Evaluating rotational harvest strategies for sea cucumber fisheries

An MSE of the Qld East Coast Sea Cucumber Fishery

White teatfish *(Holothuria fuscogilva)*

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Data confidentiality

Note that this project uses fishery dependant data, including logbook spatial catch and effort data. The data confidentiality guidelines contained within the data use agreement between CSIRO and Queensland DAFF require us to protect the intellectual property of fishers by not publishing any spatial catch data without prior permission of the fishery operators. While all care has been made to maintain data confidentiality, please inform the authors immediately if you think that confidentiality is being breached.

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Abbreviations

CSIRO	Commonwealth Scientific and Industrial Research Organisation
MSE	Management Strategy Evaluation
ECBDMF	Queensland East Coast Sea Cucumber (Bêche-de-mer) Fishery
RZS	Rotational Zoning Scheme
GBRMPA	Great Barrier Reef Marine Park Authority
GBR	Great Barrier Reef
BBZ	Burrowing Blackfish zones
EPBC	Environmental Protection and Biodiversity Conservation Act 1999

Executive summary

What the report is about

We used a management strategy evaluation (MSE) approach to evaluate the benefits of a rotational harvest strategy (the Rotational Zoning Scheme - RZS) utilised in the Queensland East Coast Sea Cucumber (Bêche-de-mer) Fishery (ECBDMF). We found that, in general, the current management arrangements result in a low risk to most fishery species, and reduce the risk of localised depletion. However, there are still risks to some highly targeted species, and there are important information gaps that could reduce uncertainty. This information is critical to the continued sustainable use of this resource on the GBR, and will provide guidance to management (Queensland Fisheries and the GBRMPA) and industry to maintain, refine or extend sustainable management practices, promote the research into critical data needs, and provide some reassurance to governments and the general public that the fishery can be managed sustainably in the long term.

Background

The ECBDMF is a relatively small State fishery with a small number of participants and modest annual catch (387 t in 2010-11) that provides livelihoods to fishers in coastal communities in north Queensland. This fishery is typical of many small scale fisheries in Queensland and Australia in that there have been few detailed stock assessments, and management strategies have been developed over time in a diffuse and opaque fashion. Adding to this difficulty for the ECBDMF is its multispecies catch, changing species targeting and relatively short (modern) history.

Management agencies and Industry have focussed on mitigating risk to fishery populations through harvest strategies that limit and spread effort. One such strategy is the RZS, where each of 154 zones is allocated a limited number of fishing days (15) only once every three years, on a rotational basis. It is a common sense approach, developed by Industry and embraced by management. However, it has not been tested and there is no real evidence that it achieves its objectives of reducing localised depletion and reducing the risk to overall fishery sustainability. Also, as sea cucumber fisheries throughout the world succumb to overexploitation driven by rising demand, there has been an increasing demand for robust assessments of fishery sustainability and a need to address local depletion concerns in the ECBDMF. Indeed, the fishery has the only commercial species closed in the GBR Marine Park due to over-exploitation (Black Teatfish).

Aim/objectives

The objective of this research was to assess the efficacy of current and alternative harvest strategies, including the Rotational Zoning Scheme (RZS), for mitigating local and population depletion risk in the Qld East Coast Sea Cucumber (Bêche-de-mer) Fishery.

Methodology

MSE is a powerful tool for investigating the efficacy of management strategies such as the RZS in mitigating risk to fishery populations and for assessing the overall sustainability of fisheries. It allows for the exploration of risk to fishery and local populations for a range of scenarios that address uncertainty surrounding stock size and population parameters for fishery species. A spatial multispecies population dynamics model was used as part of the MSE framework to describe nine of the key fishery species as well as key uncertainties. The performance of management strategies tested was assessed in terms of a number of indicators that included measures of total and local depletion per species. Assessing the utility and optimal configuration of the RZS for mitigating localised depletion, reducing risks to overall sustainability and maximising efficiency and profits of this multispecies fishery, is of interest to GBRMPA, Qld Fisheries management, other State (Northern Territory and Western Australia) and Federal (Coral Sea, Torres Strait) fisheries, and Industry. This information will be used to formulate direct management strategy advice to better ensure the sustainability of the fishery.

Results/key findings

The MSE analysis indicated that, under the current management arrangements and catch levels, the overall risk of depletion for most reef-associated species under most scenarios was low. However, some current and past highly-targeted species such as Black Teatfish and White Teatfish show some risks under higher catch scenarios, particularly with more conservative parameter estimates, and should be managed with caution and more data gathered. Most species have a considerable proportion of their population within protected zones which provides an additional sustainability benefit.

The most targeted species currently is Burrowing Blackfish, a mostly off-reef (lagoon) species with a restricted known distribution. The MSE model indicated that risks of depletion for this species were the largest of any species, exacerbated by its restricted distribution, and relatively high fishing mortality rates. These risk indications are likely conservative (for example, the reference set of models used in the testing process included biomass estimates set at half the survey estimates, even though the population estimates for Burrowing Blackfish are considered quite robust). Additional distribution and density data from unfished areas and reliable monitoring (relative abundance) would improve the assessment of this species and quantification of the risks associated with fishing.

Implications for relevant stakeholders

This fishery has been under increasing scrutiny in recent times, therefore indicators as to the sustainability of the fishery and the effectiveness of the RZS for mitigating depletion risk is of considerable interest. In a broad sense, it will improve the sustainable management of sea cucumber populations in the ECBDMF, and potentially result in higher catches than otherwise (either through increased catch or by maintaining catch levels through less precautionary management), which will result in higher value and income for coastal fishing communities along the Queensland coast.

The ECBDMF has a current GVP of approx $5M per annum, but this project has shown that there is the potential for expansion in terms of both volume and value of fishery products by spreading the fishery effort widely across the ECBDMF. However, this prediction should be further explored after the acquisition of new data to fill essential data gaps.

This research has demonstrated a benefit of implementing a RZS harvest strategy for a sea cucumber fishery that most likely has application to other sea cucumber fisheries in Australian State (NT and WA) and Commonwealth (Coral Sea, Torres Strait) waters, as well as regional fisheries in the South Pacific countries and SE Asia.

Recommendations

1. Maintain, strengthen and develop the current Rotational Zoning Scheme (RZS) in the ECBDMF. Consider increasing rotational periodicity and a wider spread of fished zones as this is likely to reduce further the risk of localised depletion and improve the overall sustainability of the fishery.
2. Address important information gaps for higher risk species such as Burrowing Blackfish and White Teatfish; including the distribution and density of Burrowing Blackfish outside the fished zones, and the density of White Teatfish throughout the fishery.
3. Address important information gaps that will increase model certainty and hence the robustness of management recommendations; especially size/age at maturity, growth and natural mortality of targeted sea cucumber species.
4. Apply MSE approach to any new species in the ECBDMF that exceed the trigger limits implemented for the fishery.

KEYWORDS: sea cucumber, holothurians, GBR, small scale fisheries, rotational harvest strategy, MSE

1 Introduction

The Queensland East Coast Sea Cucumber (Bêche-de-mer) Fishery (ECBDMF) is a relatively small State fishery with a limited participation base (18 transferable licences owned by a small number of operators) and modest annual catch (387 t landed form (salted/frozen boiled) in 2010-11; DAFF, 2012). The fishery provides an important livelihood and foreign exchange opportunity for local fishing communities in Queensland and Australia, with widespread over exploitation of sea cucumber populations across the globe (Purcell et al., 2013) and increased demand from China, resulting in the rise in value of bêche-de-mer.

The ECBDMF is perhaps the oldest commercial fishery in Queensland with beche-de-mer harvesting starting in the early 1800's (Breen, 2001; DEH, 2004; QDPIF, 2004) and continuing continued through both the first and second world wars with the fishery fading at the end of WWII (Uthicke, 2004). The fishery revived in the late 1980's (Breen, 2001; QDPIF, 2004), mostly targeting Black Teatfish (Breen, 2001; Uthicke, 2004). With this resurgence, new management systems were introduced to protect the fishery (Breen, 2001; DEH, 2004). In 1991, an overall (i.e. total for all retained species) Total Allowable Catch (TAC) was set at 500 tonnes (wet gutted weight), with individual quotas assigned to licence holders, though it appears that the TAC was never reached (Uthicke, 2004). The TAC was reduced to 380 t (wet gutted weight) in 1998, and to 361 t (landed weight – salted or par boiled and frozen) in 2006, due to the catch being reported as landed (green salted and par boiled and frozen) weight (Breen, 2001; DSEWPC, 2011; DAFF, 2012).

A reduction in catch rates of Black Teatfish and concerns over the status of the population led to the closure of that species in October 1999 (Breen, 2001; Uthicke and Benzie, 2000). Effort in the fishery switched to White Teatfish and a TAC of 127 tonnes (increased to 158 tonnes for 1 season) was introduced in 1999 (Breen, 2001). This quota has been reduced over the years, due mainly to concerns about the sustainability of the catch and the loss of fishing areas through GBRMP zoning, to the current 64 t (DPIF, 2004; DAFF, 2012). The quota was split into north and south with the majority of the quota available in the north.

In 2001, fishing for sea cucumber (Sandfish in particular) in Hervey Bay and Tin Can Bay was closed due to declining catch rates (DEH, 2004; QDPIF, 2004). However, Sandfish remains open in the remainder of the fishery.

In 2003, the fishery began targeting a new species, Burrowing Blackfish, after exploratory surveys found high densities in initially three, and subsequently seven locations, called Burrowing Blackfish zones (BBZ) (DEEDI, 2011; Leeworthy, 2007a, 2007b, 2010). Spatial TACs for Burrowing Blackfish have been implemented for these zones (DEEDI, 2011).

About that time, management implemented a performance measurement system (PMS) that included species-specific review reference points based on annual catches of all targeted species that made up the "other" quota group. If exceeded, a series of management actions would initiate, ranging from closing species and/or areas or conducting resource assessments. The review reference points were set at very conservative sustainable yield estimates in conjunction with industry and scientists with expertise in sea cucumber resource monitoring and biology.

Other management strategies implemented in the fishery include, limited entry, gear and effort restrictions, species-specific size limits, and an annual review process (QDPIF, 2004; DAF, 2012), including:

- Limited entry. In the 1980's there were almost 30 licence holders within the ECBDMF. From January 1995 entry into the fishery was limited to fishers with history, with no new licences to be handed out (DEH, 2004). The ECBDMF now has 18 licences (DSEWPC, 2011; DAFF 2012). Currently, all licences are controlled by 2 operators in the fishery,
- Gear restrictions – collection by hand only, commercial collectors allowed to use underwater breathing apparatus,
- Vessel restrictions – One main vessel that is allocated on each authority, with up to 4 small dories less than 7m in length for each authority holder,
- Up to 10 fishers per authority working at any one time,
- Species-specific minimum size limits (Sandfish 20 cm; White Teatfish 40 cm; Black Teatfish 30 cm; Prickly Redfish 50 cm; blackfish 20 cm; deepwater Redfish 20 cm; surf Redfish 25 cm; lollyfish 20 cm; greenfish 20 cm; curryfish 35 cm; elephant trunkfish 40 cm; Brown Sandfish 25 cm; leopard fish 35 cm; amberfish 50 cm; all other species 15 cm).

The implementation of the GBRMP Zoning in July 2004, when the areas protected from extractive activities (such as fishing) increased from 4.6% to 33.3%, resulted in roughly a third of the shallow reef area being closed to BDM fishing (Figure 1, Table 1). It also prompted, together with concerns over localised depletion and the overall sustainability of the fishery, the formulation and implementation of a rotational zoning scheme (RZS) in the fishery that same year (DEEDI, 2011).

1.1 Rotational Zoning Scheme (RZS)

In 2004 a Rotational Zoning Scheme (RZS) was introduced into the ECBDMF in response to concerns about localised and serial depletion of sea cucumber stocks in the ECBDMF, and the implementation of closed areas as part of the GBRMP zoning scheme (DEEDI, 2011). The RZS was designed by the members of the QLD Sea Cucumber Association. It has 154 zones, at an average size of approximately 553.2 km^2, (range 161.7 km^2 to 2092.0 km^2) and containing, on average, 95.0 km^2 of shallow reef (range 0.6 km^2 to 312.0 km^2), and 23.3 km^2 of emergent reef (range 0.1 km^2 to 117.7 km^2). The zones were mapped throughout the main reef areas of the GBRMP (Figure 1).

Each zone is available for harvesting in the fishery once every 3 years for 15 days of fishing. For example, 52 zones were open for fishing from 1 July 2004 – 30 June 2005; these zones were then closed for fishing between 1 July 2005 and 30 June 2007 and reopened for fishing on the 1 July 2008 (DSEWPC, 2011; DEEDI, 2011).

Besides the RHZ, there are also specific zones (BBZ) that are allocated for fishing Burrowing Blackfish on a continuous basis, but only where those populations have been adequately surveyed and a sustainable TAC formulated (Figure 1). These BBFZ are also supposed to be subject to ongoing monitoring of the Burrowing Blackfish populations that occur in them. Within this zoning scheme, quotas are allocated to licence holders where they are given a percentage of the TAC based on their share of the overall TAC, their ability to fish and other industry agreements (DEEDI, 2011).

Two additional "zones" were included in the scheme, based on the offshore reefs that are contained within the ECBDMF area – Saumarez Reef and Marion Reef, and these are allocated as per the rotational pattern. A developmental licence also exists for Ashmore Reef, outside the ECBDMF but within Qld waters, and this too was assigned the same fishing conditions as a rotational zone (Figure 1).

The total area of the fishery is large compared to other sea cucumber fisheries in the region: Torres Strait reef area, 2,426 km^2 (Skewes et al., 2003a); Coral Sea Fishery reef area, 12,767 km^2 (ABARES, 2013); PNG Milne Bay Fishery reef area, 1,831 km^2 (Skewes et al., 2003b).

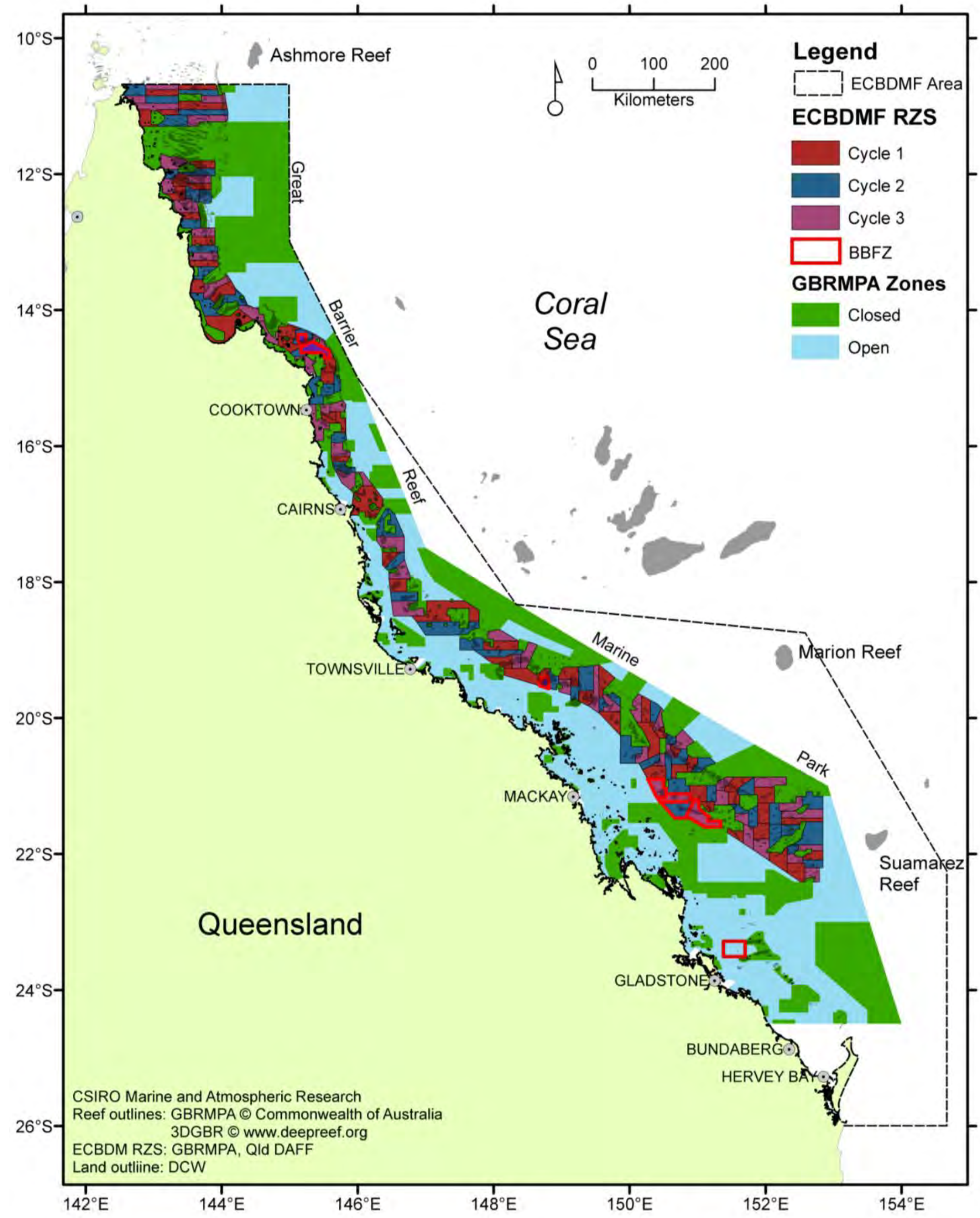

Figure 1. Map of the Queensland East Coast Sea Cucumber (Bêche-de-mer) Fishery (ECBDMF) showing 154 Rotational Zoning Scheme (RZS) zones, existing Burrowing Blackfish zones (BBFZ) and 2 ECBDMF offshore fishing zones (Suamarez and Marion Reefs), and one general fishery permit area (Ashmore Reef). The remainder of the GBRMPA area is divided into open and closed zones (to sea cucumber fishing).

Table 1. Areal extent of the fishery area, shelf, reef and dry reef habitats within the area of the ECBDMF, and areas closed to fishing. Also, the area of the Rotational Zoning Scheme (RZS), the Burrowing Blackfish (*Actinopyga spinea*) zones (BBZ) and Ashmore Reef are included.

Fishery area	Total area (km^2)	Closed to fishing (km^2)	Closed to fishing (%)
Fishery area	514,010	132,142	25.7
Shelf[1]	232,323	67,285	29.0
Reef[2]	26,143	8655	33.1
Dry reef[3]	6365	2390	37.5
RZS[4]	85,193		
RZS reef[4]	14,637		
RSZ dry reef[4]	3565		
BBZ[5]	1024		
Ashmore Reef[6]	649		
Ashmore dry reef[6]	39		

[1] Shelf is a zone adjacent to a continent (or around an island) extending from the low water line to a depth at which there is usually a marked shelf edge (GBRMPA).

[2] Reefs are rock/coral lying at or near the sea surface. Generally the boundaries of reef areas were mapped to show the outer-most extent of each coral reef that could be observed in Landsat imagery (3dGBR – Beaman, 2010; GBRMPA).

[3] Dry-reef are reefs exposed during tidal fluctuations from HAT to LAT (3dGBR – Beaman, 2010; GBRMPA).

[4] Rotational zoning scheme (RZS) are areas where fishers are restricted to fishing once every 3 years.

[5] Burrowing Blackfish zones (BBZ) are zones managed on an individual basis almost exclusively for *Actinopyga spinea.*

[6] Ashmore Reef is not part of the ECBDM Fishery area (unlike Marion and Saumarez Reefs), and is not included in the fishery area statistics. It was fished under a Developmental Fishery licence in 2008, but was included in the RZS from that year.

1.2 Species composition

The ECBDMF is a multi-species fishery for species from the Family Holothuriidae, with a small number of high valued species usually making up the bulk of the catch. The species composition of the catch has varied over the years due to species depletions, changes in market value, emerging markets and fishery, and processing technology.

Fishing in the area of the ECBDMF has been occurring since the early 1800's (Uthicke, 2004). There is little information on the species targeted during the historical fishery, though shallow species with thick body walls, such as Sandfish and Black Teatfish, would have been favoured (Uthicke, 2004; Studderd and Williams, 2003).

The modern ECBDMF fishery began in the mid 1980s, with early fishing was almost entirely focussed on Black Teatfish and Sandfish (Breen, 2001; Roelofs et al., 2003; Uthicke 2004; Figure 2). Most of the Sandfish were caught in Tin Can Bay and Hervey Bay (Breen 2001; Roelofs et al., 2003).

Sandfish catch declined between 1996-97, when over 70 t[1] was reported as fished, to be almost absent by 2000 (Figure 2). Fishers report that the early Sandfish catches were almost entirely inshore Sandfish, *Holothuria scabra*, rather than the offshore deeper Sandfish species, golden Sandfish, *Holothuria lessoni* (Appendix D).

Most of the Black Teatfish were caught between Townsville and Cooktown, the area of highest density and close to fishing ports (Uthicke and Benzie, 2000; Benzie and Uthicke, 2003; Roelofs et al., 2003). However, after a catch of over 350 t in 1993-94, the catch dropped markedly and by 1999-00 the fishery was closed due to declining catch rates in the area of the fishery (Breen, 2001, Uthicke and Benzie, 2000; Figure 2).

The catch between 1995 and 2011 showed a change in species composition, with the fishery switching to White Teatfish (Breen, 2001, QDPIF, 2004; Figure 2), with this species remaining a primary fishery species since. Catches of White Teatfish have declined over that period, from over 120 t p.a. to under 70 t p.a. (Figure 2) as the TAC for that species has declined and the fishery switched to other species such as Burrowing Blackfish. Catch rates and individual mean size for White Teatfish have remained relatively steady throughout this time (DAFF, 2012). Consistent catches of Prickly Redfish (range 9 -65 t p.a.) were also taken between 2000-01 to 2010-11 (Figure 2, Figure 3).

While blackfish (mostly Deepwater Blackfish, *Actinopyga palauensis* according to industry – see Appendix D) were caught in low numbers since 1995, Burrowing Blackfish was targeted from 2002-03 and eventually became the primary targeted species of the fishery representing 50-70% of the total catch (Figure 2). In 2008-09, curryfish increased in the catch due to rising interest in the commercial market for this species (Figure 2, Figure 3). Before 2008, curryfish were not heavily fished as there were problems with quality during processing, resulting in a low grade end product. Since then, processing techniques have since improved (DAFF, 2011; DEEDI, 2010).

Recent improvement in fishery 'technology', including improved harvesting and processing techniques, has resulted in previously low and medium value species to emerge as high value product. For example, one operator in the fishery has added two forms of bêche-de-mer products onto the market with their innovative 'Individually Quick Frozen' (IQF) and 'Vacuum Sealed' packaging (Tasmanian Seafoods, 2013). Fishery technology is also advancing towards an increase in the use of sea cucumbers for medicinal and cosmetic purposes (Bordbar, 2011).

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[1] Catch data for sea cucumber fisheries can be reported in various forms, from live to processed dried beche-de-mer. Most tropical sea cucumber fisheries report catches as dried beche-de-mer. The ECBDMF mostly records "landed weight" in logbooks and buyer returns, (sometimes mistakenly called "gutted weight") which is the form currently used for quota management and catch reporting. Number caught is also used for catch reporting in logbooks. Landed weight is either "gutted and salted", or "gutted, par boiled and frozen". Conversion data for these forms are not available for all species. However, salted form conversion factors are available for several species (Skewes et al., 2004), and average about 0.85 of gutted weight (range: 0.76 to 0.92). No conversion factors are available for par boiled and frozen product but perusal of average landed weights indicates similar weight loss factors for several species. More data is required for appropriate conversion factors.

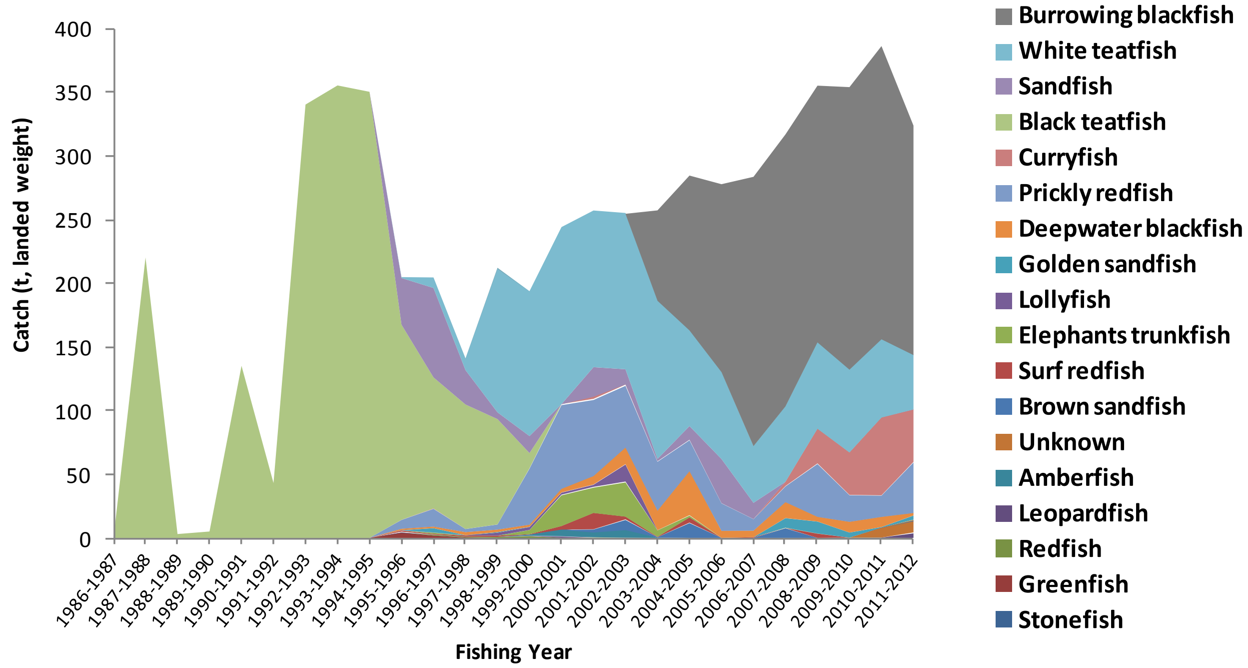

Figure 2. Estimated catch by (fiscal) year (in tonnes landed weight – gutted, salted or parboiled and frozen) for the ECBDMF (from: Uthicke (2004), 1987-88 to 1994-95; ECBDMF logbook data, 1995-96 to 1999-00; ECBDMF landing data, 2000-01 to 2011-12).

1.3 Rotational Harvest Strategies

Rotational fishing, rotating spatial harvest, or pulse fishing are used in fisheries management to give some specified level of stock protection and can help alleviate the effect of growth and recruitment overfishing, typically of sessile or sedentary stocks (Hart, 2002; Purcell, 2010). It also provides some benefits and efficiencies to fishing, management and research by reducing the number of locations where fishing, enforcement and surveys take place (Myers et al., 2000; Hebert, 2011). Simulations of populations under rotation harvest strategies have indicated that rotational harvesting increases spawner biomass (compared to equivalent long run yearly harvests), particularly under high fishing pressure (Myers et al., 2000, Humble et al., 2007).

Worldwide, rotational fishing has been used for abalone, corals, geoduck clams, sea urchins and scallop species (Sluczanowski, 1984; Caddy, 1993; Heizer, 1993; Campbell et al., 1998; Lai & Bradbury, 1998; Myers et al. 2000; Pfister and Bradbury, 1996; Hart, 2002). In Australia, scallops from Bass Strait are fished using closed area spatial management strategies. Recorded benefits have included increased protection from fishing; increased abundance, mean age and size; enhanced local reproductive potential and improved probability of larval export to surrounding areas (Dowling et al. 2008a,2008b; DSEWPC, 2013). Usually some form of preseason survey is required to assess biomass or habitat conditions, as well as the condition of the species (Dowling et al. 2008a, 2008b; Haddon et al., 2012; Hebert, 2011).

The best example of a sea cucumber rotational harvest strategy is for the Alaskan and Canadian west coast (developing) sea cucumber fishery (*Parastichopus californicus*), where a 3 year rotational harvest and modest exploitation rate (~6% annualised) have so far proved successful for maintaining populations and providing fishery efficiencies (Hebert, 2011; Humble et al., 2007; Purcell, 2010)

1.4 Need

This fishery is typical of many small-scale fisheries in Queensland and Australia in that there have been few detailed stock assessments on which to base robust management strategies. Adding to this difficulty is its multispecies catch, changing species targeting and relatively short (modern) history (fishing revived in the mid 1980s after a fifty year dormancy). Management agencies and Industry have focussed on mitigating risk to fishery populations through harvest strategies that are demonstrably conservative, and that limit and spread effort (DAFF, 2012). One such strategy is the Rotational Zoning Scheme (RZS) of the ECBDMF, where each of 154 zones are allocated a limited number of fishing days (15) once every three years, on a rotational basis (Lowden, 2005; DEEDI, 2011). It was designed to spread and limit fishing effort in response to concerns about localised depletion and to reduce the risk of over-exploitation of critical breeding populations. It is a common sense approach, developed by Industry and embraced by management. However, it has not been tested and there is no real evidence that it achieves its objectives of reducing localised depletion and reducing the risk to overall fishery sustainability. Recently, there has however, been some questions raised in management consultative fora regarding the efficacy and benefit of the RZS to the ECBDMF, as it has not been tested and there is no real evidence that it achieves its objectives of reducing localised depletion and reducing the risk to overall fishery sustainability.

The Rotational Zone Strategy (RZS) of the ECBDMF was initiated and designed by Industry, to address a perceived risk of localised depletion and ameliorate the overall risk to fishery populations. Although its compliance has been assessed as high (DEEDI, 2011), it has never been thoroughly tested as to its benefits for fishery sustainability.

This fishery has been the subject of some concern for management agencies in the past, particularly for the Great Barrier Reef Marine Park Authority (GBRMPA) and has the only fishery species closed in the GBR Marine Park due to over exploitation (Black Teatfish). Assessing the utility and optimal configuration of the RZS for mitigating localised depletion, reducing risks to overall sustainability and maximising efficiency and profits of this multispecies fishery is of interest to GBRMPA, Qld Fisheries management, other State (NT and WA) and Federal (Coral Sea, Torres Strait) fisheries, and Industry.

2 Objectives

1. Assess the efficacy of the current Rotational Zoning Scheme (RZS), for mitigating local and population depletion risk in the Qld East Coast Sea Cucumber (Bêche-de-mer) Fishery (ECBDMF).

This project will provide information on the benefits of the RZS in the ECBDMF for reducing the risk of localised depletion and stock overexploitation, while maintaining fishery income. This information will then be used to formulate direct management strategy advice to better ensure the sustainability of the fishery. The MSE approach will be used to compare the performance of the RZS with alternative harvest strategies in meeting fishery objectives of maintaining sea cucumber populations at ecologically sustainable levels and maximising efficiency and profit. This has direct relevance to the objectives of GBRMPA and Qld Fisheries, and has the interest and support of Industry.

The ECBDMF has a gross value of production (GVP — essentially landed value) of about $5M per annum. There is the potential for economic loss through unsustainable fishing practices or overly conservative harvest strategies, but also expansion in volume and/or value of fishery products if more informed stock assessments indicate the potential for increased sustainable catch. There are also likely to be potential gains from efficiencies in operating costs, as it is a dive fishery using small dinghies, operating from mother vessels. The cost of fuel and lost fishing time associated with movements a mother vessel undertakes to comply with the RZS is likely to be considerable; therefore the most efficient configuration of spatial and temporal rotation is vital for maximising efficiency and profit, while ensuring ecological sustainability.

The results will have broader applicability in terms of assessing the utility and optimal configuration of a RZS for hand collectable fisheries in other States (NT and WA) as well as Commonwealth (Coral Sea, Torres Strait) sea cucumber (and other benthic invertebrate) fisheries.

3 Methods

3.1 MSE approach

Management Strategy Evaluation is a powerful tool for investigating the efficacy of the RZS for mitigating risk to fishery populations and to compare alternative management strategies. It allows for the exploration of outcomes for a range of scenarios that address uncertainty surrounding population parameters (growth, mortality, recruitment) for fishery species. MSE has been applied to other small scale fisheries in Australia (e.g. Torres Strait rock lobster, Coral Sea beche-de-mer - Plagányi et al., 2011; 2013). A limited application to the Coral Sea beche-de-mer fishery, which also has a RZS, indicated some advantage with respect to reducing risk to targeted species (Plagányi et al., 2011), however with a restricted number of reefs, species and fishers compared to the ECBDMF.

The MSE approach shows the trade-offs between different strategies and hence informs as to which strategies reduce the risk to the resource as a whole, as well as to individual species of concern, as well as those strategies that are more efficient. This approach is particularly suited to assessing the effectiveness of a Rotational Zoning Scheme (RZS) for reducing the risk of localised stock depletion in particular. Simulation of a range of alternative implementations, such as the time between rotations, has the potential to inform improvement in management practices.

The project included a stakeholder workshop to elicit information on fisher behavioural dynamics, field information and management strategy test cases (including species and spatial management units). The program and outcomes of that workshop are contained in Appendices C and D.

Fishery dependent (logbook), survey and environmental data were used to build and calibrate a spatial age-structured operating model (OM). The modelling framework is flexible in terms of the number of species and model areas to be included. Moreover, the OM was constructed to readily represent a large number of uncertainties pertaining to data available for each species as well as the population dynamics and meta-population structure. It is an ideal tool for representing not only sea cucumber species, but also other broadcast spawners and data-poor species.

The MSE testing framework was then used to test a range of harvest strategies and highlight the trade-offs associated with the application of the RZS, and the impact on local and overall depletion of individual species, as well as the overall profits achieved. Moreover, by simulating alternative recruitment hypotheses, it was possible to explore the effects of spatial and temporal closures.

3.2 Fishery area

The spatial units used in the MSE are the RZS zones of the ECBDMF (154 zones), plus the 3 original Burrowing Blackfish zones (BBZ) (Figure 1), 2 offshore reefs (Saumarez and Marion Reefs), and a general fishery permit for Ashmore Reef, resulting in a total of 160 zones; plus the open and closed areas outside these zones resulting in a total of 162 zones to consider in the MSE.

Area estimates for the fishery, zones, and reef habitats were assembled from various sources (250k topographic maps, GBRMPA, Qld DAFF, 3dGBR - Beaman, 2010) and spatial area estimates were calculated in a GIS (Table 1). Spatial catch data from the ECBDM logbook data (Qld DAFF) was then assigned to zones spatially using derived location data.

3.3 Spatial fishery data

The focus species of the MSE were initially defined as the high and medium value species of the fishery, based on the logbook data and input from fishers and managers at the stakeholder workshop. These species have collectively made up over 92% of the catch since 1995 (Table 2).

The initial species list included Sandfish and Black Teatfish, even though these species have not been target species since 1999 and 2000 respectively. However, it was subsequently decided that Sandfish would not be modelled due to the paucity of density and habitat data for the Sandfish populations on the Queensland east coast, and the lack of fishery effort data in the logbook data.

Table 2. Focus species for the ECBDMF MSE, and their habitat area for the estimation of population size.

	Common name	Scientific name	Habitat
1	Black Teatfish	*Holothuria whitmaei*	Dry reef area
2	Brown Sandfish	*Bohadschia vitiensis*	Lagoon
3	White Teatfish	*Holothuria fuscogilva*	Reef area
4	Prickly Redfish	*Thelenota ananus*	Reef area
5	Golden Sandfish	*Holothuria lessoni*	Lagoon area
6	Curryfish Herrmanni	*Stichopus herrmanni*	Reef area
7	Curryfish Vastus	*Stichopus vastus*	Reef area
8	Deepwater Blackfish	*Actinopyga palauensis*	Reef area
9	Burrowing Blackfish	*Actinopyga spinea*	Lagoon area

The primary data source was spatial logbook data from the ECBDMF. Unfortunately the current logbook database does not contain any spatial catch data from before the 1995-96 fishing year (hereafter, termed the 1995 model year) (Figure 3). As stated above (section 2.2), there are estimates of the catch of Black Teatfish for the period prior to 1995 (Uthicke, 2004), that were obtained from the Queensland Fisheries Service. The catch between 1987 and 1995 from this data was 1,451 t (gutted weight). The catch from logbook data for Black Teatfish from 1995/96 to when the fishery was closed totalled 516 t (Figure 2), giving an overall total catch estimate of 1,967 t (gutted weight/landed weight). This is likely to be an underestimate with little or no catch recorded between 1989 and 1992 (Uthicke, 2004) (Figure 2). The lack of spatial catch data for Black Teatfish for this early period of the fishery hampered the analysis of that species. Nevertheless, we included it (taking the considerable uncertainties into account) in an attempt to model its recovery dynamics.

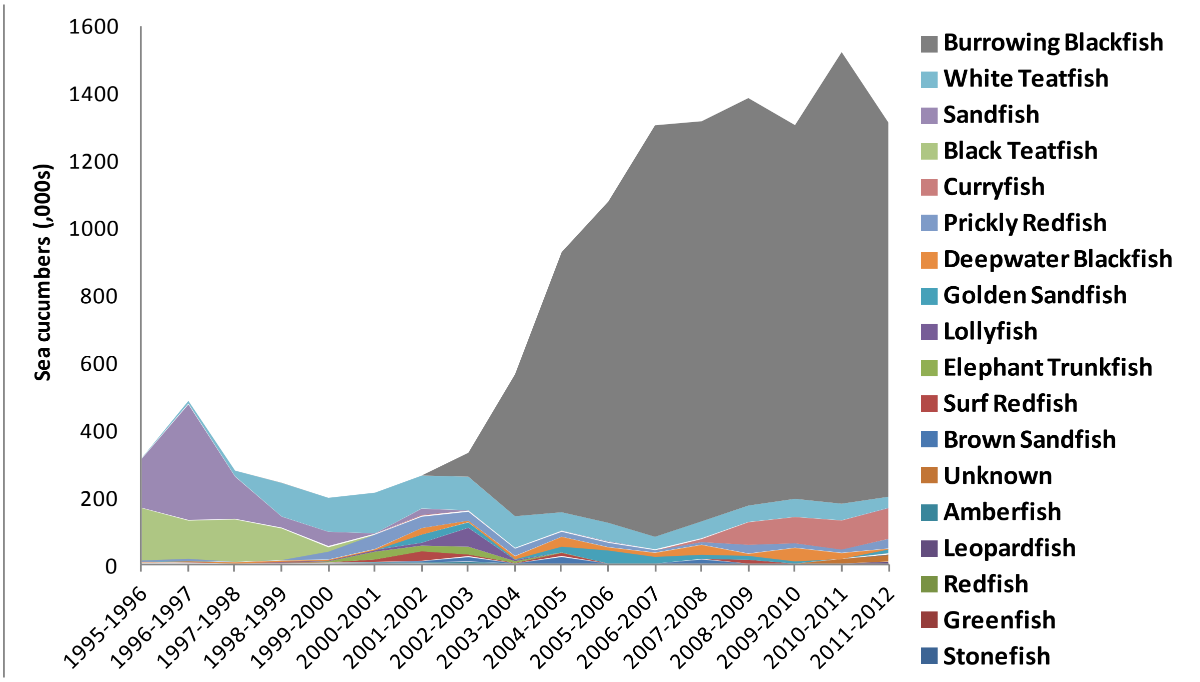

Figure 3. Catch by (fiscal) year (individual sea cucumbers) for the ECBDMF from logbook data, 1995/96 to 2011/12)

3.4 Biological parameters

The construction of the spatial age-structured operating model (OM) included information for fishery species biological parameters. These were collated from reviews of the scientific literature, the outcomes of the stakeholder workshop and existing data from field surveys.

