely that involvement and participation in management enhance the legitimacy of the management regulations, und in the end the compliance (Österblom et al., 2011).

With respect to participation and involvement, Ostrom's criterion (3) is not met for most fishermen, who want more and more direct participation in the management process.

Conclusion and outlook

Not all aspects of self-management have been fully explored in this review. It would be particularly interesting to look at the design of sanctions and conflict resolution mechanisms in a further study. Instead, we focused on the biological aspects of the fishery and management framework. However, harvesting is only one aspect in managing a common resource, although regulations tend to focus on issues related solely to harvesting, i.e. the fishing process itself. It has been argued that when we try analyze how effective the fishery manages the interactions with the resource, we should take into account all pre- and post-fishing processes as well (Basurto et al., 2020). This could be for example the agreements with the byers of the landings, or the response of the market price to management regulations. In case of the North Sea Brown Shrimp fishery, the main driver of aiming for MSC certification has been the commitment of some large retail groups to source seafood preferably from sustainable sources – which exerted pressure on the wholesalers and in the end the fishery. Nevertheless, many of the regulations are based on solid biological advice, and the management is constantly accompanied by the support of the ICES WGCRAN.

Comparison of the shrimp fishery self-management framework with other successful self-management systems has highlighted both strengths and weaknesses of the management system. The biology of the North Sea shrimp, as well as the structure of the fleet, clearly favours the success of the self-management. In addition, fishermen's own perception of compliance is high and there is a strong interest in greater participation in future management decisions.

On the other hand, there is little perceived need for management from the stock status and the impact of the fishery on the stock, despite contrary scientific findings. The management regulations are only partly accepted as appropriate to local and fishing conditions. A major weakness is the missing trust in the control and fair enforcement of the regulations. In general, the distrust to other POs, other fishermen and partly also the own representatives is a threat to the success of the management, whether it is justified or not.

Part of the challenge here is for the scientific community to better communicate the latest research to the fishery. The management recommendations from the scientific community should also be discussed more with fishers, to be appropriate and adapted to the conditions in the field. The POs, as main institution in the management scheme, should take steps to improve the trust in equal and fair conditions for all fishers. PO-specific regulations should be avoided, instead the high level of compliance by the fishers could be pronounced, and control and monitoring effort made more transparent. Last but not least, the results recommend more involvement of the single fishermen – in management decisions, but maybe also in the exchange and discussions beforehand.

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Annex Chapter III

Survey design – Questionnaire

1. Mobility/ dependence on local sub-population
   Where do you usually fish?
   Please select, multiple ticking possible!
   - My trips are shorter than 24 hours
   - I (almost) always fish from my home harbour
   - I often fish from various harbours
   - If there is little to catch on the doorstep, I still stay in this area because I know it best
   - If there are more shrimps elsewhere, I'll drive to Holland or Denmark for several days
   - I am often at sea for more than three days

2. Need for management
   How do you assess the current development? In the last 10 years...

   The Brown shrimp stock did…
   Please select!
   - …decrease
   - …increase
   - …stay the same, but with large fluctuations

   The fishing effort did…
   Please select!
   - …increase, e.g. by new larger vessels
   - …decrease, e.g. due to vessels leaving the fleet
   - …stay the same

   In times with little shrimp…
   Please select!
   - …there is more fishing effort
   - …there is less fishing effort
   - Most people always fish the same way, regardless of whether there are a lot or few shrimps

3. Management efficiency
   What measures would protect the population in the short term in an extremely bad shrimp year?
   - Weekly closure of the fishery until the catch per hour at sea increases again
   - Limitation of weekly hours at sea
   - Temporarily larger mesh sizes so that more smaller shrimps grow to consumption size
   - Fishing has no influence on the population
   - Free text

What measures would effectively reduce the amount of small and undersized shrimp in the catch?

Larger mesh sizes in the codend

Temporary closure in months and areas with small shrimps

Limitation of weekly hours at sea in months with small shrimps

Changing the sieving on board before cooking

High penalties for undersized shrimps when sieving on land

Free text

Should the management measures be implemented on a local basis?

