

**Fishery, population dynamics and stock assessment of geelbek
(*Atractoscion aequidens*), a commercially important migrant fish
species off the coast of South Africa**



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Abstract

Geelbek (*Atractoscion aequidens*) is an important fish species in South Africa's linefishery, a fishing sector defined by its fishing gear of rod and reel or handline. Distributed from Cape Point (34°21'S, 18°29'E) on the south west coast to Kosi Bay (26°51'S, 32°53'E) on the east coast, they are targeted throughout their range by the commercial linefishery, recreational anglers and small-scale fishers. The majority of geelbek are caught on the Agulhas Bank during austral summer. Due to current minimum size limits of 600 mm (total length, TL), well below the 50% size-at-maturity (950 mm TL), the majority of the catches are comprised of immature fish, making the stock vulnerable to growth overfishing. Adults (>5 years) migrate seasonally to spawn off KwaZulu-Natal and congregate in offshore shoals at night. These spawning aggregations allow fishermen to catch large numbers of fish, making geelbek also vulnerable to recruitment overfishing.

This study aims to improve understanding of the fishery and population dynamics of geelbek to help inform natural resource management of the geelbek linefishery. A stock assessment of South African geelbek was undertaken to fulfil this aim. For this purpose, spatially and seasonally explicit equilibrium per-recruit and dynamic age-structured operating models were developed for geelbek to account for the dynamic in stock structure as a result of the intra-annual coastal migration and differences in the vulnerability of life history stages to varying fishing pressure along South Africa's coastline. These models were developed using statistical programming environment R. The models were parameterised and calibrated using length and catch data from the National Marine Linefish System (NMLS) and life history parameters sourced from peer-reviewed literature.

Per-recruit analyses were performed to estimate current stock-specific fisheries mortality rates and the spawner biomass depletion. These estimates were used as input into the stochastic age-structured simulation model and calibrated using available commercial catch data (1987 - 2011). The stochastic operating model was used to predict the probability of stock recovery and long-term sustainability under eleven alternative fisheries management strategies.

The current stock status was estimated at 9.9% (approximately 10%) of the pristine spawner biomass (SB_0) using per-recruit analysis. This was compared to the stock depletion estimates of ~5 and 7% SB_0 from prior assessments conducted in the late 1990s and 1980s. This study indicated that there was a ~50 to 100% increase in spawner biomass over the past twenty years. However, this level of stock depletion is still considered critically low with respect to the previous limit management goal of increasing spawner biomass depletion rates above 25% SB_0 , the collapsed limit reference level, advised by Griffiths in 1997.

Eleven management strategies were simulated, examining the effects of decreases in harvest rates, closed seasons and areas and changes in minimum size limits, initiated in 2020, and tested over the medium (ten years) to long (twenty years) term. The least efficient management strategy was continuing at the *status quo*, with a minimum size limit of 600 mm (TL), which predicted only 1% and 2% increase in SB by 2030 and 2040, respectively. The most efficient in terms of a rapid recovery was a full fishery closure ‘control scenario’ (moratorium), which predicted a recovery to the threshold reference level for sustainable fishing at 40% SB_0 by 2025, and approaching pristine levels by 2040. Increasing the minimum size limit to the size-at-50%-maturity, 950 mm TL, had the second highest recovery rate, reaching 25% SB_0 by 2027, and nearing 40% SB_0 by 2035, at which point its trajectory is asymptotic to 40% SB_0 . Decreasing the harvest rate by 50% across all regions and seasons had the third highest recovery rate, reaching 25% SB_0 by 2035, but levelling off thereafter. All the other management strategies resulted in slight stock recoveries, but with all stock trajectories remaining below 14% SB_0 in the long term. Additionally, the impact of various strategies, such as increasing the minimum size limit to the size-at-50%-maturity, 950 mm TL, were unequal, with the east coast experiencing increasingly higher catches over time, whereas the catches for the south south west coast declined drastically throughout the year, and did not improve with time. Such unequal distribution of the impact of management intervention is a consequence of the migratory life history of the geelbek stock. These results provide comprehensive insights into the population dynamics and current impacts on the geelbek stock, suggesting that this species remain severely depleted at ~10% SB_0 . Rebuilding the stock to sustainable levels would require serious management intervention.

Keywords: Geelbek, *Atractoscion aequidens*, linefish, stock assessment, spatially and seasonally (temporally) explicit model, per-recruit model, age-structured production model, management strategy evaluation, simulation tool, fisheries management

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Acronyms and abbreviations

Please note, italics are used to differentiate model related metrics, such as state variables and parameters, from standard acronyms.

ASEM	Age-structured equilibrium model
ASPM	Age-structured production model
<i>B</i>	Biomass
<i>C</i>	Catch
<i>C_{prop}</i>	Proportion of catch
CPUE	Catch per unit effort
DAFF	Department of Agriculture, Forestry and Fisheries (of South Africa)
DEA	Department of Environmental Affairs (of South Africa)
<i>E</i>	East coast
<i>EB</i>	Exploitable biomass
EEZ	Exclusive economic zone
<i>F</i>	Fishing mortality
FIMS	Fisheries independent monitoring survey
FL	Fork length
FRP	Fisheries reference point
<i>H</i>	Harvest rate
<i>h</i>	Steepness (often <i>z</i>)
IUU	Illegal, unreported and unregulated (fishing)
KZN	KwaZulu-Natal
LMP	Linefish Management Protocol
LRP	Limit reference point
<i>M</i>	Natural mortality
MSE	Management strategy evaluation
MCM	Marine and Coastal Management
MLRA	Marine Living Resources Act of 1998
MPA	Marine protected area
<i>MSY</i>	Maximum sustainable yield
<i>N</i>	Numbers
NLS	National linefish survey
NMLS	National Marine Linefish System
OM	Operating model
OMP	Operational management procedure
<i>P1</i>	Time period one (August to November)
<i>P2</i>	Time period two (December to March)
<i>P3</i>	Time period three (April to July)
PMCL	Precautionary management catch limit
PUCL	Precautionary upper catch limit
<i>q</i>	Catchability coefficient

<i>R</i>	Recruit
SADSTIA	South African Deep-Sea Trawling Industry Association
<i>SB</i>	Spawner biomass (often, spawning biomass or spawning stock biomass, <i>SSB</i>)
<i>SE</i>	South east coast
SPR	Spawning per-recruit or spawning potential ratio
S-R	Stock recruitment (curve)
<i>SSW</i>	South south west coast
TAC	Total allowable catch
TAE	Total allowable effort
TL	Total length
TRP	Target reference point
<i>VB</i>	Vulnerable biomass
VPA	Virtual population analysis
YPR	Yield per-recruit
<i>Z</i>	Total mortality

1. Introduction

1.1. International fisheries management

The harvesting of marine resources at an ever-increasing capacity has led to a decline in many fish stocks, with several stocks being overfished (Hilborn *et al.*, 2003; Jackson *et al.*, 2001; Worm *et al.*, 2009). This decline necessitated the development of fisheries policies such as the 1982 UN Convention on the Law of the Sea and of sustainable development, and the FAO (1995) Code of Conduct for Responsible Fisheries. These policies were designed to aid the sustainable harvesting of both target (Worm *et al.*, 2009) and non-target species (Kelleher, 2005), and minimise the effects this may have on the ecosystem as a whole (Caddy, 1999; Pauly *et al.*, 2005). New fisheries management policies are focused on sustainable harvesting while maintaining ecological functioning and resilience (Pauly *et al.*, 2002) and maximising economic (Sethi *et al.*, 2010) and social benefits (Punt *et al.*, 2013a).

To achieve these goals, fisheries management policies generally work by implementing management strategies for each fishery, usually aiming to rebuild stocks to a biomass (B_{MSY}) capable of sustaining harvesting at the maximum sustainable yield (MSY). Management strategies are defined by Punt *et al.* (2013b) as “combinations of data collection schemes, stock assessment methods, and harvest control rules selected to achieve pre-specified management goals”. These strategies also need to fit the socio-economic and political environment of the country, and include all relevant stakeholders.

One of the most common fisheries management strategies are harvest control rules (HCRs) such as total allowable catch (TAC), which usually works in conjunction with restricting access to the fishery, through the allocation of specific quotas to limited fishing rights holders. For multispecies fisheries, a common control method is total allowable effort (TAE), which operates by limiting the number of boats, and/or the number of sea-days, or times people are allowed to fish. Closed seasons and/or areas are found to be particularly effective in managing stocks that have well-known, defined vulnerabilities which may create bottlenecks for the stock, through events such as spawning aggregations or limited nursery areas. Marine protected areas (MPAs) are another similar management strategy, which

provides varying levels of permanent protection, depending on their purpose and boundaries stipulated under the areas and conditions in their regulations. This protection is not just for the target species, but for the ecosystem as a whole, with the potential for spill-over effects (Kerwath *et al.*, 2013).

Different types of fisheries require different management strategies, and a wide range has been developed, including HCRs, such as changing the size at capture, controlling total catch or total effort, closing an area or season to fishing, or restricting access to the fishery through permits and rights allocations (Deroba and Bence, 2008). Each of these broad strategies has various methods of implementation. For example, changing the size at capture can refer to implementing a minimum or maximum size for a species, or applying slot limits. These limits are designed to protect the stock based on an understanding of the life history and population dynamics of the species. Froese *et al.* (2016) put forth a suggested optimum size at first capture (L_{c_opt}), which is generally slightly larger than the size at maturation. This method is designed to allow each fish the opportunity to reproduce before being targeted by the fishery. However, the complexity of fisheries management lies in the fact that no single strategy is applicable across all fisheries. To further this example, the L_{c_opt} strategy is usually not suited to species with unusual spawning strategies, such as delayed maturation, sequential hermaphroditism or semelparity. Changing the target size of a fishery can be implemented in various ways, depending on the fishery and behaviour of the target species, such as increasing net mesh size for trawl or gill fishing and hook size for longline or linefishing.

Fisheries science aims to provide the best possible management strategies, including estimates of the biomass of the stock, and its depletion status relative to designated reference points, such as pristine spawning biomass (SB_0), target biomass (B_{MSY}), threshold and limit levels (Froese *et al.*, 2017). To obtain these, several different types of quantitative stock assessment methods are available (Punt *et al.*, 2013b), which depend on the availability of fisheries and biological data to determine the parameters of mathematically described biological and ecological relationships. Without data to parameterise the models they cannot provide reliable estimates of the real situation. Different stock assessment models require different data sources. These data range across all the aspects of the fishery, including species-specific data on the biology (especially length-at-age and length-weight relationships), life history, ecological function, abundance indices, and catch and effort dynamics of the fishery (Blamey *et al.*, 2015; Brooks *et al.*, 2010). Many of these types of

data are only available for data rich fisheries, which are more prevalent in developed countries. Additionally, fisheries scientists having the necessary technical skills are required to perform the assessments and such people may also be a limiting factor (McCluskey and Lewison, 2008).

Fisheries management begins with data, which are then fitted to stock assessment models to provide estimates of population dynamics that estimate the current state of the stock. The continuation of many marine resources being overexploited is considered to be due to a mismatch between the precision of assessment and the precision of management (Caddy and Mahon, 1995; Pons *et al.*, 2017). Stock assessments seek to provide quantitative estimates that describe the stock's population dynamics as well as fisheries reference points (FRP) for fisheries management (Mace, 2001; Magnussen, 2007). Uncertainty and risk related to fisheries management and model accuracy are also being estimated quantitatively with more modern modelling approaches, however this requires high level technical skills, and there is a concern that smaller stocks and especially those in developing countries may be overlooked due to the cost of these assessments (Béné, 2003; Sowman, 2011; Sowman *et al.*, 2014). To account for uncertainty, FRPs are often separated into two types: target reference points (TRPs) and limit reference points (LRPs), below which more severe management interventions are required to achieve stock rebuilding.

One of the primary metrics for determining the stock status relates to the available spawning stock biomass of a population (SB) as it provides a meaningful measure of abundance over time and a proxy for the reproductive potential of the population. The concept of the maximum sustainable yield (MSY) is probably the most widely adopted principle to determine the target spawner biomass required to attain the maximum sustainable yield (SB_{MSY}) and the harvest rate (H_{MSY}) that will maintain the stock at the biomass level which yields the maximum sustainable level. The maximum sustainable yield concept was first introduced to fisheries science by Schaefer in 1954, who defined the MSY as the largest catch possible without decreasing the stock's potential to replace it over short periods (Gabriel and Mace, 1999; Mace, 2001; Martell and Froese, 2013). However, since absolute estimates of the maximum sustainable yield, spawner biomass and harvest rate which produce the maximum sustainable yield often have large associated uncertainties, it is more common to infer the stock status in terms of the more robust ratios for spawner biomass SB/SB_{MSY} and harvest rate H/H_{MSY} .

In the real world, however, it is usually difficult to determine even SB/SB_{MSY} , because it requires adequate knowledge about the spawner-recruitment relationship, which is one of the most difficult relationships to estimate (Lee *et al.* 2012; Punt *et al.* 2013b). As a result, it is common practice to use sensible approximations about SB/SB_{MSY} in the form of spawner biomass (SB) depletion relative to pristine spawner biomass (SB_0 , Brooks *et al.*, 2010). Depending on the biology, as well as the management region, SB/SB_{MSY} target reference points for bony fish are typically set at 30-40% SB_0 (Punt *et al.* 2013b) and limit reference points at 20-25% SB_0 . Spawner biomass levels for the 20-25% SB_0 threshold are associated with an increased risk of severely impaired recruitment (Beddington and Cooke, 1983; Common Fisheries Policy, 2013; Froese *et al.*, 2014).

Fisheries dependent and fisheries independent data are collected and fitted with fisheries assessment models to determine catch quotas based on the past, current and predicted status of the resource under various harvest regimes (Butterworth *et al.*, 2010b; Magnussen, 2007). The type of stock assessment performed is also reliant on the type of fishery, where a single-species fishery is often easier to assess than a multi-species one, due to fewer life histories and ecological functions to incorporate into research designs and mathematical models (McDonald *et al.*, 2001; Thorson *et al.*, 2011). Large, commercially important fisheries are therefore often well studied, such as the trawl fisheries for gadoid species (Hilborn *et al.*, 2003; Worm *et al.*, 2009), and some of the purse seine fisheries for small pelagic (Shannon *et al.*, 2000), and commercial longline fisheries (Ward and Myers, 2005). These fisheries are usually more data rich to data moderate than fisheries that operate on smaller scales which have less data available (Béné *et al.*, 2010), such as small-scale fisheries, due to government regulations and availability of funding for data collection and processing. Small-scale fisheries, more common in developing countries, have fewer onuses to collect and keep fishing records (Béné, 2003). Available catch statistics are also often misreported and, because of the large number of smaller role players in these fisheries, it can be difficult to collate and standardise these data (Béné, 2003; Béné *et al.*, 2010). This typically leads to small-scale fisheries being data limited and/or data poor (Cope and Punt, 2009), where data limited means that there is little data on the fisheries with which to generate reliable estimates of the state of the fishery (Punt *et al.*, 2013a), while data poor means that the data which are collected are of poor quality or there are gaps in the data series. Moreover, Costello *et al.*

(2012) found that as many as 90% of global fish stocks have insufficient data to conduct a conventional stock assessment.

Geromont and Butterworth (2014) underscored the need to increase the accuracy of data poor fisheries management estimates and predictions. However, data collection is both financially costly and timely, and this has led to a revival of research into data limited stock assessment methods (Carruthers *et al.*, 2014). While many management procedures can still be applied to unassessed stocks, such as some of the harvest control rules mentioned above (eg. TAC, TAE), their effectiveness is not easily assessed or comparable to determine the best management procedure (Carruthers *et al.*, 2014). Geromont and Butterworth (2014) and Carruthers *et al.* (2014) suggest using simulation testing to evaluate the robustness of these management procedures. Carruthers *et al.* (2014) found that fishing mortality (F) must be notably lower than the fishing mortality at maximum sustainable yield (F_{MSY}), for at least two generations to allow time for the stock to recover to around the biomass at maximum sustainable yield (B_{MSY}). After this recovery period fishing pressure can be increased to F_{MSY} . However, a precautionary approach to that level is recommended by Smith *et al.* (2011a) to prevent unforeseen elements, such as environmental changes, both long term climate changes, or shorter term changes such as *El Nino*, or a period of poor recruitment suddenly reducing the population to below B_{MSY} . Such precautionary strategies, if applied to key commercial species, should also limit the overexploitation of non-target species, for which individual assessments may not yet be possible or a priority.

The majority of the fisheries in developing countries, which are more prevalent in the southern hemisphere, are either data poor or data limited or both (Béné, 2003; Hilborn *et al.*, 2003; Ponte, 2008). Additionally, largely unregulated international fleets were responsible for past overfishing in the southern hemisphere, and still seek to fish international waters, each aiming to maximise their yield (Garcia *et al.*, 2012; Hilborn *et al.*, 2003). The current state of many exploited fish species and the health of the marine environment is still uncertain in these areas. These marine resources often form a crucial role in maintaining subsistence livelihoods, small commercial revenue and traditional techniques, which should be preserved (Berkes, 2003; Blamey *et al.*, 2015; Sowman, 2006; Sowman, 2011). However, no effective management systems can be implemented without data to inform realistic policy objectives (Punt *et al.*, 2013a). Non-compliance within stakeholder groups hinders the effectiveness of management strategies and the goal of sustainability (Harris *et al.*, 2002a; Harris *et al.*,

2002b; Sundström, 2015). Further financial costs are generated by trying to enforce management strategies in specific areas where non-compliance is a known issue (Sundström, 2015). Non-compliance also skews data and increases uncertainty (Worm *et al.*, 2009; Cochrane and Doullman, 2005; Harris *et al.*, 2002b). This uncertainty influences stock assessment models, which increases the likelihood that the final management strategies may fail to conserve or restore the stock (Cochrane and Doullman, 2005).

Illegal, unreported and unregulated (IUU) fishing contributes to overexploitation of fish stocks and hinders stock recovery efforts. Agnew *et al.* (2009) reviewed global IUU fishing and found that, across 54 countries and international waters, it resulted in losses between \$10 and \$23.5 billion annually. Additionally, they found that developing countries are most at risk from illegal, unreported and unregulated fishing. The African continent especially had to deal with increased international fishing pressure since the 1990s, as large fishing fleets from the northern hemisphere redirected their fishing efforts there, after their catches declined (Worm *et al.*, 2009).

1.2. South African fisheries

1.2.1. Overview

There are more than 20 formally recognised and managed South African fisheries (Durholtz *et al.*, 2012; Prochazka *et al.*, 2014), which cover a variety of target species, fishing methods and gear types (de Moor *et al.*, 2015). The most prominent types of fisheries are the large scale industrial fisheries, such as trawl, purse seine and longline, and the smaller, artisanal nearshore operations, such as the hand-line fishery (hereafter referred to as the linefishery). The industrial-scale South African trawl fishery focuses primarily on demersal hakes (*Merluccius capensis* and *M. paradoxus*), and has been certified by the Marine Stewardship Council since 2004 (SADSTIA). There is also demersal long-line fishing for hake and large demersal sharks. The main target species of the mid-water trawl is horse mackerel (also called maasbanker, *Trachurus capensis*), which is predominantly caught on the south coast by the large trawler, Desert Diamond. The small pelagic purse seine fishery focuses mostly on anchovy (*Engraulis capensis*) and sardine (*Sardinops sagax*) on the west coast and the apex of the Agulhas Bank on the south coast. Offshore pelagic longlining primarily targets albacore (*Thunnus alalunga*) and yellowfin tuna (*T. albacares*), bigeye (*T. obesus*), swordfish

(*Xiphias gladius*), as well as, shortfin mako (*Isurus oxyrinchus*) and blue (*Prionace glauca*) sharks. The South African linefishery is more diverse than the other fisheries, and refers to a multi-species, multi-sector, multi-area cluster fishery, encompassing subsistence, recreational and traditional small-scale commercial fishers that catch fish with hand line or rod and reel from small vessels and from the shore (Solano-Fernandez *et al.*, 2012).

In South Africa, the national fisheries management body is the Department of Agriculture, Forestry and Fisheries (DAFF), which is responsible for managing the development and sustainable use of marine and coastal resources. It is also tasked with ensuring maximum economic benefits of the fisheries sector and ensuring equitable distribution between rights holders (DAFF, 2015). DAFF, along with the Department of Environmental Affairs' (DEA) Oceans and Coasts Branch, is mandated to protect the sustainability and ecological function of marine ecosystems and to carry out necessary data collection and monitoring programs (DAFF, 2015).

In 2014, the South African fisheries sector was worth approximately R6 billion (\$446 million) per annum and directly employed ~27,000 people in the commercial sector (DAFF, 2015). Thousands more and their families depend on the social benefits of fisheries, which include food security, improved livelihoods, rural development and employment opportunities (Sowman *et al.*, 2013; Sowman *et al.*, 2014). Economic incentive, social benefits and ecological functioning are traded off against each other to attain the highest possible levels of each area of importance (DAFF, 2015). These trade-offs should be sustainable over the long term, with a just inclusion of the various stakeholders invested in South African fisheries. The Marine Living Resource Act (MLRA) of 1998 includes measures to protect these resources and allows the various departments to take emergency measures if the sustainability of a resource is heavily threatened. Some measures included increasing the number of Marine Protected Areas (MPAs) whose particular role was to protect large, mature fish, i.e. the breeding stock of a number of overexploited species. However, management of MPAs was transferred to the Protected Areas Act in 2014, managed by the Department of Environmental Affairs (DEA).

1.2.2. South African linefishery

The linefishery is divided into three sectors, which govern the allowable fishing practices: commercial, recreational and small-scale. The small-scale sector was previously known as the subsistence sector, however, the definition for inclusion was changed with the small-scale fisheries policy in 2013, currently being implemented, to ensure a more socially equitable division of fishing effort on marine resources (DAFF, 2015). These three linefishing sectors generate a combined value of approximately R500 million (\$37 million) per annum and increases to an excess of R2.2 billion (\$164 million) per annum when including secondary industries (DAFF, 2015). The multiple user groups within the South African linefishery catch over 200 species, which represent a vast spectrum in terms of abundance, resilience, distribution and value (as a commercial product, a sport-fishing prize and/or consumptive resource).



Figure 1.1: Traditional linefish catching vessels docked at Fish Hoek harbour in Cape Town, South Africa. Photograph adapted from Almaty.com, 1 March 2017.

1.2.2.1. Sectors and stakeholders

1.2.2.1.1. Commercial sector

Hook and line fishing has been carried out commercially since the mid-1800s and the effects of this long-term exploitation are still seen today in the stock abundances of valuable fish species (Griffiths, 2000), their size-structure and in several cases, a shift from valuable, long-lived reef fish to less valuable fast-to-mature fish (Yemane *et al.*, 2005). A State of Emergency was called in 2000, when the Marine Living Resource Act (MLRA) of 1998 was

invoked, leading to a large reduction in the Total Allowable Effort (TAE) to 70% of previous levels. This emergency was instated by the Minister of the Department of Environmental Affairs and Tourism (DEAT, a department which has now split into the DEA and the Fisheries Branch of DAFF). Various species targeted by this fishery are still considered over-exploited or collapsed, after this reduction in TAE, because of their specific life history characteristics (Potts *et al.*, 2013). Additionally, the TAE is considered to be regularly exceeded due to illegal fishing, interim relief measures and effort creep (Beddington *et al.*, 2007; Cochrane *et al.*, 2004).

Commercial linefishing is a low-earning, labour-intensive industry. It is important from the perspective of human livelihoods, and due to the low initial investment required, it is considered an attractive area to increase employment opportunity (Branch and Clark, 2006). However, it still has the lowest average employment income of all South African fisheries. Currently, 455 commercial boats are in operation, although only 344 are considered active at present (DAFF, 2015). This number used to be much higher (approximately 700) before the Linefish Emergency of 2000 (Potts *et al.*, 2013). However, it was discovered that 20% of the boats caught 80% of the commercial linefish catch and these vessels are still active in the fishery (DAFF, 2015). Commercial linefishers must have the correct permit and are governed by input limits, such as a TAE and species-specific size limits. Compliance is enforced in several ways, including slipway monitors and mandatory daily catch reporting (DAFF, 2015).

The total annual catch of the boat-based commercial linefishery was ~4,500 t in 2015 (NMLS, 2017). The commercial South African linefishery makes use of medium to low levels of technology, by using hand-lines, rods and reels. This gear is deployed from small (<10 m) ski-boats or displacement hull vessels with usually six to 13 fishers (Winker *et al.*, 2013). Linefishing is a relatively selective method, which has little by-catch and is usually not destructive to the marine habitat (Griffiths, 2000).

1.2.2.1.1. Recreational sector

Recreational linefishing is much larger than the commercial sector, with over 750,000 fishers, having a minimum of 4,000 vessels (DAFF, 2015). However, the total off-take by the recreational sector remains largely unknown at a national scale due to lack of mandatory catch reports and poor compliance monitoring (Sowman *et al.*, 2013). This sector is managed differently compared to the commercial sector, with output limits and closed seasons (instead

of input limits). These output limits require a permit and adherence to its conditions regarding species-specific bag and size limits. Fishers are also not allowed to sell their catch, and they have to obey various closed seasons and area limits. Catch and release is now also being promoted, as well as citizen science, which can add to the information available on stock abundance (Dunlop *et al.*, 2013). This sector does contribute to the gross domestic product (GDP) of South Africa through revenue generated through-out the process of recreational fishing.

1.2.2.1.2. Small-scale sector

Small-scale fisheries in a South African context include subsistence fishers, and those that rely on the resources for food as well as a small source of income. This includes 147 poor coastal fishing communities and those using traditional methods (artisanal fisheries practices, Branch *et al.*, 2002). For this reason this sector has not experienced a great increase in technological advancement of their fishing gear. Recommendations towards a small-scale fisheries policy (Branch *et al.*, 2002) should address past imbalances in the allocation of fishing rights. Following an extensive and protracted period of engagement a small-scale fisher policy was adopted by DAFF in 2014 and implementation is currently being commenced (Prochazka *et al.*, 2014). This policy seeks to increase community investment in sustainable management of fisheries resources. There is large overlap between this sector and existing commercial fisheries such as west-coast rock lobster and traditional linefishery in terms of personnel, gear and target species (Cockcroft *et al.*, 2002). If this sector is not managed effectively, increased conflict may arise between linefishing sectors and may place more pressure on an already strained resource (Cockcroft *et al.*, 2002). This sector had almost 30,000 active fishers along the coastline in 2006, with most (85%) of them harvesting linefish (Branch and Clark, 2006).

1.2.3. Linefish assessments and management

The South African linefishery is one of the largest sectors with regards to distribution and human involvement, making it challenging to monitor and ensure compliance with fisheries policy (Sowman, 2011), which can mean management actions are less effective (Sauer *et al.*, 1997).

The Linefish Management Protocol (LMP) was developed for the South African linefishery in 1999 (Griffiths *et al.*, 1999; Griffiths, 2000), as a result of the Marine Living Resource Act (MLRA) of 1998 (Lamberth *et al.*, 1998). The Linefish Management Protocol suggested fisheries regulations should be based on specific objectives that incorporate quantifiable reference points. Luckily, data collection programs, which begun as a shore-based observer program introduced by Dr JDF Gilchrist in 1897, had expanded under the domain of the Sea Fisheries Research Institute (SFRI), the Oceanographic Research Institute (ORI) and, later, Marine and Coastal Management (MCM), leading to DEAT and then DAFF. These programs provided the initial data required, such as catch and effort data, to calculate these reference points (DAFF, 2015). This program was enhanced and since 1985 comprehensive catch and effort data has been collected on all important species on the boat-based commercial linefishery sector. All these data have been collated and stored in the National Marine Linefish System (NMLS). Shore-based observers began confirming these recorded species-specific catch and effort data and collecting length frequencies from the boat-based fishery at important fishing areas along the coast (Blamey *et al.*, 2015). These help inform the management of the commercial linefishery, which is controlled by a TAE system.

Many linefish species have also been thoroughly studied in terms of their biology, ecology and population structure and migration patterns (Dunlop and Mann, 2013). Most stock assessments of linefish were yield- (YPR) and spawner-per-recruit (SBR) assessments, aimed at providing a reliable estimate of the stock status in regards to its depletion of the assumed pristine state (SB/SB_0 , written as $\%SB_0$). Additionally, target and threshold reference points, set at 40% and 25% SB_0 respectively by the assessors, were calculated to aid management strategies. The majority of assessed stocks were found to be collapsed ($<25\% SB_0$) in the late 1990s, which is what prompted the Linefish Emergency of 2000. Examples of estimated depletion rates for priority linefish species at that time include, silver kob (*Argyrosomus inodorus*) with 7.0% SB_0 (averaged across all coasts), dusky kob (*Argyrosomus japonicas*) with 2.3% SB_0 , dageraad (*Chrysoblephus cristiceps*) with 2.9% SB_0 , seventy-four (*Polysteganus undulosus*) with $<5\% SB_0$, slinger (*Chrysoblephus puniceps*) with 15% SB_0 , carpenter (*Argyrozona argyrozona*) with 12% SB_0 and, geelbek (*Atractoscion aequidens*) with 5% SB_0 in 1997 (Griffiths, 1997a; Griffiths, 1997b; Griffiths, 1997c). The management objective for all these species (and additional species) was to rebuild the per-recruit ratio to the threshold reference point of 25% SB_0 (Griffiths, 1997a; Griffiths, 2000).

While a combination of yield-per-recruit (YPR) in association with spawner-biomass-per-recruit (SBR) analyses has been the assessment of choice for the South African linefishery, it was limited by the assumptions inherent in that model, including a steady-state, assuming that the age or size composition of a stock is representative of the population structure, the absence of the stock-recruitment relationship, selectivity assumptions and age-independent natural mortality. Additionally, it only provides a relative estimate per-recruit catch that can be extracted from an average cohort and not of the potential yield (i.e. MSY) of the stock. Only a few stocks were assessed using additional methods, to confirm the YPR estimates, such as Virtual Population Analysis (VPA), which incorporate estimates of natural (M) and fishing (F) mortality to determine historical changes in stock abundance (MCM linefish management report, 1999, Hutton *et al.*, 2001). Booth and Punt (1998) used two additional methods to confirm their yield-per-recruit analysis of the South African panga (*Pterogymnus laniarius*) stock, namely, a surplus production model and an age-structured production model. These allowed them to make quantitative estimates and recommendations regarding catches, as well as an estimate of stock state.

DAFF, in collaboration with academic institutions, have begun re-assessing the stock assessments for high priority linefish species. This is necessary to accurately determine the current status of various stocks and provide useful management options (Winker *et al.*, 2014). There has been movement away from YPR analysis to dynamic pool models that take catch and effort time series into account, such as biomass production models and age-structured production models (ASPM), beginning with Booth and Punt's (1998) assessment of panga, to the recent assessments performed by Winker *et al.* (2014), on species such as slinger, silver kob and carpenter. These studies also took special account of the multispecies nature of the linefishery and developed a method to standardise the catch per unit effort (CPUE) of the linefish catches (Winker *et al.*, 2013; Winker *et al.*, 2014), to ensure the best use of the data collected to provide an accurate understanding of the current status of the linefish stocks.

There are many different stock assessment approaches and models, which depend on the available data describing both the fish and the fishery. For example, a complex age-structured production model (ASPM) may not be suitable if there are very little data to input. Assessments estimate a fish population's size, biomass, productivity, recruitment and age structure. More complex assessments can include more life history information, such as the

fecundity, sex ratios, somatic growth, migration patterns and predator/prey relationships (Thorson *et al.*, 2012).

The initial biological data are used to parameterise the stock, which are often taken from past research and set as a model's initial conditions (Prince, 2013). Various equations describe somatic growth of a species, such as the Schnute (Schnute and Richards, 1990) and von Bertalanffy (von Bertalanffy, 1971) equations. These quantitative biological descriptions are incorporated into some models to ensure realistic parameter ranges (Booth and Quinn, 2006). Length-weight relationships also allow the conversion of available data into more applicable proxies, since some types of data may be limited, for example, to only length frequencies of commercial catches. Recent studies (after 2000) have also included a genetic component to assess species-specific genotypes and to ensure the maintenance of the species long-term evolutionary potential (DAFF, 2015; Dunlop and Mann, 2013).

1.3. Geelbek (*Atractoscion aequidens*)

Geelbek (*Atractoscion aequidens*, commonly called Cape Salmon) is an important, commercially high-value species in the South African linefishery and is targeted throughout its South African range, from Cape Point (34°21'S, 18°29'E) on the south west coast to Kosi Bay (26°51'S, 32°53'E) on the east coast near the South African-Mozambique border.

1.3.1. Geelbek biology

Geelbek are a benthopelagic sciaenid fish, occurring off southern Africa and eastern Australia (Griffiths and Hecht, 1995). Other members of the Sciaenidae family include Beardman (*Umbrina robinsoni*) and kob species, such as the squaretail kob (*Argyrosomus thorpei*), silver kob and dusky kob. Geelbek derived its name, meaning yellow-mouthed in Afrikaans, from the yellow colouring around its mouth and the inner surface of the gills. Geelbek have an elongated, robust body with a marginate tail (unlike kob species). The body colour ranges from silvery-blue to copper, with a white underside (Heemstra and Heemstra, 2004; Mann, 2013).



Figure 1.2: Diagram of geelbek (*Atractoscion aequidens*), adapted from Heemstra and Heemstra (2004).

Geelbek are a shoaling species found at depths down to 100 m (Griffiths and Hecht, 1995). Adult fish (>5 years, 900 mm fork length) undertake an annual seasonal north-easterly migration from the Western and Eastern Cape to KwaZulu-Natal where they spawn (Griffiths and Hecht, 1995). Movement up the coast is inshore. Adults usually form spawning aggregations around reefs on the narrow KwaZulu-Natal shelf from June to November. After spawning adults return to, and disperse over, the Agulhas Bank (Hutchings *et al.*, 2002).

The Agulhas Current transports the eggs and larvae south westwards towards the nursery areas on the Agulhas Bank. Inshore features of the Agulhas Current would then distribute them into the nursery grounds onto the Agulhas Bank. Despite high egg and larvae losses to the surrounding ocean, this strategy is considered successful to cope with the short-term environmental variability of the region (Hutchings *et al.*, 2002). However, fecundity must remain high enough to sustain these losses. Geelbek have evolved this reproductive strategy to ensure sufficient recruitment retention from the spawning grounds and transport by currents to the nursery grounds (Hutchings *et al.*, 2002).

Egg incubation lasts approximately 48 hours (tested at 23°C by Connell, 2007). After one day the larva has parts of the notochord and finfolds (Connell, 2007). After 11 days the larva is still preflexion, however by day 25 it is postflexion (Connell, 2007). The larva becomes a juvenile after 135 days (tested at 23-25°C by Connell, 2007). Juveniles (0 – 1+ years) primarily occur in the inshore waters of the south-eastern Cape (Griffiths and Hecht, 1995). The small juveniles move from their nursery grounds on the south east coast to the south coast where they stay for several years before maturity (less than 6 years of age). Large adult geelbek also visit the south west coast in the summer months after spawning for a brief period, however they are not as numerous or as intensely aggregated as they are in KwaZulu-Natal.

Geelbek grow quickly initially, delaying the onset of maturity to focus on somatic growth. This should ensure they are physiologically prepared for the taxing challenges of their spawning migration (Hutchings *et al.*, 2002). This delayed maturation (>5 years) is unusual compared to other sciaenid species, such as croakers and drums, which usually reach sexual maturity at one to two years of age (Froese and Pauly, 2006). Geelbek live to a maximum age of ten years (Heemstra and Heemstra, 2004; Mann, 2013).

Geelbek are large, predatory piscivores that target small pelagic fish, specifically sardine (*Sardinops sagax*), anchovy (*Engraulis encrasicolus*) and horse mackerel (*Trachurus trachurus*; Heemstra and Heemstra, 2004). Their spawning migration coincides with the annual sardine run (Heemstra and Heemstra, 2004). Juvenile geelbek feed on smaller fish and crustaceans (Griffiths and Hecht, 1995).

1.3.2. Geelbek life history

Large catches of geelbek are made by ski-boats operating on the Agulhas Banks and smaller individuals are caught by treknetting in False Bay (Griffiths, 2000) in austral summer. During winter and spring, when the adult geelbek are aggregating to spawn near the reefs off KwaZulu-Natal (at water depths of 40 m – 60 m) they are caught intensively at night by commercial and recreational fishers (Heemstra and Heemstra, 2004; Mann, 2013). Depredation on the hooked geelbek by sharks means that landed catches would be less than the number of fish actually removed from the stock (Cochrane *et al.*, 2004). This depredation was estimated to be up to 90% of hooked geelbek by Maggs and Mann (2015, unpublished ORI report). From 2001 to 2010 annual geelbek linefishery catches ranged from a minimum of 315 t in 2002 to a maximum of 672 t in 2004 (Durholtz *et al.*, 2012), over all areas combined. Attwood *et al.* (2011) indicated the extent to which geelbek form part of the bycatch of the South African inshore trawl industry, with an average catch of 84 t from 2003 to 2006.

Their life history, whereby they migrate to their spawning grounds annually, combined with delayed maturation, means that geelbek are at greater risk from over-exploitation during their spawning aggregations. MPAs also have limited applicability for protecting migratory species, such as geelbek, unless they are strategically placed and enforced at particular times and places, e.g. during spawning aggregations (Griffiths, 2000). Additionally, years of above

or below average recruitment take several years to appear in the fishery, and often lead to a misunderstanding between fishers and scientists regarding acceptable catch levels (Anderson *et al.*, 2012). It is estimated that the spawning stock biomass of geelbek has been reduced to less than 10% of their unfished level, however, this estimate may be optimistic (Griffiths, 2000, Hutton *et al.*, 2001).

Therefore, the life history of geelbek plays a very important role dictating the management of geelbek linefishery. There is a discrepancy between the size and availability of fish on the south and south west coasts and those in KwaZulu-Natal. Fishers in the former area have longer access to smaller, juvenile fish, in contrast to the seasonally spawning fishery off KwaZulu-Natal. High fishing mortality of the juvenile fish, in accordance with the current minimum size limit for geelbek, suggest that most are caught before they have an opportunity to spawn and replenish the spawner biomass and increase recruitment (Griffiths and Hecht, 1995; Griffiths, 2000; Hutton *et al.*, 2001; Anderson *et al.*, 2012).

Combined, these different fishing pressures are likely to prevent the geelbek stock from replenishing itself each year, since less fish are able to survive to maturity, while those large and highly fecund fish are also being removed (Griffiths, 2000; Hutton *et al.*, 2001). Similar fishing pressure on overexploited stocks has been curbed by implementing a slot limit to protect both small and very large fish (Berkeley *et al.*, 2004; Lewin *et al.*, 2006). However, this may not be appropriate for the geelbek fishery as smaller fish are caught by commercial fishers in the south west and south east coasts and large fish are caught in the east coast by commercial sector, as well as the recreational sector, where they are seen as sport fishing prizes.

1.3.3. Past assessments

Past stock assessments of geelbek indicate they were recognised as collapsed 20 years ago (Griffiths and Hecht, 1995). Griffiths (2000) estimated geelbek at 5% SB_0 from YPR analysis and found that the catch per unit effort (CPUE) in 1997 had decreased to 2.8% of historic values (1897 - 1906) which he corroborated based on historical catch rates. Subsequently, Hutton *et al.* (2001) estimated 7% SB_0 using *ad hoc* tuned VPA. These low values were after the implementation of several management strategies. Initial implementation of a minimum size limit of 400 mm was set in 1940, which was later increased to 600 mm in 1991. The

minimum size limit was not set at the size-at-50%-maturity (950 mm TL), as this would have excluded most of the catch in the south west coast. A daily bag limit of ten fish per day was introduced for recreational fishers in 1985. The management recommendations with the 1997 assessment of geelbek (Griffiths, 1999) suggested a 50% reduction in commercial effort, and a decrease in the recreational bag limit from ten to two fish per day (which was later implemented). The commercial catches of geelbek have never been restricted specifically and continued to be managed according to the regional TAE for the commercial boat-based linefishery.

Hutton *et al.* (2001) performed an ad hoc tuned VPA assessment for geelbek (7% SB_0), as well as a simple deterministic age-structured model to simulate yield under different patterns of selectivity, and found the current status of the geelbek stock to be 2.3% SB_0 . They predicted that the new (at the time) size limit of 600 mm would have to be strictly adhered to, as well as have a total reduction in effort of 43%, in order to rebuild the stock to the threshold level of 25% SB_0 , and this was considered unlikely to occur due to lack of economic incentive for fishers.

All previous assessments of geelbek refer to the regional differences of the stock (Griffiths and Hecht, 1995; Griffiths, 2000; Hutton *et al.*, 2001), however, they do not account for the migration between these regions when determining the status of the stock or testing the efficacy of various management strategies (Hutton *et al.*, 2001). They also do not consider the intra-annual variation in the stock, and availability to the fishery, between the regions that are associated with geelbek being a migratory species.

Despite there being no up-to-date stock assessment for the geelbek linefishery, the raw data and catch per unit effort (CPUE) standardisation performed by Winker in 2015 for the Linefish Scientific Working Group (LSWG) at DAFF does suggest that this species is not experiencing the same recovery rates as some other linefish species. This must be considered in relation to a change in the licensing system which affected access to the fishery during the Linefish Emergency of 2000 (B- and C-type boat licenses were removed, however A-type commercial licenses continued). These commercial linefishers were suspected to have maintained the overall fishing pressure on geelbek stocks, since they would have required substitutes for the other depleted commercial linefish resources, such as yellowtail (*Seriola lalandi*), in order to land an economically viable catch (Branch and Clark, 2006).

Geelbek data are limited in the sense that the long term data are from commercial catches, and there haven't been recent fisheries observer programmes, collecting fishing effort and size structure information since 2010. Additionally, the recreational and small-scale impact on the stock is unknown. The geelbek stock structure and its spatial and temporal responses to fishing are also insufficiently understood. The age-structured spatial disaggregation of the different life history stages of geelbek make it a difficult population to assess using standard methods, such as the per-recruit analysis performed by Griffiths (2000) and the virtual population analysis (VPA) performed by Hutton *et al.* (2001). Each of the three distinct age categories of the stock have different locations, prey species and habits. Yet, an impact made to any age category will have a time-delayed impact on the other two age categories. The spawning aggregation strategy of geelbek creates a population bottleneck at KwaZulu-Natal (Griffiths and Hecht, 1995; Hutton *et al.*, 2001). There are several problems in understanding the population dynamics of geelbek in order to ensure it is afforded the opportunity to recover to a more economically and ecologically viable level, and this study aims to address and hopefully overcome these problems.

Currently, management measures for geelbek include a minimum size limit of 600 mm TL (DAFF, 2015) and a bag limit of two fish per person per day for recreational fishers. Commercial linefishers have no bag limit (DAFF, 2015), but the fleet size is restricted by a total allowable effort (TAE) for the 455 vessels. Geelbek is also red listed (since January 2017, previously orange listed) on the South African Sustainable Seafood Initiative (SASSI) list, which prompts consumers and suppliers to move away from purchasing this currently non-sustainable fish species to a species that is green listed (sustainable).

1.4. Research aims

The overall aim of this study was to improve the understanding of the population dynamics, stock abundance and the recovery potential of the South African geelbek stock. The specific objectives were: (1) to provide an update of stock status estimates for geelbek and (2) to evaluate a variety of potential rebuilding management strategies by way of stochastic simulations, which can be used to formulate a management plan for this species.

To achieve these aims, a general spatial-temporal age-structured modelling framework is developed, which is designed to account for region- and season-specific fisheries vulnerability of different life history stages. The model is parameterised based on published life history parameters sourced from peer-reviewed literature. Age-dependent migration probabilities are inferred from available region- and season-specific size composition catch data; and the migration pattern is adopted from literature, specifically Griffiths and Hecht (1995). To obtain the first estimates of the relative spawning biomass depletion and region- and season-specific harvest rates, the age-structured migration is implemented in an age-structured equilibrium model (ASEM). The ASEM results are discussed in the context of past assessments.

For the management strategy evaluation, the migration model is then implemented as an Operating Model (OM) in the form of a stochastic age-structured production model (ASPM), which allows stock projection under alternative management scenarios. The ASPM is conditioned using the region- and season-specific harvest rates derived from the ASEM and further calibrated using available linefish commercial catch time series. Finally, the ASPM OM is applied to simulate geelbek stock trajectories under eleven different management strategies, based on potential management options. The simulated stock trajectories are assessed against fisheries reference points and the alternative scenarios are evaluated in terms of stock rebuilding times, impacts on the fishery and feasibility within the current fisheries regime.

The following primary research objectives aim to direct the research approach of this study:

- Compile a review of the life history of geelbek (see previous section on geelbek)
- Quantitative description of geelbek stock by region and time period
- Understand effort dynamics of the commercial fishing sector
- Investigate impact of Linefish Emergency (of 2000) on the geelbek stock
- Identify regions of intense aggregation for possible protection measures (night bans, seasonally closed areas)
- Develop a spatially and temporally explicit age-structured base model for geelbek
- Perform a per-recruit analysis and determine the yield- and spawner-biomass-per-recruit, which indicates the current estimated stock state as the spawner biomass depletion level

- Develop a dynamic production model and use it to predict the relative stock recovery success rates of various management strategies

1.5. Structure of study

The primary aim of this study was to estimate the current stock status of geelbek, a commercially important migrant South African linefish species. To do this, Chapter 1 provides an introduction to this study, as well as outlining the known qualitative information regarding geelbek. Chapter 2 covers all methods and materials. This includes a general overview of the study area and the available data. Chapter 2 shows how length frequency data were fitted using a least squares model to derive spatially and temporally explicit selectivity parameters, which were converted into proxies for migration. A spatially and temporally explicit age-structured base model was then developed for geelbek through the use of these migration probabilities. This base model was then extended to an equilibrium model, which included a catch curve analysis and yield- and spawner-biomass-per-recruit models from which fisheries reference points were derived. The base model was further developed into a full dynamic age-structured production model, parameterised using harvest rates and selectivities generated from the equilibrium model. Chapter 3 provides the results of these analyses, including the current stock status, validation of the dynamic model with commercial catch data, and the relative success of eleven management strategies to restore the stock to threshold (25% SB_0) and target (40% SB_0) levels. Chapter 4 is a general discussion of the methods developed, the applicability and limitations of the operating model presented, and the principal findings of the study. Finally, the study is put into the context of previous work and its applicability in management, making final recommendations and suggestions for future work.

2. Methods and materials

2.1. Overview

Geelbek have complex life histories where each age-dependent life history stage has a different migration pattern for each region and each season, leading to heterogeneous fishing conditions across the South African coast. Due to these spatial and temporal variations across their life history, performing a stock assessment for this species has several challenges. Previous assessments made use of per-recruit analyses and virtual population analyses (VPAs), such as those performed by Griffiths (1999) and Hutton *et al.* (2001). However, those studies did not consider the migration of the species within the models themselves. This chapter develops an age-structured base model which incorporates geelbek migration across three coastal regions and three time periods.

Two versions of the spatially explicit age-structured production model were produced, an equilibrium (per-recruit) model and a dynamic age-structured production model. The equilibrium model determines the age-, region- and period-specific selectivity, mortalities and harvest rates, and provides an updated estimate of the current status of the stock. The dynamic model, parameterised using the values determined in the equilibrium model, incorporates the history of the fishery with respect to changes in selectivity over time. Using stochastic simulations, the dynamic model is used to evaluate the relative success of eleven management strategies in their capacity to rebuild the stock in the medium and long-term to spawner biomass depletion levels SB/SB_{MSY} in relation to the target reference point at 40% SB_0 and limit reference point at 25% SB_0 .

2.2. Study area

The study area encompasses the South African coast from Cape Point (34°21'S, 18°29'E) to Kosi Bay (26°51'S, 32°53'E). Although the linefishery is divided into three different management zones, it was discussed by Griffiths (2000), Brouwer and Griffiths (2005) and Winker *et al.* (2013) that these zones may not provide the best geographical division of the linefishery for assessment purposes and future rights allocations. The results of a multivariate

regression tree analysis in Blamey *et al.* (2015) suggested a finer division of the coast into five geographic regions. This division has been used in recent stock assessments performed under the larger umbrella project of the National Linefish Working Group (Winker *et al.*, 2016a), and it is according to these divisions that the current state of the geelbek stock will be assessed. These five regions are defined from here forth as the west, south west, south, south east and east coasts of South Africa (Figure 2.1). The boundaries between the regions south west to east are demarked by larger MPAs (i.e. De Hoop, Tsisikamma and Pondoland), providing discernible breaks in fishing effort. The east coast is the combination of the previously defined former Transkei and Kwa-Zulu Natal regions. Additionally, for the purposes of this study, the south west and south coasts are combined into a region called the south south west coast.

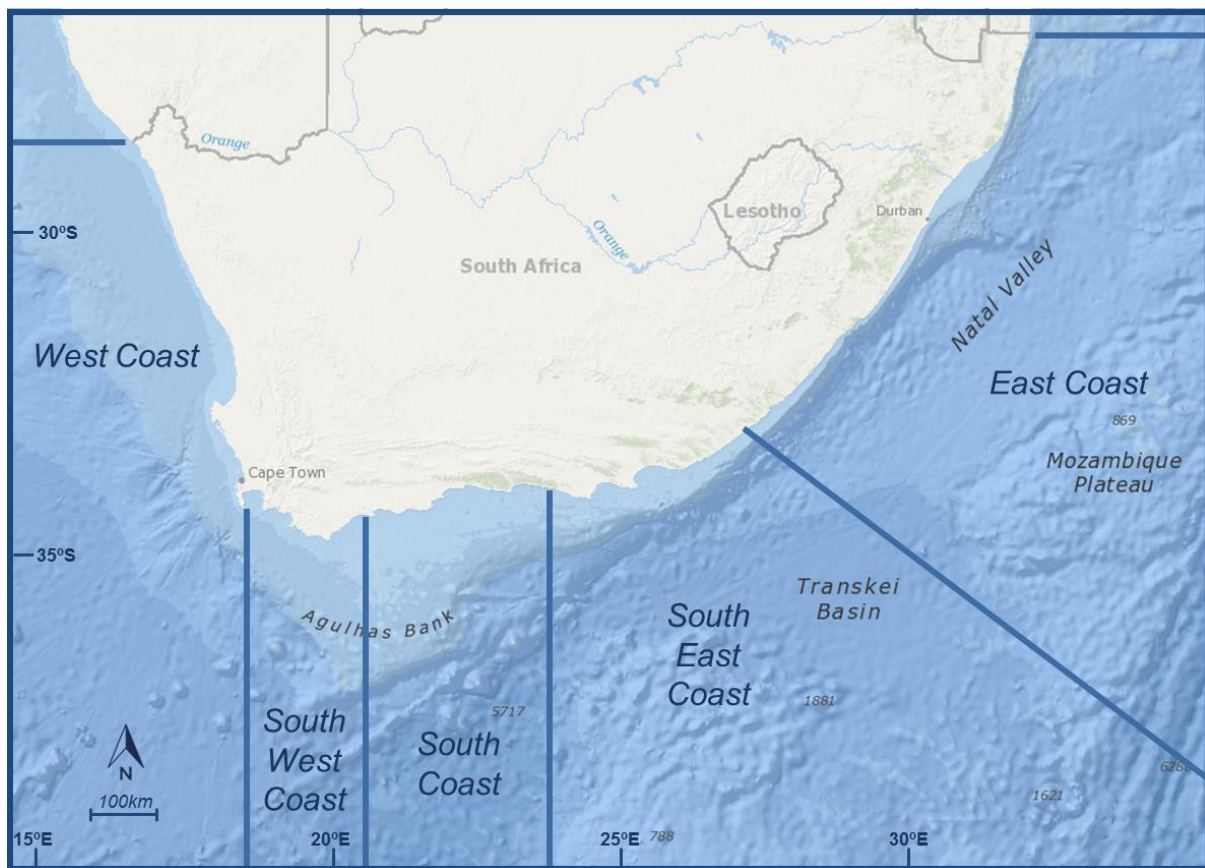


Figure 2.1: Map of South Africa showing the five management regions suggested by Blamey *et al.* (2015), namely, the west, south west, south, south east and east coasts. This study combines the south west coast and the south coast into the south south west coast. The east coast is the combination of the previously defined former Transkei and Kwa-Zulu Natal regions. The study area encompasses the South African coast from Cape Point (34°21'S, 18°29'E) on the south west coast to Kosi Bay (26°51'S, 32°53'E) near the South Africa-Mozambique border on the east coast.

2.2.1. Data sources

There were several types and sources of data used in this study, which were derived from the National Marine Linefish System (NMLS), published scientific literature and fisheries management reports. The NMLS is one of the largest geo-referenced biological datasets in the world, with over 2.7 million data points (Prochazka *et al.*, 2014; DAFF, 2015). Founded in 1985 and continuing to the present, it is a cache of South Africa's commercial catch returns, harbour returns, dealer returns, recreational angling, observer data, length frequencies and biological data for linefish. Since different data types and time series were used for different parts of this study, the description of the data and the full reasoning behind their selection and manipulation are presented under their relevant sections.

Life history information for geelbek was compiled from published literature, including Griffiths and Hecht (1995), Griffiths (2000), Hutton *et al.* (2001) and Connell (2007). These papers provided all necessary life history parameters, and are given and described in more detail under the heading 'Basic Life History' below.

2.3. Spatial and temporal migration dynamics

The life history and intrannual migration patterns of geelbek were qualitatively described in Chapter 1. This section seeks to quantitatively describe their population dynamics, referring specifically to the life history and movement of the population, as well as the impact of fishing. The movement patterns of geelbek across different life history stages of geelbek along the South African coast are illustrated Figure 2.2 (constructed based on Griffiths and Hecht, 1995, whose original migration map can be found in Appendix A, Figure A.1).

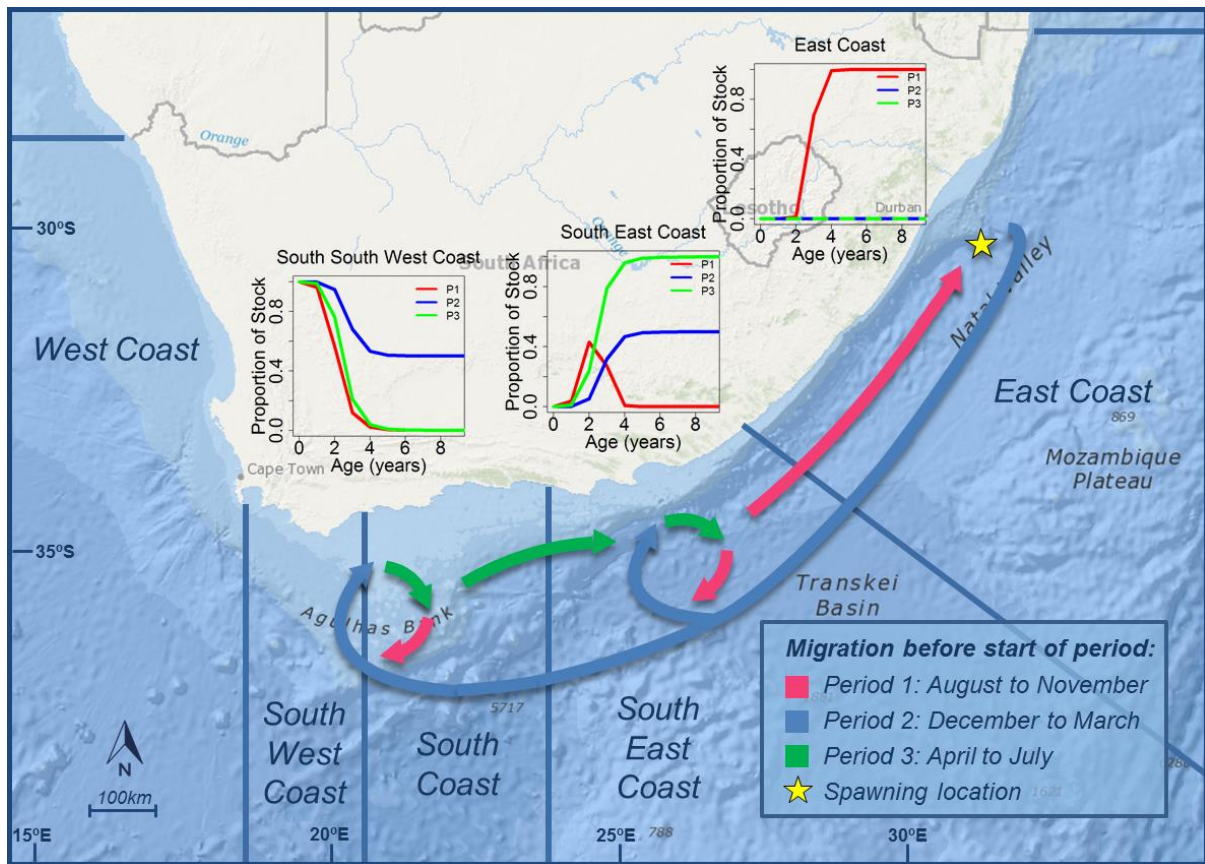


Figure 2.2: Map of the spatial and intrannual temporal distribution of the geelbek stock along the South African coast (adapted from Griffiths and Hecht, 1995). Broad arrows show the theoretical movement of the stock along the coast within a single year (twelve month period). The colour of the arrow indicates the time of migration, estimated as the instantaneous moment between the end of the previous period and start of the following period. Arrival by the start of period one, in August, is illustrated in pink, arrival by the start of period two, in December, is illustrated in blue, and arrival by the start of period three, in April, is illustrated in green. Plots of the proportion of the stock (-at-age) estimated to be in each coast at each period are shown. The colours align with each period, as they do for the migration. The five management regions suggested by Blamey *et al.* (2015) are shown, namely, the west, south west, south, south east and east coasts. This study combines the south west coast and the south coast into the south south west coast.

For convenience, the acronyms and symbols that are commonly referred to in the following sections are summarized in Table 2.1.

Table 2.1: List of acronyms and symbols used in this study, grouped into system variables, index names and state variables, together with functions and important model parameters.

Name	Symbol	Unit	Definition
<u>System variables</u>			
East coast	E		Coastal management area from Port Edward (31°01'S, 30°14'E) to Kosi Bay (26°51'S, 32°53'E) on the Mozambique border
South south west coast	SSW		Coastal management area from Cape Point (34°21'S, 18°29'E) to western Tsitsikamma National Park (33°58'S, 23°39'E)
South east coast	SE		Coastal management area from eastern Tsitsikamma National Park (34°03'S, 24°11'E) to Port Edward (31°01'S, 30°14'E)
Period one	$P1$		Period: August-November
Period two	$P2$		Period: December-March
Period three	$P3$		Period: April-July
<u>Index names (Subscripts)</u>			
Year	y		Annual time step (August to following July)
Time period	p		Intrannual temporal component, a third of a year (four months)
Coastal region	r		Spatial component
Time steps within period	ψ		Differentiates between start and mid-point of time periods
Age	a	years	Zero to nine years, biologically, extended to twelve years to incorporate senescence in the model
<u>State variables and model parameters</u>			
Population numbers	$N_{p,r,a}$	numbers	Numbers-at-age in region r during period p
Length-at-age	$L_{p,a}$	mm FL	Mean length-at-age during period p
Weight-at-age	$W_{p,a}$	gram	Mean weight-at-age during period p
Maturity-at-age	m_a		Proportion of fish (N_a) that attains maturity in $P1$
Selectivity-at-age	S_a		Age-dependent selectivity as determined by gear and minimum size limits
Vulnerability	$V_{p,r,a}$		Age-dependent proportion of fish that is vulnerable to fishing in region r and period p as result of spatial structuring
Migration probability	$\phi_{p,r,a}$		Probability for a fish of age a moving into a region r by the start of period p
Spawner biomass	SB	tons	Fraction of biomass that comprises mature fish in year y
Unfished spawner biomass	SB_0	tons	Pristine spawner biomass at carrying capacity
Exploitable biomass	EB	tons	Fraction of the population biomass that can be caught by the fishery
Vulnerable biomass	$VB_{p,r,a}$	tons	Fraction of the population biomass present in area r and period p that is vulnerable to fishing
Recruitment	R	Numbers	Number of recruits as function of the Beverton & Holt spawner recruitment relationship
Pristine recruitment	R_0	Numbers	Average number of recruits produced by pristine spawner biomass

Table 2.1: continued...

Name	Symbol	Unit	Definition
Spawner biomass per recruit	SBR	gram/fish	Average life time spawner biomass of a fish at equilibrium
Yield per recruit	YPR	gram/fish	Average life time yield of a fish at equilibrium
Natural mortality	M	1/year	Instantaneous rate of the natural mortality
Harvest rate	$H_{p,r}$	Ratio	Ratio of catch in region r and period p to the available $VB_{p,r,a}$
Steepness	h	Ratio	Fraction of the initial recruitment R_0 , if SB is at 20% compared to pristine stock levels (SB_0)

To facilitate translating the complex intrannual migration into a mathematical model, it was assumed that the migration pattern can be separated into three regions r . The three regions were grouped into south south west (SSW), south east (SE) and east (E) coasts. Each annual time step of 12 months was divided into three migration periods p of four months each. These migratory time periods, hereafter called periods $P1-P3$, begin in August, with period one ($P1$) running from August to November, period two ($P2$) from December to March and period three ($P3$) from April to July. It is important to note that the chronology of these periods does not fit within a single calendar year. These periods were determined for this study to roughly match the regional monthly catch trends scaled in proportion to the annual catch for each region (Figure 2.3). The commercial catch return data from the NMLS from 1987 to 2011 (Figure 2.4) were used for the analysis of the migratory time periods.