3.4.1 GROWTH

Estimates of species growth, age-at-maturity, and age-at-maximum size for fished animals were required for the population dynamics model. Age, length and weight data for each species were also used to generate mass-length-age relationships as part of model simulations (Table 3, Figure 4, Figure 5).

There are a number of problems associated with constructing an age-length key for holothurians, including the difficulties of accurately measuring individuals, their malleable shape, they can’t be tagged and they are able to shrink in size (e.g. see Uthicke et al., 2004, Skewes et al., 2004). There are too few data to fit a growth curve for each species. A standard approach for fisheries is to use a von Bertalanffy growth curve. However a simpler linear approach was preferred in this study for the following reasons:

- There are no suitable data to fit a two or more parameter growth curve;
- Holothurian body structure is very simple such that there is no firm basis to support invoking a more complicated assumption than that growth in length is linear with age over the age range of interest;
- The assumption of linear growth between ages 1 to 5 does not preclude the possibility of an asymptotic trend at older ages, and hence is not inconsistent with the von Bertalanffy growth equation.

The length (in mm) of an individual of species *s* at age *a* is computed as:

$$L_{s,a} = \kappa_s \cdot a \tag{1}$$

where,

$$\kappa_s = \ell_{\infty,s} / \mathrm{a}_{l\max} \tag{2}$$

under the assumption that individuals attain their maximum length $\ell_{\infty,s}$ at age a_{lmax}.

The mass (in g) of an individual of species *s* and age *a* is given by:

$$w_{s,a}^{strt} = c_s \cdot \left(L_{s,a}\right)^b \tag{3}$$

Where the constants c_s and *b* were estimated by fitting to available length-weight data for 5 species. Parameter values for the remaining species are assumed to be the same as those for the most similar of the 5 species for which data were available.

Table 3. Growth and age parameter starting estimates for sea cucumber species used in the population model (Note: Sandfish included for comparison only).

Common name	Species	Min legal size (mm)	Age maturity (yr)	Size maturity (mm)	Size maturity (kg live)	Size max length (mm)	Size max weight (kg live)	Age max length (yr)	Source
Sandfish	*Holothuria scabra*	[1]200	[D,L]2	[4]150	[2]0.184	[3]400	[3]2	[E]10 [1]6+	[1]DAFF 2012 [2]Preston 1993 [3]Purcell et al 2012 [4]QDPIF 2004
Black Teatfish	*Holothuria whitmaei*	[1]300	[E]4	[3]260		[1]560	[E]3	[E]5-10	[1]DAFF 2012 [2]Purcell et al 2012 [3]QDPIF 2004
Brown Sandfish	*Bohadschia vitiensis*	[1]150	[E]3	[3]150	[2]0.09	[2]260	[E]2.5		[1]DAFF 2012 [2]Purcell et al 2012 [3]QDPIF 2004
White Teatfish	*Holothuria fuscogilva*	[1]400	[E]4	[3]320	[3]1.175	[4]570	[E]5	[1]12+	[1]DAFF 2012 [2]FAO 1998 [3]Preston 1993 [4]Purcell et al 2012
Prickly Redfish	*Thelenota ananus*	[1]500	[E]4	[3]300	[3]1.23	[4]800	[E]12	[2]10-15	[1]DAFF 2012 [2]FAO 1998 [3]Preston 1993 [4]Purcell et al 2012
Golden Sandfish	*Holothuria lessoni*	[1]150	[E]2		[2]0.48	[2]460	[E]3	[E]6	[1]DAFF 2012 [2]Purcell et al 2012
Curryfish Herrmanni	*Stichopus herrmanni*	[1]350	[E]3	[2]220		[3]550	[E]4.5	[E]7	[1]DAFF 2012 [2]Eriksson et al 2010 [3]Purcell et al 2012
Curryfish Vastus	*Stichopus vastus*	[1]150	[E]2	[3]150		[4]360	[E]4.5	[3]6	[1]DAFF 2012 [2]Purcell et al 2012 [3]Salardiono et al 2012 [4]Purcell et al 2008
Burrowing Blackfish	*Actinopyga spinea*	[1]150	[E]3			[2,3]380	[E]1.5	[E]6	[1]DAFF 2012 [2]Purcell et al 2012 [3]FAO 1998

L = literature D = data (CSIRO) E = estimate (workshop)

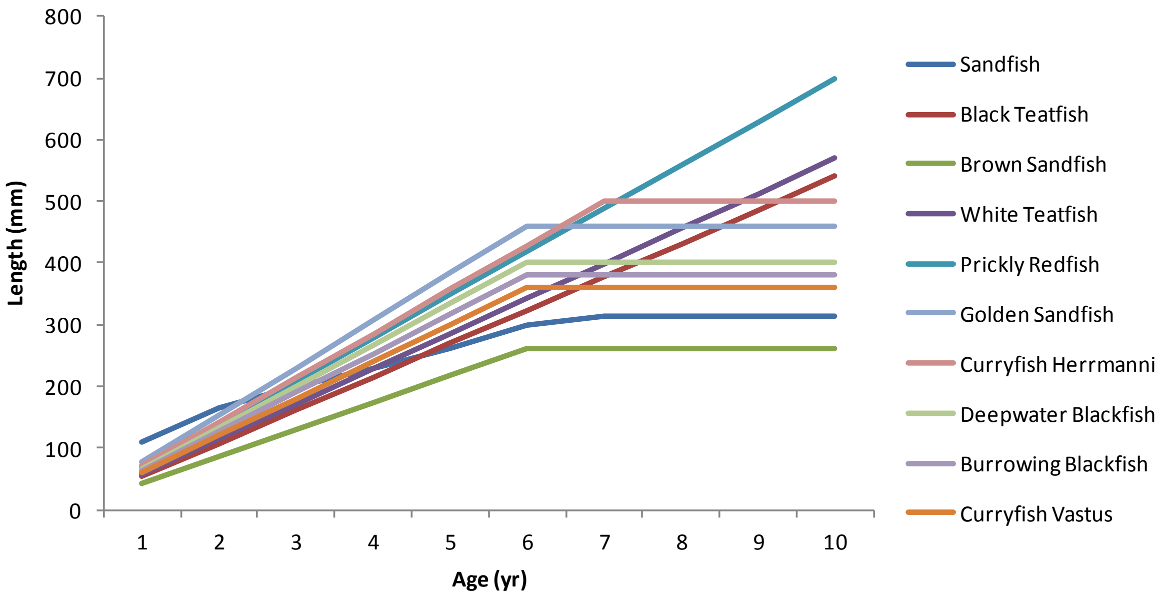

Figure 4. Model growth in length for sea cucumber species used in the population model.

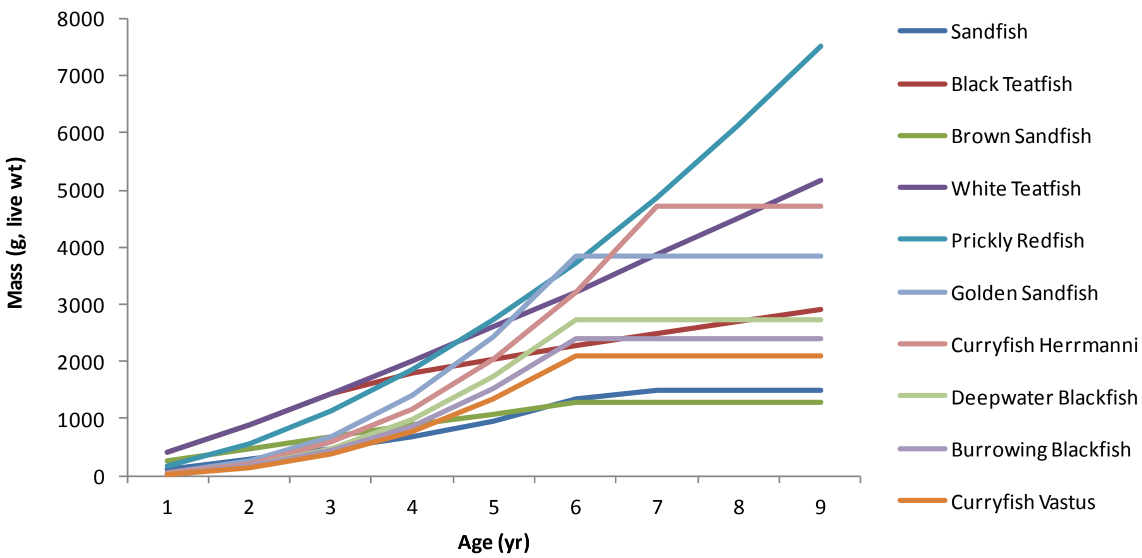

Figure 5. Model growth in weight (initial) for sea cucumber species used in the population model.

3.4.2 SELECTIVITY

The species-specific fishing selectivities $S_{s,a}$ are assumed to be knife-edge with the age-at-first-capture a_c determined using the length-age relationships described above, as the closest age corresponding to the minimum legal sizes (MLS) as shown in Table 3.

3.4.3 MATURITY AND STOCK-RECRUIT PARAMETERS

Knife-edge functions are assumed for the species-specific fecundity vectors, with the age at first maturity a_m as shown in Table 3.

The alternative model versions assume that the stock-recruitment steepness parameter h = 0.7 or h=0.5 as described below.

3.4.4 NATURAL MORTALITY

Natural mortality rates have not been well established for sea cucumber species. Mortality rates for several sea cucumber species have been reported in the literature (Table 4). These data are comparable to values calculated for sea cucumber species from the MSE model using Hoenig's Method (using maximum age) (Hoenig, 1983). We were conservative in our selection of natural mortality rate, including an annual M = 0.3 (resulting in a longevity of 15 yrs using Hoenig's method) as the lower rate scenario for Teatfish species and Prickly Redfish, and M = 0.4 for all other species (Table 5).

It is likely that natural mortality varies with age, as illustrated by mortality rate estimates for other echinoderms such as *Acanthaster plancii*, which has an estimated adult mortality rate of 0.11 (Ebert, 1973), and a juvenile mortality rates of 24.5, 4.7 and 1.6 for 1, 4 and 7 month old starfish respectively (Keesing and Halford, 1992). In a review in 1997, Gosselin and Quian (1997) found that high juvenile mortality is widespread among benthic marine invertebrates, with most populations reduced to <20% of initial numbers after 4 months; mortality remained low thereafter. They postulated that predation and desiccation were the most likely causes, but that many other factors, such as ultraviolet radiation, diseases and internal causes (energy depletion developmental and physiological defects) precluded a ranking of factors. Early high mortality is also likely to occur for sea cucumbers. They are extremely cryptic as juveniles and they display a range of defensive mechanisms that indicate high predation pressure.

Table 4. Mortality rates, *M*, for selected sea cucumber species.

Species	Rate (yr^{-1})	Method	Comment	Source
Isostichopus fuscus	0.354	Population dynamics model	Cold water species, Galapagos	Hearn et al., 2005
Isostichopus fuscus	0.354	Various empirical equations (Pauly, 1983; Djabali *et al.*, 1993; Cha´vez, 1995; Jensen, 1997)	Galapagos	Reyes-Bonilla and Herrero-Perezrul, 2003
Isostichopus fuscus	0.51 ±0.03	Empirical equations (Pauly, 1983)	Gulf of California, 24 °N	Herrero-Peaezrul et al., 1999
Holothuria scabra	1.49, 1.16	Pauly, Gulland		Dissanayake, 2007
Thenolota ananas	0.50	?		Ebert, 1978
	0.63	?		Preston, 1993
Stichopus chloronatus	1.79	?		Conand, 1990
Holothuria scabra	1.49, 1.16	Pauly, Gulland		Dissanayake, 2007
Actinopyga echinites	2.67, 2.62	Pauly, Gulland		Dissanayake, 2007
Bohadschia vitiensis	1.82, 1.01	Pauly, Gulland		Dissanayake, 2007
Stichopus vastus	0.298	Pauly		Salardiono et al., 2012
Holothuria atra	1.02	?	11°N	Ebert, 1978

Table 5. Mortality rates for species used in the MSE operating model.

Species	Natural mortality (Hoenigs)	Natural mortality MSE (min)	Natural mortality MSE (max)
Black Teatfish	0.44	0.3	0.6
Brown Sandfish	0.73	0.4	0.8
White Teatfish	0.44	0.3	0.6
Prickly Redfish	0.44	0.3	0.6
Golden Sandfish	0.73	0.4	0.8
Curryfish Herrmanni	0.62	0.4	0.8
Curryfish Vastus	0.73	0.4	0.8
Deepwater Blackfish	0.73	0.4	0.8
Burrowing Blackfish	0.73	0.4	0.8

3.5 Population density and biomass estimates

A basic requirement for the MSE operational model was starting values for population biomass by zone for the entire fishery area. Ideally, these biomass estimates should be calibrated against historical catch data to assess their likely accuracy. Detailed scientific information on the density of harvested holothurian species on the GBR are very limited. However, there were some robust density data for two species in our analysis list, Black Teatfish and Burrowing Blackfish.

Black Teatfish were surveyed in late 1998 to early 2000, around the time of the fishery closure (Uthicke and Benzie, 2000; Benzie and Uthicke, 2003; Uthicke et al., 2004). Seventy two reefs throughout the GBR were sampled, including closed and open reefs (Table 6). The density of Black Teatfish varied from north to south, so the original analysis divided the GBR into 4 sectors (Benzie and Uthicke, 2003). Most of the fishing for Black Teatfish had taken place in the two northern sectors (1 and 2). The density on the open reefs in the area of the fishery was at least 75% lower than on closed reefs in the same area (Uthicke and Benzie, 2000). The study concluded (with other evidence) that fishing on open reefs had caused the decline and that Black Teatfish populations in the area of the fishery were overexploited.

Twenty three reefs in the two northern sectors were resurveyed for Black Teatfish about one and two years after the closure of the fishery, but densities were similar to the original surveys and no recovery was detected during that time (Benzie and Uthicke, 2003; Uthicke et al., 2004).

Curryfish Herrmanni were also surveyed during the 1998-2000 survey (Benzie and Uthicke, 2003) (Table 6), with the authors reporting observations of Curryfish Herrmanni in deeper water during the survey that were not included in the estimated density. This is particularly relevant for the northern sections where the density estimate was zero, but the fishery report “good” densities and catch (ECBDMF spatial logbook data – not shown; Appendix C). They estimate the density of Curryfish Herrmanni to be about 5/ha on reefs throughout the GBR. We therefore applied the average density estimate from the entire GBR area from the 1998 survey (2.8/ha), as the density estimate in sections 1 and 2 only. Fishers also reported that the density of Curryfish Vastus was about 1/3 the density of Curryfish Herrmanni. This is very similar to the ratio observed in Torres Strait (Table 8). We therefore applied this ratio to estimate the biomass of Curryfish Vastus for the ECBDMF.

Table 6. Density estimates for Black Teatfish (*Holothuria whitmaei*), and Curryfish Herrmanni (*Stichopus herrmanni*) used as model starting population estimates (Benzie and Uthicke, 2003). Sectors are roughly quartiles of the GBR from north to south.

	Density (No. per Ha)		
Sector	Black Teatfish (Open)	Black Teatfish (Closed)	Curryfish Herrmanni
1	3	27	0
2	7	18	0.4
3	10	4	5.9
4	5	0	4.7

Industry-sponsored surveys of Burrowing Blackfish populations have taken place at several locations in the ECBDMF where Burrowing Blackfish have been “prospected” by the fishers (Leeworthy, 2007a; 2007b; 2010) (Table 7). Several other zones have been identified and fished, though not surveyed, and several have been designated as “Burrowing Blackfish zones” (BBFZ) awaiting further industry surveys (Table 7). We used data for surveyed locations, and likely proxies for those areas that have not been surveyed. After consultation with industry, a minimum habitat area of 1000 Ha was used as a conservative patch size for those areas not surveyed.

Table 7. Density estimates for Burrowing Blackfish (*Actinopyga spinea*) from surveys and proxies used as model starting population estimates.

Zone_Exp	BBFZ	Density	Area (Ha)	Status	Source
BBFZ1 (Waining)	Y	402	16749	Lightly fished	Leeworthy, 2007b
BBFZ2 (Lizard)	Y	402	53808	Lightly fished	Leeworthy, 2007b
BBFZ3 (Gould)	Y	1233	6686	Lightly fished	Leeworthy, 2007a
M37	Y	392.4	825	Virgin	Leeworthy, 2010
M40	Y	392.4	1000	Virgin	Assume M37 and 1000 Ha
O72 (Swains)	Y	172	1176	Virgin	Leeworthy, 2010
M63 (Swains)	Y	172	1176	Virgin	Leeworthy, 2010
M57 (Swains)	Y	172	1176	Virgin	Leeworthy, 2010
Capricorn – Bunker	Y	325	7202	Virgin	Leeworthy, 2010
M45	Y	392.4	1000	Virgin	Assume M37 and 1000 Ha
M46	Y	392.4	1000	Virgin	Assume M37 and 1000 Ha
M42	N	392.4	1000	Virgin	Assume M37 and 1000 Ha
M59 (Swains)	N	172	1000	Virgin	Assume Swains and 1000 Ha
M61 (Swains)	N	172	1000	Virgin	Assume Swains and 1000 Ha
M60 (Swains)	N	172	1000	Virgin	Assume Swains and 1000 Ha
Closed_317	Closed	172	1000	Virgin	Assume Swains and 1000 Ha
Closed_190	Closed	172	1000	Virgin	Assume Swains and 1000 Ha
C13 (North)	N	172	1000	Virgin	Assume Swains and 1000 Ha
O11 (North)	N	172	1000	Virgin	Assume Swains and 1000 Ha
O9 (North)	N	172	1000	Virgin	Assume Swains and 1000 Ha
O8 (North)	N	172	1000	Virgin	Assume Swains and 1000 Ha

For other species where no data exists for the GBR region, we used density estimates from Torres Strait surveys sampling in comparable habitats (Table 8, Table 9).

Table 8. Density estimates used as proxies for other species as model starting population estimates (Skewes et al., 2010).

Species	Density (No/ha)	Year	Location	Exploitation level
White Teatfish	0.6	1995-2009	East Torres Strait	Exploited
Curryfish Herrmanni	9.5	1995-2009	East Torres Strait	Virgin
Curryfish Vastus	3.8	1995-2009	East Torres Strait	Virgin
Prickly Redfish	2.3	1995-2009	East Torres Strait	Exploited

Density estimates for golden Sandfish were derived from information from the stakeholder workshop. Fishers reported that golden Sandfish were caught in the same areas as Burrowing Blackfish, but at a lower density. We used the relative CPUE rate for Burrowing Blackfish compared to golden Sandfish from the fishery logbook data. Average catch rate for golden Sandfish was 0.156 times the catch rate for Burrowing Blackfish, therefore we applied this factor to the density estimates of Burrowing Blackfish from the surveys (Table 9).

Biomass estimates were calculated from density estimates and habitat area, using estimates of habitat from maps of dry reef, reef and survey area (Table 10), average weights from logbook data, and established conversion ratios (Skewes et al., 2004).

Table 9. Density estimates used as a proxy for Golden Sandfish (*Holothuria lessoni*) as a model starting population estimate.

Zone	BBF Density (No/ha)	GSF Density (No/ha)	Survey area (Ha)
BBFZ3	1233	192.3	6686.7
Capricorn-Bunker	325	50.7	7202.8
M45	392.4	61.2	1000
M46	392.4	61.2	1000
M42	392.4	61.2	1000

Table 10. Starting model standing stock (SS) estimates used in the MSE operational model. Includes all ECBDMF (including Saumarez and Marion Reefs) and Ashmore Reef.

Species	Habitat designation	Total SS (,000s)	Closed area SS (,000s)	Status
Black Teatfish, 1980[1]	Dry reef area (mid and outer reefs)	8,681	3,583	Virgin
Black Teatfish, 2000[2]	Dry reef area (mid and outer reefs)	5,801	3,583	Overexploited
White Teatfish	Reef area (mid and outer reefs)	5,399	2,627	Exploited
Brown Sandfish	Reef area (midreefs, sectors 2-4)	1,325	407	Near virgin
Prickly Redfish	Reef area (mid and outer reefs)	5,613	1,723	Exploited
Golden Sandfish	BBF survey area	1,942	0*	Near virgin
Curryfish Herrmanni	Reef area (mid and outer reefs)	9,370	2,553	Near virgin
Curryfish Vastus	Reef area (mid and outer reefs)	2,811	766	Near virgin
Blackfish	Reef area (mid and outer reefs)	2,898	887	Exploited
Burrowing Blackfish	BBFZ Survey area, BBF fished areas	42,998	344*	Near virgin

[1] Using density estimate for closed reefs from 1998-2000 survey (Benzie and Uthicke, 2003) in fished sectors. Assumed as pre-fishery biomass

[2] From GBR wide density survey (Benzie and Uthicke, 2003) with average density applied to open and closed reefs in 4 sectors. Assumes as post fishery biomass

* Very little or no density data available for Burrowing Blackfish or Golden Sandfish outside fished areas.

3.6 Spatial Model of Sea Cucumber Populations

Below follows a description of the population model, which is based on an earlier model developed by Plagányi et al. (2011). The model includes 9 sea cucumber species, with populations distributed across 162 zones (154 original RHZ zones, 3 original BBF zones, 3 offshore reefs and open and closed areas of the GBR). The time period is 1995 to 2012, with a 20 year future projection time period. A full description of the age-structured population model is provided in section 3.6.1.

3.6.1 NUMBERS-AT-AGE

An age-structured production model (see Rademeyer et al., 2008; Plagányi & Butterworth, 2010 for examples) is simultaneously applied to each of the nine species, with sub-populations simulated in each of the 162 zones in which a species is known or assumed (based on habitat) to occur.

The resource dynamics are modelled by the following set of population dynamics equations:

$$N_{s,y+1,0,r} = R_{s,y+1,r} \tag{4}$$

$$N_{s,y+1,a+1,r} = \left(N_{s,y,a,r}\, e^{-3M_s/4} - C_{s,y,a,r}\right) e^{-M_s/4} \quad \text{for } 1 \le a \le m-2 \tag{5}$$

$$N_{s,y+1,m,r} = \left(N_{s,y,m-1,r}\, e^{-3M_s/4} + N_{s,y,m,r}\, e^{-3M_s/4} - C_{s,y,m-1,r} - C_{s,y,m,r}\right) e^{-M_s/4} \tag{6}$$

where

N_{syar} is the number of holothurians of species *s* and age *a* in zone *r* at the start of year *y* (which refers to a calendar year),

R_{syr} is the total recruitment (number of 0-year-old holothurians) in zone *r* of species *s* at the start of year *y*,

M_s denotes the (age-independent) natural mortality rate of species *s*,

C_{syar} is the predicted number of holothurians of age *a* and species *s* caught in zone *r* in year *y*, and

m is the maximum age considered (taken to be a plus-group and set equal to 5 for all species).

The population model used here assumes pulse fishing (Pope's approximation – Pope, 1984), and the approximation of the fishery as a pulse catch three-quarters into each year is because zones are fished for short periods, for example being open for 15 days of fishing once every three years. Moreover, catches are highest during spring (see Figure 6, Figure 7) and hence the pulse catch is assumed to correspond to end of September.

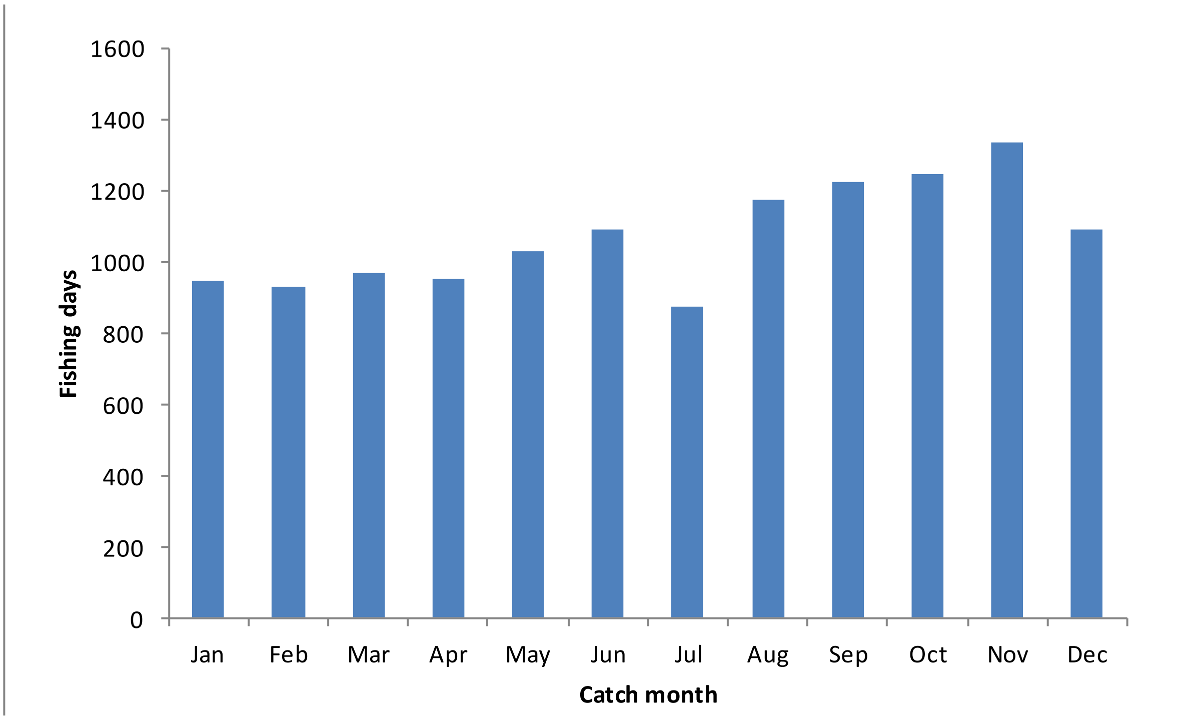

Figure 6. Total number of fishing days in the ECBDMF since 1995, by month.

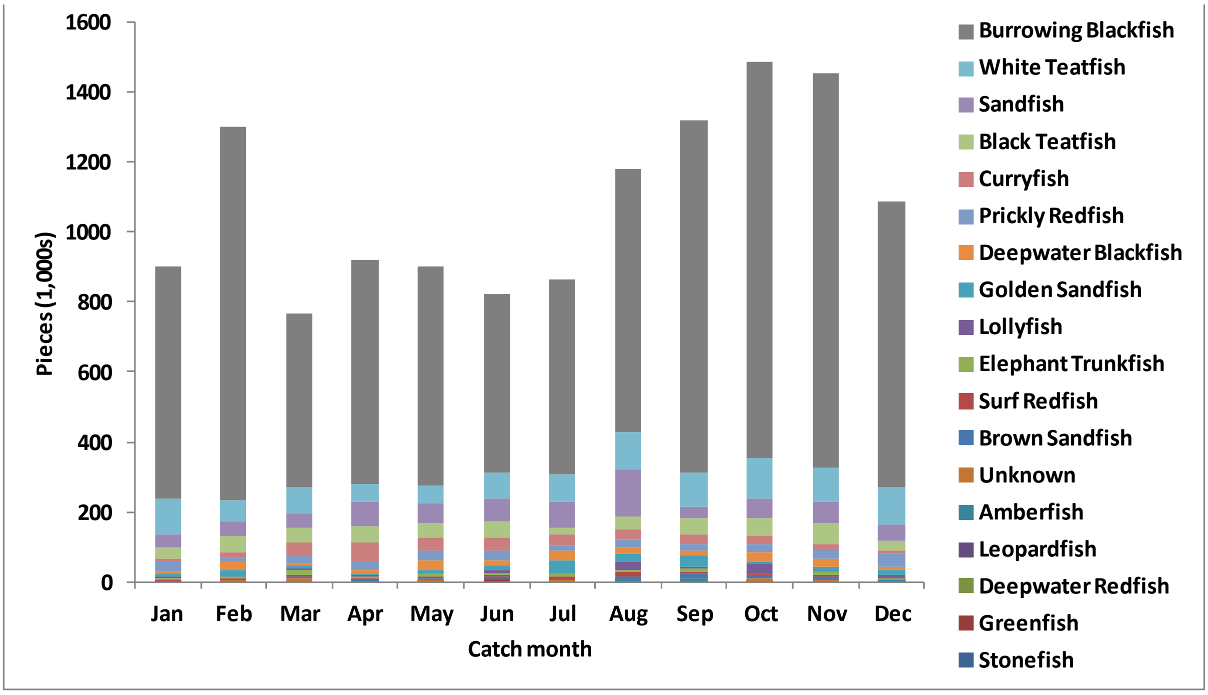

Figure 7. Total catch (in pieces) by month for the ECBDMF since 1995.

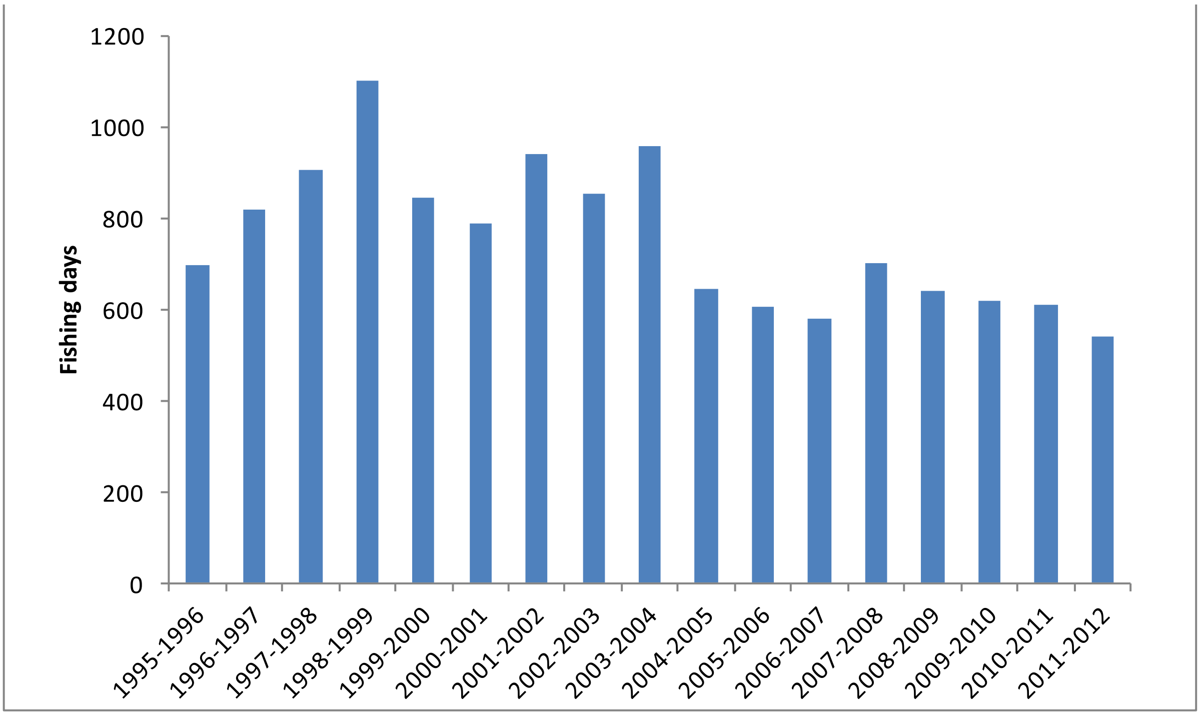

Figure 8. Number of Authority fishing days per fishing (fiscal) year, from ECBDMF logbook data.

3.6.2 RECRUITMENT

The number of recruits of species *s* at the start of year *y* is assumed to be related to the spawning stock size (i.e. the biomass of mature holothurians) by a modified Beverton-Holt stock-recruitment relationship (Beverton & Holt, 1957), allowing for annual fluctuations about the deterministic relationship, with such fluctuations varying by species but not spatially (although see also sensitivity tests). Recruitment is assumed to be local within each zone, such that:

$$R_{syr} = \frac{\alpha_s B^{sp}_{syr}}{\beta_s + B^{sp}_{syr}} e^{(\varsigma_{sy} - (\sigma_{sR})^2/2)} \tag{7}$$

where,

α_s, β_s are spawning biomass-recruitment relationship parameters for species *s*,

ς_{sy} reflects fluctuation about the expected recruitment for species *s* in year *y*, which is assumed to be normally distributed with standard deviation σ_{sR} (which is input);

B^{sp}_{syr} is the spawning biomass for species *s* in zone *r* in year *y*, computed as:

$$B^{sp}_{s,y,r} = \sum_{a=1}^{m} f_{s,a} w^{strt}_{s,a} N_{s,y,a,r} \tag{8}$$

except for Black Teatfish, which spawns in winter and hence is modified as follows:

$$B^{sp}_{s,y,r} = \sum_{a=1}^{m} f_{s,a} w^{mid}_{s,a} N_{s,y,a,r} e^{-M_s/2} \tag{9}$$

where,

w^{strt}_{sa} is the begin-year mass of a holothurian of species *s* and age *a*,

w^{mid}_{sa} is the mid-year mass of species *s* and age *a*, and

f_{sa} is the proportion of holothurians of species *s* and of age *a* that are mature.

In order to work with estimable parameters that are more meaningful biologically, the stock-recruitment relationship is re-parameterised in terms of the pre-exploitation equilibrium spawning biomass K^{sp}_s for each species *s* (and for the entire model area), and the "steepness", h_s, of the stock-recruitment relationship. Steepness is a more straightforward parameter to work with because it is the proportion of the virgin recruitment that is realized at a spawning biomass level of 20% of the virgin spawning biomass:

$$\beta_s = \frac{\left(K^{sp}_s\right)^{\gamma_s}\left(1 - 5h_s 0.2^{\gamma_s}\right)}{5h_s - 1} \tag{10}$$

and

$$\alpha_s = \frac{\beta + \left(K^{sp}_s\right)^{\gamma_s}}{SPR_{s,virg}} \tag{11}$$

where

$$SPR_{s,virg} = \sum_{a=1}^{m} f_{s,a} w^{strt}_{s,a} N^{virg}_{s,a} \tag{12}$$

with

$$N^{virg}_{s,1} = 1 \tag{13}$$

$$N_{s,a}^{virg} = N_{s,a-1}^{virg} e^{-M_s} \qquad \text{for } 2 < a < m\text{-}1 \tag{14}$$

$$N_{s,m}^{virg} = N_{s,m-1}^{virg} \; e^{-M_s} \Big/ \left(1 - e^{-M_s}\right) \tag{15}$$

where,

γ is a spawning biomass-recruitment relationship parameter with default value 1, but setting γ > 1 leads to recruitment which reaches a maximum at a certain spawning biomass, and thereafter declines towards zero, and thus have the capability of mimicking a Ricker-type relationship.

As above, *m* is the maximum age considered for species *s.*

3.6.3 TOTAL CATCH AND CATCHES-AT-AGE

The catch numbers-at-age of species *s* removed each year *y* from zone *r* is given by:

$$C_{s,y,a,r} = S_{s,a} \, F_{s,y,r} N_{s,y,a,r} \; e^{-3*M_s/4} \tag{16}$$

and hence the total annual catch (in numbers) of species *s* from zone *r* is:

$$C_{s,y,r} = \sum_{a=1}^{m} C_{s,y,a,r} \tag{17}$$

and the catch by mass is:

$$C_{s,y,r}^{mass} = \sum_{a=1}^{m} w_{s,a}^{\exp} \; C_{s,y,a,r} \tag{18}$$

where

C_{syar} is the number of holothurian of species *s* and age *a*, caught in zone *r* in year *y*,

S_{sa} is the fishing selectivity at age *a* for species *s* - assumed not to vary spatially; note when $S_{y,a} = 1$, it implies the age-class *a* is fully selected,

F_{syr} is the fished proportion of a fully selected age class of species *s* in zone *r* in year *y*, and

$w_{sa}^{\exp}$ is the mass of a holothurian of species *s* and age *a* at the time it is exploited (i.e. September).

The model estimate of the exploitable ("available numbers") component of biomass during the third quarter is given by:

$$B_{s,y,r}^{ex} = \sum_{a=1}^{m} N_{s,y,a,r} e^{-3 \cdot M_s/4} S_{s,a} \tag{19}$$

Hence the proportion of species *s* harvested each year from zone *r* is:

$$F_{s,y,r} = \frac{C_{s,y,r}}{B_{s,y,r}^{ex}} \tag{20}$$

Which allows computation of the numbers-at-age removed each year (cf Equation (16)).

3.6.4 INITIAL CONDITIONS

The resource is assumed to be at deterministic equilibrium (corresponding to an absence of harvesting) at the start of 1995, the initial year considered here. Given a value for the pre-exploitation spawning biomass $B_{s,0}^{sp}$ of each species *s*, together with the assumption of an initial equilibrium age structure, it follows that:

$$B_{s,0}^{sp} = R_{s,0} \cdot \left[\sum_{a=1}^{m-1} f_{s,a} w_{s,a}^{strt} \exp(-M_s \cdot a) + f_{s,m} w_{s,m}^{strt} \frac{\exp(-M_s \cdot m)}{1-\exp(-M_s)} \right] \tag{21}$$

which can be solved for R_0.