Yes

No

if yes:

...because otherwise too much effort would be shifted to other areas

...so that all fishermen have the same conditions

...because the North Sea shrimp is a large stock (and not regionally independent)

...to simplify the control

if no:

...to better protect local low stocks

...because even when stocks are low in some areas, fishing can still continue unlimited in others

...to offer more incentives to better manage the stock on site

Do you agree?

A larger mesh can be fooled by changing the net configuration

The undersized shrimps that escape through the larger meshes lead to higher catches later in the season

Better to leave the real 26 mm mesh and effort as it is

Better real 24 mm mesh and 2 x 4 weeks fishing stop (e.g. February and August)

4. Participation of fishermen in management

To what extent were you involved in the development of the management?

select between little (1) and fully involved (5)

To what extent was your own producer organisation involved?

select between little (1) and fully involved (5)

How much influence did the individual national fisheries have?

select between little (1) and fully involved (5)

How much influence did external organisations have?

select between little (1) and fully involved (5)

What influence do you have on subsequent decisions?

Involved in all decisions

Often heard, even if a different decision was then taken

Decisions are made at another level and then passed on to the fishermen

Should the individual fishermen be more involved, e.g. through more voting?

No, we are quite well represented through e.g. Producer Organizations

No, because unpopular but necessary decisions will not be taken

Yes, because the fisheries and producer organizations do not represent the interests of all fishermen

Yes, because unpopular decisions will get more acceptance

5. Control and compliance

How exactly is the larger mesh size controlled?

...through our own producer organisation
select between very little (1) and very strict control (6)

...in other producer organisations
select between very little (1) and very strict control (6)

...by other fishermen (e.g. in the harbour)
select between very little (1) and very strict control (6)

...by the inspector
select between very little (1) and very strict control (6)

...by the fishermen themselves
select between very little (1) and very strict control (6)

How strictly is the weekly hour limitation in case of low shrimp stocks monitored?

...through our own producer organisation
select between very little (1) and very strict control (6)

...in other producer organisations
select between very little (1) and very strict control (6)

...by other fishermen (e.g. in the harbour)
select between very little (1) and very strict control (6)

...every fisherman takes care of it himself
select between very little (1) and very strict control (6)

How strictly is the weekly hour limitation enforced in case of low shrimp stock?

I voluntarily comply with the common rules

Nobody can ignore it, even if some would like to

With a little flexibility, I can continue fishing as before

Nobody can control exactly when and how I fish anyway

The fishermen of some producer organisations/countries do not follow the rules because there is no monitoring

Who would be best placed to monitor management compliance and enforce penalties if necessary?

The PO know their fishermen the best

National authorities

A committee out of fishermen of all fleets

An external controlling

General Discussion

Recent Stock Dynamics and Unexpected Trends

During the course of this study, developments in the fishery outpaced the initial conceptual framework. Upon completion of the first chapter, the record-high landings observed in 2018 appeared to indicate a rapid recovery of the stock from the low levels seen in 2016 and 2017. This "Brown shrimp wonder" shows similarities to that one of the Baltic cod. The development parallels what was observed in the Baltic cod stock, where a prolonged decline appeared to be reversed by a surge in recruitment, only to be followed by a subsequent stock collapse (Möllmann et al., 2021; Reidt, 2012). In a similar pattern, the landings per unit effort (LPUE) for the brown shrimp fishery have steadily decreased since 2018, resulting in the second lowest landings recorded since 1987 in the year 2024 (ICES, 2025). Although a new spatially resolved dataset that would allow for the extension of the analysis presented in Chapter I is not yet available (ICES, 2025), preliminary evidence suggests that the declining trend observed in the first quarter of the year has persisted. Specifically, LPUE values in February 2025 have fallen below the fourth reference value of the harvest control rule (pers. Comment P. Oberdörffer). Despite recent advances in our understanding of the biology and life-history traits of *C. crangon* (Temming et al., 2022), the underlying causes and mechanisms driving this decline remain uncertain.