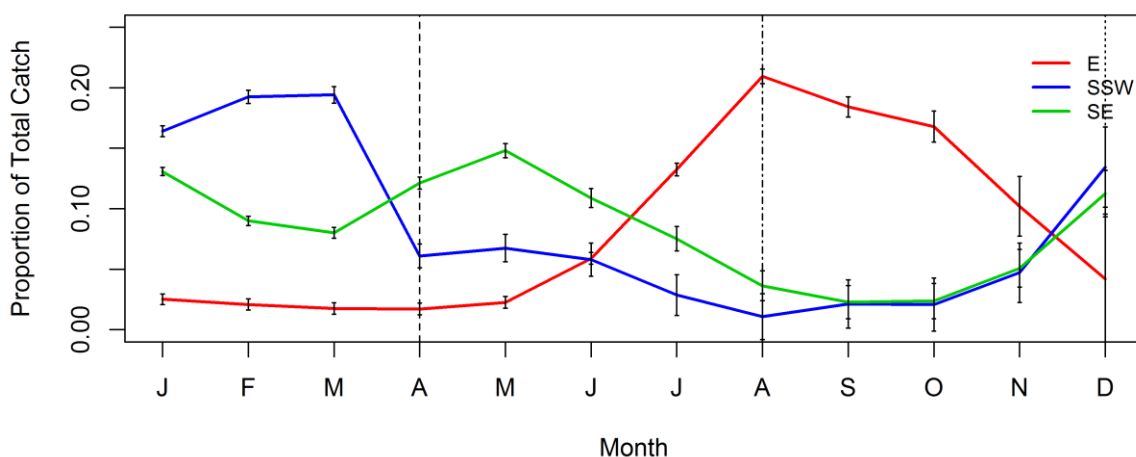


Figure 2.3: Proportional regional commercial catch returns of geelbek in the South African linefishery, averaged by month from 1987 to 2011 and divided into three coastal regions: the south south west (SSW , blue line), south east (SE , green line) and east (E , red line) coasts. The standard deviation for each region's monthly catch is depicted by error bars.

The model makes use of two specific timestamps for each of the three periods, namely, the beginning of each period and the midpoint. These were incorporated using an additive fraction ψ_p (Equation 2.1). The start of a period was differentiated from the midpoint of a period through the use of the following superscripts, namely, ψ_p^0 for the start of period p and $\psi_p^{0.5}$ for the midpoint of period p .

$$\psi_p = \begin{cases} 0 \\ 1/6 \\ 2/6 \\ 3/6 \\ 4/6 \\ 5/6 \end{cases} \quad (2.1)$$

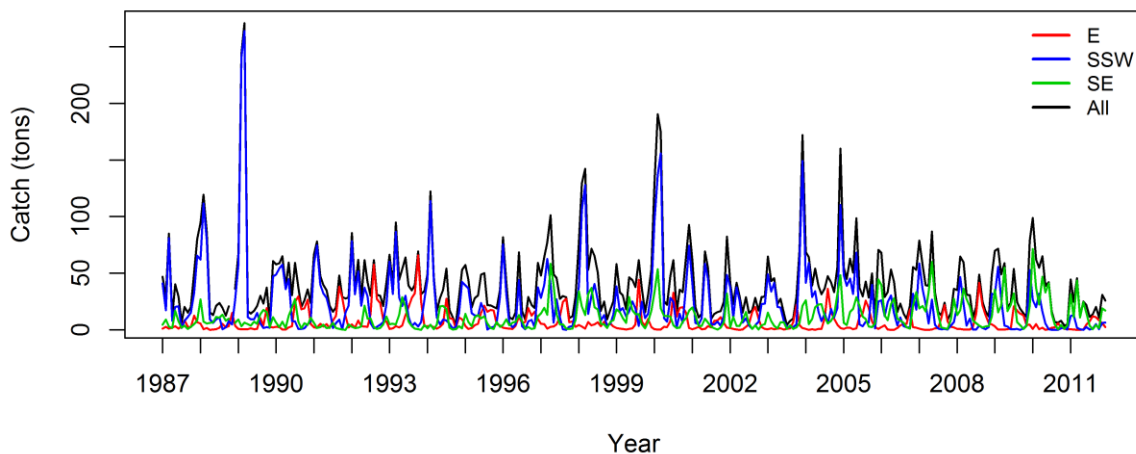


Figure 2.4: Monthly regional commercial catch (in tons) of geelbek in the South African linefishery from 1987 to 2011. The catch is divided into the three coastal regions: the south south west (SSW, blue line), south east (SE, green line) and east (E, red line) coasts, as well as the total catch for the whole coast (All, black line).

Abundance of geelbek in region r during period p was assumed to be influenced by migration probability (ϕ), recruitment as a function of spawning biomass (SB), natural mortality (M) and harvest rate (H) determined by the catch (C). An overview of spatial-temporal population dynamics, illustrating the interrelationships among the three periods p and regions r , is provided in Figure 2.5.

The assumed spatial-temporal population dynamics are initiated by an eastward migration of large mature fish from *SE* into *E* by the start of *P1*, while juveniles and sub-adults remain in *SSW* and *SE*, respectively. During *P1*, the large, mature fish spawn and recruits of the newly spawned fish enter the population, at the given age of a_0 . By the start of *P2*, there are no longer any fish in *E*, and they have been dispersed between *SSW* and *SE*, depending on their age. Those fish that have reached the threshold age for migration then move from *SSW* to *SE* by *P3*, and those that have not, remain in *SSW*. Thereafter, the cycle repeats itself, with the mature fish (>5 years) migrating from *SE* into *E* by the start of *P1* to renew the cycle.

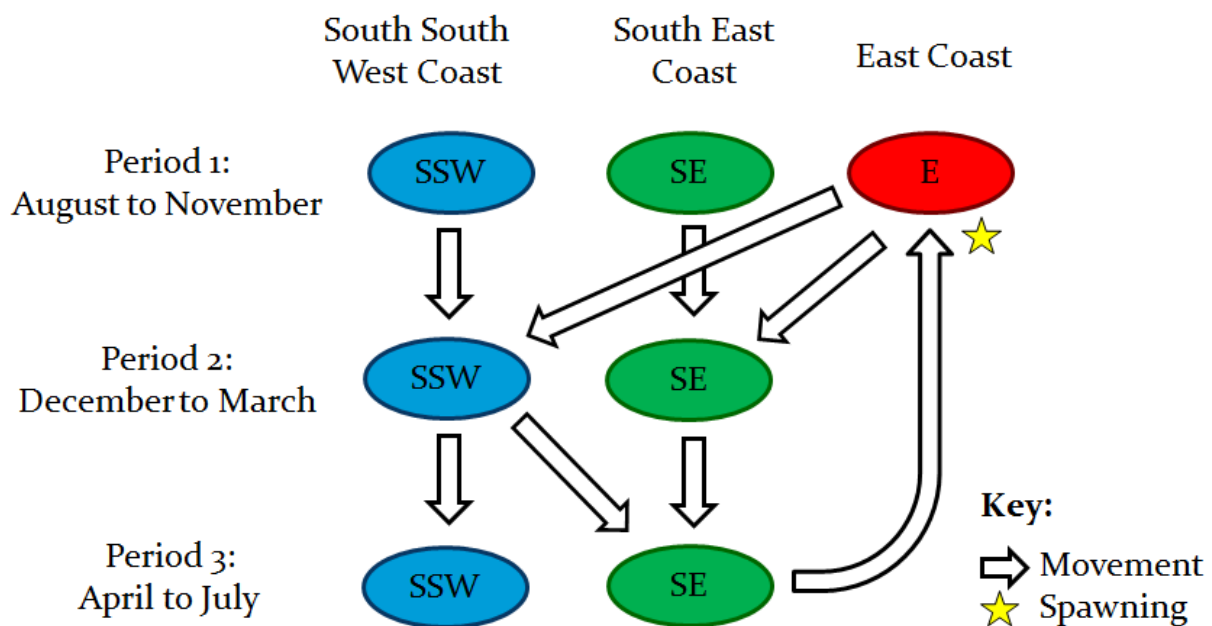


Figure 2.5: Spatial and temporal migration dynamics of South African geelbek across three coastal regions, namely the south south west (SSW), south east (SE) and east (E) coasts, and three time periods, with period one (*P1*) running from August to November, period two (*P2*) from December to March and period three (*P3*) from April to July. Arrows indicate direction of movement of a proportion of the stock, and the yellow star indicates the annual spawning event in the east coast (E) in period one (*P1*).

Underlying each movement in the model schematic, there is an age-structured apportionment of the population. The life history of the population and the mechanics behind the spatial and temporal migration are incorporated into the basic model structure according to the equations and techniques outlined below. In the following section, the reasoning behind the data selection and the processes used to quantify population movement are outlined in detail, firstly how these parameters were derived, what they represent and why they were selected as quantitative proxies for intrannual stock migration.

2.3.1. Inferring migration from spatial-temporal size information

The NMLS database stores various sources of geelbek data, including commercial catches by weight from spatially referenced mandatory catch returns and length frequency data from landing sites by fish observers. First, disaggregated monthly catches were used to corroborate the appropriateness of the split into the three periods. The length data, disaggregated by region and period, were analysed in detail to infer movement size-dependent probability from seasonal and region patterns in the observed size structure which were both disaggregated by region and period.

Monthly commercial catches from the commercial catch returns were sourced from the NMLS for the period 1985 to 2011 ($n = 1440$, Figure 2.3 and Figure 2.4). These data were then truncated to 1987 to 2011 to ensure sampling efforts were comparable, as was not considered the case at the beginning of the data collection program in 1985 and 1986, during which the sampling effort was changing (considering number of annual samples). Variations in monthly catches were investigated, with the view that strong intra-annual fluctuations could only be as a result of either the selectivity of the fishing or the natural movement of the stock, assuming constant natural mortality. The instantaneous rate of natural mortality per year (M) was assumed to be constant, as, owing to the data limited situation of the geelbek stock, there was insufficient data to determine an age-specific natural mortality rate. This assumption of constant rate of natural mortality has been used in similar cases by Punt (1997), Weyl *et al.* (2004), Froese (2006) and Smith *et al.* (2011b).

Fluctuations within catch were present not only in terms of weight, but also the size frequency of fish in the catch. Considering the available data, length frequency data from 1987 to 2011 (the last available sampling year), were selected as the best available option to decouple the catch biomass into a size structure for each region and period.

These length frequency data (in fork length, FL) were assigned to a 20 mm size class between 260 mm to 1300 mm, and divided between regions and periods. The frequency of each size class was used to determine the cumulative length frequency distribution for each regional and period dataset scaled such that the highest frequency equals one at 100% selectivity. Logistic ogives were initially fitted to the proportional cumulative length frequency data by predicting values based on an initially assumed length-at-50% selectivity L_{50} as the

midpoint of the slope, and δ_{s50} as the slope of the ogive. Sum of squares was used to solve for L_{s50} and δ_{s50} . The updated values for L_{s50} and δ_{s50} were used to update the logistic ogive overlaid on the proportional cumulative frequency data (Figure 2.6).

The peak in the frequency of smaller fish, between 400 to 550 mm, in the south east coast, is an artefact of the dynamic nature of the geelbek stock and changes in its management. This specifically reflects the increase of the minimum size limit from 400 mm to 600 mm in 1992.

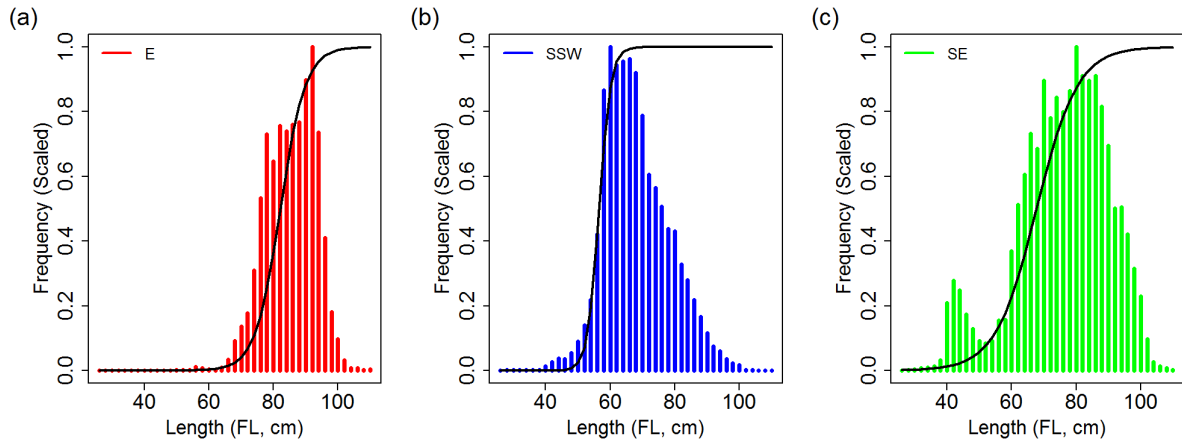


Figure 2.6: Length frequency histograms (coloured bars) and region-specific cumulative length frequency ogives (black lines) for South African geelbek from 1987 to 2011 for regions r and time periods p for the (a) east coast from August to November, (b) south south west coast for December to March, and (c) south east coast for April to July.

If visually determined to fit the data appropriately, the least-squared estimates of L_{s50} and δ_{s50} were taken as the parameters describing the size at which fish were selected in each region and period (Table 2.2) hereafter called selectivity. The selectivity-at-length is described using these parameters below:

$$L_s = \frac{1}{1 + e^{-(L - L_{s50})/\delta_{L_s}}} \quad (2.2)$$

where L_s is the length-at-selectivity, L is the length, L_{s50} is the length-at-50% selectivity and δ_{s50} is the slope of the ogive.

The observed length frequency pattern was assumed to represent intrannual migration. Consequently the shape of the logistic ogives derived from the length frequency data were used as a proxy to determine the likelihood of individual size classes of fish being in a specific region in a specific period. To determine the migration from these proportion-at-size graphs they were then converted to proportion-at-age graphs using the length-age key and Von Bertalanffy growth curves.

The estimated proportions-at-age for each region were then combined for each period into probabilities, such that each age class of the population was represented by 100% when accounted for over all three regions in each period (Figure 2.7). Logistic (sigmoid) ogives were used to describe the cumulative frequency of a sample. The single logistic curve describes only the ascent of the curve until 100%, whereas double logistic ogives describe both the ascent, to 100%, and the descent, to 0%, of the frequency distribution. A single logistic selectivity ogive to describe the migration probability at age for the east coast (*E*) for period one (*P1*), assuming that all large enough specimens take part in the spawning migration and are fully represented the size sample. Consequently, a double logistic selectivity curve assumed for the south east (*SE*) in period 1 to compensate for larger fish that had left to east, where the descending ogive was taken as inverse proportional to ascending ogive for *E* in *P1*. Similarly, the selectivity curve for the south south west coast (*SSW*) was chosen as the inverse of the south east coast (*SE*) curve to ensure the full population was accounted for. In period two (*P2*) there was assumed to be zero probability of fish migrating into the east coast (*E*), with all fish that were there, being divided, according to their age class, between the south east coast (*SE*) and the south south west coast (*SSW*). For large age classes the fish are divided equally between the two coasts, however, smaller fish were given a higher probability of moving into the south south west coast (*SSW*) than the south east coast (*SE*; c.f. Griffith and Hecht, Figure A.1). Period three (*P3*) was again assumed to have zero probability of fish migrating into the east coast (*E*), with all fish that were there, being divided, according to their age class, between the south east coast (*SE*) and the south south west coast (*SSW*). However, a higher percentage of sub-adults and all adults are assumed to move into the south east coast (*SE*) by period three (*P3*). If these fish were already in the south east coast, they were retained, while all the sub-adults and adults from the south south west coast (*SSW*) moved into the south east coast (*SE*). Considering an inter-annual cycle, all mature adults in the south east coast (*SE*) in period three (*P3*) then migrated into the east coast (*E*) by period one, to be present for spawning. Some sub-adults remained in the south

east coast for period one. These selectivity curves are reflected in the migration probabilities they form below and are illustrated as such in Figure 2.7.

Table 2.2: Selectivity-at-length ogive parameters per region per year. L_{s50} is the length (FL) at 50% selected in mm, and δ_{s50} is the slope of the curve, corresponding to L_{s50} .

Region	L_{s50} (mm)	δ_{s50} (mm)
$E_{p=1}$	779.6	19.5
$SSW_{p=2}$	648.0	27.7
$SE_{p=3}$	705.4	44.0

2.3.2. Selectivity

Selectivity s (also known as gear selectivity) refers to the property of the fishers' gear to select for geelbek across their size distribution (Equation 2.3). Selectivity can also be affected by the minimum size limit (600 mm total length), as the fishers are obligated to return undersize fish to the water. Selectivity has the form of a two parameter logistic function, which does not take spatial or temporal targeting into account. The length-frequency ogive parameters for the region of the south south west coast were used as the selectivity parameters for geelbek across all regions, since this is where the fishery's catch range is limited by selectivity only. Only the length-at-age variable changed across periods to incorporate intrannual growth and which used the midpoint of each period.

$$s_{p,a} = \frac{1}{1 + e^{-(L_{0.5,p,a} - L_{s50,r=SSW})/\delta_{s,r=SSW}}} \quad (2.3)$$

where $s_{p,a}$ is the selectivity-at-age, for each period p , $L_{0.5,p,a}$ is the length-at-age at the midpoint of each period p . $L_{s50,r=SSW}$ is the length at which 50% of the fish are retained in region r of the south south west coast, and $\delta_{s50,r=SSW}$ is the slope of the single logistic ogive for this region.

2.3.3. Vulnerability

Vulnerability $v_{p,r,a}$ of the stock refers to the proportion of the stock susceptible to the fishery (Equation 2.4). Vulnerability is assumed here to have the same two parameter logistic form as

selectivity, however, vulnerability is spatially and temporally explicit. The region specific length-frequency ogive parameters were used as the vulnerability parameters for each region. The length-at-age variable changed across periods to incorporate intrannual growth, using the mid-point of each period.

$$v_{p,r,a} = \frac{1}{1 + e^{-(L_{p,a} - L_{s50,r})/\delta_{s,r}}} \quad (2.4)$$

where $v_{p,r,a}$ is vulnerability-at-age, for each period p , $L_{0.5,p,a}$ is the length-at-age at the mid-point of each period p . $L_{s50,r}$ is the length at which 50% of the fish are retained in each region r , and $\delta_{s50,r}$ is the slope of the logistic ogive for each region r .

The primary migration pattern of each period was ascertained. These migration patterns were then incorporated into the mathematical model through the use of region-, period- and age-specific movement probabilities describing immigration, emigration and residency (Figure 2.5). These movement probabilities $\phi_{p,r,a}$ describe the proportion of numbers-at-age fish (N,a) moving for period p in region r and at age a . The law of probabilities (that the sum of all probabilities must always equate to one) was maintained for the population across each period. The migration probabilities are determined relative to each other. It was assumed that the natural mortality M is applied equally across all periods and coasts, and was included as a separate term in the model, and therefore did not alter these proportions. Fishing mortality F was also removed from these proportions as it was decided to incorporate this loss through the harvesting and selectivity terms, and not the migration terms. This also allows the spatially and temporally explicit base model to be compared to a basic per-recruit model to ensure the full population is accounted for without fishing pressure.

2.3.4. Period one

The primary migration pattern of period one was assumed to be the adult spawning migration into the east coast, which was assumed to have occurred by the start of the period. This east coast migration pattern was calculated using a two parameter logistic function with the length-frequency parameters for the east coast (Equation 2.5). Due to the length-at-age distribution, this migration probability only operates on larger fish.

The migration probability of period one for the south east coast was likewise calculated using the same logistic function form as the east coast, but with length-frequency ogive parameters for the south east coast. This ‘half-way’ but incomplete east coast migration applies primarily to the smaller sized immature sub-adults through the length-at-age distribution.

Lastly, the migration probability for the south south west coast was taken as the inverse of the south east coast migration, and accounted for those fish that remained in the south south west coast and did not attempt the eastward spawning migration. The length-at-age variable used for all coasts in determining the migration probability of period one was the mid-point of the previous year’s period three. Note, this prior period three may fall within the same chronological year as the following period one.

$$\phi_{p=1,r,a} = \begin{cases} \frac{1}{1 + e^{-(L_{0.5,p=3,a} - L_{s50,r=E})/\delta_{s,r=E}}} & \text{for } r = E \\ 1 - \frac{1}{1 + e^{-(L_{0.5,p=3,a} - L_{s50,r=SE})/\delta_{s,r=SE}}} & \text{for } r = SSW \\ \frac{1}{(1 + e^{-(L_{0.5,p=3,a} - L_{s50,r=SE})/\delta_{s,r=SE}})(1 + e^{-(L_{0.5,p=3,a} - L_{s50,r=E})/\delta_{s,r=E}}} & \text{for } r = SE \end{cases} \quad (2.5)$$

where $\phi_{p=1,r,a}$ is the migration probability for period one $p=1$, for each region r , for each age a . $L_{0.5,p,a}$ is the length-at-age at the mid-point of each period p . $L_{s50,r}$ is the length at which 50% of the fish are retained in each region r , and $\delta_{s50,r}$ is the slope of the logistic ogive for each region r .

2.3.5. Period two

By the start of period two the stock is assumed to migrate down the coast from the east coast using the fast-moving Agulhas Current into the south south west coast and south east coast. This includes the new recruits which were spawned in the east coast in period one. This migration probability distribution splits the whole population according to age, with 100% of smaller fish migrating into the south south west coast, up to the point of maturity, where the sub-adult and adults are divided equally between the south south west and south east coasts, such that:

$$\phi_{p=2,r,a} = \begin{cases} 0 & \text{for } r = E \\ 1 - \frac{0.5}{1 + e^{-(L_{0.5,p=1,a} - L_{s50,r=SE})/\delta_{s,r=SE}}} & \text{for } r = SSW \\ \frac{0.5}{1 + e^{-(L_{0.5,p=1,a} - L_{s50,r=SE})/\delta_{s,r=SE}}} & \text{for } r = SE \end{cases} \quad (2.6)$$

where $\phi_{p=2,r,a}$ is the migration probability for period two $p=2$, for each region r , for each age a . $L_{0.5,p,a}$ is the length-at-age at the mid-point of each period p . $L_{s50,r}$ is the length at which 50% of the fish are retained in each region r , and $\delta_{s50,r}$ is the slope of the logistic ogive for each region r .

The assumption made with this migratory pattern is that all newly spawned recruits enter the south south west coast by the following period. This is a mathematical simplification of biological processes, since it may take longer than a single period for the eggs and larvae to appear in the south south west coast, especially since the south east coast is considered a nursery area. However this does impact the model, as mortality for juvenile fish is not affected by fishing and natural mortality is assumed to be constant with age and region.

2.3.6. Period three

The adults and sub-adults then begin the spawning migration once more, and cross over from the south south west coast into the south east coast by the start of period three. This south east coast migration pattern was calculated using a two parameter logistic function with the length-frequency ogive parameters for the south east coast (Equation 2.7). Due to the length-at-age distribution, this migration probability primarily operates on larger fish. Meanwhile, the smaller sized life history stages, such as the juveniles and new recruits, remain in the south south west coast during period three. The migration probability for the south south west coast was calculated as the inverse of the south east coast migration. No fish were assumed to have reached the east coast by the start of period three. The length-at-age variable used for all coasts in determining the migration probability of period three was the mid-point of period two of the same year:

$$\phi_{p=3,r,a} = \begin{cases} 0 & \text{for } r = E \\ 1 - \frac{1}{1 + e^{-(L_{0.5,p=2,a} - L_{s50,r=SE})/\delta_{s,r=SE}}} & \text{for } r = SSW \\ \frac{1}{1 + e^{-(L_{0.5,p=2,a} - L_{s50,r=SE})/\delta_{s,r=SE}}} & \text{for } r = SE \end{cases} \quad (2.7)$$

where $\phi_{p=3,r,a}$ is the migration probability for period three $p = 3$, for each region r , for each age a . $L_{0.5,p,a}$ is the length-at-age at the mid-point of each period p . $L_{s50,r}$ is the length at which 50% of the fish are retained in each region r , and $\delta_{s50,r}$ is the slope of the logistic ogive for each region r .

These migration probabilities for fish at any age at each region and period are illustrated in Figure 2.7, which shows a general distribution of the stock by age across the regions and coasts, compared to the schematic format of Figure 2.5. It can also be seen that the rule of probabilities is not violated.

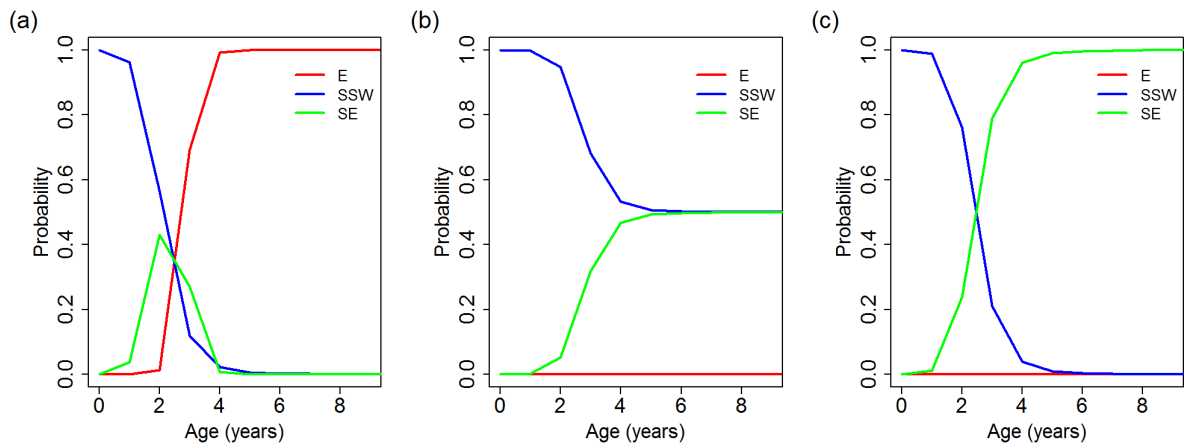


Figure 2.7: Migration probabilities of geelbek for every age class a , for all regions r , east (red line), south south west (blue line) and south east (green line) coasts, for each time period p , with (a) period one from August to November, (b) period two from December to March and (c) period three from April to July. These probabilities indicate the probability of a fish of that age moving into that coast by the start of that period.

2.3.7. Basic life history

The life history parameters used as input to model the geelbek population were derived from Griffiths and Hecht (1995), the most comprehensive biological study performed on geelbek in South Africa. Additional biological information was gleaned from Connell (2007), Griffiths (2000) and Hutton *et al.* (2001) and these are summarised in Table 2.3.

Table 2.3: Geelbek stock population parameters for Von Bertalanffy growth function derived from literature, specifically Griffiths and Hecht (1995).

Name	Symbol	Value	Unit
Asymptotic length	L_{inf}	1124.011	mm
Growth coefficient	κ	0.27	
Age at length 0	a_0	-0.723	years
Weight-at-length parameter a	a_w	8.42E-06	
Weight-at-length parameter b	b_w	3.01	
Natural mortality	M	0.38	
Maximum age	a_{max}	9	years
Age at 50% maturity	$a_{50\%mat}$	5	years

2.3.7.1. Length-at-age

Length-at-age, for each period p , $L_{p,a}$ was calculated using the Von Bertalanffy growth function. Intrannual growth across periods was incorporated with the addition of the specific period additive fraction ψ_p . Despite the findings by Griffiths and Hecht (1995) that the Schnute growth function more precisely matched the biological growth data for geelbek, specifically at the extremities of the curve, it was decided to use the Von Bertalanffy growth function since its parameters were considered to be more biologically relevant and more widely understood. Additionally, the difference in length for the younger ages was not considered a primary issue as the model deals with commercial data and all fish that are exploited in the fishery and the model are large enough to be accurately represented by both the Schnute and Von Bertalanffy growth curves. For difference in length at greater ages, the divergence was not considered sufficient to have to use the Schnute growth function within the model.

$$L_{p,a} = L_{\infty} (1 - e^{-\kappa(a - a_0 + \psi_p)}) \quad (2.8)$$

where L_{∞} is the maximum asymptotic length, κ is the growth coefficient, a_0 is the theoretical age at zero length and ψ_p is an additive fraction specific to each period.

2.3.7.2. Length-weight relationship

Weight-at-age, for each period p , $W_{p,a}$ was estimated as a function of the weight to length conversion parameters a_w and b_w and length-at-age $L_{p,a}$, such that:

$$W_{p,a} = a_w L_{p,a}^{b_w} \quad (2.9)$$

Intrannual growth was incorporated by determining weight using the aligned length at the midpoint of each period, using the sequence for p in ψ_p .

2.3.7.3. Maturity

The age at first maturity $a_{maturity}$, which is the point of 50% maturity was determined by Griffiths and Hecht (1995) to occur at five years of age, and 100% maturity at six years. The model uses the deterministic metric for 50% maturity taken to be fixed at five years of age (Equation 2.10).

$$m_a = \begin{cases} 0 & \text{if } a < a_{maturity} \\ 0.5 & \text{if } a = a_{maturity} \\ 1 & \text{if } a > a_{maturity} \end{cases} \quad (2.10)$$

where m_a is the maturity at age a .

2.4. Age-structured equilibrium model (ASEM)

The equilibrium model, which is the focus of this section, operates under the assumption that the population is in a steady-state where mortality (for the age-specific natural M and fishing F mortality) and stock recruitment relationship R estimates are constant. This is a realistic assumption since the fishery has yielded low catch rates consistently, reflecting a population state that is both collapsed and not recovering at present.

2.4.1. Per-recruit analyses

2.4.1.1. Unfished basic per-recruit analysis

The unfished numbers per-recruit (NO') was calculated for each age, as if the population were derived from a single fish, and how the rate of natural mortality affects population production. This was initially done using an annual time scale, and this assumption was considered valid since the mortality remains constant across all regions and age classes. This simplistic version (Equation 2.11), was used primarily to confirm the correct operation of the migration model, and to ensure all parts of the population were accounted for during the various stages of movement and not subsequently lost from the population. This was tested both with the unfished and the fished spawner biomass.

$$NO'_a = \begin{cases} 1 & \text{if } a = 0 \\ NO'_{a-1} e^{-M} & \text{if } 0 < a_{\max} \\ NO'_{a-1} e^{-M} / (1 - e^{-M}) & \text{if } a = a_{\max} \end{cases} \quad (2.11)$$

where NO' is the initial simple population number for age a , and M is the natural mortality of the species (constant over age).

2.4.1.2. Region- and season-specific explicit per-recruit model for unfished population

The initial population was modelled using the three time periods and the three regions described above. To aid ease of consideration, the flow of the model was altered so that the east coast region (depicted in red in all figures), where spawning occurs in period one, is the permanent starting point of the model. Thereafter the stock moves into the south south west coast region (depicted in blue in all figures) in period two and lastly, some move into the south east coast region (depicted in green in all figures) in period three.

The indexing of the equations follows a set pattern of year y (only applicable for the dynamic age-structured production model), period p , region r and age a , which is described in Table 2.1. The notation for region r was specifically chosen to avoid potential confusion between coast c and catch C . All symbols used in the equations are summarised in Table 2.1. There

are several recognised sub-populations with the geelbek stock, namely the larval, juvenile, sub-adult, adult groups, and these are a result of age-related behaviour and migratory patterns. However, in the model these age classes were amalgamated into two new age divisions. Firstly, the larval age class which had an age of zero years, represented as $a=0$ in these following equations, but as $a=1$ in the R script for the model, which allows necessary mathematical and coding techniques to be used. Secondly, the juveniles, sub-adults and adults were amalgamated together to represent the proportion of the population for which age was between one and the maximum age (a_{max}), which was extended from the biological maximum of nine years, to twelve years, to account for senescence in the population. This age class is called the adult age class and included those fish which were equal to the maximum age for periods two and three, represented as $0 < a < a_{max}$. The movements of this large age class were directed by the migration probability as a function of age.

The initial population is modelled as a proportion of the entire population, as is standard with per-recruit analyses. Since the spawning grounds are in the east coast, this is the initial starting point for the initial population $N0$ (Equation 2.12).

$$N0_{p=1,r,a=0} = \begin{cases} 1 & \text{for } r = E \\ 0 & \text{for } r = SSW \\ 0 & \text{for } r = SE \end{cases} \quad (2.12)$$

where $N0$ is the initial population number at time period p set to $p=1$, for region r and age a , set to $a=0$.

The equations below show the dynamics for all the coasts, and it is important to note that none of the population remains in the east coast for periods two or three and the numbers-at-age and all other metrics for the east coast in these periods are effectively zero. However, by the start of period two the population has been divided according to age and migration probabilities between all three regions (Equation 2.13) and allowed to die with a third of natural mortality M . The larval age class of $a=0$, were only acted upon by the migration probability $\phi_{p,r,a}$ and natural mortality M . However, the other age class sub-populations of juveniles, sub-adults and adults were collectively calculated as a function of the proportion of

the preceding region's population that was expected to migrate into the new region, and the existing population at the region which remains there in the new period. This could be summarised as the other region's probability of moving into the new region, and the current population's probability of remaining there. Each region and period had a unique mathematical expression describing their dynamics based on the biological dynamics of the species which have been incorporated into the model (Figure 2.5) as well as the law of probability (Figure 2.7).

The natural mortality M was input as a third of the annual natural mortality due to the three consecutive and additive time periods across the span of twelve months. The migration probabilities employed make use of the fundamental assumption of probability and equate to one, which allows the complimentary probabilities to represent residency within a region from period to period.

Period two splits the population after spawning in the east coast in period one and divides the population according to age between the south south west and south east coasts. The smaller fish are retained in the south south west coast if they were there previously, and likewise those larger immature fish that were in the south east coast in period one remain there. It is only the mature spawning proportion of the population which is then divided equally between the two coasts as illustrated in Figure 2.7.

$$NO_{p=2,r,a} = \begin{cases} 0 & \text{for } r = E \\ (NO_{p=1,r=E,a} \phi_{p=2,r=SSW,a} + NO_{p=1,r=SSW,a}) e^{(-M/3)} & \text{for } r = SSW \\ (NO_{p=1,r=E,a} \phi_{p=2,r=SE,a} + NO_{p=1,r=SE,a}) e^{(-M/3)} & \text{for } r = SE \end{cases} \quad (2.13)$$

where N is the population number at time period p , for region r and age a , natural mortality M and migration probability ϕ for time period p , for region r and age a . Each equation is divided by region r , going from the east coast (E), to the south south west coast (SSW) to the south east coast (SE).

The larval stages remained subject only to migration probability and natural mortality in period three. The adult ages class operated under a set of complimentary migration

probabilities determining whether they would migrate into a new region (and which region) or continue to reside in their current region.

$$NO_{p=3,r,a} = \begin{cases} 0 & \text{for } r = E \\ (NO_{p=2,r=SSW,a} (1 - \phi_{p=3,r=SE,a}))e^{(-M/3)} & \text{for } r = SSW \\ (NO_{p=2,r=SSW,a} \phi_{p=3,r=SE,a} + NO_{p=2,r=SE,a})e^{(-M/3)} & \text{for } r = SE \end{cases} \quad (2.14)$$

where N is the population number at time period p , for region r and age a , natural mortality M and migration probability ϕ for time period p , for region r and age a . Each equation is divided by region r , going from the east coast (E), to the south south west coast (SSW) to the south east coast (SE).

A unique situation arises however, where there needs to be a more complex description of the migration in period one from the perspective of the adult age class. This is required since the model makes use of indices of the previous age, and in period one, this crosses into the previous annual age, and not just earlier within the year like for periods two and three. The period one fish are brought back into the model through computation in R whereby the population is moved both forward and backward in time simultaneously to provide the population numbers for adults (Equation 2.15), which is particularly necessary for the east coast.

$$NO_{p=1,r,a=a+1} = \begin{cases} (NO_{p=3,r=SE,a-1} \phi_{p=1,r=E,a-1})e^{(-M/3)} & \text{for } r = E \\ (NO_{p=3,r=SSW,a-1} (1 - \phi_{p=1,r=SE,a-1}))e^{(-M/3)} & \text{for } r = SSW \\ (NO_{p=3,r=SSW,a-1} \phi_{p=1,r=SE,a-1} + \dots\dots NO_{p=3,r=SE,a-1} (1 - \phi_{p=1,r=E,a-1}))e^{(-M/3)} & \text{for } r = SE \end{cases} \quad (2.15)$$

where N is the population number at time period p , for region r and age a , natural mortality M and migration probability ϕ for time period p , for region r and age a . Each equation is divided by region r , going from the east coast (E), to the south south west coast (SSW) to the south east coast (SE). Note the continuation of the longer expression for the south east coast, unto a second line (\dots). This system of continuation follows below.

2.4.1.3. Region- and season-specific explicit per-recruit model for fished population

The effects of fishing were then added to the above model, through region and period specific harvest regimes $H_{p,r}$, these only operated on sub-populations vulnerable to the fishery, namely the sub-adults and adults, and not the larval age class. For the population dynamics of the system see the description provided for the above model.

The following equations are to highlight the addition of a harvest rate $H_{p,r}$ and gear selectivity s . The methods used to determine these region and period specific harvest rates is described below, in the section called ‘Estimating current harvest levels.’

$$N_{p=1,r,a=0} = \begin{cases} 1 & \text{for } r = E \\ 0 & \text{for } r = SSW \\ 0 & \text{for } r = SE \end{cases} \quad (2.16)$$

$$N_{p=2,r,a=0} = \begin{cases} 0 & \text{for } r = E \\ N_{p=1,r=E,a} \phi_{p=2,r=SSW,a} e^{(-M/3)} & \text{for } r = SSW \\ N_{p=1,r=E,a} \phi_{p=2,r=SE,a} e^{(-M/3)} & \text{for } r = SE \end{cases} \quad (2.17)$$

$$N_{p=2,r,0<a} = \begin{cases} 0 & \text{for } r = E \\ (N_{p=1,r=E,a} \phi_{p=2,r=SSW,a} (1 - s_{p=1,a} H_{p=1,r=E}) + \dots N_{p=1,r=SSW,a} (1 - s_{p=1,a} H_{p=1,r=SSW})) e^{(-M/3)} & \text{for } r = SSW \\ (N_{p=1,r=E,a} \phi_{p=2,r=SE,a} (1 - s_{p=1,a} H_{p=1,r=E}) + \dots N_{p=1,r=SE,a} (1 - s_{p=1,a} H_{p=1,r=SE})) e^{(-M/3)} & \text{for } r = SE \end{cases} \quad (2.18)$$

$$N_{p=3,r,a} = \begin{cases} 0 & \text{for } r = E \\ (N_{p=2,r=SSW,a} (1 - \phi_{p=3,r=SE,a}) (1 - s_{p=2,a} H_{p=2,r=SSW})) e^{(-M/3)} & \text{for } r = SSW \\ (N_{p=2,r=SSW,a} \phi_{p=3,r=SE,a} (1 - s_{p=2,a} H_{p=2,r=SSW}) + & \text{for } r = SE \\ \dots \dots N_{p=2,r=SE,a} (1 - s_{p=2,a} H_{p=2,r=SE})) e^{(-M/3)} & \end{cases} \quad (2.19)$$

Returning to period one at equilibrium:

$$N_{p=1,r,a=a+1} = \begin{cases} (N_{p=3,r=SE,a-1} \phi_{p=1,r=E,a-1} (1 - s_{p=3,a-1} H_{p=3,r=E})) e^{(-M/3)} & \text{for } r = E \\ (N_{p=3,r=SSW,a-1} (1 - \phi_{p=1,r=SE,a-1}) (1 - s_{p=3,a-1} H_{p=3,r=SSW})) e^{(-M/3)} & \text{for } r = SSW \\ (N_{p=3,r=SSW,a-1} \phi_{p=1,r=SE,a-1} (1 - s_{p=3,a-1} H_{p=3,r=SSW}) + & \text{for } r = SE \\ \dots \dots N_{p=3,r=SE,a-1} (1 - \phi_{p=1,r=E,a-1}) (1 - s_{p=3,a-1} H_{p=3,r=SE})) e^{(-M/3)} & \end{cases} \quad \dots (2.20)$$

where, for all the above equations, N is the population number at time period p , for region r and age a , natural mortality M , migration probability ϕ for time period p , for region r and age a , selectivity s for each period p and age a , and harvest rate H for region r . Each equation is divided by region r , going from the east coast (E), to the south south west coast (SSW) to the south east coast (SE).

2.4.2. Spawner biomass per-recruit analysis

2.4.2.1. Recruitment

The Beverton Holt Stock Recruitment relationship was added to the model to represent recruitment R , ie. the new fish entering the population each year. This relationship is a function of the steepness parameter h , where α and β are the calculated parameters of the Beverton and Holt spawner-recruitment relationship of the form:

$$R_0 = SBO / SBRO \quad (2.21)$$

$$\alpha = \frac{SBR0(1-h)}{4h} \quad (2.22)$$

$$\beta = \frac{(5h-1)}{4R_0h} \quad (2.23)$$

This relationship is re-parameterized such that there is only one parameter h which is the fraction of the initial recruitment $R0$, if the egg production is at 20% compared to pristine stock levels.

$$R = \frac{SB}{\alpha + \beta SB} \quad (2.24)$$

where R is current recruitment, SB is the spawner biomass, and α and β are the Beverton and Holt spawner-recruitment parameters.

$$R_{Dep} = \frac{R}{R_0} \quad (2.25)$$

where R_{Dep} is the depletion in current recruitment and R_0 is recruitment at the pristine stock state.

2.4.2.2. Spawner biomass

$$SBR0 = \sum_{a_{min}}^{a_{max}} N_{p=1,r=E,a} W_{p=1,a} m_a \quad (2.26)$$

$$SBR = \sum_{a_{min}}^{a_{max}} N_{p=1,r=E,a} W_{p=1,a} m_a (1 - s_{p=1,a} H_{p=1,r=E} \gamma) \quad (2.27)$$

$$SB = SBR * R \quad (2.28)$$

$$SB_{Dep} = \frac{SBR * R}{SB_0} \quad (2.29)$$

where SB_0 is the unfished spawner biomass per-recruit, SB is the fished spawner biomass per-recruit, $N_{p,r,a}$ is the population numbers per period p , region r and age a , W is the weight specific to each period and age, m_a is the probability of sexual maturity with age, $s_{p,a}$ is the selectivity-at-age, $H_{p,r}$ is the harvest rate specific to each period and region, and γ is the symbol denoting the pre-spawning catch proportion. This value was estimated to be 0.6. SB is the spawner biomass and R is the current recruitment. SB_{Dep} is the spawner biomass depletion and SB_0 is the pristine spawner biomass.

2.4.3. Yield per-recruit analysis

$$YPR_{p,r,a} = \sum_{a_{\min}}^{a_{\max}} N_{p=1,r=E,a} W_{0.5,p=1,a} v_{p=1,r=E,a} H_{p,r} e^{(-M/6)} \quad (2.30)$$

$$YPR_{p,r} = \sum_{a_{\min}}^{a_{\max}} N_{p,r,a} W_{0.5,p,a} v_{p,r,a} H_{p,r} e^{(-M/6)} \quad (2.31)$$

$$Y_{p,r} = YPR_{p,r} R \quad (2.32)$$

where $YPR_{p,r,a}$ is the yield per-recruit for each period p , region r and age a , $N_{p,r,a}$ is the population numbers per period, region and age, $W_{p,a}$ is the weight specific to each period and age, $v_{p,r,a}$ is vulnerability-at-age, for each period, region and age, $H_{p,r}$ is the harvest rate specific to each period and region, and R is the current recruitment.

2.4.4. Equilibrium function

All the above life history equations and population dynamics were incorporated into an equilibrium function in R, allowing the status of the population to be extracted in the form of a few essential descriptive parameters, namely the spawner biomass, the spawner biomass depletion level (from the chosen pristine stock state), the recruitment depletion and the yield of the stock given a set selectivity.

2.4.5. Estimating current harvest levels

2.4.5.1. Catch curve analysis

Catch curve analysis is used to determine the instantaneous total mortality Z a species experiences due to the combination of (instantaneous) fishing pressure F and natural mortality M . The analysis is based on the evidence that catches of a species decline inversely to age or length, first introduced by Edser (1908). This is a logical deduction as once fish are recruited fully into a fishery, and there is no external influx, these numbers can only decline with time (Chapman and Robson, 1960). Catch curves are for accounting for the growth-specific impacts of gear selectivity within a fishery, which can be calculated as a function of length or age, depending on the available data.

Pauly's (1984) length-converted catch curve approach was used, which accounts for the stack-up effect of the non-linear growth rate of most fish species, including geelbek (see length-at-age equations for geelbek, specifically, Von Bertalanffy growth function, Equation 2.8, and Schnute growth function, in Griffiths and Hecht, 1995). This approach was previously used to determine the total mortality of other prominent South African linefish species, such as shad, blacktail and bronze bream (Winker *et al.*, 2016a).

The catch curve analysis was performed using length frequency data obtained from a recent catch monitoring program (using slipway observers) housed in the NMLS, from 2008 to 2010, which contained 29754 individual records. These data were selected, instead of the larger length frequency data set (from 1987 to 2011), which is used elsewhere in the study, to ensure the total mortality estimates were as current as possible. This helps cement the steady-state assumption of the per-recruit analysis, in regards to inter-annually constant mortality rates.

The catch curve was calculated using the natural logarithm of frequency of each length class over time. A linear regression is applied to the downward portion of the slope, which starts from the first length selected into the fishery and extends to the maximum length (L_{inf}) of the species. Several assumptions must be met for the model to be accepted. Firstly, selectivity must be constant for the population once they've been fully recruited into the fishery, a violation of this assumption would, for example, be a fishery managed using slot limits. Secondly, the constituents of the total mortality, fishing pressure and natural mortality, must

remain constant, as well as other parameters such as the catchability and inter-annual recruitment. The inter-annual recruitment, while assumed constant in the model, is accepted to fluctuate in the real world. Lastly, the population is assumed to be closed, with no immigration or emigration. This process is quantitatively described below:

$$t_i = t_0 - \frac{1}{K} \log\left(1 - \frac{L_i}{L_{inf}}\right) \quad (2.33)$$

where t_i is time indexed over the length class indice i , where t_0 is the time at smallest length, analogous with a_0 , K is kappa, the growth coefficient of the population, L_i is the length at each length class and L_{inf} is the maximum length of the species.

$$dt_i = -\frac{1}{K} \log\left(1 - \frac{L_{i2}}{L_{inf}}\right) + \frac{1}{K} \log\left(1 - \frac{L_{i1}}{L_{inf}}\right) \quad (2.34)$$

where dt_i is the rate of growth for each time t_i during a particular length class, L_{i1} and L_{i2} are the lower and upper bounds of length class L_i , and these equations provide the necessary terms for the final catch curve, which is of the form:

$$\log(f_i / dt_i) = a + bt_i \quad (2.35)$$

where f_i is the frequency of fish in length class i , and a and b are the linear coefficients of the transformed relationship. The modulus value of the slope b is considered to be the total mortality Z , returning to the original catch curve described by Ricker (1954; expounded 1975).

For this study, this method was applied individually to each of the three different regions, providing unique Z estimates for each region. The numbers n of length frequency data from the 2008 to 2010 observer program for each region were: $n_E = 2,950$, $n_{SSW} = 12,786$, $n_{SE} = 14,016$. Total mortalities Z calculated for each region, in their dominant time period, were: $Z_{p=1,r=E} = 0.873$, $Z_{p=2,r=SSW} = 1.294$ and $Z_{p=3,r=SE} = 0.812$.

2.4.5.2. Natural mortality

Natural mortality M was assumed to be constant across all periods, regions and ages. Mortality for this model was taken as the mean of the instantaneous M estimates from Hoenig (1983) and Jenson (1996), and Pauly's (1980) empirical estimate.

$$\log(M^H) = 1.44 - 0.982 \log(a_{\max}) \quad (\text{Hoenig, 1983}) \quad (2.36)$$

$$M^J = 1.5K \quad (\text{Jensen, 1996b}) \quad (2.37)$$

$$\log(M^P) = -0.0152 - 0.279 \log(L_{\text{inf}}) + 0.6543 \log(K) + 0.463 * \log(T) \quad (\text{Pauly, 1980}) \quad (2.38)$$

where a_{\max} is the maximum age for the stock under assessment, and K (kappa) is the growth coefficient of the population, L_{inf} is the maximum length of the species and T is the mean annual water surface temperature, set to 16°C (an assumed average across all regions).

The mean M estimates (constant for all ages a) were then calculated as:

$$M = \frac{1}{3}(M^P + M^J + M^H) \quad (2.39)$$

The final mortality estimate was taken to be 0.38.

2.4.5.3. Fishing mortality

Instantaneous fishing mortality was calculated per region using a constant estimate of natural mortality of 0.38, and the total mortality from the catch curve analysis per region.

$$F_r = Z_r - M \quad (2.40)$$

where Z_r is the total mortality per region r , derived from the catch curve analysis, F_r is the mortality due to fishing per region and M is the natural mortality.

Therefore, fishing mortalities F_r calculated for each region were: $F_E = 0.651$, $F_{SSW} = 0.914$,

$F_{SE} = 0.533$. These regional instantaneous estimates of fishing mortality were used later in the study to parameterise the per-recruit and dynamic age-structured production models.

2.4.5.4. Harvest rates

The global instantaneous total mortality estimate had to be split into region and period specific harvest rates for use as input in the spatially and temporally explicit per-recruit model. For this purpose, the total mortality rate of the south east coast was used as it is considered to be the midpoint in the fishery, both biologically and geographically. The total harvest rate per period was then calculated as:

$$H_{p=3,r=SE} = 1 - e^{-(Z_{p=3,r=SE} - M)} \quad (2.41)$$

where $H_{p=3,r=SE}$ is the harvest rate for the south east coast in period three, but applied to the entire fishery (i.e. the harvest rate equivalent to a global F), Z is the instantaneous total mortality for the south east coast in period three and M is the natural mortality.

The commercial catch return data from 1985 to 2015 were then used, and divided into regions where the number of records for each region (summed per month) were: $n_E = 372$, $n_{SSW} = 697$, $n_{SE} = 371$. These catch data were then further separated into periods, and the catch proportion was calculated for every region and period.

The vulnerable biomass was then calculated for period two in the middle of the year, across all regions. Then a measure for the proportional vulnerable biomass VB_{prop} was found, whereby

$$VB_{prop,p,r} = EB_{p=2} / VB_{p,r} \quad (2.42)$$

where $VB_{p,r}$ is the vulnerable biomass specific to each region r and period p , and $v_{p,r,a}$ is vulnerability-at-age, for each period p and region r , which is given by

$$VB_{p,r} = \sum_{a_{min}}^{a_{max}} N_{p,r,a} W_{0.5,p,a} v_{p,r,a} e^{(-M/6)} \quad (2.43)$$

and EB is the exploitable biomass predicted by the ASEM for the middle of the year corresponding to period two ($p = 2$), such that:

$$EB_{p=2} = \sum_r VB_{p=2,r} \quad (2.44)$$

The region and period specific harvest rates were then calculated as follows:

$$H_{p,r} = C_{prop,p,r} VB_{prop,p,r} H_{p=3,r=SE} \quad (2.45)$$

where $H_{p,r}$ is the harvest rate, $C_{prop,p,r}$ is the catch proportion, $VB_{prop,p,r}$ is the vulnerable biomass proportion, all of which are specific to each region r and period p , and $H_{p=3,r=SE}$ is the harvest rate calculated from the total mortality Z of the south east coast. This process was repeated iteratively until the relative catches by region and period predicted by ASEM approximated observed proportion of catches.

2.5. Dynamic age-structured production model (ASPM)

2.5.1. Operating model

The dynamic age-structured production model for geelbek incorporated all the life history parameters, population dynamics and migration probabilities described earlier in this chapter. The difference between the equilibrium yield per-recruit model and the dynamic model was the introduction of time through the index year y , which can be seen in the age-structured production model (ASPM) equations in Appendix B. The model was designed so that the dynamic year boundaries could be easily altered to test a range of scenarios with ease. These included the chosen start year for the model of 1950, which provided a sufficient period for the simulated harvesting to cause population decline to the suspected population exploitable level of ~5% of pristine spawner biomass SB_0 . The harvesting rates for the simulation's burn-in period were the same as the current harvesting rates calculated for the geelbek stock. To ensure the dynamic model most accurately represents the geelbek stock, several real world factors were incorporated. The first of these was the implementation in 1985 of a minimum size limit for geelbek of 400 mm (total length), which was later increased to 600 mm (total

length) in 1992 (Griffiths and Hecht 1995). The other major shift in the linefishery was the Linefish Emergency of 2000, where the TAE over the whole linefishery was decreased by 70%. However, this was done by mostly removing boat licenses with B and C licenses. The specialised vessels targeting geelbek were primarily A licenses, and thus continued to catch at rates similar to before this intervention. It was therefore decided to not alter the harvest regime in 2000 in the model. This decision was based on an analysis of the model output compared to the commercial catch return data from the NMLS for that period. The ability of the model to perform adequately was roughly assessed using this method of visual comparison between these commercial catch returns (from 1987 to 2011) and the simulated median value produced by the model.

The model continues to predict the population under the current management strategy until the evaluation management strategy is implemented. To aid understanding, the year 2020 was chosen as the starting year of the various management strategies. Thereafter, there were various time periods which were chosen at which to evaluate the success or failure of the management strategy. These management strategy evaluation time periods were chosen as medium-term, of ten years, and long-term, of twenty years. A short-term evaluation period of five years is only indicated in the numeric results for comparison to the medium and long term management strategy evaluations. The short term evaluation period was not included as it was considered necessary to give the population a minimum of two generation times in which to reflect the stock rebuilding attempts. The model then extends another ten years into an additional predictive period, to put the long term evaluation result into perspective. These evaluation (of ten and twenty years) and viewing (an additional ten years) periods are easily altered in the initial model set-up.

The dynamic model consists of several initial input sections. Firstly, the annual parameters are set, namely the start and end dates, the data analysis period and the management evaluation periods. Thereafter, the number of simulations is chosen, and this determines the accuracy of the final model output, since the final model is the median result (with 95% confidence intervals) of the number of simulations. The harvest parameters are then defined for the various sections of the model, including the historic changes in size limits and implementation of the chosen management strategy for that model run. A separate parameter accounts for changes in size limits for the predictive model.

The model incorporates historic changes by first reading in the population dynamics parameters (Table 2.3) and then the applicable set of harvest parameters. The equilibrium function is run using these parameters and the resulting population dynamics are used in the following dynamic spatially explicit age-structured production model until such time as a shift in harvest strategy was implemented (eg. 1992 increase in size limit to 600 mm total length). The then current age-structured production model is halted, then new harvest parameters are read in and overwrite the previous ones. The equilibrium function is also overwritten with the new parameters, and the dynamic spatially explicit age-structured production model continues modelling the population using the new parameters. This is repeated for each change in harvesting experienced by the population.

2.5.2. Simulation

The age-structured production model described above was then incorporated into a simulation framework that allowed the number of simulations to easily be changed at the start of the overall operating model, depending upon the degree of precision required by each user. The final number of simulations used to evaluate the management scenarios was 1,000.

The constraints of the simulation model were stated upfront and were easily changeable. This also explained the various time scales the model was using, from 1950 as its initial start year, to 1987 as the start year of data analysis, to 2011 as the end year of data analysis, to the current year 2017, and onwards to a range of future scenarios. These were defined within the boundaries of ten and twenty years. The years when large changes were implemented into the fishery, such as the increase in the minimum size limit from 400 mm to 600 mm in 1992. The Linefish Emergency of 2000 was not included here, as discussed earlier, it is considered to only have minimally decreased the commercial exploitation of geelbek. Since managerial applicability was a primary aim of this study, the simulation model includes a predictive function which will be discussed in further detail later.

The results of each individual model run were saved, and all these individual runs were then summarised to obtain the final model results, taken as the final model output. The method of summarising was to use the median of all the results (solid black line) with standard confidence intervals of 97.5% and 2.5% (grey region). The median was used instead of the

mean as it was less affected by outliers. Additionally, it was seen that, when the number of simulations is sufficiently high, the median and the mean converge.

Individual model runs were saved in designated simulation matrices, so that any specific run could be investigated if required. Additionally, due to technicalities in the model, in regards to the temporal structure of the model and the coding techniques, these matrices were redefined to match the time scales specified at the start of the simulation model. All model outputs were then saved for each management strategy, as well as the overall results, as comma delimited files (extension .csv), with their title describing the relevant metric, region and period.

2.5.3. Model calibration

Commercial catch data were used to ground truth the model. This was done by converting the data into the same format as the summarised, final model output and assessing their precision. As mentioned above, the precision was honed through increasing the number of simulations of the dynamic model. However, the precision of the model as a whole was only tested once this precision was determined. Model accuracy was assessed using the commercial catch data extracted from the NMLS, which is plotted alongside the model output in Chapter 3.

It is important to note that these data only represent the commercial impact of the fishery, and that which is reported or observed as being caught. These estimates should be used with some caution. A scaling factor for the recreational sector was considered, however, the scope of this sector is highly uncertain, and therefore remained excluded for this stage of the model.

The data were split according to the spatial and temporal designation of the geelbek model. Each catch record has a location recorded with it, so it was simple to divide these according to their appropriate coasts. However, it is important to note that boats may have crossed these boundary areas as they reflect the region the boats docked at, and not where they actually caught the fish.

Temporally, the catches were summed into monthly catches and then aggregated into the three time periods of the model. These time periods began with August in 1987 (month 8), and the second time period for the first official year of the model included the catches from December 1987 to March 1988. These were assigned year, time period, coast and cumulative

time period identifiers. The model output was set to align to these periods despite them crossing inter-annual bounds of the real world. Four subsets of data were produced in this format, one for each coast and a combined coastal total.

Since there was a single summed value for the catches at any given time period and region, the median of the simulation results for catch was used as the final model output for a given overall model run. Note that due to high recruitment variability (recruitment sigma), despite the number of runs, model outputs are liable to vary. The final model catch output was overlaid on the commercial catch returns data and the accuracy of the model output was evaluated visually.

If the model's catch output had low precision when compared with the catch data, various input parameters were changed, within reasonable bounds. These input parameters included the original pristine spawner biomass, the catch rates for each coast, the steepness coefficient h and the recruitment sigma. Initially the coastal catch rates were changed according to period and region (with nine overall combinations), however, this was viewed as unrealistic in terms of the managerial applicability of the model, which is a key aim of this study. Therefore, the catch rates were only changed according to region, with the thought that the model should already have sub-divided the population sufficiently so that, despite a potentially high catch rate, the intrannual migration would take precedence. Each change to the input parameters was done on the basis that only one change was affected for each model assessment. These results with the highest level of precision of the model with the catch data was used in the end.

2.5.4. Management strategy selection and implementation

The benefit of the dynamic model is twofold in that it allows the model to be conditioned using real catch data, and that the model, if deemed an acceptable estimate of reality, may be used to predict the outcome of various management scenarios. The simulation model was designed to incorporate easy implementation of various management strategies and to determine their effectiveness in returning the geelbek stock to a sufficient threshold reference level (as mentioned in Chapter 1, in regards to fisheries reference points FRP) with the primary two reference levels being 25% and 40% of the original spawner biomass.

To ensure ease of use, and to maintain the relative scale of the final model, the management options are provided upfront. There are only two broad management strategies that can be implemented within the model itself, being a change in the harvesting regimes, or a change in the size limit, which alters the catchability of each fish, in regards to the exploitable biomass available to the fishery. These management strategies are only implemented in the model in year 2020, in accordance with the motto of the statistical ecology field, whereby applicability and recourse to real life considerations is key. Any management strategies tested using this model and found to be potentially useful, would only be able to be implemented by 2020 (if not later), due to the time taken for proper legislative consultation and implementation.

While many management strategies were discussed above, they are all able to be translated into one of these two management test options. Again, this was initially created to apply only to the commercial sector for the geelbek linefishery. Many management options might result in the same decrease in catch rate. Closed seasons are a special case and were provided for in the model as well, where the catch rate of a single region may be dramatically decreased (as a complete desisting of fishing is considered unlikely in regards to compliance).

3. Results

The results provided here cover the two different elements to the geelbek operating model, namely the age-structured equilibrium model and the dynamic age-structured production model. The results for the equilibrium model are presented first. These include the catch curve analysis estimates of total mortality Z and regional and seasonal harvest rates H , and the age-structured dynamics between regions and intra-annual time periods. The current stock status is also estimated, in relation to current fishing mortality F .

The results from the equilibrium model were used as input parameters for the dynamic age-structured production model. The results from these management strategy evaluation simulations span several metrics of the stock, such as spawner biomass depletion rate, and the relative stock metrics of numbers, biomass and exploitable biomass, and the estimated catch. These metrics are illustrated for each region and period from 1987 to 2050.

3.1. Age-structured equilibrium model (ASEM)

3.1.1. Catch curve analysis

Determining the mortality to apply to the species was done through a catch curve analysis (Figure 3.1), split by region. The value of total mortality was determined for each region, and the total mortality estimate for the stock was the mean of the east and south east coasts, $Z = 0.84$. The south south west coast was not included as the migration of larger fish out of this region is considered to have likely biased the analysis. The natural mortality M was calculated as $M = 0.38$, and the mortality due to fishing F (across all regions and periods) was taken as the difference of these two values, with $F = 0.46$. This was then converted in an estimated total harvest rate of $H = 0.37$ per region (across all periods).

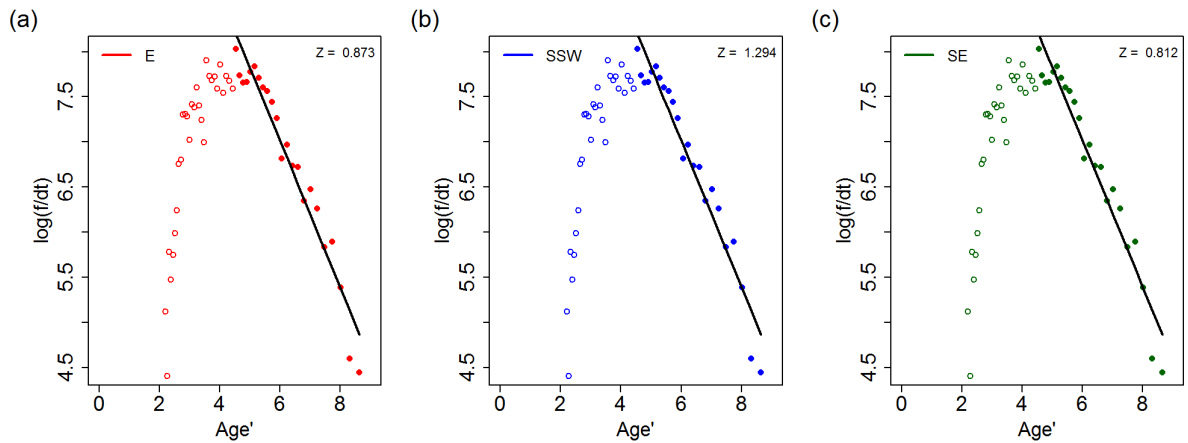


Figure 3.1: Catch curve analysis of total mortality Z (black lines) for South African geelbek from 2008 to 2010 for regions r (a) east, (b) south south west, and (c) south east coasts, summed over all time periods p . The region specific total mortalities Z_s are shown in each plot.