3.6.1 PRIMARY UNCERTAINTIES IN THE BASELINE MODEL

The following four factors were assumed to account for most of the uncertainty regarding the key considerations of resource status and productivity: a) the natural mortality of each species; b) the steepness parameter of the stock-recruitment functions; c) the underlying recruitment pattern (stochastic and variable versus deterministic) and d) the starting (1995) biomass. A Reference Set (RS) (Rademeyer et al., 2007) was thus constructed to include a sufficiently representative range of potential estimates of current population status and productivity (Table 11), as follows:

M. Natural mortality:

MH: the average mortality estimates for each species were used, together with the growth parameters (length-weight-age relationships) computed as shown in Table 3.

ML: the lower bound of the mortality estimates were used for each species, and because this is a slow growth scenario, were combined with slow growth assumptions for the two Teatfish species for which slow growth has been proposed as likely (Uthicke et al., 2004). Hence for Black Teatfish, White Teatfish and Prickly Redfish, the maximum size parameters as shown in Table 3 and as input to Equation (2) were instead reduced to 400mm, 500mm and 500mm respectively.

H. Steepness parameter:

HH: *h* is fixed at 0.7 (Myers et al., 2000);

HL: *h* is fixed at a more conservative value of 0.5;

R. Recruitment frequency:

RH: Recruitment is assumed to be stochastic with random fluctuations about the underlying stock-recruit curve;

RL: Recruitment is assumed to be deterministic with the recruitment for each species in each of the zones determined by the stock-recruit relationship.

K. Starting biomass:

K: The starting (1995) biomass was fixed at the input values given in Table 10, except for Black Teatfish for which half the value was used;

KL: The starting (1995) biomass was assumed to be 0.5 times the K values.

3.7 Reference set of operating models

Given key uncertainties regarding major considerations of resource status and productivity, the full Reference Set (RS) of 16 Operating Models (OMs) spanning these uncertainties, rather than a single OM, was constructed for the sea cucumber resource (Table 11).

For each harvest strategy tested, 10 replicates of each of the 16 RS cases (i.e. a total of 160 simulations per zone per species) were projected over a 20-year period into the future. The different replicates represent alternative plausible future “states of nature” that are compatible with the available information. These different replicates vary due to stochastic effects, namely recruitment variability.

The largest differences between the 16 OMs was due to the starting spawning biomass level (K and KL) followed by the recruitment variability assumption, with recruitment scenarios with stochasticity added (RH) leading to more negative spawning biomass trajectories than deterministic recruitment scenarios (RL) (Figure 9). The next largest effect was due to the mortality and growth scenario MH-GF compared with the low mortality and slow growth scenario ML-GS, with this particularly evident for both the Teatfish species for which a slow growth scenario was coupled with a low mortality rate scenario (Figure 9). The recruitment variability was set relatively high (sigma = 0.5) and hence largely swamped variability due to changing the steepness of the stock-recruit curve but some differences were evident (HH and HL) (Figure 9).

Table 11. Summary of the Reference Set (RS) of 16 alternative model combinations of the four primary uncertainties included in the operating model. The low (ML) and high (MH) mortality scenarios are coupled with slow (GS) and fast growth (GF) scenarios respectively. The recruitment steepness h options used are 0.7 (HH) and 0.5 (HL). RH and RL are the stochastic and deterministic recruitment options respectively. K and KL represent the initial and 0.5 starting (1995) biomass options.

Case	Mortality (M)	S-R Steepness (H)	Recruitment (R)	Growth (G)	Biomass (K)
1	ML	HH	RH	GS	K
2	ML	HL	RL	GS	K
3	ML	HH	RL	GS	K
4	ML	HL	RH	GS	K
5	MH	HH	RH	GF	K
6	MH	HL	RL	GF	K
7	MH	HL	RH	GF	K
8	MH	HH	RL	GF	K
9	ML	HH	RH	GS	KL
10	ML	HL	RL	GS	KL
11	ML	HH	RL	GS	KL
12	ML	HL	RH	GS	KL
13	MH	HH	RH	GF	KL
14	MH	HL	RL	GF	KL
15	MH	HL	RH	GF	KL
16	MH	HH	RL	GF	KL

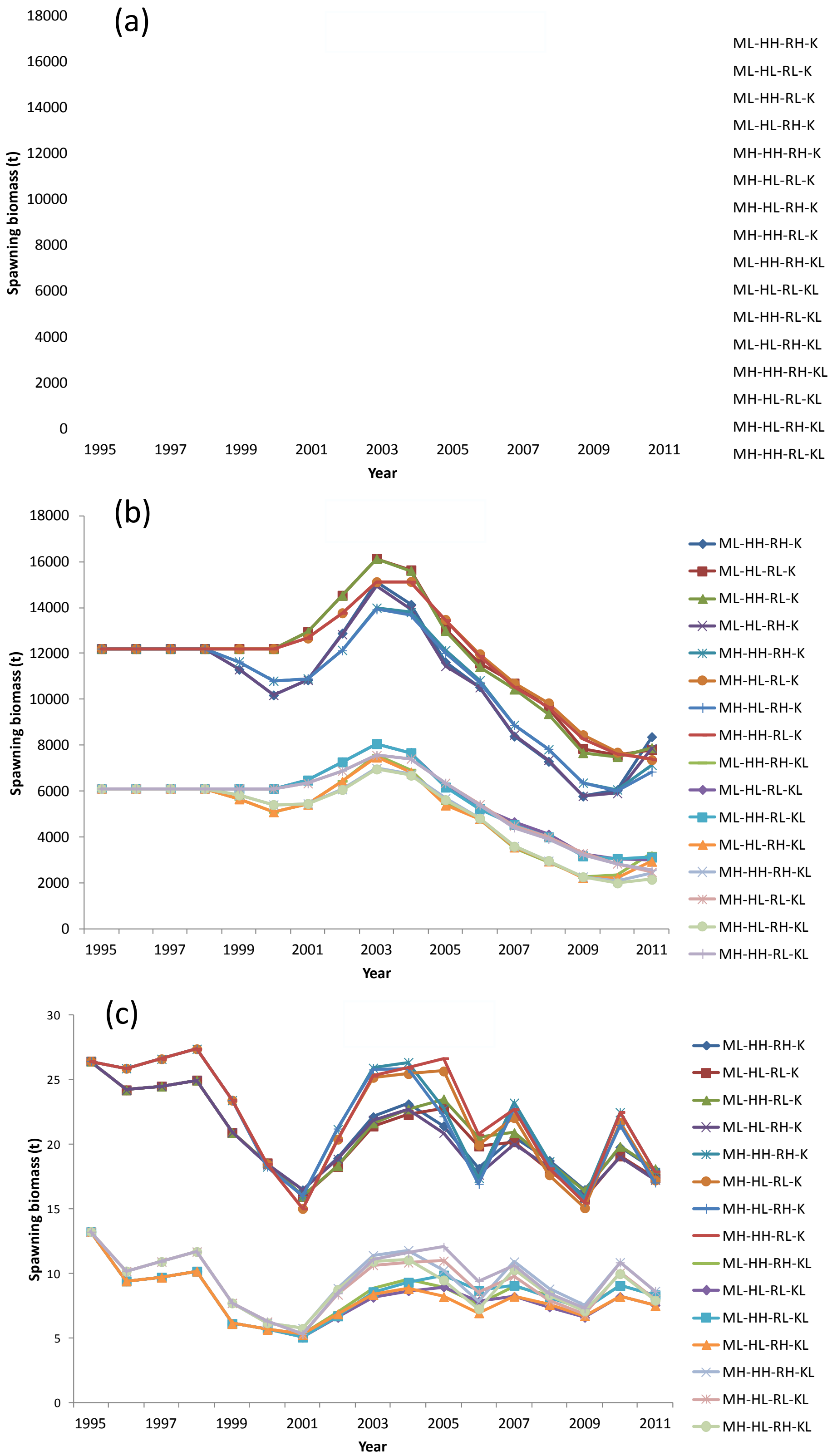

Figure 9. Illustrative example of differences between the 16 OMs comprising the Reference Set (RS) shown for (a) Curryfish Herrmanni, (b) Burrowing Blackfish and (c) Black Teatfish at illustrative zones with biomass and catch. See Table 11 for summary of model versions.

3.8 Model calibration

We assume 1995 represents the pristine (no fishing) condition for all species except Black Teatfish as there was only fairly limited fishing of those species prior to this (Figure 2). In the case of Black Teatfish, we used the estimate of "pristine" biomass as the application of closed area density to the area of the early Black Teatfish fishery (northern zones), as per Benzie and Uthicke (2003). Collectively the model includes a broad range of starting values given there are 9 species and 162 zones. We use the starting biomass values as a proxy for an average *K*, but it is important to note that the populations are highly variable and hence in good years the biomass may exceed *K*. Moreover, the Reference Set as described above incorporates simulations that use starting biomass at half the calculated estimate.

Considerable time was spent calibrating the model, particularly to cross-check and correct errors such as catches being recorded from a zone but no biomass estimates being available for that zone. Moreover, the model was useful in highlighting zones for which the recorded catches (in numbers but converted also to biomass in the model) exceeded survey-based biomass estimates for that species. The primary model diagnostic used was the annual fishing proportion as this cannot exceed one – the model assumed that fishers could catch a maximum of 99% of the available (i.e. animals older than the age-at-first-selectivity) biomass in a zone in any given fishing season. Nonetheless, some problems could not be resolved for some species in some zones as this is a data rather than model issue – for example, for White Teatfish, it appears that the catches in many of the zones, particularly those close to Cairns and Cooktown, exceed the biomass estimates calculated from the proxy Torres Strait density and reef area. For these zones it is likely that the biomass is underestimated due to an underestimated zonal density or habitat area (there is a high likelihood of unmapped deep habitat for White Teatfish, for example).

For these zones, the fishing proportion is simply capped and it doesn't have a big effect on the model results overall because there are a total of 9 species on 162 reefs, and 16 alternative population trajectories simulated on each of these reefs, plus 10 replicates (to simulate alternative future environmental variability) of each of these for the future projections (Table 12). The proportion of the total zones that each species is present in the model is summarised in Table 12.

Table 12. Summary of the total number of simulations over which the final model results are averaged for each species.

Species	No. of simulations	Proportion of zones present
Black Teatfish	23200	0.89
Brown Sandfish	10400	0.40
White Teatfish	23680	0.91
Prickly Redfish	23680	0.91
Golden Sandfish	1440	0.06
Curryfish Herrmanni	23840	0.91
Curryfish Vastus	23840	0.91
Deepwater Blackfish	24000	0.92
Burrowing Blackfish	3200	0.12
Total	157280	

As an illustration of how the model works, a single trajectory is shown for a single species as an example, namely the golden Sandfish in a heavily fished zone (Figure 10). The populations of each species vary considerably from year to year in response to variable (and sometimes intermittent) recruitment as well as fishing pressure (from logbook data). Hence the inter-annual recruitment variability is shown, together with the historic fishing proportion that is seen to vary from year to year. The spawning biomass of this species declines in response to heavy fishing, but some recovery is modelled towards the end of the historic period. The responses of the different species in the model will all be different not only because of differences in fishing effort, but also because of differences in life history parameters and characteristics, as well as the age-at-maturity and age-at-first capture. In addition, instead of a single trajectory for each species in each zone, as in the golden Sandfish example (Figure 10), a Reference Set of simulations is used as discussed in the Reference Set section.

3.9 Validating the model

Unfortunately there are no relative indices of abundance to which we can fit the model; however we were able to test the model against the assumption of the “pristine” (1980) biomass for Black Teatfish (Uthicke, 2000; Benzie and Uthicke, 2003). These data indicate that the Black Teatfish population decreased to 38% of the pristine biomass estimate by year 2000 in the northern fished zones, and the preliminary model wasn’t able to match this decrease for most zones (Figure 11) – at least not in such a way that the population would subsequently recover in the absence of fishing. This was due to most of the fishing occurring before the implementation of compulsory logbooks (and therefore is not represented in the logbook data we are using to represent catch). The total catch of Black Teatfish between 1987 and 1995 has been estimated at approximately 1,451 t (gutted weight) (Uthicke, 2004), compared to 516 t (landed weight) from the logbook data between 1995/96 and when the fishery closed in 1999. To enable more realistic modelling of the Black Teatfish population, the starting biomass was adjusted to half the original estimates.

A second challenge in the modelling involved balancing recruitment with population growth. For Teatfish species in particular, where the low mortality-slow growth scenarios are considered likely, under pulsed and sporadic recruitment (RH), local Black Teatfish populations were unable to sustain themselves in the model, and continue to decline even if future catches are set to zero. A model diagnostic that was used was that a recovery is expected with no fishing, even if slow. On the other hand, if we have constant (albeit variable) recruitment, it’s hard to see the impact of catches that were taken in a few years because only the older age classes are targeted and there are sufficient incoming recruits to fill the gap, whereas sea cucumber populations such as Black Teatfish have been observed to decline rapidly in response to fishing (Uthicke, 2004; Skewes et al., 2004). Hence to more accurately calibrate the model for Teatfish in particular, the recruitment variability has been skewed slightly so that in some (randomly determined) years the recruitment is lower than average (but not zero). Collectively these changes to the preliminary model yielded a more realistic population trajectory for Black Teatfish (Figure 12) that compares better with the survey data collected in 1999-2000 (Uthicke, 2000; Benzie and Uthicke, 2003).

An important model diagnostic was that the model populations should have the same features as observed in the field – for example, high natural variability even in the absence of fishing, and the ability to replicate boom and bust cycles under fishing. Although realistic, this confounds understanding of the impacts of fishing over and above natural variability and hence we included a performance statistic that compared each projected population under fishing with an equivalent no-fishing projection. To assess whether the modelled population fluctuations were realistic, we compared them with survey data available for four of the same species in Torres Strait where there have been several surveys of sea cucumber populations (Skewes et al., 2004, Skewes et al., 2010). In all four cases (Black Teatfish, blackfish, White Teatfish and Prickly Redfish) the extent of modelled variability compared well with observed variability from field observations (Figure 13), further validating the usefulness of the model.

An additional model diagnostic that was used for all species to assess whether the modelled populations were as realistic as possible was to examine the historic fishing proportion estimates (catch as a proportion of population numbers of all ages exceeding the age at first capture) because these are bounded by zero and a maximum of one. Hence very low values suggest the biomass estimates used may be too high, whereas consistently high values suggest the biomass may have been underestimated (as was the case for White Teatfish in some zones). Figure 14 provides an example of the historic variability in fishing mortality of Black Teatfish applied to the RZS zones, with each bar representing the fishing proportion in a zone, and the gaps are zero historic fishing in the remaining zones. The high fishing proportion estimates (capped at 0.99) in some zones may be realistic considering the age at first capture is set at 4 years for Black Teatfish (the model assumes no younger/smaller animals are caught) and these larger individuals are not as cryptic as the smaller individuals. However, most fished zones are fished at between 0.1 and 0.3, which represents a heavy but realistic fishing pressure for those targeted zones (Figure 14).

Finally, we checked that populations showed a realistic population recovery under a no fishing scenario. For Black Teatfish, we modelled the original and half starting biomass (Low K) scenarios in a heavily fished zone (Figure 15). This shows a slow recovery after heavy fishing under both starting biomass scenarios with spawning biomass staying at depleted levels for a decade or more, before a slow recovery, especially under the more likely Low K scenario. A comparison of the spawning biomass trajectories for White Teatfish and Prickly Redfish are also shown, illustrating the potential for sporadic increases in spawning biomass (Figure 15) after heavy fishing. Highly fluctuating spawning biomass is also likely the result of the recruitment of juveniles and variable year class strength.

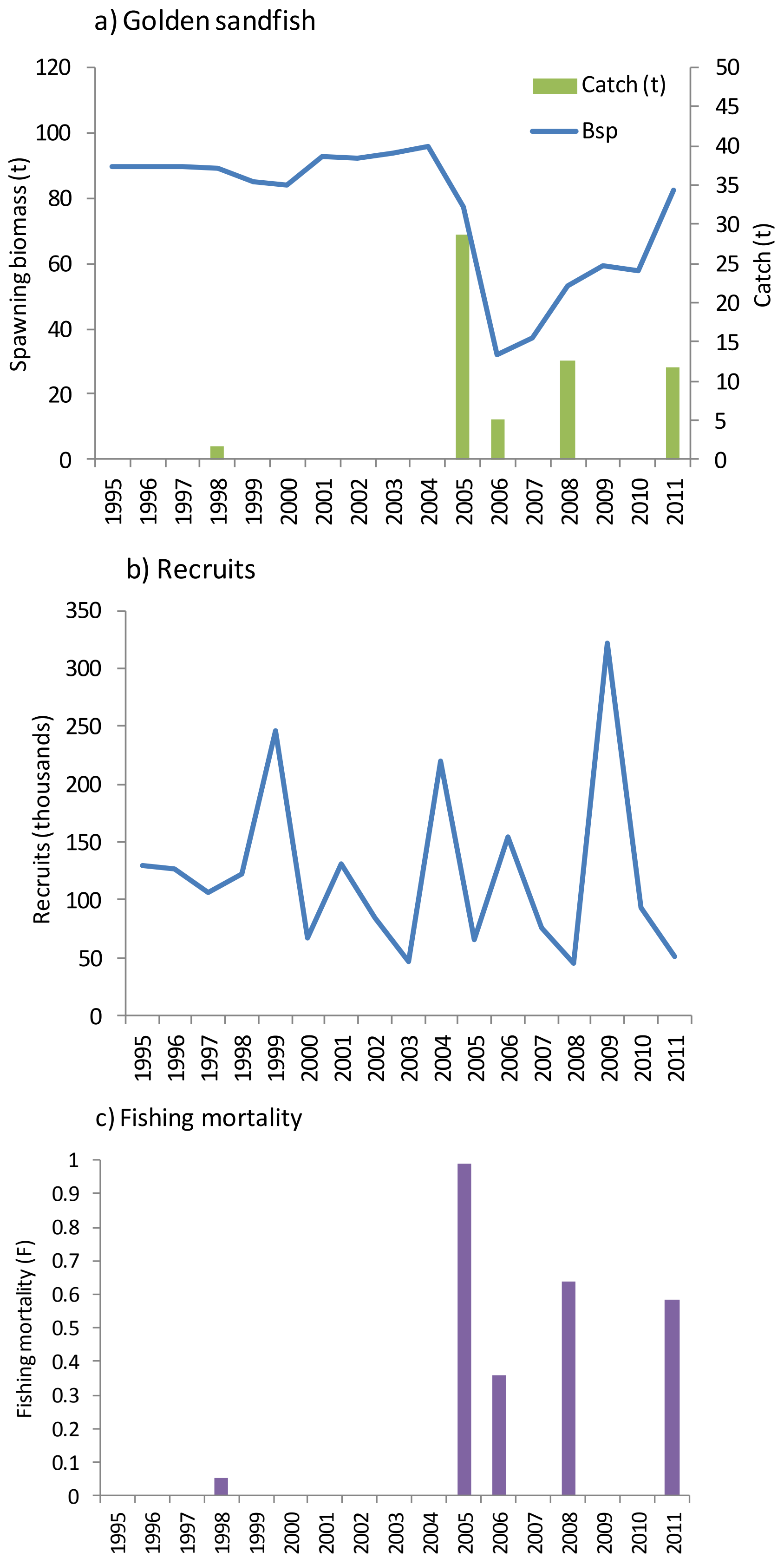

Figure 10. (a) Illustrative model trajectory for a single species, Golden Sandfish (*Holothuria lessoni*) from 1995 to 2012 in one of the 162 zones as shown with: a) estimated spawning biomass and total historic catch, (b) example of the inter-annual variability in recruitment simulated over this period and, (c) fishing mortality estimates computed within the model. (Spawning biomass is in live wt)

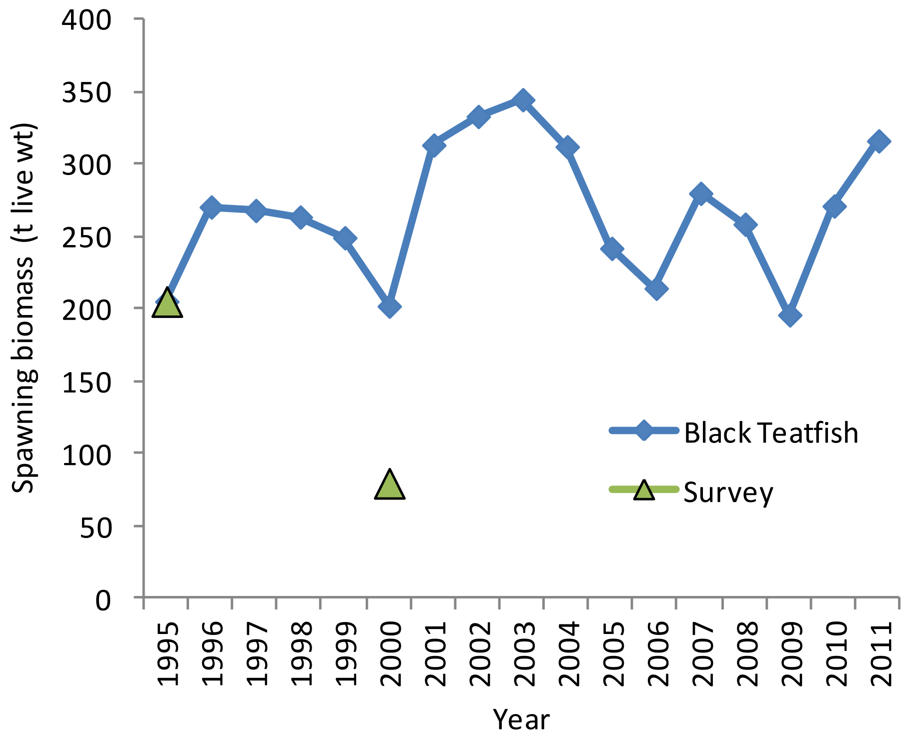

Figure 11. Original model parameters for Black Teatfish in Zone 113 that failed to match available survey data for 2000.

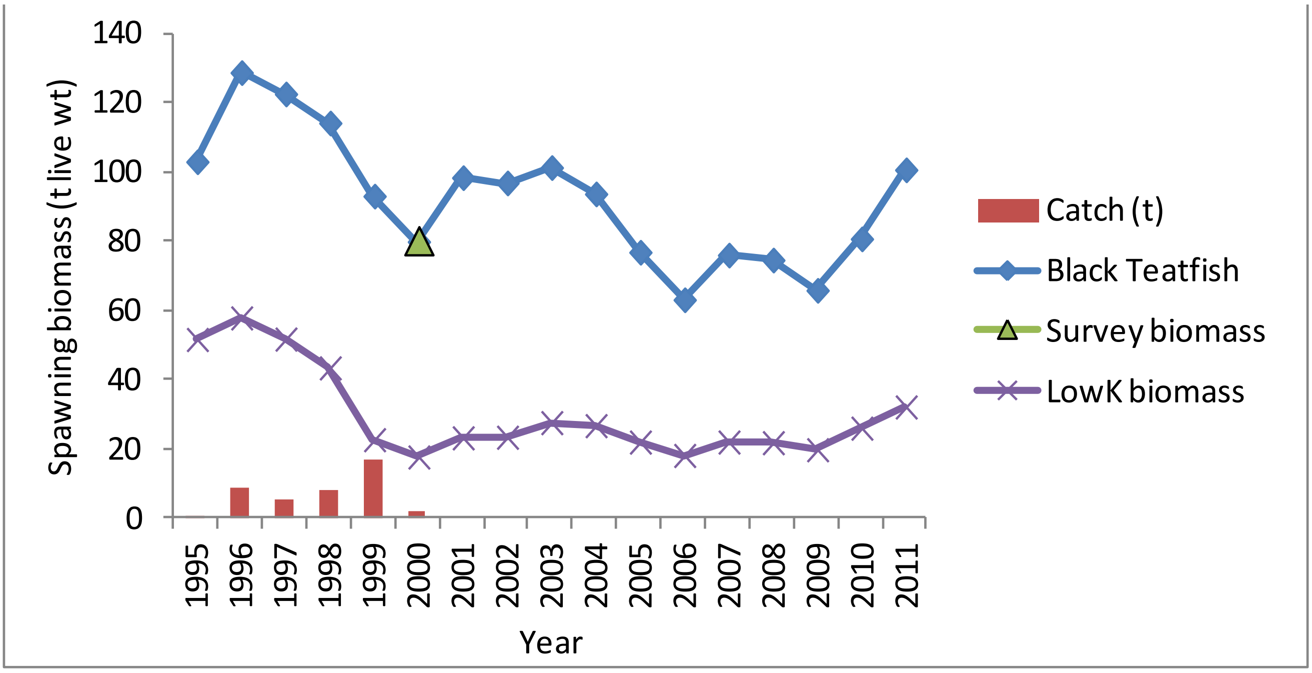

Figure 12. Revised base-case model spawning biomass (t) (Bsp) of Black Teatfish in one of the high catch zones, plotted on the same axis as the historic catches (after converting to units of tons) (note that the exploitable biomass will be similar to Bsp). This plot shows a single illustrative replicate of each of 2 of the 16 model simulations, one with starting value as is (after halving the starting biomass estimates for Black Teatfish) and a KL version with half this again as starting biomass. The survey point is the actual survey biomass estimate from 1999 (Uthicke, 2000; Benzie and Uthicke, 2003).

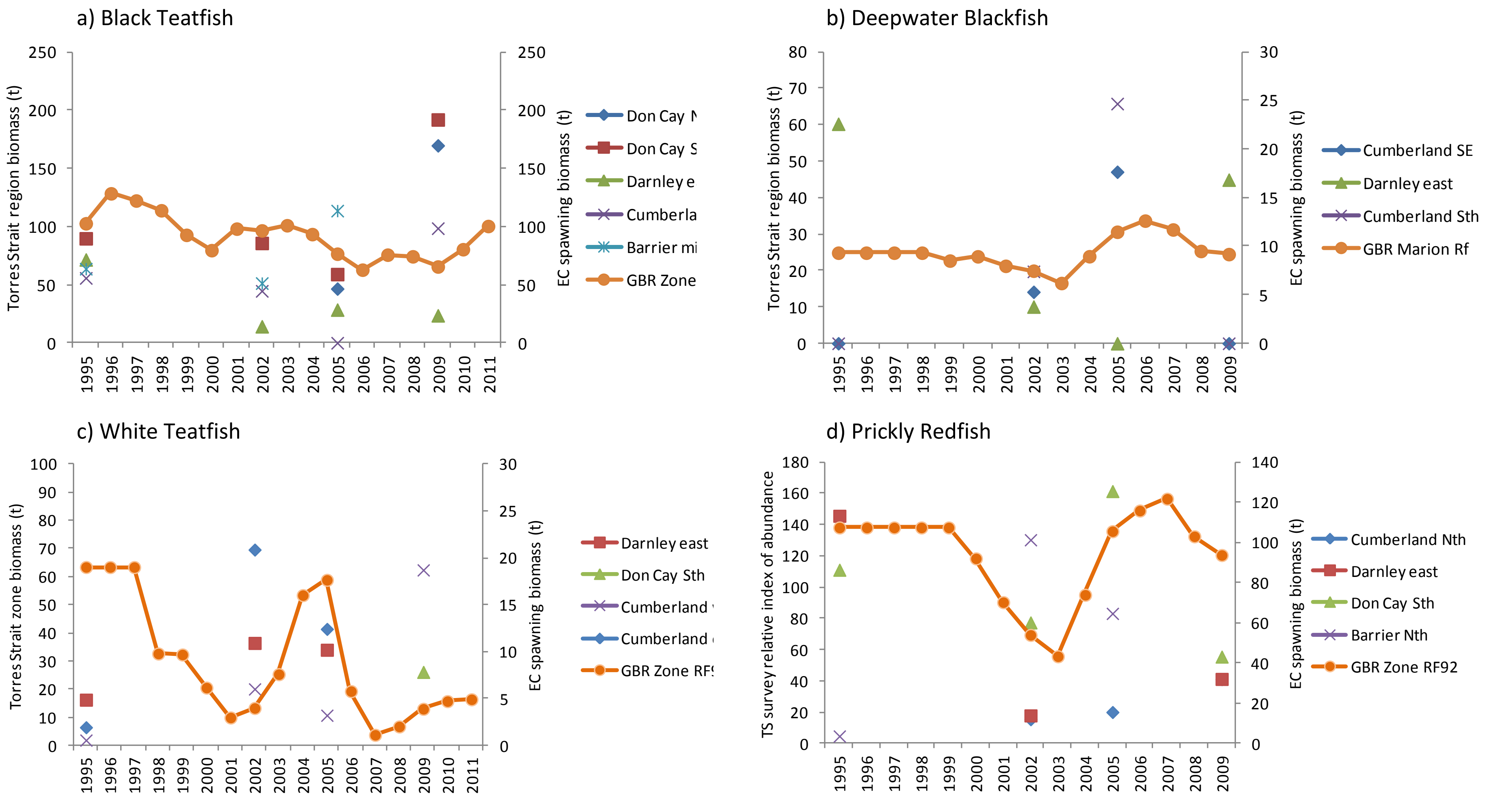

Figure 13. Illustrative examples of a) Black Teatfish, b) Deepwater Blackfish, c) White Teatfish and d) Prickly Redfish spawning biomass model trajectories for selected zones in the ECBDMF, compared with survey biomass data from Torres Strait zones to compare the range of variability that can be expected in sea cucumber populations.

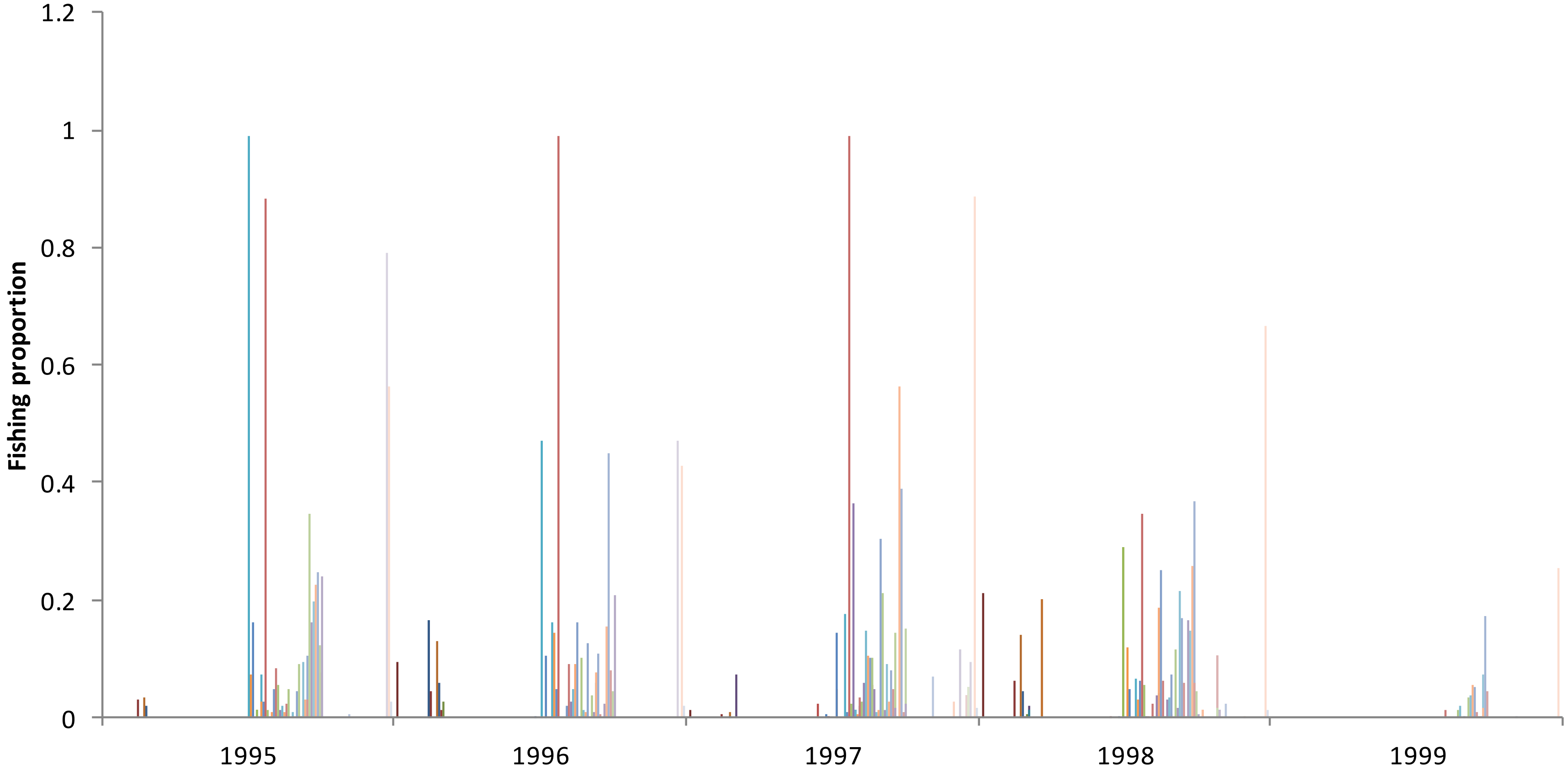

Figure 14. Example of the variability in fishing mortality for Black Teatfish across the years 1995 to 1999 and across individual zones in the ECBDMF, with each bar representing the fishing proportion in a zone, and the gaps are zero historic fishing in the remaining zones.

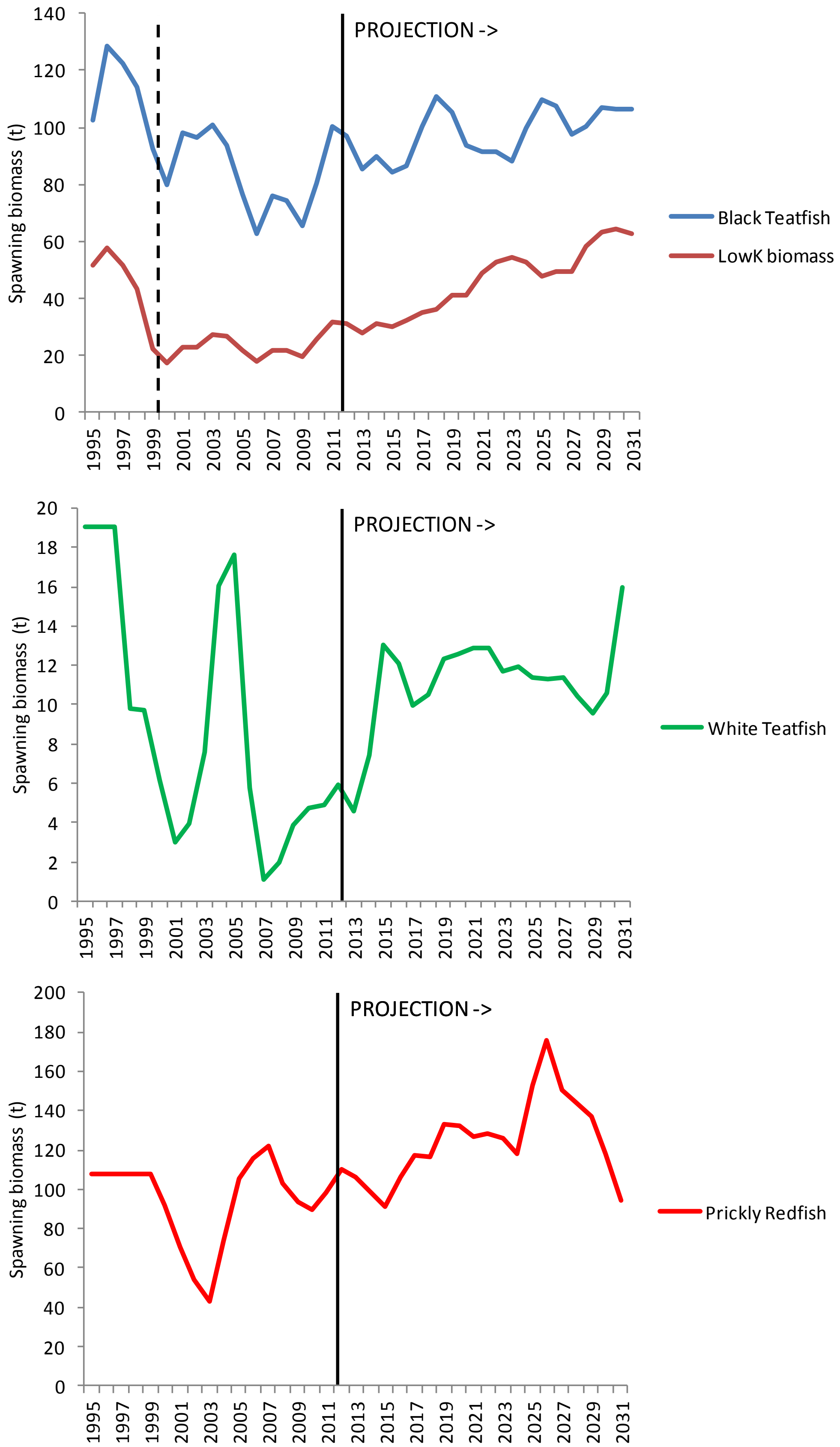

Figure 15. Spawning biomass trajectories for three species in heavily fished zones: a) Base-case and half base case (Low K) Black Teatfish spawning biomass, including projection period with zero TAC b) White Teatfish with projection period with zero TAC and c) Prickly Redfish with projection period with zero TAC. A single simulation (first case of Reference Set) and single replicate only is shown.

3.10 Performance Statistics

The following performance statistics, related to the objectives above, were computed for each harvest strategy tested in order to assess the utility and optimal configuration of the RZS for mitigating localised depletion, reducing risks to overall sustainability and maximising efficiency and values of this multispecies fishery. Projections were conducted over 20 years.

3.10.1 RESOURCE STATUS

- $B_{2032}^{sp} / B_{1995}^{sp}$ the expected spawning biomass at the end of the projection period, relative to the starting (1995) level (used as a proxy for K), for each species averaged across entire area and for each zone.
- $B_{2032}^{sp} / B_{2012}^{sp}$ the expected spawning biomass at the end of the projection period, relative to the current 2012 level, for each species averaged across entire area and for each zone.
- Measure of how well management achieves the default reference level of 48%K: the percentage of all individual runs that ended above 48% of the comparable no-fishing case at the end of the projection period, for each species averaged across entire area and for each zone. Note: 0.48K is the default Maximum Economic Yield (MEY) adopted in the Commonwealth Harvest Strategies (DAFF, 2007; 2013). Although it is very uncertain if this biomass level would result in MEY, it is still a useful reference point for this analysis, and was recommended at the Stakeholder workshop for the project (Appendix D).
- As above, but based on ratio of spawning biomass at the end of the projection period, relative to the current 2012 level.
- Risk of local depletion: percentage of all individual runs across all zones that ended below *Blim=0.2* of the comparable no-fishing reference case at the end of the projection period (i.e. when considering all possible future projection outcomes for a species over the entire fished area, how likely is it that local depletion will occur because the biomass in a local zone drops below 20% of what it might have been if no fishing had occurred). This is equivalent to the default Limit reference point for the Commonwealth harvest strategies (DAFF, 2007; 2013).
- Risk of depletion below 40% unfished: as above, but a more conservative risk measure.