Predation, Mortality, and Environmental Interactions

Meanwhile, the most recent ICES advice (ICES, 2024), reports an increasing spawning stock biomass for whiting (Merlangius merlangus) in the North Sea. The younger year classes of whiting are recognized as significant predators of mainly small *C. crangon* (Jansen, 2002). However, previous studies have generally found no consistent correlation between predator populations—such as whiting—and the abundance of *C. crangon* (Hufnagl et al., 2010; Siegel et al., 2005). Notably, the 0-group whiting experienced a peak in abundance during 2019 and 2020, both years without effort restrictions imposed by the Harvest Control Rule (HCR) (ICES, 2024). Despite the overall increase in North Sea whiting populations, predation pressure on *C. crangon* in the Wadden Sea is reported to remain lower than in previous decades (Escalona, 2024). A further limitation is that total mortality, which has shown an increasing trend since 2010, is not currently disaggregated into natural and fishing mortality (ICES, 2025). This lack of distinction makes it difficult to attribute the observed decline in *C. crangon* stocks to any development of predator populations with certainty.

A leading hypothesis for the observed decline is the increasing mean temperature of the Wadden Sea. Although adult brown shrimp (*Crangon crangon*) do not exhibit a strong preference for specific temperature ranges (Reiser et al., 2016, 2014), rising temperatures can accelerate larval development, potentially resulting in a mismatch between larval stages and their planktonic food availability (Hünerlage et al., 2019). Previous studies have even identified positive effects of cold winter temperatures on brown shrimp recruitment (Siegel et al., 2005). Additionally, water temperature may influence springtime larval drift, a process likely essential for transporting larvae to productive coastal feeding grounds (Daewel et al., 2011; Hufnagl et al., 2014). Notably, an extreme drift anomaly in 2018 has been suggested as a major factor contributing to the unusually high abundance of brown shrimp observed later that year (Stanev et al., 2019).

Fishery as a potential driver of stock decline

However, none of the environmental factors discussed so far has been clearly linked to the decline of the Crangon stock. The conclusion drawn in the first chapter—that winter fishing is the most probable driver pushing the stock to lower levels—therefore remains valid. For species such as the European anchovy, which shares a similar life-history strategy, it is well established that they can readily adapt to changing environmental conditions (Fréon et al., 2005). At the same time, however, these species are vulnerable to increased mortality during specific periods, as only reproduction that occurs within a limited "window of opportunity" is successful under certain environmental conditions (Fréon et al., 2005). Applying this concept to brown shrimp suggests they may also be acutely susceptible to fishing during the winter months, when the primary cohort contributing to subsequent catch season is produced. During winter egg development times are extended, and mature females are spatially concentrated (Schulte et al., 2020; Temming et al., 2017). As noted in chapter I, fishing effort off the Dutch coast explained more than 60% of the variability in LPUE off Schleswig-Holstein in July and August, while no correlation could be found for LPUE in later months. Initially, this was discussed in the manuscript for Chapter I as being caused by a second recruitment of local origin, overlapping with the first one from the southern areas. It was assumed that this second recruitment peak originates from eggs spawned in May and June. The higher temperatures lead to accelerated development of the eggs and larvae, resulting in less impact from fishing and higher dependence on environmental parameters (Temming et al., 2017). However, the extension of the original time series of Chapter I by two more years in the CRANMAN project (Temming et al., 2022) resulted in additional significant correlations of the effort in January and February off the Dutch coast and the LPUE in September and October off the Southern and Northern German coast. The potential impact of the fishery on recruitment seems thus to be more severe than initially proposed.

As a promising approach, additional environmental factors could increase the significant correlation between fishing effort and LPUE. Including environmental variables in stock-recruitment models has improved prediction accuracy for other opportunistic species, and has been applied successfully to the management of Pacific sardine fisheries (Haltuch et al., 2019; Herrick et al., 2006). Importantly, it is now recognized that short-lived species are not inherently less vulnerable to fishing than long-lived, slow-growing species as was previously assumed; on the contrary, they may face equal or even higher risks of overexploitation (Hilborn, 1992; Jennings et al., 1998; Pinsky et al., 2011; Reynolds et al., 2005). For forage fish populations, which, like brown shrimp, are characterized by short life cycles and high recruitment potential, a consistent pattern has been observed: persistent high fishing pressure for several years prior to population collapse, followed by a rapid decline in recruitment, and a delayed implementation of management measures to reduce fishing mortality (Essington et al., 2015).