3.1.2. Per-recruit analysis

The spatially and intra-annually explicit base model simulated the numbers-at-age for each region and period (Figure 3.2), comparing the unfished (NO) and fished (NA) base models. In period one, the east coast has a high number of age zero fish that were just spawned, as well as the adult spawners. The juvenile fish in the stock are found in period one in the south south west coast, while the south east coast houses the smaller number of sub-adults during this period. In period two, the south south west coast shows the migration of the recruits into this region after being spawned in the east coast, which then remains there throughout the year until they reach the age-at-50%-maturity (five years). The numbers for the south south west coast also incorporate half of the adult fish in period two. The other half of the adult fish is in the south east coast in period two. In period three only juveniles remain in the south south west coast. All the sub-adults and adults are found in the south east coast in period three. There are no fish of any age in the east coast in periods two and three. The unfished base model predicts greater numbers of fish older than two years compared to the fished base model.

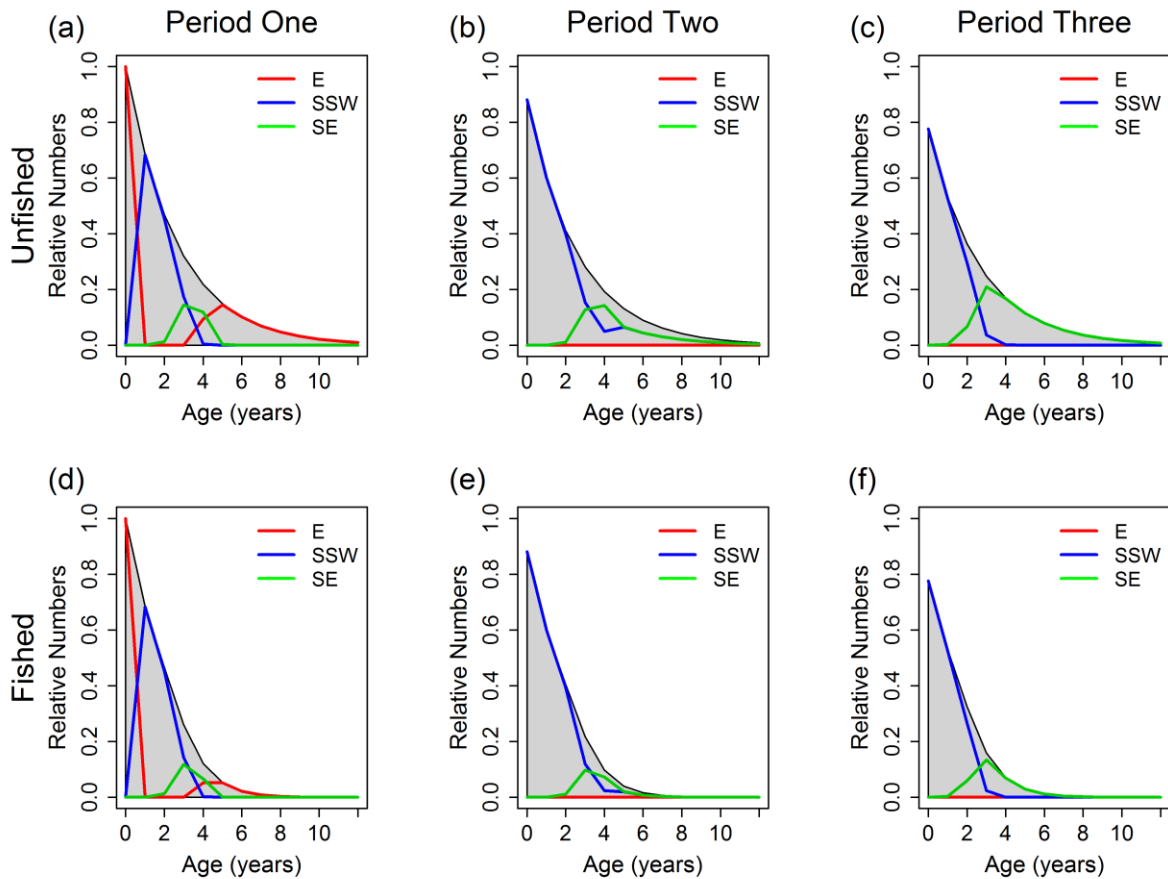


Figure 3.2: Relative (to pristine SB_0) simulated stock numbers-at-age of the South African geelbek for each region and time period for the (a) to (c) unfished (NO) and (d) to (f) fished (NA) base models. Regions are the east (E , red line), south south west (SSW , blue line) and south east (SE , green line) coasts, respectively, with the total across all regions shaded in grey (total as black line). The three intra-annual time periods are, respectively, (a) and (d) period one (August to November), (b) and (e) period two (December to March) and (c) and (f) period three (April to July).

The yield for each age class is a function of the gear selectivity applied by the fishers to the fish, and the current management strategy of a minimum size limit of 600 mm (total length). Figure 3.3 illustrates the catch-at-age for each region and period. Catches are only present in the east coast in period one, due to availability of fish, and the fish that are available are seen to all be older fish (minimum three years, but most are five years or older). However, there are still greater catches in the south south west coast in period one than in the east coast, although these are all younger fish (less than five years). The catches for the south east coast in period one are very small. The greatest catch period for the south south west coast is in period two when the adults have completed spawning and are split between the south south west and south east coasts. The previous year's recruits have also grown enough at this stage to be susceptible to the fishery, leading to increases in young fish caught, as well as a proportion of the older fish. In the south east coast in period two the catch consists of sub-

adult fish, with an equal catch proportion of older adult fish as the south south west coast. The catch in the south south west coast for period three is much smaller, as the sub-adult and adults have moved into the south east coast by this period, and the recruits that are newly available to the fishery may have been caught in period two. The catch in period three in the south east coast is predominantly sub-adult with some adult fish. The spatially and intra-annually explicit base per-recruit model had several other outputs, such as the yield, vulnerable biomass, exploitable biomass, spawner biomass and initial recruitment. These outputs were iteratively optimised to determine the exact disaggregation of the total harvest rate (derived from the previously calculated fishing mortality) according to region and period.

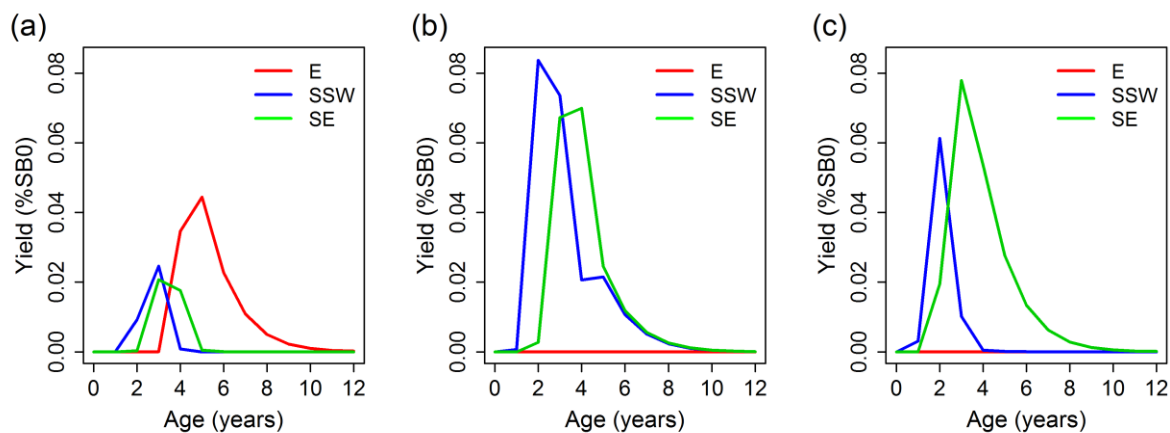


Figure 3.3: Yield (as a proportion of SB_0) for each age class of the South African geelbek for each region and time period. Regions are the east (red line), south south west (blue line) and south east (green line) coasts, respectively. The three intra-annual time periods are, respectively, (a) period one (August to November), (b) period two (December to March) and (c) period three (April to July).

The total mortality was predicted by the model (which uses harvest rates instead of fishing mortalities) for each region and compared to the observed data and results from the catch curve analysis. The results are summarised in Table 3.1. It can be seen that the predicted values are much closer to each other than the observed values. The observed value for the south south west coast was an artefact of the lack of large fish in this region for most of the year, as larger fish are only found in this region in period one.

Table 3.1: Total annual mortality Z for each region for observed catch data (from 1987 to 2011) and predicted by the catch curve analysis.

Z_E		Z_{SSW}		Z_{SE}	
Predicted	Observed	Predicted	Observed	Predicted	Observed
0.87	0.87	0.85	1.29	0.76	0.81

The proportion of the catch distributed between each region and period was then compared between the model output and the observed data (Table 3.2). These were the same data used to determine the catch curves. Proportions are used since this model is relative to the initial spawner biomass input value.

Table 3.2: Proportion of catch (C_{prop}) distributed between each region and period, for observed catch data (from 1987 to 2011) and predicted catches by the model.

Period	$C_{prop, E}$		$C_{prop, SSW}$		$C_{prop, SE}$	
	Observed	Predicted	Observed	Predicted	Observed	Predicted
<i>P1</i>	0.14	0.14	0.04	0.04	0.04	0.04
<i>P2</i>	0	0	0.26	0.25	0.20	0.21
<i>P3</i>	0	0	0.09	0.09	0.22	0.23

The proportion of vulnerable biomass of the stock compared to the exploitable biomass was used as a proxy for the division of the harvest rate as a factor of migration between periods. The proportion of vulnerable biomass was determined by dividing the total exploitable biomass $EB = 532.73$ tons by the vulnerable biomass for each region and period (Table 3.3).

Table 3.3: Annual estimated vulnerable biomass $VB_{p,r}$ (tons) specific to each region and period.

Period	VB_E	VB_{SSW}	VB_{SE}
<i>P1</i>	221.70	115.74	119.64
<i>P2</i>	0	289.21	222.10
<i>P3</i>	0	149.63	327.63

These two sets of proportions, namely the catch proportions ($C_{prop,p,r}$) and the vulnerable biomass proportions ($VB_{prop,p,r}$) were combined (multiplied) with the total regional harvest rate ($H_r = 0.37$) for the stock to obtain region and period specific harvest rates (Table 3.4). These new harvest rates ($H_{p,r}$) were also shown as relative proportions according to period (Table 3.5).

Table 3.4: Harvest rates ($H_{p,r}$) specific to each region and period, across one year.

Period	H_E	H_{SSW}	H_{SE}
<i>P1</i>	0.14	0.05	0.06
<i>P2</i>	0	0.17	0.18
<i>P3</i>	0	0.10	0.14

Table 3.5: Proportion of harvest rate ($H_{p,r}$) distributed between each region divided into harvesting effort according to period.

Period	H_E	H_{SSW}	H_{SE}
<i>P1</i>	1	0.17	0.15
<i>P2</i>	0	0.52	0.49
<i>P3</i>	0	0.31	0.36

The model also estimated the yield (in tons, Table 3.6), however, this is relative to the initial spawner biomass (SB_0) and set depletion values (~5%). Therefore, the proportion of the total annual yield by region and period (Table 3.7) was considered to have a greater applicability in aiding understanding of the model output and informing the dynamic model.

Table 3.6: Annual estimated yield $Y_{p,r}$ (tons) specific to each region and period.

Period	Y_E	Y_{SSW}	Y_{SE}
<i>P1</i>	27.67	7.90	8.90
<i>P2</i>	0	50.03	42.41
<i>P3</i>	0	17.11	46.27

Table 3.7: Proportion of annual estimated yield $Y_{p,r}$ (% of total annual yield) specific to each region and period.

Period	Y_E	Y_{SSW}	Y_{SE}
<i>P1</i>	0.14	0.04	0.04
<i>P2</i>	0	0.25	0.21
<i>P3</i>	0	0.09	0.23

3.1.3. Current stock status

The current status of the geelbek stock was determined using an iterative function which makes use of the spatially and intra-annually explicit equilibrium function. This determined the stock status under a range of harvest rates and size selectivities. Calculated using an arbitrary value for pristine spawner biomass (SB_0) of 1,000 tons, the model estimated the current spawner biomass (SB) to be 99.47 tons. The current status of the geelbek stock is therefore estimated to be 9.94% SB_0 (spawner biomass depletion) as determined by current fishing pressure and size selectivity. This is illustrated graphically as an isopleth in Figure 3.4, along with relevant thresholds. This plot shows the dynamics between fishing pressure and size-at-50%-selectivity for the stock, which indicates that fishing pressure would have to be decreased from over 0.4 to under 0.19 at current size selectivity, in order for the population status to be approximately at 25% SB_0 . In order to reach 40% SB_0 , which is thought to be the threshold for sustainable harvesting, the fishing pressure would have to be

reduced to 0.12 at current size selectivity. However, the isopleth also shows that there is the potential for recovery at relatively higher rates of fishing mortality, if the size-at-50%-selectivity is increased.

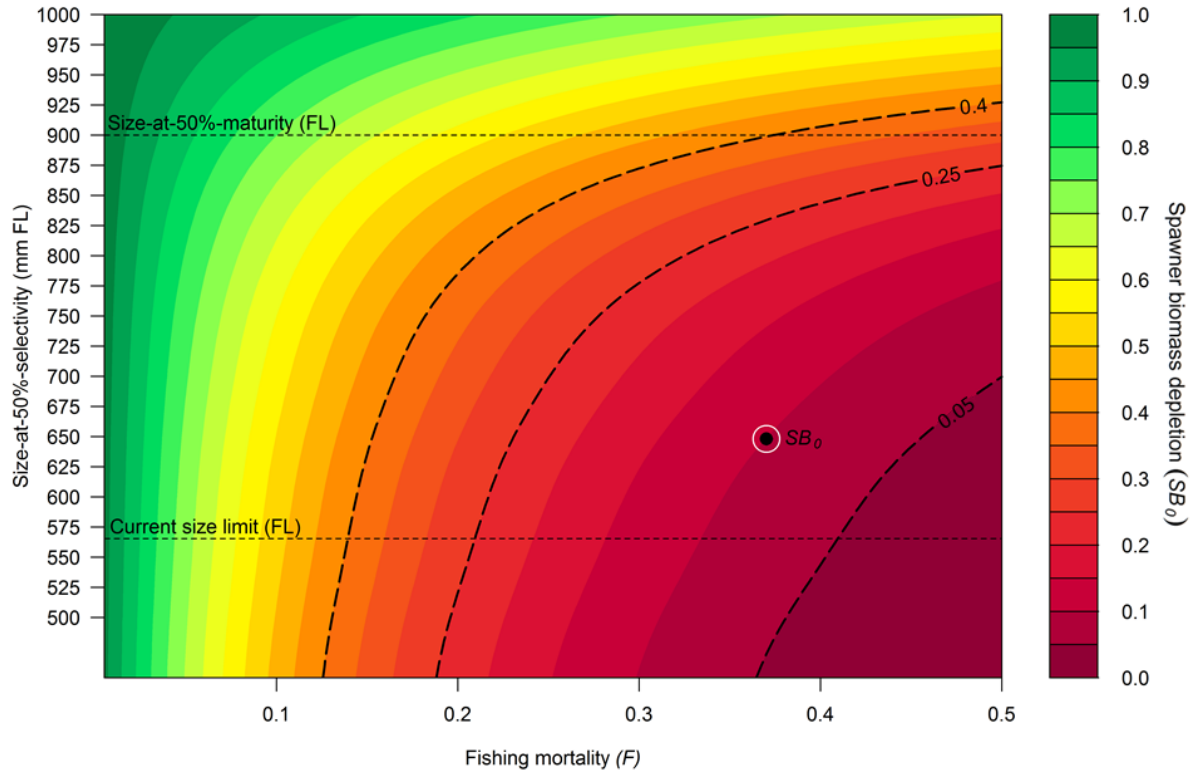


Figure 3.4: Proportion of spawning stock biomass (colour intensity) under a range of harvesting regimes representing fishing mortality and size-at-50%-selectivity by the fishery. Dashed black lines indicate reference points of 40%, 25% and 5% SB_0 , and pertinent population dynamics values, namely the current minimum legal size limit and the size at 50% maturity.

The recruitment potential R was also shown to be decreased from pristine values. The model used an initial steepness parameter $h = 0.85$ for the stock recruitment relationship (ratio of recruitment potential at 20% SB_0 compared to 100% SB_0). The depletion in recruitment potential was found to be $R/R_0 = 0.71$. This is considered a feasible result considering that the current SB is estimated at 9.94% of pristine.

3.2. Dynamic age-structured production model (ASPM)

The equilibrium per-recruit model combined with catch data for the stock, allowed harvest rates to be calculated that are specific to each region and period. These harvest rates were then incorporated into a dynamic age-structured production model which was designed to model the history of the stock. The production model was initialised with a pristine stock of 3,500 tons in 1950, ten years after the first minimum size limit of 400 mm (TL) was implemented for the species. The value for the pristine stock was estimated by simulating catches that aligned with the observed catches, however, the majority of the model results remain relative. The gear selectivity was specific to this size limit, until 1992 when the selectivity in the model is updated to account for the current minimum size limit of 600 mm (TL). During this time, the model is aligned with the commercial catch data from 1987 to 2011, a time period which is called the data period. However, the region and period specific harvest rates were calculated using only the most recent data from 2008 to 2010, as these were assumed to best reflect the current harvesting regime. The alignment between the observed and predicted data is therefore only truly relevant from 2008 to 2010, however the full data period is shown to display the long term, dynamic nature of the commercial catches. The current harvesting regime is applied until 2020, when the model updates all the relevant harvest and selectivity parameters. The updates are the assumed quantitative effect of the implementation of one of eleven constructed management strategies. Each strategy is implemented in 2020 and assessed after a medium term evaluation period of ten years and a long term evaluation period of twenty years. A further additional prediction period was added on to this from 2040 to 2050 to observe the stock recovery. The spawner biomass depletion is used as a proxy for stock status and recovery rates shown using this metric. The final model was run for 1,000 simulations and the median results are displayed, along with the 95% confidence intervals (CIs).

3.2.1. Model calibration with commercial catch trends

The model's accuracy was assessed by displaying the observed commercial catches for the geelbek linefishery and the median catches predicted by the dynamic model (Figure 3.5). The observed catches were organised according to the same regional and time period clustering as those from the model. The model predicted accurately for all regions, especially in the 2008 to 2010 period. Larger deviations between the observed and predicted data were seen in the

east coast from 1990 to 1994, in the south south west coast in 1988, 1989, 1997, 2000, 2004 and 2005, and in the south east coast in 1997, 1998, 2000, 2007 and 2010. When these deviations are considered for all regions, there is less deviation, with only three larger deviation cycles (assumed as recruitment variation), namely, in 1988 and 1989, in 1997, 1998 and 2000, and in 2004 and 2005. Output such as this was produced for every model run and management scenario, however, since this model validation occurs before differences in harvesting regimes between strategies, they were considered too repetitive and only one instance, using the median of all simulations, is shown, which applies to all management strategies. This was performed since every final model output is nearly identical for all of the following scenarios due to the high number of simulation runs converging on the 'true' catch. Not only was the magnitude of the catches assessed but also the regional proportion per period and year (Figure 3.6). The regional proportions of catches are more consistent in the predicted data than in the observed, however the predicted data are seen to usually lie within the bounds of the observed catch proportions per region. The greatest area of agreement between predicted and observed catches is between 2008 to 2010, the period used to derive the harvest rates.

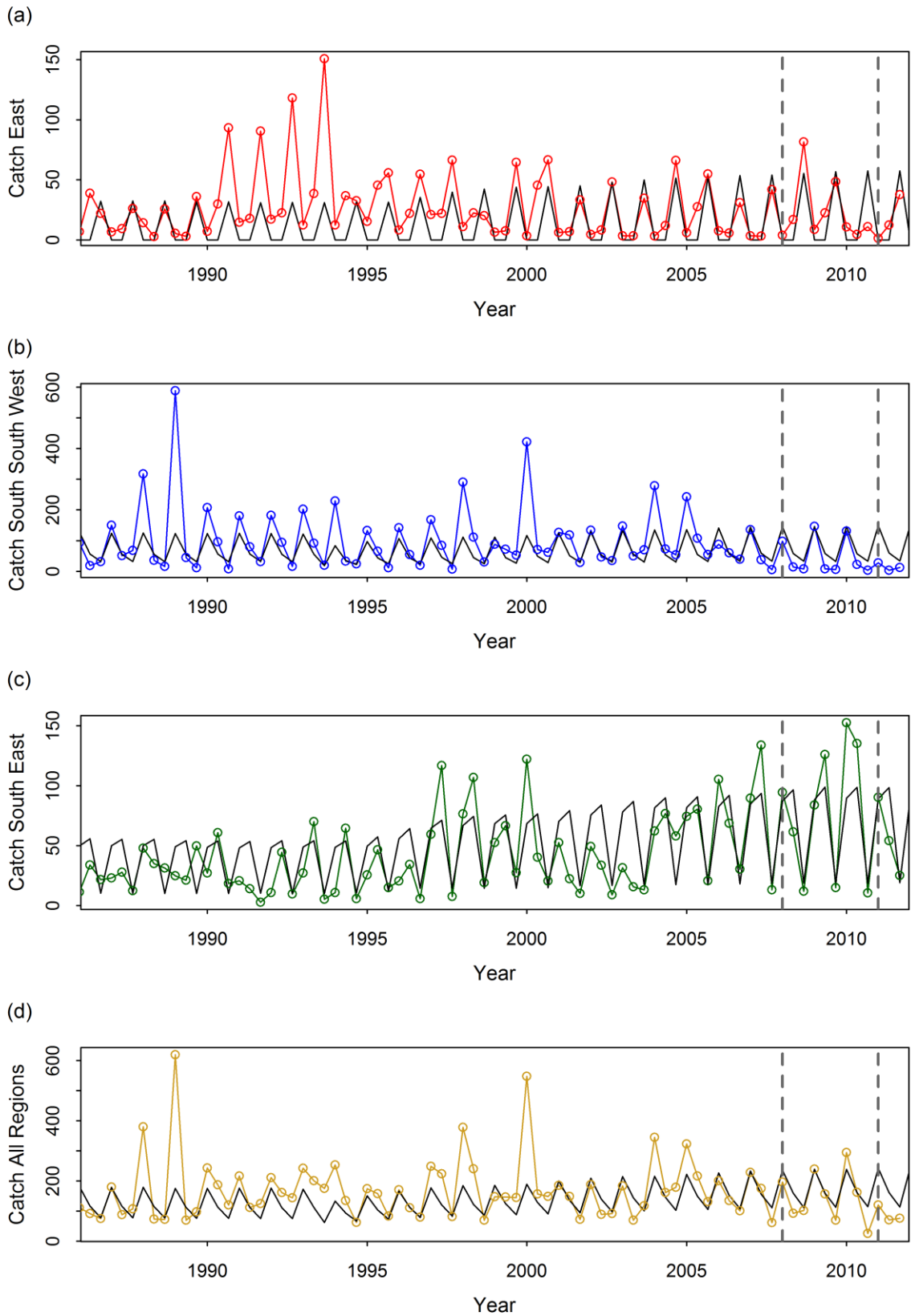


Figure 3.5: Median simulated stock catch trajectories (black lines) compared to the regional catches (connected coloured circles, obtained from the NMLS) of the South African geelbek from 1987 to 2011. Each year was divided into three periods, respectively, period one (August to November),

period two (December to March) and period three (April to July), and began with period one in August of 1987, until period three of July 2011. Each region was represented separately, with (a) east (connected red circles), (b) south south west (connected blue circles), and (c) south east (connected green circles) coasts, and combined, with (d) representing all coasts (connected yellow circles). The period from 2008 to the end of 2010, which was used to derive the harvest rates, is indicated with dashed grey lines.

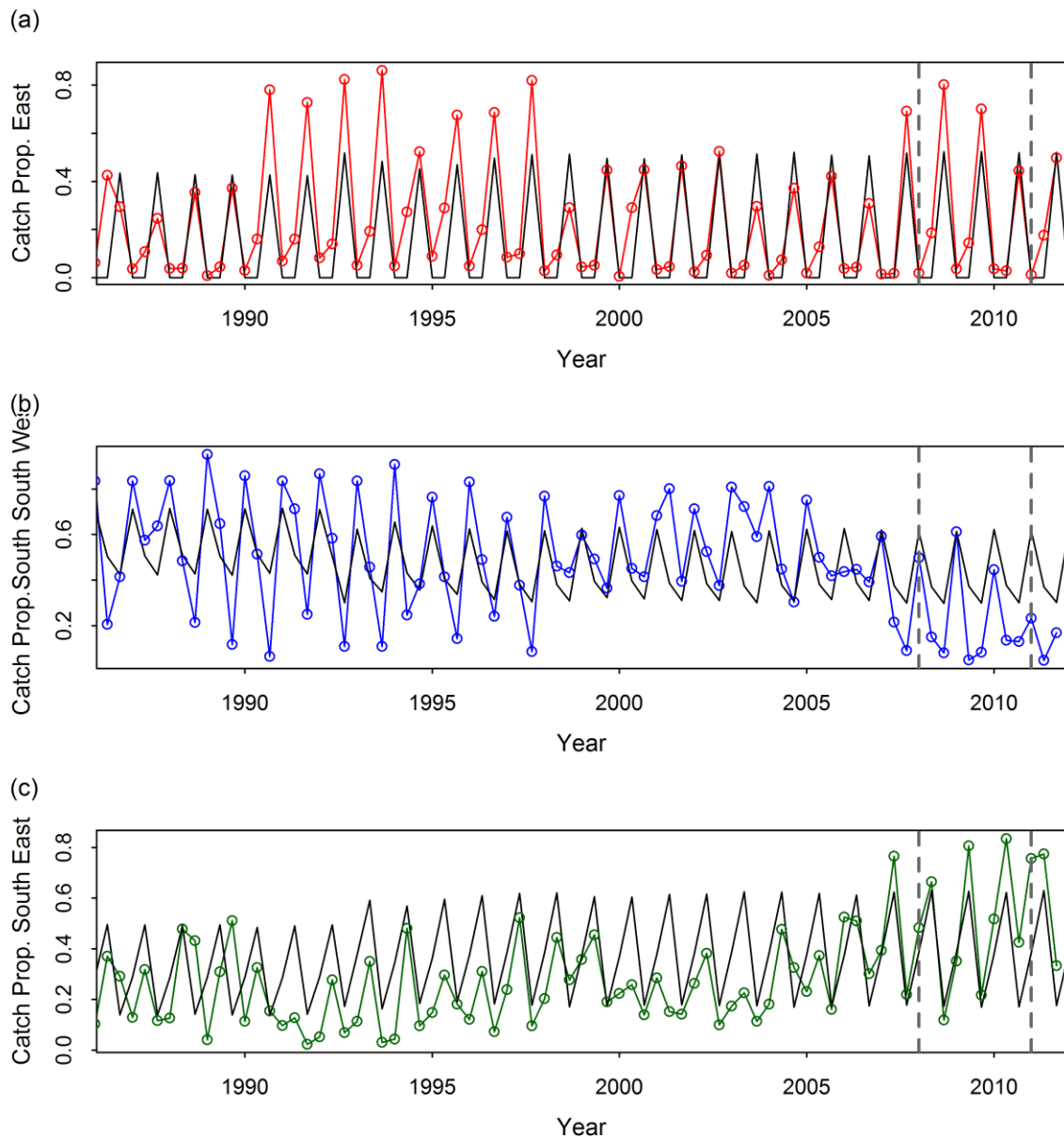


Figure 3.6: Proportional median simulated stock catch trajectories (black lines) compared to the regional catches (connected coloured circles, obtained from the NMLS) of the South African geelbek from 1987 to 2011. Each year was divided into three periods, respectively, period one (August to November), period two (December to March) and period three (April to July), and began with period one in August of 1987, until period three of July 2011. Each region was represented separately, with (a) east (connected red circles), (b) south south west (connected blue circles), and (c) south east (connected green circles) coasts. The period from 2008 to the end of 2010, which was used to derive the harvest rates, is indicated with dashed grey lines.

3.3. Management strategy evaluation

Eleven different management strategies were selected to test the efficacy of the age-structured dynamic model in dealing with a wide range of management options. The first management strategy outlined below in Table 3.8 is the base case where management follows the current *status quo*, and the second is a complete moratorium on harvesting geelbek. While the moratorium might be considered an unrealistic option, it allows the full range of potential recovery to be observed.

To avoid unnecessary repetition, only two management strategies will be described in detail. The remainder are to be found in Appendix C. However, results of all the management strategies are summarised in the later subsection Comparison of Management Strategies. Of the two that will be expounded upon, the first will be the *status quo*, as a guide in regards to the model output, and to see the current expected trajectory of the stock. The second is management strategy 11, which is a strategy to increase in minimum size limit to the size-at-50%-maturity, 950 mm TL.

Table 3.8: Summary of management strategies, specifically their strategy type, implementation in the model (and related number) and symbol.

Strategy type	MS	Management strategy	Symbol
No change	1	<i>Status quo</i>	$H_{CURRENT}$
Reduce H	2	Moratorium	$H = 0$
	3	Reduce H by 10% across all regions and periods	$90\% H_{CURRENT}$
	4	Reduce H by 20% across all regions and periods	$80\% H_{CURRENT}$
Closed season and area	5	Reduce H by 50% across all regions and periods	$50\% H_{CURRENT}$
	6	Close season in period one in east coast for spawning season	$H_{E.P1} = 0$
	7	Close season in period two in south south west coast	$H_{SSW.P2} = 0$
Increase minimum size limit (SL)	8	Close season in period three in south east coast	$H_{SE.P3} = 0$
	9	Increase minimum size limit to 650 mm TL (50 mm increase)	$SL = 650\text{ mm}$
	10	Increase minimum size limit to 700 mm TL (100 mm increase)	$SL = 700\text{ mm}$
	11	Increase minimum size limit to 950 mm TL (size-at-50%-maturity)	$SL = 950\text{ mm}$

3.3.1. How to interpret the model output

The results of the dynamic age-structured production model all take a similar format. To illustrate this, the base case of the *status quo* shall be used (where the management strategy of 600 mm TL is maintained, along with current harvest rates for each coast and period). The model output for the dynamic age-structured production model has a burn-in period from 1950 to 1987, the start of the data period, where the stock is fished down to current stock

estimates using current harvest strategies over past management strategies. The state of the population during the data collection period was estimated to be 5% SB_0 , extending upwards to 10% SB_0 by the implementation year of 2020, in approximate alignment with the results from the per-recruit analysis. The impact of increasing the minimum size limit from 400 mm TL to 600 mm TL in 1992 can be seen in the later recovery. These features common to all management strategy simulations, and are therefore only depicted once, in Figure 3.7.

The results for each management strategy are presented graphically. The spawner biomass depletion is shown in a composite plot, which first shows the overall level of stock spawner biomass depletion, and secondly shows a zoomed in version of the spawner biomass depletion. This is taken as the primary metric used to determine the state of the stock, and it is derived using only the estimated model output for the spawning population present in the east coast region in the spawning season of period one. While the stock has a greater biomass than the spawning biomass, this cannot contribute to the long term recovery of the stock.

Thereafter, the model output is split by region and period, with the regions starting at the east coast, followed by the south south west, and then the south east coast (viewed left to right). This arrangement does not display the geographical placement of the regions, which would have be represented by moving from the south south west coast to the south east coast and then to the east coast (viewed left to right). However, when generated, the geographically accurate method was considered confusing as it does not reflect the simplified model structure (shown in Figure 2.5, in Chapter 2). The time periods begin with period one, August to November, in the first row, then period two, December to March (of the subsequent year), in the second row, and finally period three, April to July, in the third row.

The current display structure allows the spawning biomass to spawn in the east coast, then in the south south west in period two the new recruits are seen, especially in the Number plot. This metric was included especially for this function, as it shows the prominence of the new recruits per region, which would otherwise be overlooked if only the Biomass B or Exploitable Biomass EB metrics were seen. The Biomass B plot is included as it shows the entire biomass of the population, which, while it might seem to erase smaller fish, it is necessary to view the differences in cases were the exploitable biomass is being changed and measured, such as with the change in the minimum size limit. Exploitable Biomass EB is included as a common and necessary fisheries metric, which relates to the Catch C metric.

All these metrics are displayed in a composite graph made of nine sub-plots, one for each region and period.

The model output seen in the following figures is illustrated using a black line to denote the median of the metric, for the number of simulations (1,000 runs in final simulations), with the 95% confidence intervals of the metric's simulation runs are shown in grey around the median. There are three reference levels shown in the graphs (if applicable to the metric), namely, the target reference level of 40% SB_0 which is the assumed level at which the fishery can operate sustainably, the limit reference level of 25% SB_0 , which is the level at which the stock is considered critically depleted, and the 5% SB_0 , a level which is considered severely depleted, and aligns with the current estimated level of spawner biomass for geelbek. The background of the plots indicates the relevant evaluation time periods of the model. These are different from the three intra-annual time periods, and will be called evaluation periods to avoid confusion. The first evaluation period is the model burn in stage, represented by the purple shaded block. This evaluation period is only included once (Figure 3.7) to illustrate the burn-in of the model, down to current spawner biomass depletion levels. The second evaluation period is the data period, from 1987 to 2011, which extends as the pre-evaluation period until the implementation of a management strategy, and is represented by the blue shaded block. This period extends until 2020, the time at which each management strategy is implemented, to allow for the introduction of ongoing data collection inclusion. The second evaluation period is the medium term evaluation period, a period of ten years from 2020 to 2030, and is represented by the pink shaded block. The third evaluation period is the long term evaluation period, a period of twenty years from 2020 to 2040, however, it is shown in relation to the medium evaluation period, as an additional ten years of evaluation, and is represented by the yellow shaded block from 2030 to 2040. The fourth evaluation period is an additional prediction period of ten years, from 2040 to 2050, to show the trajectory of the stock beyond the confines of the long term evaluation period, and is represented by the green shaded block. These plotting features are illustrated below in an example spawner biomass depletion graph of the *status quo* (Figure 3.7), to aid understanding of subsequent plots.

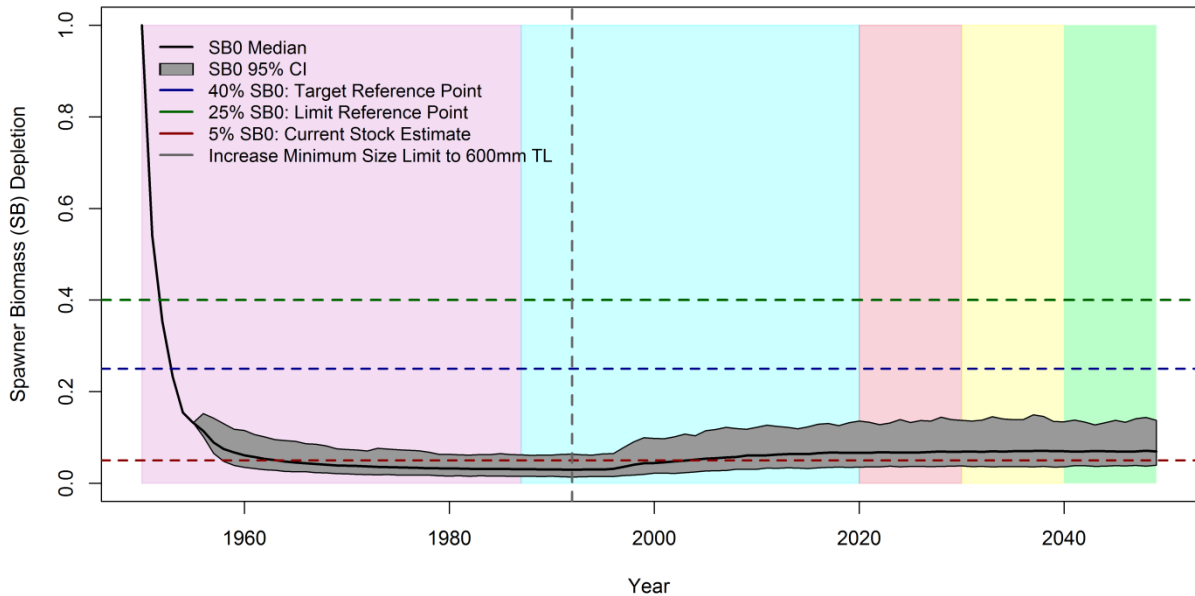


Figure 3.7: Median relative (to pristine) simulated stock spawner biomass depletion trajectory (black line) of the South African geelbek from 1987 to 2050, with the harvesting regime remaining at the *status quo* from 2020 to 2050. The depletion level is displayed relative to the pristine population state (value of one). The 95% confidence limits are indicated (grey shaded areas). The burn-in period of the model, from 1950 to 1987 is shaded purple. The NMLS data period from 1987 to 2011 is shaded blue, which extends as the pre-evaluation period until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area). Fisheries reference points of 40% SB_0 (dashed green line), 25% SB_0 (dashed blue line) and 5% SB_0 (dashed red line) are also included.

3.3.2. Simulation scenarios

An overview of each management strategy type is briefly described for this section, any management strategy simulations pertaining to that strategy type are illustrated in Appendix B and a summary of all management strategies is to be found in the Comparison section below. However, two cases are described in full, management strategy one, maintaining the *status quo*, and management strategy 11, which implements an increase in the minimum size limit from 600 mm TL to 950 mm TL, the size-at-50%-maturity for the species.

3.3.2.1. Strategy type: Status quo (base case)

3.3.2.1.1. Management strategy 1: Status quo (base case)

The overall state of the stock is aligned with the spawning stock biomass, and the results primarily use this metric. The spawning stock biomass declined sharply from the assumed pristine state (set at 1950, Appendix B), dropping to approximately 5% SB_0 by 1977, and was 3.5% SB_0 at the start of the data collection period (blue area) using the current harvesting

regime (Figure 3.8). The population remains at this $\sim 5\%$ SB_0 level for the whole of the data collection period, increasing to $\sim 7\%$ SB_0 by 2020, the start of the prediction period (pink area). Figure 3.8b shows a zoomed in version of Figure 3.8a, to display the stochasticity of the population and to get a better take on the rate of decline and recovery at lower stock levels.

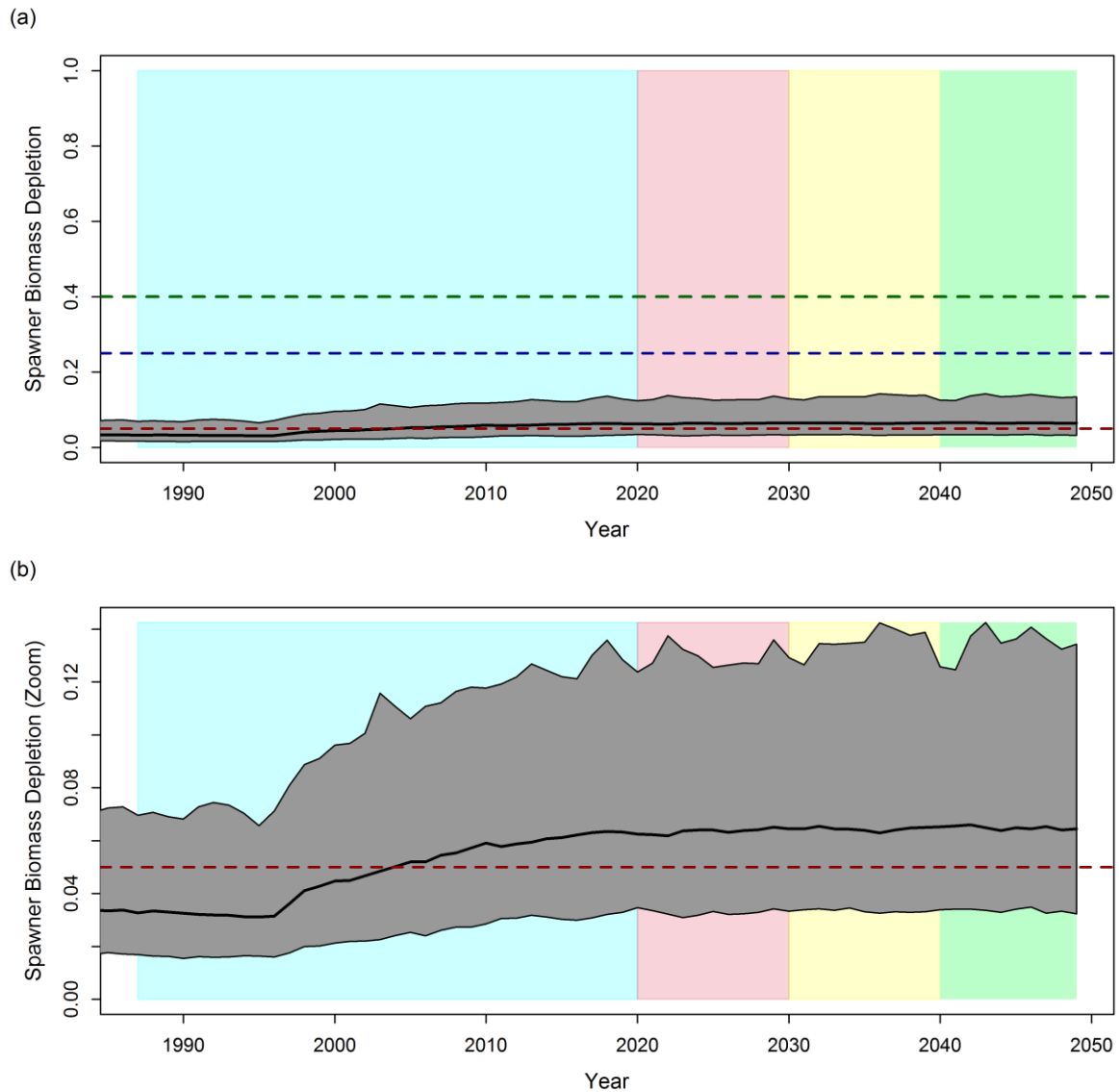


Figure 3.8: Median relative (to pristine) simulated stock spawner biomass depletion trajectory (black line) of the South African geelbek from 1987 to 2050, with the harvesting regime remaining at the status quo from 2020 to 2050. The depletion level is displayed relative to (a) the pristine population state and (b) the current estimated population level of $\sim 5\%$ pristine state. The 95% confidence limits are indicated (grey shaded areas). The NMLS data period from 1987 to 2011 is shaded blue, which extends as the pre-evaluation period until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area). Fisheries reference points of 40% SB_0 (dashed green line), 25% SB_0 (dashed blue line) and 5% SB_0 (dashed red line) are also included.

The simulated population, however, is larger and more dynamic than just the spawning stock biomass (which only represents the adults in the east coast in period one). Below are several metrics of the population, to display the spatial and temporal intra-annual migration of the stock. Figures are composite plots of nine graphs, one for each unique region and period combination. Regions are displayed from the east, to the south south west, and the south east coastal regions (left to right) and align with the original migration model flow diagram (Figure 2.5). While there are more metrics generated by the model, numbers of fish N , biomass B , exploitable biomass EB and catch C were chosen. These metrics were scaled relative to the value of the metric at the pristine stock state, except for the catch.

The numbers of fish N (Figure 3.9) for the east coast show the presence of fish in that region only in period one, and accounts for the spawning stock and the new recruits only. The south south west coast has a fairly equal division in terms of number of fish across the three periods, however, the highest proportion is clearly in period two. The south east coast shows a small proportion of the stock present in period one, which represents those sub-adult fish that attempted the spawning migration yet were not successful, meaning they only travelled part of the journey, and aborted it halfway through. There are higher numbers of fish in the south east coast in period two and three, with the highest in period three. The heightened proportion in period three is due to the adult and sub-adult fish on their spawning migration through that region. Values are not reported for numbers of fish, since they are relative to the input value for SB_0 and are meaningless out of the context of the model.

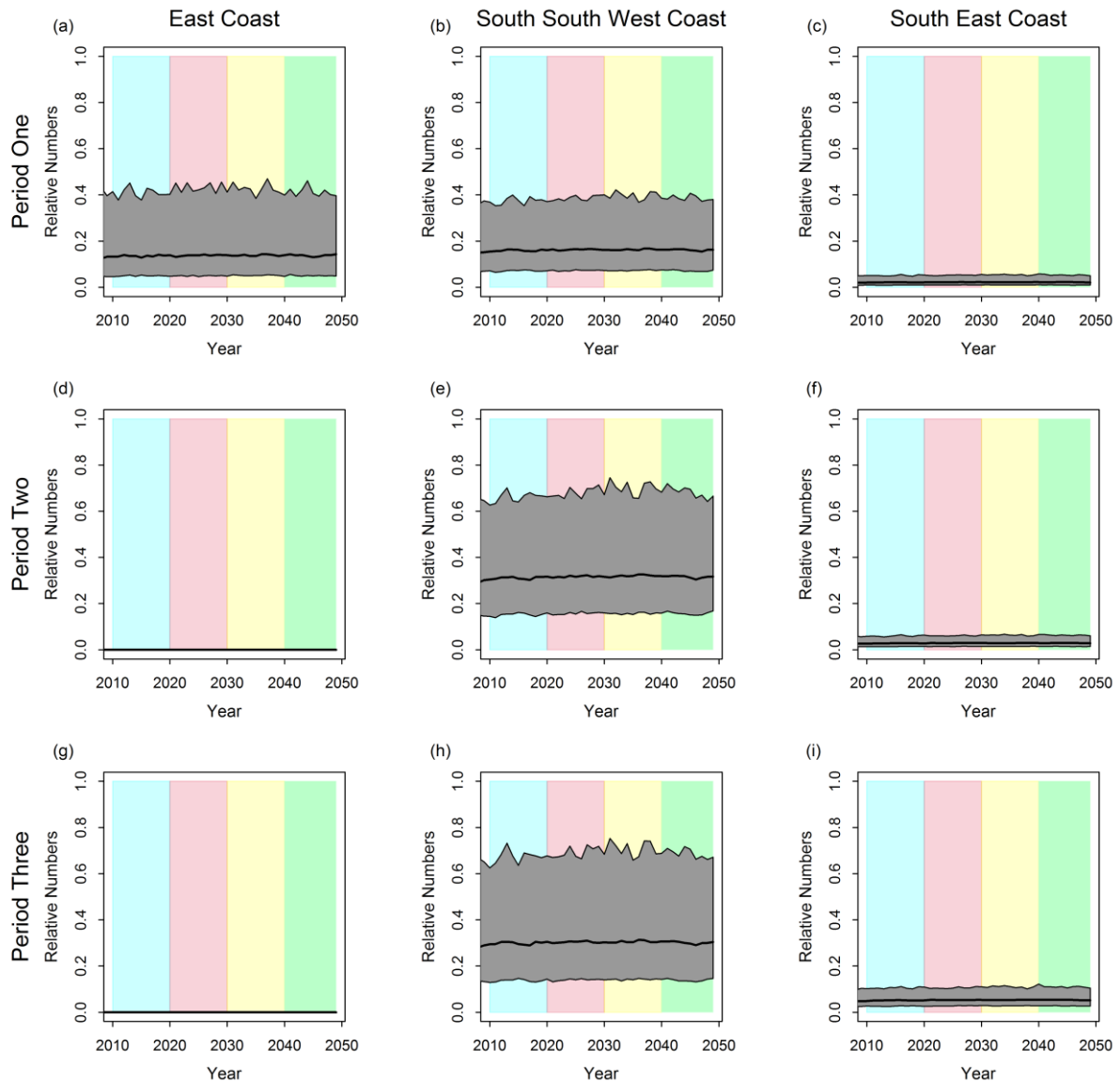


Figure 3.9: Median relative (to pristine) stock numbers trajectories (black lines) of the South African geelbek from 2010 to 2050, with the harvesting regime remaining at the status quo from 2020 to 2050. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

The biomass B of the population (Figure 3.10) shows a very different picture in terms of quantity than the numbers of fish (Figure 3.9), especially in period one. This difference is mostly because of the new recruits that enter the population in the east coast in period one, however, the biomass metric primarily reflects the biomass of the spawning stock. There is no biomass for the east coast in periods two or three. The south south west coast has the most

similar display to the numbers of fish, because there is a mix of ages reflected throughout the periods which averages out the numbers of fish across an average biomass for a fish being half grown. Period two shows the highest biomass for the south south west coast. The south east coast shows the difference between biomass and numbers, because there are relatively few fish, spread across the periods, yet the biomass for those fish is relatively high.

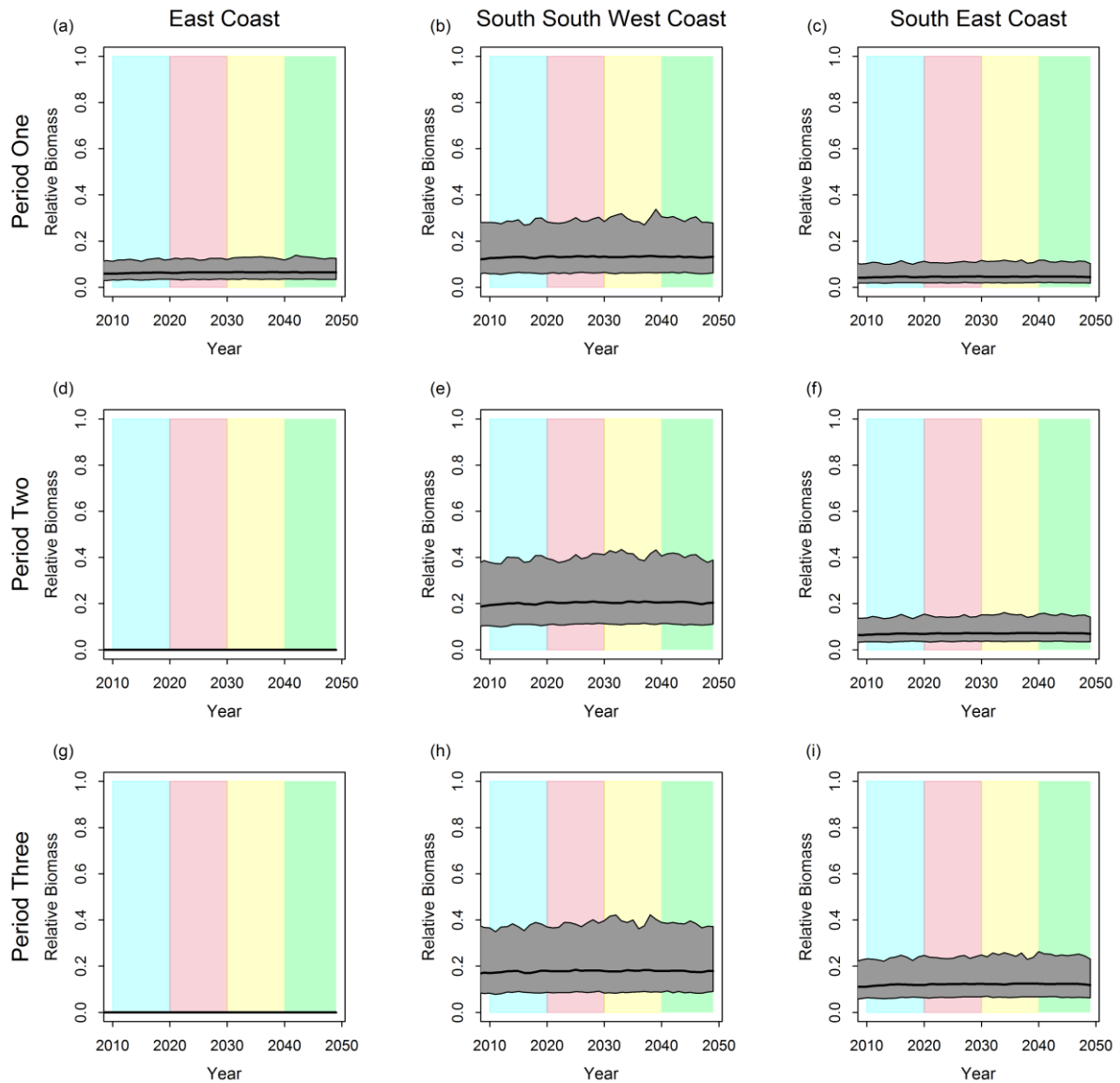


Figure 3.10: Median relative (to pristine) stock biomass trajectories (black lines) of the South African geelbek from 2010 to 2050, with the harvesting regime remaining at the status quo from 2020 to 2050. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

The third relative metric is the exploitable biomass EB of the stock across the regions and periods (Figure 3.11). Exploitable biomass of the stock is the proportion of the stock that is vulnerable to the fishing gear, as well as a function of migration, being in the correct region and period to be caught by the fishery, and within the relevant management regulations specific to the history of the fishery. This metric is displayed as it is relevant to the fishery and is useful in understanding the link between biomass (Figure 3.10) and catch (Figure 3.12). The biomass and exploitable biomass are the same in the east coast in period one, with no fish present in the other two periods. The exploitable biomass shows no sudden declines or dips during the simulation period in any of the regions or periods.

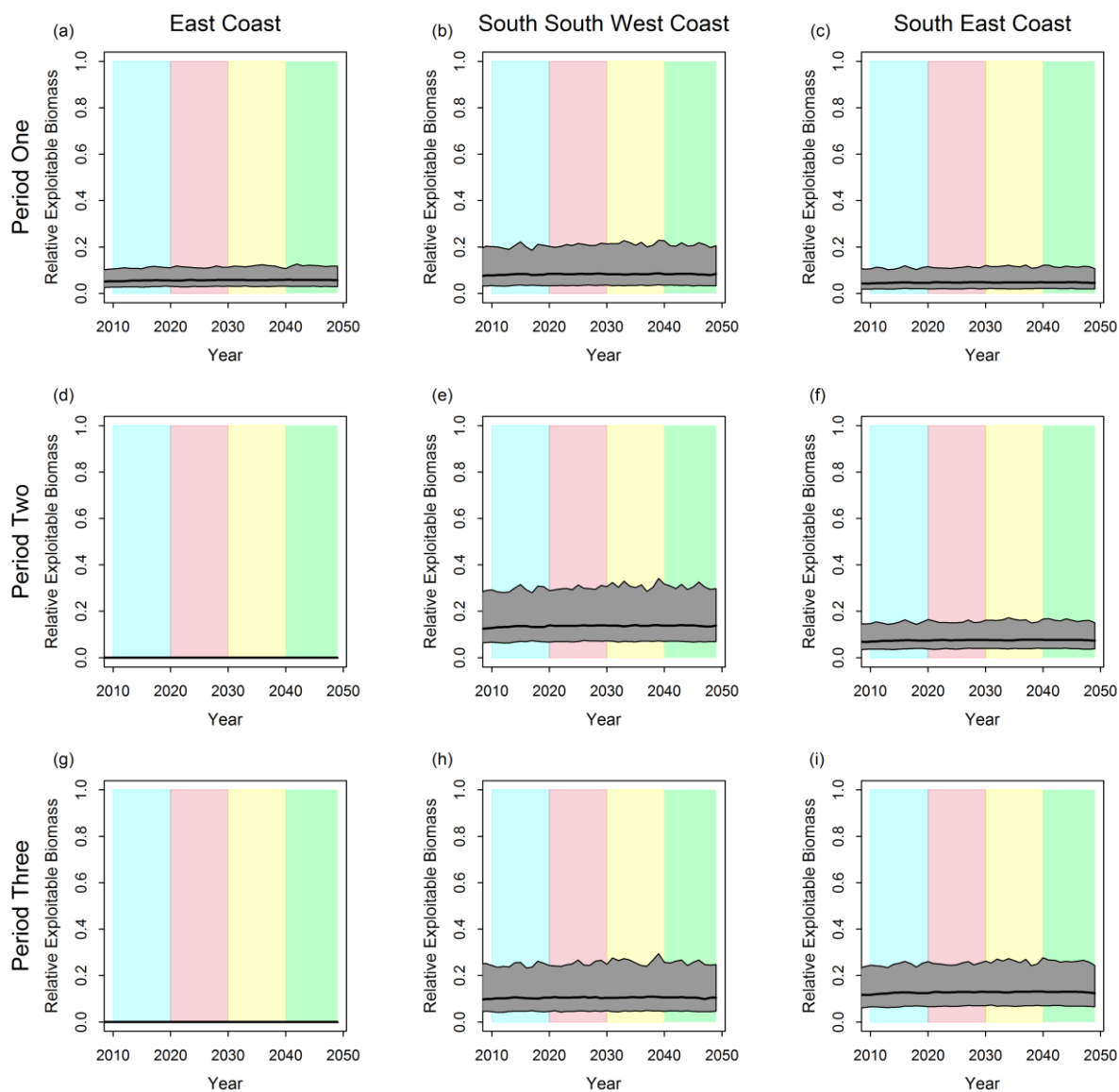


Figure 3.11: Median relative (to pristine) stock exploitable biomass trajectories (black lines) of the South African geelbek from 2010 to 2050, with the harvesting regime remaining at the status quo from

2020 to 2050. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

The last model metric displayed here is the catch (Figure 3.12). This is the predicted catch calculated by the model, based on the NMLS commercial catch data. Catches remain low and steady through this projection across all regions and periods, when there is no change in management strategy.

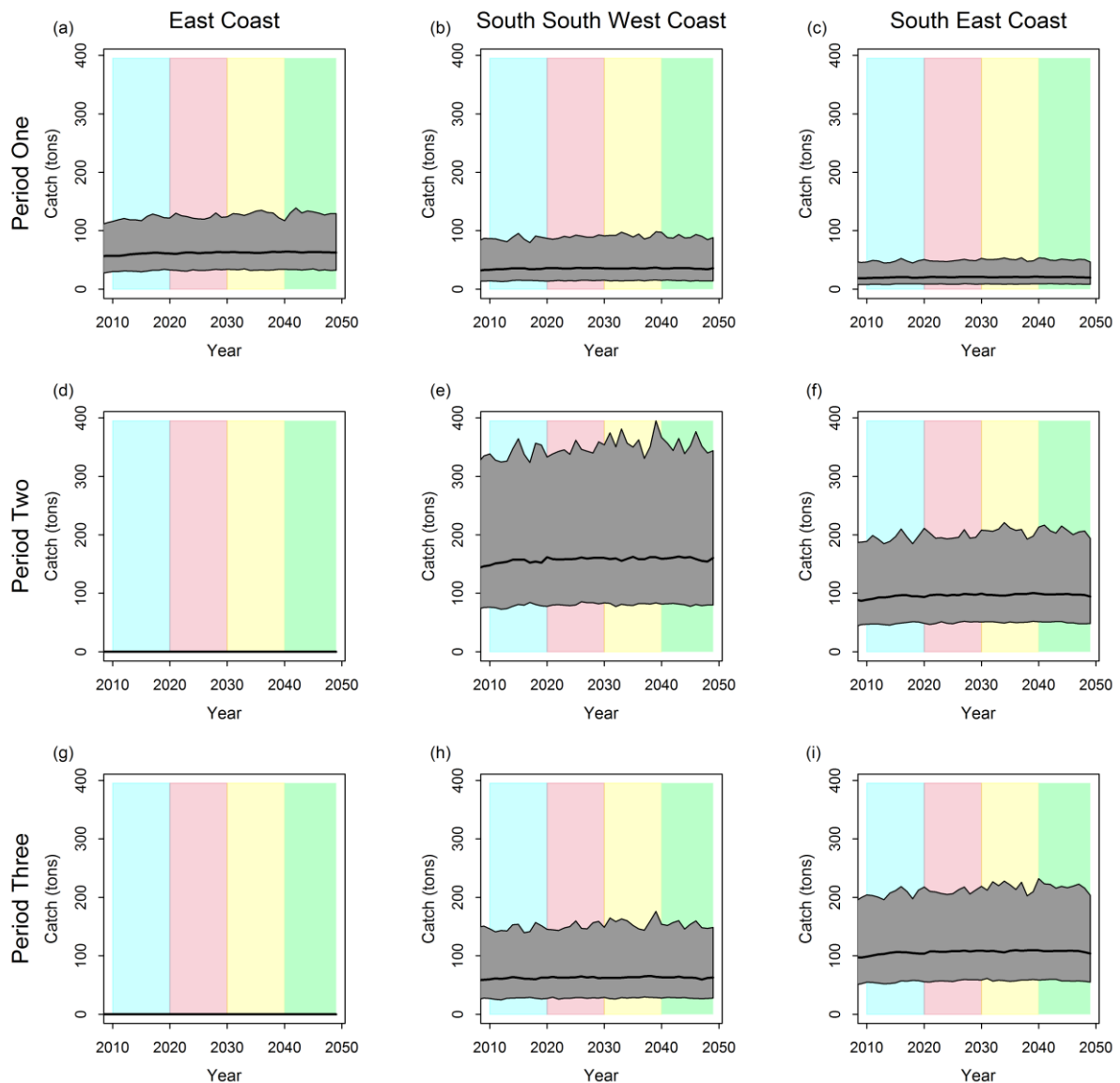


Figure 3.12: Median simulated stock catch trajectories (black lines) of the South African geelbek from 2010 to 2050, with the harvesting regime remaining at the status quo from 2020 to 2050. The nine

subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

3.3.2.2. Strategy type: Reduce national harvesting pressure

Various options were used for this strategy, outlined in Table 3.8 and would be implemented through a reduction in the total allowable effort TAE. Of the four management strategies which reduce the national harvesting pressure, the greatest recovery was found when there was a full moratorium and a 50% reduction in harvesting pressure (SB_0 summarised in Figure 3.13). Decreasing the harvest rate by 50% across all regions and seasons had the third highest recovery rate, reaching 25% SB_0 by 2033, but levelling off thereafter.