3.10.2 UTILISATION

- Average catch: $\frac{1}{20}\sum C_y$ over 2012 to 2032 (for each zone as well as the entire area, and for three groups of species: very high, high and medium value).
- Average annual value ($ million) computed as the landed weight of each species multiplied by current average market prices. This does not account for costs of monitoring and adaptive management

3.10.3 CATCH VALUE

Average annual value ($ million) computed as the landed weight of each species multiplied by current average market prices. Sandfish and golden Sandfish were regarded as very high value species, and we assumed an average value of $200/kg dry, and an average conversion factor of 18% of salted landed weight (Skewes et al., 2004). We then used the relative value of very high, high, and medium (no low value species included here) and their landed weight (Table 13).

Table 13. Value categories and multiplier for sea cucumber species in the catch. VH=very high value; H=high value; M=medium value.

Species	Value	Multiplier
Black Teatfish	H	0.8
Brown Sandfish	M	0.5
White Teatfish	H	0.8
Prickly Redfish	M	0.5
Golden Sandfish	VH	1
Curryfish Herrmanni	M	0.5
Curryfish Vastus	M	0.5
Deepwater Blackfish	M	0.5
Burrowing Blackfish	M	0.5

4 Results

4.1 Historic population trajectories

The median spawning biomass trajectories over 1995-2011 are shown in Appendix F (Figure 26 to Figure 34) for each species and for a selected ten reefs, chosen based on corresponding to the highest biomass estimates, as indicated. The biomass for the lumped closed (C) and other open (O) areas was computed by lumping together the populations from the constituent areas outside the RZS zones. For each species, the median biomass in each zone was computed and these were added together to yield an estimate of the total spawning biomass in all the RZS zones, as well as across the entire region, i.e. including the closed areas (Figure 16).

Populations were generally stable across all simulations in the closed areas, except in the case of the Black Teatfish and White Teatfish which were subject to heavy historic fishing. This is reflected in the declining population trends for these species (Figure 16, Figure 26, Figure 28). There were also fairly marked declines evident for Burrowing Blackfish in response to high catches in recent years (Figure 16, Figure 34) and stochastic “environmental” factors. Golden Sandfish also showed some declines in some zones due to high catches in those years (Figure 30).

4.2 Projected population trajectories with no fishing

The median projected spawning biomass trajectories from 2012 to 2031 are shown in Figure 35 to Figure 43, assuming in this instance zero future catches. For each species in each zone, the median is based on all 160 projected simulations, and hence each median incorporates both the uncertainty represented by the reference set (RS) of 16 OMs, as well as uncertain future environmental states. These projections are likely conservative as they incorporate slow growth and stochastic and pulsed recruitment possibilities, and as explained above, there are indications that some of the initial biomass estimates may be too low. The same set of random outputs was used to generate sets of 160 no-fishing projections for each species and zone, as a baseline for comparisons with a range of future harvest strategies.

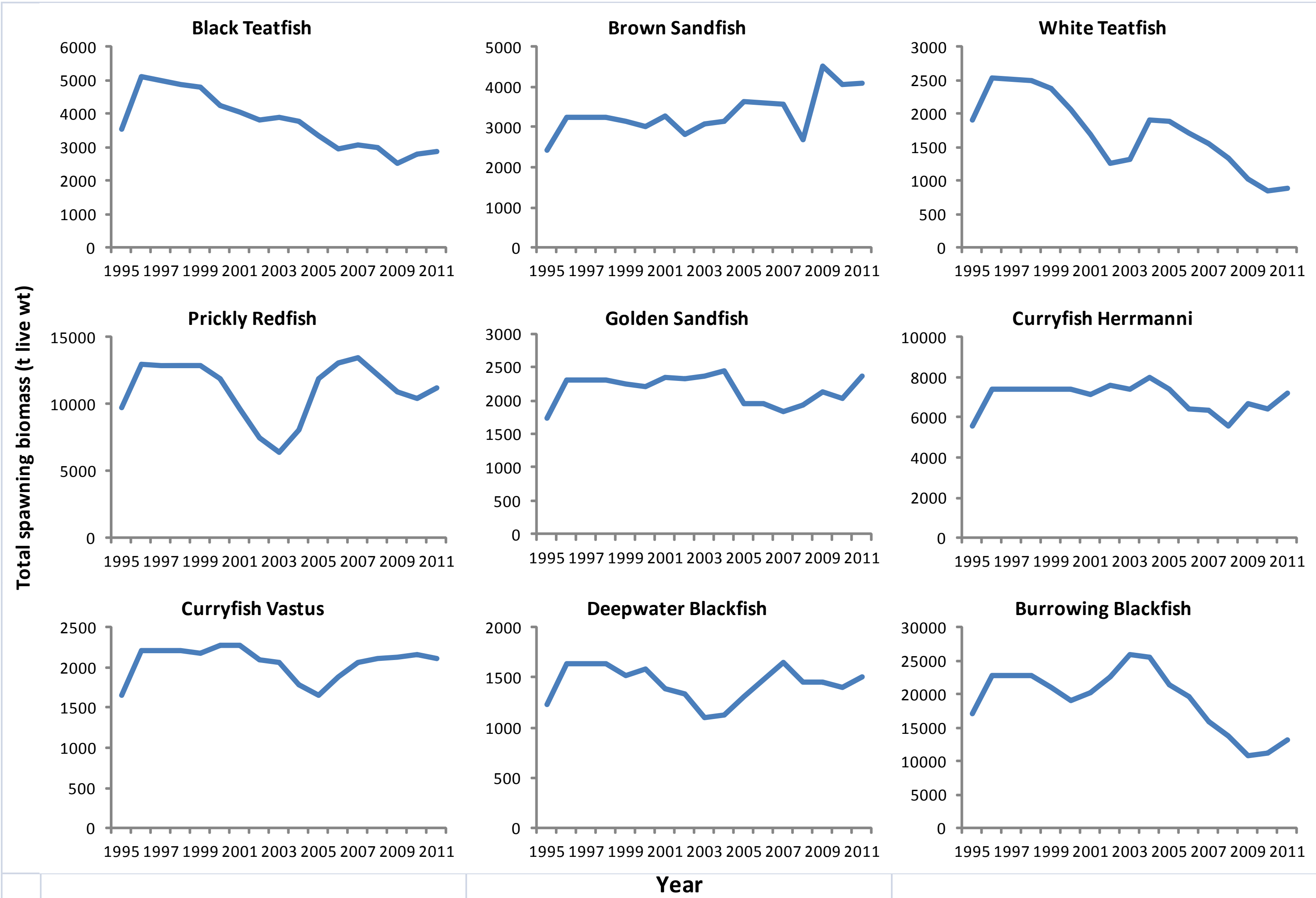

Figure 16. Median of total spawning biomass (t live weight) of each species in the ECBDMF over the historic period 1995 to 2011.

4.3 Projected populations with current management strategies

To test the efficacy of the current management arrangements, including the RZS, spatial TACs for White Teatfish and Burrowing Blackfish and species-specific size limits, we simulated future fishing assuming it would take place in a similar manner to recent fishing, with a total Commercial Total Allowable Catch (TAC) of no more than 361 tonnes of landed form (salted/frozen boiled), spatial TACs for White Teatfish and similar catches to recent years by applying fishing pressure as per historical (2009-10 to 2011-12) catch to the model population, and current size limits. The model simulates a 3-yearly rotational harvest whereby an individual zone can be fished only once every three years. Although the current TAC for Black Teatfish is zero, a hypothetical future TAC of 58 t, being the approximate catch in the final three years of fishing, is used to test the efficacy of a RZS on this population.

The median and 90th percentiles of the projected spawning biomass over the next 20 years for each of the species in selected illustrative zones are shown in Figure 44 to Figure 52, and the projected total spawning biomass for each species in the ECBDMF is shown in Figure 17. These results indicate that, given the starting values used for the population model and under current fishing pressure overall the catches are sustainable for all species,. Interestingly, the estimated biomass trajectory for White Teatfish which was quite negative during the initial fishing down that occurred under high catches in the late 1990s (Figure 16), shows a positive biomass trajectory after the implementation of spatial TACs and reduced fishing pressure to more sustainable levels. This resulted in a positive trajectory in the future under current catch rates.

Performance statistics for all species are shown in Table 14, reinforcing the low risk of overall depletion for most species. Highest risk species were Burrowing Blackfish and Black Teatfish (with 58 t TAC). Golden Sandfish also showed some small risk of high overall depletion (Table 14). Overall the RZS with current catches appears to perform well in terms of maintaining stock biomass above 48% (a typically adopted default target spawning biomass level) of the comparable no-fishing case. The fishing"/ no-fishing statistic controls for the large assumed recruitment variability that influences population trends, and hence estimation of statistics such as the relative depletion at the end of the projection period compared to the start (Table 14).

To assist in interpreting the summary results, examples of the variability in the predicted future depletion ratio (measured in terms of the spawning biomass at the end of the projection period relative to the comparable no-fishing reference case) under the current RZS for the nine model species across all zones are shown in Figure 18. Two illustrative simulations are shown for each species, with the first one that uses the starting biomass estimate and the second uses a more conservative value that is half this, to account for the uncertainty in the biomass estimates. A single replicate only is shown, corresponding to a single environmental variability scenario. Missing bars show zones where a species doesn't occur or no data are available to inform the analysis. This highlights that some species have a higher local depletion risk, such as Black Teatfish (low K), and the 2 curryfish species. Golden Sandfish and Burrowing Blackfish also have some risk of depleted zones under the Low K scenario (which is unlikely given the population estimates for Burrowing Blackfish at least). There is a clear benefit to spreading the catch amongst many zones. However overall when considering the median and 90th percentiles across all zones for each species (i.e. for each zone the median is computed from the 160 simulations shown in each of the plots in Figure 18), the RZS is seen to perform satisfactorily (Table 14; Figure 44; Figure 18).

For most species, one-third as much or an equivalent biomass is estimated to occur within the closed areas, and for these species the biomass in the closed zones would provide a harvesting buffer (Figure 19). However, golden Sandfish and the Burrowing Blackfish are two exceptions (Figure 19).

This is mostly due to the lack of survey data for the closed areas in the ECBDMF, and represents a major gap in the knowledge of the fishery.

Table 14 also summarises the average annual catch of each species in terms of numbers and landed catch, yielding a total annual multispecies harvest of approximately 260t (305t if we include Black Teatfish). The corresponding estimated value of this catch is $4.92 million ($6.2 million with Black Teatfish), which is used as a baseline comparison with alternative simulation scenarios. Figure 20 shows the split of the total catch in terms of very high (golden Sandfish), high (Teatfish) and medium value species. Thus although the bulk of the catch is comprised of the medium value species, golden Sandfish and Teatfish are disproportionately important in terms of economic value. Thus for example, Burrowing Blackfish are the dominant species in terms of mass, comprising 61% of the total catch in the base-case model run and hence economically very important, but similarly White Teatfish, which comprise only 10% of the catch are responsible for 19% of the total earnings.

Table 14. Summary of the performance of the RZS when considering the percentage of simulations for each of the nine species shown that are depleted below a specified level relative to the comparable no-fishing reference case, together with a summary of the average annual catch landed (in terms of numbers and tons landed product), and the average value of the catch ignoring any costs of monitoring and adaptive management.

Species	Risk of depletion below B_{lim} of 20% unfished	Risk of depletion below 40% unfished	Proportion of Bsp(2032) > 48% unfished	Proportion of Bsp(2032)/ Bsp(2012) > 48%	Average annual catch (no.)	Average annual catch (t landed wt)	Average annual value ($ million)
Black Teatfish (closed)	0.00	0.00	1.00	1.00	0	0	0.000
Brown Sandfish	0.00	0.00	1.00	1.00	316	0.2	0.003
White Teatfish	0.00	0.01	0.87	1.00	14251	17.2	0.497
Prickly Redfish	0.00	0.00	0.99	1.00	12393	20.1	0.361
Golden Sandfish	0.04	0.05	0.94	0.98	5245	3.0	0.110
Curryfish Herrmanni	0.00	0.02	0.95	1.00	33714	17.2	0.309
Curryfish Vastus	0.01	0.01	0.98	0.98	13213	6.7	0.121
Deepwater Blackfish	0.02	0.03	0.96	0.98	4378	1.6	0.028
Burrowing Blackfish	0.08	0.17	0.81	0.96	775028	193.8	3.488
Total					858538	259.8	4.92
Black Teatfish (with TAC)	0.03	0.10	0.88	0.93	48703	45.3	1.303
Total (inc. BTF TAC)					907241	305.1	6.22

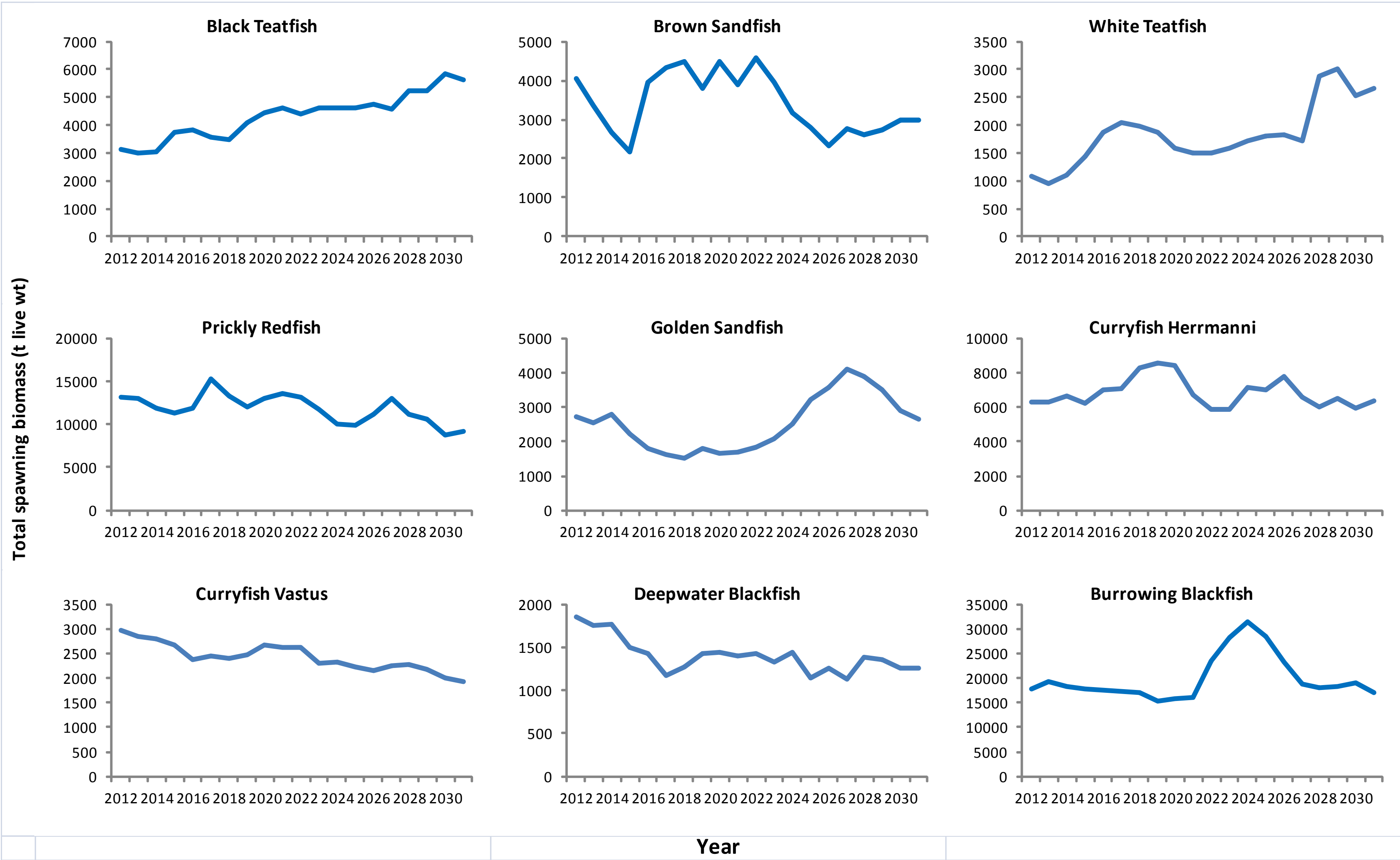

Figure 17. Median of total projected spawning biomass (t) of each species over from 2012 to 2032, when assuming continued future implementation of the RZS and TACs similar to current levels, as well as a TAC of 58t for Black Teatfish.

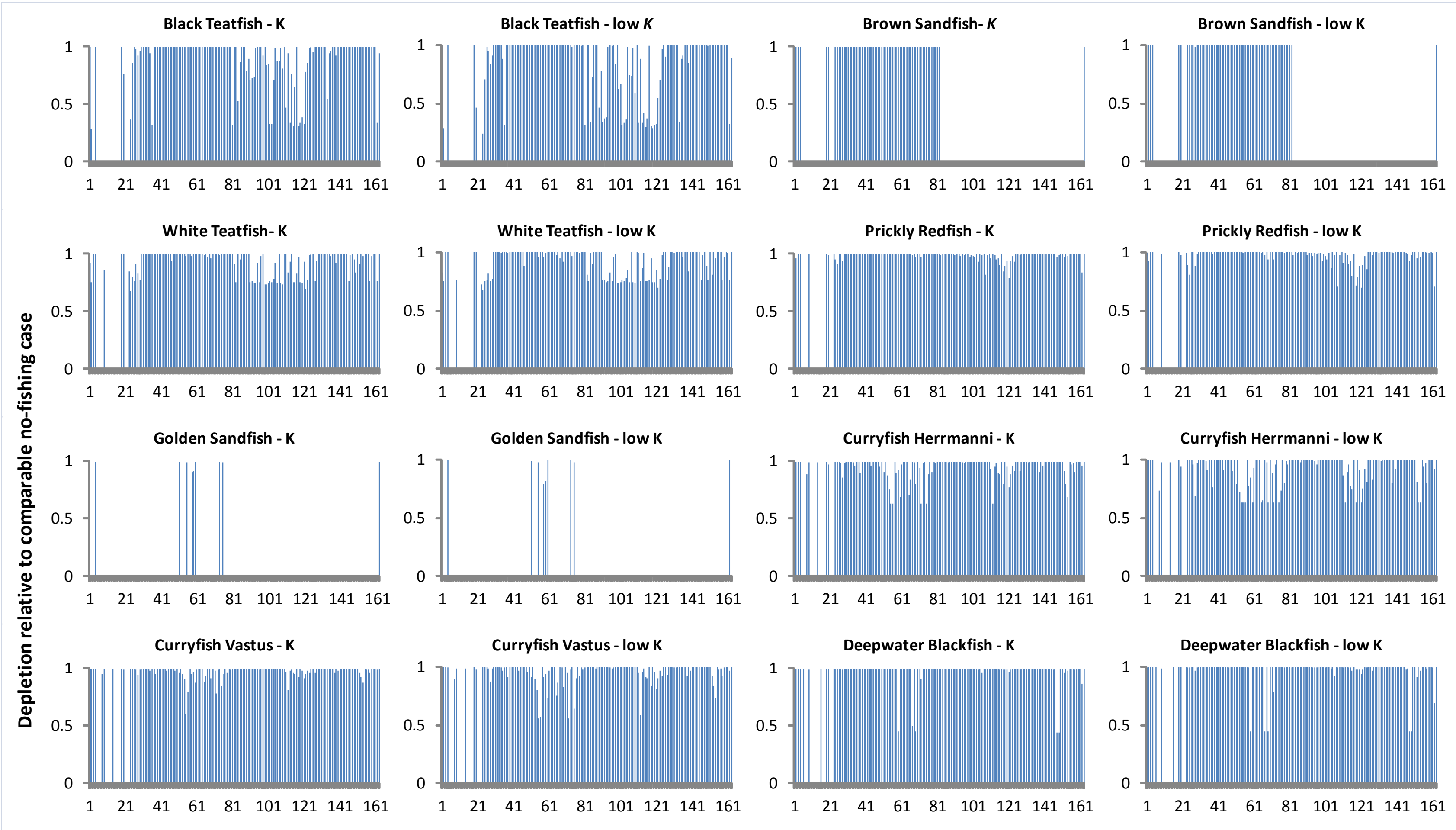
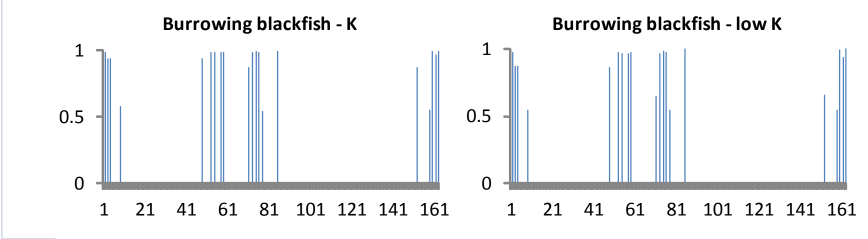

Figure 18. Examples of the variability in the predicted future depletion ratio (measured in terms of the spawning biomass at the end of the projection period relative to the comparable no-fishing reference case) under the current RZS for all species at all 162 zones (missing bars indicating no data for a species in that zone), and from a normal and lower carrying capacity (low *K*) simulation with the starting biomass halved.

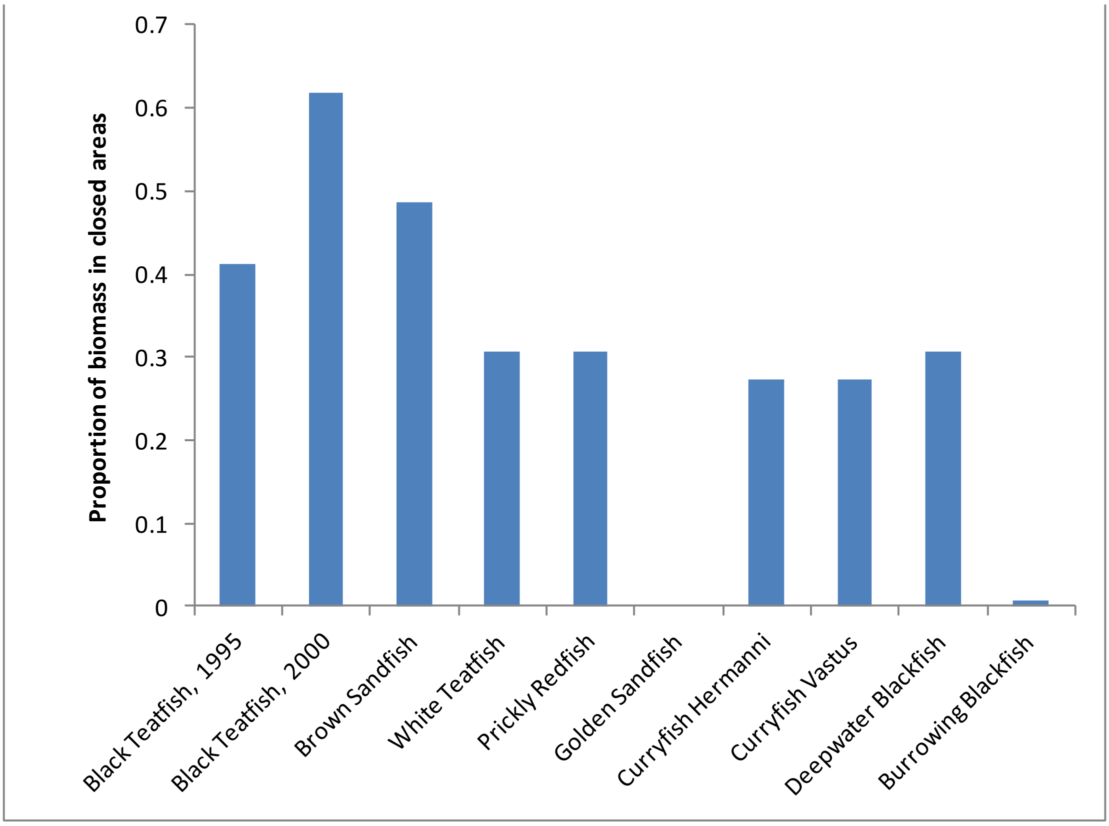

Figure 19. Proportion of total spawning biomass per species that is in closed areas of the ECBDMF.

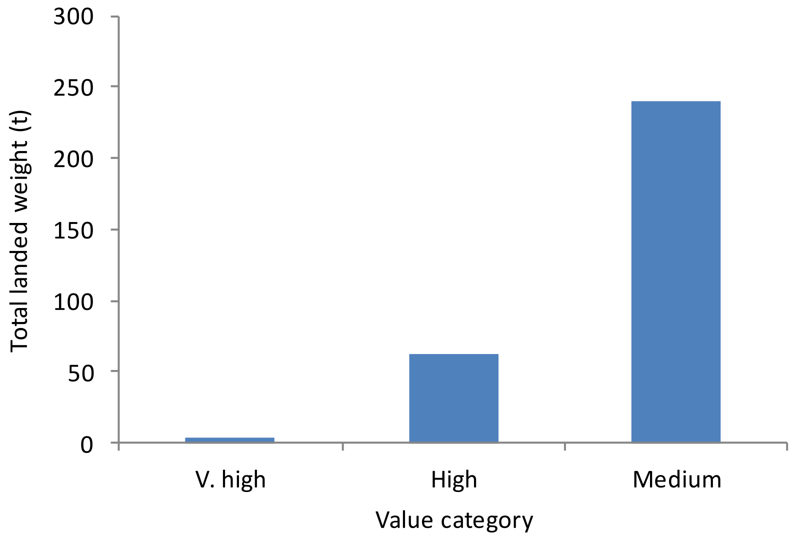

Figure 20. Base-case summary of average annual total landed mass (t) of the 9 species considered, shown grouped by product value categories.

4.3.1 REVISED RZS CASE

The model applied fishing pressure as per historical (2009-10 to 2011-12) catch (in terms of numbers and zones fished) to the model population. However upon further inspection, we noted that in the case of White Teatfish, Deepwater Blackfish and Burrowing Blackfish, the model average projected catch did not successfully match the observed average catches (Table 14). This was largely because some fished zones did not have enough fishery sized animals to provide the projected catches at similar level as in the recent past (i.e. the total of all individuals that are at or above the age-at-first-selectivity) due to underestimates of density, habitat area, fishing effects or environmental variability). It is assumed in the model that fishers can take a maximum of 99% of the fishable stock in the zone (though this will rarely be the case), and hence the catch from that zone is adjusted downwards. This can particularly be expected to be the case for simulations using a lower K value and slower growth scenarios for example. Note too that these simulations assume perfect knife-edge selectivity – thus for example, for White Teatfish, animals are considered mature from age 4 upwards in the model and the age-at-first-capture is 5 years, hence even if almost all animals aged five years or more are caught, the model assumes no 4-year olds will be caught (because the average size is less than the minimum legal size) and hence that these animals have at least one year to spawn before being subject to fishing (but see also later sensitivity re age-at-maturity).

We were able to force the model to try and improve the match to the historical catch by allowing relatively more catch from more well stocked zones to offset reduced catches in zones with lower available biomass. This was successful for the two blackfish species but was only partially successful for White Teatfish. This again highlights the likelihood that population estimates in fished zones for White Teatfish populations are too conservative, especially when coupled with our half K and slow growth scenarios. The fact that catches can continue to be sustained into the future even though in some zones it isn't possible to always catch as much as was caught previously from a zone demonstrates the effectiveness of minimum size limits, provided they are chosen appropriately and fishers comply with regulations. This allows protection of some individuals and spawning biomass which will then become available after a period of growth. These results suggest too that for slower-growing species such as WTF, there should be an advantage in allowing a longer time between harvests (as occurs with a RZS) because the abundance of larger-sized individuals builds up, simultaneously boosting spawning and increasing catch rates (and overall catches given our simulations suggest that it isn't always possible to maintain the same catch from a zone). It is important also to note that the considerable environmental variability simulated in the model will be a major reason biomass and catches fluctuate from year to year in the projections, but as this is a natural state of affairs, we control for this by evaluating performance relative to a no-fishing case and hence assessing whether or not adding fishing pressure to the system results in worse overall performance.

Overall, the risk of depletion for all species under the revised catch scenario was still very low, and the median spawning biomass trajectories for the entire fishery showed only low levels of depletion (relative to the no-fishing case) for most species (Table 15, Figure 21). The blackfish species did however increase markedly in risk, especially for Burrowing Blackfish for which nearly one-quarter of all model projections (across all simulations, replicates and zones) had a final spawning biomass estimate less than 40% of the comparable unfished level, and relatively poor performance in terms of maintaining the stock above a default target level in all zones (but not when considering the total biomass across all zones) (Table 15).

As previously, projected spawning biomass trajectories for each species fluctuated widely as a result of the alternative environmental scenarios assumed, as well as the large number of alternative models that results are averaged over. To assist in assessing the impacts of fishing and avoid drawing erroneous conclusions based on population trends and environmental signals, the projected spawning biomass trajectories are shown here relative to the comparable no-fishing case (Figure 53 to Figure 70). Hence for every model simulation and replication, the spawning biomass at each future time step is divided by that from the equivalent no-fishing case, yielding 160 depletion trajectories for each zone and each species, which are in turn used to compute the median and 90th percentiles. The first set of results (Figure 53 to Figure 61) is for 10 of the 163 zones where each species is most abundant. However, as before, there is little difference between fished and no-fished trajectories (i.e. ratio = 1) in some zones either because no or relatively little fishing occurs in those zones, despite apparent high biomass based on survey and habitat information. From the performance statistics of the revised RZS case, (Table 15), it is clear that under this future catch scenario there is a predicted risk of localised depletion in some zones. To graphically illustrate this, the next set of plots (Figure 62 to Figure 70) is as above except that the 10 zones shown are instead those with potentially the highest fishing mortalities (based on comparison between recent average catches and the model biomass estimates). Species that showed predicted localised depletion in these high fishing zones (local biomass<0.20 of comparable no-fishing case) include BTF, WTF, golden Sandfish, both curryfish species, blackfish and BBF. Note however that these plots highlight the worst case scenarios in some of the most heavily impacted zones, and the lack of local density data is probably the main contributing factor in most cases. When averaged across the full set of zones, and particularly when considering also the considerable biomass in the closed areas, the overall risk to the resource is very low and the overall level of depletion is similarly not substantial.

Table 15. Summary of the performance of the revised RZS base case with increased catch for White Teatfish, Deepwater Blackfish and Burrowing Blackfish. Landed catch for Burrowing Blackfish is also modified using actual average landed weight for that species (model weight was 303.8 t). Risk considers the percentage of simulations for each of the nine species shown that are depleted below a specified level relative to the comparable no-fishing reference case, together with a summary of the average annual catch landed (in terms of numbers and tons landed product), and the average value of the catch ignoring any costs of monitoring and adaptive management.

Species	Risk of depletion below B_{lim} of 20% unfished	Risk of depletion below 40% unfished	Proportio n of Bsp(2032) > 48% unfished	Proportio n of Bsp(2032) /Bsp(2012) > 48%	Average annual catch (no.)	Average annual catch (t landed wt)	Average annual value ($ million)
Black Teatfish (with TAC)	0.03	0.10	0.88	0.93	48703	45.3	1.304
Brown Sandfish	0.00	0.00	1.00	1.00	316	0.2	0.003
White Teatfish	0.00	0.02	0.80	0.995	25798	31.2	0.899
Prickly Redfish	0.00	0.00	0.99	1.00	12393	20.1	0.361
Golden Sandfish	0.04	0.05	0.94	0.98	5245	3.0	0.110
Curryfish Herrmanni	0.00	0.02	0.95	1.00	33714	17.2	0.309
Curryfish Vastus	0.01	0.01	0.98	0.98	13213	6.7	0.121
Deepwater Blackfish	0.05	0.09	0.90	0.91	15098	5.4	0.098
Burrowing Blackfish	0.11	0.24	0.73	0.93	1215100	215.1	3.872
Total (inc BTF TAC)					1369580	344.2	7.077

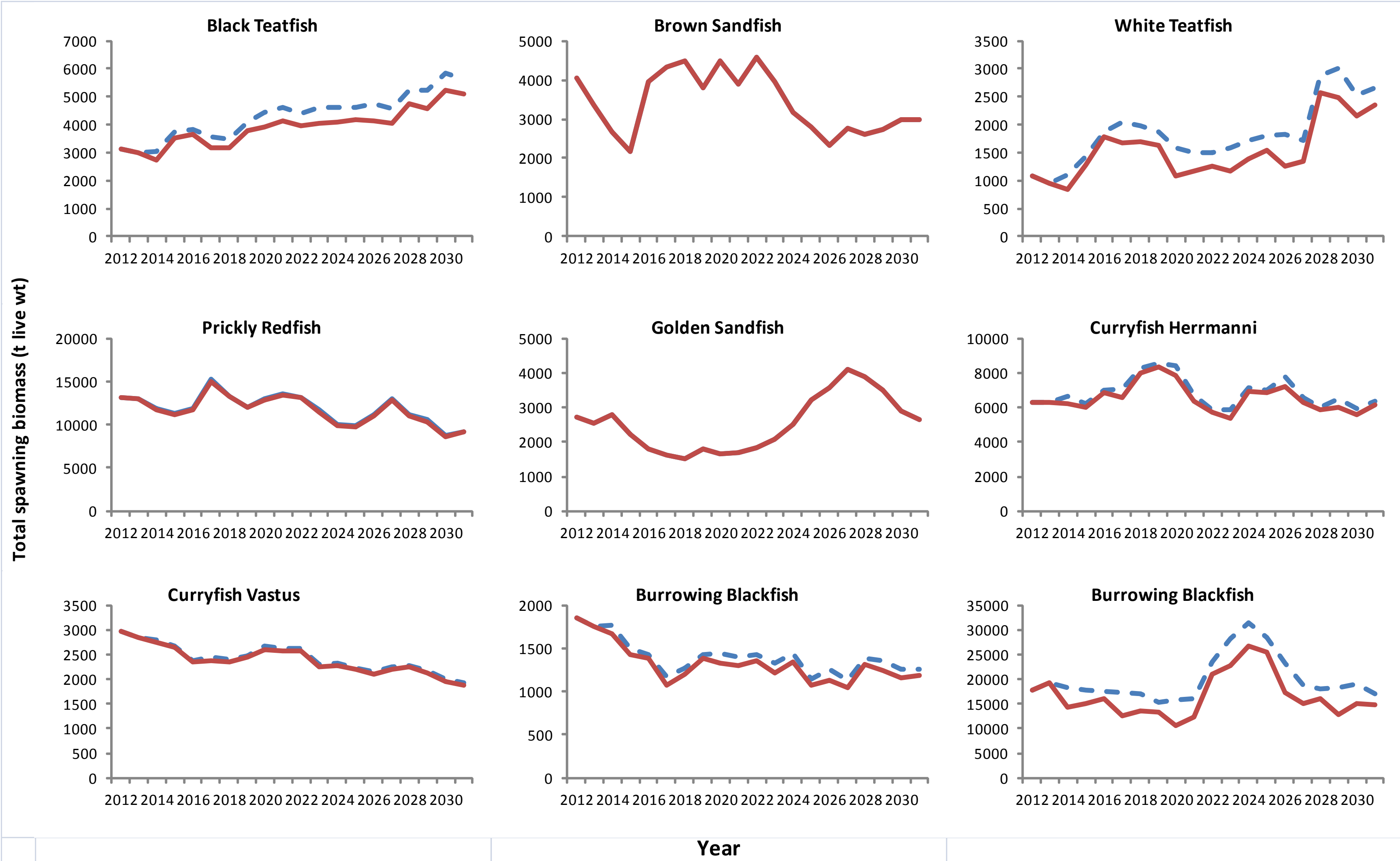

Figure 21. Revised based case RZS median of total projected spawning biomass (t live wt) for each species from 2012 to 2032, when assuming continued future implementation of the RZS and TACs similar to current levels, and with catch levels increased to more closely match catch 2009-10 to 2010-11, as well as a catch of 58t for Black Teatfish. Comparison is made with the no fishing biomass trajectories (dashed line); where dashed line is not apparent, the trajectories are essentially coincident

4.4 Rotational Zone Strategy benefits

The primary aim of this project was to test the RZS for mitigating localised depletion, reducing risks to overall sustainability and maximising efficiency and profits of the ECBDMF. For comparison, simulations were done assuming similar catches and a spatial TAC for White Teatfish, but with no RZS — hence instead of rotating catches at a zone once every three years, fishers were assumed to catch one-third of the catch each year. Again for Black Teatfish, an illustrative TAC of 58t was assumed.

The resultant projections are shown in Figure 71 to Figure 79, with summary results in Table 16. The risk of depletion was greater with no RZS for Burrowing Blackfish, both Teatfish species and, to a lesser extent, Curryfish Herrmanni (Table 16). This was also reflected in the risks to localised depletion for the same species, but particularly Black Teatfish (under a 58 t TAC scenario), White Teatfish and Curryfish Herrmanni (Figure 22).

To illustrate this further, selected examples of individual trajectories were calculated for White Teatfish, Black Teatfish and Curryfish Herrmanni (Figure 23). In zones where the catch isn't particularly large compared with the stock biomass, there are relatively small differences in the spawning biomass projections under current catch levels with and without a RZS implemented. However, as evident from the second example for each species, in zones where catches are high relative to standing stock, a RZS performs better with respect to final model biomass because the population is afforded a chance to recover between fishing pulses. This assumes that no animals younger than the minimum legal size are taken (note too that the spawning biomass differs slightly from the exploitable biomass which is computed as the sum of all animals older than the age-at-first-capture that are available to fishers at the end of the third quarter). This is particularly the case for slower growing species such as the White Teatfish, where spawning biomass recovers between rotational fishing pulses to a greater extent than the yearly fishing scenario. In contrast, in the absence of a RZS, high catches could not be maintained in some zones and the spawning biomass of the Teatfish species declines to very low levels (Figure 23). When integrated across the full set of 162 fishing zones, there are only small differences only in the total biomass of each of these three species, as fishing pressure in most zones is modest or low (Figure 21), but these differences will be amplified under heavier fishing pressure and increase the risk of localised depletion in these high fishing zones. Model results therefore support the hypothesis that a RZS is primarily beneficial in reducing the risk of local depletion.