In small pelagic fish species, constant catchability due to schooling behavior did accelerate resource depletion (Mackinson et al., 1997). In the brown shrimp fishery, recent years of declining catches have been accompanied by increasing prices for the product, thereby economically offsetting low landings—as occurred in 2016—while encouraging above-average fishing effort (Goti-Aralucea et al., 2021; ICES, 2019a). The combined effect of unfavorable environmental conditions and high fishing pressure—especially when fishing intensity is not adjusted according to stock status—can elevate the risk of stock collapse substantially (Herrick et al., 2006). This risk increases further when the fishery responds to declining landings by increasing effort in response to rising market prices.

Of particular concern is the observed reduction in the proportion of large shrimp, primarily mature females, in recent years. In earlier years, the fraction of shrimp larger than 60mm frequently constituted up to 25%, and of shrimp larger than 70mm up to 4% of all shrimps larger than 45mm in the Dutch and German survey catches. The high proportions have not been observed since 2013, with the fraction larger than 60mm decreasing to less than 18% and the fraction larger than 70mm to less than 2% (ICES, 2025). Since the possibility of recruitment overfishing is at least supported by statistical analysis, management intervention should be considered. In the absence of effective measures, the current low abundance of the stock would pose a considerable risk of both stock and fishery collapse.

Evaluating management implications: Challenges and Approaches in Managing Short-Lived Species

Most management plans for long-lived species employ population models to generate stock forecasts under various catch scenarios, ultimately producing advice on catch levels that are intended to ensure stock health and sustainability (ICES, 2019b). However, this approach is generally not feasible for short-lived species. The management of r-strategists, such as C. crangon, presents distinct challenges due to high variability in abundance, strong dependence on environmental factors, and often poorly understood stock–recruitment relationships (Fréon et al., 2005; Siple et al., 2019). As a result, adaptive management strategies tend to outperform predictive management in these cases, since reliable forecasts of abundance and stock dynamics are rarely possible (Fréon et al., 2005).

In the absence of established MSY estimates, related biological reference points, or dedicated survey data for predicting seasonal abundance, the current Harvest Control Rule (HCR) relies on commercial LPUE as a proxy for *C. crangon* stock status (Addison et al., 2024). Such HCRs are known as empirical harvest control rules; frequently, these are based on pre-season surveys rather than fishery-dependent data (Uriarte et al., 2023). For short-lived species, minimizing the time lag between the acquisition of stock status information and the implementation of management actions increases management effectiveness (Dichmont et al., 2006; Sánchez-Maroño et al., 2021).

The stepwise reduction of fishing effort when LPUE drops below predefined reference values, as implemented in the brown shrimp management plan, is an example of a proportional threshold harvesting approach. This methodology is considered advantageous for species with high uncertainty in stock estimates or substantial variability due to environmental factors (Addison et al., 2024; Engen et al., 1997). In these systems, fishing effort is reduced whenever the abundance index falls below a reference point (Lande et al., 1997). However, the main disadvantage of such approaches is the resultant uncertainty for the fishery sector, complicating investments and planning. Reports from the brown shrimp fleet indicate that irregular fishing opportunities and persistently low catches during effort-restricted periods have led to difficulties in crew recruitment (pers. comment P. Oberdörffer).

Nevertheless, simulation results presented in Chapter II indicate that an even stricter approach—closing the fishery entirely, rather than merely reducing effort, when reference thresholds are breached—may yield improved outcomes. While such effort limitations would be more severe, particularly for the most active vessels, the resulting annual reduction in fishing effort remains relatively modest compared to previous studies, such (Temming et al., 2013), where a 12 months effort reduction of approximately 35% was necessary to restore the stock from 70% to 100% of average levels. In the present simulations, annual stock biomass reached a low of 65% of the long-term average in the recruitment-failure scenario. In this scenario, the most stringent HCR approach responds with a 5.9% effort decrease, the HCR as currently implemented (HCR72) with a 3.3% effort decrease. On a monthly scale, the lowest simulated biomass in the recruitment failure scenario was 51% of the long-term average in July. The lowest simulated LPUE fell to 50% of the long-term average in August and September in the recruitment-failure scenario. Under the current HCR design, effort reduction in these cases would have been only 16%—and as such insufficient to raise LPUE above the reference value in the following month. The lowest reference value in the management plan still permits up to 24 hours at sea per vessel, even if LPUE falls to as low as 36% of the long-term average in March—a month likely crucial for recruitment.