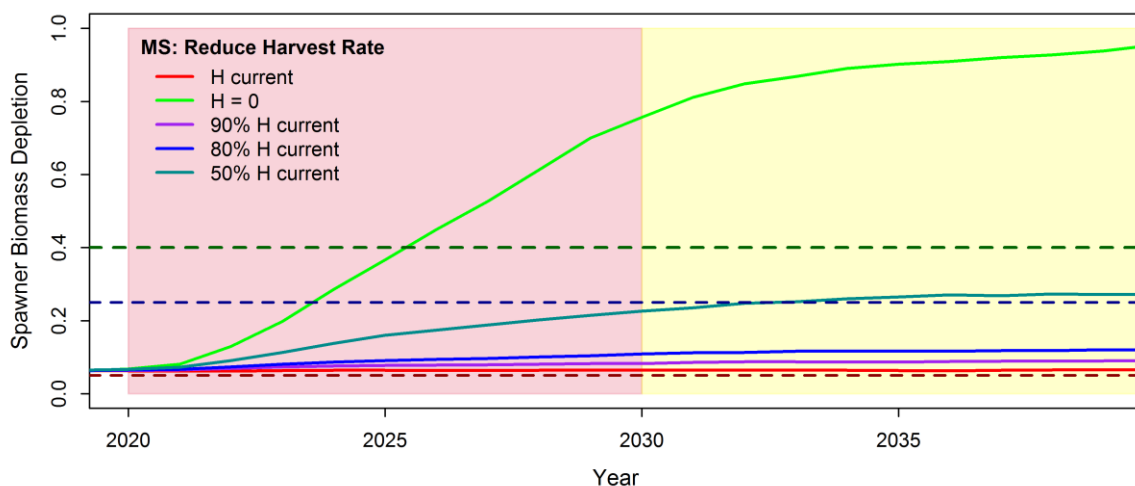


Figure 3.13: Median relative (to pristine) simulated stock spawner biomass depletion trajectories (coloured lines) of the South African geelbek from 2020 to 2040, for management strategies which reduce harvest rates. The medium term evaluation extends from 2020 to 2030 (pink shaded area), the long term evaluation extends from 2020 to 2040 (yellow shaded area). Fisheries reference points of 40% SB_0 (dashed green line), 25% SB_0 (dashed blue line) and 5% SB_0 (dashed red line) are also included.

3.3.2.2.1. Management strategy 2: Moratorium

The complete alternative to the previous management strategy of leaving the stock under the current management strategy is to remove all national harvesting pressure ($H = 0$) and implement a full moratorium on catching geelbek nation-wide. This strategy is the only one

to yield a recovery of the stock to above the target reference point of 40% SB_0 . Under this management strategy, the stock was predicted to recover to the critical limit reference point by 2023 and to the threshold reference level for sustainable fishing at 40% SB_0 by 2025, both occurring within the medium term evaluation period. The stock was also predicted to approach a full stock recovery of 100% SB_0 , assumed to be the carrying capacity K of the stock, by 2040 which is within the long term evaluation period (of twenty years), as seen in Figure 3.13.

3.3.2.3. Strategy type: Closed seasons and areas

A potential management scenario that is considered to be biologically important is to close the spawning grounds off the east coast to fisheries during the spawning season. To test this, the catch rates for the east coast in period one were decreased from 100% to 0.0001% (in acceptance that harvesting pressure will never reduce to complete zero). While this strategy is initially aimed at the commercial sector to test the potential impact and potential for recovery of the stock, it is suspected to have greater impacts than predicted here, since the recreational sector, which especially targets geelbek during their spawning aggregation, would also be under the ordinance of the closed season.

While it seems that a significant stock recovery is already underway considering the gradients of the stock, it is important to remember that the stock level before 2020 is still at an estimated 10.64% SB_0 (Figure 3.14). The increase due to the decreased harvesting in the east coast region in the spawning time (period one), does push the stock above this severely depleted threshold, however, this increase is mild and not the sharp recovery that was hoped for. What is interesting is the catches do improve, especially in the other coasts, such as the south south west coast (Figure C.25). Indeed, the recovery for closing the east coast in period one and the south south west coast in period two are almost identical (Figure 3.14). However, the greatest improvement for the closed seasons and area management strategy is that for closing the south east coast in period three to protect the sub-adults and adults.

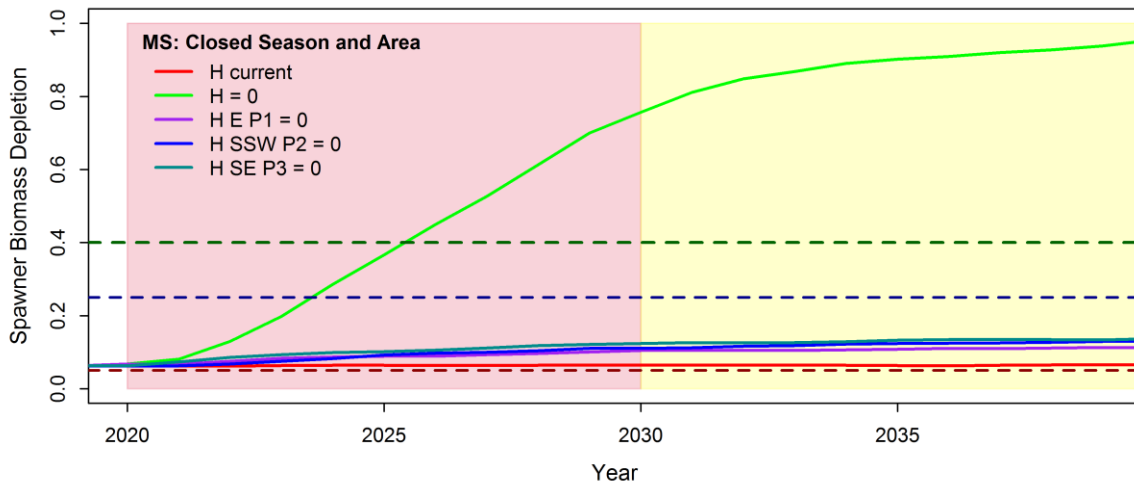


Figure 3.14: Median relative (to pristine) simulated stock spawner biomass depletion trajectories (coloured lines) of the South African geelbek from 2020 to 2040, for management strategies which implement closed season and areas. The medium term evaluation extends from 2020 to 2030 (pink shaded area), the long term evaluation extends from 2020 to 2040 (yellow shaded area). Fisheries reference points of 40% SB_0 (dashed green line), 25% SB_0 (dashed blue line) and 5% SB_0 (dashed red line) are also included.

3.3.2.4. Strategy type: Increase minimum size limit

Three cases were tested for the minimum size limit change, namely increasing the minimum size limit to 650 mm, 700 mm and 950 mm (total length). There was very little increase in spawner biomass in the implementation of the two smaller size limits. Predicted recovery rates of 6 and 7% SB_0 , respectively, were found for the end of the medium term evaluation period, and by the end of the long term evaluation period they were found to barely increase to 8 and 10% SB_0 , respectively (Figure 3.15). The greatest recovery was achieved by increasing the minimum size limit to the size-at-50%-maturity for the species, 950 mm (total length), shown in Figure 3.15 which is expounded below.

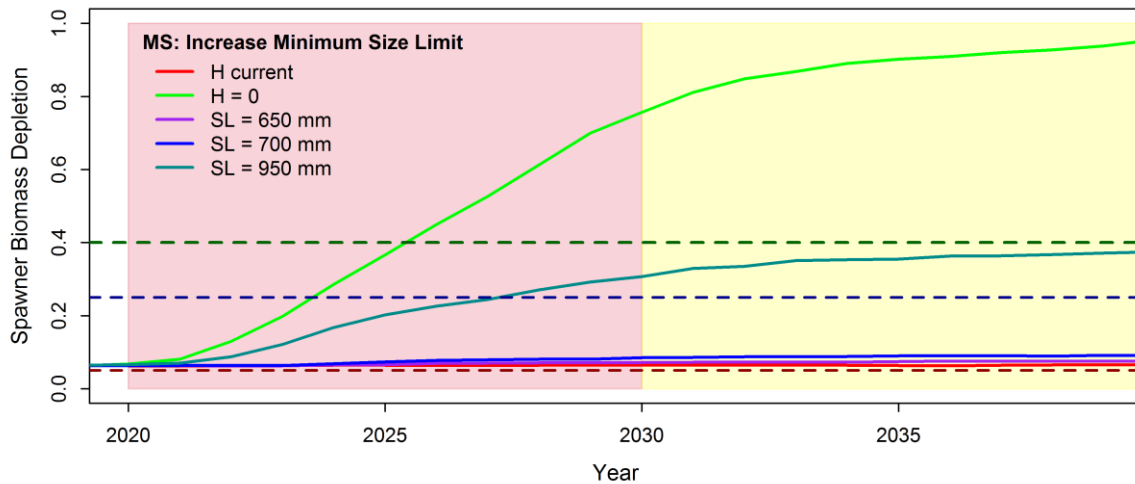


Figure 3.15: Median relative (to pristine) simulated stock spawner biomass depletion trajectories (coloured lines) of the South African geelbek from 2020 to 2040, for management strategies which increase the minimum size limit. The medium term evaluation extends from 2020 to 2030 (pink shaded area), the long term evaluation extends from 2020 to 2040 (yellow shaded area). Fisheries reference points of 40% SB_0 (dashed green line), 25% SB_0 (dashed blue line) and 5% SB_0 (dashed red line) are also included.

3.3.2.4.1. Management strategy 11: Increase minimum size limit to size-at-50%-maturity 950 mm

Increasing the minimum size limit to the size-at-50%-maturity for the species, 950 mm TL, predicted the second highest recovery rate for the stock, reaching 25% SB_0 by 2027, and nearing 40% SB_0 by 2035, at which point its trajectory is asymptotic to 40% SB_0 (Figure 3.16).

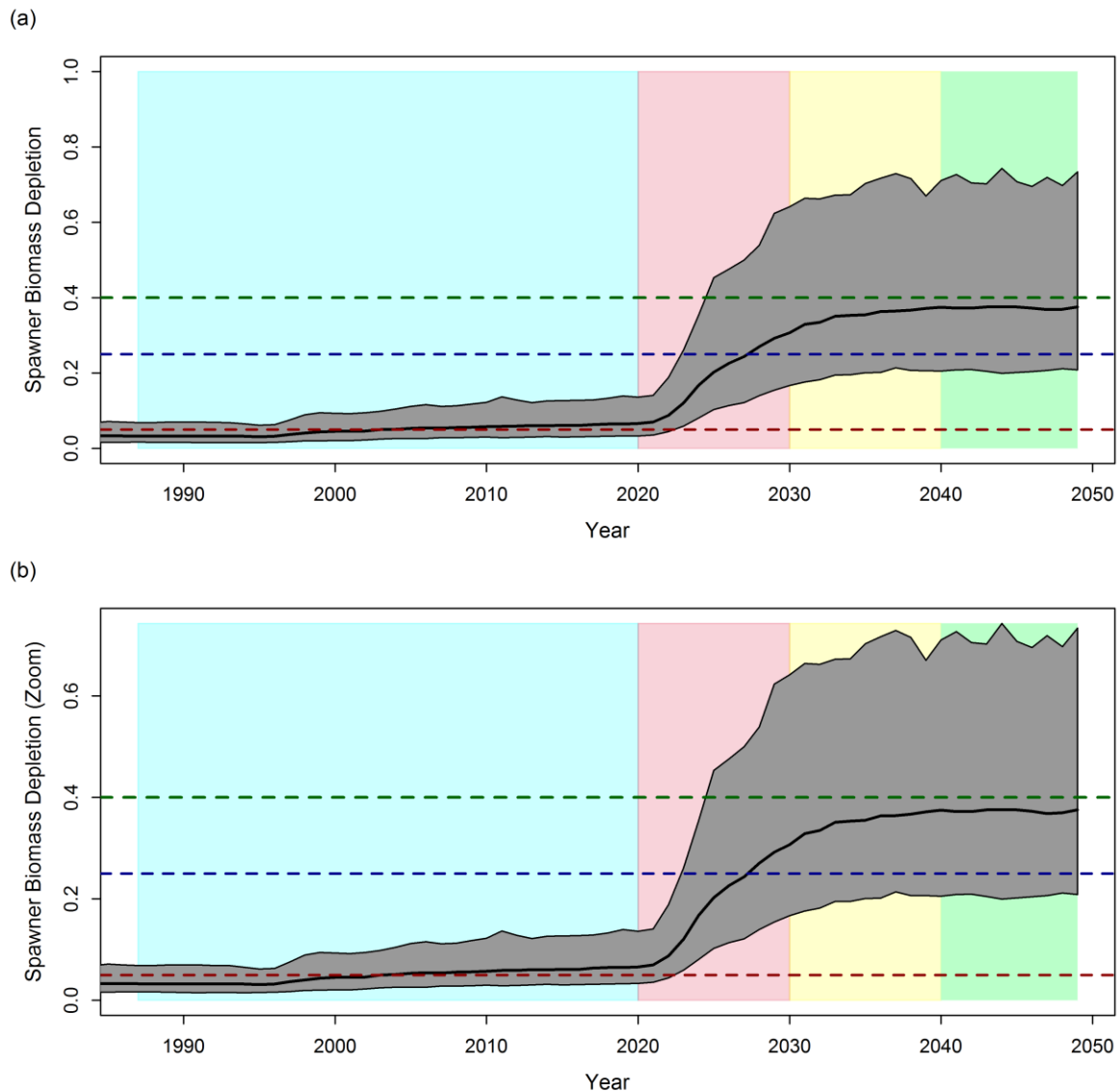


Figure 3.16: Median relative (to pristine) simulated stock spawner biomass depletion trajectory (black line) of the South African geelbek from 1987 to 2050, with an increase in the minimum size to the size-at-50%-maturity 950 mm TL from 2020 to 2050. The depletion level is displayed relative to (a) the pristine population state and (b) the current estimated population level of ~5% pristine state. The 95% confidence limits are indicated (grey shaded areas). The NMLS data period from 1987 to 2011 is shaded blue, which extends as the pre-evaluation period until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area). Fisheries reference points of 40% SB_0 (dashed green line), 25% SB_0 (dashed blue line) and 5% SB_0 (dashed red line) are also included.

The relative stock numbers show the classic high numbers of adults and new recruits in the east coast in period one, declining as the new recruits suffer natural mortality and the rest of the stock experiences the fishing pressure for the year (Figure 3.17). The greatest increase in relative stock numbers is seen in the south south west coast in period two, when the new

recruits enter the fishery. These smaller individuals bolster the relative stock numbers for all periods in the south south west coast, and in the south east coast in period three. The relative stock numbers in the east coast in period one experience a delayed increase, compared to the south south west coast.

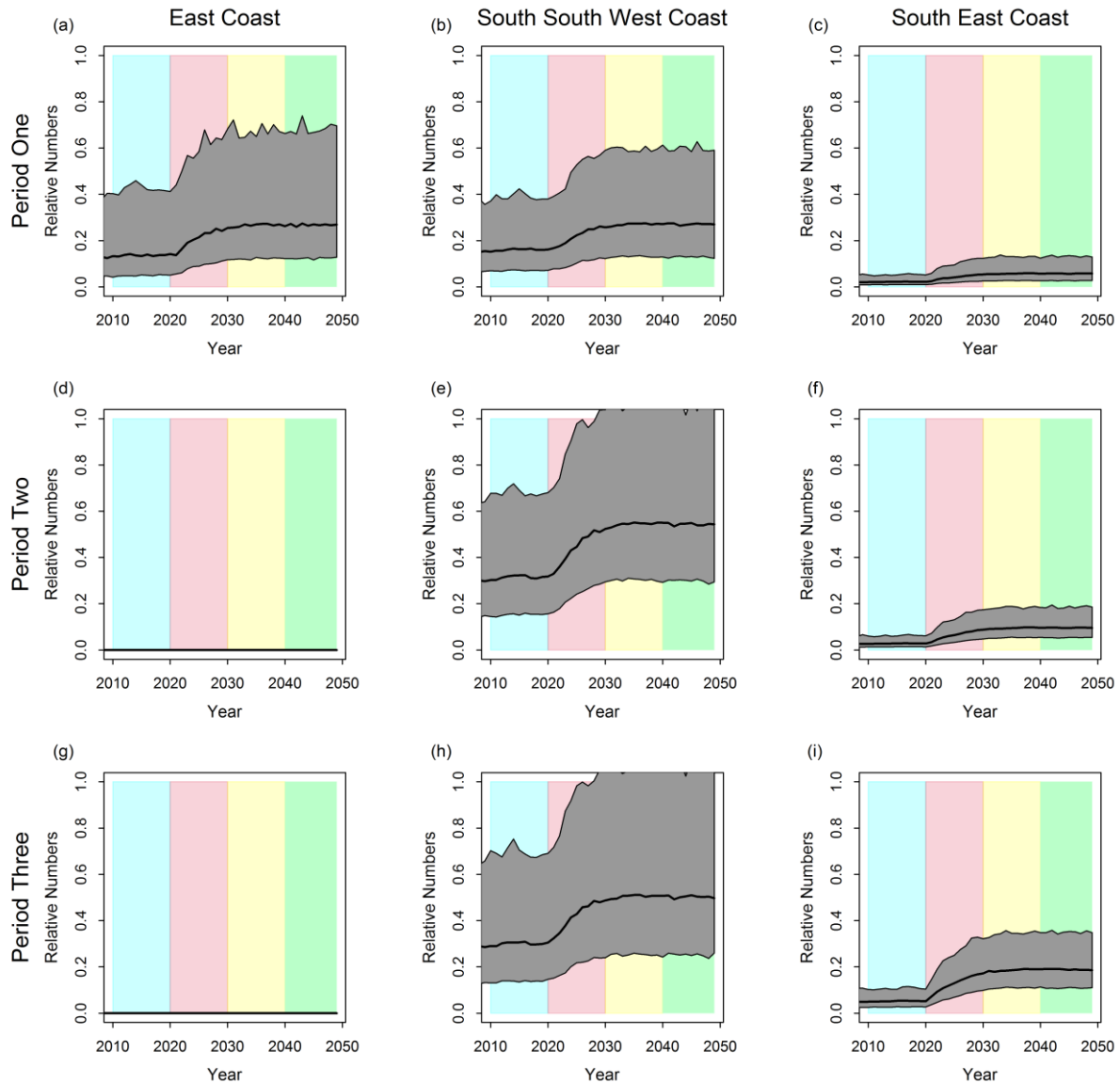


Figure 3.17: Median relative (to pristine) stock numbers trajectories (black lines) of the South African geelbek from 2010 to 2050, with an increase in the minimum size to the size-at-50%-maturity 950 mm TL from 2020 to 2050. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Time periods progress from top to bottom, and are, respectively, period one (August to November), period two (December to March) and period three (April to July). The 95% confidence limits are indicated (grey shaded areas). The NMLS data period from 1987 to 2011 is shaded blue, which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

The biomass across all regions and periods (Figure 3.18) shows the direction of movement of the bulk of the stock more clearly than the numbers did. The biomass in the south east coast in period three is especially large and indicative of the sub-adults and adults making the spawning migration into the east coast in period one. Under this management strategy most fish are protected and can reach their growth potential.

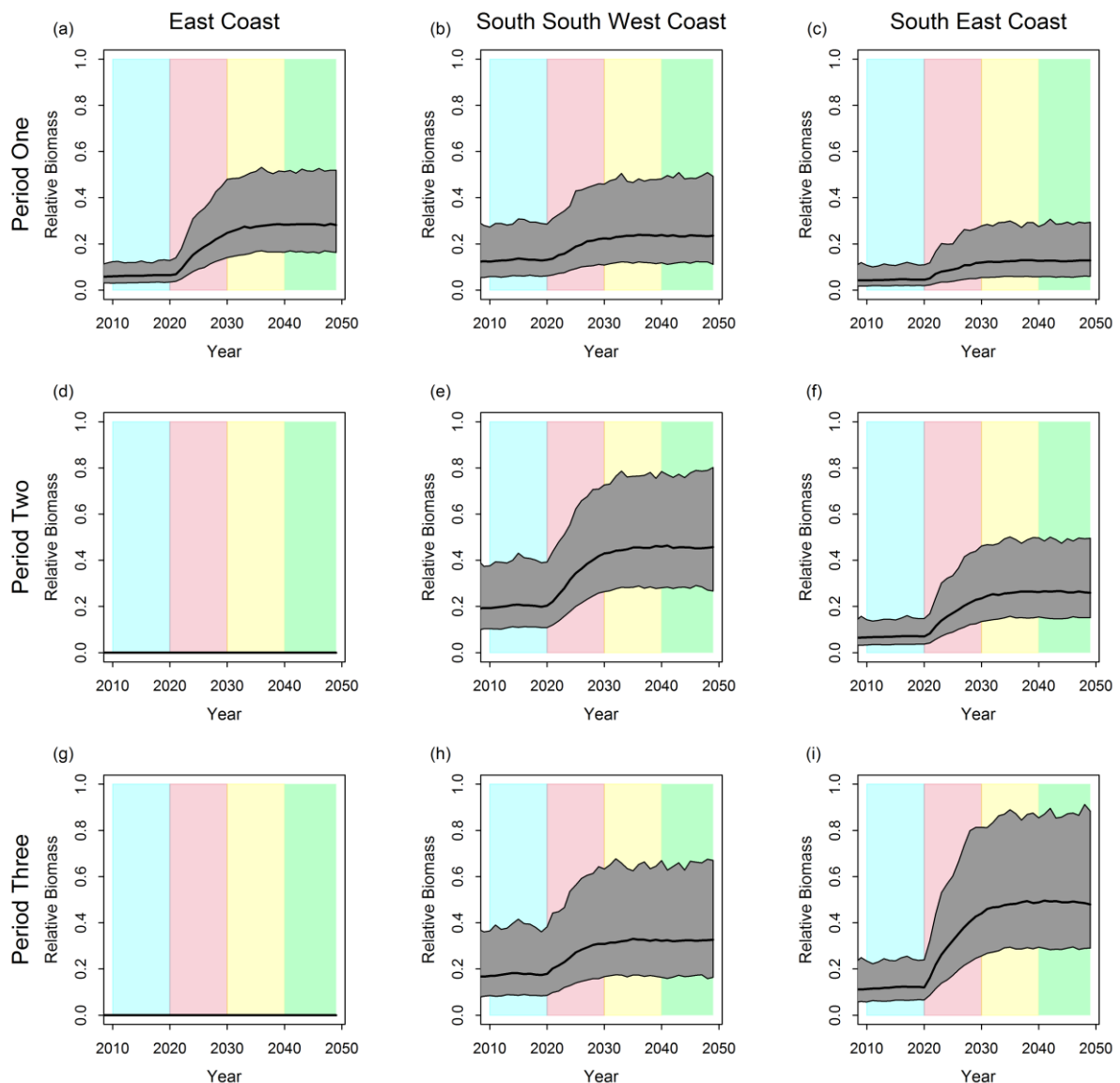


Figure 3.18: Median relative (to pristine) stock biomass trajectories (black lines) of the South African geelbek from 2010 to 2050, with an increase in the minimum size to the size-at-50%-maturity 950 mm TL from 2020 to 2050. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Time periods progress from top to bottom, and are, respectively, period one (August to November), period two (December to March) and period three (April to July). The 95% confidence limits are indicated (grey shaded areas). The NMLS data period from 1987 to 2011 is shaded blue, which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

The exploitable biomass shows the actual impact to the fishery of such a management action, with the drops in exploitable biomass appearing for both increases in size limit throughout the history of the stock (Figure 3.19). This management strategy shows a large increase in the exploitable biomass of the east coast in period one, while the exploitable biomass of the south south west coast is only maintained in period two, and that only after a ten year period of stock rebuilding, dropping to none in periods one and three. The exploitable biomass in the south east coast recovers faster than the south south west, however it still takes seven years to return to previous levels in period two and surpass them in period three.

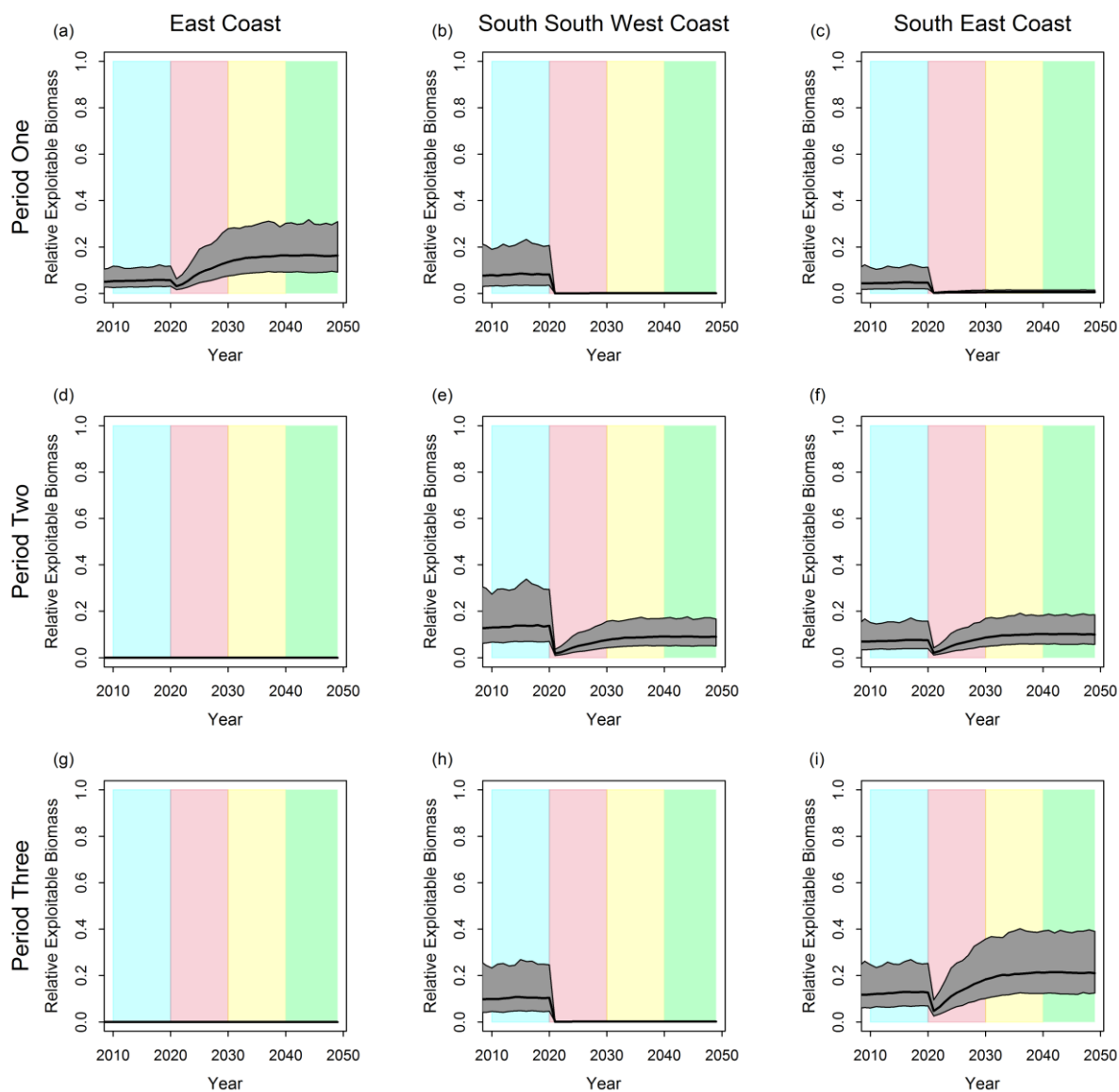


Figure 3.19: Median relative (to pristine) stock exploitable biomass trajectories (black lines) of the South African geelbek from 2010 to 2050, with an increase in the minimum size to the size-at-50%-

maturity 950 mm TL from 2020 to 2050. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Time periods progress from top to bottom, and are, respectively, period one (August to November), period two (December to March) and period three (April to July). The 95% confidence limits are indicated (grey shaded areas). The NMLS data period from 1987 to 2011 is shaded blue, which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

This management strategy works on a trade-off, by preventing growth overfishing by protecting immature fish, however, regions which rely on immature fish are effectively removed from the fishery. The potential catch of regions which usually target immature fish immediately declines to zero (Figure 3.20). The only region to fully benefit from this management strategy is the east coast. The impact on the south east coast could be considered equalised after stabilisation and the south south west coast suffers the most, in both periods one and three (Figure 3.20).

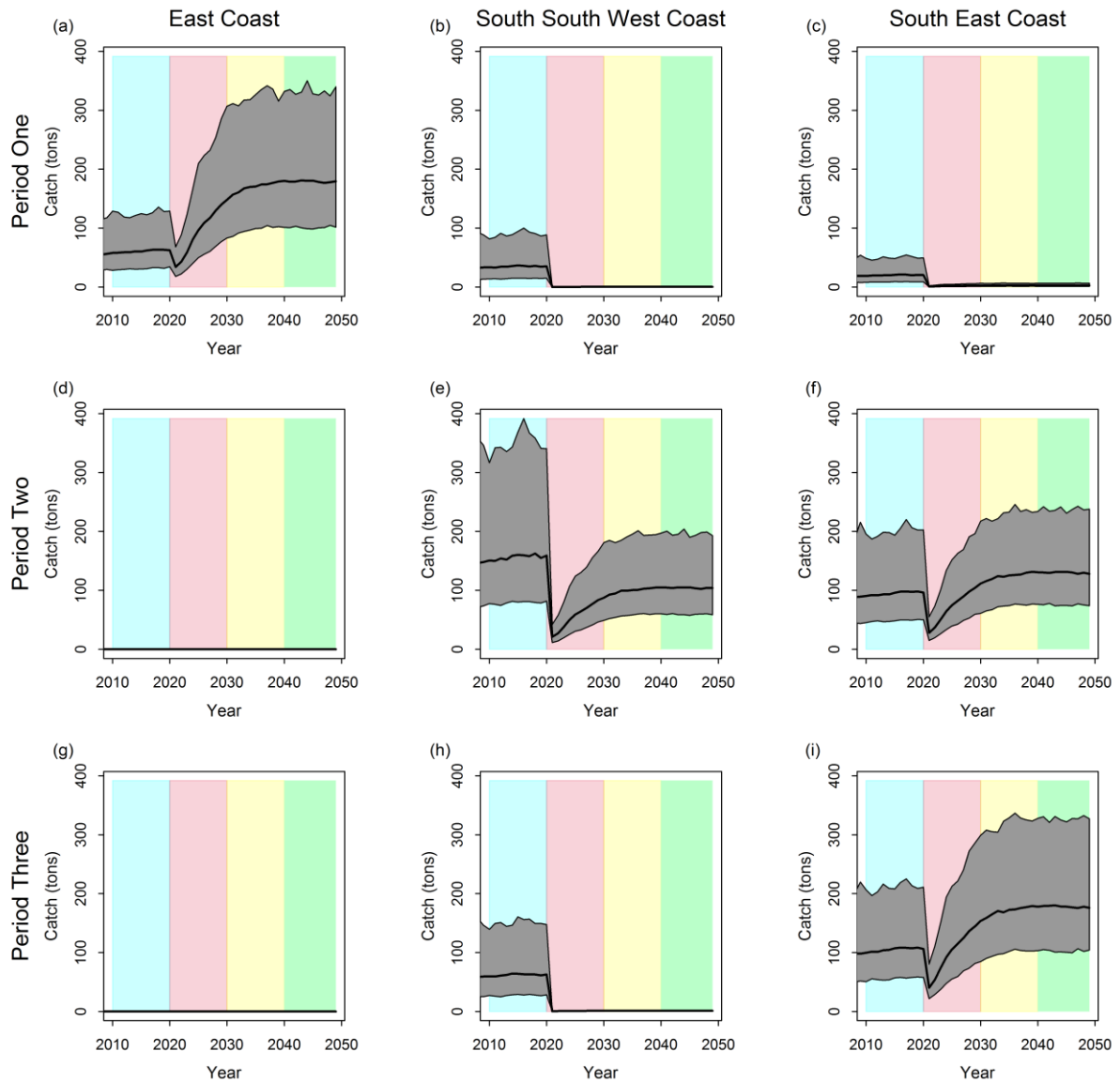


Figure 3.20: Median simulated stock catch trajectories (black lines) of the South African geelbek from 2010 to 2050, with an increase in the minimum size to the size-at-50%-maturity 950 mm TL from 2020 to 2050. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Time periods progress from top to bottom, and are, respectively, period one (August to November), period two (December to March) and period three (April to July). The 95% confidence limits are indicated (grey shaded areas). The NMLS data period from 1987 to 2011 is shaded blue, which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

3.3.3. Comparison of management strategies

All the management strategies are summarised below in Figure 3.21 and Figure 3.22. Figure 3.21 compares the spawner biomass depletion rates between each strategy type, with management strategy one, *status quo* and management strategy two, moratorium, used as comparative baselines across all strategy types. This figure is a composite and extended version of Figure 3.13, Figure 3.14 and Figure 3.15 for comparison. Figure 3.22 indicates their stock recovery rates at the end of each evaluation period, illustrated as a boxplot. These results are also quantitatively described in Table 3.9, which also displays the short term recovery rates, after only a five year period, as well ten and twenty years. All these recovery rates follow from the ASPM estimated stock depletion level of ~6.3% SB_0 .

It appears the only full stock recovery option is a full moratorium on geelbek, which should be implemented for seven years in order to reach a 40% SB_0 threshold, and beyond that to further recover the stock towards a conservative estimate of its pristine state. This conservative estimate approximates at 85% SB_0 due to using the median of the log normal distribution in the recruitment equation which incorporates stochasticity into the model. If the mean were to be used instead of the median, this stock estimate would be closer to 100% SB_0 . The second best recovery option is increasing the minimum size limit to the size-at-50%-maturity for the species, 950 mm TL, however, as seen above, this starkly redistributes the exploitable biomass of the stock, and effectively closes the south south west coast in periods one and three, and in the south east in period one. However, this strategy never recovers the stock above the 40% SB_0 target reference point, and remains at an asymptotic approach. The third highest recovery rate was to decrease the harvest rate by 50%, however, the stock recovery from this management strategy is less effective than half the recovery of a full moratorium and does not recover the stock sufficiently above the 25% SB_0 limit reference point of severe depletion.

Management strategy 1, which was the *status quo* base case is the poorest performing strategy in terms of stock recovery and long term catch potential. However, all other management strategies, excluding the three mentioned above, performed poorly, and were unable to recover the stock to the 25% SB_0 limit reference point. Their recovery rates remained all below 15% SB_0 , even after the long term evaluation period (Appendix C).

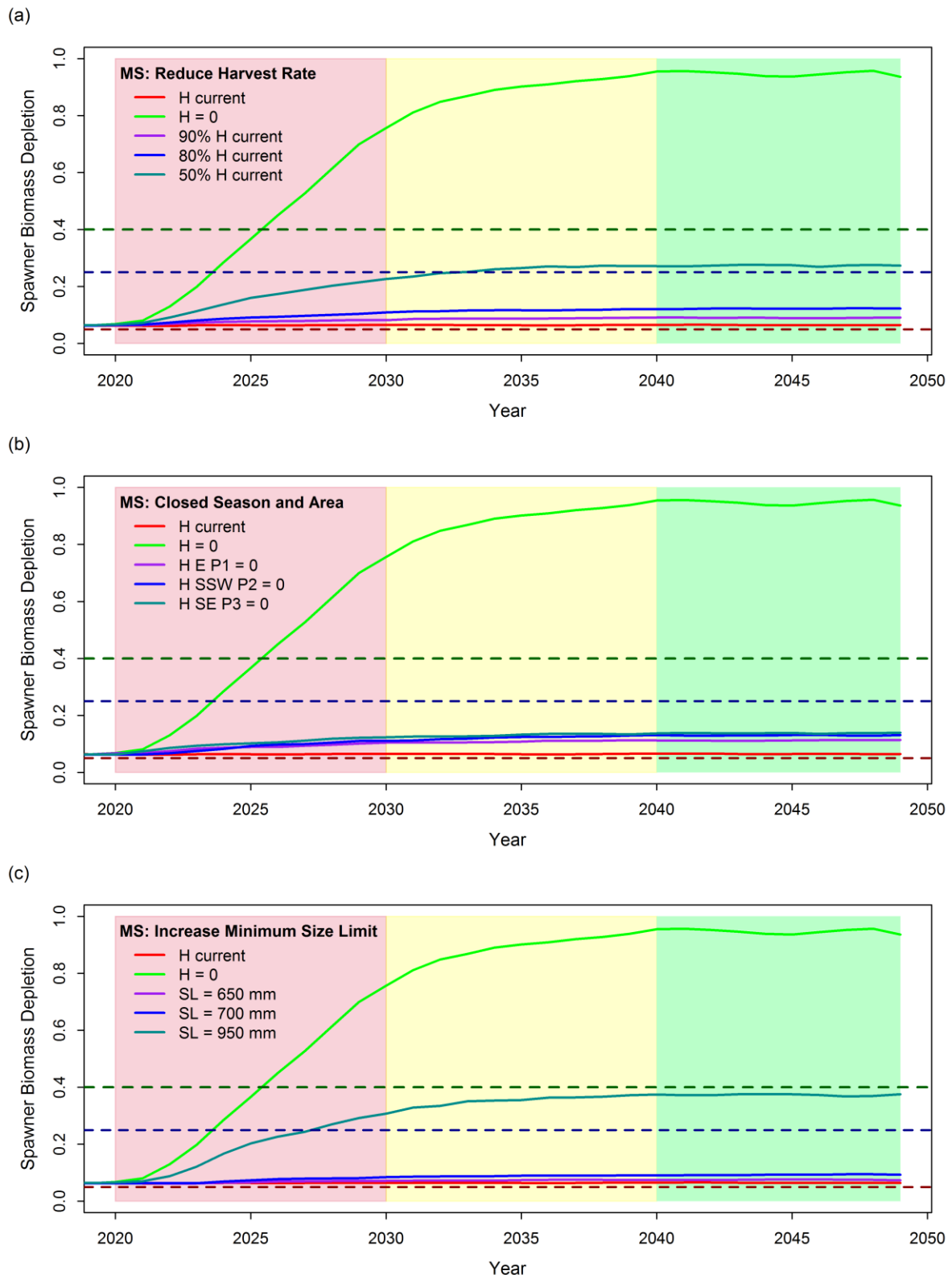


Figure 3.21: Median relative (to pristine) simulated stock spawner biomass depletion trajectories (coloured lines) of the South African geelbek from 2020 to 2050, for all management strategies. Management strategies are divided by strategy type such that (a) illustrates a reduction in harvest rate, (b) illustrates closed seasons and areas and, (c) illustrates an increase in the minimum size limit. The two extreme cases of the *status quo* ($H_{current}$) and the moratorium ($H = 0$), as displayed in all sub-plots for comparison. The medium term evaluation extends from 2020 to 2030 (pink shaded area), the

long term evaluation extends from 2020 to 2040 (yellow shaded area). Fisheries reference points of 40% SB_0 (dashed green line), 25% SB_0 (dashed blue line) and 5% SB_0 (dashed red line) are also included.

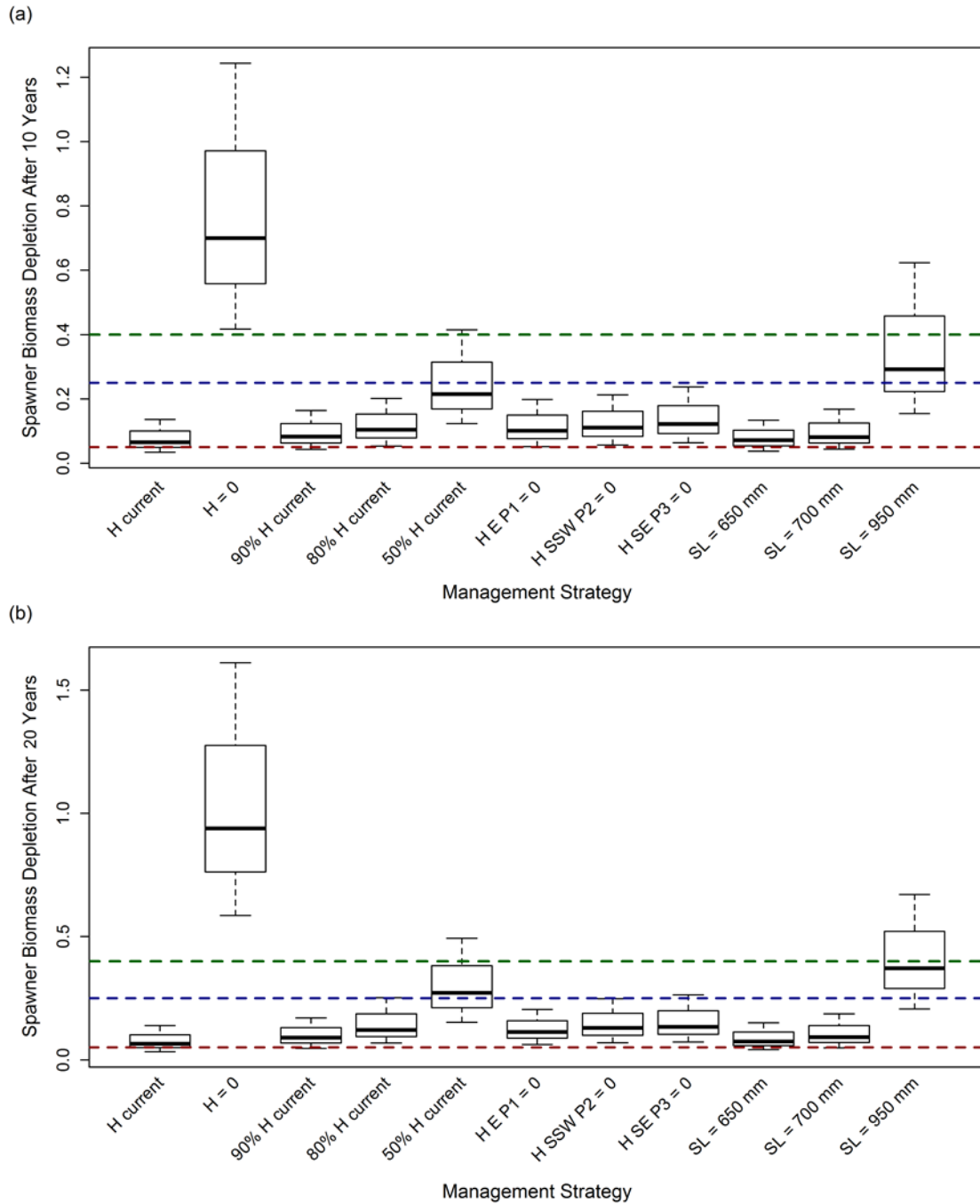


Figure 3.22: Box and whisker plots of spawner biomass depletion as a measure for stock status, after (a) ten years, and (b) twenty years, for all eleven management strategies (see Table 3.8 for individual descriptions). The solid line represents the median, the box encompasses the interquartile range and the whiskers extend to the extreme values. Fisheries reference points of 40% SB_0 (dashed green line), 25% SB_0 (dashed blue line) and 5% SB_0 (dashed red line) are also included.

Table 3.9: Spawner biomass depletion rates (as percentages of pristine state, % SB_0) for simulated South African geelbek stock, as a proxy for stock recovery rate. The recovery rates of the eleven management strategies evaluated are described, in relation to a starting stock state of 6.3% SB_0 (a) after a short term evaluation period of five years, (b) after a medium term evaluation period of ten years, and (c) after a long term evaluation period of twenty years. The median values (% SB_0) of the 10000 simulation runs are presented, along with the lower and upper 95% confidence intervals (CI) for each evaluation period. High median recovery rates ($\geq 25\%$ SB_0) are in bold.

Management Strategy	(a) % SB_0 after Short Term Evaluation (5 years)			(b) % SB_0 after Medium Term Evaluation (10 years)			(c) % SB_0 after Long Term Evaluation (20 years)		
	Median	Lower CI	Upper CI	Median	Lower CI	Upper CI	Median	Lower CI	Upper CI
	1 $H_{CURRENT}$	6.41	3.18	12.99	6.51	3.42	13.59	6.5	3.31
2 $H = 0$	28.52	15.03	54.53	69.98	41.71	124.36	93.83	58.52	161.12
3 $90 H_{CURRENT}$	7.58	3.91	14.66	8.25	4.3	16.39	9.03	4.6	17.04
4 $80 H_{CURRENT}$	8.69	4.67	17.79	10.41	5.36	20.17	12.08	6.82	25.17
5 $50 H_{CURRENT}$	13.76	7.07	25.91	21.49	12.32	41.47	27.15	15.23	49.33
6 $H_{E.P1} = 0$	8.69	4.56	17.43	10.1	5.22	19.84	11.33	6.18	20.46
7 $H_{SSW.P2} = 0$	6.41	3.18	12.99	6.51	3.42	13.59	6.5	3.31	13.87
8 $H_{SE.P3} = 0$	9.89	5.26	19.33	12.16	6.35	23.73	13.39	7.25	26.36
9 $SL = 650 mm$	6.52	3.29	13.54	7.13	3.78	13.42	7.47	4.12	15.02
10 $SL = 700 mm$	6.89	3.59	13.65	8.11	4.41	16.83	9.17	4.84	18.69
11 $SL = 950 mm$	16.74	8.06	35.42	29.23	15.43	62.34	37.17	20.64	67.03

These results show how a quantitative description of the spatially and intra-annually explicit migration of South African geelbek can estimate the harvest rates applied to the stock according to specific regions and time periods. The results also show a critically low current stock status for South African geelbek of 9.94% SB_0 from an equilibrium per-recruit analysis with stock recruitment potential of 0.73 R/R_0 , and an even more conservative stock estimate of 6.3% SB_0 from a dynamic age-structured production model. The age-structured production model can also indicate the likely potential for stock recovery given a range of different management strategies, with a full moratorium on harvesting geelbek appearing to be the only effective recovery option.

4. Discussion

This study has introduced a comprehensive age-structured modelling framework to approximate spatial and seasonal population dynamics of the migratory coastal fish species geelbek (*Atractoscion aequidens*). The model was specifically developed to account for region- and season-specific fisheries' vulnerability of different life history stages and explicitly includes somatic growth, natural mortality, recruitment and size- and age-specific fisheries mortalities. The seasonal migration pattern was broadly adopted from Griffiths and Hecht (1995). Age-dependent migration probabilities and regional selectivities were inferred from available region- and season-specific size composition commercial catch data. To obtain first estimates of the relative spawning biomass depletion and region- and season-specific harvest rates, an Age-Structured Equilibrium Model (ASEM) approach was implemented within a per-recruit stock assessment framework.

The results for the current stock state suggested that the geelbek spawning biomass is approximately 10% SB_0 of pristine levels, which shows improvement compared to the stock depletion estimates of ~5 and 7% SB_0 from prior assessments conducted in the late 80s and 90s (Griffiths *et al.*, 1999; Hutton *et al.*, 2001). The results of this study indicated that there was a ~50 to 100% increase in spawner biomass over the past twenty years (from 1997 to 2017). However, this level of stock depletion is still considered insufficient with respect to the minimal management goal of increasing spawner biomass depletion rates towards 25% SB_0 , the collapsed limit reference level, advised by Griffiths in the Linefish Management Protocol of 1999.

The ASEM was used to condition a region- and season-specific age-structured production model (ASPM) to simulate the geelbek population regime under alternative management strategies. The ASPM was parameterised using the harvest rates and selectivities generated from the ASEM, and was further calibrated with commercial catch data and incorporated past changes in management rules in the history of the stock. The burn-in period prior to management implementation period is therefore also useful to assess population trends. For example, the spawner biomass trajectory of the ASPM went from below 5% SB_0 in 1980s to

7% SB_0 by 2010, which further corroborated previous assessment results by Griffiths *et al.* (1999), Griffiths (2000) and Hutton *et al.* (2001).

Evaluation of eleven management strategies, using stochastic simulations, showed the only management strategies that predicted a recovery rate above the limit reference point of 25% SB_0 were a moratorium, increasing the minimum size limit to the size-at-50%-maturity, 950 mm TL, or a reduction in harvest rate of 50%. Of these strategies the moratorium is considered to be the most efficient strategy for management when aiming towards maximum recovery of the stock, however, it is not considered necessarily feasible within the political and socio-economic background of South Africa. Alternatively, closing the south east coast from April to July, results in a stock recovery of 12.2% and 13.4% SB_0 , after ten and twenty years, respectively. While this does not meet the recovery goal, it is considered the most feasible strategy out of the current options, as it yields the highest stock recovery rate with the seasonal closure options (which are considered feasible).

4.1. Per-recruit analysis

Fishery stock assessments are designed to aid management decisions by providing quantitative analyses of expected stock responses to specified fisheries management strategies (Hilborn and Walters, 1992). Beverton and Holt's (1957) per-recruit model is one of the most widely used models in stock assessments (Jensen, 1996a; Booth and Buxton, 1997; Brouwer and Griffiths, 2006; Govender *et al.*, 2006), in particular when considering that it forms the basis for determining fisheries reference points within a wide range of age-structured assessment frameworks (Punt *et al.* 2013b).

Per-recruit models quantify the relationship between somatic growth and mortality in order to predict the lifetime yield and spawner biomass of a cohort (or stock), under various combinations of fishing mortality (F) and size selective harvesting (Buxton, 1992). The conventional yield- or spawner biomass per-recruit model can be extended to an age-structured equilibrium model (ASEM) by incorporating a spawner-recruit relationship to account for potential recruitment impairment at low stock abundance (Clark, 1997; Hilborn 2010). In general, per-recruit models represent an important tool to assess the desired age-specific level of exploitation of a stock (Buxton, 1992).

Per-recruit analysis is often the method of choice when accurate long-term catch data are not available (Jensen, 1996b; Griffiths, 1997a). The model is parameterised using the following life history parameters: growth function (length-age relationship), length-weight relationship and length- (or age-)at-maturity, and estimates of total, natural and fishing mortality (Butterworth *et al.*, 1989; Punt, 1993). These low data requirements make it an ideal assessment tool in data-limited situations, where, for example, length composition data is the only information available to researchers and managers of small-scale and data-poor fisheries (Hordyk *et al.*, 2014).

However, the per-recruit approach relies on a number of assumptions that are prone to violations. These typically include: (1) that M can be estimated adequately from empirical relationships, (2) that fishing mortality can be externally estimated from catch curve analysis with M assumed to be known (i.e. $F = Z - M$) and constant with age, (3) that recruitment of the stock is constant (or that on average years of good recruitment negate years of poor recruitment), and (4) that the observed length- or age-structure of the stock is in equilibrium. Despite this, per-recruit assessments can compare reasonably well with full age-structured assessments (Booth and Punt, 1998; Winker *et al.* 2013). Similarly, stock depletion estimates for geelbek, as inferred from previous per-recruit analysis (Griffiths, 1997a), historical catch rate comparison (Griffiths, 2000) and ad-hoc VPA (Hutton *et al.* 2001), were surprisingly coherent with the results from this study.

Extending assessment models to account for spatial structuring and migration can often be key to obtain reliable stock status estimates (Goethel *et al.* 2011), especially when fisheries impacts differ strongly among regions (Ying *et al.*, 2011) and life history stages (Booth, 2000). Despite this, spatial structuring within (or between) stocks are seldom incorporated into stock assessments (Goethel *et al.* 2011). This study added an additional intra-annual temporal component to incorporate the spatial patterns of the stock, as a pre-requisite for uncoupling the differential impacts of alternative management strategies for rebuilding the South African geelbek stock.

4.1.1. Region- and season-specific migration

Monthly proportions of commercial catch data across the whole of the geelbek stock's range were used here to infer regional and intra-annual migration. Length frequency data were then used in a least squares regression to generate length- (which converted to age-) structured selectivity ogives (Hutton *et al.* 2001). These were then transformed into equations describing the age-structured, spatially and temporally explicit proxies for migration (using probabilities). The explicit incorporating of migration into a per-recruit analysis is novel and may be useful in the stock assessment of other migratory species. This method differs to others, for example the multistock dispersion of South African sardine (*Sardinops sagax*), the primary prey species of geelbek, by de Moor *et al.* (2017), which allowed for mixing between two stocks, but not intra-annually.

4.1.2. Region- and season-specific harvest rates

Catch curve analysis allows for the estimation of total mortality Z , and therefore, fishing mortality F , after several years of exposure to a specific exploitation level (Griffiths 1997b). The results of this analysis can then be used as input in the per-recruit analysis to infer the current stock status. However, due to the age-dependent migration dynamics of geelbek, it was important to conduct separate catch curve analyses for each region and period. The assumptions and choices made in the development of these values were later validated when the raw commercial catch data aligned very closely to the predicted catches from the dynamic age-structured production model, which was parameterised with these harvest rates.

4.1.3. Stock assessment of South African geelbek stock

This study estimated stock state at 10% SB_0 of pristine levels, compared to the prior assessment stock depletion estimates of ~5 and 7% SB_0 from Griffiths (1999) and Hutton *et al.* (2001). These previous assessments of geelbek differed from this study in several ways. Hutton *et al.* (2001) used a VPA to determine stock depletion, and they only considered two regions, namely the Cape and Kwa-Zulu Natal. However, their perspective of regional separation was that they shared the resource, and rather investigated the impact of cooperative versus non-cooperative management. This did not take into account the intra-annual migration between regions, nor did it consider the age-structured division of the stock and its migration. Hutton *et al.* (2001) claimed that increases in the minimum size limit, to

700 or 800 mm TL, while necessary to recover the stock, are unlikely to be complied to. Griffiths (1999) treated the stock as a single unit and performed a basic per-recruit analysis. By contrast, Griffiths (1997b) disaggregated a per-recruit analysis for dusky kob, also a sciaenid, like geelbek, to accommodate the differences in inshore and offshore fishing pressure. The difference between those studies and this one is the incorporation of age-structured region- and season-specific migration.

Booth (2000) highlights the importance of incorporating the spatial patterns of the fishers when conducting a stock assessment. To account for difference in size structure and fishing mortality, Brouwer and Griffiths (2006) conducted region-specific per-recruit analyses of carpenter (*Argyrozona argyrozona*), by treating each assessment as a separate stock. However, the geelbek stock is a single stock with an intra-annual age-structured migration, which precluded a similar approach for this study. The updated assessment of geelbek herein allows these factors to be reflected in the differential harvest rates and age-dependent selectivities (and exploitable biomass) for each region and period. The migration results in large changes in the exploitable biomass between each region and season, and this is critical in understanding the dynamics of the fishery.

A feature of this study is that, using length data, the two models (equilibrium per-recruit and dynamic age-structured production) reflected similar results for stock status (9.9% SB_0 and 6.3% SB_0 , respectively). Here it is noted that while the age-structured production model used the harvest rates derived from the per-recruit model for the final output, the production model was initially run using harvest rates estimated purely from the commercial catch data and a similar depletion result was obtained.

4.2. Towards management strategy evaluation

Management of natural resources requires understanding of population dynamics, supported by data, within the scope of feasible management procedures (Winker *et al.*, 2016b). Management procedures should begin by defining clear management targets, ideally quantitative, and extend to decision-making, stakeholder engagement and strategy implementation (Punt *et al.*, 2014). The interactive and dynamic nature of these processes has associated uncertainties, which may be used to undermine and legally waylay management

strategy implementation by stakeholders with alternative objectives. Therefore, management strategy recommendations now need to incorporate stakeholder engagement (Smith *et al.*, 1999) into quantitative resource assessments (Butterworth *et al.*, 2010a; Punt *et al.*, 2014).

Ideally, such resource assessments would be grounded in accurate, long-term data, allowing the production of robust quantitative analyses (Punt *et al.*, 2014). These analyses should then produce advice on harvesting regimes to achieve the targets considered for optimal resource use. However, many countries are restricted by lack of technical expertise and the expense involved in consistent data collection (Butterworth *et al.*, 2010b; Punt *et al.*, 2014).

A potentially suitable framework to help overcome these challenges is known as Management Strategy Evaluation (MSE; Smith *et al.* 1999) or Operating Management Procedures (OMP; Butterworth and Punt, 1999). MSE uses simulation testing to evaluate the risk of alternative management strategies to the population and stakeholder interests (Smith *et al.* 1999; Punt *et al.* 2014). The core of MSE is to develop the most plausible population simulation model, referred to as an operating model (OM) based on the best biological and ecological data, which simulates population metrics, such as numbers (at-age). The OM then compares the population trajectory under alternative management strategies against multiple predetermined management targets. MSE is a powerful tool to provide decision support in determining the most suitable management strategy, and is widely considered best practice in fisheries management (Punt *et al.* 2014). As a first step, this study focused on four components of MSE: (1) Developing a minimal realistic operating model (OM) to simulate the population dynamics of the stock, (2) conditioning the model based on the best available data, (3) formulating alternative fisheries management strategies and (4) assessing each management strategy against established fisheries reference points (of 25% and 40% SB_0).

Specifically, this study presents a simulation tool, coded in R, to assess the response of the geelbek stock to alternative management strategies. This simulation tool was applied in the production of forecasting of stochastic population trajectories for eleven different management strategies. Long-term trends of stock recovery and region- and season-specific population and catch metrics can be produced for any evaluation period. Feasible strategies, with sufficient recovery trends, may be presented as management recommendations. The simulation tool was designed to provide a simple to understand interface (Appendix D), which allows the stock assessment of geelbek to be updated easily, through updating the

commercial catch data file which is used to generate the catch curve analysis. It also allows detailed changes without requiring understanding of the entire operating model, such as altering the input parameters of the age-structured production model (ASPM) and adding new management strategies if desired. An example of an input parameter which may easily be changed using the simulation interface is the steepness parameter of the Beverton Holt stock recruitment relationship h . A value of $h = 0.85$ was initially chosen to match similar species, such as dusky kob (*Argyrosomus japonicus*) in their recent stock assessment (Winker *et al.*, 2016a). However, for knife-edge recruitment, a value of $h = 0.999$ (~ 1) may be applied.

The data period chosen to derive the selectivity ogive parameters can also be altered, reflecting either a short or long term perspective with regard to the dynamics of the stock. The benefit of this is it accounts for the possibility of changes within the fishery that may be reflected in the commercial catch data. Examples of such changes are the Linefish Emergency of 2000 with a 70% reduction in TAE for the linefishery as a whole, yet the geelbek catches did not decline proportionally (reasons explained in Introduction). This has applicability for the current changes in the linefishery, whereby some commercial fishers have shifted into the small-scale sector (Branch *et al.*, 2002), with the current implementation of the small-scale fisheries policy (DAFF, 2015). This sector-based redistribution results in apparent declines in commercial catch, which is an artefact of a division of catch records (LSWG by communication, 2017).

4.2.1. Identifying management strategy options for the South African geelbek stock

Fisheries may be managed according to biological, socio-economic or political objectives. Whereas the biological objective may be the sustainable long-term viability of the stock (Griffiths, 1997a), the socio-economic objective will seek to maximise catches in the short term (Hutton *et al.*, 2001), and the political objective may seek greater exploitation of natural resources (Branch and Clark, 2006). The feasibility of management interventions typically depends on the specific fishery, species' population dynamics and legislation, and may be strongly influenced by the political environment. These management interventions form a management 'toolbox' which contains; total allowable catch (TAC), total allowable effort (TAE, based on harvest or catch), size limits (minimum, maximum and slot limits), area

limits, closed seasons and closed times (for example, night fishing prohibited). Each of these possible interventions has associated benefits and limitations, dependent on the situation.

Maunder *et al.* (2006) emphasise the need to test the rigour and robustness of the management strategies used for evaluation. Therefore, potential management strategies had to meet the following requirements: possible quantitative implementation within the operating model, logical in regards to potential recovery of the stock given the complex population dynamics and life history of geelbek, and feasible within the realm of management application or comparison.

For the multispecies linefishery in South Africa, which is managed using a TAE system, the direction of species-directed effort cannot be controlled among the ‘basket of species’ contained in the linefishery. Based on current protocol, the regional TAE (numbers of boats and crew) is determined based on the status of eight primary commercial target stocks. However, if several stocks are fished sustainably while a few remain collapsed decision-makers can evaluate the options of either impacting the entire fishery by reducing the national TAE in order to promote rebuilding of the species of concern or implementing alternative management strategies. Severe reduction of the overall TAE by, nominally, 70%, took place during Linefish Emergency of 2000.

The geelbek stock remains collapsed as a result of ongoing growth and recruitment overfishing. The per-recruit analysis indicated the impact of this dual pressure, which, at its current intensity, is likely to prevent stock rebuilding. According to the South African linefish management protocol (LMP), the management objective should be to increase the stock to a sustainable level, with sufficient buffer in spawning biomass, or to sustainably harvest the stock at a desired level (without the need for a potentially more stringent recovery period).

The success of the eleven management strategies to restore the stock to threshold (25% SB_0) and sustainable (40% SB_0) levels was evaluated over the medium (ten years) and long term (twenty years).

4.2.1.1. Reduction in harvest rate

For this type of management strategies, the rates of stock recovery were projected for any overall reduction in harvest rate, which was assumed to a proxy for total allowable effort (TAE). This strategy was considered challenging, with respect to management implementation, due to the multispecies nature of the TAE controlled linefishery. The only method to influence the direct effort expended on a single species in the linefishery is to instate a moratorium, effectively removing this species from the linefishery's available 'basket-of-species.' Decreasing the harvest rate by 50% recovered the stock to far less than half of the moratorium's trajectory (a quarter), showing the non-linear impact in the reduction of harvest rates, and providing evidence that current harvest rates are too high when even halving them only recovers the stock to the collapsed reference point, and no further, in 15 years. A moratorium is not considered feasible under the current socio-economic and political landscape of South Africa.

4.2.1.2. Closed seasons and/or areas

Closed areas, such as marine protected areas (MPAs), can be a successful management strategy for long-lived, resident species when strategically placed to ensure a maximum level of protection. They may have different access regulations and/or harvesting controls, depending on the season and target species (i.e. partial closure). Kerwath *et al.* (2013) showed that MPAs can bolster fish resources through spill over. Here, the combination of mixed seasons and areas were considered appropriate given the migratory nature of geelbek, as opposed to permanent area closures, such as MPAs. Each region had a corresponding season which had the greatest catches of geelbek. These are, the east coast in period one, the south south west coast in period two and the south east coast in period three.

Griffiths and Hecht (1995) suggested the catches off KwaZulu-Natal, along the east coast, to be one of the key pressures on the stock, given that the spawning aggregations in this area are well known and specifically targeted. Consequently, this spawning fishery was deemed to cause high mortalities of large mature fish in the stock, thereby directly diminishing the overall egg production potential. Fishing practices such as these are considered to be a threat to the sustainability of the Australian stock of the tropical sciaenid species, the blackspotted croaker (*Protonibea diacanthus*), comparable to geelbek, whose stock level is also depleted (Semmens *et al.* 2010).

Somewhat surprisingly, the evaluation of management strategy six showed that a closed season and area along the east coast during spawning season (period one, from August to November) is not sufficient to recover the geelbek stock, with the spawner biomass only rebuilding to 11.3% SB_0 after twenty years. The primary reason suspected for this slow recovery may be partially attributed to the ‘tragedy of the commons’ phenomenon (Hardin, 1968). If the harvesting pressure is released on the east coast, and the stock begins to increase, greater catches will be extracted in the other regions and periods under constant harvest rate, so that net gain in rebuilding fairly low. Past actions by the fisheries management bodies, such as moratoria on other linefish species and the Linefish Emergency of 2000, highlight severe management intervention to deal with this issue. The ‘tragedy of the commons’ is potentially greater for geelbek, since it is one of the more high value commercial species, along with species such as red steenbras and seventy-four, which provide economic incentive to fishers (Hutton *et al.*, 2001). Additionally, it is prized in recreational sport-fishing.