Although the total catch and value of the currently harvested species were similar under the two scenarios (Table 14, Table 16), it was nonetheless possible to sustain slightly higher overall catches under the RZS system. Note that the actual realised catches in each model scenario may be less than the planned catch if insufficient exploitable biomass is available in a zone. When tested across the full range of uncertainty encompassed by using alternative models (the Reference Set), alternative environmental forcing scenarios (the replicates), alternative life histories (the nine species) and a large number of spatial areas (the 162 zones), the RZS system yielded a medium annual landed catch and value of 305t and $6.22 million compared with 296t and $6.07 million with no spatial rotation (Table 14, Table 16). Hence even under relatively conservative catch levels, there appears to be a slight economic benefit to implementing a RZS, and this is predicted to increase further as catch levels increase. In addition, if the costs of harvesting are taken into account, the net economic benefits of a RZS may be even greater as it isn't necessary to travel to all zones every year, and giving time for the biomass in a zone to increase between harvests will improve catch rates and therefore fishing efficiency. Spreading the fishing effort across zones does potentially incur a short-term cost in that fishers are unable to remain in areas close to their home port and thereby reduce travel costs, but in the longer term there is no net benefit to this strategy because of the local depletion effect.

Overall our results suggest that the RZS is successful in mitigating localised depletion, reducing risks to overall sustainability and maximising efficiency and profits of the ECBDMF. As a further illustration of this, Figure 80 to Figure 88 show the ratio of projected spawning biomass from our revised base case with a RZS applied compared to the same revised no-RZS case (therefore comparing equivalent scenarios). As previously, the no-RZS simulations were run assuming similar total catch over the 20-year projection period but instead of rotating catches at a zone once every three years, fishers were assumed to catch one third of the catch each year. Again for Black Teatfish, an illustrative TAC of 58t was assumed. The plots show projected depletions (no-RZS/RZS) such that values less than unity indicate performance is worse in the no-RZS case compared with the RZS. The selected plots are those zones with the greatest fishing mortality for each species. While there is no detectable difference in some cases, particularly for the larger Burrowing Blackfish zones (e.g. BFZ1, 2 and 3) the performance in the absence of a RZS is substantially worse in many cases, for example, White Teatfish and Curryfish Herrmanni. This is both in terms of the relative depletion level of the resource as well as the increased risk of dropping to very low biomass levels, based on the lower 90th percentile as shown in Figure 80 to Figure 88.

Table 16. Summary of the performance statistics when assuming an absence of a RZS but with the same average total catches. An illustrative future TAC of 58t for BTF is tested. Summary statistics are the proportion of simulations for each of the nine species shown that are depleted below a specified level relative to the comparable no-fishing reference case, together with a summary of the average annual catch landed (in terms of numbers and tons landed product), and the average value of the catch ignoring any costs of monitoring and adaptive management

Species	Risk of depletion below B_{lim} of 20% unfished	Risk of depletion below 40% unfished	Proportion of Bsp(2032) > 48% unfished	Proportion of Bsp(2032)/ Bsp(2012) > 48%	Average annual catch (no.)	Average annual catch (t landed wt)	Average annual value ($ million)
Black Teatfish	0.11	0.14	0.85	0.87	48173	44.8	1.290
Brown Sandfish	0.00	0.00	1.00	1.00	302	0.2	0.003
White Teatfish	0.06	0.16	0.78	0.96	15277	18.5	0.532
Prickly Redfish	0.00	0.01	0.99	1.00	12035	19.5	0.351
Golden Sandfish	0.05	0.05	0.93	0.95	4912	2.8	0.103
Curryfish Herrmanni	0.06	0.09	0.88	0.93	34551	17.6	0.317
Curryfish Vastus	0.01	0.02	0.97	0.97	12796	6.5	0.117
Deepwater Blackfish	0.04	0.04	0.96	0.96	3978	1.4	0.026
Burrowing Blackfish	0.19	0.21	0.76	0.83	739412	184.9	3.327
Total					871436	296.2	6.07

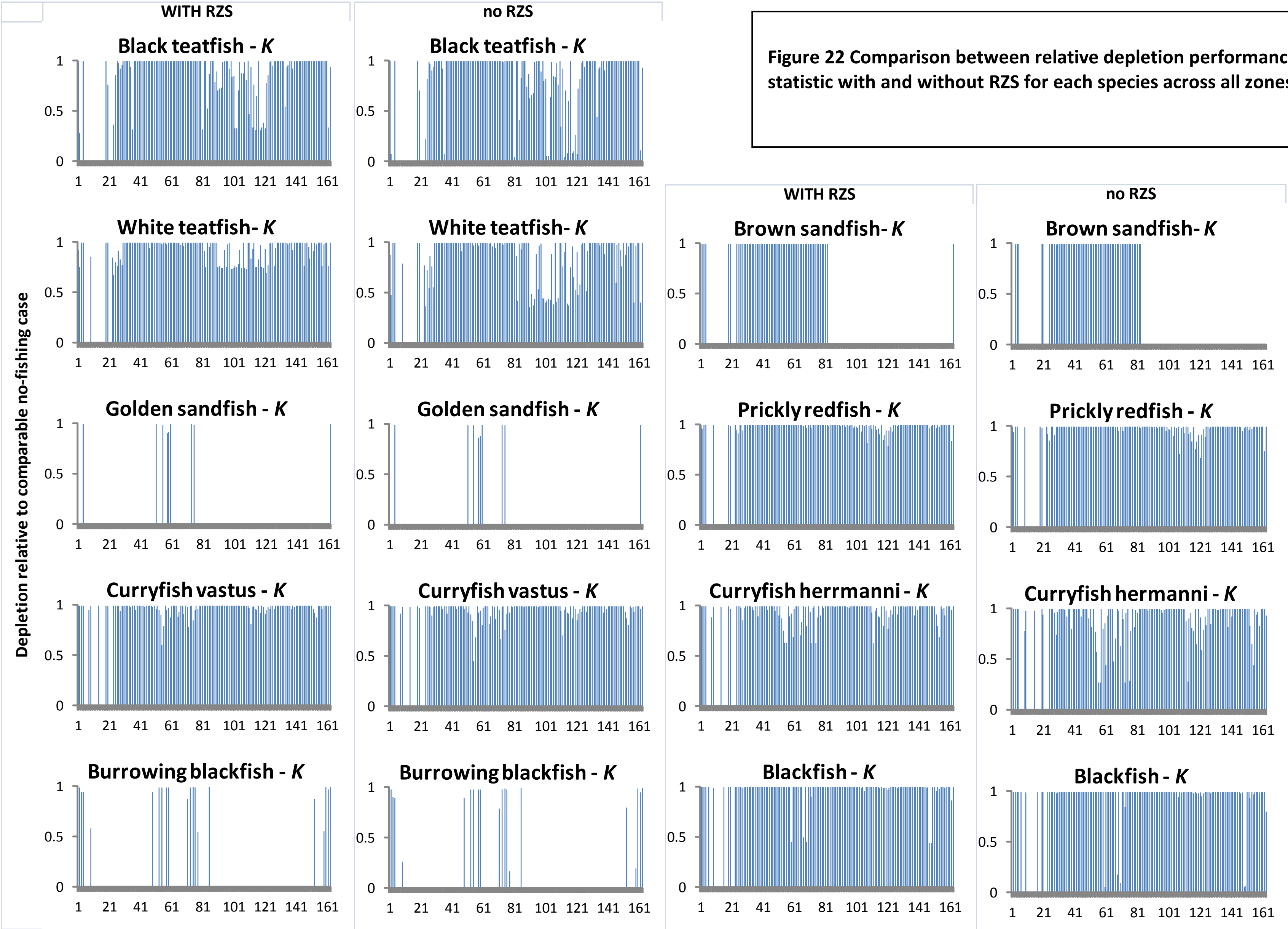

Figure 22 Comparison between relative depletion performance statistic with and without RZS for each species across all zones.

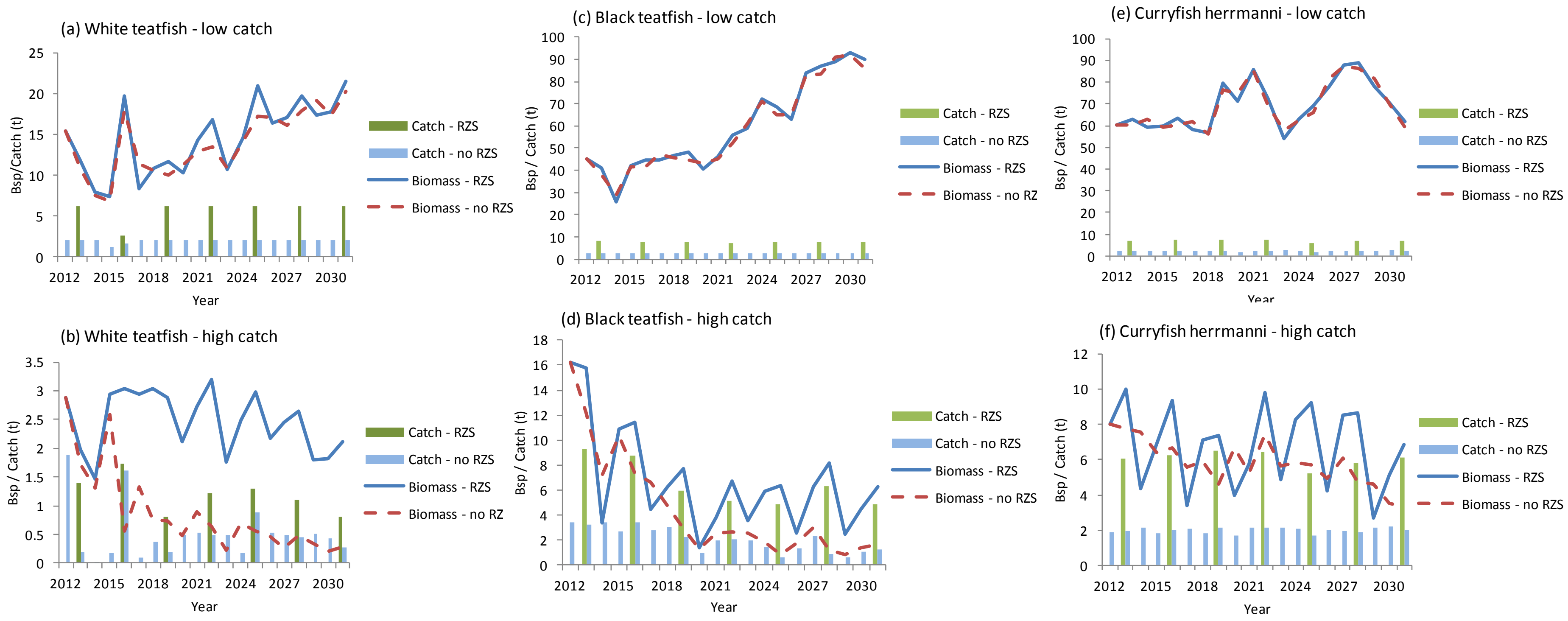

Figure 23. Comparison between illustrative model spawning biomass projections with and without a RZS system implemented, and with the corresponding catches (t) shown as bars, for (a, b) White Teatfish; (c, d) Black Teatfish and (e, f) Curryfish Herrmanni. The top row is low catch and bottom very high catch scenarios. For each species, trajectories are a single simulation and replication at a single zone only.

4.5 Rotational Zone Strategy with higher future TACs

A range of simulations were done with gradually increasing future TACs but still implemented under a 3-year RZS system. This was both to increase understanding of what happens as catches are increased, to highlight sensitive species and zones, and because the absolute abundance of the various sea cucumber species is highly uncertain. Zone projections for each species with continued future implementation of the RZS but with TACs set to three times higher than current levels are shown in Figure 89 to Figure 97, and summary performance statistics are shown in Table 17. Species which started crashing include the golden Sandfish and Burrowing Blackfish, with substantially higher overall depletion risk (Table 17). Black Teatfish also showed a high depletion risk under this scenario.

When assuming that the fishing pattern continues in a similar manner to the recent past, it wasn't in fact possible to triple the catch (Table 17 compared with Table 14) as the targeted zones became too depleted. Additional simulations described below explore the effect of spreading the total catch more widely across zones.

Table 17. Summary of the performance of the RZS under very high catch levels (3X), including a future catch for BTF. Summary statistics are the proportion of simulations for each of the nine species shown that are depleted below a specified level relative to the comparable no-fishing reference case, together with a summary of the average annual catch landed (in terms of numbers and tons landed product), and the average value of the catch ignoring any costs of monitoring and adaptive management.

Species	Risk of depletion below B_{lim} of 20% unfished	Risk of depletion below 40% unfished	Proportion of Bsp(2032) > 48% unfished	Proportion of Bsp(2032)/ Bsp(2012) > 48%	Average Annual Catch (no.)	Average annual catch (t landed wt)	Average annual value ($ million)
Black Teatfish	0.06	0.18	0.81	0.89	99364	92.4	2.661
Brown Sandfish	0.00	0.00	1.00	1.00	948	0.5	0.009
White Teatfish	0.00	0.02	0.83	1.00	20670	25.0	0.720
Prickly Redfish	0.00	0.00	0.96	0.99	30306	49.1	0.884
Golden Sandfish	0.13	0.18	0.80	0.85	11175	6.5	0.233
Curryfish Herrmanni	0.00	0.05	0.89	0.98	58693	29.9	0.539
Curryfish Vastus	0.03	0.07	0.91	0.91	31294	16.0	0.287
Deepwater Blackfish	0.03	0.05	0.95	0.96	7398	2.7	0.048
Burrowing Blackfish	0.14	0.28	0.66	0.89	1708150	427.0	7.687
Total					1967998	649.1	13.1

4.6 Spreading catches spatially with and without a RZS

The simulations above assume that the future fishing spatial pattern is similar to the recent past, whereas the aim of this set of simulations was to assume future fishing effort is spread across more zones. This is an additional way of testing the RZS because it approximates a situation in which fishers spread their total effort across a broader spatial area rather than focussing more intensively on selected zones (for example, those close to port as might be chosen based on economic efficiencies). In addition, we tested applying the same fishing proportion *F* to all zones (with data for a species) with and without a RZS. Hence for the case with a RZS, we used an illustrative *F* of 0.3 applied every three years to every zone, whereas in the absence of a RZS, we applied a comparable *F* of 0.1 so that the total catches would be approximately the same over the 20 year projection period.

Interestingly, results suggested that even with much higher total catches, the effect of spreading fishing effort spatially substantially reduced the risk of overfishing (Table 18 compared with Table 14 – baserun with RZS). Moreover, results suggest that, given the starting values for biomass and starting population parameters, higher total catches are sustainable for this sea cucumber fishery if fishers were able to spread their effort across multiple zones coupled with a RZS i.e. spatial and temporal spreading of fishing effort, and fish zones proportionally to their biomass (noting that this is theoretical investigation only whereas in reality would require an inordinate amount of survey and other information to implement). This indicated that the primary risk to populations is from depletion of heavily targeted zones in the fishery (even under a RZS), resulting in localised depletion of some species in these zones.

When comparing the constant F applied to all zones scenarios with and without a RZS, the no-RZS resulted in a greater overall depletion of individual species even though on average the total catch was slightly less (Table 18). In particular, golden Sandfish and Deepwater Blackfish were relatively more depleted under a constant F strategy with no-RZS (Table 18). Example projections for these two species are shown in Figure 98 and Figure 99.

Table 18. Summary of the performance statistics when assuming (a) RZS with F=0.3 for all fishing zones once every three years and (b) no RZS with F=0.1 for all fishing zones applied every year to all zones. Hypothetical future catches for BTF are also tested. Summary statistics are the proportion of simulations for each of the nine species shown that are depleted below a specified level relative to the comparable no-fishing reference case, together with a summary of the average annual catch landed (in terms of numbers and tons landed product).

(a)

Species	Risk of depletion below B_{lim} of 20% unfished	Risk of depletion below 40% unfished	Proportion of Bsp(2032) > 48% unfished	Proportion of Bsp(2032)/ Bsp(2012) > 48%	Average annual catch (no.)	Average annual catch (t landed wt)	Average annual value ($ million)
Black Teatfish	0.00	0.00	0.95	1.00	155253	144.4	4.158
Brown Sandfish	0.00	0.00	1.00	0.99	205192	112.9	2.031
White Teatfish	0.00	0.00	0.90	1.00	34632	41.9	1.207
Prickly Redfish	0.00	0.00	0.99	0.99	170290	275.9	4.966
Golden Sandfish	0.00	0.00	0.94	0.90	102723	59.6	2.145
Curryfish Herrmanni	0.00	0.00	1.00	1.00	135471	69.1	1.244
Curryfish Vastus	0.00	0.00	0.99	0.94	139861	71.3	1.284
Deepwater Blackfish	0.00	0.00	0.96	0.89	82285	29.6	0.533
Burrowing Blackfish	0.00	0.00	0.97	1.00	1091800	272.9	4.913
Total					2117507	1077.6	22.48

(b)

Species	Risk of depletion below B_{lim} of 20% unfished	Risk of depletion below 40% unfished	Proportion of Bsp(2032) > 48% unfished	Proportion of Bsp(2032)/ Bsp(2012) > 48%	Average annual catch (no.)	Average annual catch (t landed wt)	Average annual value ($ million)
Black Teatfish	0.00	0.00	0.93	1.00	139788	130.0	3.744
Brown Sandfish	0.00	0.00	1.00	0.98	184813	101.6	1.830
White Teatfish	0.00	0.00	0.87	1.00	30984	37.5	1.080
Prickly Redfish	0.00	0.00	0.96	0.97	156531	253.6	4.564
Golden Sandfish	0.00	0.00	0.89	0.89	94186	54.6	1.967
Curryfish Herrmanni	0.00	0.00	1.00	1.00	121463	61.9	1.115
Curryfish Vastus	0.00	0.00	0.99	0.87	127030	64.8	1.166
Deepwater Blackfish	0.00	0.00	0.90	0.85	73196	26.4	0.474
Burrowing Blackfish	0.00	0.00	0.96	1.00	966358	241.6	4.349
Total					1894349	972.0	20.29

4.7 Sensitivity Analyses

Considerable initial sensitivity analyses were used to inform choice of the Reference Set, namely exploring primary uncertainties regarding pristine biomass, the form of the stock-recruitment relationship and frequency of spawning, and bounding the range of likely uncertainty regarding natural mortality rates and growth rates. The results so far presented have been integrated across this range of uncertainties.

To further test the sensitivity of the MSE outputs to variation in basic assumptions, the following additional sensitivity tests were run:

1. Pulsed recruitment assumption: randomly generated 50% probability of no recruitment in a year.
2. 1995 Biomass estimate (K): instead of reference set using K and 0.5*K, use double the biomass estimates (change to K and 2*K);
3. Age-at-first maturity: increase the age-at-first-maturity by one year (equivalent to increasing the size at first maturity) so that there is a longer time before individuals can contribute to the spawning biomass, but the age/size at first capture remains as current.
4. Age-at-first maturity with higher TAC: as above, but also assume higher future TACs (x3).
5. Lower natural mortality rates: we reduced the natural mortality rate, *M*, by half, to a range 0.15 to 0.3 for Teatfish and Prickly Redfish, and 0.2 to 0.4 for other species - and correspondingly applied slower growth rates to these model reference cases (cf Table 11). The lower mortality rate of 0.15 would result in over 86% of a cohort surviving each year, and a longevity of approximately 30 years (using Hoenig's formula).
6. Greater recruitment variability: for each species, fluctuation about the expected recruitment is assumed to be normally distributed with standard deviation σsR (which is input as 0.5 in the base-case) which is increased here to 0.8;
7. Less recruitment variability: as above but σsR reduced to 0.2;
8. Variable recruitment on a finer scale i.e. recruitment pulses tied with larval "plumes" rather than widespread environmental stimulus, hence different sets of random recruitment residuals generated for each zone.

Given the large number of outputs produced by the model scenarios, results are not shown for all tests (but are available on request). Rather, some summary comments and illustrative results are shown. In general the overall conclusion, that the RZS with current TAC levels performs well, is robust across the range of sensitivities tested.

The model outputs were sensitive to changes in the age-at-maturity. The risk of depletion increases markedly for Burrowing Blackfish and Black Teatfish when immature sea cucumbers are exposed to fishing (Table 19, Figure 24). This highlights the importance of good data to inform choice of a minimum legal size which takes into account the age, or size, at maturity. Fortunately the current catch levels are sufficiently conservative for most species so that risk of overall depletion was predicted to be low even if there is some error in the best estimates of the age at first maturity. However if simulations are run with much higher TACs and these more conservative age at maturity estimates, local populations have a higher risk of crashing, including Black Teatfish (with a 58 t TAC), golden Sandfish and Burrowing Blackfish (Table 19). The risk to golden Sandfish (Figure 102) and Burrowing Blackfish (Figure 103) (Figure 24) highlights the increased risk of overfishing for species with no refuge population (for this case, these two species have no, or only small closed populations in the model).

Increasing the recruitment variability magnifies the inter-annual fluctuations modelled for each species, and slightly increases the risk of local depletion, for Burrowing Blackfish in particular (see e.g. Figure 104, Table 20). Conversely, decreasing the level of assumed recruitment variability slightly decreases the risk of depletion below pre-specified levels (Table 20). However, these changes to overall species risk were not great. An example of the more damped population trajectories that result when reducing the allowed extent of recruitment fluctuations is shown in Figure 105 using Brown Sandfish as an example. Selection of the correct level of recruitment variability has been informed by survey information from other regions, but additional survey data from the ECBDMF would refine modelling efforts. In general though even given uncertainty as to the exact level of recruitment fluctuations, the RZS performed well across a range of levels.

The base-case model assumed a common environmental stimulus would affect all zones each year, with the resultant impact on local populations simulated using randomly generated recruitment residuals. A common environmental stimulus was assumed as the base-case because it assisted in interpreting species-specific and zone-specific differences without confounding from different environmental drivers. Although no data are available to inform exactly what the historic (and potential future) patterns of recruitment variability were, overall the model reflected the typical nature and amplitude of sea cucumber population fluctuations and hence is still appropriate to test alternative harvest strategies. In any case, the model results were based on a large number of alternative possible population trajectories (9 species in 162 zones with a plausible 160 trajectories per zone per species where it occurred). Also, multiple sensitivity analyses were run to test the impacts of assuming recruitment is variable at a smaller scale, for example because recruitment pulses are tied to larval “plumes” rather than a widespread environmental stimulus. Examples of the model results when assuming inter-zonal differences in recruitment variability are shown for White Teatfish and Burrowing Blackfish (Figure 106 to Figure 109). Overall the RZS performed equally well under a scenario of greater spatial differences in recruitment variability.

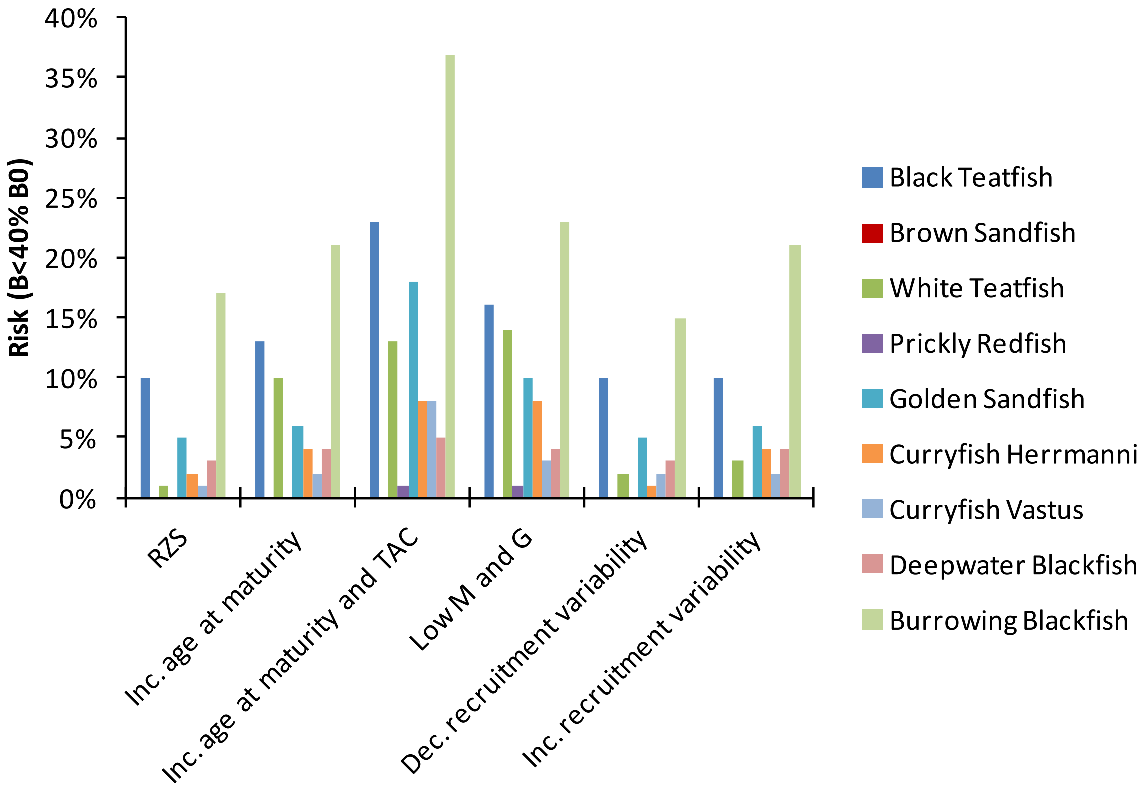

Figure 24. Summary of performance statistics for sensitivity analysis for depletion risk (defined as probability of biomass being reduced below 40% B_0).

Table 19. Comparison between base-case and sensitivity scenarios assuming a 1-year older age-at-maturity to illustrate the worsening of performance statistics if age-at-maturity is larger.

	a) Base case (current RZS and catch)				**b) Increase age-at-maturity**				**c) Increase age-at maturity with higher TAC**			
Species	Risk of depletion below B_{lim} of 20% unfished	Risk of depletion below 40% unfished	Proportion of Bsp(2032) > 48% unfished	Proportion of Bsp(2032)/Bsp(2012) > 48%	Risk of depletion below B_{lim} of 20% unfished	Risk of depletion below B_{lim} of 40% unfished	Proportion of Bsp(2032) > 48% unfished	Proportion of Bsp(2032)/Bsp(2012) > 48%	Risk of depletion below B_{lim} of 20% unfished	Risk of depletion below B_{lim} of 40% unfished	Proportion of Bsp(2032) > 48% unfished	Proportion of Bsp(2032)/Bsp(2012) > 48%
Black Teatfish	0.03	0.10	0.88	0.93	0.11	0.13	0.86	0.87	0.21	0.23	0.77	0.78
Brown Sandfish	0.00	0.00	1.00	1.00	0.00	0.00	1.00	1.00	0.00	0.00	1.00	1.00
White Teatfish	0.00	0.01	0.87	1.00	0.02	0.10	0.80	0.99	0.02	0.13	0.75	0.98
Prickly Redfish	0.00	0.00	0.99	1.00	0.00	0.00	0.99	1.00	0.00	0.01	0.96	0.98
Golden Sandfish	0.04	0.05	0.94	0.98	0.06	0.06	0.93	0.97	0.15	0.18	0.80	0.85
Curryfish Herrmanni	0.00	0.02	0.95	1.00	0.00	0.04	0.92	0.99	0.00	0.08	0.83	0.95
Curryfish Vastus	0.01	0.01	0.98	0.98	0.01	0.02	0.98	0.94	0.04	0.08	0.90	0.87
Deepwater Blackfish	0.02	0.03	0.96	0.98	0.04	0.04	0.96	0.96	0.05	0.05	0.94	0.94
Burrowing Blackfish	0.08	0.17	0.81	0.96	0.20	0.21	0.75	0.82	0.35	0.37	0.60	0.66

Table 20. Comparison between base-case and sensitivity scenarios assuming much greater or lesser level of variability in recruitment and the effect on the performance statistics for each of the species as shown.

	a) Lower mortality and growth rates				b) Increase recruitment variability				c) Decrease recruitment variability			
Species	Risk of depletion below B_{lim} of 20% unfished	Risk of depletion below 40% unfished	Proportion of Bsp(2032) > 48% unfished	Proportion of Bsp(2032)/Bsp(2012) > 48%	Risk of depletion below B_{lim} of 20% unfished	Risk of depletion below B_{lim} of 40% unfished	Proportion of Bsp(2032) > 48% unfished	Proportion of Bsp(2032)/Bsp(2012) > 48%	Risk of depletion below B_{lim} of 20% unfished	Risk of depletion below B_{lim} of 40% unfished	Proportion of Bsp(2032) > 48% unfished	Proportion of Bsp(2032)/Bsp(2012) > 48%
Black Teatfish	0.10	0.16	0.83	0.88	0.04	0.10	0.88	0.93	0.04	0.10	0.88	0.93
Brown Sandfish	0.00	0.00	1.00	1.00	0.00	0.00	1.00	0.83	0.00	0.00	1.00	1.00
White Teatfish	0.07	0.14	0.80	0.99	0.02	0.03	0.81	0.99	0.00	0.02	0.87	1.00
Prickly Redfish	0.00	0.01	0.98	1.00	0.00	0.00	0.92	0.95	0.00	0.00	1.00	1.00
Golden Sandfish	0.09	0.10	0.89	0.92	0.04	0.06	0.91	0.89	0.05	0.05	0.95	0.98
Curryfish Herrmanni	0.04	0.08	0.90	0.96	0.00	0.04	0.91	0.99	0.00	0.01	0.97	1.00
Curryfish Vastus	0.03	0.03	0.96	0.97	0.01	0.02	0.97	0.89	0.01	0.02	0.98	0.99
Deepwater Blackfish	0.03	0.04	0.96	0.97	0.03	0.04	0.90	0.86	0.02	0.03	0.97	0.98
Burrowing Blackfish	0.18	0.23	0.74	0.87	0.13	0.21	0.73	0.93	0.06	0.15	0.83	0.98

5 Discussion

This project used an MSE approach to assess the depletion risk, catch and value of the multispecies Queensland East Coast Sea Cucumber (Bêche-de-mer) Fishery (ECBDMF). The approach includes the construction of an operational model (OM) that uses available survey and catch data, together with all other available information on growth and life history characteristics, to simulate “generic” meta-populations that could then be used to represent a realistic spatial assemblage of sea cucumber species for use in testing alternative management strategies.

Depending on the amount of information available for each species in each zone in which it occurred (catch and biomass primarily) some of the model populations can be expected to resemble the actual in situ populations fairly closely. However it is important to note that the approach taken here has not been to propose a single past and future projected trajectory for each species, but rather a probability distribution of possible past and future trajectories using a broad range of input biomass and population parameters for each species (the reference set - RS) that encompasses uncertainty in both our understanding of the underlying population status and dynamics, as well as environmental variability. As more data become available, the probability envelope of projected outcomes will narrow and thereby enable provision of more precise management advice.

We weighted all scenarios equally, and given the large uncertainties, results were interpreted fairly generally across species and spatial zones to uncover general trends rather than focusing too closely on specifics. Despite the large uncertainties, it was still possible in most cases to distinguish between alternative catch levels and harvest strategies. The method we used for testing across a wide range of scenarios for the underlying dynamics of the resource follows closely the approach of Plagányi et al. (2011), and suggests that even when including these major uncertainties, it is possible to reliably discriminate between alternative management strategies in the case of data poor fisheries.

While the risk metrics are useful for comparing alternative management strategies, and are indicative of sustainability given the model inputs, unfortunately, there are insufficient data available to precisely assess the status of the ECBDMF sea cucumber stocks. As more data become available, the probability envelope of projected outcomes will narrow and thereby enable provision of more precise management advice. The methodology developed as part of this project is well suited to test the priority that should be accorded to different data collection types and methodologies, as well as the performance of proposed control rules that use these data as inputs. In particular, it is evident from this study that uncertainty in the current status of sea cucumber species in the ECBDMF would be reduced if more robust density and biomass data were available, particularly for White Teatfish and also for Burrowing Blackfish populations in areas outside the current targeted zones.

The primary aim of the current analysis was to test the Rotational Zoning Scheme (RZS) for mitigating localised depletion, reducing risks to overall sustainability and maximising efficiency and profits of the ECBDMF. The base-case model run therefore simulated future fishing assuming it would take place in a similar manner to recent fishing, with a total Commercial Total Allowable Catch (TAC) of no more than 361 tonnes of landed form (salted/frozen boiled), and with the catch primarily being made up of nine species. Moreover, the model simulated a 3-yearly rotational harvest whereby one third of 156 individual zones were available to be fished only once every three years. When tested across the full range of uncertainty encompassed by using alternative model inputs (the RS), alternative environmental forcing scenarios (the replicates), alternative life histories (the nine species) and a large number of spatial areas (the 162 model zones), the RZS is seen to reduce local and overall depletion risk, and increase catch and values in comparison to the no-RZS scenario (Figure 25). Hence even under relatively conservative catch levels, there appears to be an economic benefit to implementing a RZS, and this is predicted to increase further as catch levels increase. In addition, if the costs of harvesting are taken into account, the net economic benefits of a

RZS may be even greater as it isn't necessary to travel to all zones every year, and giving time for the biomass in a zone to increase between harvests will improve catch rates and therefore fishing efficiency.

There was a consistently greater (or at least equivalent) risk associated with the no RZS scenario for all species, with a substantial increase in the risk of depletion for White Teatfish, Black Teatfish (if fished with a 58 t TAC), Burrowing Blackfish and to a lesser extent Curryfish Herrmanni. In zones where catches are high relative to standing stock, a RZS allows high catches to be sustained probably because unfished (at least for a time) cohorts can progress through the size at maturity during the closed years to breed unhindered by fishing. When integrated across the full set of 162 fishing zones, there are small differences only in the total biomass of each of these three species, but these differences will be amplified in zones that are under heavier fishing pressure. Model results therefore support the hypothesis that a RZS is primarily beneficial in reducing the risk of overall and localised depletion.

Although these results illustrate the potential for localised depletion in some zones, and hence reinforce the need for management approaches such as the RZS that encourage a spread of fishing effort across wider areas, model results for individual zones should not be interpreted too closely. This is because we acknowledge large remaining uncertainties in model biomass estimates for example. Hence the model output is not intended as a stock assessment, but rather is used to compare alternative management strategies and does so using a very wide range of alternative standing stock and productivity estimates for a number of species with very different life histories. Thus, overall the robustness of results is tested across a large range of uncertainties. In general across a very broad range of uncertainties, our modelling results collectively suggest that the current fishing levels are sustainable, and that there is a noticeable benefit in applying a 3-year RZS as opposed to fishing annually in each zone.

Sea cucumber populations are likely naturally variable even in the absence of fishing. In setting up the Reference Set of OMs, key uncertainties were included such that the model populations had the same features as observed in the field – for example, high natural variability even in the absence of fishing, and the ability to replicate boom and bust cycles under fishing. Although realistic, this confounds understanding of the impacts of fishing over and above natural variability. We controlled for this to some extent by evaluating trajectories and computing risk statistics relative to comparable no-fishing scenarios. Future work, aided by data collection, will strive to reduce the broad range of future outcomes projected by the model.

Given limited survey data to fit the model, a number of diagnostics were used to assess how well the model represented reality. These included a) realistic fishing proportion estimates across zones; b) populations declining in response to heavy fishing pressure and recovering under no-fishing scenarios; c) recruitment and population fluctuations occurring on roughly the same scale as observed. One diagnostic feature of sea cucumber populations that we were able to replicate in the OM was the slow recovery observed for Teatfish populations, in particular, with 20 -30 year recovery periods simulated in the model.

Nonetheless, some problems could not be resolved for some species in some zones as this is a data rather than model issue – for example, for White Teatfish it appears that the catches in many of the zones, particularly those close to Cairns and Cooktown, exceed the biomass estimates calculated from the proxy Torres Strait density and reef area. For these zones it is likely that the biomass is underestimated due to the underestimate of density or habitat area (there is a high likelihood of unmapped deep habitat for White Teatfish, for example). This gives us some reassurance that the biomass estimates used in the model are not overly optimistic, for this species at least. Also, industry reports high abundance of most other species addressed in the model, particularly Prickly Redfish, Curryfish Herrmanni and Brown Sandfish. However, there is little doubt that White Teatfish in particular has been heavily targeted in the past, so in the absence of good survey data, we should be cautious about the low depletion risk for this population.

For some species the fishing proportion estimates hit the upper bound of the model biomass in some of the smaller zones, but were perhaps too low in other larger and more important zones where it's important that high fishing pressure is modelled as impacting the population. Hence future surveys and further information would improve estimates of population abundance and hence improve the model. In general the approach used here was to focus on getting it right for the more important zones, which sometimes means slightly over-estimating the impact on a few small zones.

The model assumed that recruitment was local to each zone because these are relatively large areas and many of them are widely separated from each other so zones are primarily self seeding. However some sharing of larvae between adjacent zones is probable, and this could be investigated further in future work. In particular, using hydrodynamic models of the GBR and larval duration will assist in informing regions where recruitment sharing is most likely. The assumption of local recruitment used in this model may therefore be slightly conservative, for example because recruitment in a heavily fished zone is not assumed boosted by a neighbouring closed region. However, the stock biomass in closed regions is accounted for and added to total population estimates.

The analysis has also led to further insights into the operational dynamics of the fishery and gaps in biological knowledge of targeted species. For example, comparisons between spatially disaggregated catch and survey data (converted to equivalent units) provided a clearer overview of spatial and species-specific patterns of abundance and productivity. A closer analysis of existing growth curve relationships necessitated a revision of what was known about this aspect of the biology, and this study led to the derivation of revised growth curves for all 9 species, which although preliminary, are a useful and essential starting point for future studies. Model results were sensitive to somatic growth rate and age at maturity assumptions and more research is needed to reduce this critical uncertainty. Model simulations were useful in reducing the uncertainty associated with the nature and scale of recruitment in the various species, for example in exploring what level and pattern of recruitment variability was compatible with Black Teatfish observed dynamics.