No threshold value which indicates a possible collapse of the stock, or a recruitment impairment have been defined for the Brown shrimp population, and no conclusions on the risk of considerable population declines can be drawn from the relation of LPUE or biomass to the long-term average. A study on forage fish, which share some life history characteristics with Brown shrimp such as short lifetime, high reproductive potential and strong dependence on environmental factors, defined 25%

and 15% of the long-term average biomass as reference points for stock collapse (Essington et al., 2015). The biomass levels in the simulation used here are still significantly higher than the 25% threshold associated with stock collapse in the study by Essington et al., but no further effort reduction is required by the management plan once the LPUE (as a proxy for biomass) falls further below the last reference value.

These findings suggest that, in times of critical stock status, the present HCR design may be too slow and unambitious in responding to stock declines. By contrast, a more drastic measure involving a 99% effort reduction for two weeks performed considerably better in simulations, leading to a rapid increase in LPUE. Such results point towards possible improvements in HCR design for this fishery. Notably, in the scenarios and HCRs tested, this sharp approach did not reduce total marketable shrimp landings but did reduce overall effort and costs.

Similarly, (Essington et al., 2015) found that a simulated HCR which closed forage fisheries at 50% of long-term average biomass resulted in only modestly reduced catches while enabling fast stock recovery. A comparable strategy could prove successful for the brown shrimp fishery, potentially avoiding the prolonged effort restrictions in the two simulated scenarios with the HCR72 approach, which is equivalent to the HCR as currently implemented. In both scenarios, the effect of the HCR on the effort was too low to raise the LPUE above the reference values in the first two weeks, resulting in additional weeks with effort restriction. If a short but substantial reduction in fishing effort can trigger a significant rebound in stock abundance and subsequent landings, it may also help secure greater support from the industry for a revised HCR.

The view of the fishery

While the findings from Chapters I and II clearly indicate the need for species-specific management measures—ideally incorporating stronger and more efficient effort reduction rules than those currently in place—the perception within the fishery itself is markedly different. Many fishers maintain that the fishery has little to no impact on the target stock, and the majority reject the regionalization of the HCR, despite this being an explicit recommendation from the ICES working group (ICES, 2022). While a gradual increase in mesh size up to 26 mm was initially intended to address growth overfishing, only the initial steps up to 24 mm for the part of the Danish and 25mm for all other fleets were realized. Due to limited acceptance within the fleet, plans for further increases were abandoned and eventually replaced by measures reducing fishing effort.

A key challenge arising from the rejection of the scientific recommendations by the fishery is the effective communication of scientific findings to individual fishers. In personal discussions, the impact of the fishery on the recruitment as described in Chapter I have often been questioned—in contrast to some acceptance of the possible influence of strong whiting year classes. The hypothetical influence of the predator whiting aligns with fishers' anecdotal observations, but for this, no scientific evidence and no significant correlation in the data has yet been found. The recent scientific recommendations such as the meshsize increase or replacing the current HCR with a stricter cut in effort are derived from modelling exercises that assume a steady-state fishery with only selected variables manipulated. However, reality is more complex. The *C. crangon* stock exhibits high year-to-year variability, with many influencing factors still not fully understood. The estimated effect of the current HCR, as discussed above, appears quite limited. Consequently, the predicted benefits of various management measures, as projected by simulation models, cannot be observed in practice. Notably, since the implementation of management measures in 2016, the stock began to decline—a situation that understandably prompts fishers to question whether the management itself may be contributing to reduced catches.

Establishing new form of communication and direct exchanges between scientists and fishers could be an important first step in fostering trust in scientific research (Dickey-Collas et al., 2010). In contrast to other fisheries, where the management authority is communicating the scientific results to the fishery and translating them into management action (van Densen and McCay, 2007), in the case of the self-management, science and the fishery have to communicate directly. Although it is questionable whether open communicating the flaws and uncertainties of the scientific results would increase acceptance among fishers, it could reduce frustration when contradictory recommendations are presented, e.g. from different modeling approaches (ICES, 2025) or are withdrawn due to new findings (van Densen and McCay, 2007).