A concern regarding this system is the impact of concentrated fishing effort on predictable fish aggregations (Sadovy and Domeier, 2005; Erisman *et al.* 2011). Although catches in this region are predicted to increase under a constant harvest rate, the concern is that with predictable fish aggregations, a noted increase in stock will encourage new fishers to enter the fishery. An increase in harvest rate in this region and season could have severe impacts on the stock and catch potential in other regions as a result of recruitment overfishing. Additionally, shoaling species are at greater risk from fishers than more dispersed species, as less effort is required to locate more fish to catch (Maggs *et al.*, 2016).

When considering the catch rates for geelbek, disaggregated by region, growth overfishing may be considered the most serious issue for the species, as the catch rates have historically (prior to 2006) been highest in the south south west coast, the area inhabited mostly by juveniles. However, a closure of this region in period two (management strategy 7), when regional catches are at their highest, showed the lowest stock recovery of all strategy types, on par with the *status quo*. As above, it is hypothesized that this strategy fails to protect the juveniles during the other periods, and only protects half of the adult stock, those that are in the south south west coast in period two. The other half of the adult stock is in the south east coast and thus not protected by this management strategy. This regional distribution of catch

was based on the recent (since 2006) increase in catch in the south east coast in period two and simultaneous decline in catch in the south south west coast. The OM reflects this recent shift in its region- and period-specific harvest rates.

Additionally, this strategy is not considered feasible within the socio-economic landscape of South Africa, as it effectively prevents fishers in the south south west coast from catching the large, adult geelbek, which are mainly available between February and April (within period two). It may even prompt fishers to make up this loss of opportunity by increasing their harvesting of juvenile geelbek during the open seasons (Attwood and Bennett, 1990).

A closed season for the south east coast in period three (management strategy 8), yielded the highest recovery rate, 13.4% SB_0 after twenty years, compared with the closed season and area management strategy type. While it does not reach the stock recovery target of 25% SB_0 , the collapsed limit reference point, it is the fourth most successful management strategy (of the eleven total strategies). It is also the second most successful strategy when comparing recovery rates only between those feasible for implementation (closed season and area and minimum size limit strategy types).

This relatively high recovery rate (within the management strategy type) is due to the protection of all the adults in the stock, as well as all the sub-adults. The greatest proportion of the stock is accumulated in this region and period, and it is logical that this strategy provides the greatest recovery rate through the greatest proportion of protection.

A possible reason why the closed season and area management strategies had relatively low recovery rates was that they were implemented with the assumption that they would solve the primary bottlenecks of the stock in regards to growth and recruitment overfishing. However, as discussed above, the closed seasons and areas are likely to simply shift the fishing pressure to other, open regions and periods.

Additionally, closed seasons and areas are liable to create issues in the political landscape of South Africa, as only some fishers would be disadvantaged while others would benefit. Closed seasons and areas would exclude fishers based on location and seasonality. It is expected there would be an increase in illegal, unreported and unregulated (IUU) fishing in

defiance of this management strategy, which would require monitoring and increased law enforcement, the capacity for which is currently lacking.

4.2.1.3. Minimum size limits

Minimum size limits are a core tool in fisheries management, especially for fisheries, such as the commercial South African linefishery, that operate under effort (and not catch) controls (TAE). They are one of the few management strategies that are species specific within multispecies fisheries, and have been used extensively to prevent growth overfishing (Allen *et al.*, 2013). Ideally, the length at first capture for most species should be greater than the size-at-50%-maturity (Froese, *et al.*, 2008; Froese, *et al.*, 2016), but there are situations where species benefit more from the implementation of slot limits, which can protect against both growth and recruitment overfishing (Gwinn *et al.* 2015). A potential issue with this management strategy is compliance, which requires monitoring and law enforcement. The issue of poor compliance was described in Maggs *et al.* (2016) in regards to their study of garrick (*Lichia amia*), which, like geelbek, is a popular recreational target species. Another important aspect is considering the effects of barotrauma on post-release survival (Coggins *et al.* 2007). Kerwath *et al.* (2013) investigated these impacts, and found internal and external signs of barotrauma occurring in the majority of studied species, which led to significant post-release mortality. Barotrauma was most frequent (99% of cases) for the linefish species silver kob (*Argyrosomus inodorus*), a sciaenid similar to geelbek (Kerwath *et al.* 2013). It was recommended that this mortality be factored into stock assessments and subsequent management strategies to account for this unseen mortality (Kerwath *et al.* 2013).

The Linefish Management Protocol recommended increases in the minimum sizes for the primary linefish species, such as silver kob (Griffiths, 1997c) and dusky kob (Griffiths, 1997b). Minimum size limits are often set at the size-at-50%-maturity (Griffiths *et al.* 1997). For geelbek, the simulated increase in the minimum size limit to size-at-50%-maturity of 950 mm TL, resulted in the second highest recovery rate of all evaluated management strategies. However, as a result of the delayed maturity of geelbek the implementation of this strategy would exclude a large portion of the stock from the fishers on the south south west coast throughout most of the year, and the south east coast (to a lesser extent), due to the age-structured migratory life history of geelbek. By contrast, increasing the minimum size limit to

650 or 700 mm TL did not produce the expected recovery rate for the stock, with the stock remaining below 13% SB_0 after twenty years for both strategies.

The complexities surrounding the management of a migratory stock such as geelbek become evident when considering the unequal regional impacts of a size limit increase, whereby the one region paying the cost in reduced fishing is often not necessarily going to benefit in the long-term, while other regions or fishing sectors will. The simulation results suggest that any minimum size limit below the size-50%-maturity still leaves the stock open to growth overfishing (Griffiths *et al.*, 1997; Allen *et al.*, 2013; Maggs *et al.*, 2016). Any size limit increase is likely to be unpopular among fishers. The generally poor recovery rates predicted for intermitted size limit increase of 650 – 750 mm TL, suggest that such a ‘compromise’ is least suitable, and should not be implemented in the current management of the South African geelbek stock.

The above situation is not unique to South African geelbek, which can be best illustrated using the Californian example of the white seabass (*Atractoscion nobilis*), a Pacific sciaenid, which also aggregates to spawn and had been severely depleted as result of multiple fisheries impacts. The stock’s spawning aggregations used to be targeted by commercial and recreational fishers (similar to geelbek) until successful management strategies were implemented (Aalbers and Sepulveda, 2012). These strategies included an initial ban of coastal gillnets around the California coastline (Allen *et al.*, 2007), then a bag limit of one fish, <710 mm TL (average size-at-50%-maturity across sexes), per fisher per day was implemented, and a ban on commercial fishing for a portion of the spawning season. The recovery of this species, from ~5% SB_0 to 18% SB_0 from 1970 to 2008 indicates the power of severe management interventions which combine management strategies to address stock vulnerabilities. Unfortunately, a recent decline in simulated spawner biomass was seen from 2008 to 8% SB_0 in 2014, in the stock assessment performed by Valero and Waterhouse (2016). The cause for this decline is currently unclear.

4.3. Management recommendations

The South African geelbek stock is currently estimated at 10% of the pristine spawner biomass (SB_0). While there was stock recovery present in the past twenty years, the stock is

still considered severely depleted, and in need of a species specific management strategy to increase the recovery rate of the stock. After investigation into various types and intensities of management strategies, very few are able to provide a predicted recovery rate above the limit reference point of 25% SB_0 . Management strategies also need to be considered in regards to their impact to fishers and the potential for an unequal distribution of cost and benefit.

The only strategy to potentially recover the stock above 40% SB_0 was a full moratorium for five to ten years, in line with the goal of rebuilding the stock to a sustainable level. However, it is accepted that such a strategy will be challenging to implement within the political and socio-economic background of South Africa. Despite this, it is deemed the most successful management intervention and therefore a full cessation of the harvesting of geelbek (moratorium) is recommended, for a minimum of five years, to a suggested ten years, to recover the stock to above the sustainable target reference point of 40% SB_0 .

Additionally, since a moratorium would apply equally across all regions, periods and linefishing sectors, it is also considered, at least, equitable in its exclusion, and profitable, for all, in the long term. The disadvantages are shared equally by all those who target geelbek, however, fishers who specifically target geelbek will be at a greater disadvantage to those that target other species or have more of a mixed catch. These specialists are considered to be the source of the heavy pressure on the geelbek stock, even after the Linefish Emergency of 2000.

The complexity of the management of geelbek across the coast is considered as support for the moratorium strategy because it is conceptually the easiest to monitor (whereby anyone who landed geelbek would be fined). However, reassessment will be required after the moratorium, which is impossible without updated size data, which is obtained from commercial catches. It is therefore suggested that the fishery be opened for a short period, of one to two years, with a precautionary approach, to allow collection of this data. The precautionary approach would include a conservative increase of the minimum size limit to the size-at-50%-maturity level, to prevent re-crashing the stock (Myers and Mertz, 1998). Post-moratorium ASPM simulations were run using current harvest rates, for conceptual consideration only, and the stock trajectory declined as sharply as it had recovered under this strategy (within 5 years). An additional recommendation, based on the multi-pronged strategy

used for white seabass in California, includes closing the east coast spawning fishery from August to November (period one) and excluding recreational fishing (or decreasing the bag limit to one fish per fisher per day), until after the reassessment. The simulation tool provided by this study can then determine the extent of stock recovery, as well as re-evaluating potential management strategies, including combinations of strategies (possible within the simulation tool), towards ensuring a viable, long term, sustainable fishery.

After the moratorium, it is recommended that the harvesting pressure remain light (this operating model can aid in determining quantitative harvesting and reference levels) on this species (for any strategy type). This is key, as it is very difficult for even a simple management strategy to be applied to a migratory stock, such as geelbek, in which different components are harvested in different regions and periods, with certainty of the future stock trajectory. The initial moratorium management strategy would result in higher catch-per-unit-effort (CPUE) for all components of the geelbek fishery. Therefore, a management strategy that would maintain the stock at a precautionary and sustainable level, above 40% SB_0 , should be considered. The precise management strategy to reduce the long term harvest rate on geelbek, post-moratorium, is not prescribed or discussed in this study. It is acknowledged this is a difficult task due to the multispecies, multi-area and multisector nature of the linefishery and its effort control system.

4.4. Future research directions

While this study is considered to provide a rigorous and innovative stock assessment of geelbek, there are still additional steps that can be taken which are currently considered to be beyond the scope of this study. The following are suggested as advisable avenues of future research.

Accurate up-to-date re-assessment of the geelbek stock requires size data to determine the region- and season-specific harvest rates. The re-instating of a national observer programme to collect regional size data throughout the year is therefore the first recommendation for future work.

If a moratorium is implemented for geelbek, management evaluation testing should be conducted to ensure that the management strategy implemented after the moratorium maintains both the stock at sustainable levels and provides a sufficient catch for fishers. A new range of management strategies should be put forward at this time, although these may overlap with the ones already evaluated in this study. In order to ensure accurate stock predictions, new catch and harvest rates would have to be decided on and calculated into the age-structured production model. The subsequent management strategy would have to provide sufficient catch, in a manner that aimed for equality in catch opportunity across regions and seasons, while also maintaining the stock at a sustainable, preferably precautionary, level.

The rigor of the model may also be improved through sensitivity testing of all variable input parameters, such as the stock recruitment steepness parameter h . Punt and Cope (2017) outlined a three parameter stock-recruitment relationship, as a method to decrease the uncertainty around the stock-recruitment parameters, which should be considered. Other input parameters that are advised to be tested or critically evaluated are the pristine spawner biomass (specifically for the dynamic model) and the pre-spawning-catch ratio (which incorporates harvesting of adults before they are able to spawn). The current design of the operating model and management tool allows such changes to be fairly easily tested, as they can be altered immediately from the simulation tool interface (which runs the operating model).

It is important to remember the recreational and small-scale linefishing sectors which also contribute to the overall fishing pressure on the geelbek stock. Therefore, after validating the input parameters of the model, it is suggested that a proxy or additional harvesting consideration, be implemented to account for the impact of the recreational and small-scale sectors. However, this is acknowledged to be difficult as the impact of these sectors is so uncertain, hence their exclusion from this study. It is therefore advised that efforts are made to quantify these impacts, although no suggestions on how to do so are discussed herein.

Once the other linefishing sectors have been incorporated into the operating model, other management strategies specific to those sectors may be evaluated. An example of this would be a management strategy specific to the recreational sector, by, for example, decreasing the bag limit from two fish per fisher per day to one. This would instantly halve the recreational

impact on the stock. The impact of illegal, unreported and unregulated (IUU) fishing should also be incorporated into a factor within the model.

Once the model has been re-finalised with the above suggestions, it is suggested that the calculation of region- and season-specific reference points be prioritised. These should be formulated in such a way that the various management strategies may also be tested and reference points are able to be derived for each strategy.

Lastly, it is suggested that possible environmental impacts on stock recruitment be investigated, especially with predicted climate change related issues, such as a strengthening and warming of the Agulhas Current.

4.5. Conclusion

Taking migration probabilities into account within a per-recruit type model can be considered an innovative approach to quantify the stock status for fishes with complex life histories. Based on this concept it was possible to develop a full spatial-temporal age-structured modelling framework with only basic life history parameters, length frequency data and catch data. Quantitative descriptions of these estimated dynamics are possible and can be incorporated into both age-structured equilibrium per-recruit and dynamic production models. These can further be used to evaluate the response of a stock to a range of management strategies within management frameworks, such as MSE. The methods developed and employed in this study will therefore likely have applications and implications on the management of other data limited/poor migratory species. The approach of using the size selectivity curves (length selectivity ogives) as proxies for migration probabilities should be applicable to other migratory species. The relative ease of quantifying migration patterns also makes this method attractive to fisheries scientists who may be less comfortable with more complex models.

Additionally, the method used herein for determining the regional and intra-annual harvest rates might also prove useful in stock assessments of fisheries which would benefit from such disaggregation, as recommended for striped bass (*Morone saxatilis*) by Secor (1999). This approach to spatial and temporal division according to the catch history is aligned with the

recommendations made by Cope and Punt (2011) who stress the necessity for understanding the spatial structure of the stock and thus aligning management actions accordingly.

A key conclusion of this study is that geelbek stock remains in a collapsed state. A potential recovery of geelbek, through feasible management interventions, is aided by the results of this study and the availability of the accompanying management simulation tool. A strength of this study is that, using length data, the two models (equilibrium per-recruit and dynamic age-structured production) reflected similar results for stock status (9.9% SB_0 and 6.3% SB_0 , respectively).

Additional recovery potential of this stock may come from other directions. The World Wide Fund (WWF) - South Africa's Southern African Sustainable Seafood Initiative (SASSI) considered the results of this study, and moved geelbek from the orange list to the red list (January 2017). SASSI guides consumer choice of marine products, as well as being linked to large-scale suppliers, vendors and outlets, such as restaurants. There is a hope that this system will help reduce the demand for geelbek, and therefore change the species targeting of fishers (to more green listed species).

Lastly, as pointed out by Griffiths (1997b), successful management of the South African geelbek stock requires a holistic approach that considers all phases of their life history. This study has embraced that approach, with the hope that the stock may recover and become a viable living marine resource for South Africa once again.

5. References

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6. Appendices

6.1. Appendix A: Map of geelbek migration by Griffiths and Hecht (1995)

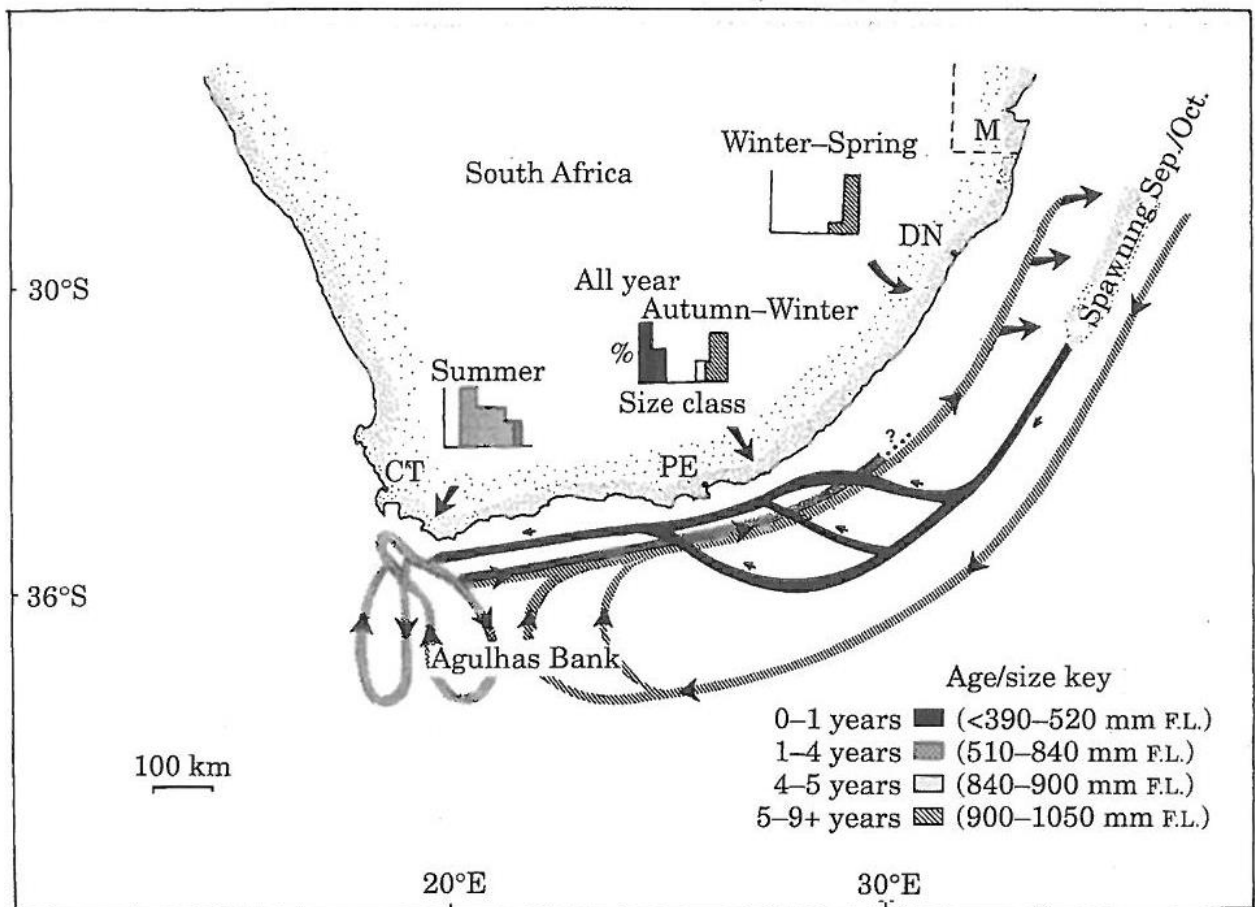


Figure A.1: The theoretical migratory life-history cycle of the three age-related sub-populations of *Atractoscion aegidens* along the South African eastern seaboard. For clarity of the presentation the seaward limits of the migrations are not to scale, and the spawning area is correctly sited only in the longshore direction. M, Mozambique; DN, Durban; PE, Port Elizabeth; CT, Cape Town. Extracted from Griffiths and Hecht (1995).

6.2. Appendix B: Dynamic age-structured production model equations

Equations describing the dynamic age-structured production model. These reflect the same region- and season-specific structure as the equilibrium per-recruit model described in the Methods and materials chapter, with the added dynamic year y term. Descriptions of the parameters used (with the exception of the year y term) are found in the Methods and material chapter. The model was initialised using a per-recruit approach for $y = 1$, which assumed a starting point at pristine spawner biomass, with no harvesting in the first two periods of the first year. Thereafter, harvesting is incorporated into the model.

6.2.1. Initialisation of dynamic age-structured production model

6.2.1.1. Period one

$$N_{0,y=1,p=1,r=E,a} = \begin{cases} R_0 & \text{if } a = 0 \\ N_{0,p=1,r=E,a-1} e^{-M} & \text{if } 0 < a_{\max} \\ \frac{N_{0,p=1,r=E,a-1} e^{-M}}{1 - e^{-M}} & \text{if } a = a_{\max} \end{cases}$$

$$N_{y=1,p=1,r,a} = \begin{cases} N_{0,p=1,r=E,a} \phi_{p=1,r=E,a} & \text{for } r = E \\ N_{0,p=1,r=E,a} \phi_{p=1,r=SSW,a} & \text{for } r = SSW \\ N_{0,p=1,r=E,a} \phi_{p=1,r=SE,a} & \text{for } r = SE \end{cases}$$

6.2.1.1.1. Spawner biomass per-recruit for the initial stock (excludes harvesting)

$$SBR_{y=1} = \sum_{a_{\min}}^{a_{\max}} N_{y=1,p=1,r=E,a} W_{p=1,a} m_a$$

6.2.1.1.2. Initial unfished equilibrium recruitment

$$N_{y=1,p=1,r=E,a=0} = SB_{y=1} / \alpha + \beta * SB_{y=1}$$

6.2.1.2. Period two

$$N_{y=1,p=2,r,a=0} = \begin{cases} 0 & \text{for } r = E \\ N_{y,p=1,r=E,a} \phi_{p=2,r=SSW,a} e^{(-M/3)} & \text{for } r = SSW \\ N_{y,p=1,r=E,a} \phi_{p=2,r=SE,a} e^{(-M/3)} & \text{for } r = SE \end{cases}$$

$$N_{y=1,p=2,r,0 < a \leq a_{\max}} = \begin{cases} 0 & \text{for } r = E \\ (N_{y,p=1,r=E,a} \phi_{p=2,r=SSW,a} (1 - s_{p=1,a} H_{p=1,r=E}) + \dots N_{y,p=1,r=SSW,a} (1 - s_{p=1,a} H_{p=1,r=SSW})) e^{(-M/3)} & \text{for } r = SSW \\ (N_{y,p=1,r=E,a} \phi_{p=2,r=SE,a} (1 - s_{p=1,a} H_{p=1,r=E}) + \dots N_{y,p=1,r=SE,a} (1 - s_{p=1,a} H_{p=1,r=SE})) e^{(-M/3)} & \text{for } r = SE \end{cases}$$

6.2.1.3. Period three

$$N_{y=1,p=3,r,0 < a \leq a_{\max}} = \begin{cases} 0 & \text{for } r = E \\ (N_{y,p=2,r=SSW,a} (1 - \phi_{p=3,r=SE,a}) (1 - s_{p=2,a} H_{p=2,r=SSW})) e^{(-M/6)} & \text{for } r = SSW \\ (N_{y,p=2,r=SSW,a} \phi_{p=3,r=SE,a} (1 - s_{p=2,a} H_{p=2,r=SSW}) + \dots N_{y,p=2,r=SE,a} (1 - s_{p=2,a} H_{p=2,r=SE})) e^{(-M/6)} & \text{for } r = SE \end{cases}$$

6.2.2. Dynamic age-structured production model

6.2.2.1. Period one

$$SBR_y = \sum_{a_{\min}}^{a_{\max}} N_{y,p=1,r=E,a} W_{p=1,a} m_a (1 - s_{p=1,a} H_{p=1,r=E} \gamma)$$

where γ is the symbol denoting the pre-spawning catch proportion. This value was estimated to be 0.6 (pre.SBC in the simulation tool).

$$N_{y,p=1,r,a=0} = \begin{cases} SB_y / (\alpha + \beta * SB_y) \varepsilon_{\text{Recruitment},y} & \text{for } r = E \\ 0 & \text{for } r = SSW \\ 0 & \text{for } r = SE \end{cases}$$

Stochasticity was included in the ASPM through yearly recruitment error $\varepsilon_{\text{Recruitment},y}$ that was assumed to be lognormal, with a chosen lognormal standard deviation of 0.6 in the simulation tool (RecSigma).

$$N_{y,p=1,r,0 < a \leq a_{\max}} = \begin{cases} N_{y-1,p=3,r=SE,a-1} \phi_{p=1,r=E,a-1} (1 - s_{p=3,a-1} H_{p=3,r=SE}) e^{(-M/3)} & \text{for } r = E \\ N_{y-1,p=3,r=SSW,a-1} (1 - \phi_{p=1,r=SE,a-1}) (1 - s_{p=3,a} H_{p=3,r=SSW}) e^{(-M/3)} & \text{for } r = SSW \\ (N_{y-1,p=3,r=SSW,a-1} \phi_{p=1,r=SE,a-1} (1 - s_{p=3,a} H_{p=3,r=SSW}) + & \text{for } r = SE \\ \dots\dots\dots N_{y-1,p=3,r=SE,a-1} (1 - \phi_{p=1,r=E,a-1}) (1 - s_{p=3,a} H_{p=3,r=SE}) e^{(-M/3)} & \end{cases}$$

6.2.2.2. Period two

$$N_{y,p=2,r,a=0} = \begin{cases} 0 & \text{for } r = E \\ N_{y,p=1,r=E,a} \phi_{p=2,r=SSW,a} e^{(-M/3)} & \text{for } r = SSW \\ N_{y,p=1,r=E,a} \phi_{p=2,r=SE,a} e^{(-M/3)} & \text{for } r = SE \end{cases}$$

$$N_{y,p=2,r,0 < a \leq a_{\max}} = \begin{cases} 0 & \text{for } r = E \\ (N_{y,p=1,r=E,a} \phi_{p=2,r=SSW,a} (1 - s_{p=1,a} H_{p=1,r=E}) + & \text{for } r = SSW \\ \dots\dots\dots N_{y,p=1,r=SSW,a} (1 - s_{p=1,a} H_{p=1,r=SSW})) e^{(-M/3)} & \\ (N_{y,p=1,r=E,a} \phi_{p=2,r=SE,a} (1 - s_{p=1,a} H_{p=1,r=E}) + & \text{for } r = SE \\ \dots\dots\dots N_{y,p=1,r=SE,a} (1 - s_{p=1,a} H_{p=1,r=SE})) e^{(-M/3)} & \end{cases}$$

6.2.2.3. Period three

Note there are no age zero fish anymore, as they've grown since being spawned in period one, and recruited in period two.

$$N_{y,p=3,r,0 < a \leq a_{\max}} = \begin{cases} 0 & \text{for } r = E \\ N_{y,p=2,r=SSW,a} (1 - \phi_{p=3,r=SE,a}) (1 - s_{p=2,a} H_{p=2,r=SSW}) e^{(-M/3)} & \text{for } r = SSW \\ (N_{y,p=2,r=SSW,a} \phi_{p=3,r=SE,a} (1 - s_{p=2,a} H_{p=2,r=SSW}) + & \text{for } r = SE \\ \dots \dots N_{y,p=2,r=SE,a} (1 - s_{p=2,a} H_{p=2,r=SE})) e^{(-M/3)} & \end{cases}$$

6.2.3. Fishery metrics of biomass, exploitable biomass and catch (general forms)

6.2.3.1. Biomass (B)

$$B_{y,p,r,a} = N_{y,p,r,a} W_{0.5,p,a} e^{(-M/6)}$$

$$B_{y,p,r} = \sum_{a_{\min}}^{a_{\max}} B_{y,p,r,a}$$

6.2.3.2. Exploitable biomass (EB)

$$EB_{y,p,r,a} = N_{y,p,r,a} W_{0.5,p,a} s_{p,a} e^{(-M/6)}$$

$$EB_{y,p,r} = \sum_{a_{\min}}^{a_{\max}} EB_{y,p,r,a}$$

6.2.3.3. Catch (C)

$$C_{y,p,r,a} = N_{y,p,r,a} W_{0.5,p,a} s_{p,a} H_{p,r} e^{(-M/6)}$$

$$C_{y,p,r} = \sum_{a_{\min}}^{a_{\max}} C_{y,p,r,a}$$

6.2.3.4. Length-length-relationship

The relationship between the total length (TL) and the fork length (FL) was described in Griffiths and Hecht (1995). All life history parameters and equations use fork length. The exceptions are the suggested minimum size limits, which are then converted using the equation below into fork length. All length measurements in the model, are in millimetres.

$$TL = 1.06FL - 0.757$$

Griffiths and Hecht (1995)

6.3. Appendix C: Additional management strategy evaluation results

Additional management strategies outlined below, these include all strategies mentioned in Table 3.8, excluding strategies 1 and 11, which are included in the Results chapter.

6.3.1. Management strategy 2: Moratorium

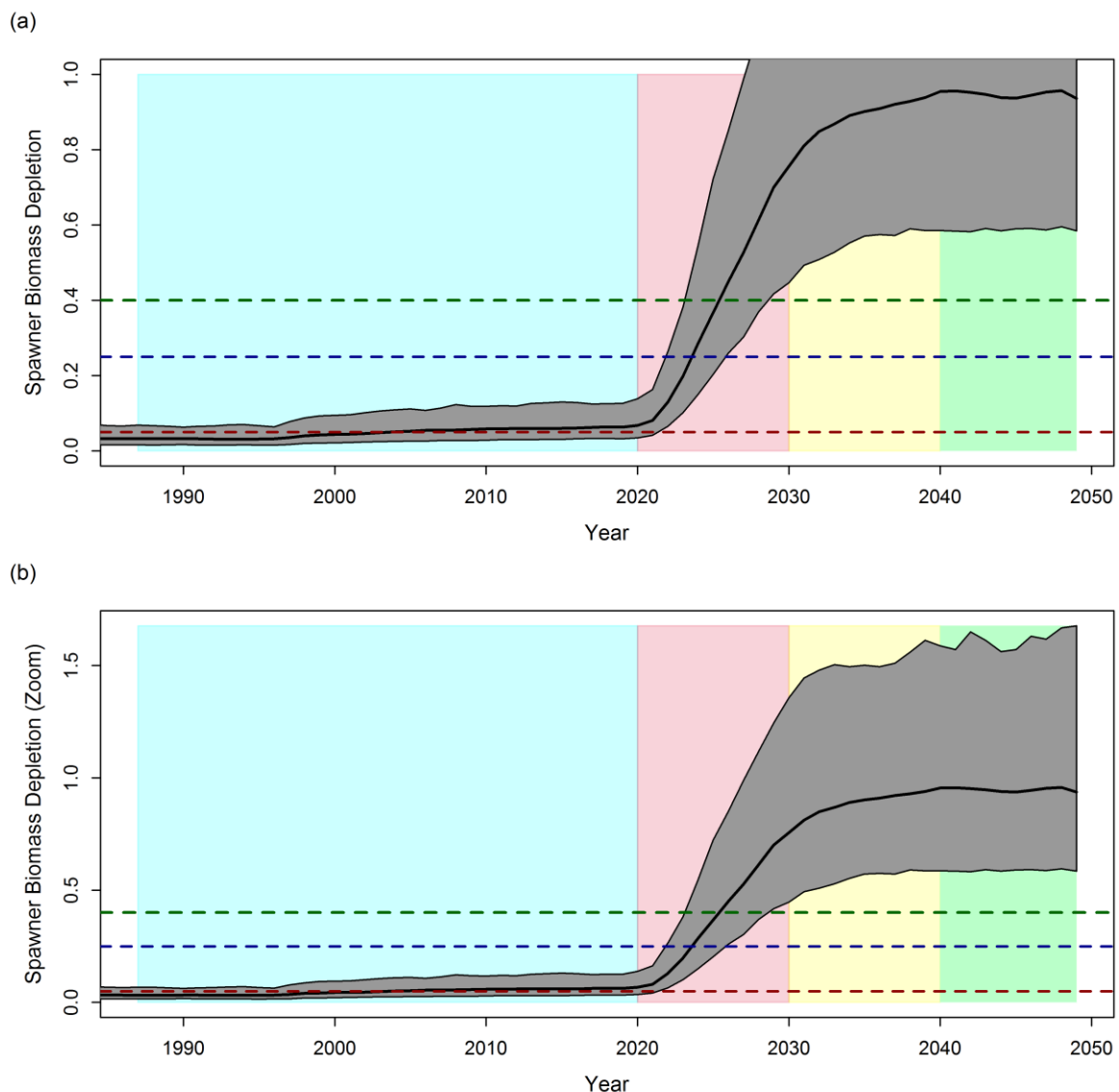


Figure C.1: Median relative (to pristine) simulated stock spawner biomass depletion trajectory (black line) of the South African geelbek from 1987 to 2050, with the implementation of a national moratorium on harvesting geelbek from 2020 onwards. The depletion level is displayed relative to (a) the pristine population state and (b) the current estimated population level of ~5% pristine state. The 95% confidence limits are indicated (grey shaded areas). The NMLS data period from 1987 to 2011 is shaded blue, which extends as the pre-evaluation period until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink

shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area). Fisheries reference points of 40% SB_0 (dashed green line), 25% SB_0 (dashed blue line) and 5% SB_0 (dashed red line) are also included.

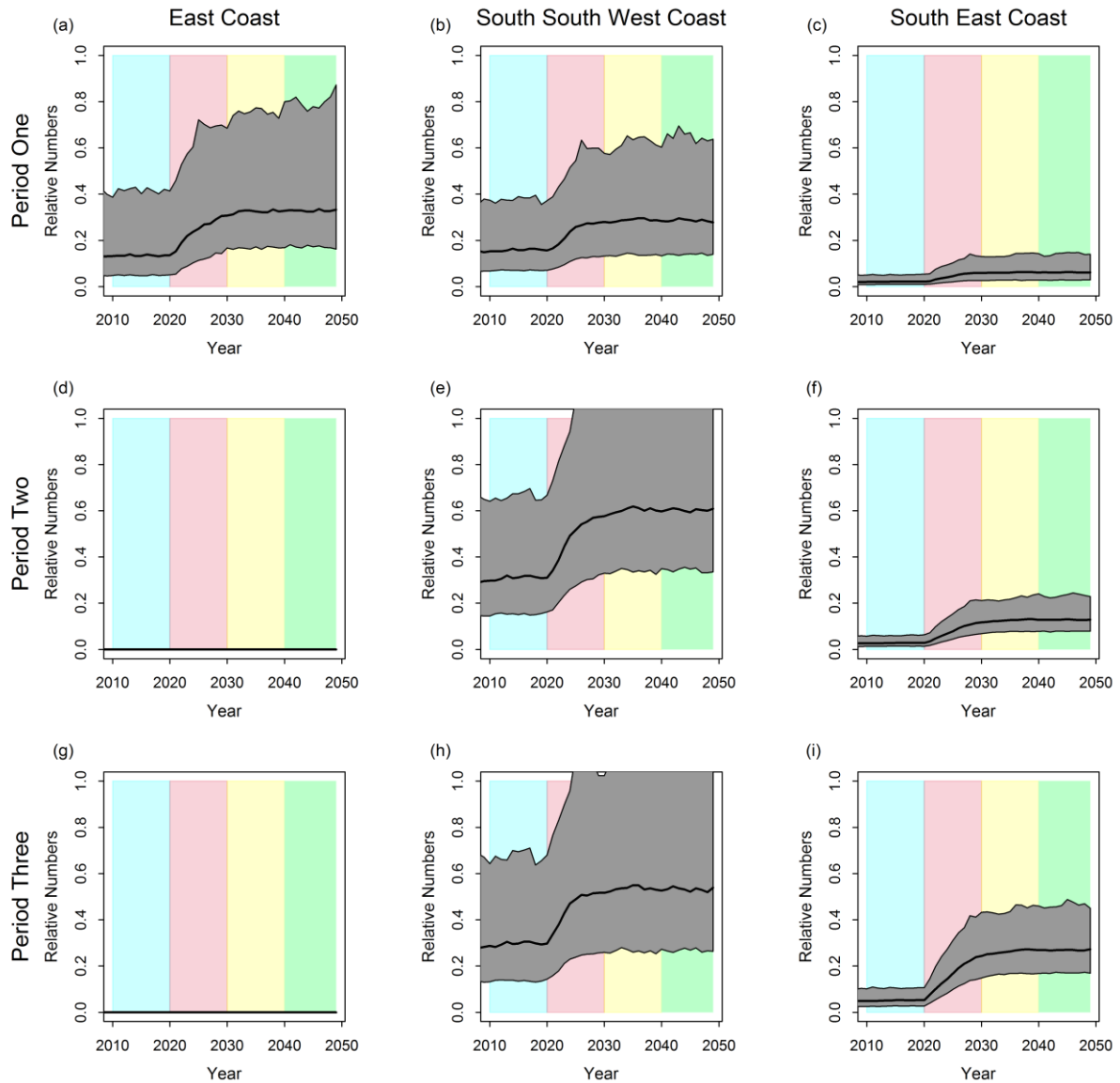


Figure C.2: Median relative (to pristine) stock numbers trajectories (black lines) of the South African geelbek from 2010 to 2050, with the implementation of a national moratorium on harvesting geelbek from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

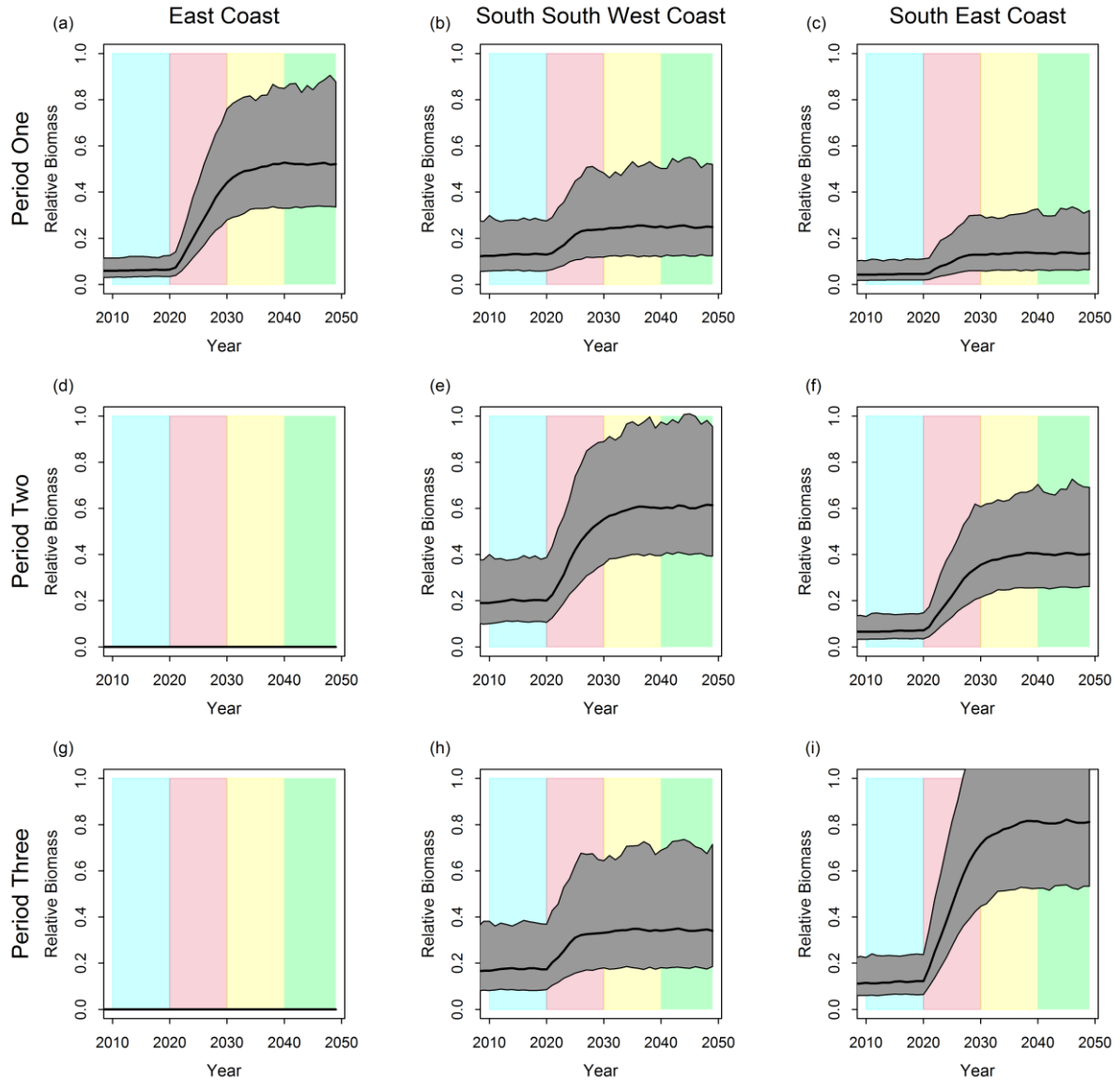


Figure C.3: Median relative (to pristine) stock biomass trajectories (black lines) of the South African geelbek from 2010 to 2050, with the implementation of a national moratorium on harvesting geelbek from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

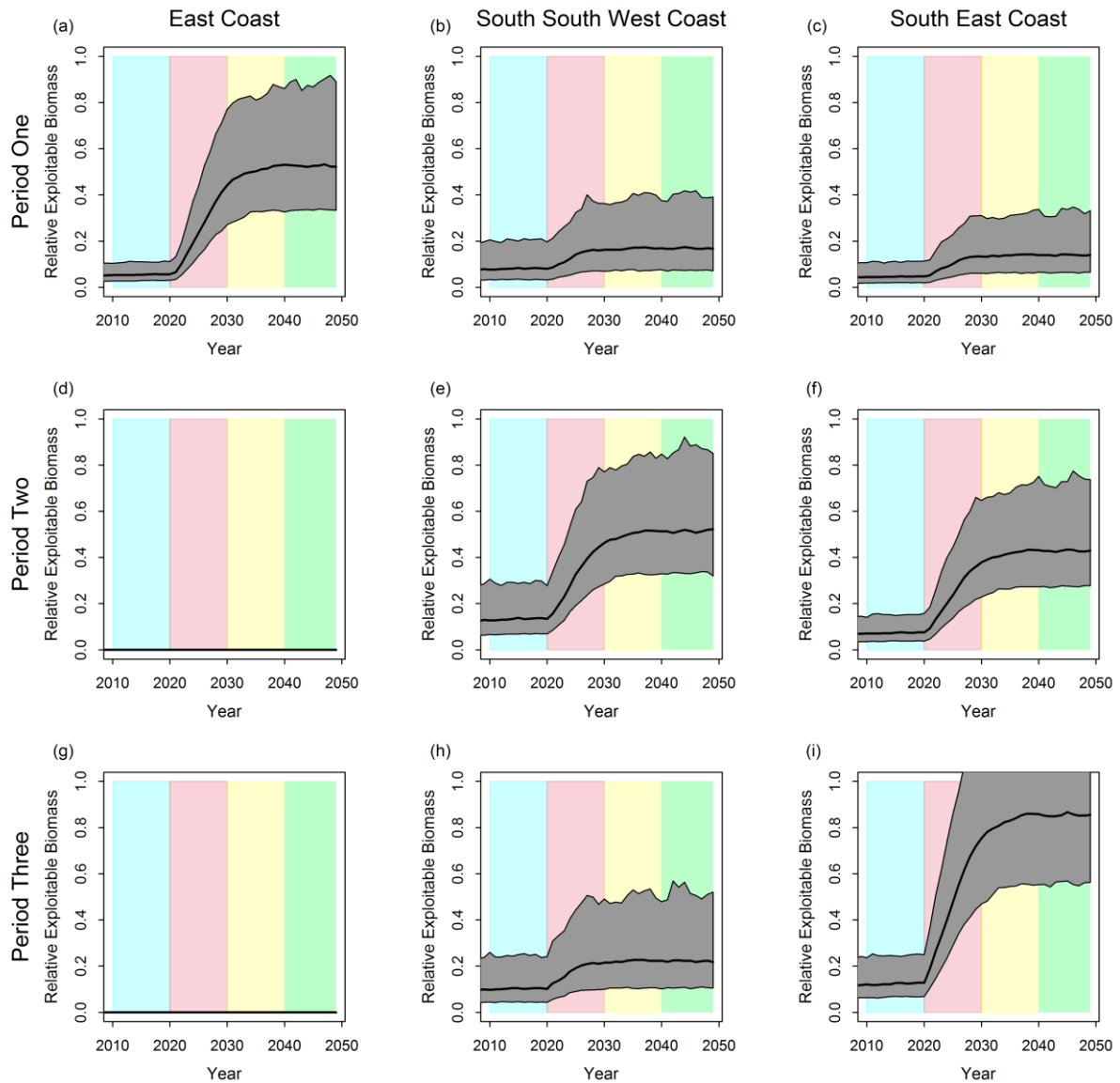


Figure C.4: Median relative (to pristine) stock exploitable biomass trajectories (black lines) of the South African geelbek from 2010 to 2050, with the implementation of a national moratorium on harvesting geelbek from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

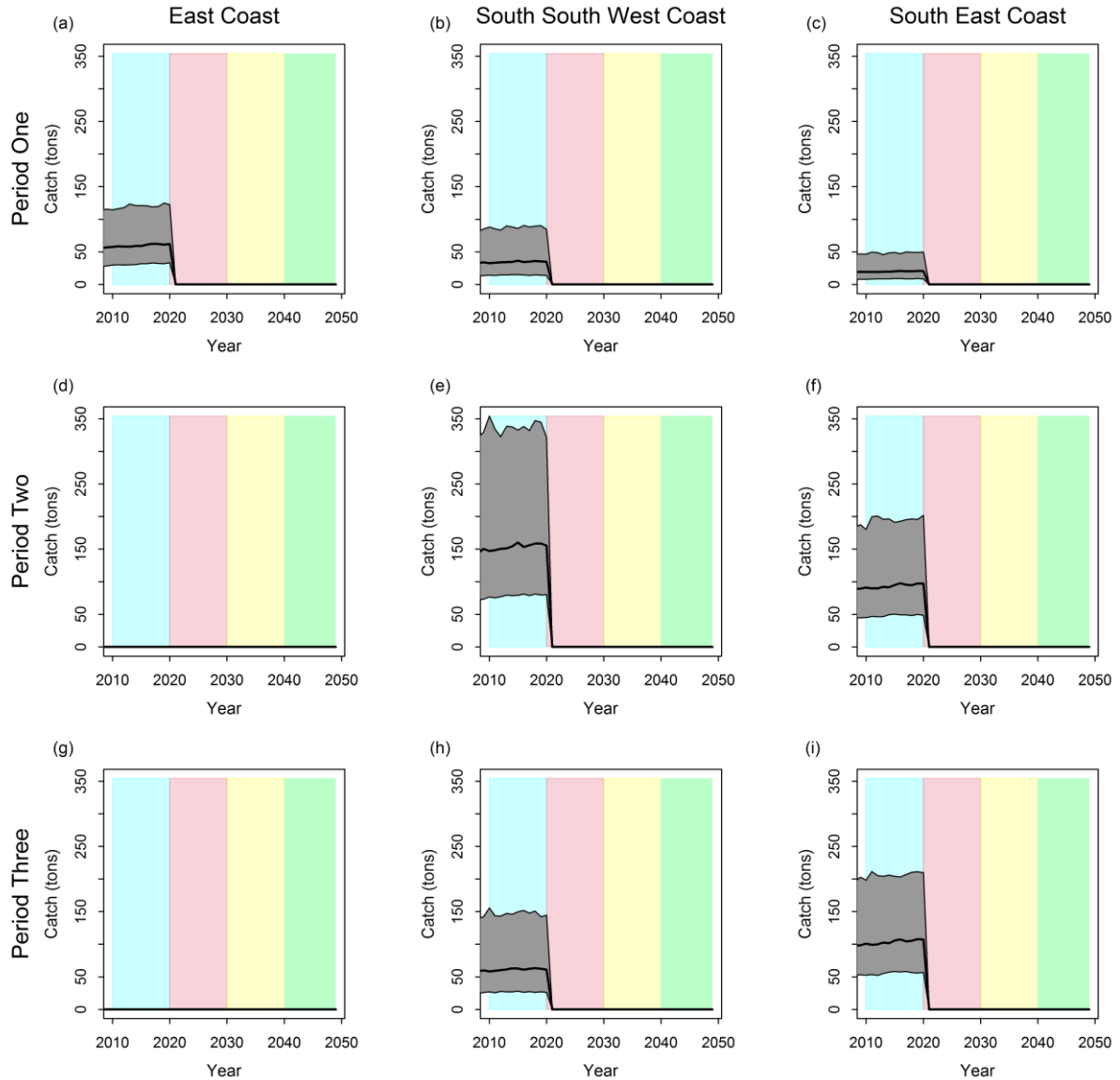


Figure C.5: Median simulated stock catch trajectories (black lines) of the South African geelbek from 2010 to 2050, with the implementation of a national moratorium on harvesting geelbek from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

6.3.2. Management strategy 3: Reduce H by 10% across all regions and periods

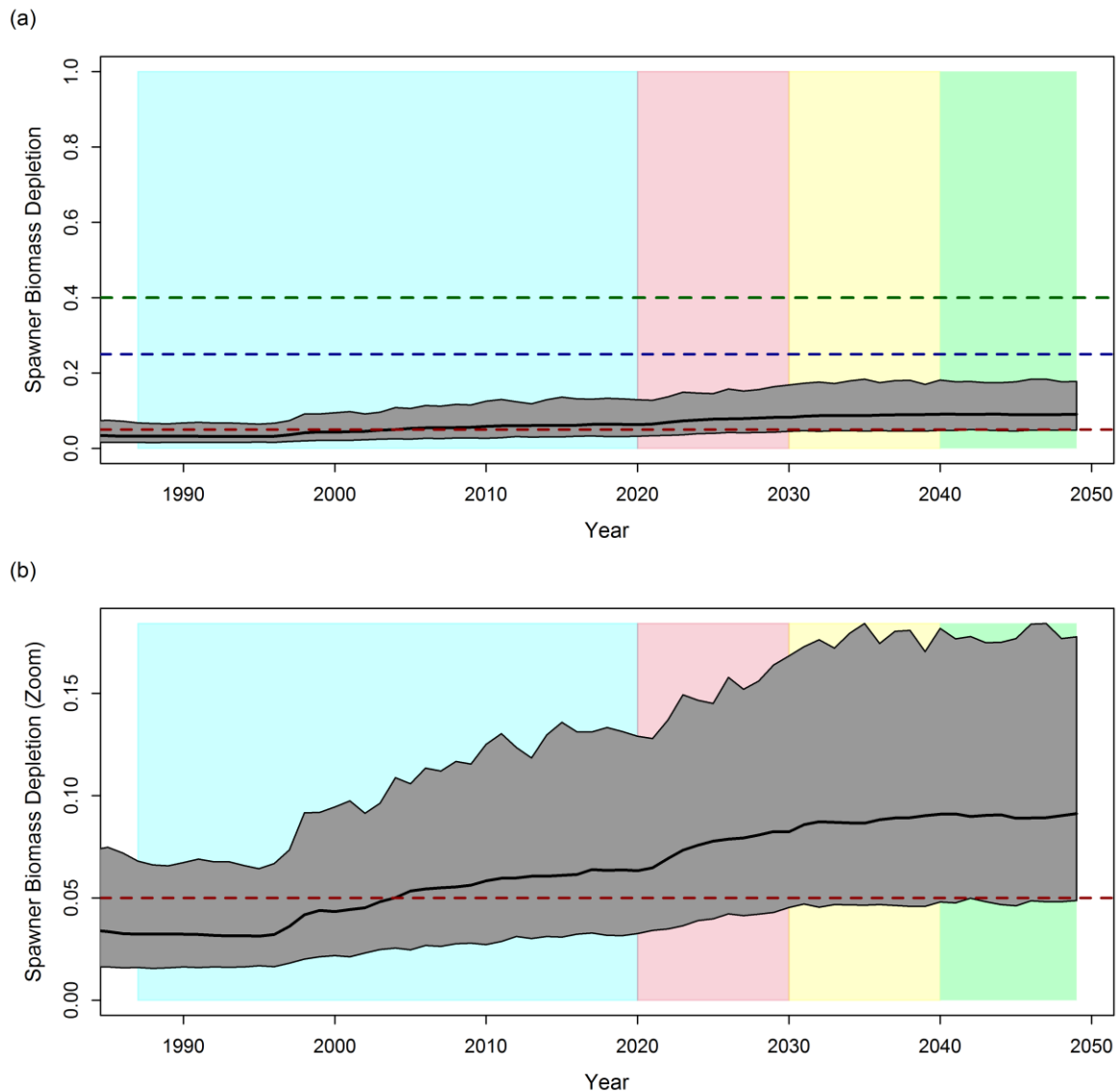


Figure C.6: Median relative (to pristine) simulated stock spawner biomass depletion trajectory (black line) of the South African geelbek from 1987 to 2050, with a national 10% reduction in harvesting of current levels from 2020 onwards. The depletion level is displayed relative to (a) the pristine population state and (b) the current estimated population level of ~5% pristine state. The 95% confidence limits are indicated (grey shaded areas). The NMLS data period from 1987 to 2011 is shaded blue, which extends as the pre-evaluation period until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area). Fisheries reference points of 40% SB_0 (dashed green line), 25% SB_0 (dashed blue line) and 5% SB_0 (dashed red line) are also included.

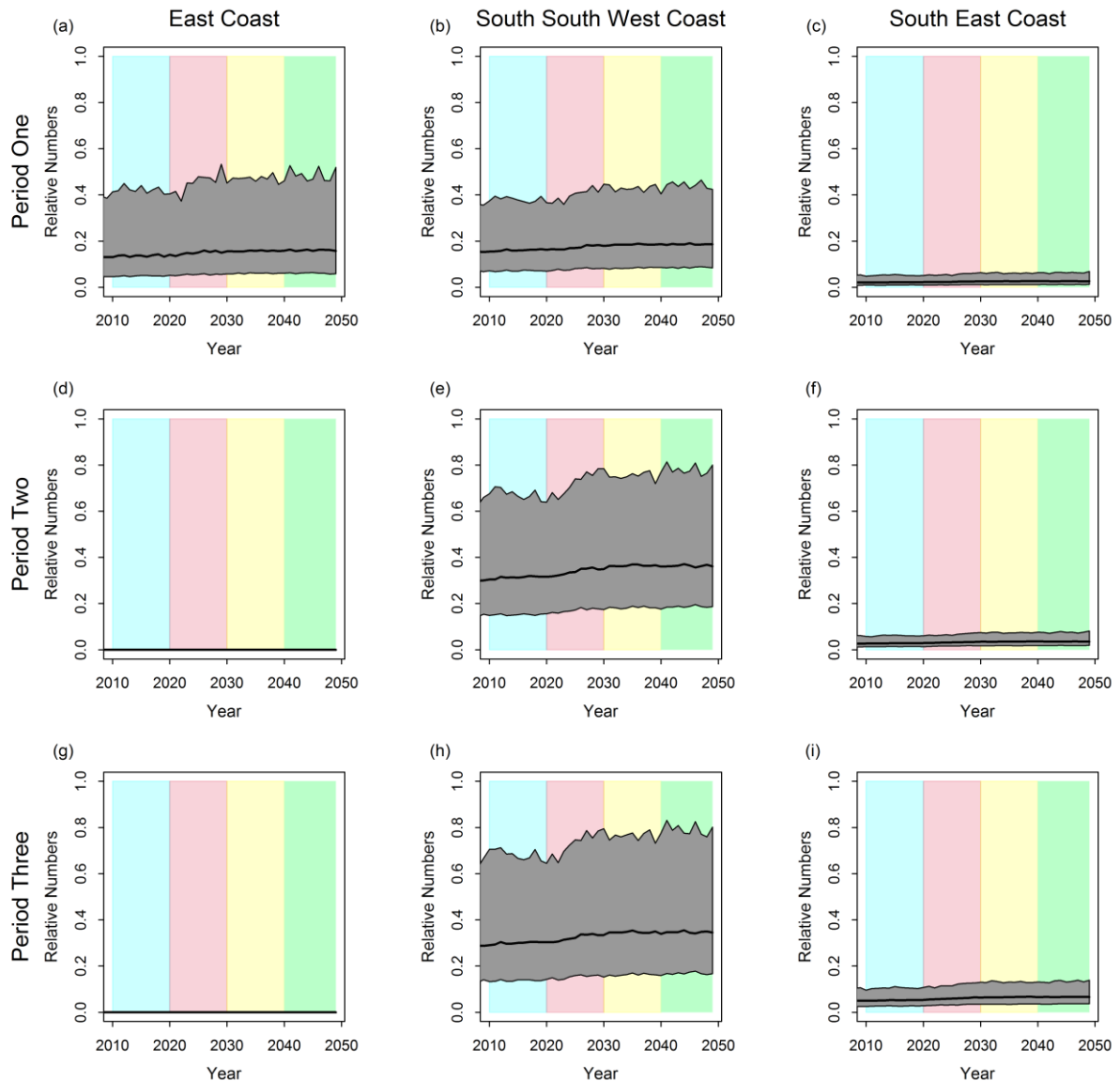


Figure C.7: Median relative (to pristine) stock numbers trajectories (black lines) of the South African geelbek from 2010 to 2050, with a national 10% reduction in harvesting of current levels from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

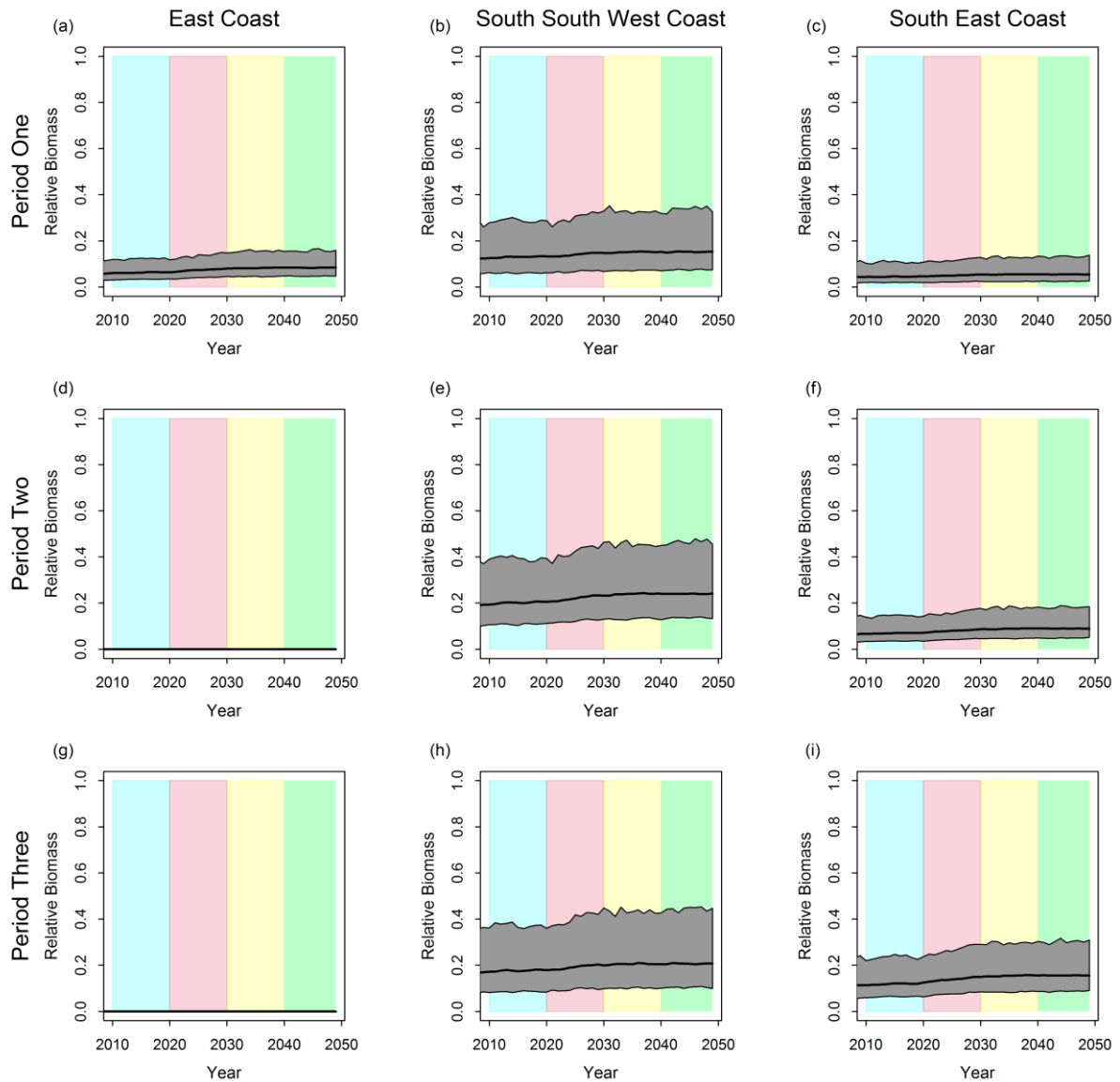


Figure C.8: Median relative (to pristine) stock biomass trajectories (black lines) of the South African geelbek from 2010 to 2050, with a national 10% reduction in harvesting of current levels from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