This study is the first to comprehensively integrate all available stock status information on the ECBDMF. Although there is still insufficient data to precisely assess the status of species stocks in the ECBDMF, the analysis outputs and performance metrics indicate that the current management arrangements are sustainable for those species currently targeted by the fishery. Naturally, consideration should also be given to the ecological role of sea cucumbers in reef and lagoon habitats of the GBRMP. This analysis is not able to include those considerations. However, the sustainable use of high and some medium value species, the current lack of fishing on highly abundant low value species and substantial proportion of closed areas in the GBRMP will provide some level of assurance to the protection of ecological function of this group. More research is required on this aspect to provide a truly ecosystem-based management approach.

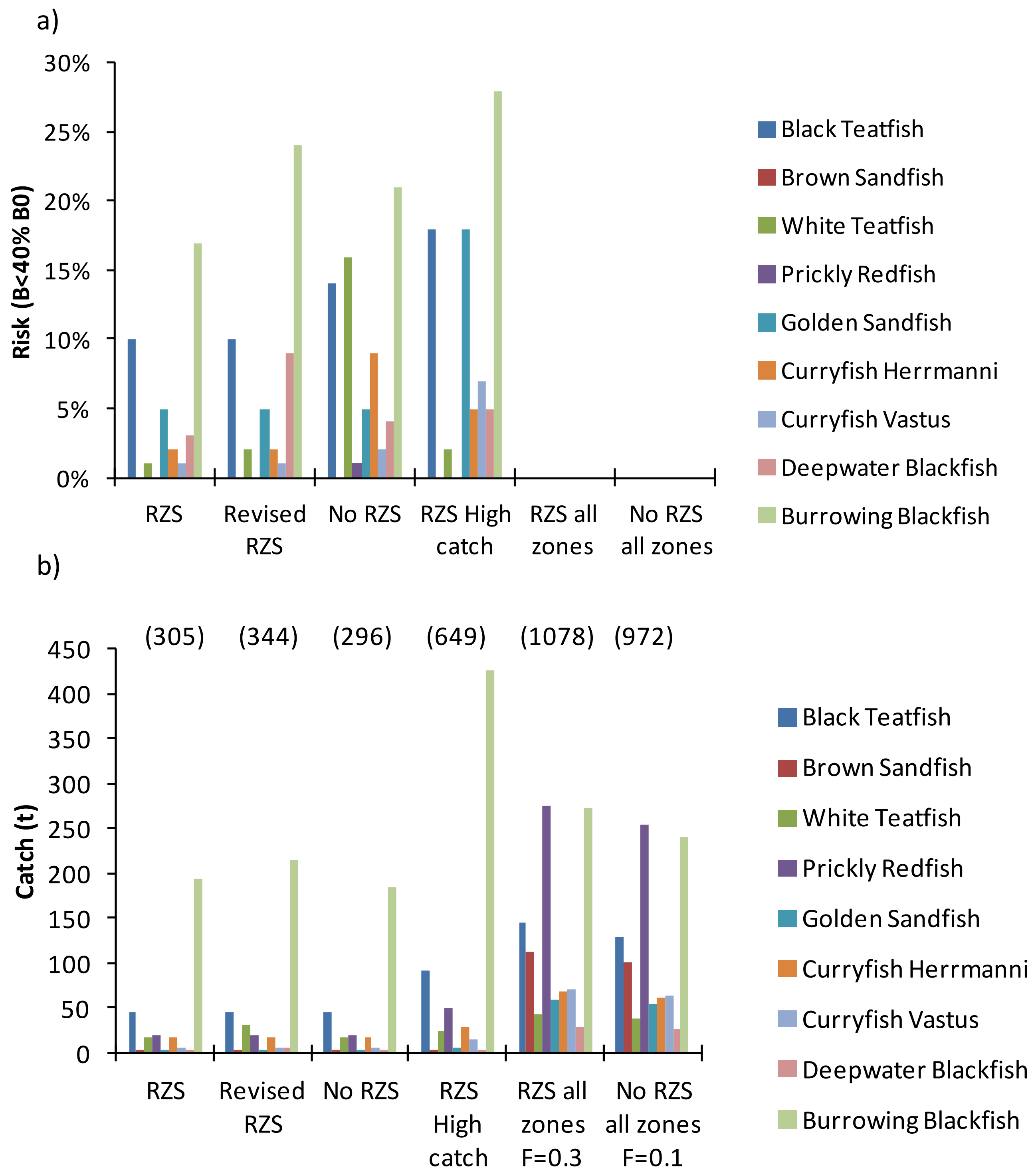

Figure 25. Summary of performance statistics for management strategies for a) Depletion risk (defined as probability of biomass being reduced below 40% of the comparable no-fishing biomass level), and b) estimated catch for 9 species (with average annual catch in tonnes at top). The "all zones" results assume fishing effort is spread evenly across all available zones.

6 Conclusion

The primary aim of the project was to test the effectiveness of the Rotational Zoning Scheme (RZS) for mitigating localised depletion and reducing risks to overall sustainability of the multispecies ECBDMF. To do this, we applied a Management Strategy Evaluation (MSE) approach that, in this case, combines a spatial and age structured population model(s) (OM) with a management module to compare stock performance under different management scenarios. Using this approach, we were able produce performance statistics that illustrated the overall status of the stock under current management arrangements by comparison with a no fishing case, and the efficacy of the RZS in its own right by comparison with the no-RZS case.

Ideally the OM of the MSE is calibrated and validated using population estimates and monitoring data from the fishery. However, we only had data for three species, Black Teatfish, Curryfish Hermanni and Burrowing Blackfish. For the remaining 6 species we had to use proxies from Torres Strait where more extensive surveys have been conducted. Also, the OM requires species population parameters such as growth, natural mortality and size at maturity. Reliable information on sea cucumber population parameters is scarce and uncertain. To address these primary uncertainties, we used a range of values in the OM, and where there was uncertainty, included values that would result in a precautionary approach to the model outputs (e.g. using half starting biomass, low mortality and growth, and conservative recruitment parameters). We also used extensive sensitivity analyses to illustrate parameters with high importance and leverage.

This resulted in a large body of outputs, which makes the task of drawing solid conclusions difficult. Nonetheless, we consider that the outputs of the MSE show:

1. The risk of depletion for most reef associated species under most scenarios is low. Prickly Redfish in particular was estimated to be at low risk of deletion across all applied scenarios. However, other current and past highly targeted species such as Black Teatfish and White Teatfish were estimated to be vulnerable to more substantial risks under higher catch scenarios, and with more conservative parameter estimates, and should be managed with caution and more data gathered. Most species have a considerable proportion of their population within protected zones (estimated range 27% to 49% - assuming full compliance) which provides an additional sustainability benefit.
2. The species that is currently the most intensively targeted is Burrowing Blackfish, an off-reef (lagoon) species with a restricted proven distribution. The risks of depletion from the MSE model for this species are the largest of any species, exacerbated by its restricted distribution in the model, and relatively high fishing mortality rates. These risk indicators are likely conservative, We consider these risk indications to be conservative (for example, the reference set of models used in the testing process included biomass estimates set at half the survey estimates, even though the population estimates for Burrowing Blackfish are considered quite robust). Additional distribution and density data from unfished areas and reliable monitoring (relative abundance) would improve the assessment of this species and quantification of the risks associated with fishing.
3. The RZS provides a benefit in terms of reduced risk, particularly for zones with higher fishing mortality and particularly for White Teatfish and Curryfish. While the value of the landed product is similar for both RZS and non-RZS management approaches, it is likely that the RZS strategy will provide efficiencies by reducing the number of zones fished, and therefore reduce costs and increase fishery profit. The highly targeted Burrowing Blackfish, which is currently fished on an annual basis in the dedicated blackfish zones, would appear to benefit from a rotation harvest strategy as well, but this result is mostly due to fishing in non-BBZ zones where population estimates are not available and very conservative proxies are used. This illustrates the need for surveys in these non-BBZ zones before targeted fishing takes place.

This study is the first to comprehensively integrate all available information on the ECBDMF. Although there are still insufficient data available to precisely assess the status of species stocks in the ECBDMF, this has been a valuable exercise in itself and has led to further insights into the biology and management of the fishery. For example, comparisons between spatially disaggregated catch and survey data (converted to equivalent units) provided a clearer overview of spatial and species-specific patterns of abundance and productivity. A closer analysis of existing growth curve relationships necessitated a revision of what was known about this aspect of the biology, and this study led to the derivation of revised growth curves for all nine species, which although preliminary, are a useful and essential starting point for future studies. Model results were sensitive to somatic growth rate and age at maturity assumptions and more research is needed to reduce this critical uncertainty. Model simulations were useful in reducing the uncertainty associated with the nature and scale of recruitment in the various species, for example in exploring what level and pattern of recruitment variability was compatible with BTF observed dynamics.

The ECBDMF has a current GVP of approx $5M per annum, but this project has shown that there is potential for expansion in terms of both volume and value of fishery products by spreading the fishery effort widely across the GBR. However, this assumption should be further explored only after the acquisition of new data to fill essential data gaps, particularly the density of Burrowing Blackfish outside the BBFZ zones and in closed areas of the GBRMP. Also, the potential for controlled catch of Black Teatfish throughout the fishery will potentially lead to increased profitability. Caution should be noted regards the indications of a slow recovery for this species.

This research has demonstrated a benefit of implementing a RZS harvest strategy for a sea cucumber fishery that would most likely have application to other sea cucumber fisheries in Australian State (NT and WA) as well as Commonwealth (Coral Sea, Torres Strait), as well as regional fisheries in the South Pacific countries and SE Asia. It is likely that the configuration of the RZS in the ECBDM fishery (three year cycle) would have application to other fisheries.

7 Implications

This fishery has been under increasing scrutiny in recent times, due to the lack of integrated stock assessments, diffuse and opaque management strategy development over many years, and apparent overexploitation of at least one species (Uthicke et al., 2004; GBRMPA, 2012; DAFF, 2012, Erikson and Byrne, 2013). The fishery is also subject to sustainability requirements of the GBRMPA, Queensland (Fisheries Act) and Commonwealth (EPBC Act) agencies. Therefore any information that provide indicators as to the sustainability of the fishery, the effectiveness of the RZS for mitigating depletion risk, or priority information gaps, is of considerable interest, especially given that there is a compliance cost to both the fishery and management agencies. The outputs from this research will address that information need to some extent, and provide the framework for future research and data gaps. In a broad sense, it will improve the sustainable management of sea cucumber populations in the ECBDMF, and potentially result in higher catches than otherwise (either through increased catch or by maintaining catch levels through less precautionary management), which will result in higher value and income for coastal fishing communities along the Queensland coast.

The ECBDMF has a current GVP of approx $5M per annum, but this project has shown that there is the potential for expansion in terms of both volume and value of fishery products by spreading the fishery effort widely across the ECBDMF. However, this assumption should be further explored after the acquisition of new data to fill essential data gaps, particularly the density of Burrowing Blackfish outside the BBFZ zones and in closed areas of the GBR Marine Park. Also, if the modelled recovery of Black Teatfish populations can be confirmed by surveys, the potential for a controlled catch throughout the fishery will potentially increase industry profitability. Caution should be noted regarding the indications of a slow recovery for this species.

This research has demonstrated a benefit of implementing a RZS harvest strategy for a sea cucumber fishery that would most likely have application to other sea cucumber fisheries in Australian State (NT and WA) and Commonwealth (Coral Sea, Torres Strait) waters, as well as regional fisheries in the South Pacific countries and SE Asia. There is also some interest in periodic fishing in the South Pacific countries that may provide a solution to intractable overexploitation problems for sea cucumber fisheries in the region (Cohen and Foale, 2013; Purcell, 2010).

8 Recommendations

1. Maintain, strengthen and develop the current Rotational Zoning Scheme (RZS) in the ECBDMF. Consider increasing rotational periodicity and a wider spread of fished zones as this is likely to reduce further the risk of localised depletion and improve the overall sustainability of the fishery.
2. Address important information gaps for higher risk species such as Burrowing Blackfish and White Teatfish; including the distribution and density of Burrowing Blackfish outside the fished zones, and the density of White Teatfish throughout the fishery.
3. Address important information gaps that will increase model certainty and hence the robustness of management recommendations; especially size/age at maturity, growth and natural mortality of targeted sea cucumber species.
4. Apply MSE approach to any new species in the ECBDMF that exceed the trigger limits implemented for the fishery.

8.1 Further Development

While the outputs will be useful in making explicit the trade-offs between alternative management strategies in a broad sense, continued development of the fishery will benefit from the acquisition of new data and application of the MSE approach to formulate and test finer scale spatial management strategies and adaptive approaches.

The MSE operating model relies on spatial estimates of biomass and species population parameters to simulate natural populations. Much of this data is uncertain or relies on proxies from other regions. Although we took a conservative approach to model risk parameters and the use of a Reference Set to investigate scenarios, the assessment and management of the fishery will always benefit from better information. In this regard, biomass estimates of all species fished in the fishery appears to be a primary determinant of future potential catches and risk. Given the limitations of CPUE data as an index of relative abundance for this fishery, a time-series of survey data or mark-recapture studies (using emerging technologies) would be particularly helpful in refining model biomass estimates and projected population trends. Better population parameters estimates, especially for age-at-maturity and somatic growth, would be valuable as these have a major influence on estimates of risk parameters measuring overall sustainability.

Given the targeting high catch rates of Burrowing Blackfish in the ECBDMF, survey data from areas outside the “Burrowing Blackfish zones” (BBZ), and reliable relative abundance data from fished areas to validate the operational model would appear to be the highest research priorities for that species. Although dedicated survey data would provide the best information, there may also be the potential to use the recently completed Great Barrier Reef Seabed Biodiversity Project (Pitcher et al., 2007) to estimate the distribution and abundance of this important fishery species.

Anecdotal reports indicate that the Black Teatfish population may have recovered in the depleted norther section of the fishery. A resurvey using similar protocols to that used by Uthicke et al (2004) to assess the relative density of the Black Teatfish populations in the previously fished area of the ECBDMF would provide information on the recovery rates of this species.

The MSE framework could be updated in a number of ways. In addition to updating parameter estimates and attempting to fit to additional data (e.g. survey data) that become available, the modelling framework is extremely flexible and would enable testing of a broad range of alternative scenarios and harvest strategies. Hence, for example, alternative recruitment scenarios (such as the extent of sharing of recruits between zones) could be investigated by linking with hydrodynamic models of the GBR and larval duration to inform as to which regions recruitment sharing is most likely to occur.

Also, the current model does not include positive density dependence (Allee effect, or depensation) where fertilisation success, and therefore larval recruitment, is reduced at low densities. This has been hypothesised to be responsible for population crashes and slow recovery for sea cucumber fisheries (Uthicke et al., 2009; Friedman et al., 2010). There is currently little information with which to model these effects, however, some sensitivity modelling could be attempted using this MSE approach. Population model's of red sea urchin (*Strongylocentrotus franciscanus*) that include depensatory effects have indicated sharp threshold values at K=0.3-0.5; but also indicate that refugia, aggregating behaviours (especially during spawning), post harvest spatial density patterns and even local hydrodynamics all influence the effect (Qinn et al., 1993; Pfister and Bradbury, 1996). It is possible that the risk metric of 40% biomass that we utilised, together with a management strategy incorporating multiple closed areas of the GBR, non-uniform fishing patterns and rotational harvesting, would provide an appropriate limit reference point until more is known of the depensatory effects of low spawner density.

This project has demonstrated the benefit of the RZS for reducing the risk to localised depletion, especially in highly fished zones. It also demonstrated a benefit for further spreading effort among fished zones (for the same catch), to the extent where risk was apparently eliminated. Of course there would be operating and compliance costs to implementing such strategies, however, the MSE provides a platform for further assessment of tradeoffs between values, costs and sustainability for the ECBDMF. The cost of fuel and lost fishing time associated with movements the mother vessel undertakes to comply with the RZS is likely to be considerable; therefore the most efficient configuration of spatial and temporal rotation is vital for maximising efficiency and value, while ensuring ecological sustainability. More information is required on the operating costs of the fishery operators before a full economic analysis could be undertaken. However, the results are indicative of efficiencies in the current scheme.

Additionally, it would be possible to develop a more sophisticated location choice model to simulate potential future fishing behaviour and distribution based on parameters such as proximity to ports, economic considerations, stock abundance, survey information or management guidelines. Hence for example, Plagányi et al. (2011) modelled location choice in the Coral Sea hand collectibles fishery based on a simple function describing utility by zone. The TAC or effort is then distributed in accordance with the relative utility of each zone. A bioeconomic model could readily be coupled with the MSE framework. This would necessitate collecting and collating cost and revenue data describing the fleet, and could then be used to calculate more robust estimates of profit under alternative scenarios.

The MSE framework could also be used to test the performance (both biologically and economically, and even socially) to a range of additional harvest strategies. For example alternative rotational periods could be considered, as well as explicitly testing control rules to trigger movement away from local reefs once they become depleted below pre-specified levels (as measured using survey or CPUE information for example).

9 Extension and Adoption

This project has produced direct management strategy advice to increase the sustainability of the ECBDMF. The RZS was formulated by industry in response to concerns regarding the sustainability of the fishery, therefore the key finding that the RZS reduces risk and increases value to the fishery further entrenches its use and the resulting demonstrated sustainability benefits for the RZS for the fishery. This has direct relevance to the objectives of GBRMPA and Qld Fisheries, and has the interest and support of Industry. Indeed, there have been recent discussions about changes to the RZS for the fishery that will benefit from the products of this research.

The outputs of this research have been reported directly to fishery stakeholders (industry and management including GBRMPA and Qld DAFF) through the dissemination of technical and summary reports, and dedicated seminars at management and port meetings. The background, objectives and approach to the analysis was communicated to industry stakeholders during the Stakeholder Workshop in April 2013, and during an Industry Liaison meeting in January 2014. We also communicated the results of the project to national and international fisheries researchers during a Data Poor Fisheries Conference in Hobart in December 2013.

The outputs of the project will be communicated to stakeholders in other small-scale invertebrate fisheries in Australia and the region. This information has already influenced management decisions in the Torres Strait sea cucumber fishery, and a proposal is under development to apply a similar approach there to manage the sea cucumber fishery in a co-management setting. Similarly, there is currently a RZS in the Coral Sea fishery that has very little information to inform management. The positive response to RZS illustrated in this study will bolster that low data fisheries sustainability credentials.

Glossary

Note that many of the definitions given below are taken from Rademeyer et al. (2007)

Assessment:	A mathematical population model coupled to a statistical estimation process that integrates data from a variety of sources to provide estimates of past and present abundance, fishing mortality and productivity of a resource.
B_{MSY}:	The level of species biomass corresponding to deterministic Maximum Sustainable Yield (MSY).
CPUE:	Catch Per Unit Effort.
Conditioning:	An operating model is “conditioned” on available information to ensure that it does not reflect assumptions incompatible with existing information which would render it implausible – this process is similar (sometimes identical) to an assessment.
HCR:	Harvest Control Rule – a set of well-defined rules used for determining a management action in the form of a TAC or allowable fishing effort.
Limit reference points:	Conditions to be avoided.
Management objectives:	Broad objectives pertaining to the development of a MP for the management of a resource as set by decision makers – these will typically relate to the conflicting aims of maximizing catches, and minimising large inter-annual changes in catch limits and the risk of unintended resource depletion.
MP:	Management Procedure – the combination of pre-defined data, together with an algorithm to which such data are input to provide a value for a TAC or effort control measure, which has been tested by simulation for robust performance in the presence of uncertainties.
MP Approach:	A feedback control approach to resource management, which also provides a framework to deal with uncertainty about resource status and dynamics.
MSE:	Management Strategy Evaluation – the process of testing alternative MPs by simulation, in particular for robust performance in the presence of uncertainty.
MSY:	Maximum Sustainable Yield – the maximum yield/catch that can be taken from a resource on an ongoing sustainable basis.
MSYL:	Maximum Sustainable Yield Level – the stock level at which the MSY is achieved.
OM:	Operating Model – a mathematical-statistical model used to describe the underlying resource dynamics in the MP simulation testing process, and to generate future data when projecting forward.
Performance statistics:	Statistics that summarise different aspects of the results of a simulation trial used to evaluate how well a specific MP achieves some or all of the overall objectives of management for the scenario under consideration.

Reference Point:	Particular levels that reflect stock status (e.g. spawning biomass (B_{sp}) or fishing mortality rate (*F*)).
TAC:	Total Allowable Catch to be taken from a resource within a specified period.
Target reference points:	Specify where management should aim, which stakeholders usually decide.
Threshold reference points:	Used to put up a flag when getting closer to a limit reference point.

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Appendix A Intellectual Property

Fishery data (catch and effort data): Restricted access. There are currently only 2 operators in the fishery, therefore the spatial catch and effort data used in the spatial MSE model is not available for public viewing.

MSE analysis outputs: CSIRO provides the model outputs for the public good.

Management recommendations: CSIRO provides management recommendations under the caveats listed in the Disclaimer at the start of the report. Other than that, they are open to public viewing.

Appendix B Researchers and project staff

List of researchers

Mibu Fischer	CSIRO Marine and Atmospheric Research
Nicole Murphy	CSIRO Marine and Atmospheric Research
Ricardo Pascual	CSIRO Marine and Atmospheric Research
Éva Plagányi	CSIRO Marine and Atmospheric Research
Timothy Skewes	CSIRO Marine and Atmospheric Research

List of participants of stakeholder workshops

Belinda Aumuller	Seafresh Pty Ltd (Cairns)
Kerrod Beattie	Qld DAFF (Brisbane)
Martin Cunningham	Skipper, Seafresh Pty Ltd (Cairns)
Phil Gaffney	Qld DAFF (Brisbane)
Chauncey Hammond	Tasmanian Seafoods Pty Ltd
Vinnie Hunt	Tasmanian Seafoods Pty Ltd
Ben Leahey	Skipper, Tasmanian Seafoods Pty Ltd
Grant Leeworthy	Industry scientist, Tasmanian Seafoods Pty Ltd
Megan Leslie	Qld DAFF (Brisbane)
Kurdis Lowden	Seafresh Pty Ltd (Cairns)
Rob Lowden	Seafresh Pty Ltd (Cairns)
Randall Owens	GBRMPA (Townsville)
Doug Zhamel	Qld DAFF (Brisbane)

Appendix C Stakeholder workshop agenda

Management Strategy Evaluation (MSE) for the Qld East Coast Beche-de-mer Fishery

Tuesday, 23 April 2013

Commences 9:00am, ends 4:00pm

Fisheries Queensland, Dept. of Agriculture, Fisheries and Forestry

80 Ann St, Brisbane

AGENDA

Time	Topic	Presenter / notes
8.30am	Morning coffee	Document collection
9 – 9:15 am	Welcome, introductions and housekeeping	TS welcome participants, everyone introduces themselves. PG housekeeping (evacuation, toilets etc)
9:15 – 9:30 am	Project overview	Background to project; meeting objectives. (Tim)
9:30 – 10:00 am	Fishery description	Area fished; history of fishery; research; management (Tim). Feedback from stakeholders.
10:00 – 10:30 am	Fishery surveys	Overview of population surveys undertaken by industry (Leeworthy). Feedback from stakeholders.
10:30 – 11:00 am	Morning tea	
11:00 – 11:30 am	MSE introduction	How does it work; what are we trying to achieve. (Eva)
11:30 – 12:30 pm	MSE preliminary outputs	Present preliminary MSE outputs. Comments from stakeholders (Eva/Ric)
12:30 – 1:30 pm	Lunch	
2:00 – 2:30 pm	Improving assumptions and model inputs	Review important assumptions and model inputs. Elicit information to fill data gaps. (Tim\Eva\Ric)
1:30 – 2:00 pm	Strategies to test	Detailed discussion re strategies to test (Eva\Tim)
2:30 – 3:00 pm	Recommendations for improving the research & stakeholder buy-in	Will the MSE project fulfil fishery needs? What other research is required. (Tim)
3:00 – 3:30 pm	Afternoon tea	
3:30 – 3:45 pm	Future plans	Project plan & report, Stakeholder communication, Post-project follow-ups (Tim)
3:45 – 4:00	Final comments from each stakeholder	Each attendee gets 2 minute. Feedback sheets handed out for filling out.

Appendix D Meeting notes

Management Strategy Evaluation (MSE) for the Qld East Coast Beche-de-mer Fishery

Tuesday, 23 April 2013

Fisheries Queensland, Dept. of Agriculture, Fisheries and Forestry, 80 Ann St, Brisbane

List of participants

Lowden, Rob (RL)	Seafresh Pty Ltd (Cairns)
Lowden, Kurdis (KL)	Seafresh Pty Ltd (Cairns)
Cunningham, Martin (MC)	Skipper, Seafresh Pty Ltd (Cairns)
Hammond, Chauncey (CH)	Tasmanian Seafoods Pty Ltd
Leeworthy, Grant (GL)	Industry scientist, Tasmanian Seafoods Pty Ltd
Leahey, Ben (BL)	Skipper, Tasmanian Seafoods
Owens, Randall (RO)	GBRMPA (Townsville)
Phil Gaffney (PG)	QldDAFF (Brisbane)
Megan Leslie (ML)	QldDAFF (Brisbane)
Beattie, Kerrod (KB)	QldDAFF (Brisbane)
Plagányi, Éva (EP)	CSIRO (Brisbane)
Pascual, Ricardo (RP)	CSIRO (Brisbane)
Skewes, Tim (TS)	CSIRO (Brisbane)

Fishery area/habitats

- Lots of discussion on this.
- What was the maximum depth that delineates the reefs and shelf areas included in the study area (RL)? The response was that the habitats delineated include the GBR shelf (<200m approx) and reef and lagoon habitats (<100 m) of the off-shelf reefs.
- While much of the deeper habitat is inaccessible it contains species of interest. This is important for defining the habitat so will be important in the modelling (RL).

RZS Zones

- 157 RZS zones in Industry scheme (RL)
- We have 157 on shelf plus 3 offshore. We need to sort this out ASAP.
- Grant has some info for these zones. (GL)

Fishery catch

- Discussion on dominant species in catch
- Early catches were concentrated on Black Teatfish and Sandfish (*H. scabra*) (RL)
- Very few *A. miliaris* (hairy blackfish) in the catch. Mostly Deepwater Blackfish, *A. palauensis* (chunkies) (RL).
- Much of the early Burrowing Blackfish (BBF) catch was labelled as Blackfish. The smaller sizes in the logbook data are most likely all BBF. (RL)
- GL has lots of data on Burrowing Blackfish.
- Brown Sandfish may be targeted more in the future (RL)

- Fishers were keen to make the point that there are many potentially commercial species on the GBR (CH, RL)

Model Species

- Group discussed the best 8 species to include in the MSE. Mostly the discussion was based on value, and current and future targeting.
- Remove deepwater Redfish, surf Redfish and blackfish (*A. miliaris*) – very few of these in the catch.
- Include "chunky" blackfish (*A. palauensis* – Deepwater Blackfish)
- Include two species of curryfish, *S. herrmanni* and *S. vastus*. (They do see *S. ocellatus* but only in smaller numbers)
- Include Brown Sandfish (*B. vitiensis*)
- Final list
    1. Sandfish *Holothuria scabra*
    2. Black Teatfish *Holothuria whitmaei*
    3. Brown Sandfish *Bohadschia vitiensis*
    4. White Teatfish *Holothuria fuscogilva*
    5. Prickly Redfish *Thelenota ananus*
    6. Golden Sandfish *Holothuria lessoni*
    7. Curryfish (common) *Stichopus herrmanni*
    8. Curryfish (vastus) *Stichopus vastus*
    9. Deepwater Blackfish *Actinopyga palauensis*
    10. Burrowing Blackfish *Actinopyga spinea*

Species habitats

1. Sandfish *Holothuria scabra*
2. Black Teatfish *Holothuria whitmaei*
3. Brown Sandfish *Bohadschia vitiensis*
    - Brown Sandfish found in many sandy lagoon habitats of inner reefs, and is a dominant species in the GBR from Townsville to Mackay. (MC)
    - 85% of reefs have Brown Sandfish. (RL)
    - They do come out of a day, especially the larger ones, however, if you disturb one, they will all disappear. (RL, MC)
4. White Teatfish *Holothuria fuscogilva*
    - Protected bays (from SE trades) on outside of reef (MC)
    - Outer shelf reefs where eddies form from tidal flows (MC)
5. Prickly Redfish *Thelenota ananus*
6. Golden Sandfish *Holothuria lessoni*
    - Golden Sandfish and BBF caught together (MC, RL, GL).
7. Curryfish (common) *Stichopus herrmanni*
8. Curryfish (vastus) *Stichopus vastus*
9. Blackfish (deepwater) *Actinopyga palauensis*
    - There is some habitat crossover between *A. palauensis* (chunkies) and BBF. Chunkies are found in the 10-25 m zone and on reefs as well. They like rubbly reef, clear water and current (2.5-3 knots). They have a thick body wall, large yellow anal teeth and corrosive skin. (RL).
    - Chunkies (*A. palauensis*) like to live in areas with water speed of 2-3 knots. Could possibly delineate habitat using hydrodynamic models? (MC)
    - More in the southern GBR than the northern (MC)
10. Burrowing Blackfish *Actinopyga spinea*
    - GL has lots of data on Burrowing Blackfish.
    - Need to delineate BBF habitat, especially the Lizard patch, Cap Bunker patch and Swains patches which extend into green zones. (GL)
11. Other species

- Lots of *S. ocellatus* (Curryfish) in some areas, partic deep inshore (MC). Appears that there is lots of predation on them of a night. (MC)
- Plenty of Lollyfish (*H. atra*) throughout the GBR. (MC, BL, RL)
- Can be lots of Stonefish, but they are very cryptic during the day. (MC)

Species population parameters

- Max size estimates from the field (in live weight)
- Size at t = infinity (mostly MC and RL):
  - Prickly Redfish 12 kg (1 metre)
  - BBF 1.5 kg
  - Sandfish 2 kg
  - Black Teatfish 3 kg
  - Deepwater Redfish 1.5 kg
  - White Teatfish 4 -5 kg
  - Gold Sandfish 3 kg
  - Curryfish (all 3 species) 4.5 kg
  - Blackfish (chunkies) 2 kg
  - Brown Sandfish 2.5 kg

- Age at maturity, $a_{(mat)}$ (mostly MC, BL, GL and RL) (in yrs)
  - Sandfish 2
  - Golden Sandfish 2
  - Curryfish *S. herrmanni* 3
  - Blackfish 3
  - Burrowing Blackfish 2
  - Black Teatfish 4
  - White Teatfish 3
  - Prickly Redfish 4
  - Curryfish *S. vastus* 3
  - Brown Sandfish 2

- Growth rate
  - Function of temperature, except for deep species (40 m or more deep) especially for shallow species (25 m or less deep). (RL, MC)

- Age to max size
  - Brown Sandfish age to max ~6y. (MC)

- Recruitment dynamics
  - Will Bowman of Tasmanian Seafoods in the NT will have some insights into Sandfish recruitment, and larval life. (CH)

- Mortality rate
  - Use estimates formulated by GL of M and age at max size using Hoenegs equation for BBF. (GL)

Biomass Estimates

- TS presented the available information on likely abundance data for GBR population.
- Multiplying ones presented by TS by a factor of 2 those values are defensible. (RL)
- Estimate of densities from fishers (MC, BL):
  - *S. herrmanni* (Curryfish Herrmanni) 5/ha
  - *S. vastus* (Curryfish Vastus) 1.5 to 2 /ha
  - Brown Sandfish 5/ha

- GL has some data for Brown Sandfish. Will pass on to TS.
- The BBF populations have not been surveyed in the Closed areas of the GBR, but are likely to be found there. (GL, RL, All)
- It is likely that the Lizard Island BBF population extends into the neighbouring Closed area by about 33% of the area. (GL)

Past research

- GL presentation. Included analysis on quantifying BBF stock size in several BBF Zones, resurveys of Gould reef, managing profitability, survey transect methodology, pattern analysis, spatial harvest pattern.

MSE Approach

- Contact Will Bowman in NT about Sandfish recruitment model. Connectivity between habitat location is species dependent. Consult Will on this. (CH)
- Habitat distance and sea flow current should be incorporated in the model. Larvae viable for 20 days. (MC)
- Dominant species can change dramatically after approximately 3 nautical miles. (radius of neighbourhood?) (MC)
- Concern that MSE will be turned into a management tool rather than an evaluation tool. (CH)
- What do the fishers have to do to reopen closed species and areas? Some closed areas have 20 individual per hectare of Black Teatfish. (RL)

Performance measures

- Some ideas for performance measures include: (All)
    - B_{MSY} = 48% (based on Commonwealth harvest strategies)
    - Average annual variability
    - Risk of depletion for entire fishery and among zones (20% limit reference point)

- Other outputs from MSE/project
    - How important are the green zones (RL, RO)
    - What are the data needs for managing the fishery (CH, PG, RO)
    - Recommendations for criteria for BTF re-opening (RL, All)
    - Potential data collection by fishers (distribution/ density/size) (All)

Scenarios to test

- 1.5 or double the fishery effort (All)
- Variations on model abundance estimates
    - Lizard Island +25% biomass estimate
    - M37, X2 area
    - Capricorn Bunker, x2 area
    - Curryfish, X2 density
    - *S. vastus*, half curry estimate
    - Green zones in Swains with BBF ie Storm cay
    - Brown Sandfish density, 5/Ha Townsville to Mackay
    - Golden Sandfish, 1.5 X current biomass
- Different age at maturity
- Recruitment sharing for BBF
- Growth v water temperature - for shallow species only
    - 23 degrees Swains
    - 26 degrees Cooktown

Future activities

- Need to outline the “when, where, who and how” of interaction with industry in the future (CH)

Appendix E MSE workshop questionnaire

MSE workshop participants Questionnaire Responses

Number of Evaluations: 10

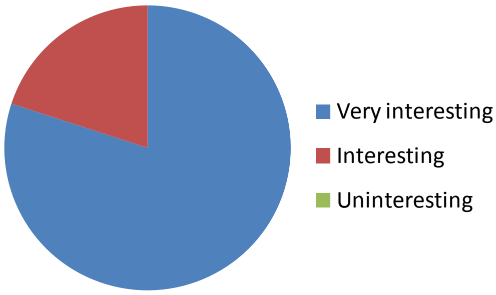
<u>Sectors</u>

Fishers:	3
Industry:	2
Managers:	2
Scientist:	2
Licensing Officer:	1

<u>Questions</u>

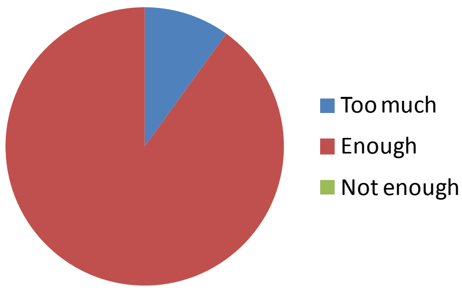
Q1. I found the workshop…

Very interesting:	8
Interesting:	2
Uninteresting:	0



Q2. The amount of information presented at the workshop was…

Too much:	1
Enough:	9
Not enough:	0

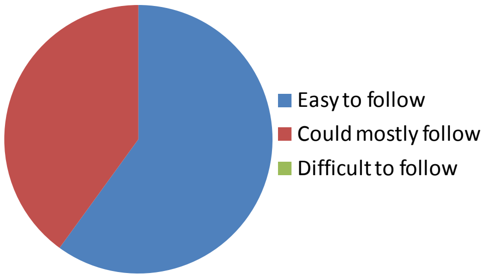


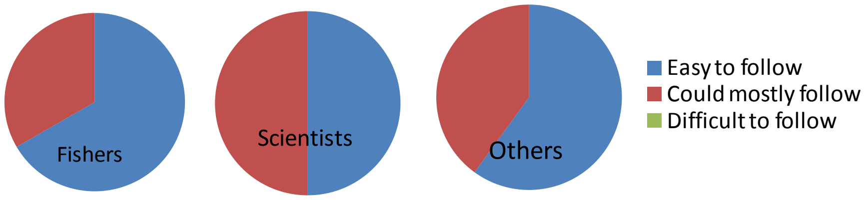
Q3. The workshop was presented so it was…

Easy to follow: 6

Could mostly follow: 4

Difficult to follow: 0



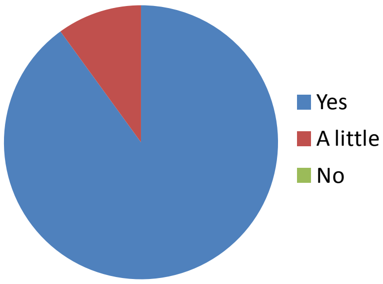


Q4. Did you find the information provided to be relevant to your needs?

Yes: 9

A little: 1

No: 0

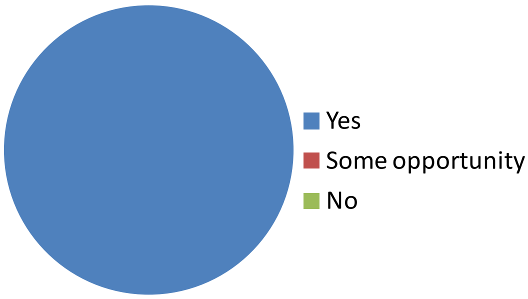


Q5. The workshop allowed me to provide comments and ask questions?

Yes: 9

Some opportunity: 0

No: 0

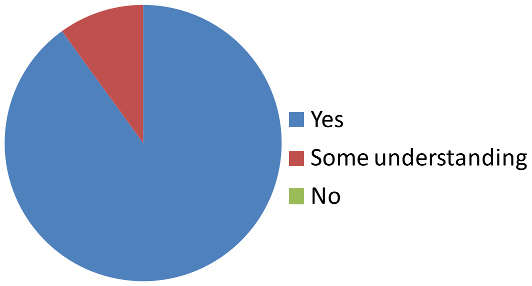


Q6. This workshop assisted me to understand the methods used in the MSE?

Yes: 9

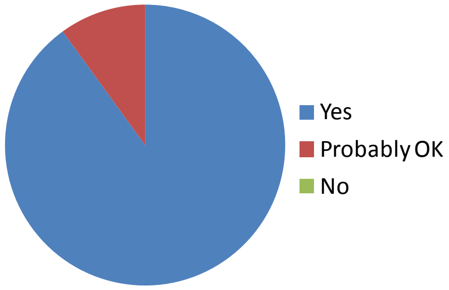
Some understanding: 1

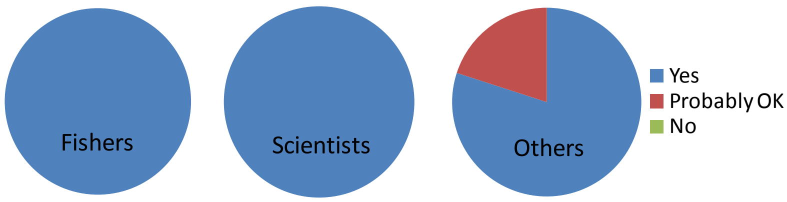
No: 0



Q7. The MSE addresses an adequate range of management strategies?