One common question of fishers of the Brown shrimp fleet in the last years was whether the previously detected growth overfishing would still occur, as effort in the last years did decrease. From the further decline of catches, despite reduced effort, one could reason that fishing pressure has no impact on the population level. Fishers usually rely on personal and specific experiences regarding the state of the stock and fishing pressure. The scientific recommendations rely mostly on aggregated, large-scale data, which is the analyzed and often communicated in graphs. However, the ability to read and understand graphic displays widely differs, as do the capacities and capabilities to analyze the own business and logbook data among fishers. A step forward could maybe be an approach to apply the trend analysis of Chapter I to individual logbook data in a workshop, and maybe then aggregate the data on a group level, to display how scientific methods work. On the other hand, fishers have information on hidden increases in effort, such as shorter processing times, adjustments to the netting and longer working hours, which are not reflected in the scientific data. However, this information could improve our understanding of what is happening in the field.

The findings presented in Chapter III also suggest that involving the fishing sector more closely in management design and decision-making processes could yield significant benefits. For example, in the Bay of Biscay anchovy fishery, close collaboration between scientists and stakeholders resulted in an HCR that is well-adapted to local conditions and widely accepted, balancing conservation objectives with the economic viability of the fleet (Uriarte et al., 2023).

Ideally, such participatory processes should involve the majority of fishers directly. Many do not feel adequately represented by POs and report feeling excluded from management. Rather than fostering the often-cited "level playing field," recent management decisions have instead created specific regulations for each national fleet. In the Danish fleet, fishers can even choose between two different combinations of meshsize and effort reduction (Addison et al., 2024). The question arises about the efficacy in reducing the existing distrust among POs and between fishers of different nationalities.

Persistent conflicts and divisions—between organized and non-organized fishers, among POs, and between national fleets have already hindered previous management initiatives (Aviat et al., 2011; Steenbergen et al., 2015). The economic background and pressure can vary within the fleets. Fishers who did invest in a new vessel or new equipment often have to pay back their loans, and thus may be forced to go out even when catches are low (Respondek et al., 2014). Some of the larger boats stay at sea up to 9 days, with two crews working in shifts (Aviat et al., 2011) and continue fishing throughout the year, even in Winter when the weather conditions are harsh. In the past, bad weather conditions were a kind of natural closed season for the spawning stock, especially in January and February.

The age of the national fleets differ, within the Danish fleet most vessels were replaced by new types around 2006, while the average age of the German fleet is about 34 years (Aviat et al., 2011). In the Dutch fleet, many large beam trawlers of the flatfish fisheries switched to shrimp fishing due to lack of fish quotas in the late 90s, as predicted by (Salz and de Wilde, 1990). This resulted in more than 60% of the Dutch fleet made up of vessels larger than 20m with more than 200kW engine power, while the Danish and German fleet have a mean length of 17m (Aviat et al., 2011). A particular conflict exists between larger and smaller vessels, equivalent to mobile versus "home-bound" fishers. This is epitomized in correspondence from a Dutch fisher describing a powerful "big fleet," perceived as less constrained by regulations affecting the "coastal" fleet and as taking a disproportionately large share of the catch (Addison et al., 2017). This fleet segment is likely reflected in the cluster of mobile and active Dutch fishers identified in Chapter III, who perceive regulations as less restrictive and express less support for increased participatory management.

Closer communication and interaction between scientists, POs, and the fishing community could bring substantial benefits for all stakeholders (Sampedro et al., 2017). This analysis suggests that the primary threats to the effectiveness of the current management system are mistrust among participants, low acceptance of regulatory measures, and the fragmentation of the fleet into groups with sometimes competing interests. Nevertheless, there is also clear interest and willingness within large segments of the fleet for greater involvement in management. In the absence of a third-party management authority, it may fall to the POs to take a leading role in reshaping the management framework, thereby increasing acceptance and fostering a stronger sense of ownership among fishers.