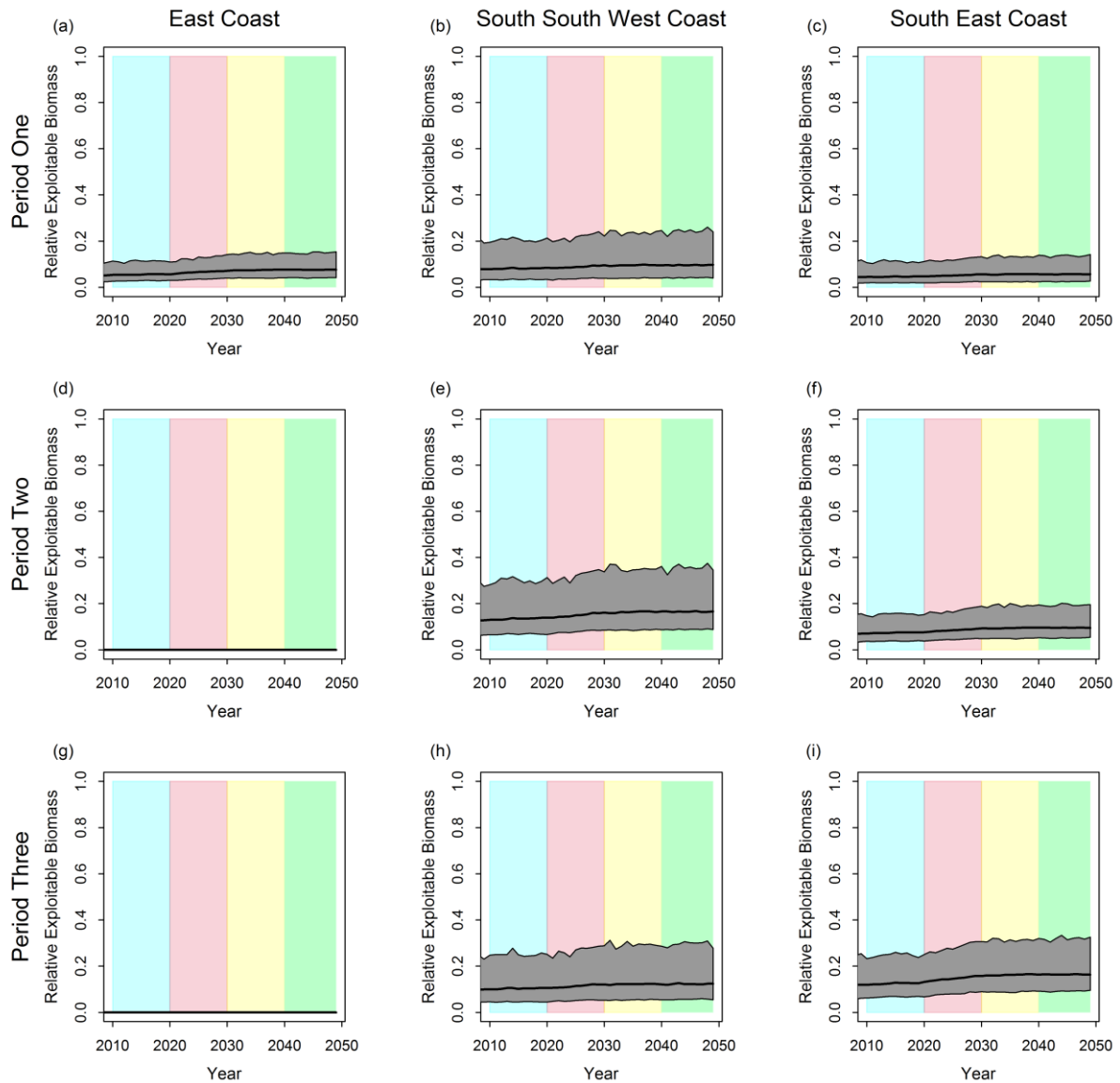


Figure C.9: Median relative (to pristine) stock exploitable biomass trajectories (black lines) of the South African geelbek from 2010 to 2050, with a national 10% reduction in harvesting of current levels from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

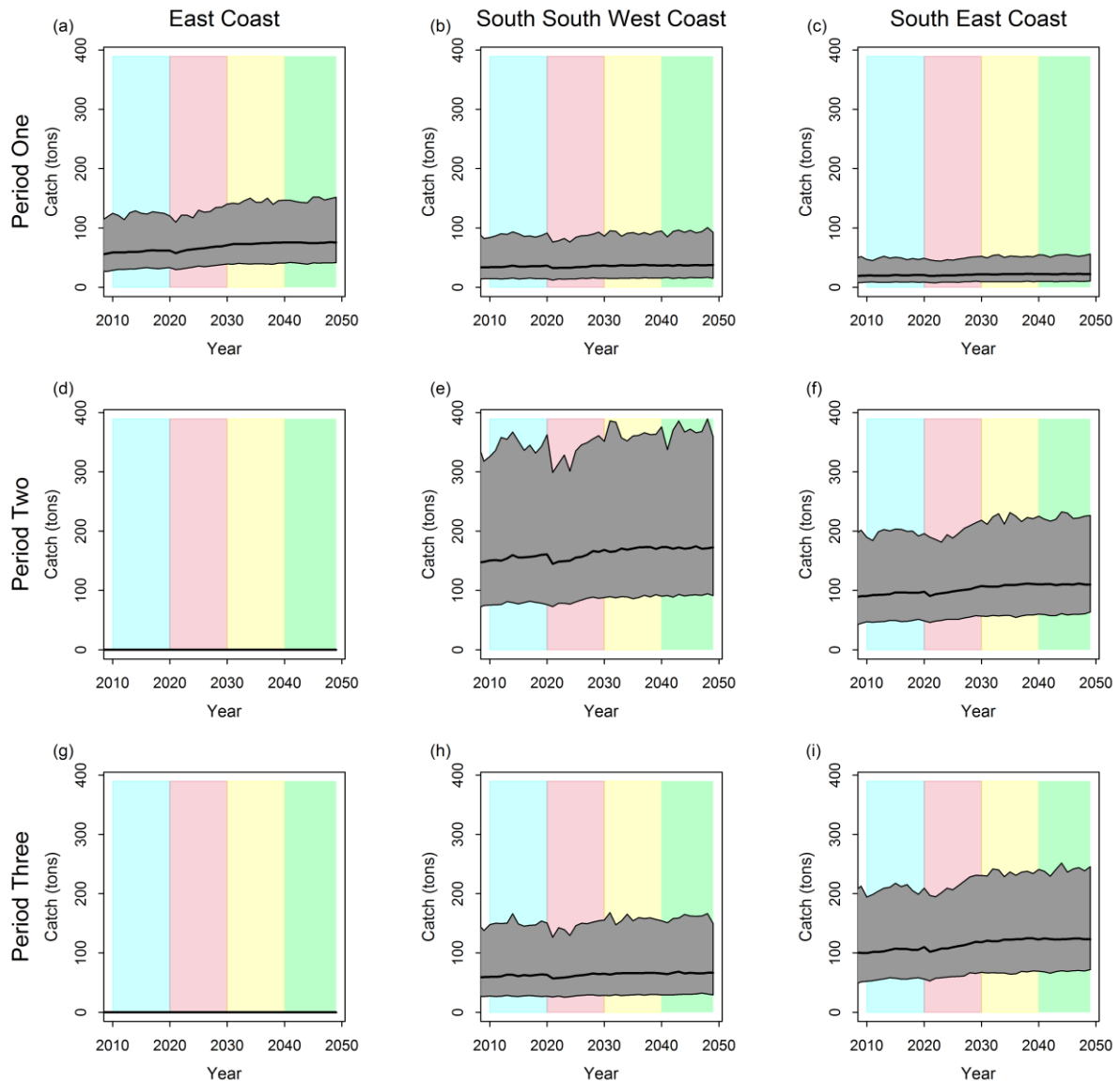


Figure C.10: Median simulated stock catch trajectories (black lines) of the South African geelbek from 2010 to 2050, with a national 10% reduction in harvesting of current levels from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

6.3.3. Management strategy 4: Reduce H by 20% across all regions and periods

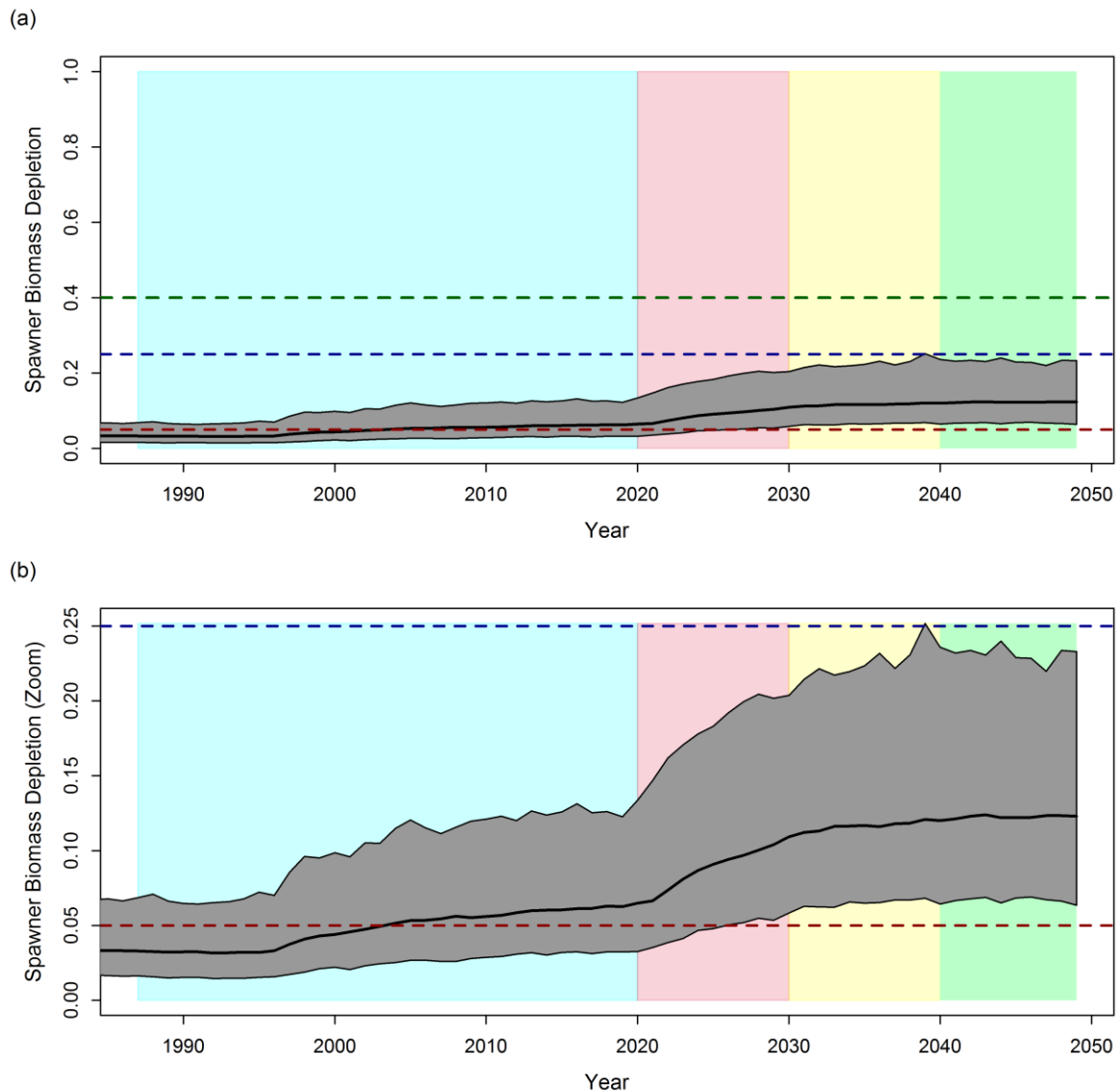


Figure C.11: Median relative (to pristine) simulated stock spawner biomass depletion trajectory (black line) of the South African geelbek from 1987 to 2050, with a national 20% reduction in harvesting of current levels from 2020 onwards. The depletion level is displayed relative to (a) the pristine population state and (b) the current estimated population level of ~5% pristine state. The 95% confidence limits are indicated (grey shaded areas). The NMLS data period from 1987 to 2011 is shaded blue, which extends as the pre-evaluation period until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area). Fisheries reference points of 40% SB_0 (dashed green line), 25% SB_0 (dashed blue line) and 5% SB_0 (dashed red line) are also included.

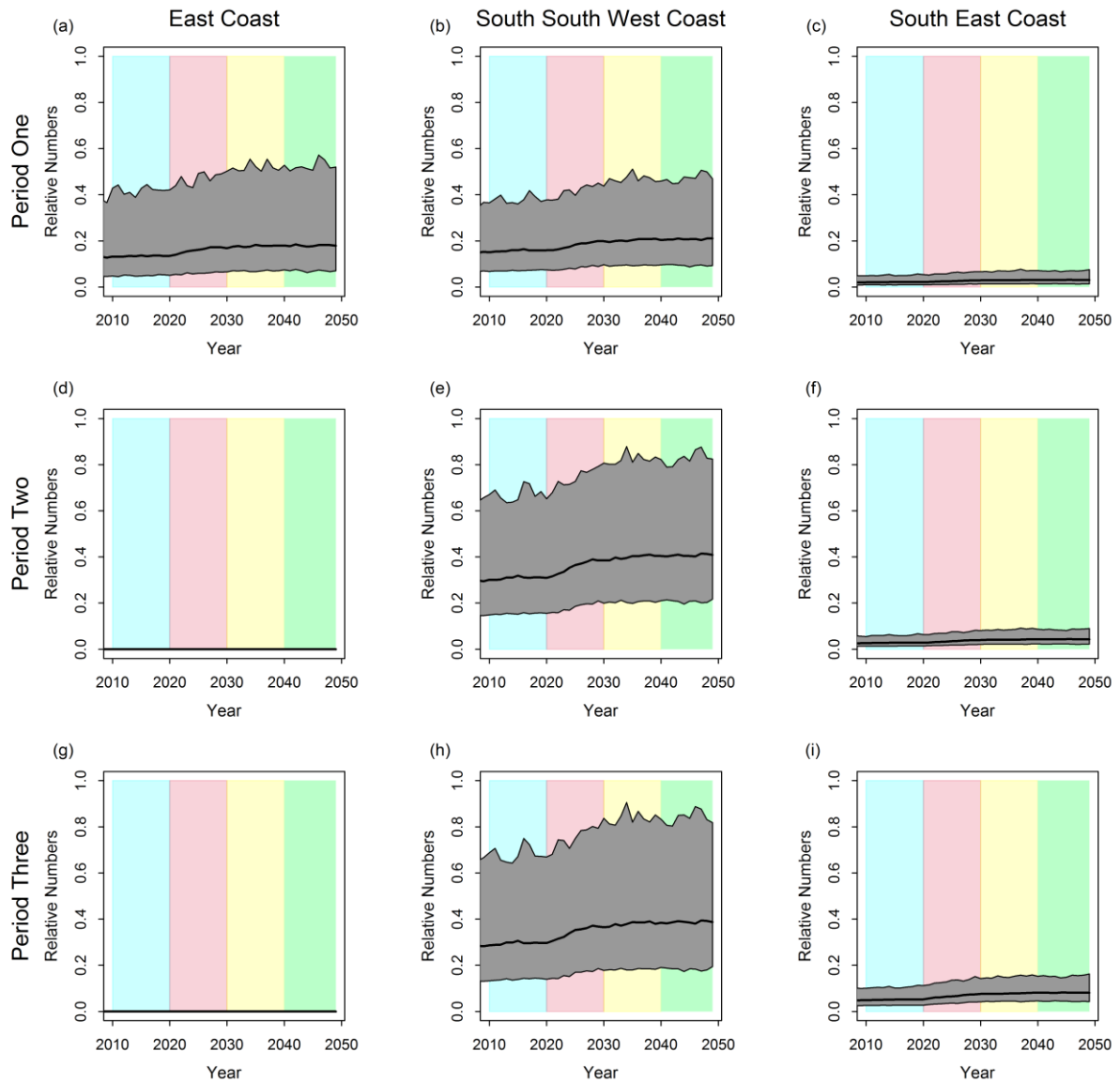


Figure C.12: Median relative (to pristine) stock numbers trajectories (black lines) of the South African geelbek from 2010 to 2050, with a national 20% reduction in harvesting of current levels from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

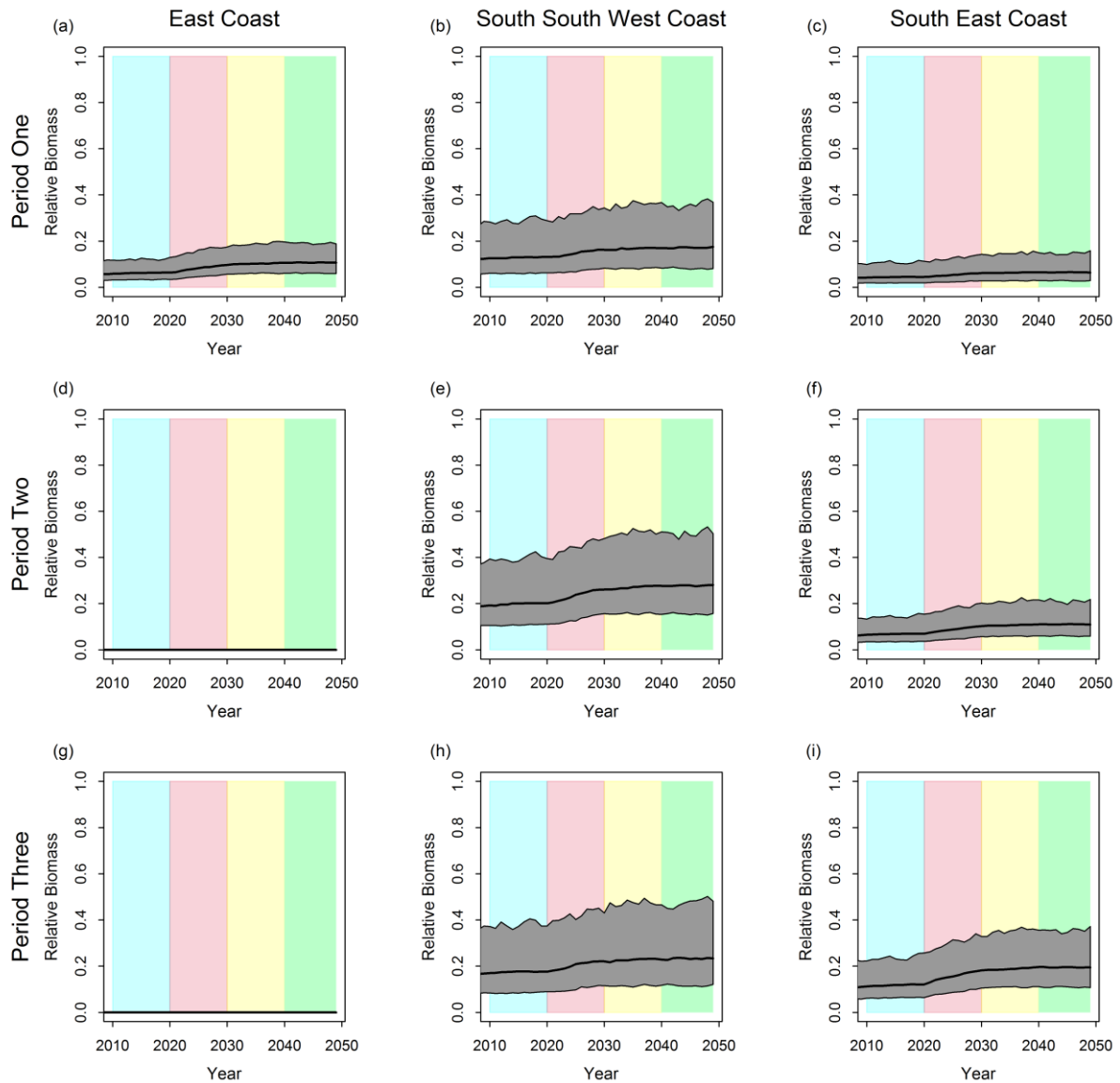


Figure C.13: Median relative (to pristine) stock biomass trajectories (black lines) of the South African geelbek from 2010 to 2050, with a national 20% reduction in harvesting of current levels from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

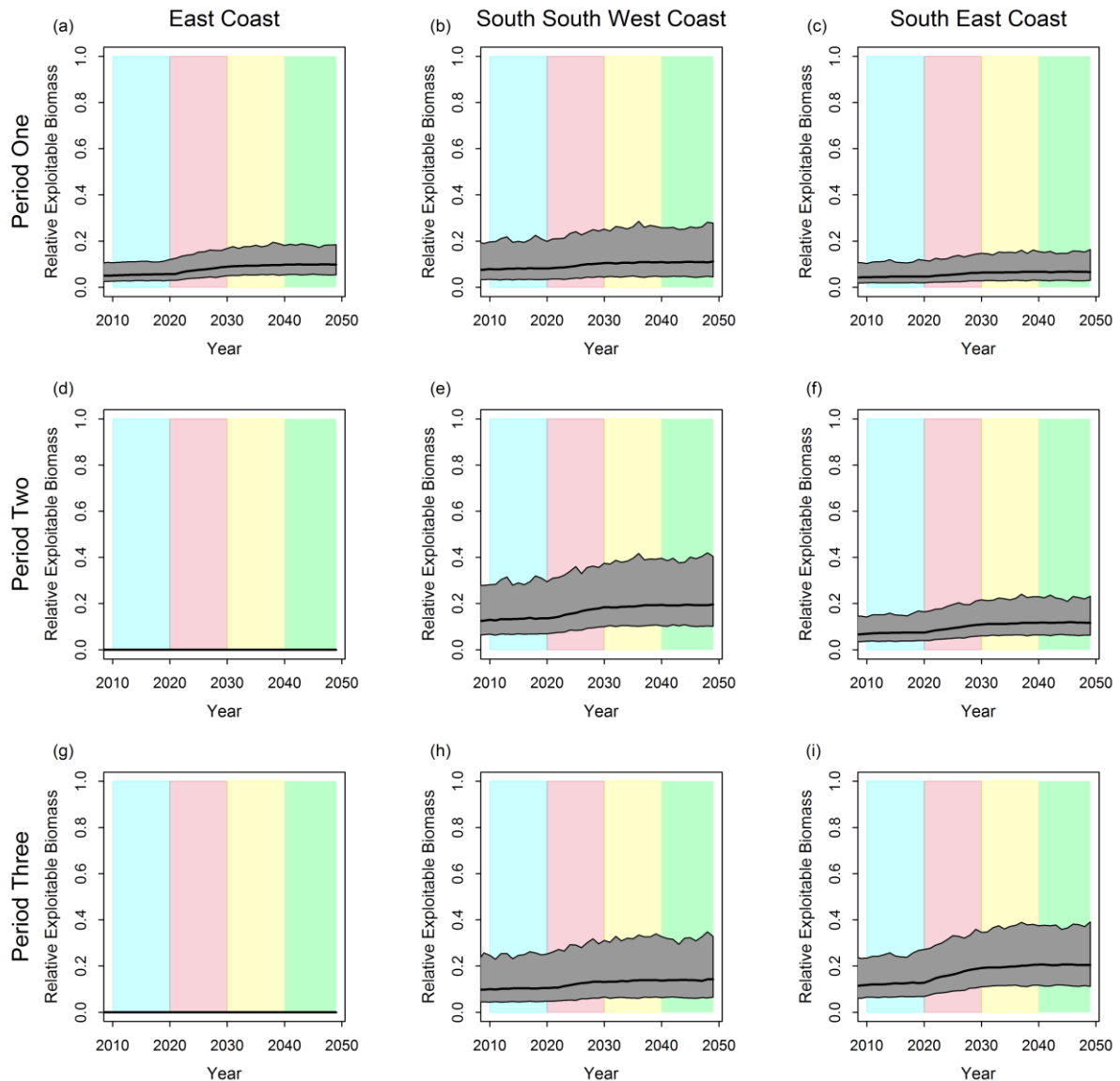


Figure C.14: Median relative (to pristine) stock exploitable biomass trajectories (black lines) of the South African geelbek from 2010 to 2050, with a national 20% reduction in harvesting of current levels from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

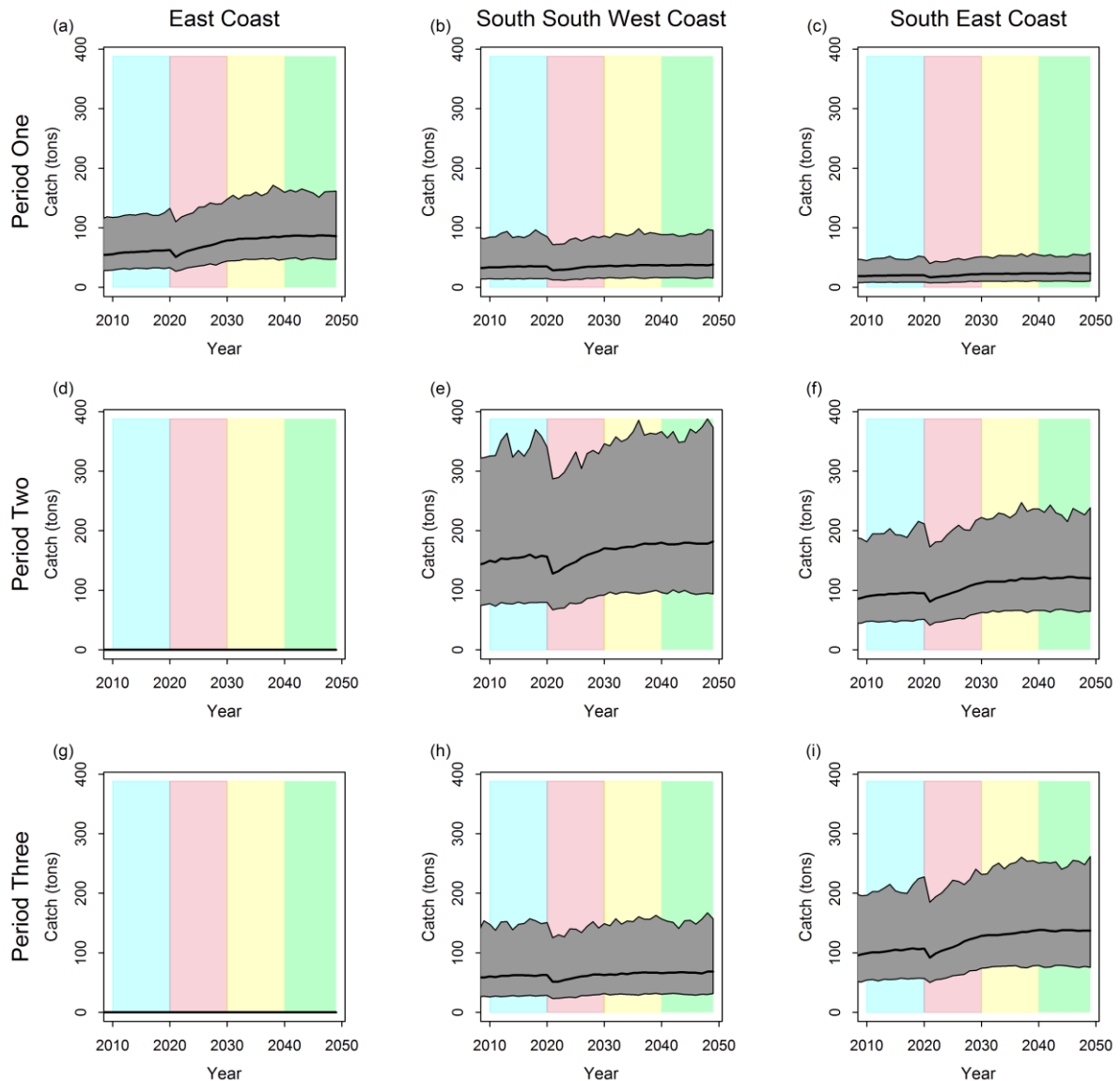


Figure C.15: Median simulated stock catch trajectories (black lines) of the South African geelbek from 2010 to 2050, with a national 20% reduction in harvesting of current levels from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

6.3.4. Management strategy 5: Reduce H by 50% across all regions and periods

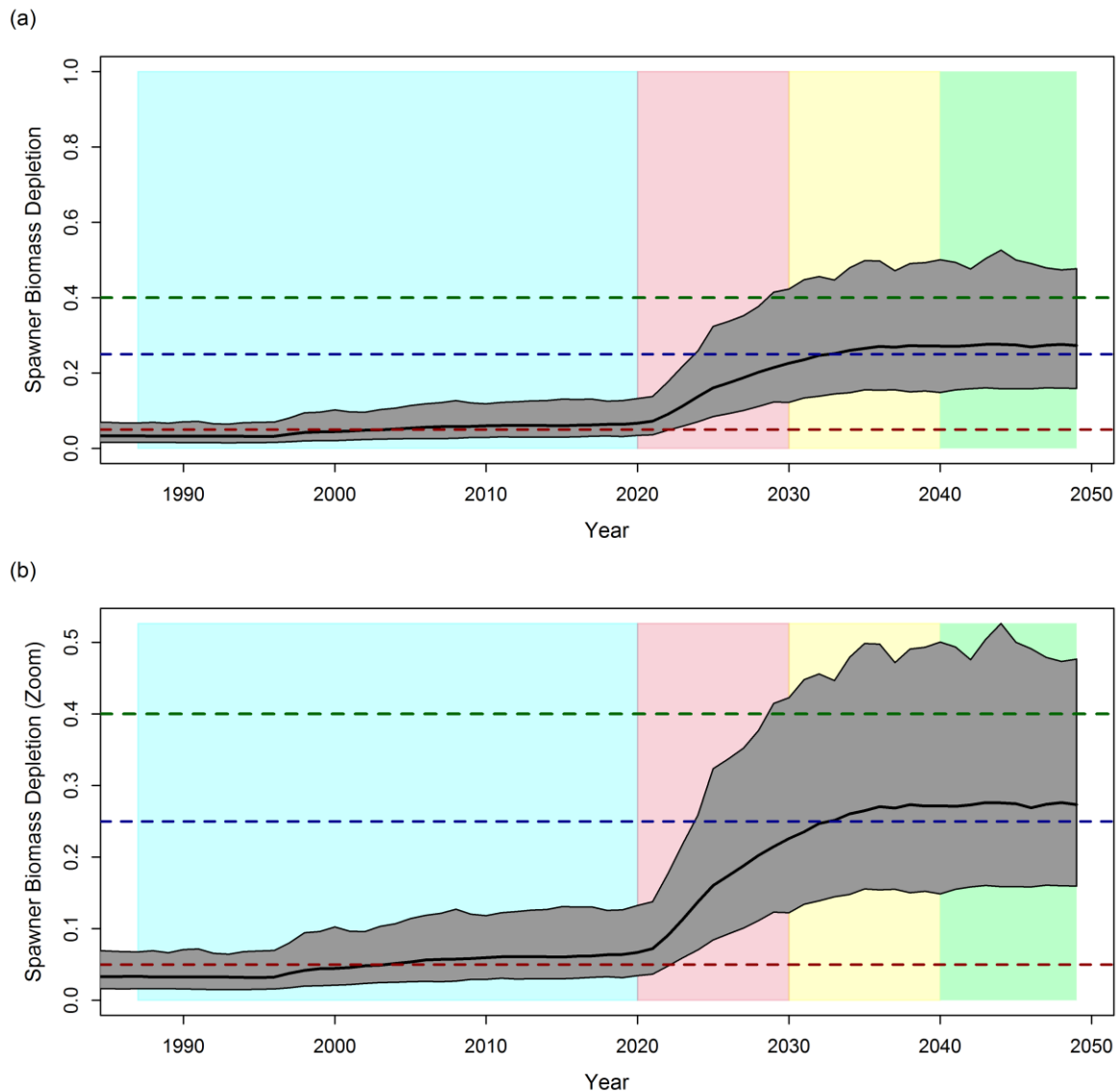


Figure C.16: Median relative (to pristine) simulated stock spawner biomass depletion trajectory (black line) of the South African geelbek from 1987 to 2050, with a national 50% reduction in harvesting of current levels from 2020 onwards. The depletion level is displayed relative to (a) the pristine population state and (b) the current estimated population level of ~5% pristine state. The 95% confidence limits are indicated (grey shaded areas). The NMLS data period from 1987 to 2011 is shaded blue, which extends as the pre-evaluation period until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area). Fisheries reference points of 40% SB_0 (dashed green line), 25% SB_0 (dashed blue line) and 5% SB_0 (dashed red line) are also included.

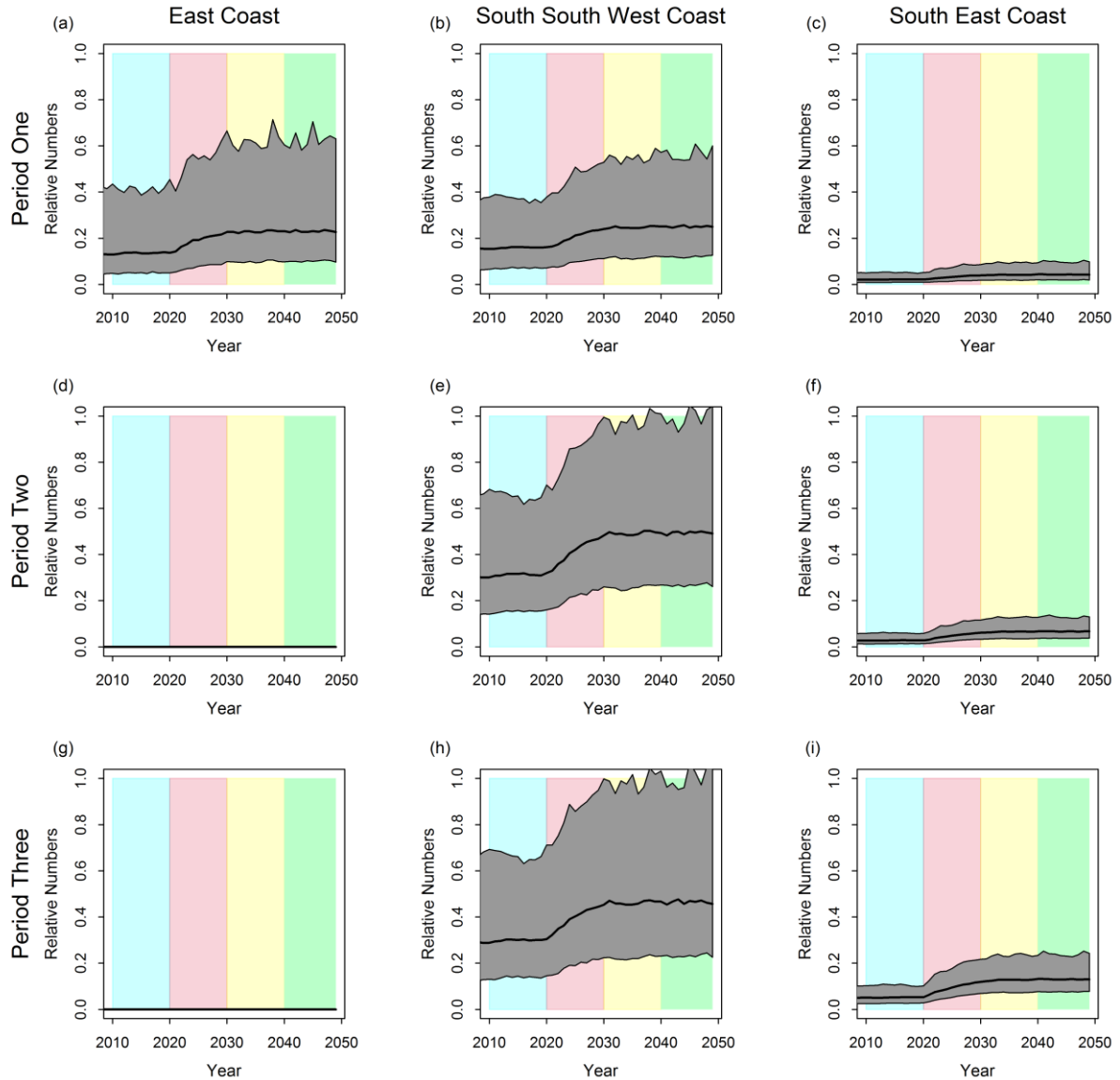


Figure C.17: Median relative (to pristine) stock numbers trajectories (black lines) of the South African geelbek from 2010 to 2050, with a national 50% reduction in harvesting of current levels from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

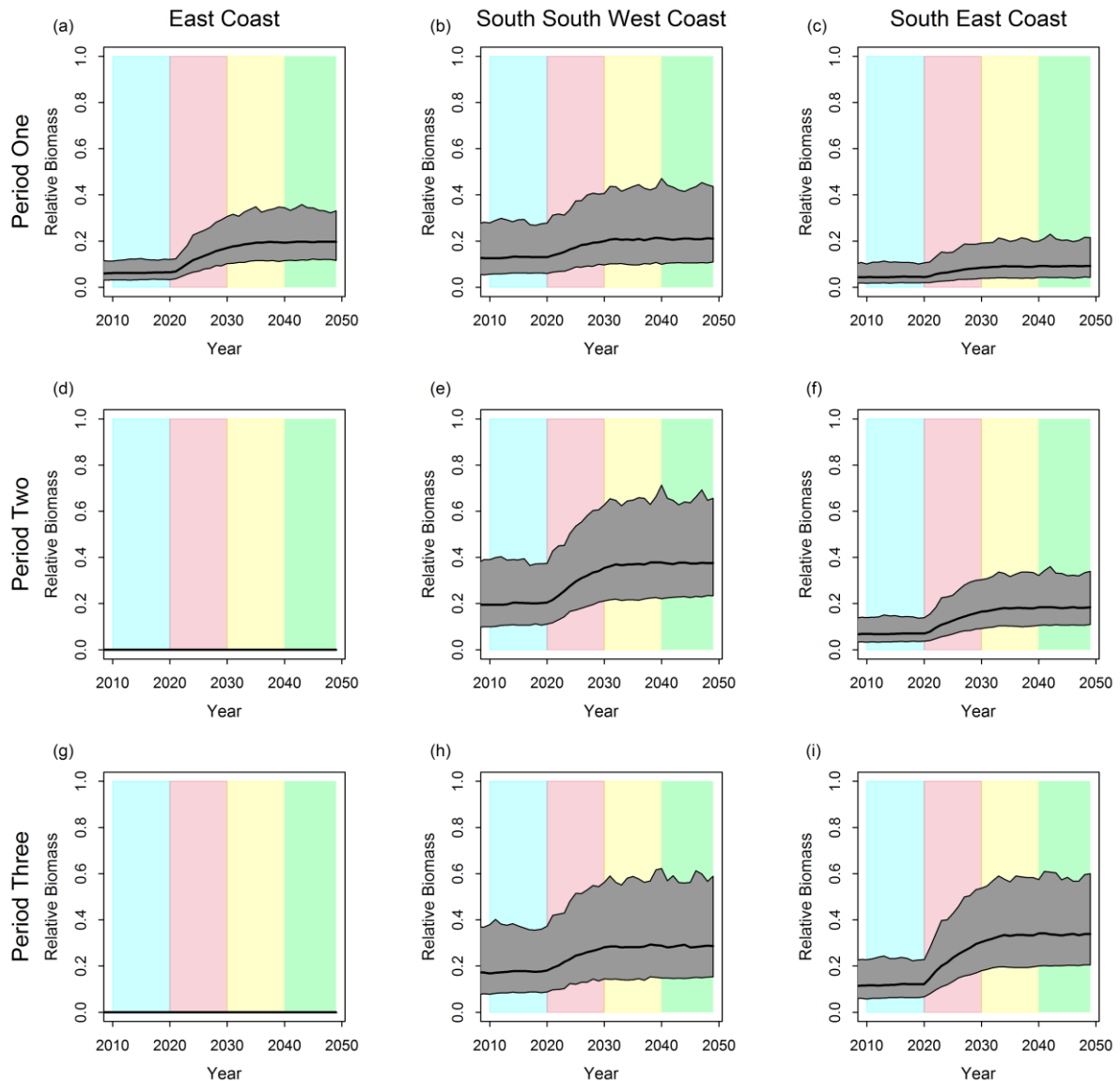


Figure C.18: Median relative (to pristine) stock biomass trajectories (black lines) of the South African geelbek from 2010 to 2050, with a national 50% reduction in harvesting of current levels from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

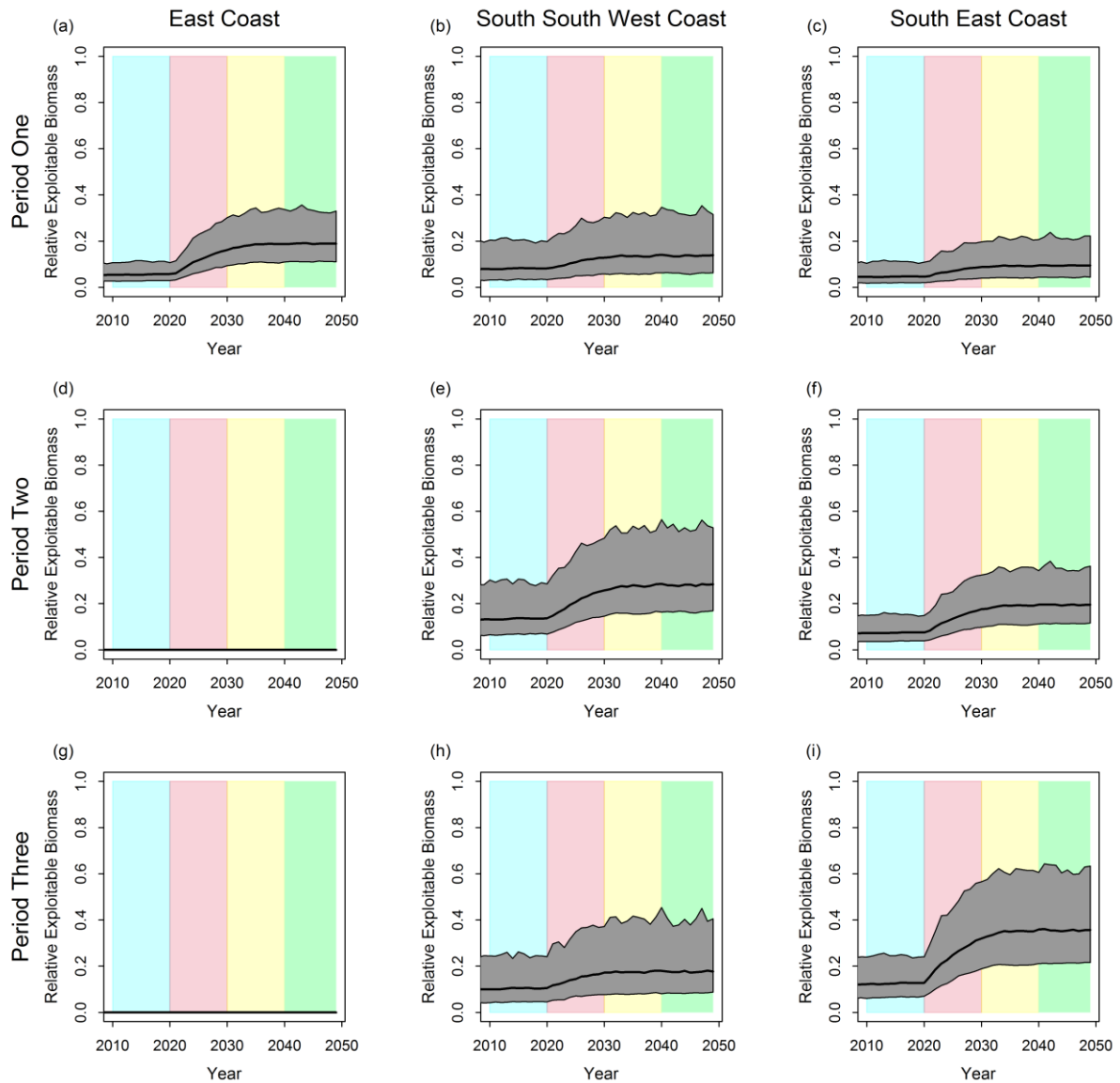


Figure C.19: Median relative (to pristine) stock exploitable biomass trajectories (black lines) of the South African geelbek from 2010 to 2050, with a national 50% reduction in harvesting of current levels from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

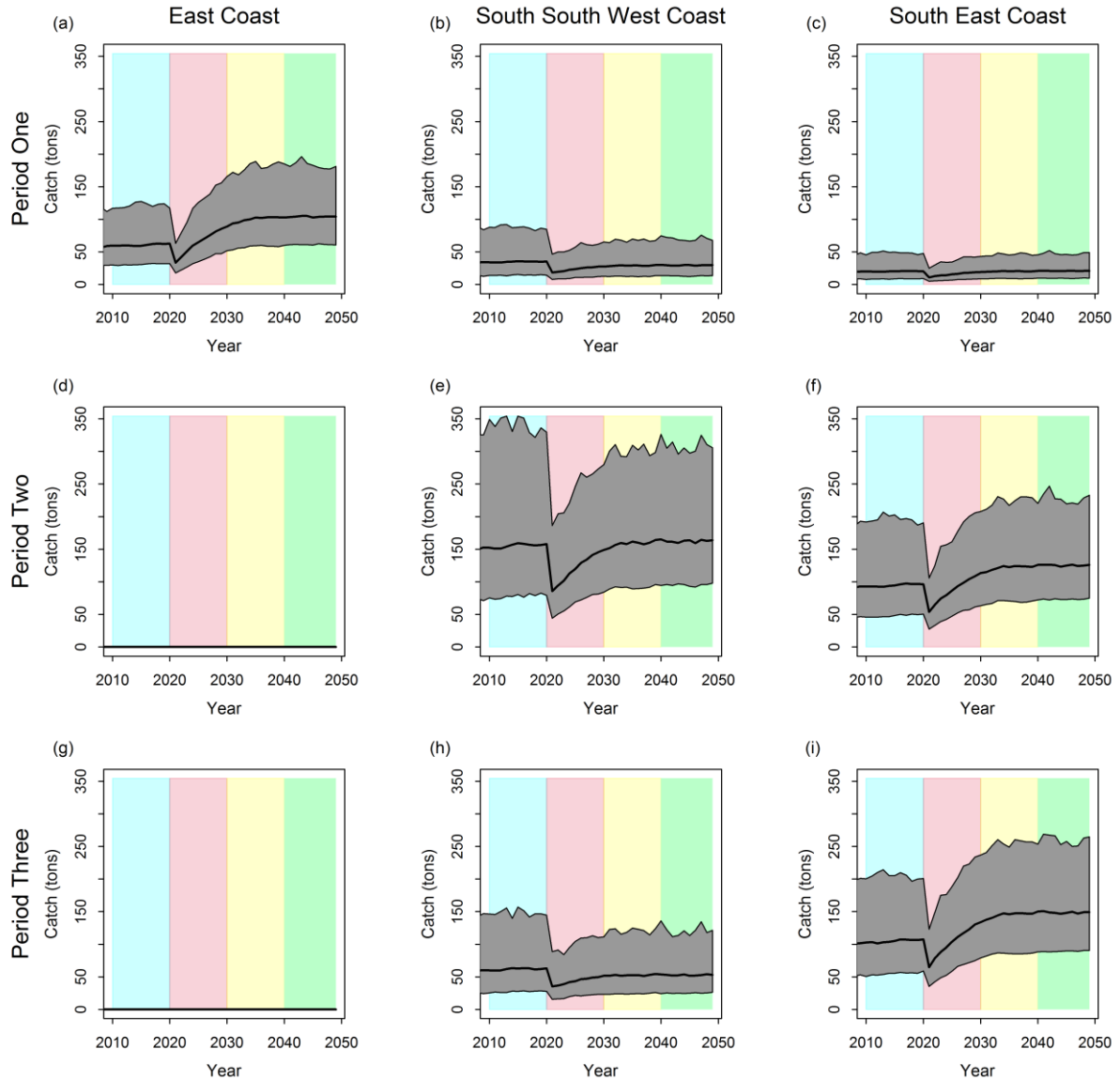


Figure C.20: Median simulated stock catch trajectories (black lines) of the South African geelbek from 2010 to 2050, with a national 50% reduction in harvesting of current levels from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

6.3.5. Management strategy 6: Close east coast in period one (August to November)

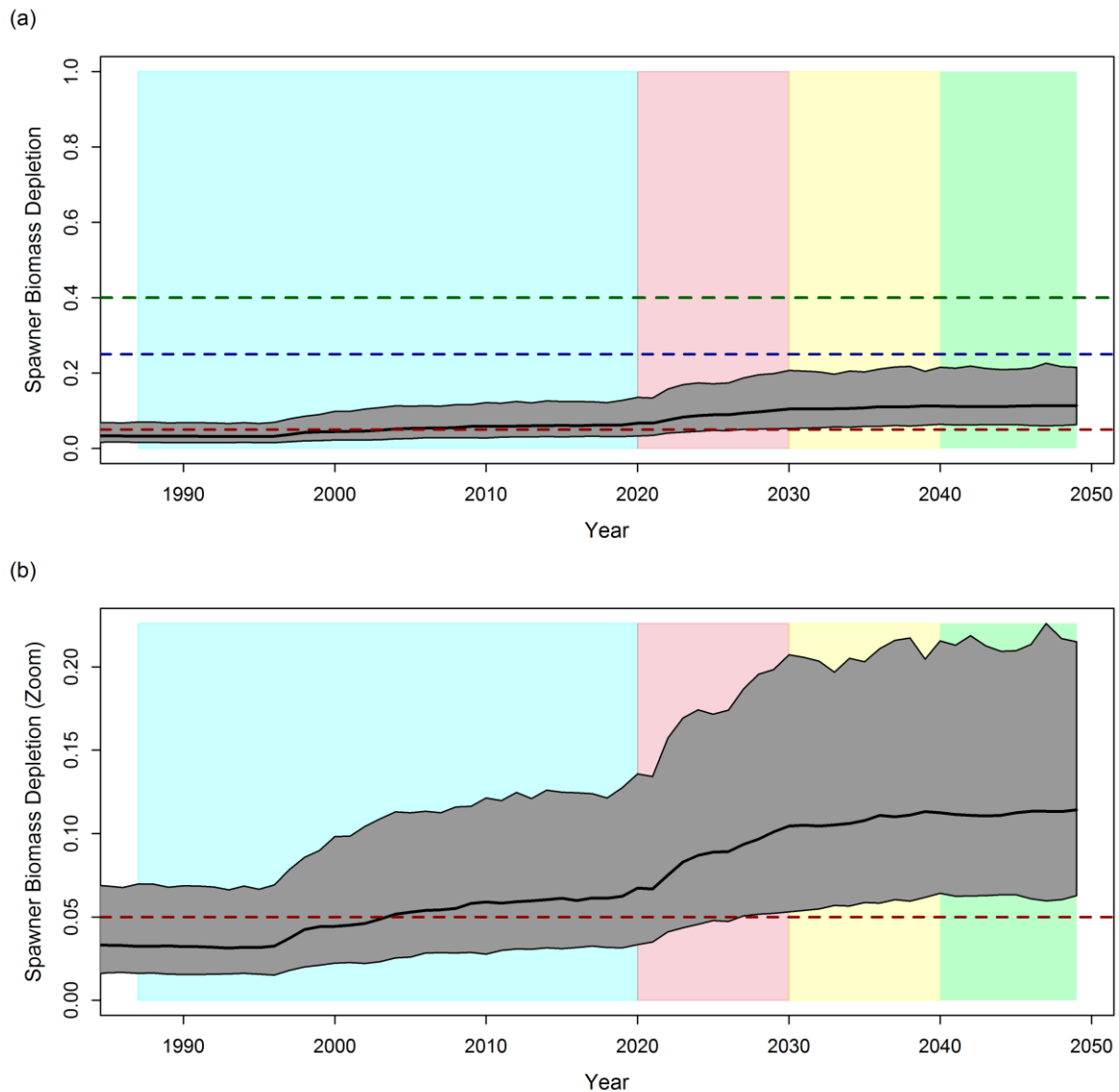


Figure C.21: Median relative (to pristine) simulated stock spawner biomass depletion trajectory (black line) of the South African geelbek from 1987 to 2050, with the implementation of a closed season and area in the east coast in period one (August to November), from 2020 onwards. The depletion level is displayed relative to (a) the pristine population state and (b) the current estimated population level of ~5% pristine state. The 95% confidence limits are indicated (grey shaded areas). The NMLS data period from 1987 to 2011 is shaded blue, which extends as the pre-evaluation period until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area). Fisheries reference points of 40% SB_0 (dashed green line), 25% SB_0 (dashed blue line) and 5% SB_0 (dashed red line) are also included.

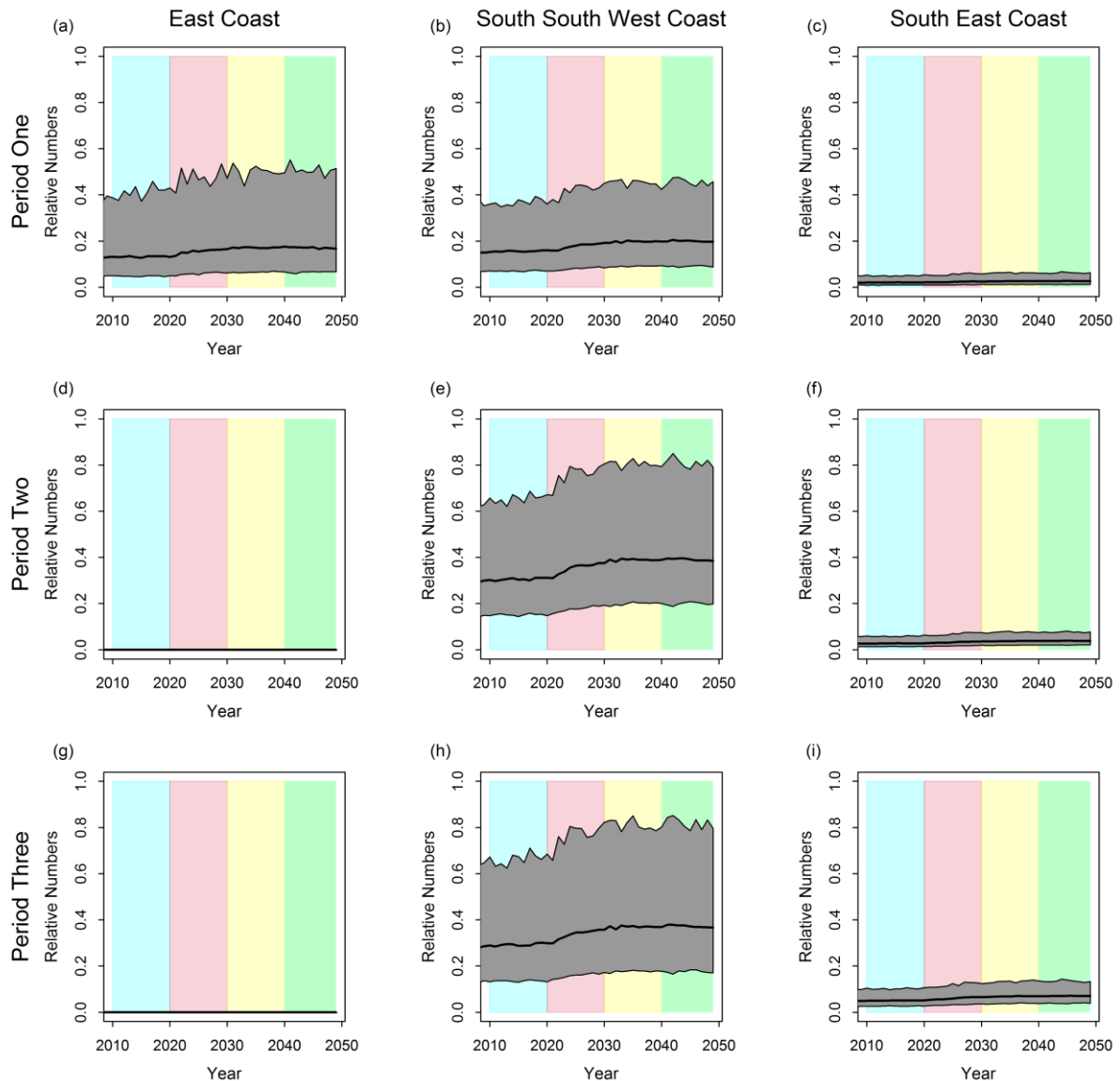


Figure C.22: Median relative (to pristine) stock numbers trajectories (black lines) of the South African geelbek from 2010 to 2050, with the implementation of a closed season and area in the east coast in period one (August to November), from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

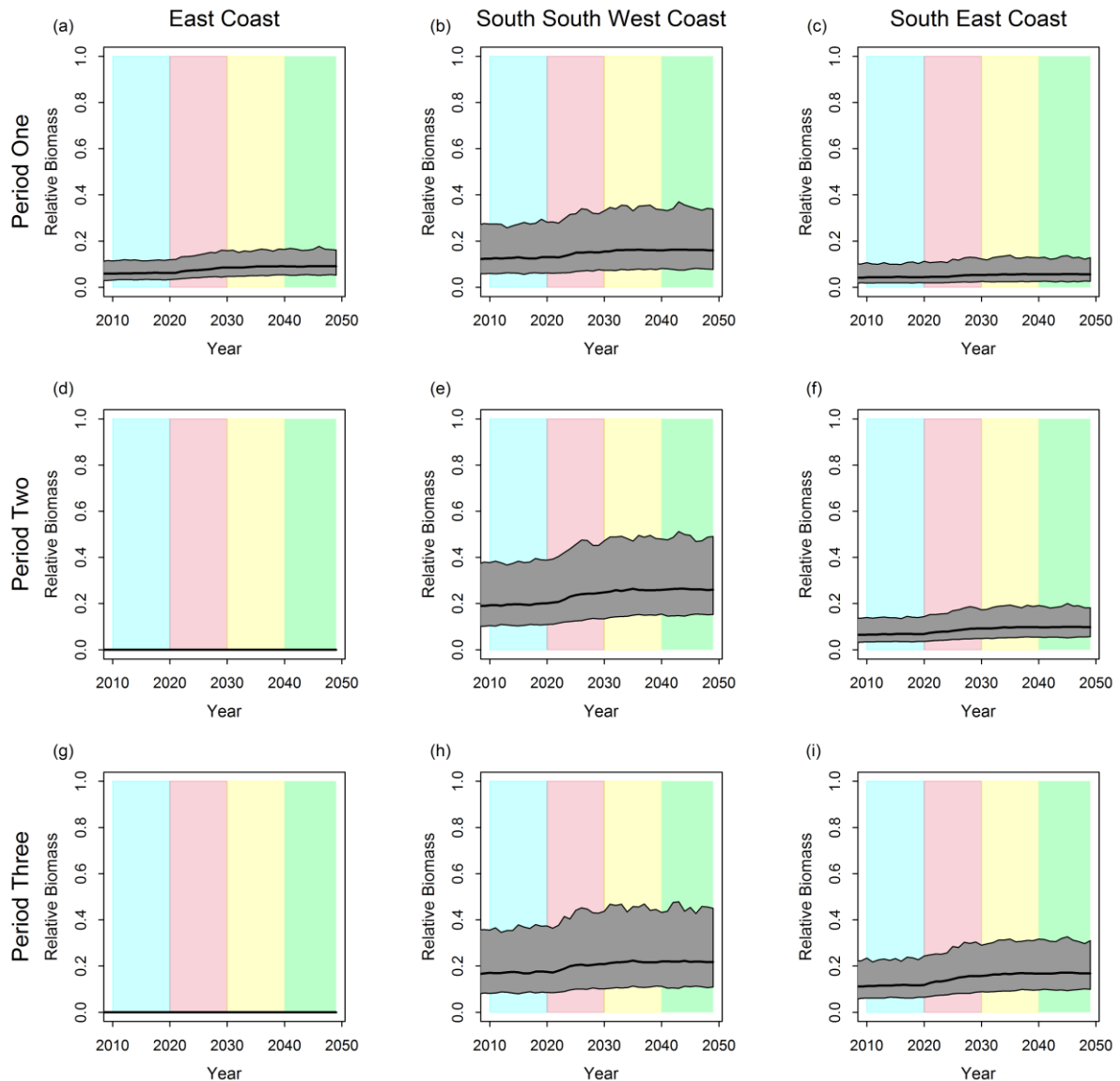


Figure C.23: Median relative (to pristine) stock biomass trajectories (black lines) of the South African geelbek from 2010 to 2050, with the implementation of a closed season and area in the east coast in period one (August to November), from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

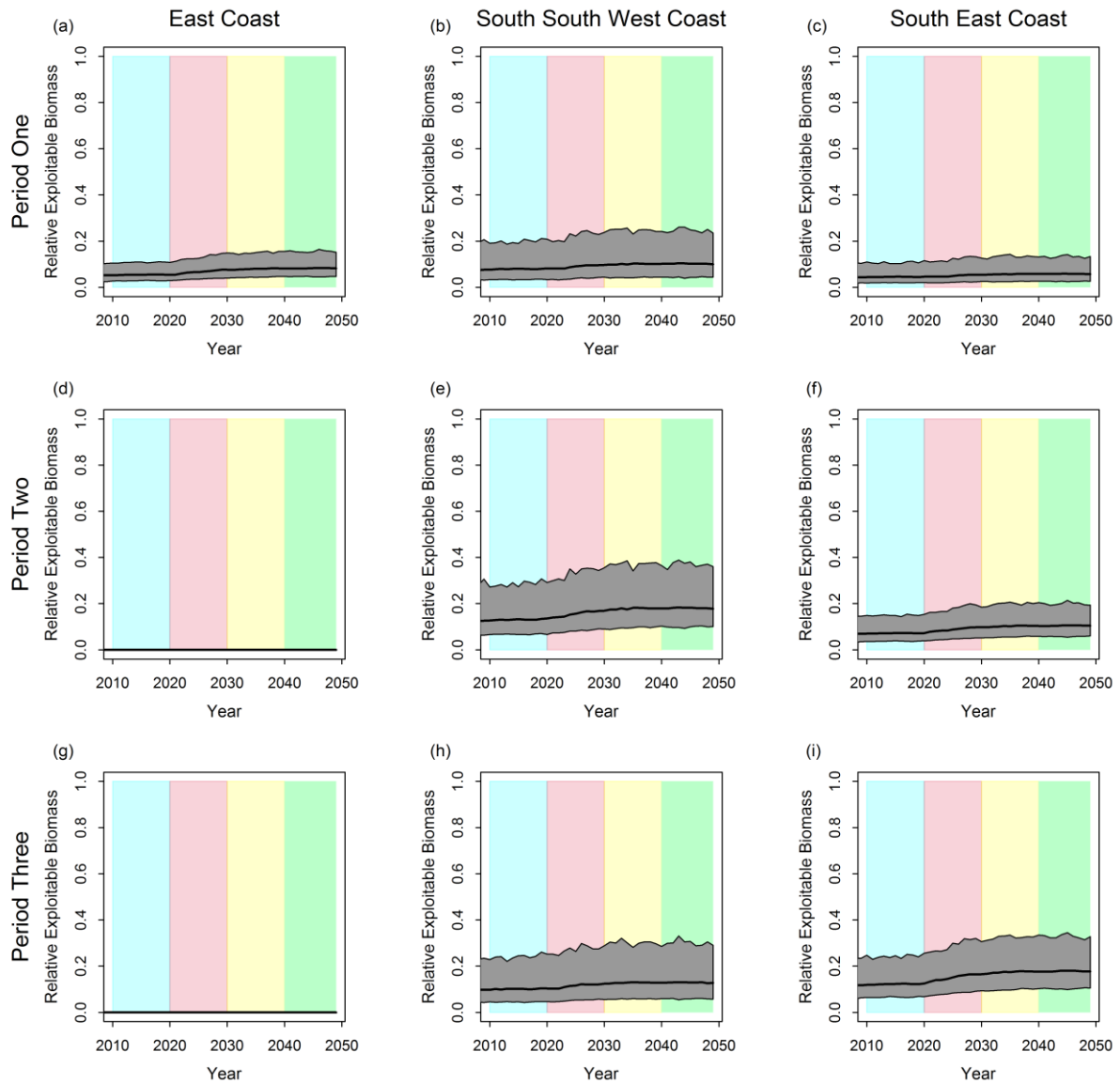


Figure C.24: Median relative (to pristine) stock exploitable biomass trajectories (black lines) of the South African geelbek from 2010 to 2050, with the implementation of a closed season and area in the east coast in period one (August to November), from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

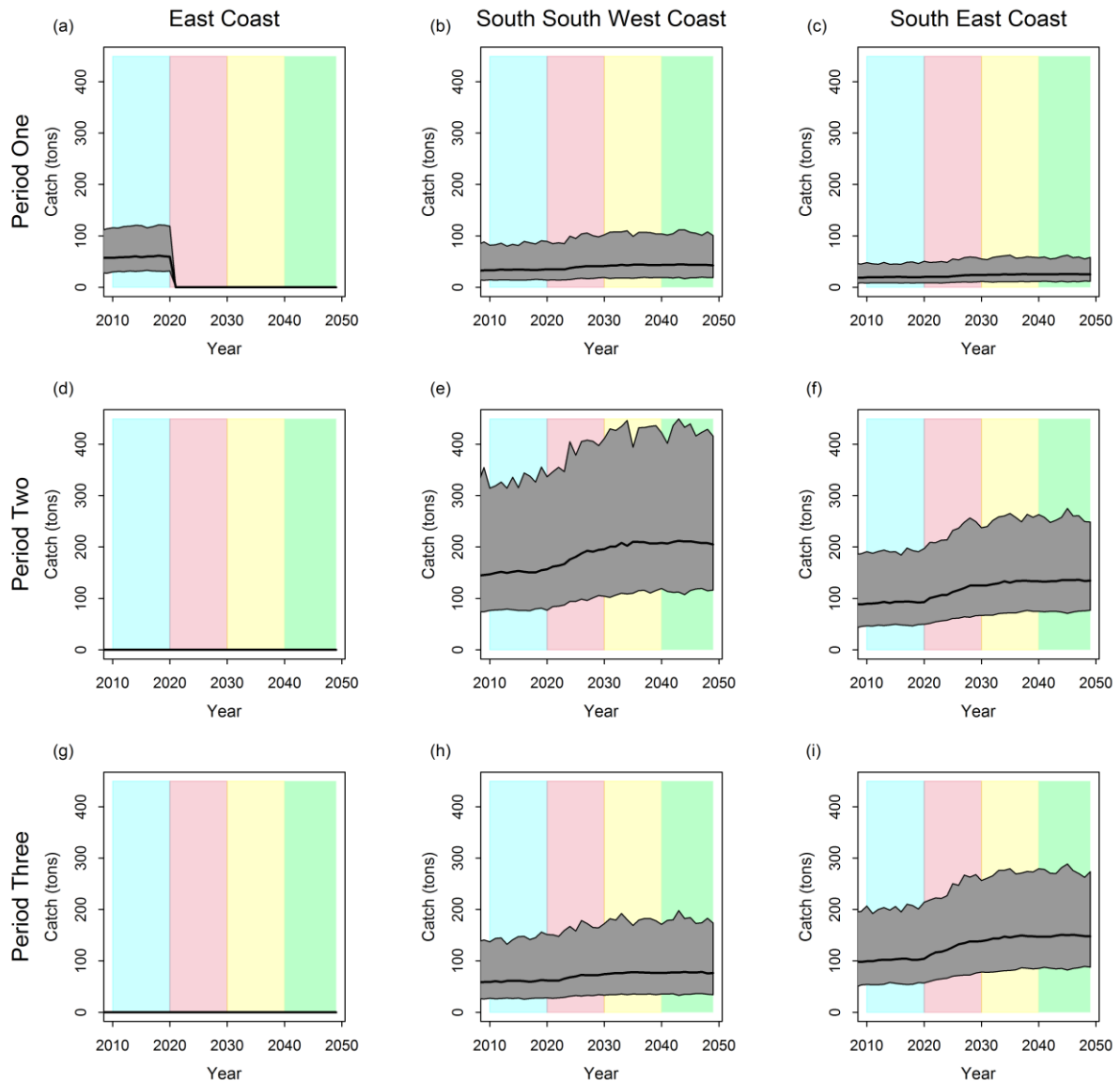


Figure C.25: Median simulated stock catch trajectories (black lines) of the South African geelbek from 2010 to 2050, with the implementation of a closed season and area in the east coast in period one (August to November), from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

6.3.6. Management strategy 7: Close south south west coast in period two (December to March)

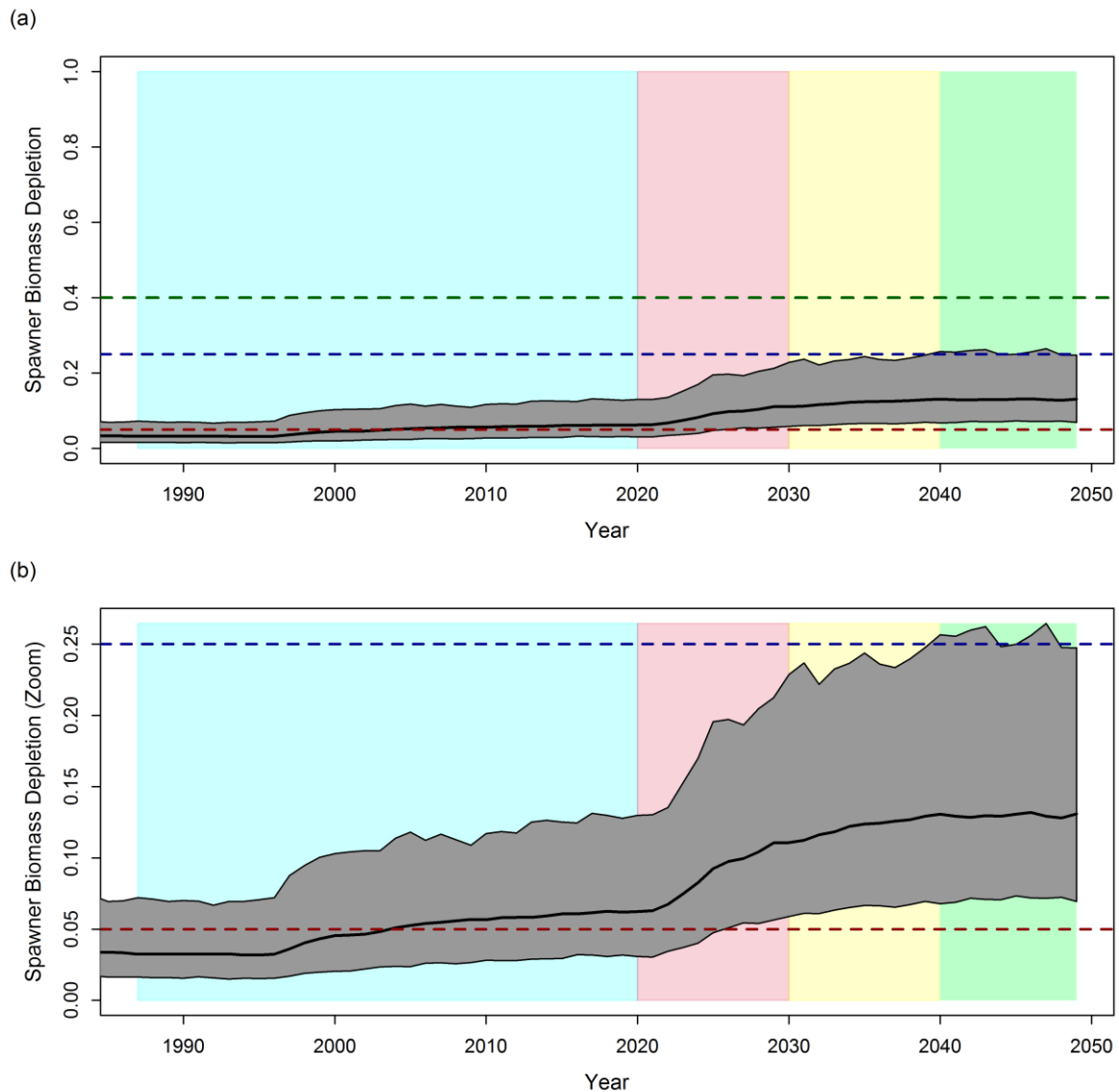


Figure C.26: Median relative (to pristine) simulated stock spawner biomass depletion trajectory (black line) of the South African geelbek from 1987 to 2050, with the implementation of a closed season and area in the south south west coast in period two (December to March), from 2020 onwards. The depletion level is displayed relative to (a) the pristine population state and (b) the current estimated population level of ~5% pristine state. The 95% confidence limits are indicated (grey shaded areas). The NMLS data period from 1987 to 2011 is shaded blue, which extends as the pre-evaluation period until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area). Fisheries reference points of 40% SB_0 (dashed green line), 25% SB_0 (dashed blue line) and 5% SB_0 (dashed red line) are also included.