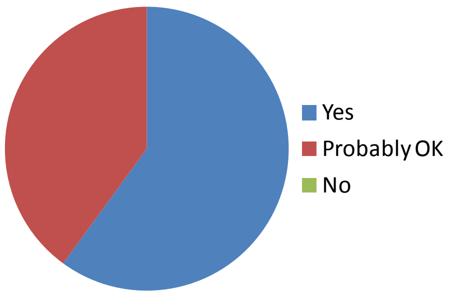
Yes:	9
Probably OK:	1
No:	0

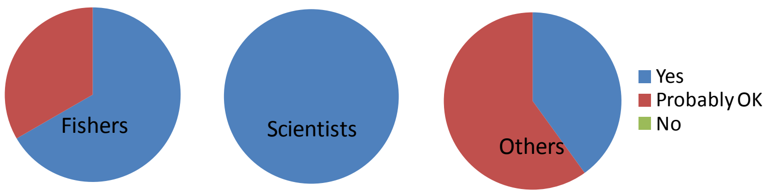




Q8. The MSE produces enough indicators to evaluate each management strategy?

Yes:	6
Probably OK:	4
No:	0





<u>Was there a component of the MSE that you would have liked more time on?</u>

Possibly a little early to comment yet. (Manager)

Spatial components - but brilliant start. (Scientist)

<u>Other comments?</u>

I think at times when the floor was open the focus stuffed away from the subject. If the session was more strictly chaired it would have been easier to follow. Otherwise, very informative and lots of exciting new prospects beginning to present themselves. (Industry)

Well put together and engaged industry - hopefully has set a way for the future. (Manager)

Very interesting. Thank you (Fisher)

Excellent work Tim and Eva! (Scientist)

Well run workshop - MSE is welcome by industry and hopefully can be followed up every 3 years with future evaluation. Well Done! (Industry)

An exciting project. We look forward to the results and working toward a sustainable future. (Fisher)

What I could follow was easy to follow! (Scientist)

Appendix F Model spawning biomass, 1995 - 2012

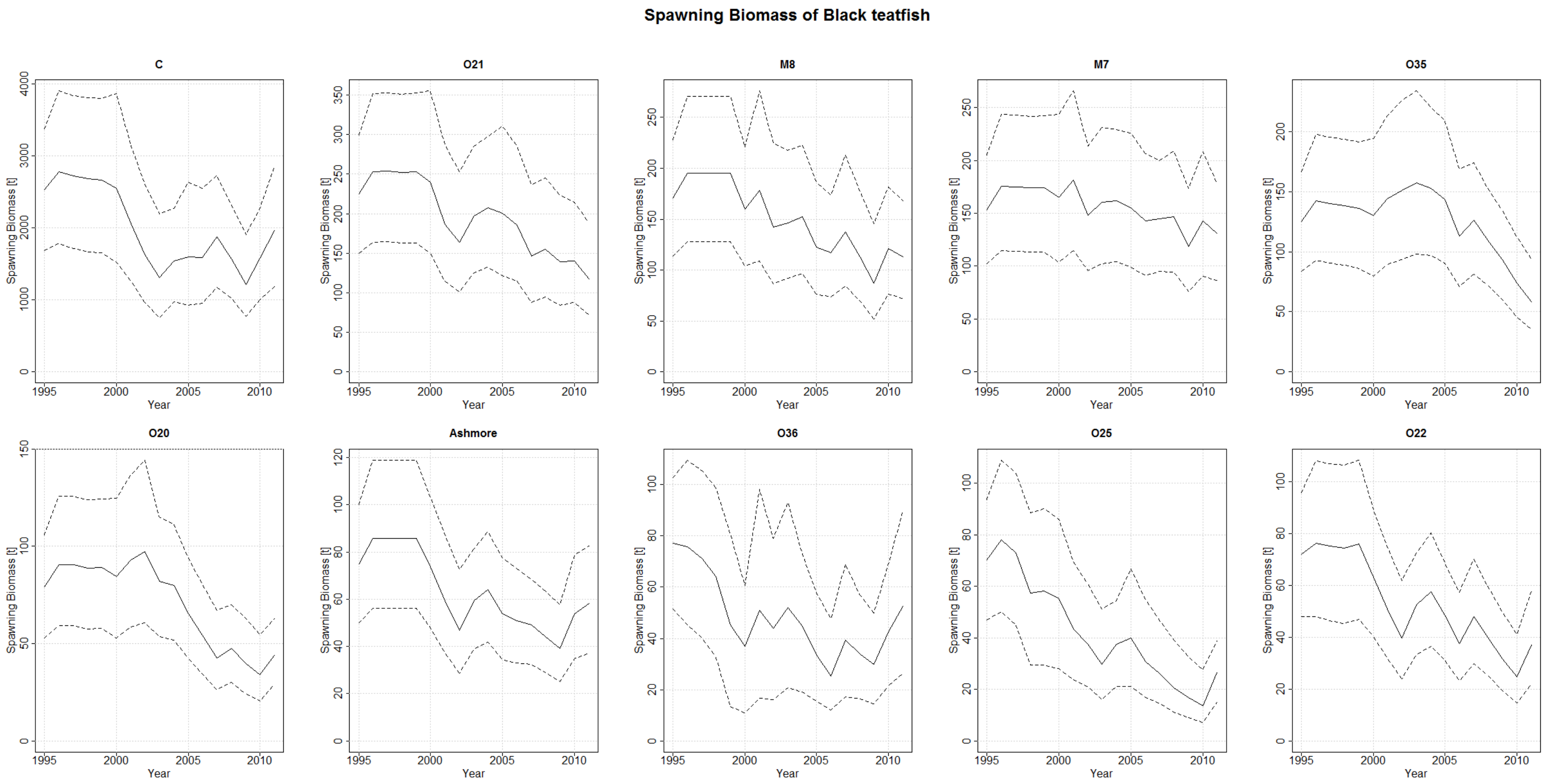


Figure 26. Spawning biomass (t) trajectories from 1995 to 2012 for Black Teatfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations.

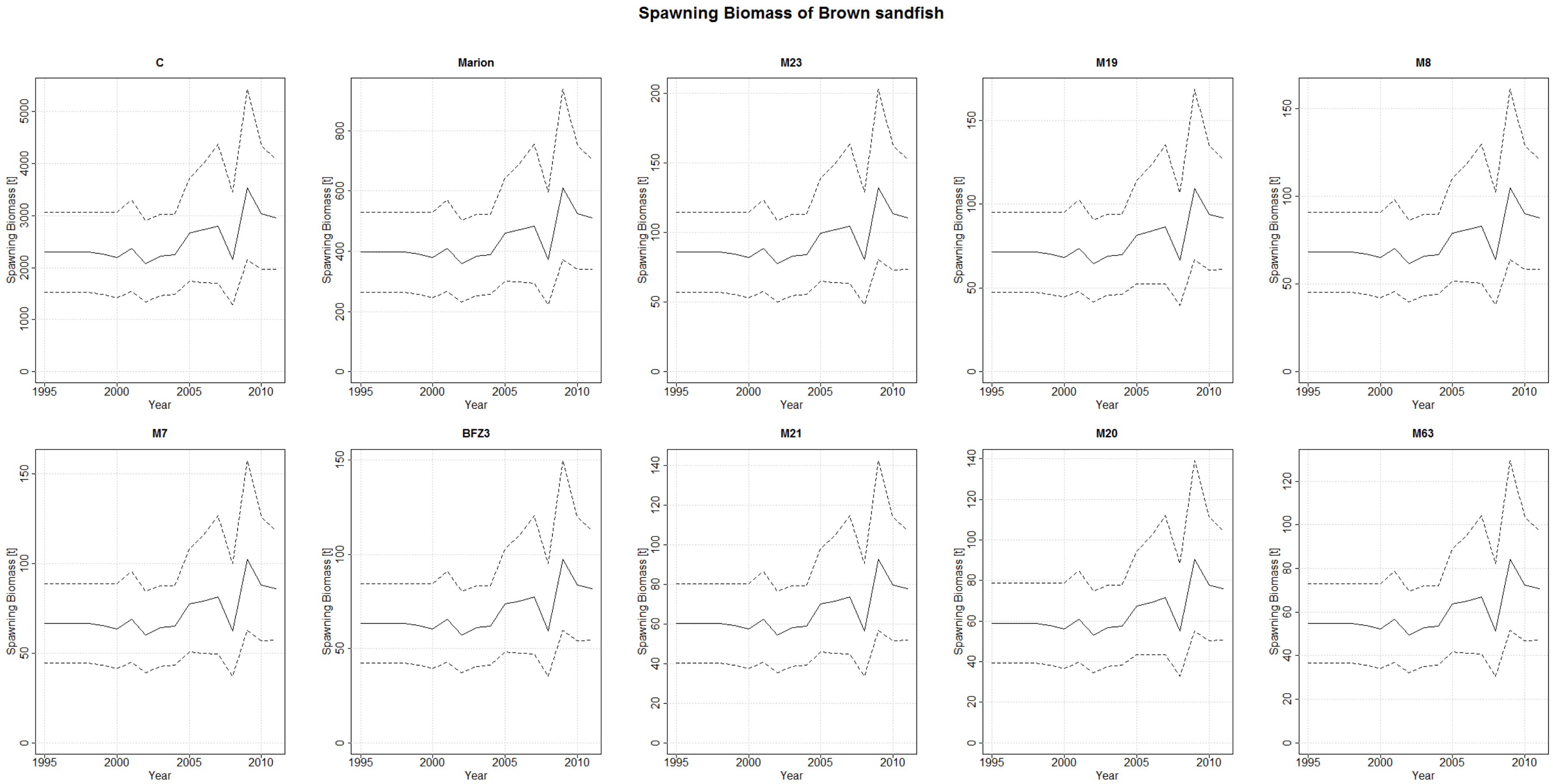


Figure 27. Spawning biomass (t) trajectories from 1995 to 2012 for Brown Sandfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations.

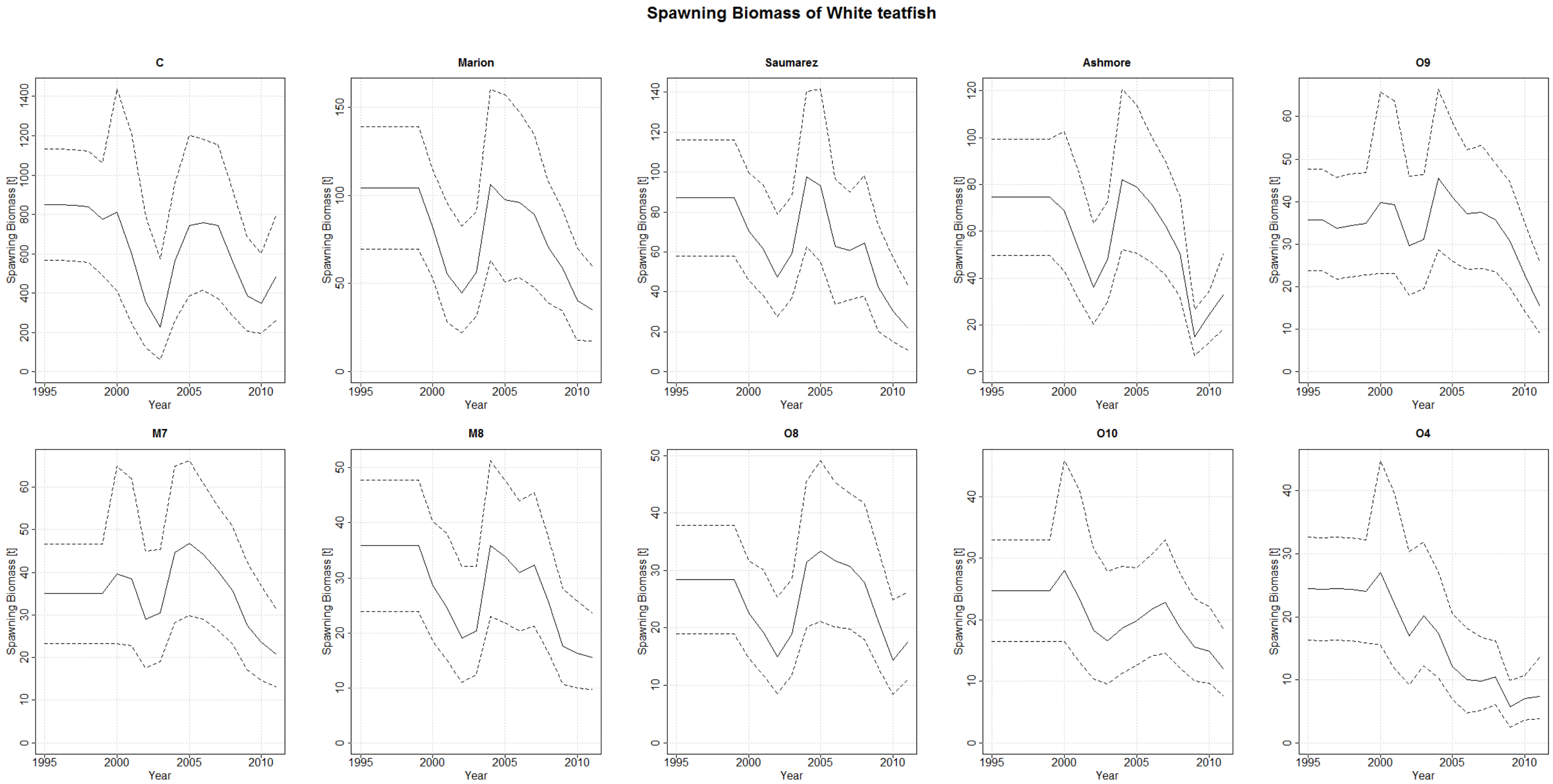


Figure 28. Spawning biomass (t) trajectories from 1995 to 2012 for White Teatfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations.

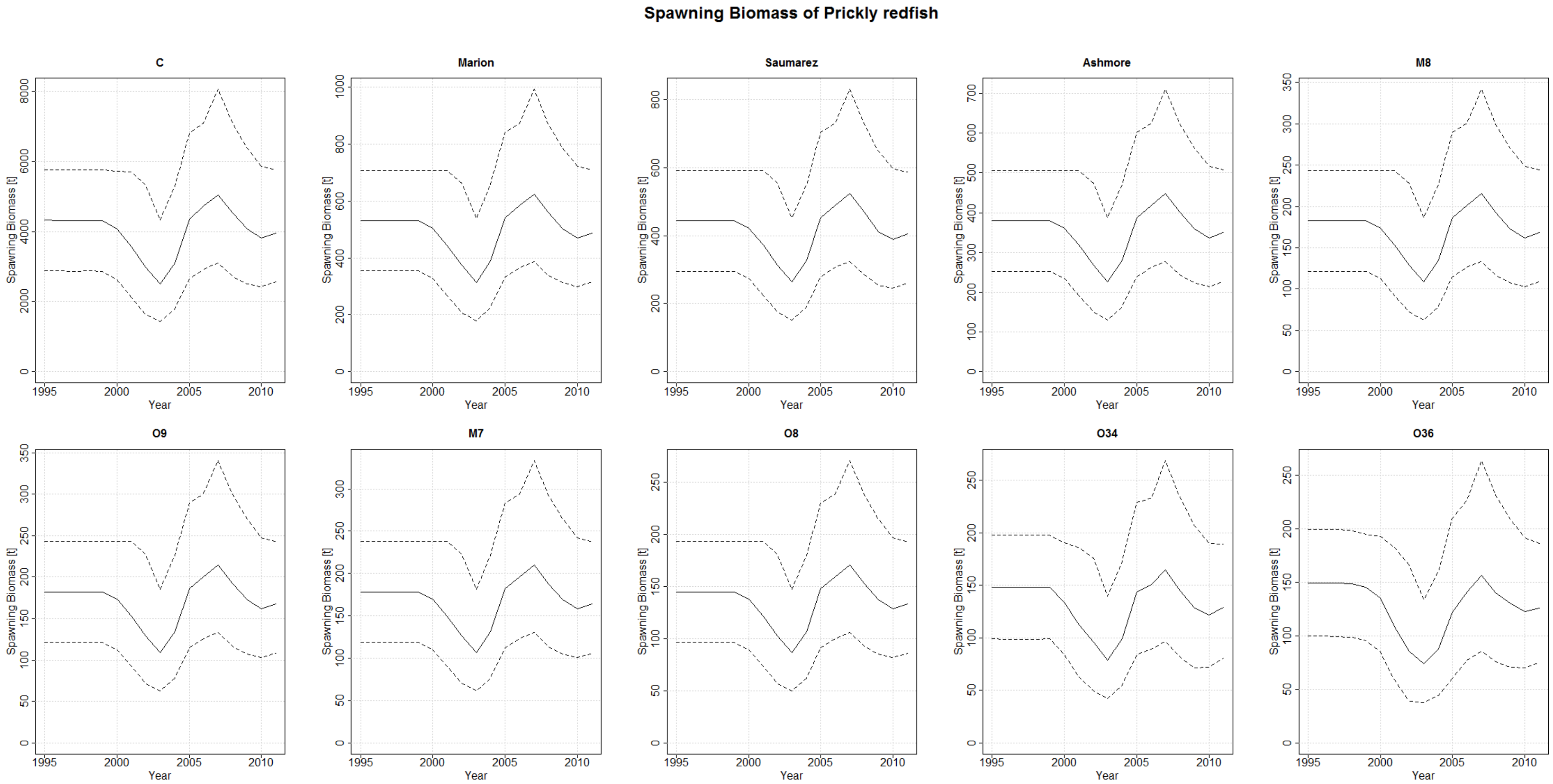


Figure 29. Spawning biomass (t) trajectories from 1995 to 2012 for Prickly Redfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations.

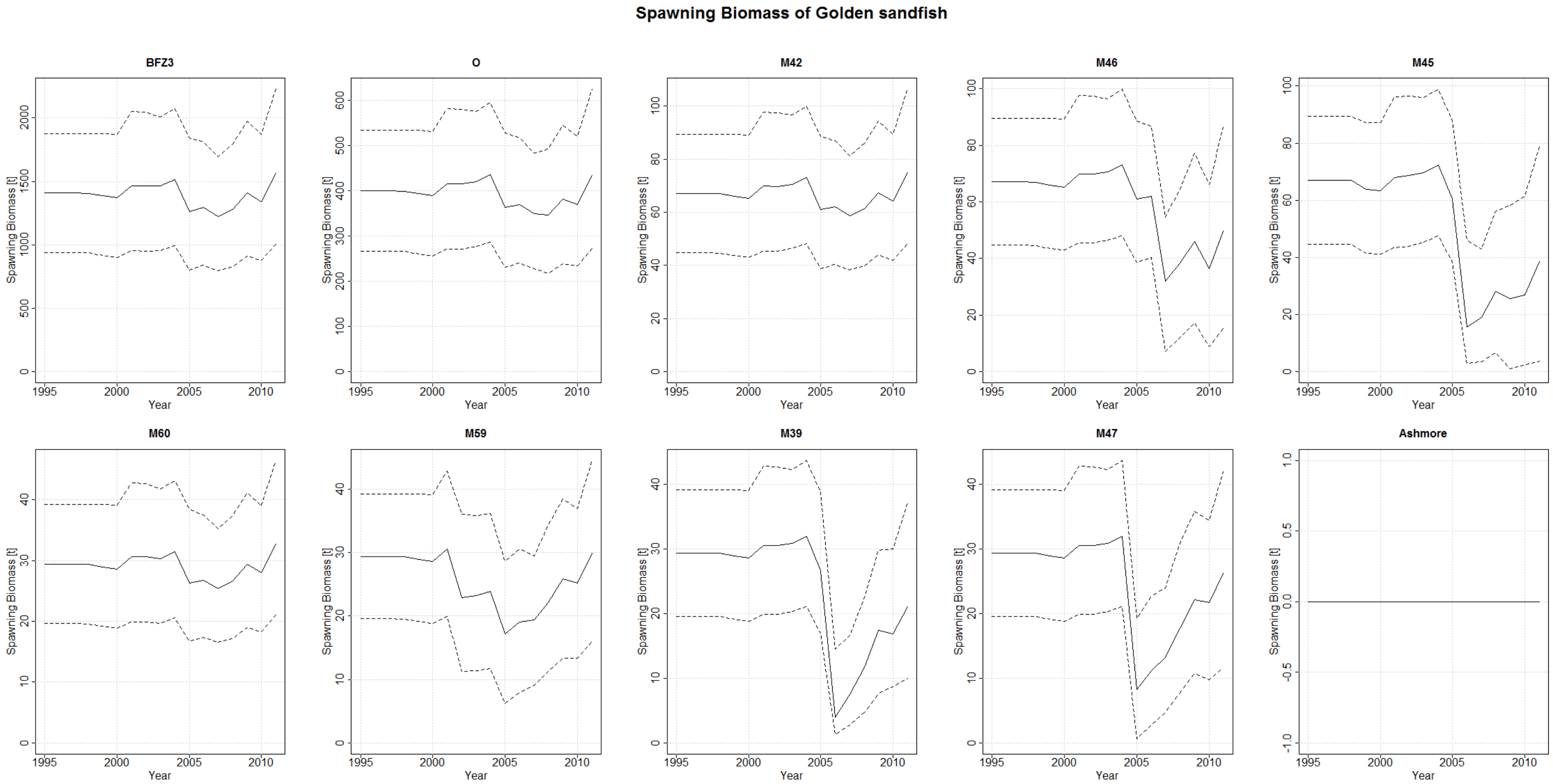


Figure 30. Spawning biomass (t) trajectories from 1995 to 2012 for golden Sandfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations.

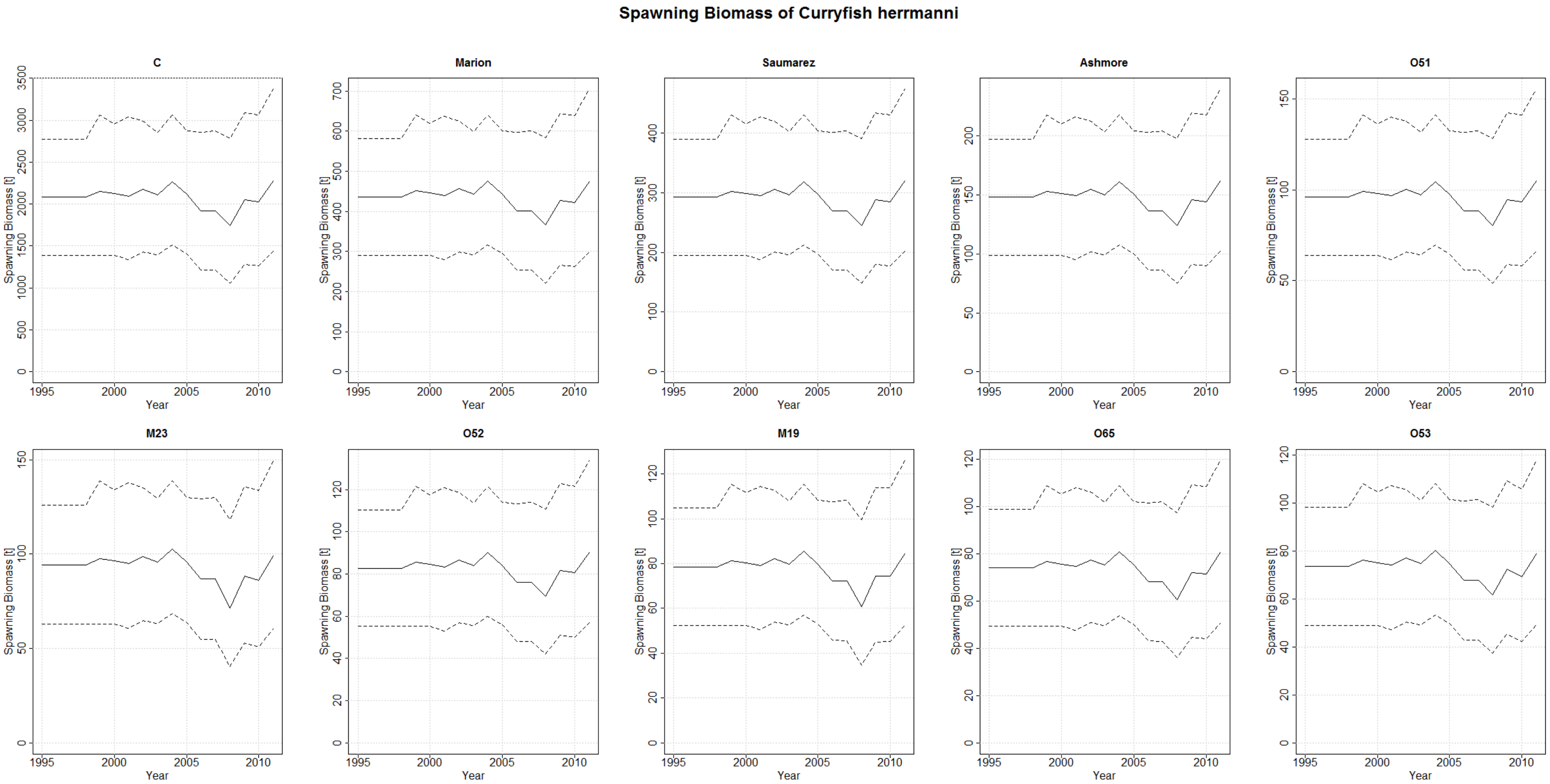


Figure 31. Spawning biomass (t) trajectories from 1995 to 2012 for Curryfish Herrmanni in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations.

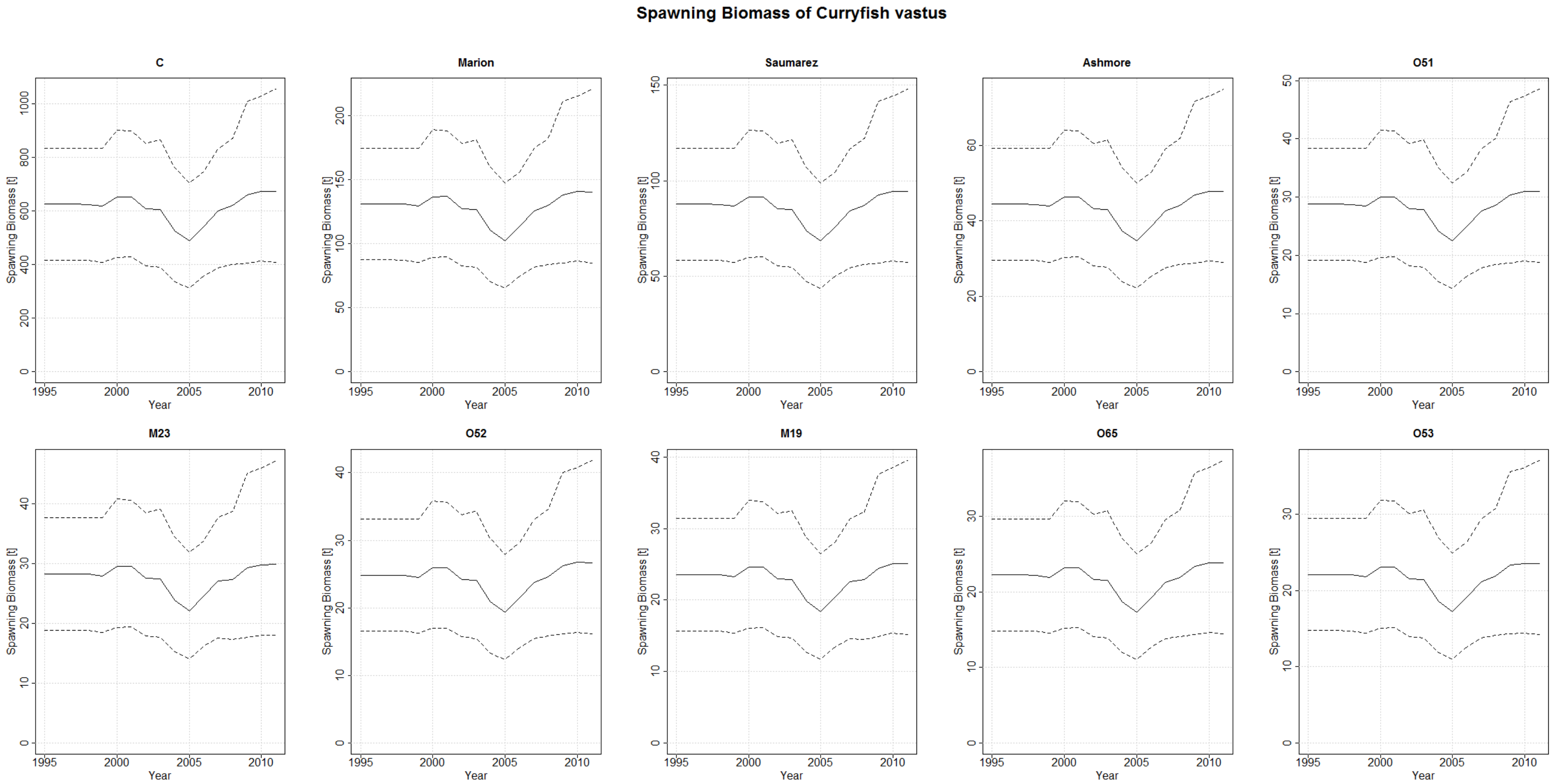


Figure 32. Spawning biomass (t) trajectories from 1995 to 2012 for Curryfish Vastus in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations.

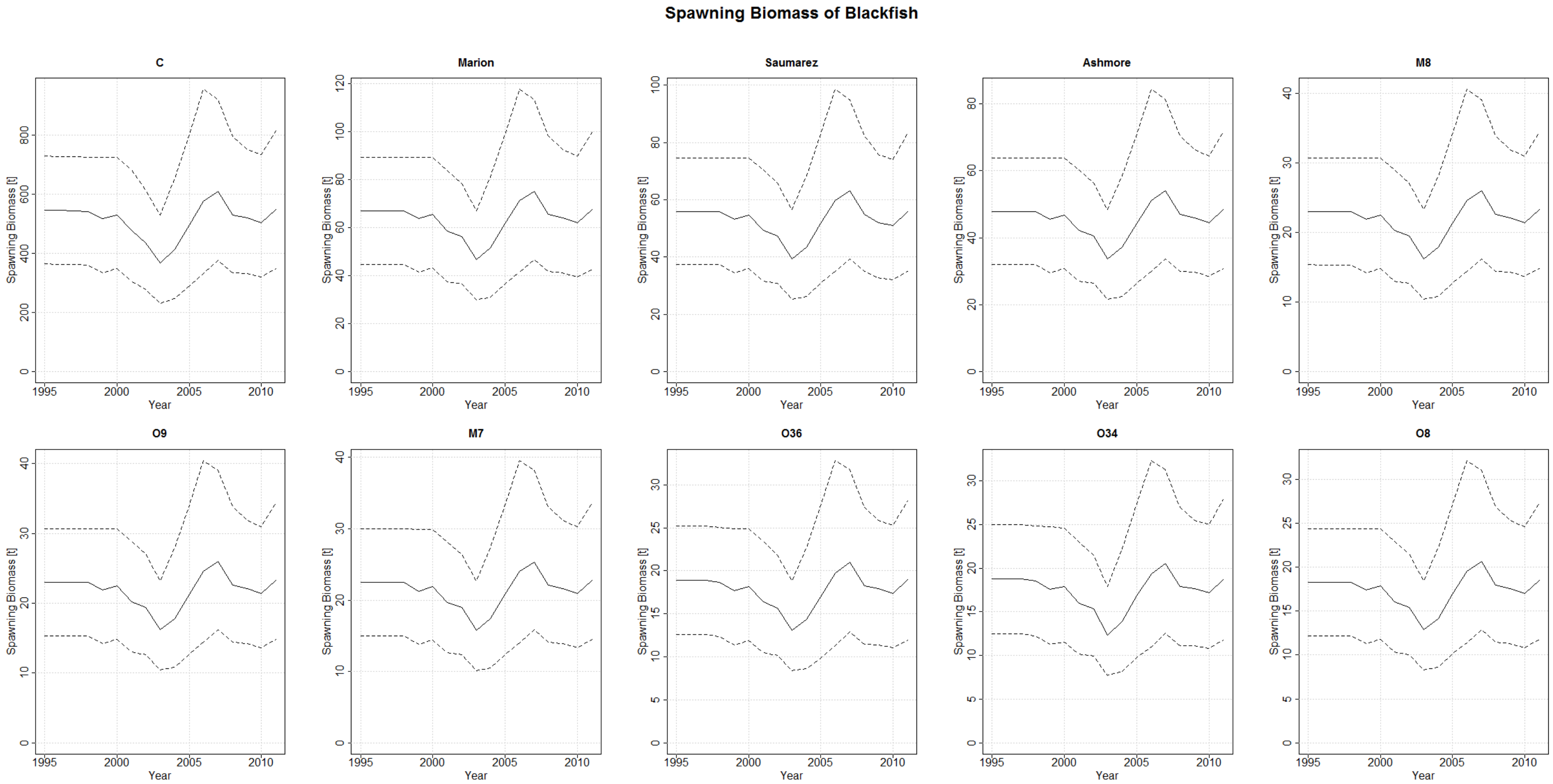


Figure 33. Spawning biomass (t) trajectories from 1995 to 2012 for blackfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations.

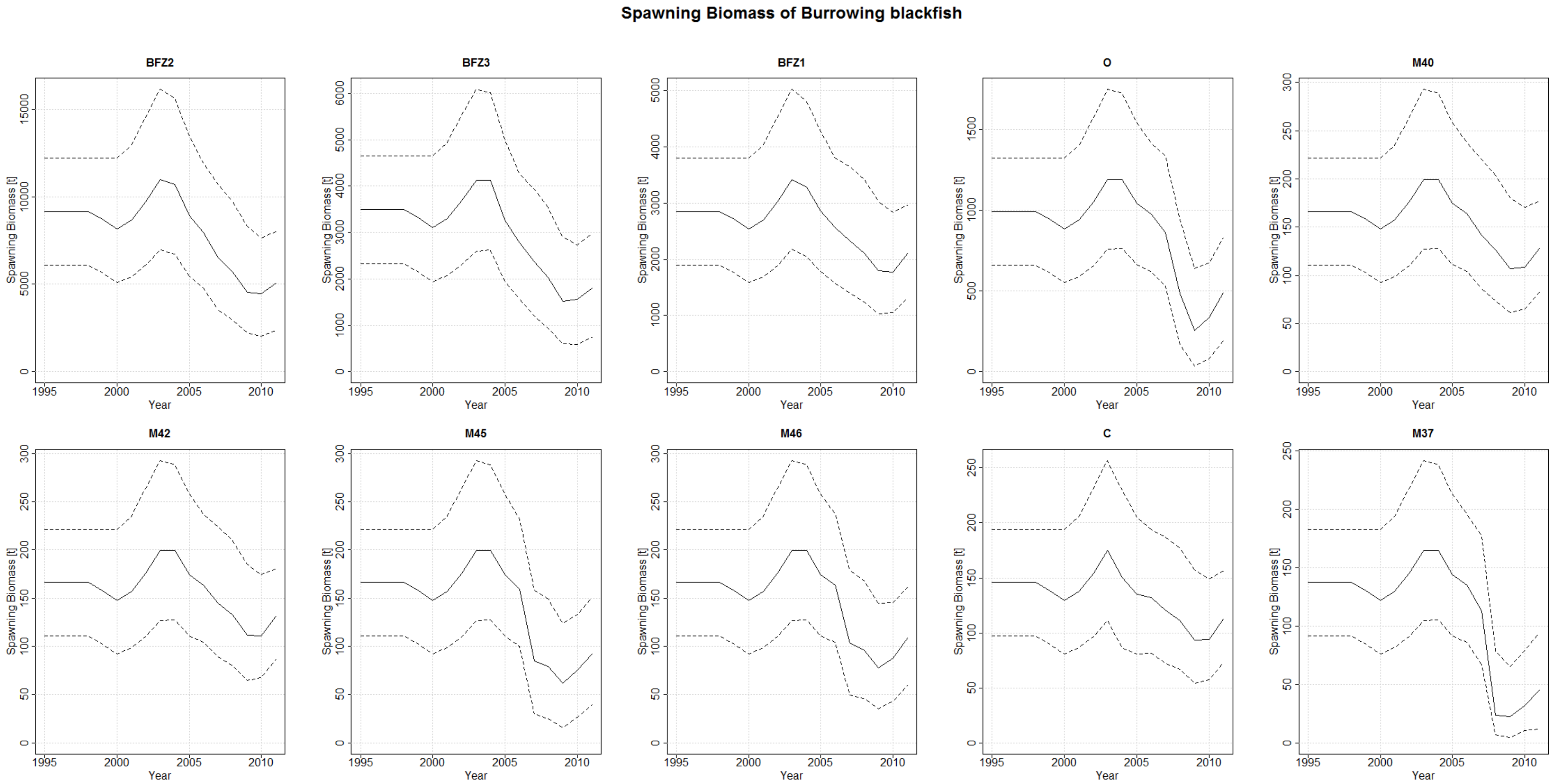


Figure 34. Spawning biomass (t) trajectories from 1995 to 2012 for Burrowing Blackfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations.