Conclusion

The brown shrimp (*Crangon crangon*) fishery currently finds itself at a unique and pivotal point in its history. After many years of stalled management attempts, a breakthrough was achieved not due to biological concerns or market dynamics, but rather in response to third-party certification requirements of the Marine Stewardship Council (MSC). Despite this progress, recent developments and the scientific evidence presented in this dissertation indicate that an effective, responsive stock management system is now more urgently needed than ever before. The actual status of the stock relative to MSY or other established biological reference points remains undetermined. However, the results of this work demonstrate that *C. crangon* is currently at increased risk, and that the present harvest control rule (HCR)—while an important step forward—is not sufficiently robust to handle severe declines. Both field observations and simulation studies indicate that current effort reductions are too limited to provide adequate protection, especially in critical periods.

More stringent and targeted measures, such as protecting aggregations of egg-bearing females during winter, should be investigated collaboratively with fishers to maximize effectiveness and acceptance. One of the central challenges is to build trust among the fishers and encourage a sense of ownership and responsibility for the management of the fishery. While many fishers still perceive little impact of the fishery on the stock and remain skeptical of scientific advice, perceived compliance with the regulations and rules is high. A shared willingness to discuss key topics—such as the regionalization of the HCR—reveal a solid foundation for moving forward. Greater involvement of fishers in management design could stimulate innovative solutions and foster a sense of shared responsibility for the resource, supported by better communication of scientific results and knowledge.

The brown shrimp fishery thus has significant potential to serve as a best-practice example for the sustainable management of short-lived species, especially in situations where national management is lacking or fragmented. However, as external management authorities play only a minor role, it will fall to the POs to lead efforts in uniting fleet sectors, harmonizing regulations, and facilitating direct exchange and transparency. Drawing on experiences from other participatory fisheries, a stronger partnership between science, management, and fishers themselves will be essential to address both stock conservation and socio-economic viability.

One major obstacle to stricter HCR is the fishery's struggling economic situation. After years of low landings and high energy costs, there are few savings left to tide them over until the stock allows for sufficient landings again. The financial situation of the POs is likely to be similar. National governments of the main fleets should facilitate the transition phase by providing financial compensation while the fleet is in port, for example.

If the current challenges are met with appropriate, inclusive management solutions, the brown shrimp fishery may not only secure its own future, but also provide valuable lessons for similar fisheries worldwide that are grappling with environmental variability, uncertainty, and the need for locally tailored solutions.

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Author contributions

Chapter I. Connectivity of local sub-stocks of Crangon crangon in the North Sea and the risk of local recruitment overfishing

Georg Respondek, Claudia Günther, Ulrika Beier, Katinka Bleeker, Eva Maria Pedersen, Torsten Schulze, Axel Temming

Georg Respondek developed the concept of the study, compiled the dataset, did the statistical analysis and wrote the manuscript. Claudia Günther helped with the statistical analysis and reviewed the information on the life cycle of C. crangon. Ulrika Beier reviewed the manuscript and helped with the interpretation of the Dutch data. Katinka Bleeker helped in the compilation of the dataset. Eva Maria Perdersen reviewed the manuscript and helped with the interpretation of the Danish Data. Torsten Schulze helped with the initial R-script and facilitated the requests for the VMS and logbook data. Axel Temming supervised the statistical analysis, the interpretation of the results and reviewd the manuscript.

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Chapter II. Investigating the effectiveness of the harvest control rule of the North Sea brown shrimp fishery using shrimp specific Y/R simulation model

Georg Respondek, Claudia Guenther, Axel Temming

Georg Respondek developed the concept of the study, implemented the scenarios in the population model, did the statistical analysis and wrote the manuscript. Claudia Günther developed the standard run of the population model and reviewed the manuscript. Axel Temming supervised the development of the concept of the study, the interpretation of the results and reviewed the manuscript.

Chapter III. A paved road or a stony path? Investigation of the circumstantial settings and user perceptions in the Brown Shrimp Self-Management

Georg Respondek, Axel Temming

Georg Respondek developed the concept of the study, designed the questionnaire for the survey, did the statistical analysis and wrote the manuscript. Axel Temming supervised the development of the survey and reviewed the manuscript.

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Hiermit versichere ich an Eides statt, die vorliegende Dissertation selbst verfasst und keine anderen als die angegebenen Hilfsmittel benutzt zu haben. Die eingereichte schriftliche Fassung entspricht der auf dem elektronischen Speichermedium. Ich versichere, dass diese Dissertation nicht in einem früheren Promotionsverfahren eingereicht wurde.

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