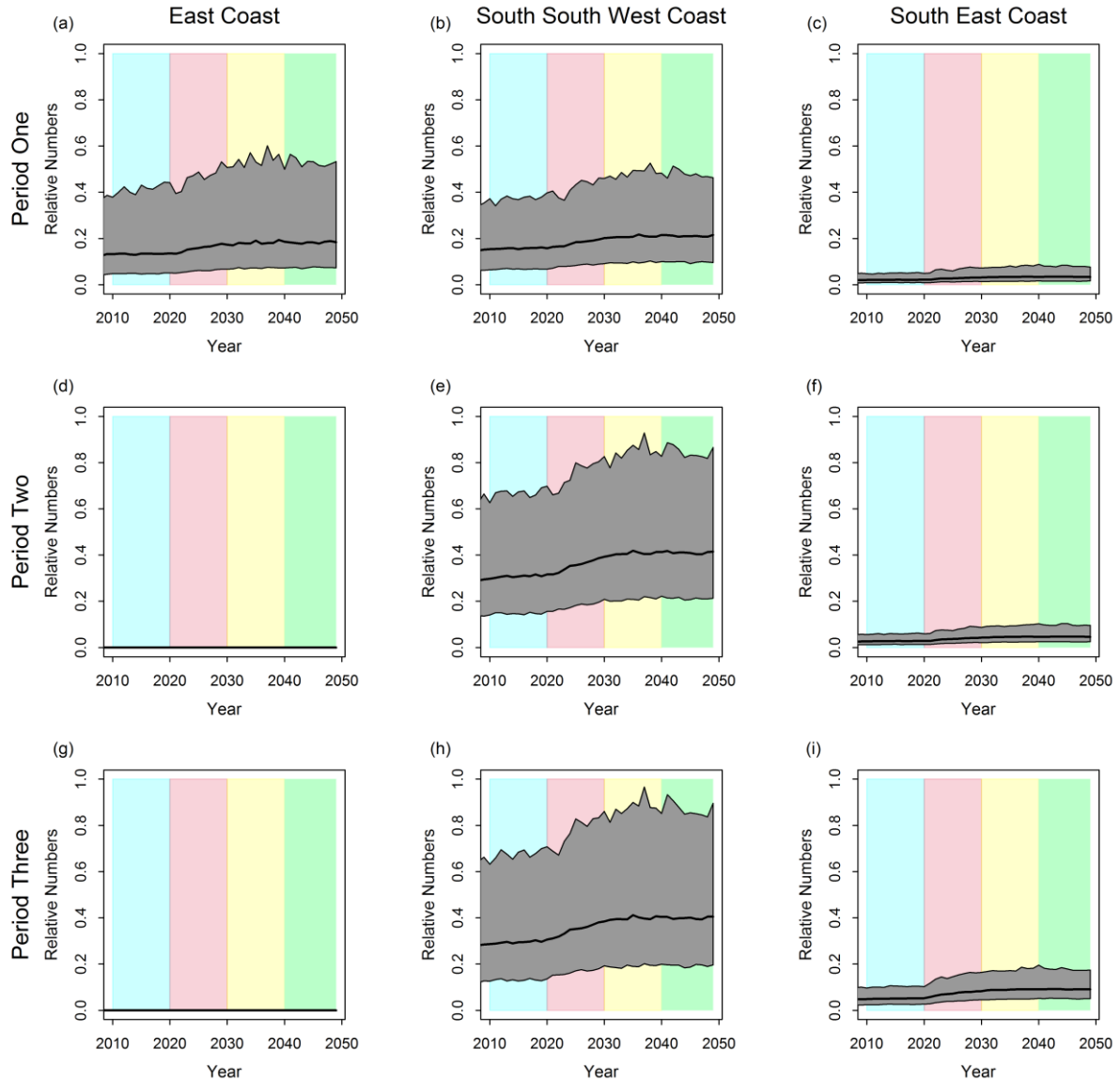


Figure C.27: Median relative (to pristine) stock numbers trajectories (black lines) of the South African geelbek from 2010 to 2050, with the implementation of a closed season and area in the south south west coast in period two (December to March), from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

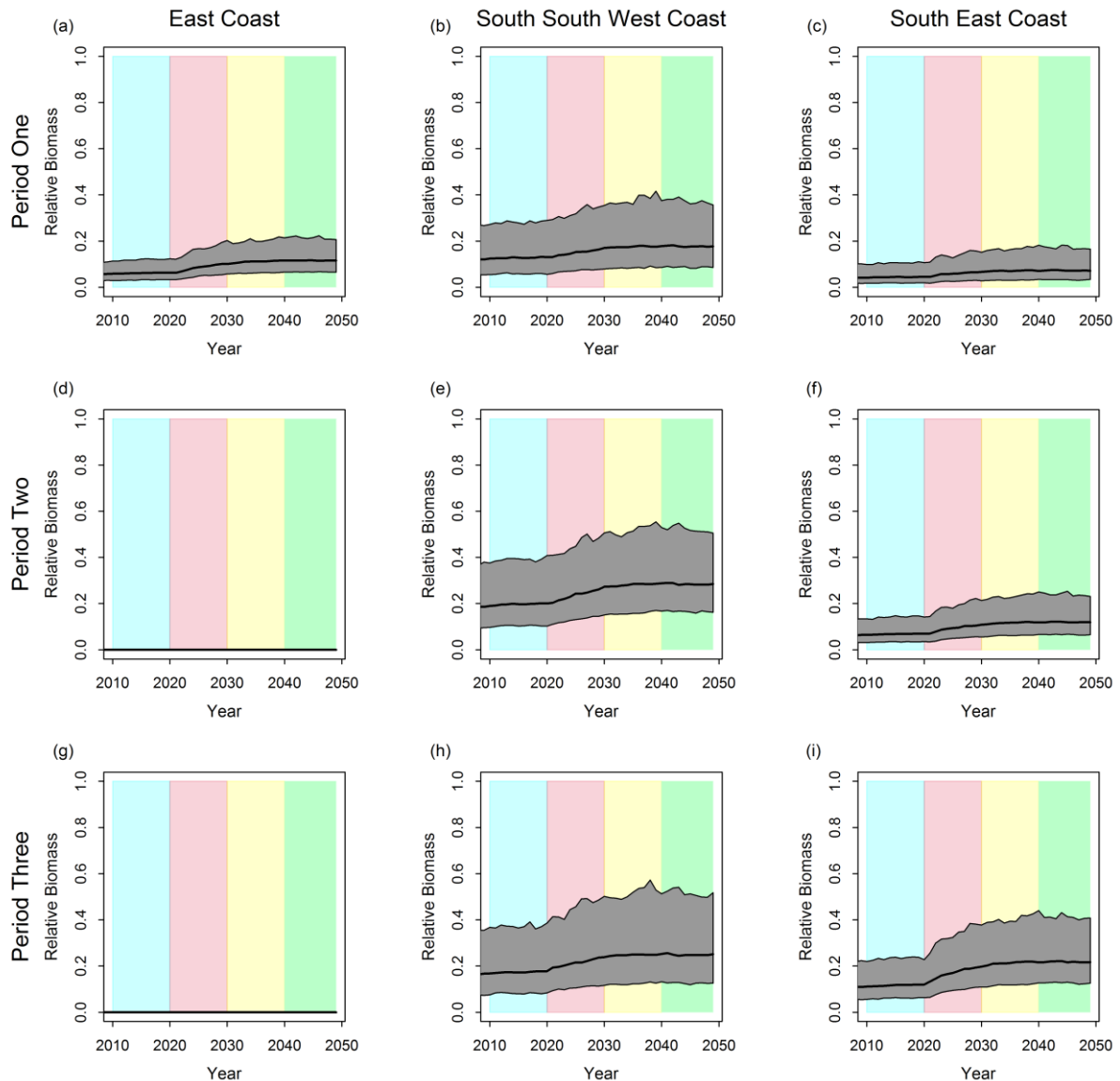


Figure C.28: Median relative (to pristine) stock biomass trajectories (black lines) of the South African geelbek from 2010 to 2050, with the implementation of a closed season and area in the south south west coast in period two (December to March), from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

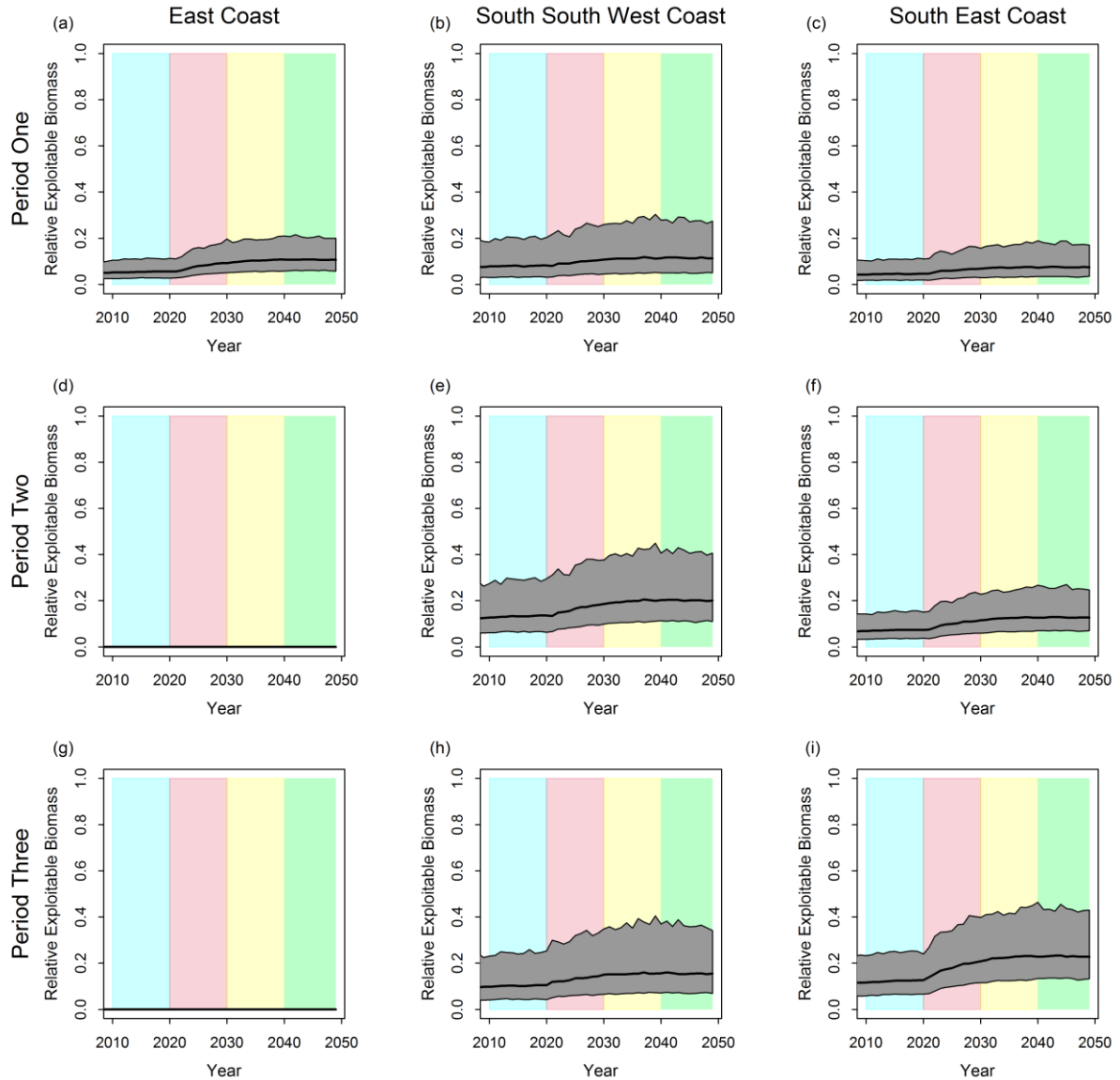


Figure C.29: Median relative (to pristine) stock exploitable biomass trajectories (black lines) of the South African geelbek from 2010 to 2050, with the implementation of a closed season and area in the south south west coast in period two (December to March), from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

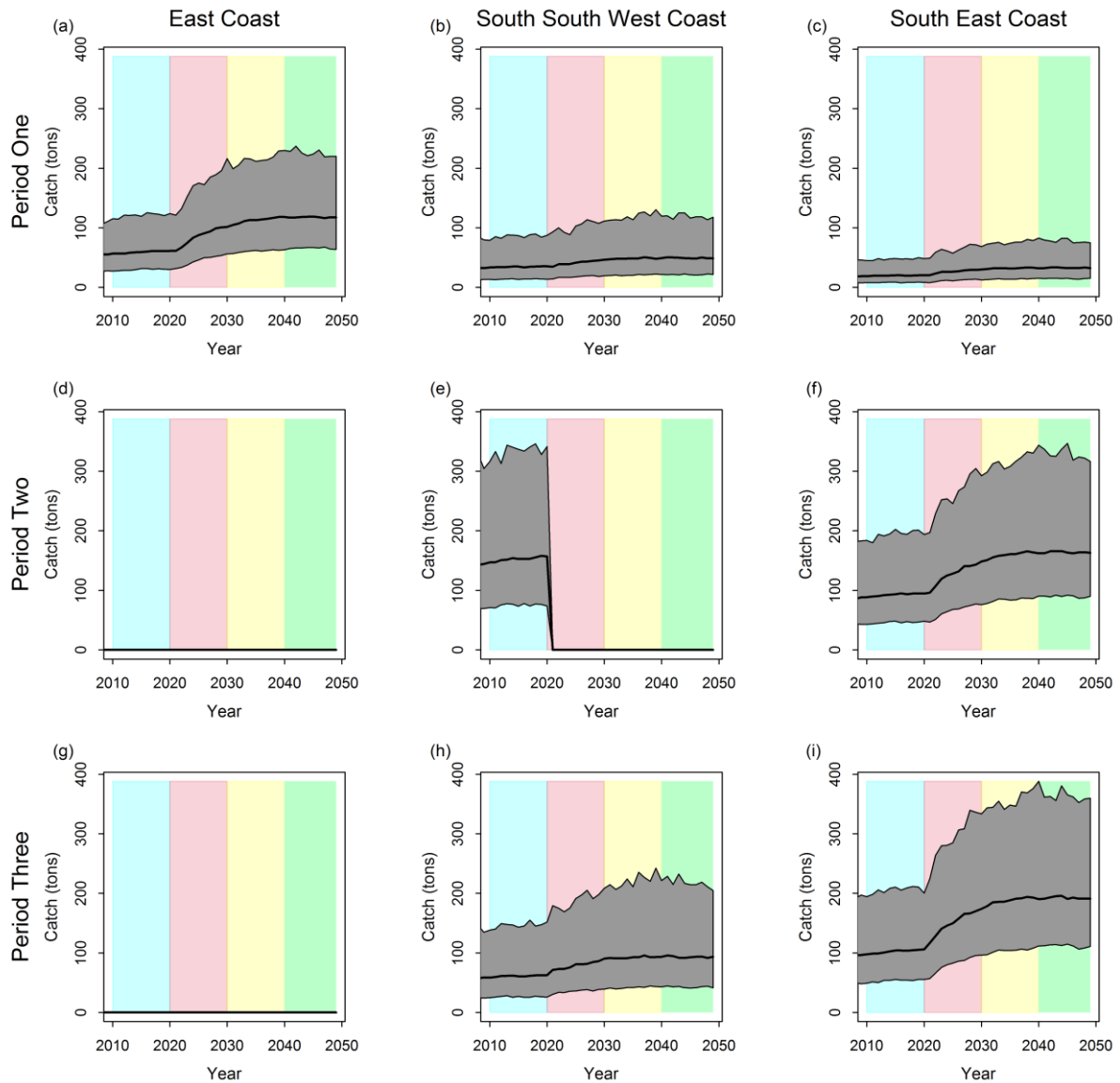


Figure C.30: Median simulated stock catch trajectories (black lines) of the South African geelbek from 2010 to 2050, with the implementation of a closed season and area in the south south west coast in period two (December to March), from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

6.3.7. Management strategy 8: Close south east coast in period three (April to July)

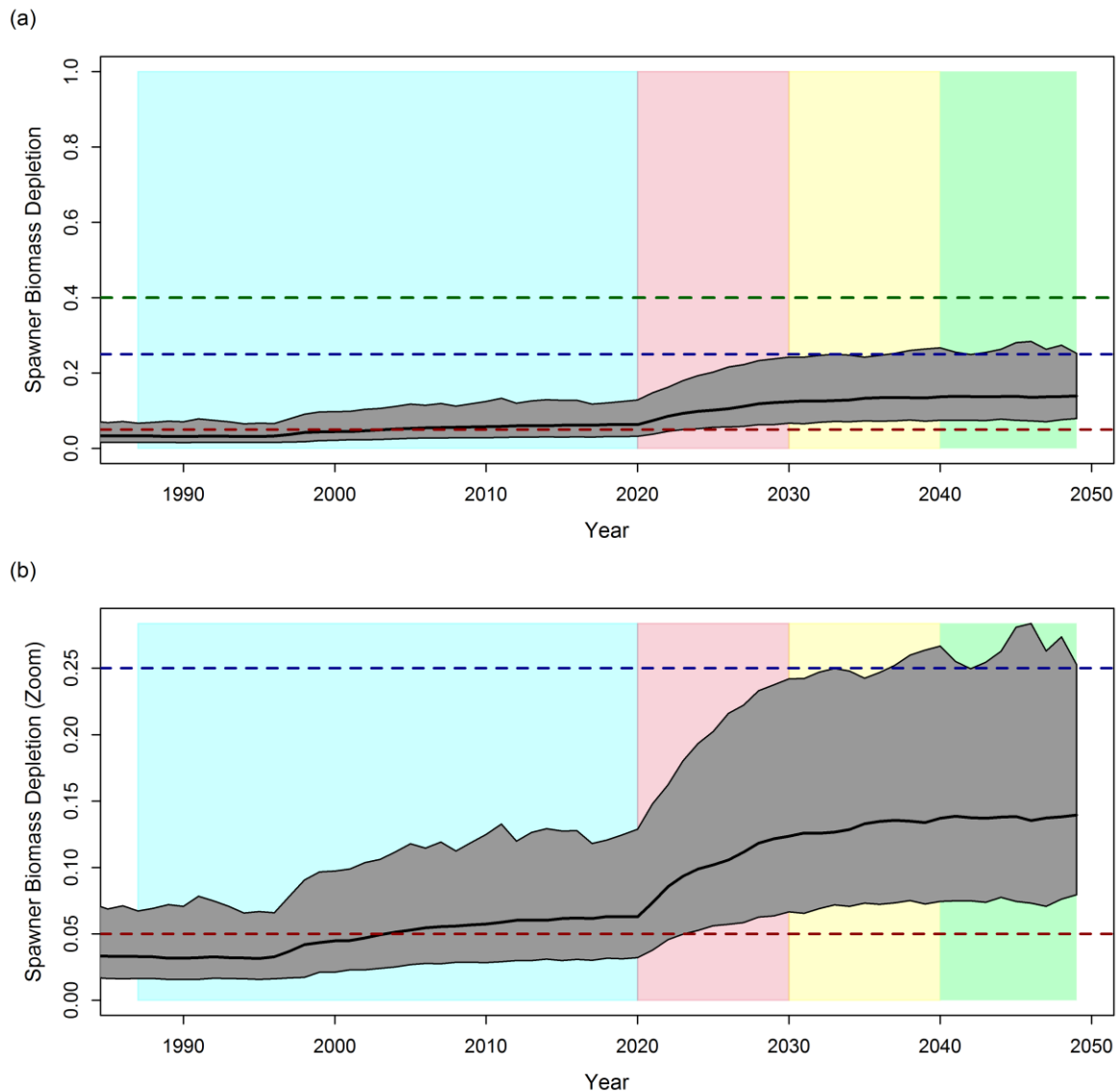


Figure C.31: Median relative (to pristine) simulated stock spawner biomass depletion trajectory (black line) of the South African geelbek from 1987 to 2050, with the implementation of a closed season and area in the south east coast in period three (April to July), from 2020 onwards. The depletion level is displayed relative to (a) the pristine population state and (b) the current estimated population level of ~5% pristine state. The 95% confidence limits are indicated (grey shaded areas). The NMLS data period from 1987 to 2011 is shaded blue, which extends as the pre-evaluation period until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area). Fisheries reference points of 40% SB_0 (dashed green line), 25% SB_0 (dashed blue line) and 5% SB_0 (dashed red line) are also included.

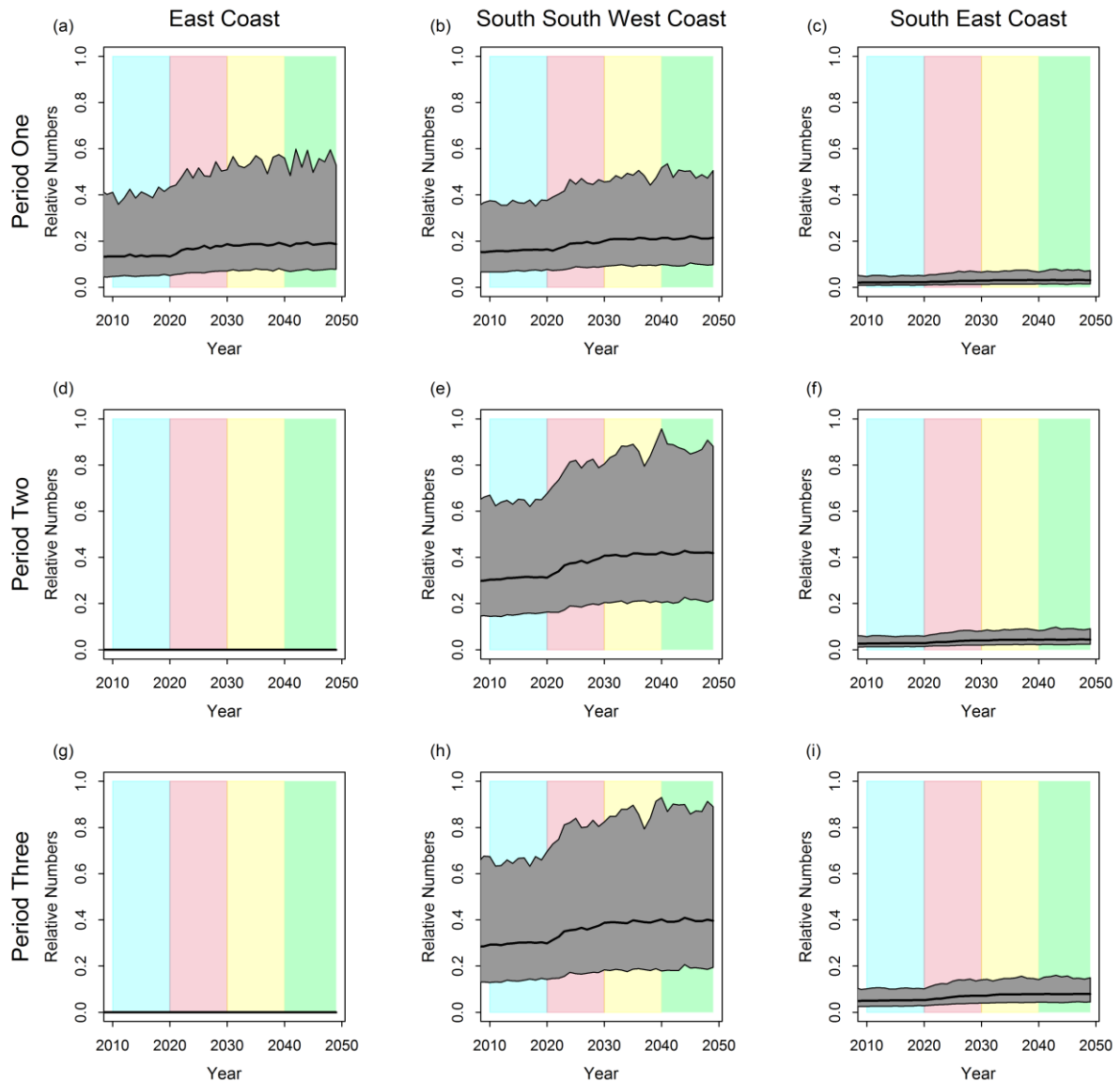


Figure C.32: Median relative (to pristine) stock numbers trajectories (black lines) of the South African geelbek from 2010 to 2050, with the implementation of a closed season and area in the south east coast in period three (April to July), from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

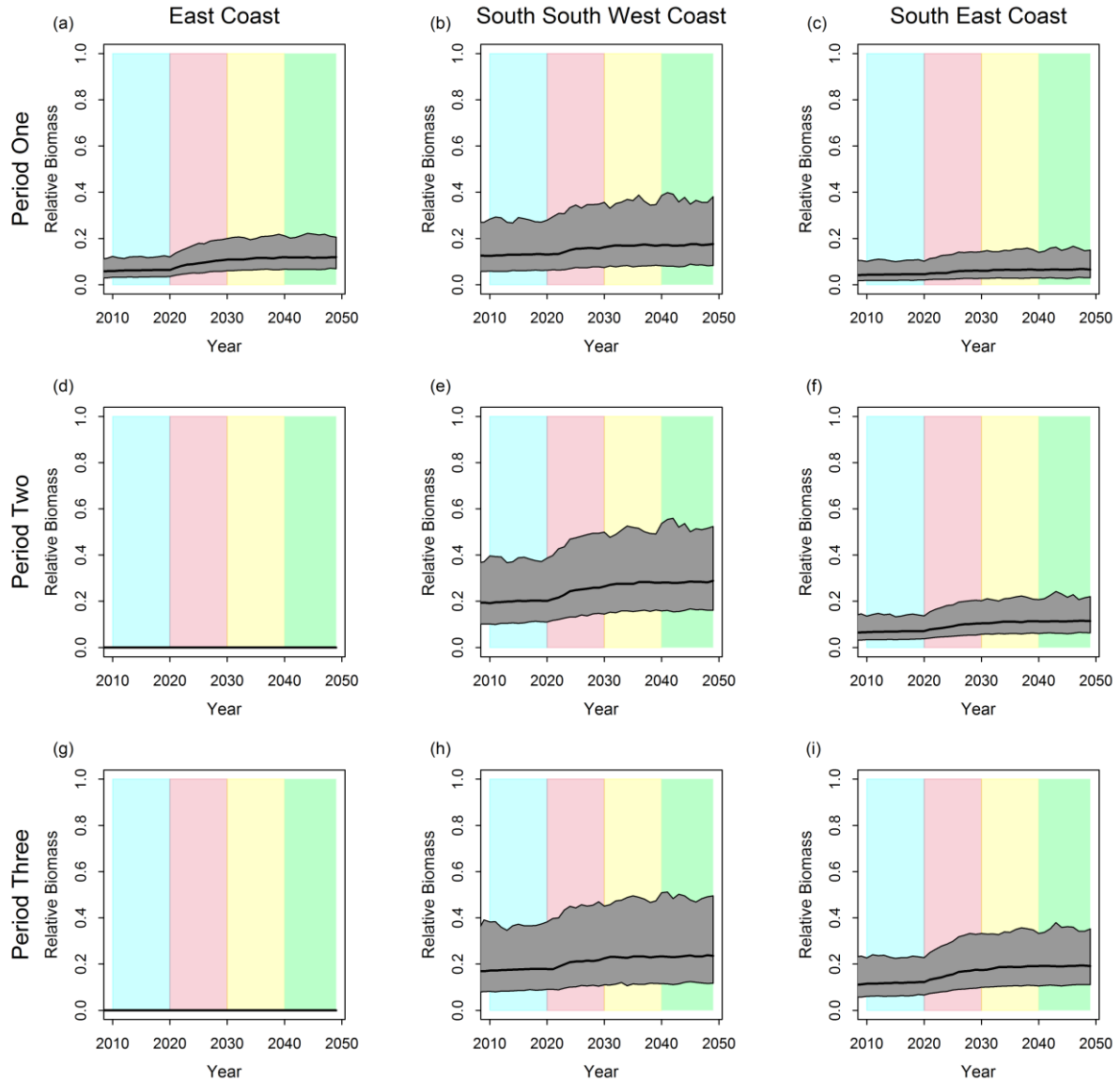


Figure C.33: Median relative (to pristine) stock biomass trajectories (black lines) of the South African geelbek from 2010 to 2050, with the implementation of a closed season and area in the south east coast in period three (April to July), from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

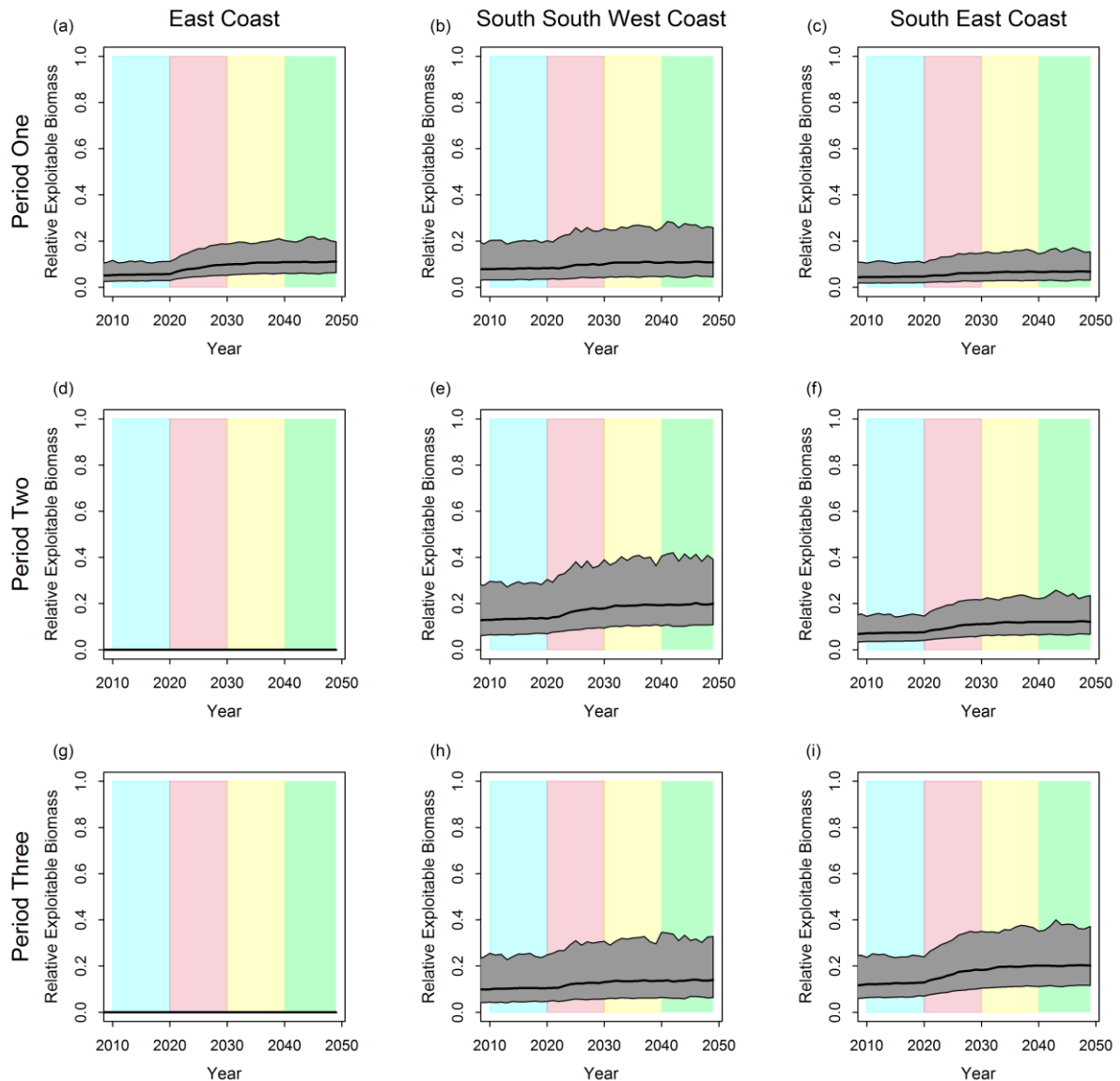


Figure C.34: Median relative (to pristine) stock exploitable biomass trajectories (black lines) of the South African geelbek from 2010 to 2050, with the implementation of a closed season and area in the south east coast in period three (April to July), from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

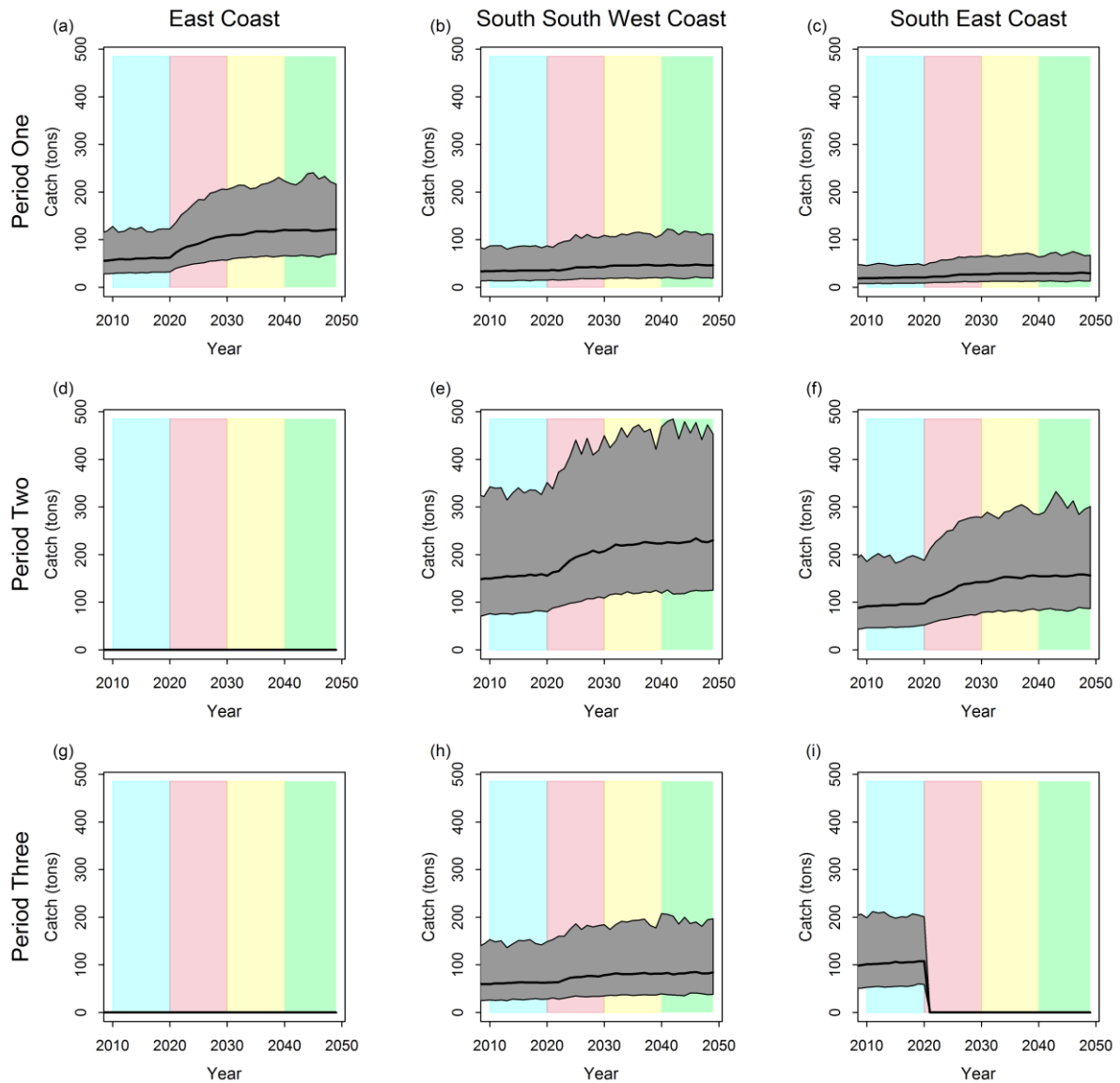


Figure C.35: Median simulated stock catch trajectories (black lines) of the South African geelbek from 2010 to 2050, with the implementation of a closed season and area in the south east coast in period three (April to July), from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

6.3.8. Management strategy 9: Increase minimum size limit to 650 mm TL

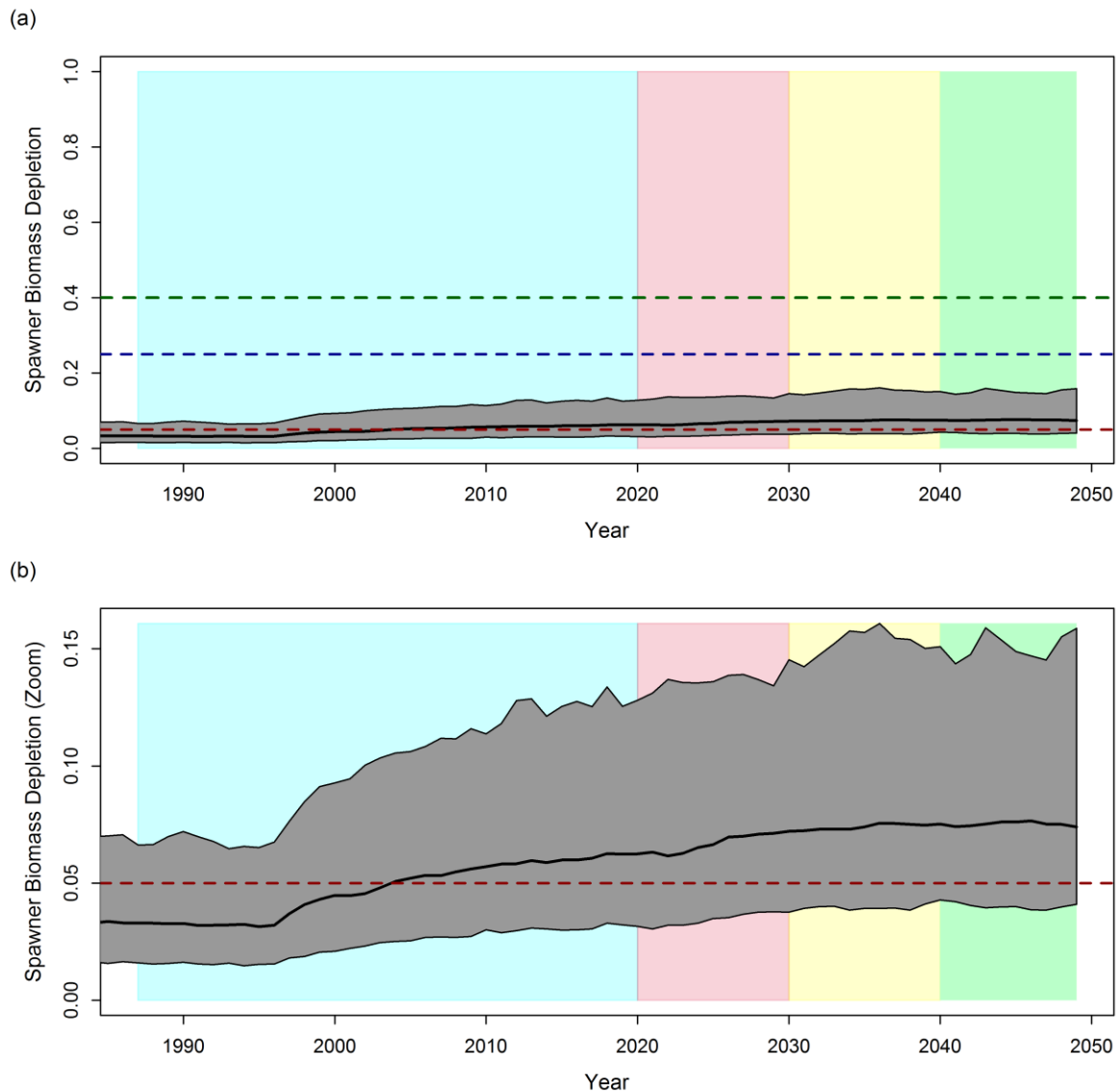


Figure C.36: Median relative (to pristine) simulated stock spawner biomass depletion trajectory (black line) of the South African geelbek from 1987 to 2050, with an increase in the minimum size limit to 650 mm TL (an increase of 50 mm) from 2020 onwards. The depletion level is displayed relative to (a) the pristine population state and (b) the current estimated population level of ~5% pristine state. The 95% confidence limits are indicated (grey shaded areas). The NMLS data period from 1987 to 2011 is shaded blue, which extends as the pre-evaluation period until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area). Fisheries reference points of 40% SB_0 (dashed green line), 25% SB_0 (dashed blue line) and 5% SB_0 (dashed red line) are also included.

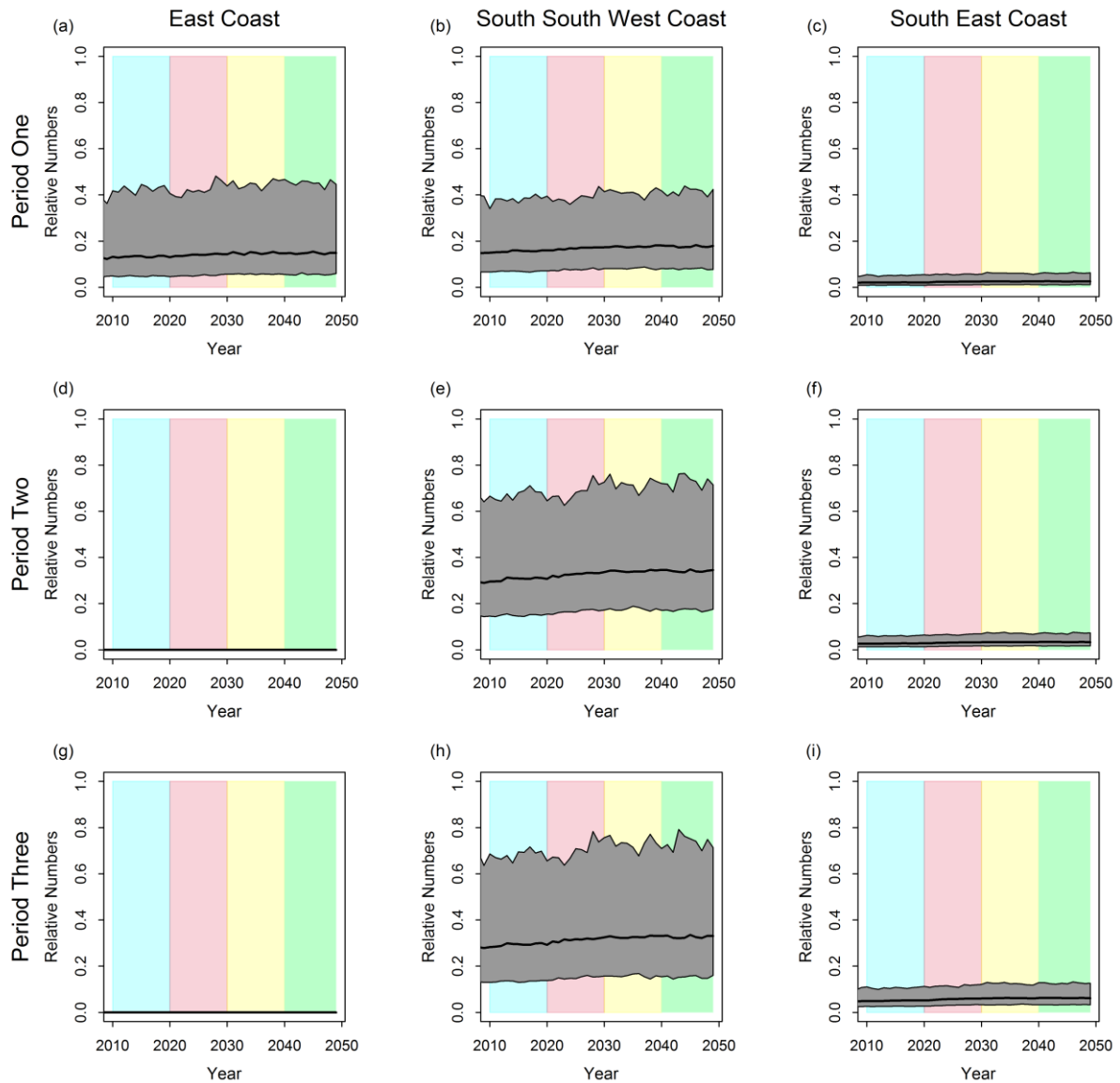


Figure C.37: Median relative (to pristine) stock numbers trajectories (black lines) of the South African geelbek from 2010 to 2050, with an increase in the minimum size limit to 650 mm TL (an increase of 50 mm) from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

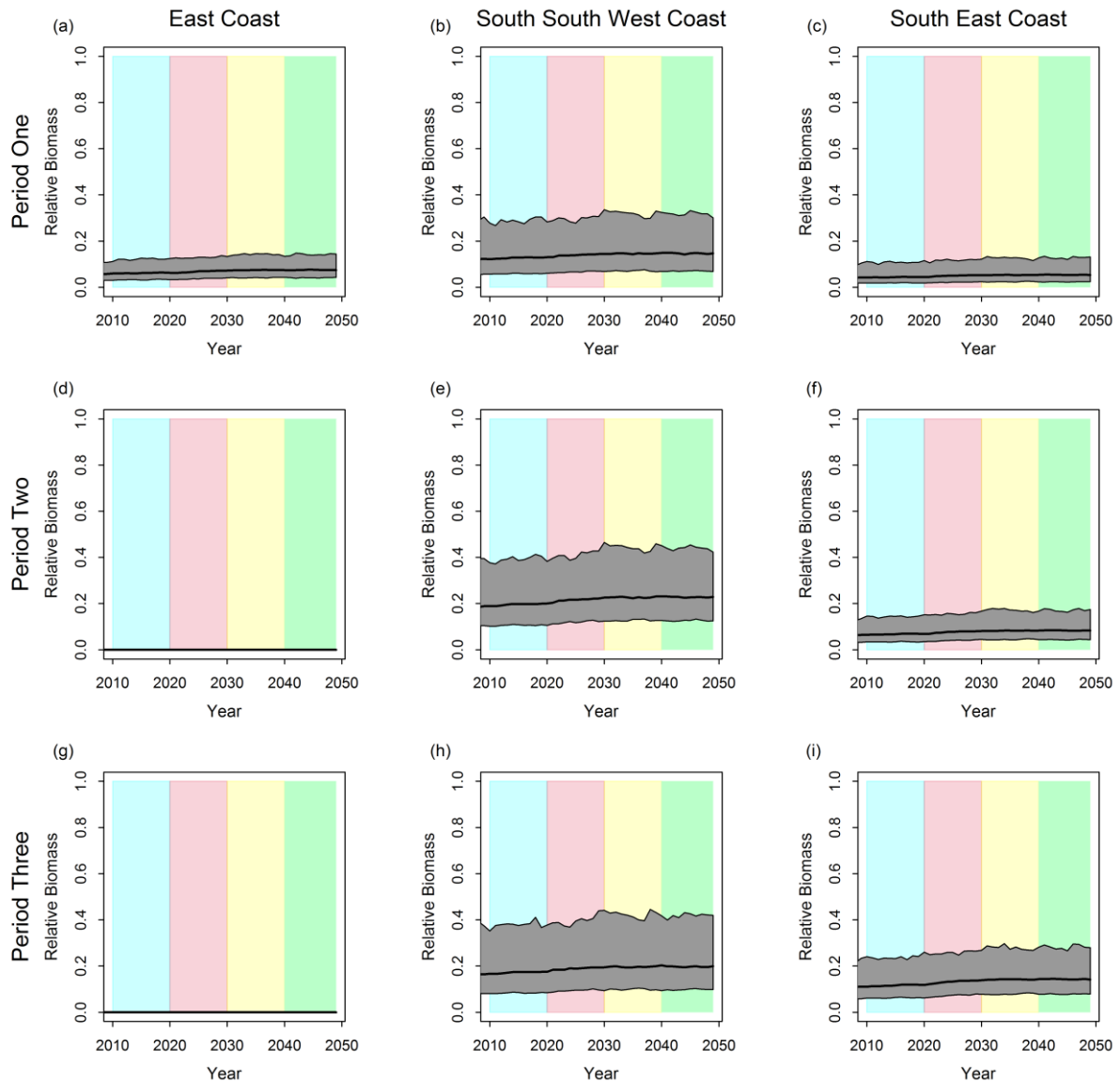


Figure C.38: Median relative (to pristine) stock biomass trajectories (black lines) of the South African geelbek from 2010 to 2050, with an increase in the minimum size limit to 650 mm TL (an increase of 50 mm) from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

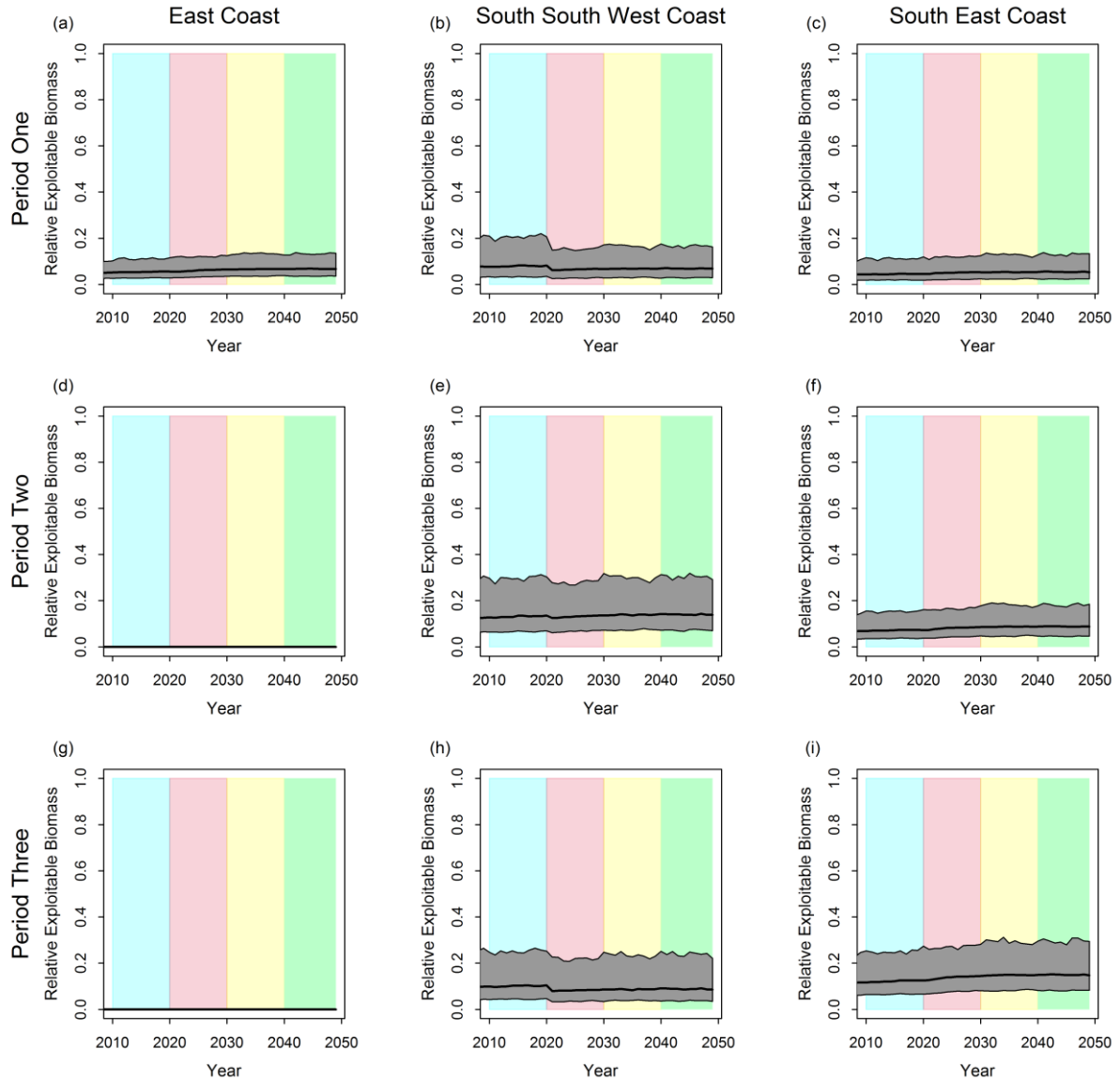


Figure C.39: Median relative (to pristine) stock exploitable biomass trajectories (black lines) of the South African geelbek from 2010 to 2050, with an increase in the minimum size limit to 650 mm TL (an increase of 50 mm) from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

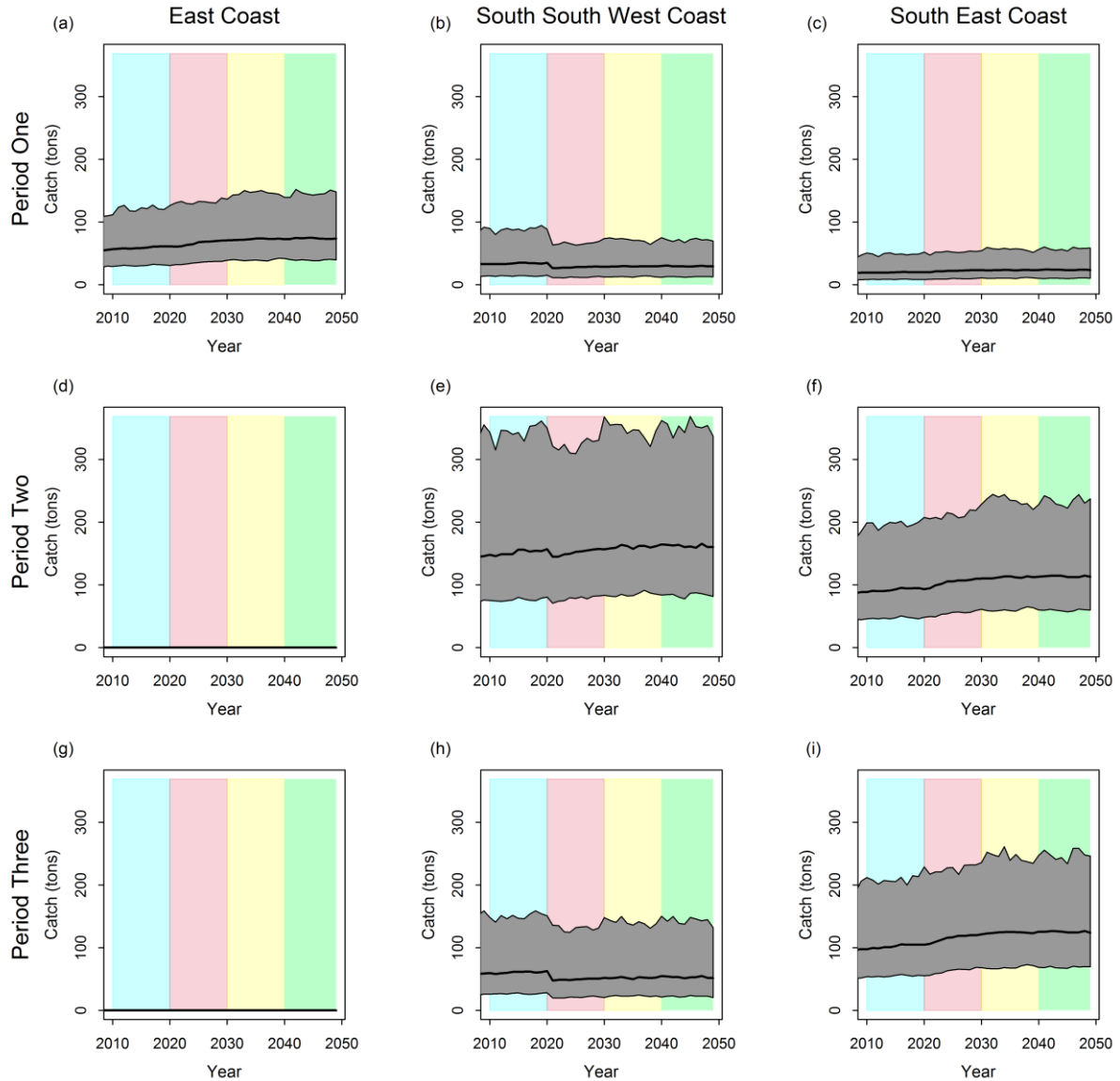


Figure C.40: Median simulated stock catch trajectories (black lines) of the South African geelbek from 2010 to 2050, with an increase in the minimum size limit to 650 mm TL (an increase of 50 mm) from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

6.3.9. Management strategy 10: Increase minimum size limit to 700 mm TL

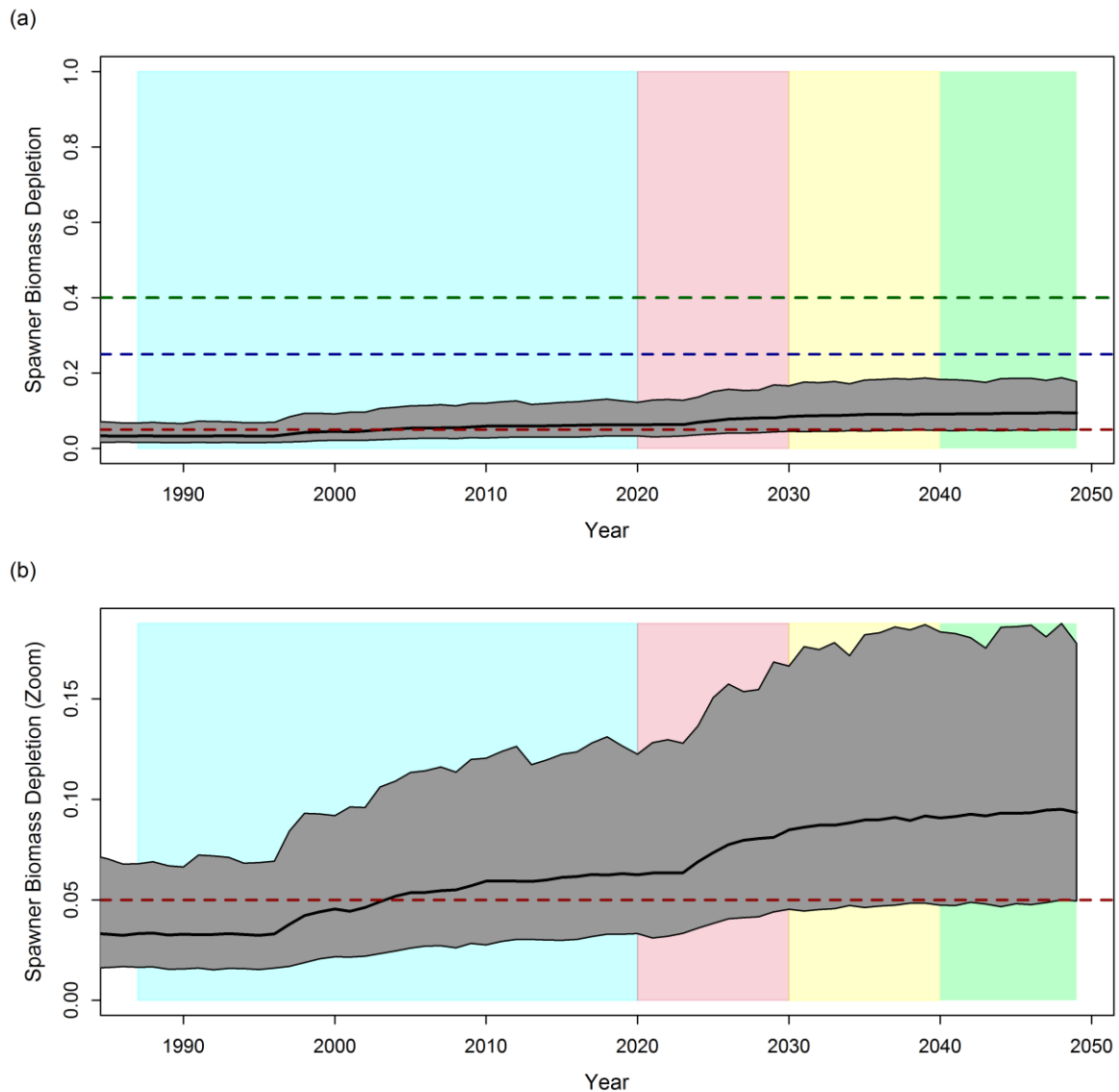


Figure C.41: Median relative (to pristine) simulated stock spawner biomass depletion trajectory (black line) of the South African geelbek from 1987 to 2050, with an increase in the minimum size limit to 700 mm TL (an increase of 100 mm) from 2020 onwards. The depletion level is displayed relative to (a) the pristine population state and (b) the current estimated population level of ~5% pristine state. The 95% confidence limits are indicated (grey shaded areas). The NMLS data period from 1987 to 2011 is shaded blue, which extends as the pre-evaluation period until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area). Fisheries reference points of 40% SB_0 (dashed green line), 25% SB_0 (dashed blue line) and 5% SB_0 (dashed red line) are also included.

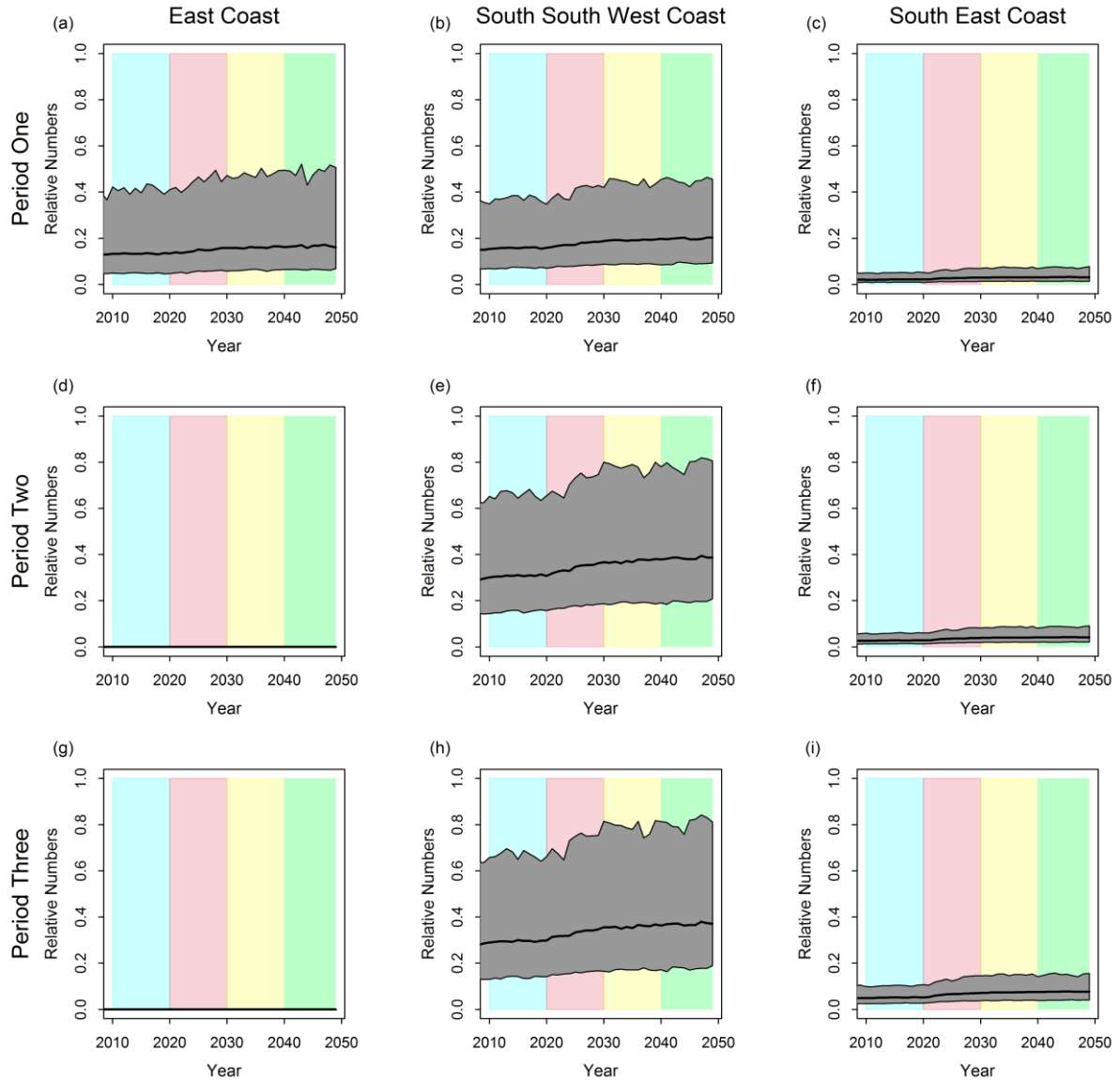


Figure C.42: Median relative (to pristine) stock numbers trajectories (black lines) of the South African geelbek from 2010 to 2050, with an increase in the minimum size limit to 700 mm TL (an increase of 100 mm) from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

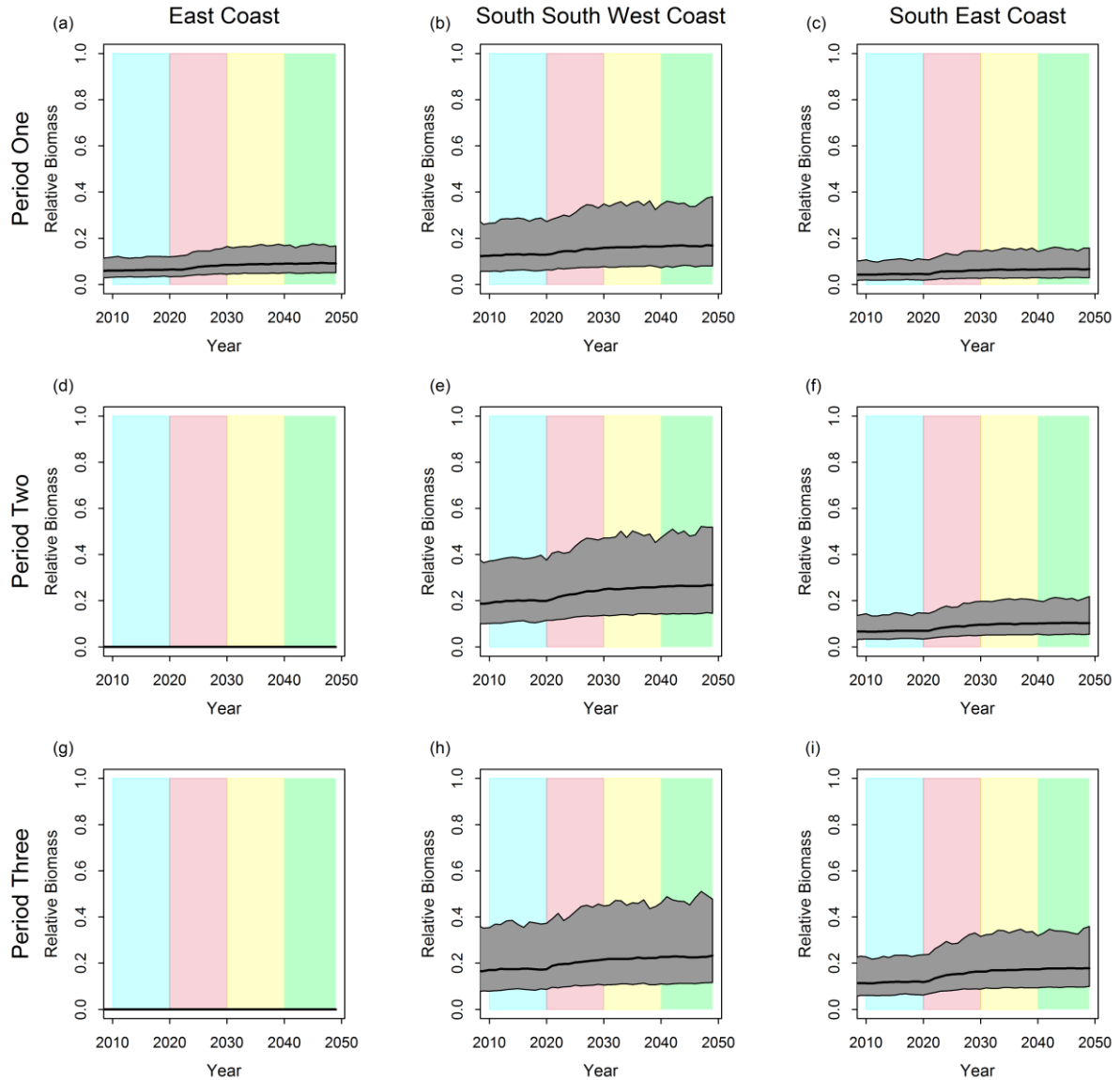


Figure C.43: Median relative (to pristine) stock biomass trajectories (black lines) of the South African geelbek from 2010 to 2050, with an increase in the minimum size limit to 700 mm TL (an increase of 100 mm) from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

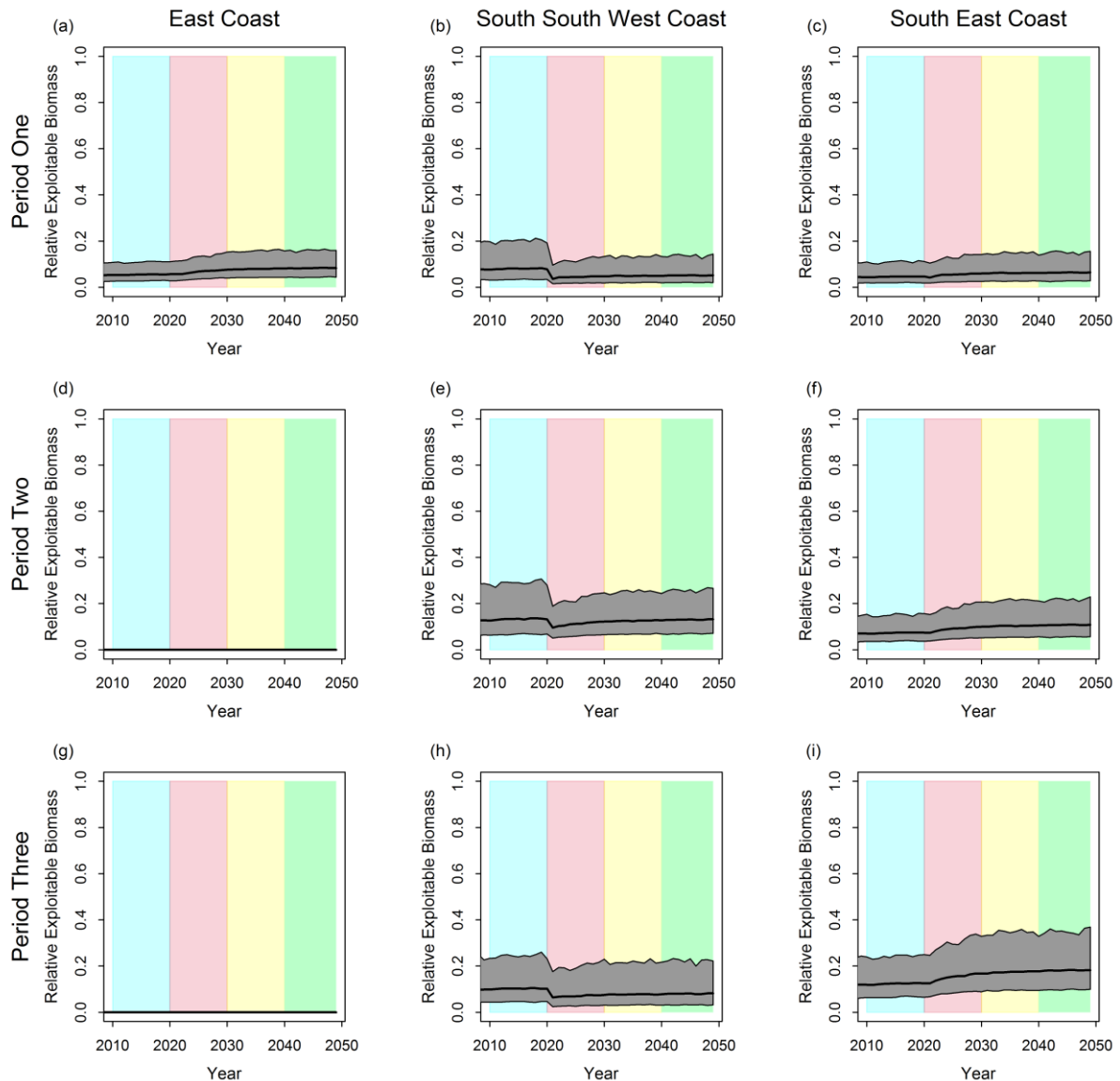


Figure C.44: Median relative (to pristine) stock exploitable biomass trajectories (black lines) of the South African geelbek from 2010 to 2050, with an increase in the minimum size limit to 700 mm TL (an increase of 100 mm) from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

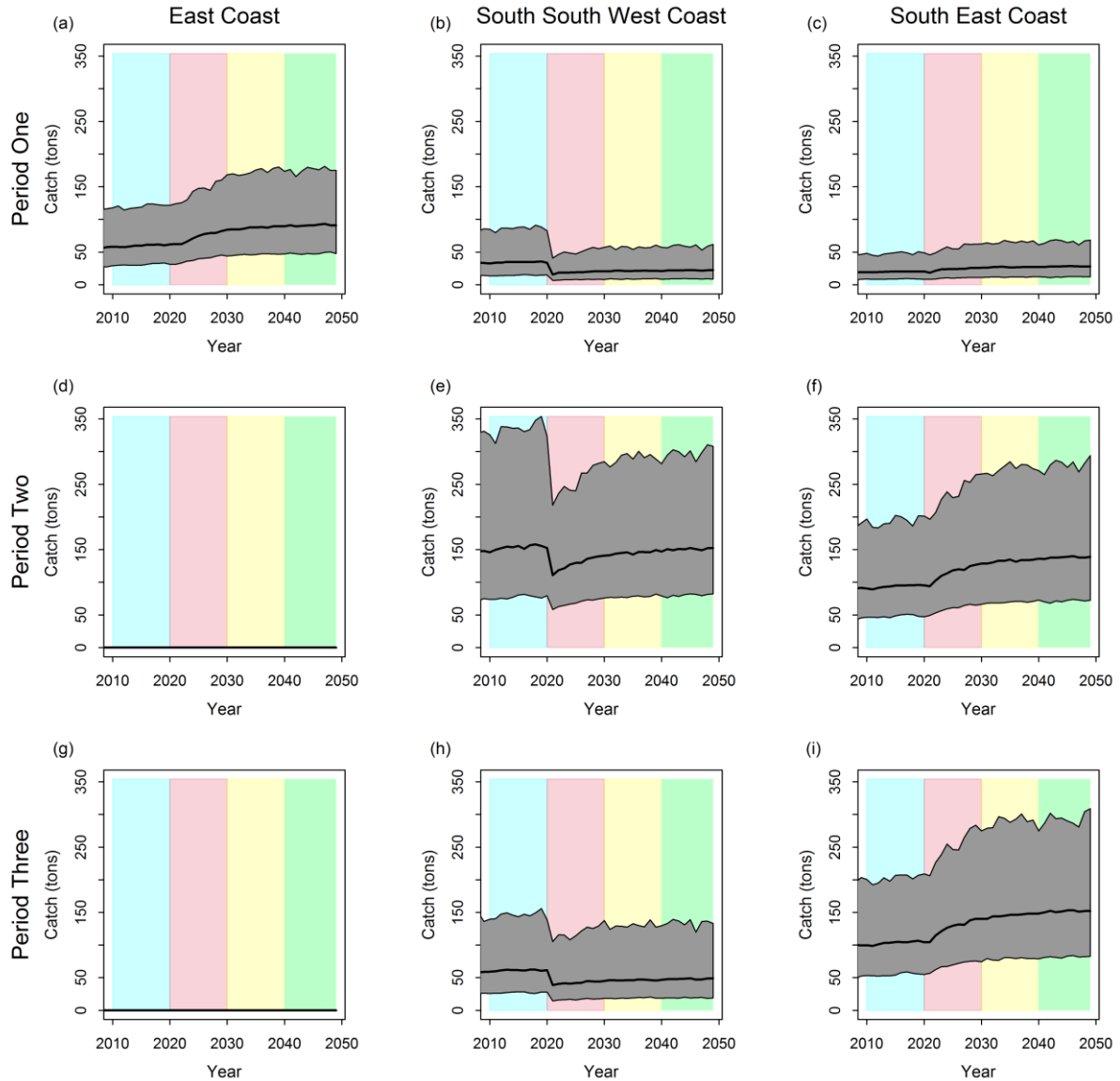


Figure C.45: Median simulated stock catch trajectories (black lines) of the South African geelbek from 2010 to 2050, with an increase in the minimum size limit to 700 mm TL (an increase of 100 mm) from 2020 onwards. The nine subplots (a to i) display the intrannual migration of the stock across three regions and three time periods. Period one refers to August to November, period two refers to December to March and period three refers to April to July. The 95% confidence limits are indicated (grey shaded areas). A pre-evaluation period extends from 2010 to 2020 (blue shaded area), which extends until the implementation of a management strategy at 2020. The medium term evaluation period of ten years extends from 2020 to 2030 (pink shaded area). The long term evaluation period of twenty years extends from 2020 to 2040 (yellow shaded area, from 2030 to 2040). An additional prediction period of ten years extends from 2040 to 2050 (green shaded area).

6.4. Appendix D: Geelbek operating model (GLBK OM) in R

This appendix contains the instructions and interface for the management simulation tool: Geelbek Operating Model (GLBK OM). It also contains an excerpt from the Age-Structured Equilibrium Model (ASEM), which contains the base migration model for geelbek.

6.4.1. Instructions for geelbek operating model (GLBK OM)

The **Geelbek Operating Model (GLBK OM)** runs two separate spatially and temporally explicit models regarding South African geelbek.

- 1) An **Age-Structured Equilibrium Model (ASEM)** which contains:
 - (i) Catch curve analysis using commercial catch data
 - (ii) Per-recruit model
 - (iii) Generates region and period specific selectivity parameters and harvest rates, among other results (see Model Output below).

- 2) A dynamic **Age-Structured Production Model (ASPM)** which contains:
 - (i) Dynamic age-structured production model which incorporates the history of the stock (regarding an increase in the minimum size limit from 400 mm to 600 mm in 1992).
 - (ii) Estimated pristine stock biomass $SB_0 = 3500$ tons (found through calibration with commercial catch data, and can be edited).
 - (iii) Parameterised using region and period specific selectivity parameters and harvest rates generated by the ASEM.
 - (iv) Simulations: Any number of model simulations can be run (suggested 100 - 10000). Final model output shows the median and lower and upper quantiles of all the simulations.
 - (v) Management Strategy Evaluation: 11 Different management strategies (MS) are tested (Table D.1 below, a repeat of Table 3.8 in the thesis Results chapter).

Both models incorporate the spatial and temporal migration dynamics of South African geelbek across three coastal regions, namely the south south west (*SSW*), south east (*SE*) and

east (*E*) coasts, and three time periods, with period one (*P1*) running from August to November, period two (*P2*) from December to March and period three (*P3*) from April to July (Figure 2.5). Figure D.1, below, illustrates this as a schematic diagram, while Figure D.2 displays this in map format (repetitions of Figure 2.2 and Figure 2.3, respectively, in the thesis Methods and materials chapter).

The model is in a Windows folder called **GLBK OM**.

- The folder contains 2 sub-folders, **GLBK ASEM** and **GLBK ASPM**, these **contain the source code** to run the models and **should not be edited** in any way.
- There are also 2 R files in the GLBK OM folder: ‘**GLBK OM Primary File.R**’ and ‘**GLBK OM Primary File Mini.R**’ which **run the model**.
- It is recommended to use ‘**GLBK OM Primary File Mini.R**’ to **run the model**.
- **Only use one of these 2 files at a time**, as one is simply a more condensed version (the Primary File Mini) than the other (Primary File). The Primary File explains the different parts of the Age-Structured Production Model (GLBK ASPM) in more detail.

How to run the model using ‘GLBK OM/GLBK OM Primary File Mini.R’:

- 1) Ensure you have R and RStudio installed and working on your computer.
- 2) Select a location for the GLBK OM folder. Eg. C:\DanielleRStudio\GLBK OM
- 3) Open the GLBK OM folder.
- 4) Open GLBK OM Primary File Mini.R in RStudio (or R).
- 5) Go to lines 7 and 8 of the code which are:

```
# SET WORKING DIRECTORY
PrimaryFile = "C:/DanielleRStudio/GLBK OM"
```

- 6) Change the PrimaryFile location to the location of your GLBK OM folder.
Eg. PrimaryFile = "C:/Work/Research/MSD_Danielle/GLBK OM"

- 7) Go to line 28 of the code and set the number of simulations you want to run of the Age-Structured Production Model (GLBK ASPM).

Eg. # SET NUMBER OF SIMULATIONS FOR TESTING OF GEELBEK OPERATING MODEL (ASPM)

```
nsims = 1000    #Number of simulations (should be at least 200 for final runs)
```

*While 200+ simulation runs are recommended, a lower number such as 20 simulation runs is sufficient for quick parameter checking [not for final results].

- 8) Additional: Scroll down the code and inspect the parameters used for the running of the Age-Structured Production Model (GLBK ASPM) in more detail. These parameter values are considered the best possible choices; however, some of these can be set to another logical value.
- 9) Select all the code (Ctrl+A) in the file 'GLBK OM Primary File Mini.R' and run it (Ctrl+R).
- 10) The GLBK OM model can take between 5 minutes (20 simulation runs) to 2 hours (1000 simulation runs) to run (using a laptop with an i7 Intel processor with 8gigs of RAM).

How to find and understand the GLBK OM model output/results:

- 1) Open the GLBK OM folder after running the model as instructed above.
- 2) You will see 2 new sub-folders: **GLBK ASEM Results** and **GLBK ASPM Results**
- 3) The **GLBK ASEM Results** folder contains the following files:
 - (i) **6 CSV Excel files**, specifically:
 - (a) 'ASEM Selectivity Parameters by Region.csv'
 - (b) 'ASEM Total Mortality Z Obs vs Pred.csv'
 - (c) 'ASEM Harvest Rates by Region and Period.csv'
 - (d) 'ASEM Stock State from Per Recruit Model.csv'
 - (e) 'ASEM Vulnerable Biomass from Per Recruit Model.csv'
 - (f) 'ASEM Yield from Per Recruit Model.csv'
 - (ii) **4 PNG Image files**, specifically:
 - 1) 'ASEM Catch Curves by Region.png'
 - 2) 'ASEM Selectivity by Region.png'
 - 3) 'ASEM Per Recruit Numbers Fished Unfished.png'

4) 'ASEM Spawner Biomass Isopleth.png'

4) The **GLBK ASPM Results** contains the following folders:

(a) **11 MS (Management Strategy) folders**, which each contain **Results** and **Plots folders**:

1) **Results folder** contains **many excel csv files**, which contain the numeric data of all the simulation runs for every metric in the model. It is suggested to **avoid these** unless necessary.

Each file is named according to: The specific management strategy number, the metric, the region, the period, and then any additional qualifiers, such as quantiles or relative metrics. Eg. MS.1.NAA.E.PI is Management Strategy 1, for Numbers-at-age, in the East Coast, in Period 1.

2) **Plots folder** contains several image files describing the basic stock metrics. These metrics are:

(i) **Spawner biomass depletion**

1) 'MS.1.1 ASPM SB Dep Double.png'

2) 'MS.1.b1 ASDM SB Dep Single.png'

3) 'MS.1.b2 ASDM SB Single.png'

(ii) **Population metrics of numbers, biomass, exploitable biomass** (both relative and in relation to the model input parameters) and **catch** (in relation to model) **across all regions and periods**.

1) 'MS.1.4 ASPM 9 N Relative.png'

2) 'MS.1.5 ASPM 9 B Relative.png'

3) 'MS.1.6 ASPM 9 EB Relative.png'

4) 'MS.1.b4 ASPM 9 N.png'

5) 'MS.1.b5 ASPM 9 B.png'

6) 'MS.1.b6 ASPM 9 EB .png'

7) 'MS.1.b7 ASPM 9 C.png'

(b) **1 MSE (Management Strategy Evaluation) Summary Results Plots** folder, which contains the following **files**:

(1) 'Data Analysis Catch'.png

(2) 'Data Analysis Catch Proportion'.png

(3) 'SB Dep MS Split All'.png

(4) 'SB Dep MS All Medium Eval Projection Only'.png

(5) 'Boxplot SB Dep MS All'.png

(6) ‘Table of Spawner Biomass Depletion Values for All Evaluation Periods.csv’

5) The sub-folders **GLBK ASEM Results** and **GLBK ASPM Results** can be **deleted** to save space, or **copied to another location to ensure the results are saved**. Otherwise the **model is designed to over-write old model results** in favour of new ones.

An overview of the spatial and temporal dynamics and management strategies mentioned at the start of these instructions are illustrated below:

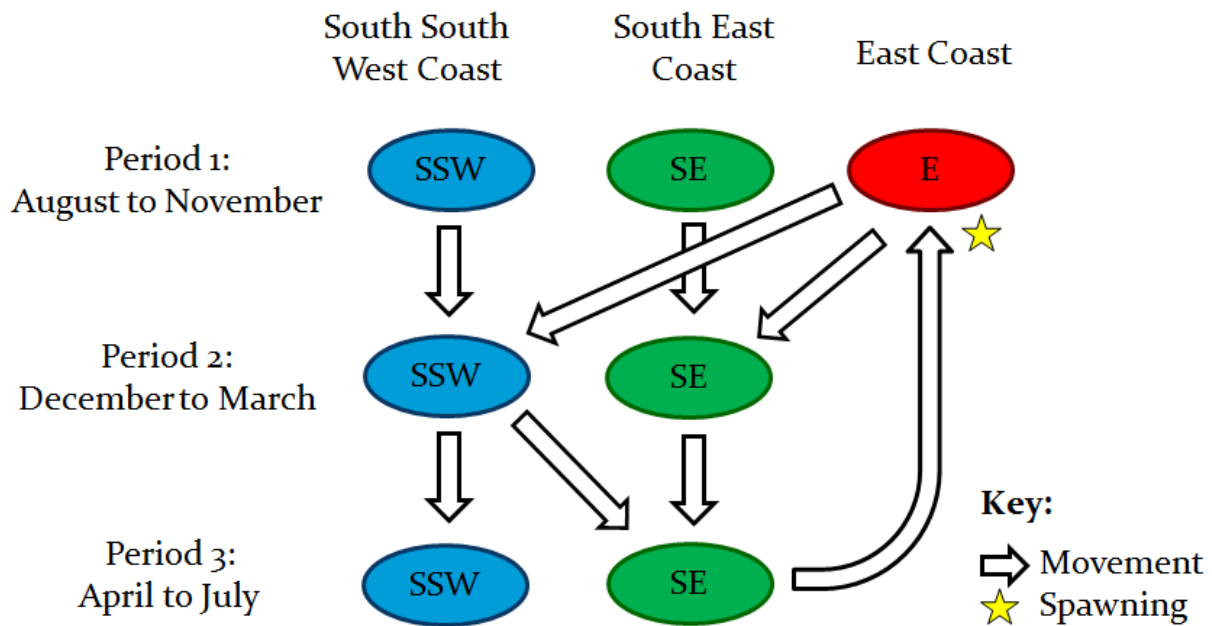


Figure D.1: Spatial and temporal migration dynamics of South African geelbek across three coastal regions, namely the south south west (SSW), south east (SE) and east (E) coasts, and three time periods, with period one (P1) running from August to November, period two (P2) from December to March and period three (P3) from April to July. Arrows indicate direction of movement, and the yellow star indicates the annual spawning event in the east coast (E) in period one (P1).

Table D.1: Summary of management strategies in regards to spatially and temporally explicit (region and period specific) harvest rates for the species and their implementation in the GLBK OM.

Strategy type	MS	Management strategy	Symbol
No change	1	<i>Status quo</i>	$H_{CURRENT}$
Reduce H	2	Moratorium	$H = 0$
	3	Reduce H by 10% across all regions and periods	$90\% H_{CURRENT}$
	4	Reduce H by 20% across all regions and periods	$80\% H_{CURRENT}$
	5	Reduce H by 50% across all regions and periods	$50\% H_{CURRENT}$
	Closed season and area	6	Close season in period one in east coast for spawning season
7		Close season in period two in south south west coast	$H_{SSW,P2} = 0$
8		Close season in period three in south east coast	$H_{SE,P3} = 0$
Increase minimum size limit (SL)	9	Increase minimum size limit to 650 mm TL (50 mm increase)	$SL = 650\text{ mm}$
	10	Increase minimum size limit to 700 mm TL (100 mm increase)	$SL = 700\text{ mm}$
	11	Increase minimum size limit to 950 mm TL (size-at-50%-maturity)	$SL = 950\text{ mm}$

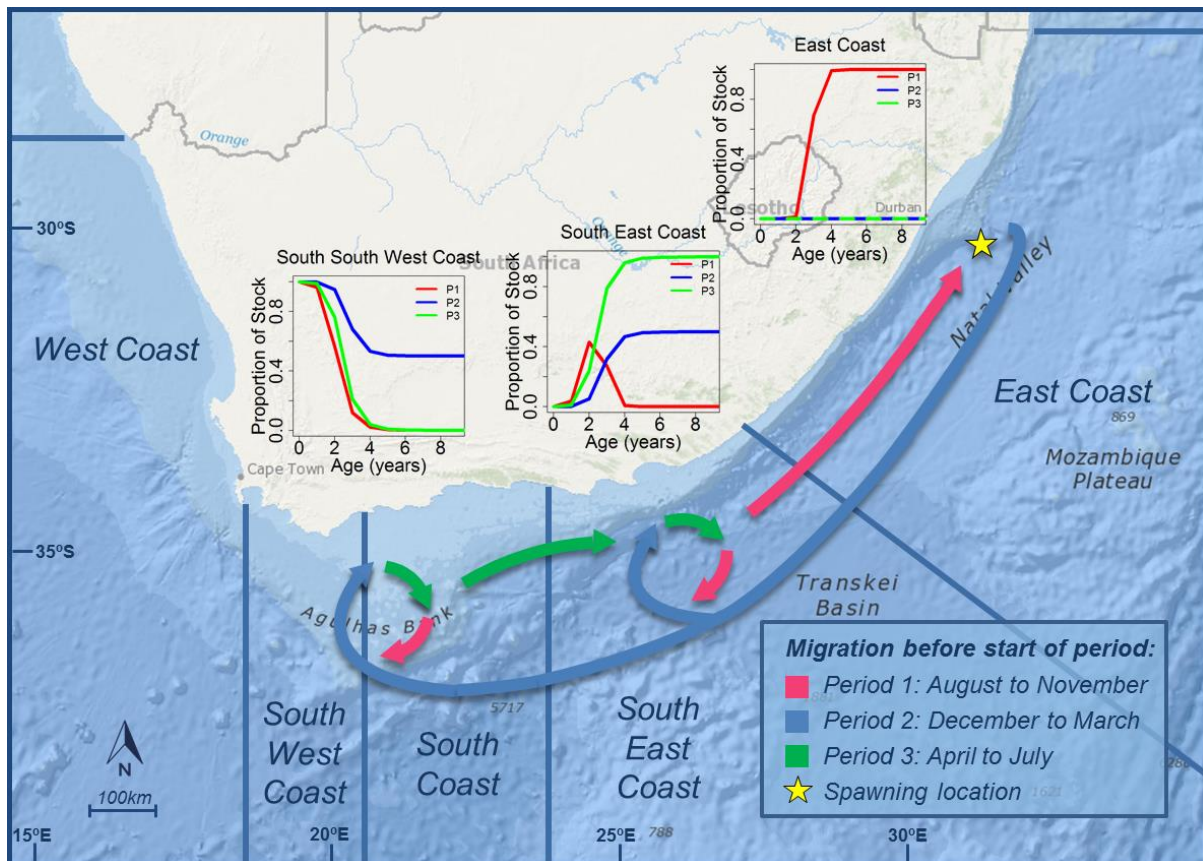


Figure D.2: Map of the spatial and intrannual temporal distribution of the geelbek stock along the South African coast (adapted from Griffiths and Hecht, 1995). Broad arrows show the theoretical movement of the stock along the coast within a single year (twelve month period). The colour of the arrow indicates the time of migration, estimated as the instantaneous moment between the end of the previous period and start of the following period. Arrival by the start of period one, in August, is illustrated in pink, arrival by the start of period two, in December, is illustrated in blue, and arrival by the start of period three, in April, is illustrated in green. Plots of the proportion of the stock (-at-age) estimated to be in each coast at each period are shown. The colours align with each period, as they do for the migration. The five management regions suggested by Blamey *et al.* (2015) are shown, namely, the west, south west, south, south east and east coasts. This study combines the south west coast and the south coast into the south south west coast.

6.4.2. Interface for geelbek operating model (GLBK OM)

As mentioned in the instructions above, the Geelbek Operating Model is run from a single file, which operates as the user interface. While the condensed file ‘GLBK OM Primary File Mini.R’ is recommended above, the full interface ‘GLBK OM Primary File.R’ is shown below (Code D.1).

Code D.1: Reproduction of the file 'GLBK OM Primary File.R', which serves as the user interface for the management simulation tool for geelbek: Geelbek Operating Model (GLBK OM).

```
#####
# PRIME CODE FOR GEELBEK OPERATING MODEL BY DANIELLE BOYD AND HENNING WINKER #
#####

# SET WORKING DIRECTORY
PrimaryFile = "C:/DanielleRStudio/GLBK OM"
setwd(paste(PrimaryFile))

# OVERVIEW OF REGION- AND SEASON-SPECIFIC MIGRATION (AND SYMBOLS)
# REGIONS
    # East Coast = E
    # South South West Coast = SSW
    # South East Coast = SE
# PERIODS
    # Period 1 = P1: August to November = Months 8 to 12: Move at 8, Caught at 10
    # Period 2 = P2: December to March = Months 12 to 4: Move at 12, Caught at 2
    # Period 3 = P3: April to July = Months 4 to 8: Move at 4, Caught at 6

# Migration Probabilities (MigProb) refer to the probability of moving INTO a coast by the start of the period
# Eg. MigProb.E.P1 = Migration Probability that a fish will move INTO THE EAST COAST BY PERIOD 1 (so the
    actual movement is from the population currently in SE and P3)

#####
# PRIME CODE FOR GEELBEK AGE-STRUCTURED EQUILIBRIUM MODEL #
#####
source("GLBK ASEM/GLBK ASEM Catch Curve.R")
#Contains Catch Curve analysis, Selectivity parameters, Harvest rates and Per-Recruit Model

#####
# PRIME CODE FOR GEELBEK AGE-STRUCTURED PRODUCTION MODEL #
#####

# SET NUMBER OF SIMULATIONS FOR TESTING OF GEELBEK OPERATING MODEL (ASPM)
nsims = 1000                #Number of simulations (should be at least 200 for final runs)

# SET VALUES FOR SIMULATION TESTING OF GEELBEK OPERATING MODEL (ASPM)
start.year = 1950           #Start year for burn-in
size.limit.change.year = 1992 #Size limit changed from 400mm to 600mm, affecting gear selectivity
data.year = 1987           #Year dataset starts properly
end.data.year = 2011       #Year dataset ends properly
change.year = 2020         #Year management changes are implemented for harvest (H) and gear selectivity
                            (sel.Gear)
```

```

medium.eval.year = 2030      #End of Medium Term Evaluation Period
long.eval.year = 2040      #End of Long Term Evaluation Period
end.year = 2050           #End year
SB0 = 3500                #Assumed starting Spawner Biomass, equal to K in this scenario!!
SB0ref = 0.05             #Spawner Biomass depletion at the start
RecSigma = 0.6           #Recruit sigma, the inherent variability of recruitment variation
M = 0.38                  #Natural mortality, can also be calculated within model
h = 0.85                  #Steepness, can also be calculated within model
pre.SBC = 0.6             #Proportion of pre-spawning catch (assume this much of spawning stock is caught
                           before spawning event, 1 = 100% caught)

#####
# MODEL SIMULATION #
#####

Management.Strategy = seq(1,11,1)

for (m in 1:length(Management.Strategy)){
  source(paste0("GLBK ASPM/MS Defined/MS (",m, ").R"))
  Assessment = paste("MS.", Management.Strategy[m], sep= "")

source("GLBK ASPM/Initial Parameters and Life History Equations.R")
source("GLBK ASPM/Simulation Matrices Define.R")
for(s in 1:nsims){

# INITIAL BURN IN OF MODEL WITH SIZE LIMIT OF 400 MM
source("GLBK ASPM/Harvest Parameters Initial.R")
source("GLBK ASPM/Model Initial.R")

# CURRENT MODEL WITH SIZE LIMIT OF 600 MM (MAJORITY OF DATA ALIGNS WITH THIS PERIOD)
source("GLBK ASPM/Harvest Parameters Current.R")
source("GLBK ASPM/Model Current.R")

# PREDICTIVE MODEL APPLYING VARIOUS MANAGEMENT STRATEGIES
source("GLBK ASPM/Harvest Parameters Predict.R") #This file requires MS loop to operate.
source("GLBK ASPM/Model Predict.R")

source("GLBK ASPM/Simulation Matrices Fill.R")
}
source("GLBK ASPM/Simulation Matrices Refine.R")
source("GLBK ASPM/Data Analysis.R")
source("GLBK ASPM/Results Save.R")
source("GLBK ASPM/Results Save Plots.R")
}
source("GLBK ASPM/Results Summary Plots.R")
#####

```

6.4.3. Excerpt from age-structured equilibrium model (ASEM)

The following code (Code D.2) is a partial excerpt from the file ‘GLBK ASEM Equilibrium Function.R’, which forms part of the Age-Structured Equilibrium Model (ASEM), a component of the Geelbek Operating Model (GLBK OM). The code is located within a function which determines the stock status for geelbek, and which is sourced from within the file ‘GLBK ASEM Catch Curve.R’, which is further sourced from the user interface for the management simulation tool for geelbek: Geelbek Operating Model (GLBK OM).

This excerpt contains some of the life history equations, including those for region- and period-specific selectivity and migration probabilities. It also contains the spatially and temporally explicit base model for geelbek, and is shown in both unfished and fished per-recruit analyses (as well as a basic unfished per-recruit analysis with no migration, for comparison).

Code D.2: Partial reproduction of the file ‘GLBK ASEM Equilibrium Function.R’. The code below is located within a function which determines the stock status for geelbek.

```
#####  
# AGE-STRUCTURED EQUILIBRIUM PER-RECRUIT MODEL FOR GEELBEK OPERATING MODEL #  
Computes Spawner Biomass (SB), Yield and Exploitable Biomass (EB) with Beverton and Holt (S-R)  
#####  
  
# LIFE HISTORY  
#Length-at-age at start of time period (L is for movement)  
L = Linf*(1-exp(-kappa*(age-a0))) #Used for plotting graphs  
L.P1 = Linf*(1-exp(-kappa*(age-a0+(0/6))))  
L.P2 = Linf*(1-exp(-kappa*(age-a0+(2/6))))  
L.P3 = Linf*(1-exp(-kappa*(age-a0+(4/6))))  
  
#Length-at-age in middle of time period (Lhalf is for catch)  
Lhalf.P1 = Linf*(1-exp(-kappa*(age-a0+(1/6))))  
Lhalf.P2 = Linf*(1-exp(-kappa*(age-a0+(3/6))))  
Lhalf.P3 = Linf*(1-exp(-kappa*(age-a0+(5/6))))  
  
#Weight-at-age at start of time period (W is for movement)  
W = aLW*L^bLW #Used for plotting graphs  
W.P1 = aLW*L.P1^bLW  
W.P2 = aLW*L.P2^bLW  
W.P3 = aLW*L.P3^bLW  
  
#Weight-at-age in middle of time period (Whalf is for catch)  
Whalf.P1 = aLW*Lhalf.P1^bLW
```

```
Whalf.P2 = aLW*Lhalf.P2^bLW
```

```
Whalf.P3 = aLW*Lhalf.P3^bLW
```

```
#Maturity-at-age
```

```
mat = NULL
```

```
for (a in 1:length(age)){
```

```
  if(a<(amat+1)) mat[a] = 0
```

```
  if(a==(amat+1)) mat[a] = 0.5
```

```
  if(a>(amat+1)) mat[a] = 1 }
```

```
# SELECTIVITY OGIVE OUTCOMES FOR ALL PERIODS
```

```
#Gear Selectivity (for ASEM)
```

```
sel.Gear.P1 = 1/(1+exp(-(Lhalf.P1-SL)/selpar.delta.SSW.P2))
```

```
sel.Gear.P2 = 1/(1+exp(-(Lhalf.P2-SL)/selpar.delta.SSW.P2))
```

```
sel.Gear.P3 = 1/(1+exp(-(Lhalf.P3-SL)/selpar.delta.SSW.P2))
```

```
#Migration Probabilities Providing Movement (Move at start of period)
```

```
#Period 1 (Use P3 as you use a-1 to get to P1)
```

```
MigProb.E.P1 = 1/(1+exp(-(L.P3-selpar.E.P3)/selpar.delta.E.P3))
```

```
MigProb.SSW.P1 = 1-1/((1+exp(-(L.P3-selpar.SE.P3)/selpar.delta.SE.P3)))
```

```
MigProb.SE.P1= 1/((1+exp(-(L.P3-selpar.SE.P3)/selpar.delta.SE.P3)))
```

```
#Period 2
```

```
MigProb.E.P2 = rep(0,length(age))
```

```
MigProb.SSW.P2 = 1-(0.5/((1+exp(-(L.P1-selpar.SE.P1)/selpar.delta.SE.P1))))
```

```
MigProb.SE.P2 = 1-MigProb.SSW.P2
```

```
#Period 3
```

```
MigProb.E.P3 = rep(0,length(age))
```

```
MigProb.SSW.P3 = 1-1/((1+exp(-(L.P2-selpar.SE.P2)/selpar.delta.SE.P2)))
```

```
MigProb.SE.P3 = 1/((1+exp(-(L.P2-selpar.SE.P2)/selpar.delta.SE.P2)))
```

```
#Selectivity (Use Lhalf, since C is at Phalf, using Pope's Approximation)
```

```
#Period 1
```

```
sel.E.P1 = 1/(1+exp(-(Lhalf.P1-selpar.E.P1)/selpar.delta.E.P1))
```

```
sel.SSW.P1 = 1/((1+exp(-(Lhalf.P1-selpar.SSW.P1)/selpar.delta.SSW.P1)))
```

```
sel.SE.P1 = 1/((1+exp(-(Lhalf.P1-selpar.SE.P1)/selpar.delta.SE.P1)))
```

```
#Period 2
```

```
sel.E.P2 = 1/(1+exp(-(Lhalf.P2-selpar.E.P2)/selpar.delta.E.P2))
```

```
sel.SSW.P2 = 1/((1+exp(-(Lhalf.P2-selpar.SSW.P2)/selpar.delta.SSW.P2)))
```

```
sel.SE.P2 = 1/((1+exp(-(Lhalf.P2-selpar.SE.P2)/selpar.delta.SE.P2)))
```

```

#Period 3
sel.E.P3 = 1/(1+exp(-(Lhalf.P3-selpar.E.P3)/selpar.delta.E.P3))
sel.SSW.P3 = 1/((1+exp(-(Lhalf.P3-selpar.SSW.P3)/selpar.delta.SSW.P3)))
sel.SE.P3 = 1/((1+exp(-(Lhalf.P3-selpar.SE.P3)/selpar.delta.SE.P3)))

#####
# Per-Recruit Analysis: Unfished (N0) with Migration #
#####

N0.E.P1 = 1
N0.SSW.P1 = N0.SE.P1 = 0
N0.SSW.P2 = N0.SE.P2 = N0.E.P2 = NULL
N0.SSW.P3 = N0.SE.P3 = N0.E.P3 = NULL

# Start age loop for Period 2

a = 1

while (a <= (length(age)))
{

# Period 2

# Juvenile, Sub-adult and Adult age classes for all Regions
if(a <= length(age))
{
  N0.E.P2[a] <- 0 # No fish retained or incoming
  N0.SSW.P2[a] <- ((N0.E.P1[a]*MigProb.SSW.P2[a]+N0.SSW.P1[a])*exp(-(M/(3))))
  N0.SE.P2[a] <- ((N0.E.P1[a]*MigProb.SE.P2[a]+N0.SE.P1[a])*exp(-(M/(3))))
}

# Period 3

# Juvenile, Sub-adult and Adult age classes for all Regions (Now includes age-1)
if(a <= length(age))
{
  N0.E.P3[a] <- 0 # No fish retained or incoming
  N0.SSW.P3[a] <- (N0.SSW.P2[a]*(1-MigProb.SE.P3[a])*exp(-(M/(3))))
  N0.SE.P3[a] <- ((N0.SSW.P2[a]*MigProb.SE.P3[a]+N0.SE.P2[a])*exp(-(M/(3))))
}

# Period 1

a = a + 1

# Juvenile, Sub-adult and Adult age classes for all Regions

```

```

if(a <= length(age))
{
  N0.E.P1[a] <- ((N0.SE.P3[a-1]*MigProb.E.P1[a-1])*exp(-(M/(3))))
  N0.SSW.P1[a] <- ((N0.SSW.P3[a-1]*(1-MigProb.SE.P1[a-1]))*exp(-(M/(3))))
  N0.SE.P1[a] <- ((N0.SSW.P3[a-1]*MigProb.SE.P1[a-1]+N0.SE.P3[a-1]*(1-MigProb.E.P1[a-1]))*exp(-(M/(3))))
}

# Period 2 and 3

# Adult age class for all Regions
if(a == length(age))
{
  N0.E.P2[a] <- 0 # No fish retained or incoming
  N0.SSW.P2[a] <- ((N0.E.P1[a]*MigProb.SSW.P2[a]+N0.SSW.P1[a])*exp(-(M/(3))))
  N0.SE.P2[a] <- (N0.E.P1[a]*MigProb.SE.P2[a]+N0.SE.P1[a])*exp(-(M/(3)))

  N0.E.P3[a] <- 0 # No fish retained or incoming
  N0.SSW.P3[a] <- (N0.SSW.P2[a]*(1-MigProb.SE.P3[a]))*exp(-(M/(3)))
  N0.SE.P3[a] <- (N0.SSW.P2[a]*MigProb.SE.P3[a]+N0.SE.P2[a])*exp(-(M/(3)))
}
}

#####
# Per-Recruit Analysis: Unfished (n0) with NO Migration #
#####

# CHECK POINT ONLY: Ensure migration does not cause any loss or gain in population (for unfished population)

n0 = 0
for (a in 1:length(age))
{
  if(a==1) n0[a] <- 1
  if(a>1 & a<=length(age)) n0[a] <- n0[a-1]*exp(-M)
}

#####
# Per-Recruit Analysis: Fished (NA) with Migration #
#####

# Per-Recruit
NA.E.P1 = 1
NA.SSW.P1 = NA.SE.P1 = 0

# Define NA vectors
NA.SSW.P2 = NA.SE.P2 = NA.E.P2 = NULL
NA.SSW.P3 = NA.SE.P3 = NA.E.P3 = NULL

```

```

# Start age loop for Period 2

a = 1

while (a < (length(age)))
{

# Period 2

# Larval age class for all Regions
if(a==1)
{
NA.E.P2 <- 0 # No fish retained or incoming
NA.SSW.P2 <- NA.E.P1[a]*MigProb.SSW.P2[a]*exp(-M/(1*3))
NA.SE.P2 <- NA.E.P1[a]*MigProb.SE.P2[a]*exp(-M/(1*3))
}

# Juvenile, Sub-adult and Adult age classes for all Regions
if(a <= length(age))
{
NA.E.P2[a] <- 0 # No fish retained or incoming
NA.SSW.P2[a] <- (NA.E.P1[a]*MigProb.SSW.P2[a]*(1-sel.Gear.P1[a]*H.E[1])+NA.SSW.P1[a]*(1-
sel.Gear.P1[a]*H.SSW[1]))*exp(-(M/3))
NA.SE.P2[a] <- (NA.E.P1[a]*MigProb.SE.P2[a]*(1-sel.Gear.P1[a]*H.E[1])+NA.SE.P1[a]*(1-
sel.Gear.P1[a]*H.SE[1]))*exp(-(M/3))
}

# Period 3

# Juvenile, Sub-adult and Adult age classes for all Regions (Now includes age-1)
if(a <= length(age))
{
NA.E.P3[a] <- 0 # No fish retained or incoming
NA.SSW.P3[a] <- NA.SSW.P2[a]*(1-MigProb.SE.P3[a]*(1-sel.Gear.P2[a]*H.SSW[2]))*exp(-(M/3))
NA.SE.P3[a] <- (NA.SSW.P2[a]*MigProb.SE.P3[a]*(1-sel.Gear.P2[a]*H.SSW[2])+
NA.SE.P2[a]*(1-sel.Gear.P2[a]*H.SE[2]))*exp(-(M/3))
}

a = a + 1

# Period 1

# Juvenile, Sub-adult and Adult age classes for all Regions
if(a>1 & a<=length(age))
{

```

```

NA.E.P1[a] <- NA.SE.P3[a-1]*MigProb.E.P1[a-1]*(1-sel.Gear.P3[a-1]*H.SE[3])*exp(-(M/(3)))
NA.SSW.P1[a] <- NA.SSW.P3[a-1]*(1-MigProb.SE.P1[a-1])*(1-sel.Gear.P3[a-1]*H.SSW[3])*exp(-(M/(3)))
NA.SE.P1[a] <- (NA.SSW.P3[a-1]*MigProb.SE.P1[a-1]*(1-sel.Gear.P3[a-1]*H.SSW[3])+
  NA.SE.P3[a-1]*(1-MigProb.E.P1[a-1])*(1-sel.Gear.P3[a-1]*H.SE[3]))*exp(-(M/(3)))
}

# Period 2 and 3

# Adult age class for all Regions (Fill Period 2 and 3 given while() a+1 condition)
if(a == length(age))
{
  NA.E.P2[a] <- 0 # No fish retained or incoming
  NA.SSW.P2[a] <- (NA.E.P1[a]*MigProb.SSW.P2[a]*(1-sel.Gear.P1[a]*H.E[1])
    +NA.SSW.P1[a]*(1-sel.Gear.P1[a]*H.SSW[1]))*exp(-(M/3))
  NA.SE.P2[a] <- (NA.E.P1[a]*MigProb.SE.P2[a]*(1-sel.Gear.P1[a]*H.E[1])+
    NA.SE.P1[a]*(1-sel.Gear.P1[a]*H.SE[1]))*exp(-(M/(3)))

  NA.E.P3[a] <- 0 # No fish retained or incoming
  NA.SSW.P3[a] <- (NA.SSW.P2[a]*(1-MigProb.SE.P3[a])*(1-sel.Gear.P2[a]*H.SSW[2]))*exp(-(M/(3)))
  NA.SE.P3[a] <- (NA.SSW.P2[a]*MigProb.SE.P3[a]*(1-sel.Gear.P2[a]*H.SSW[2])+
    NA.SE.P2[a]*(1-sel.Gear.P2[a]*H.SE[2]))*exp(-(M/(3)))
}
}

#####
# Spawning Biomass Per-Recruit (SBR), Recruitment and Yield #
#####

# Compute Unfished Spawning Biomass Per-Recruit (SBR0)
SBR0 = sum(N0.E.P1*W.P1*mat)

# Compute the Unfished Beverton Holt Stock Recruitment (S-R) shape parameters as a function of the steepness
parameter h
R0 = SB0/SBR0
alpha= SBR0*(1-h)/(4*h)
beta = (5*h-1)/(4*h*R0)

# Compute Fished Spawning Biomass Per-Recruit (SBR)
SBR = sum(NA.E.P1*(1-sel.Gear.P1*H.E[1]*pre.SBC)*W.P1*mat)

# Determine Equilibrium Recruitment as a Function of H
recruits = (SBR-alpha)/(beta*SBR)
recruits = ifelse(recruits<0,0,recruits)

# Yield Per-Recruit per Region and Period

```

Region E

$$YPR.E.P1 = \text{sum}(NA.E.P1 * Whalf.P1 * sel.Gear.P1 * H.E[1] * \exp(-M/(2*3)))$$

$$YPR.E.P2 = \text{sum}(NA.E.P2 * Whalf.P2 * sel.Gear.P2 * H.E[2] * \exp(-M/(2*3)))$$

$$YPR.E.P3 = \text{sum}(NA.E.P3 * Whalf.P3 * sel.Gear.P3 * H.E[3] * \exp(-M/(2*3)))$$

Region SSW

$$YPR.SSW.P1 = \text{sum}(NA.SSW.P1 * Whalf.P1 * sel.Gear.P1 * H.SSW[1] * \exp(-M/(2*3)))$$

$$YPR.SSW.P2 = \text{sum}(NA.SSW.P2 * Whalf.P2 * sel.Gear.P2 * H.SSW[2] * \exp(-M/(2*3)))$$

$$YPR.SSW.P3 = \text{sum}(NA.SSW.P3 * Whalf.P3 * sel.Gear.P3 * H.SSW[3] * \exp(-M/(2*3)))$$

Region SE

$$YPR.SE.P1 = \text{sum}(NA.SE.P1 * Whalf.P1 * sel.Gear.P1 * H.SE[1] * \exp(-M/(2*3)))$$

$$YPR.SE.P2 = \text{sum}(NA.SE.P2 * Whalf.P2 * sel.Gear.P2 * H.SE[2] * \exp(-M/(2*3)))$$

$$YPR.SE.P3 = \text{sum}(NA.SE.P3 * Whalf.P3 * sel.Gear.P3 * H.SE[3] * \exp(-M/(2*3)))$$

By Region Only

$$YPR.E = \text{sum}(YPR.E.P1, YPR.E.P2, YPR.E.P3)$$

$$YPR.SSW = \text{sum}(YPR.SSW.P1, YPR.SSW.P2, YPR.SSW.P3)$$

$$YPR.SE = \text{sum}(YPR.SE.P1, YPR.SE.P2, YPR.SE.P3)$$

Vulnerable Biomass Per-Recruit per Region and Period

Region E

$$VBR.E.P1 = \text{sum}(NA.E.P1 * Whalf.P1 * sel.E.P1 * \exp(-M/(2*3)))$$

$$VBR.E.P2 = \text{sum}(NA.E.P2 * Whalf.P2 * sel.E.P2 * \exp(-M/(2*3)))$$

$$VBR.E.P3 = \text{sum}(NA.E.P3 * Whalf.P3 * sel.E.P3 * \exp(-M/(2*3)))$$

Region SSW

$$VBR.SSW.P1 = \text{sum}(NA.SSW.P1 * Whalf.P1 * sel.SSW.P1 * \exp(-M/(2*3)))$$

$$VBR.SSW.P2 = \text{sum}(NA.SSW.P2 * Whalf.P2 * sel.SSW.P2 * \exp(-M/(2*3)))$$

$$VBR.SSW.P3 = \text{sum}(NA.SSW.P3 * Whalf.P3 * sel.SSW.P3 * \exp(-M/(2*3)))$$

Region SE

$$VBR.SE.P1 = \text{sum}(NA.SE.P1 * Whalf.P1 * sel.SE.P1 * \exp(-M/(2*3)))$$

$$VBR.SE.P2 = \text{sum}(NA.SE.P2 * Whalf.P2 * sel.SE.P2 * \exp(-M/(2*3)))$$

$$VBR.SE.P3 = \text{sum}(NA.SE.P3 * Whalf.P3 * sel.SE.P3 * \exp(-M/(2*3)))$$

By Region Only

$$VBR.E = \text{sum}(VBR.E.P1, VBR.E.P2, VBR.E.P3)$$

$$VBR.SSW = \text{sum}(VBR.SSW.P1, VBR.SSW.P2, VBR.SSW.P3)$$

$$VBR.SE = \text{sum}(VBR.SE.P1, VBR.SE.P2, VBR.SE.P3)$$

#####