Appendix G Projected spawning biomass – no fishing, 2012 - 2031

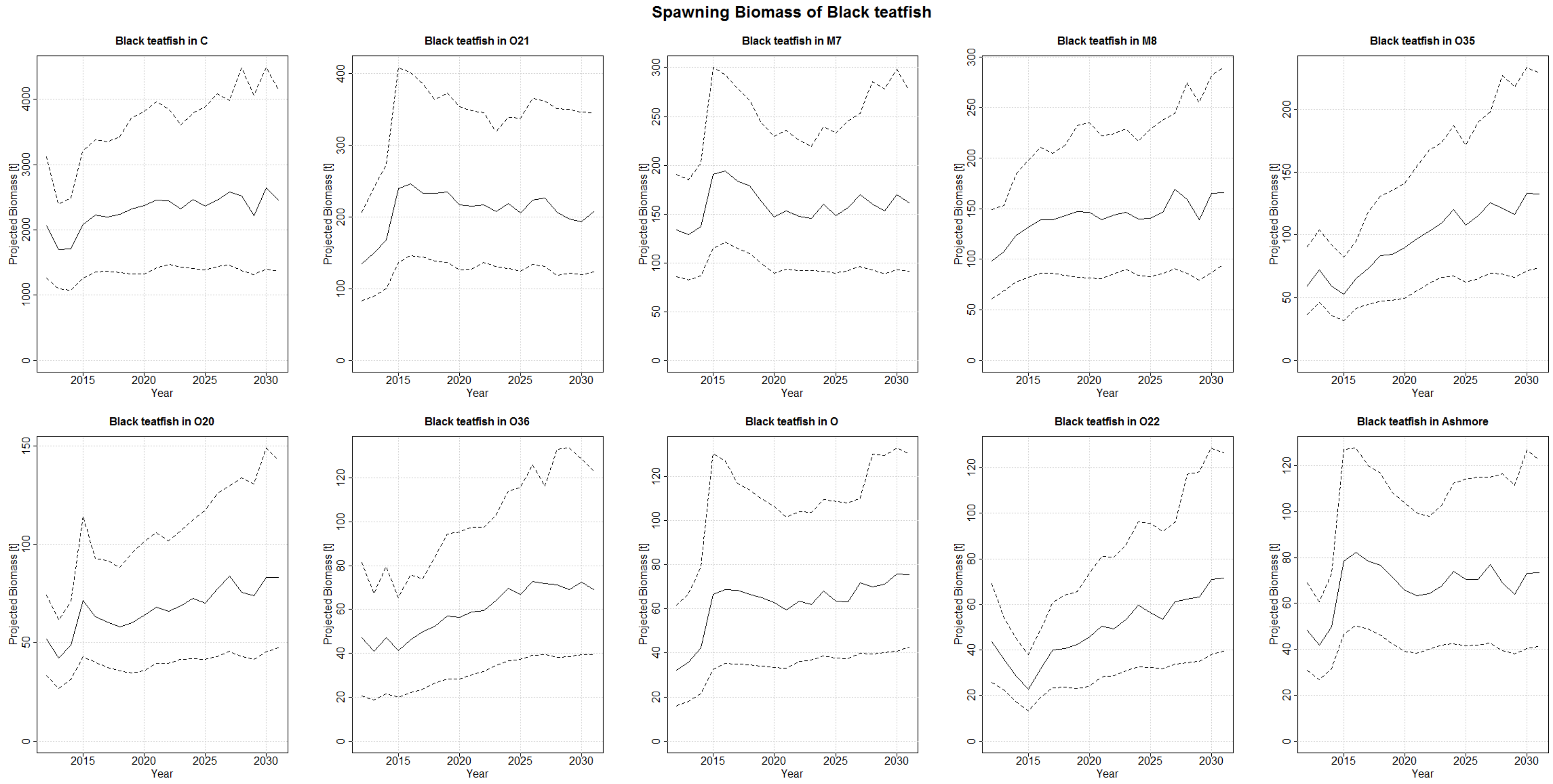


Figure 35. Projected spawning biomass (t) trajectories from 2012 to 2031 for Black Teatfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume zero future fishing.

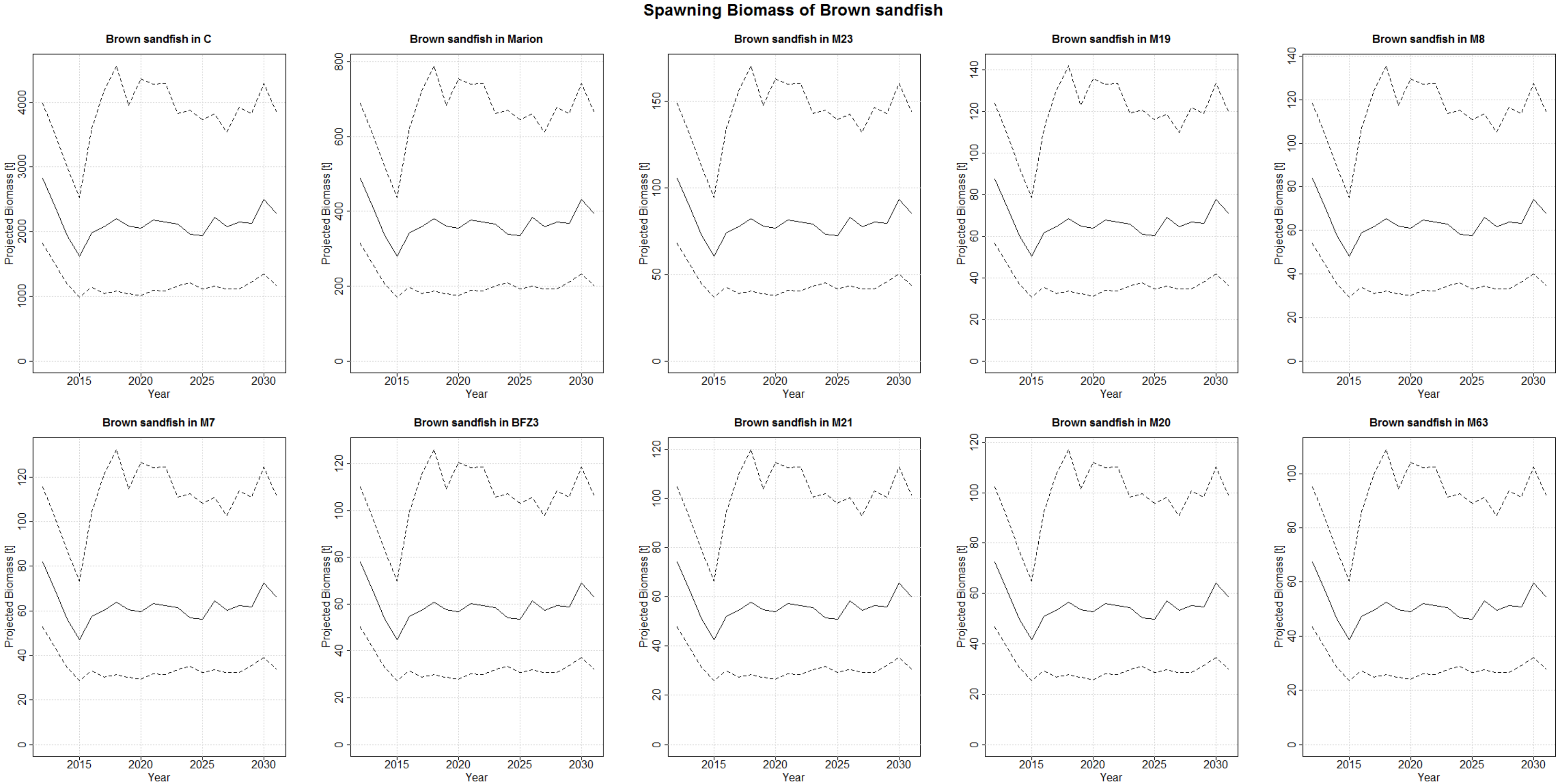


Figure 36. Projected spawning biomass (t) trajectories from 2012 to 2031 for Brown Sandfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume zero future fishing.

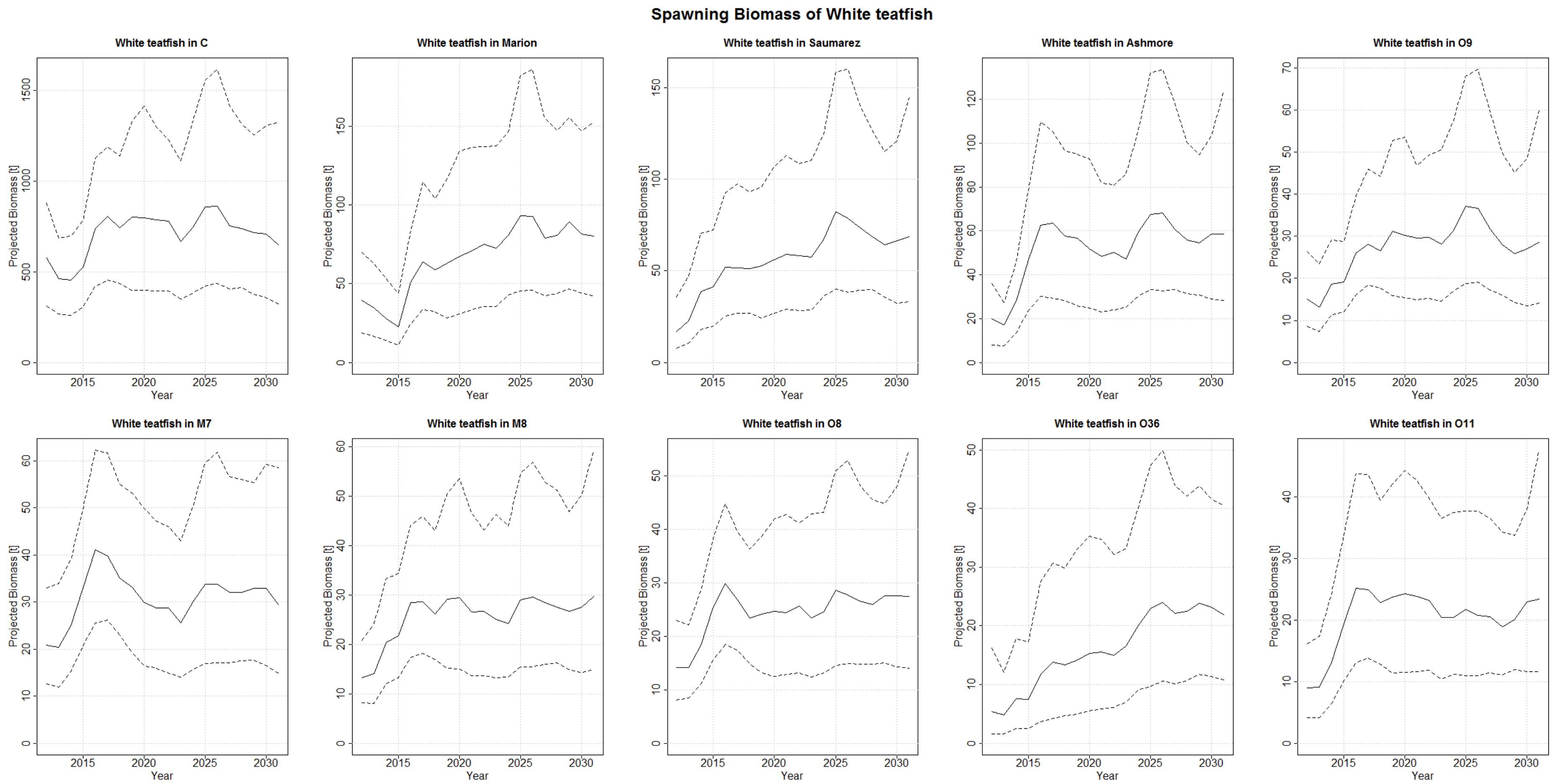


Figure 37. Projected spawning biomass (t) trajectories from 2012 to 2031 for White Teatfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume zero future fishing.

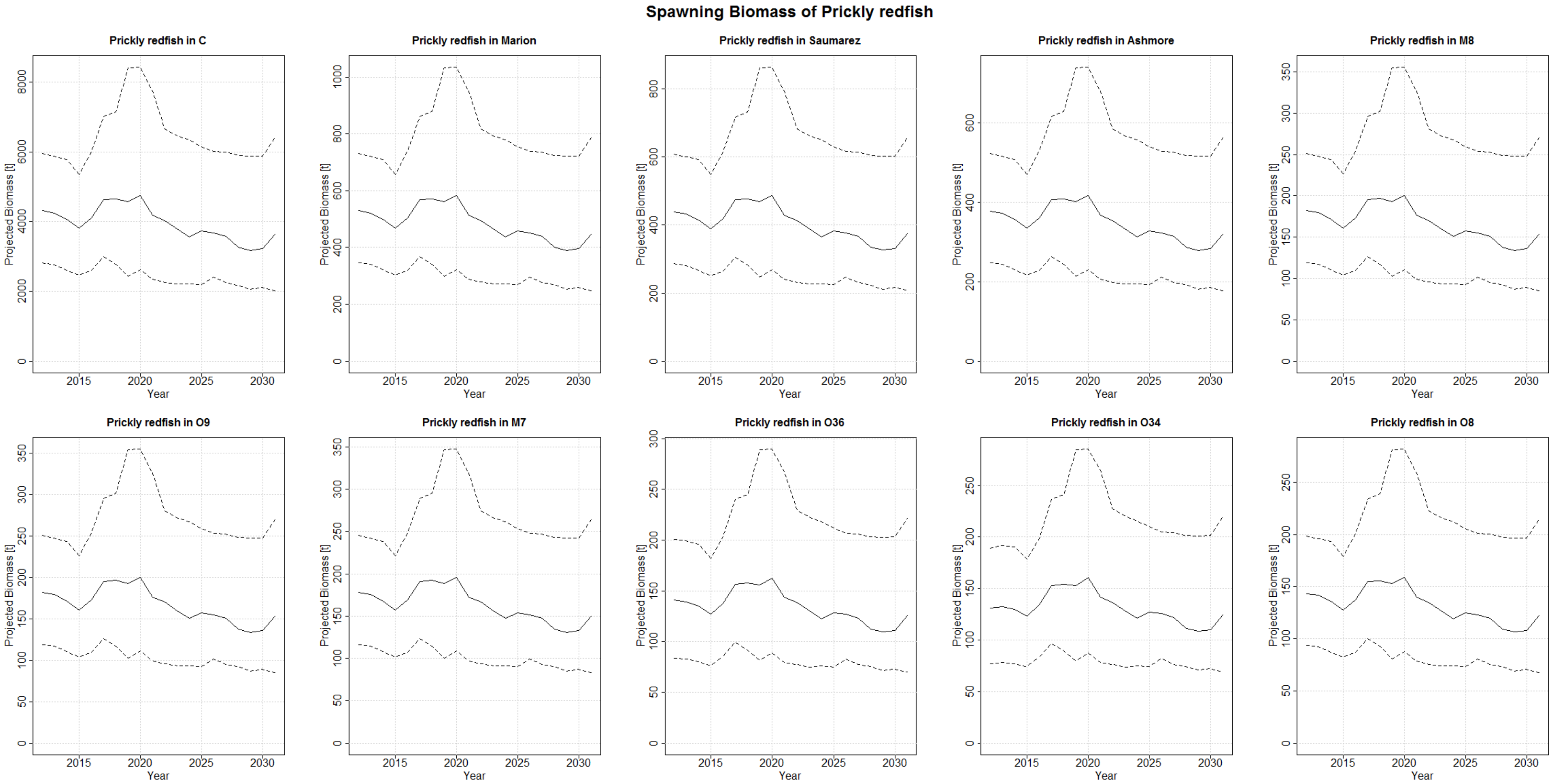


Figure 38. Projected spawning biomass (t) trajectories from 2012 to 2031 for Prickly Redfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume zero future fishing.

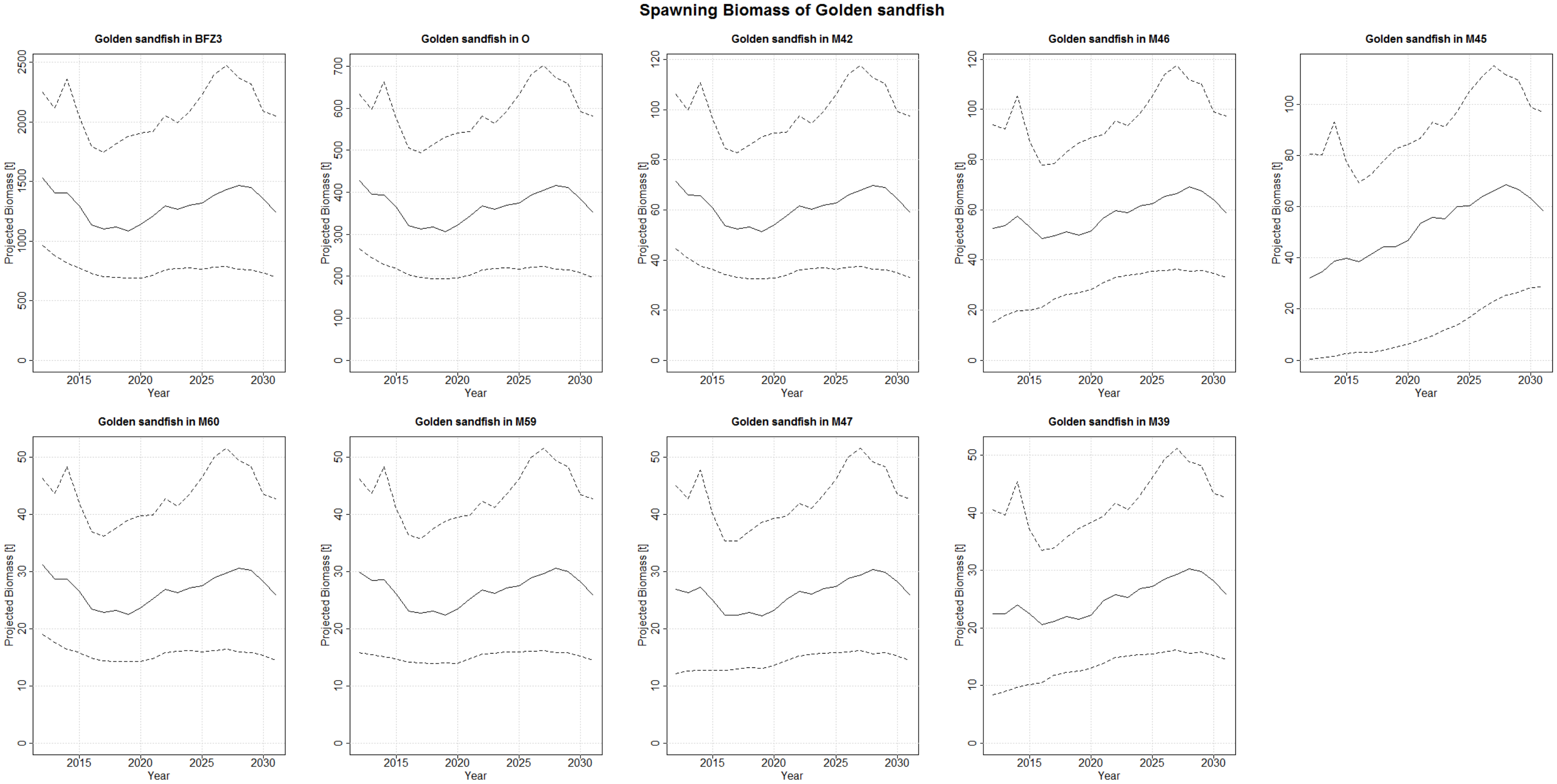


Figure 39. Projected spawning biomass (t) trajectories from 2012 to 2031 for golden Sandfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume zero future fishing.

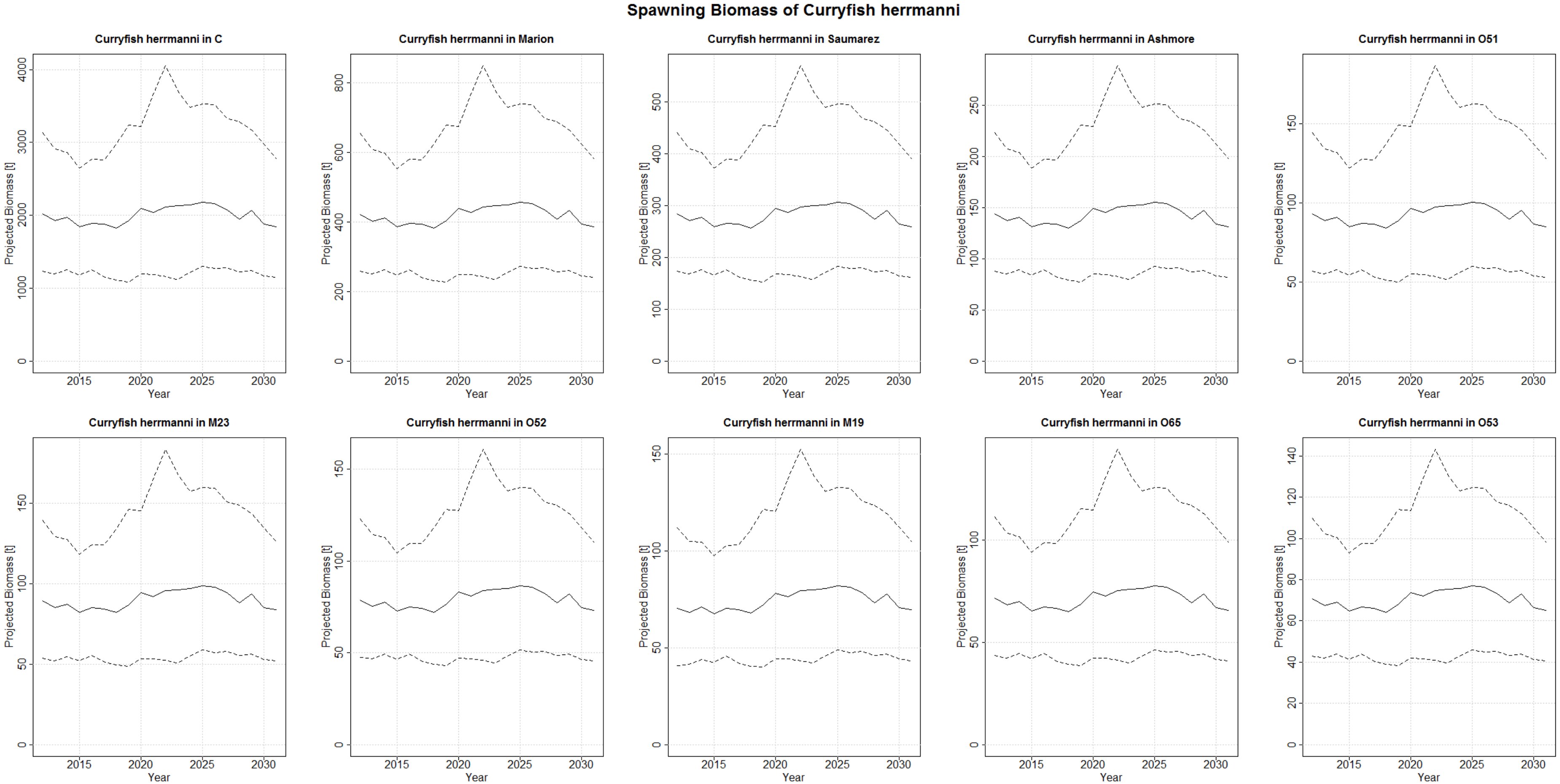


Figure 40. Projected spawning biomass (t) trajectories from 2012 to 2031 for Curryfish Herrmanni in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume zero future fishing.

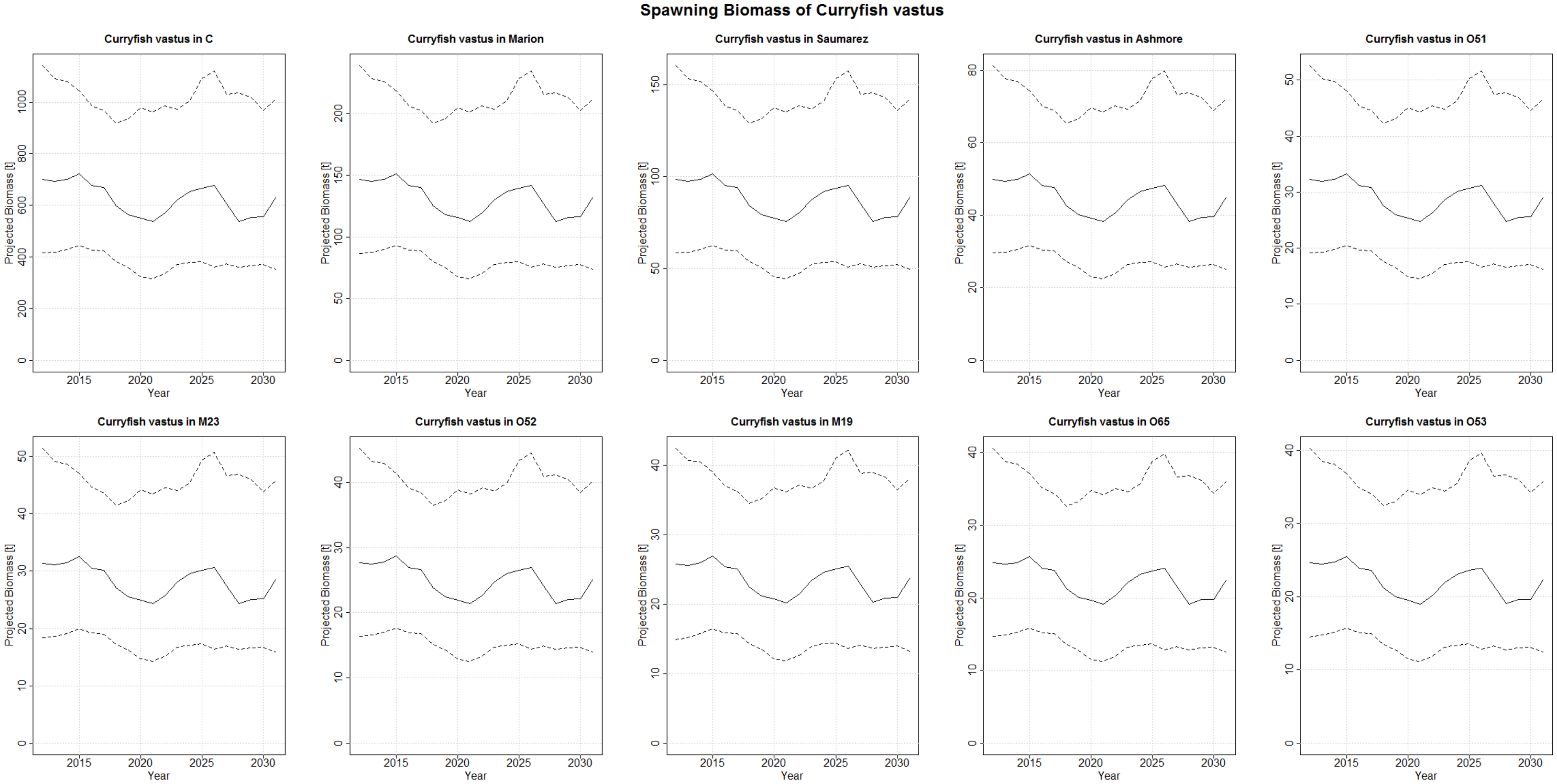


Figure 41. Projected spawning biomass (t) trajectories from 2012 to 2031 for Curryfish Vastus in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume zero future fishing.

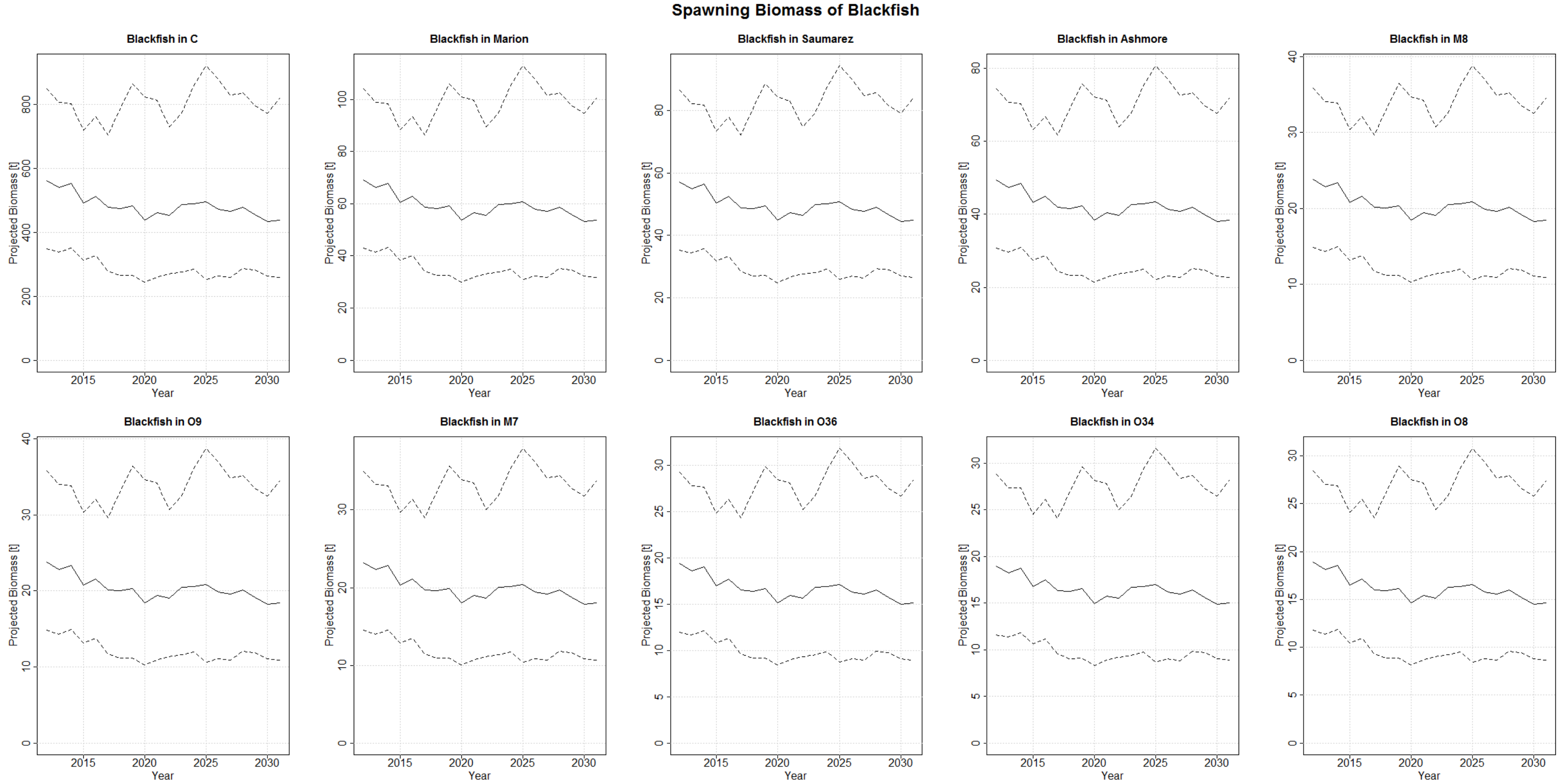


Figure 42. Projected spawning biomass (t) trajectories from 2012 to 2031 for blackfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume zero future fishing.

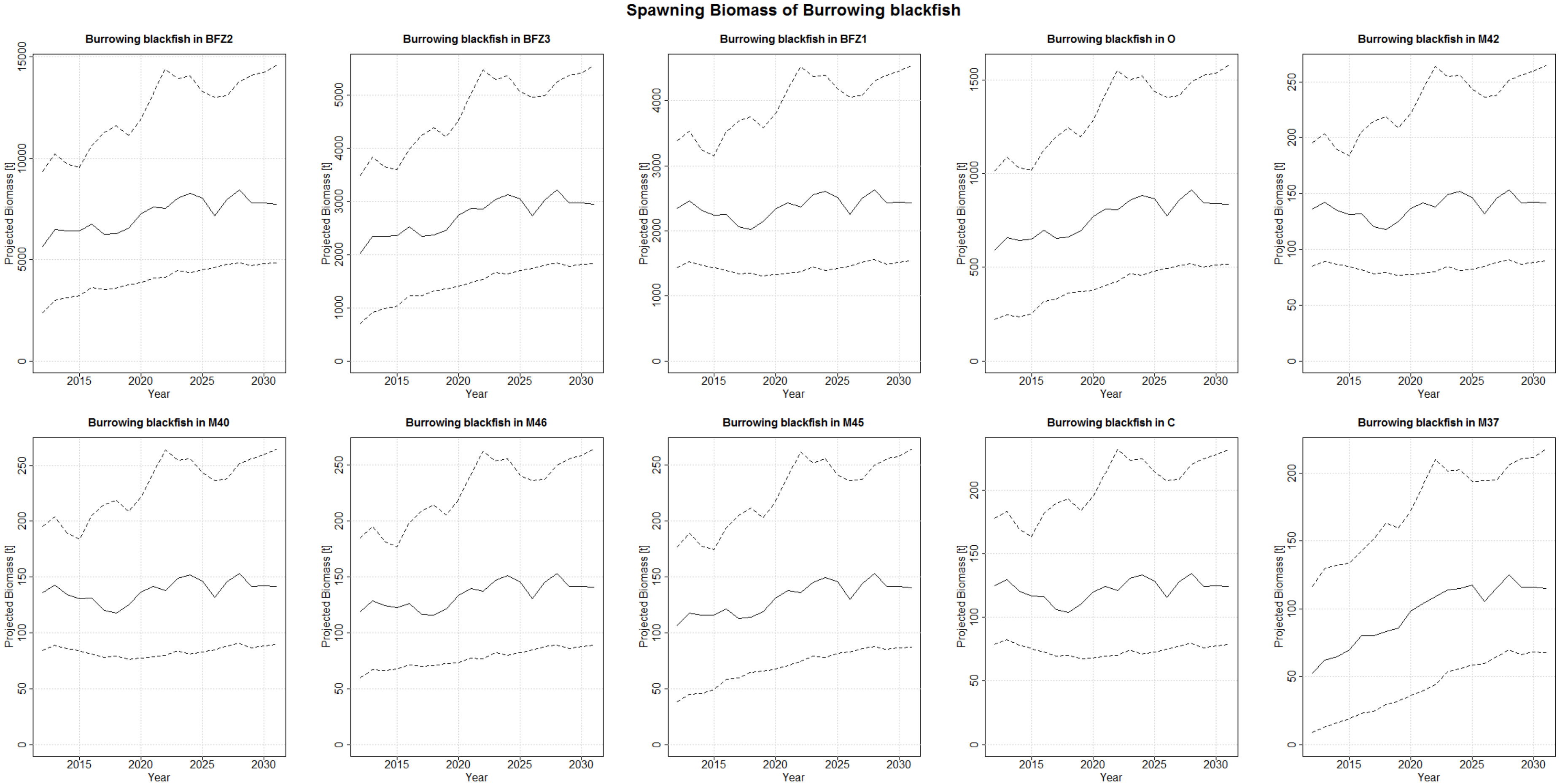


Figure 43. Projected spawning biomass (t) trajectories from 2012 to 2031 for Burrowing Blackfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume zero future fishing.

Appendix H Projected spawning biomass – RZS and current catch, 2012 - 2031

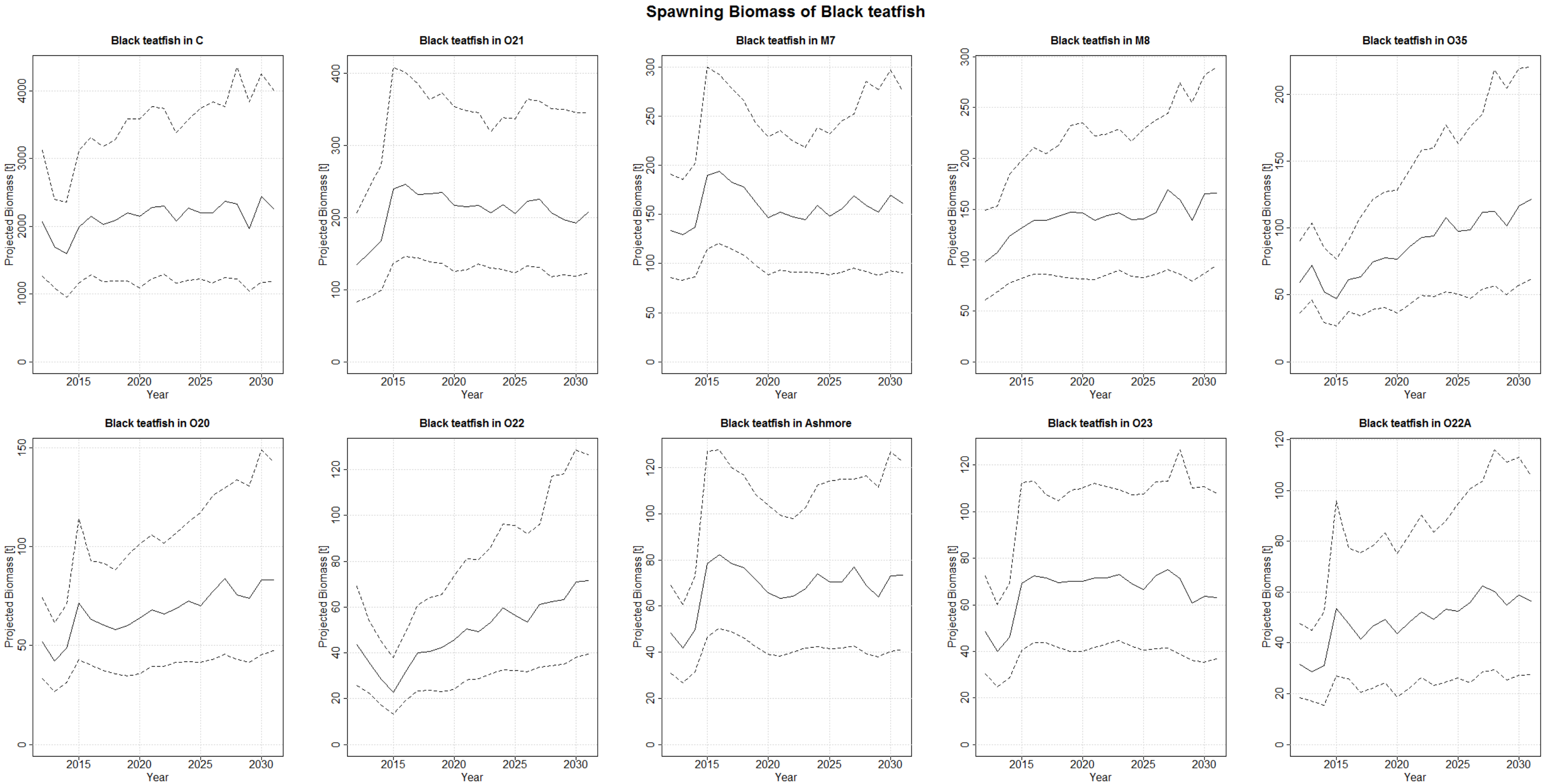


Figure 44. Projected spawning biomass (t) trajectories from 2012 to 2031 for Black Teatfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels. Note the Black Teatfish TAC is currently zero, but for illustrative purposes the projections assume a future annual catch of 58t.

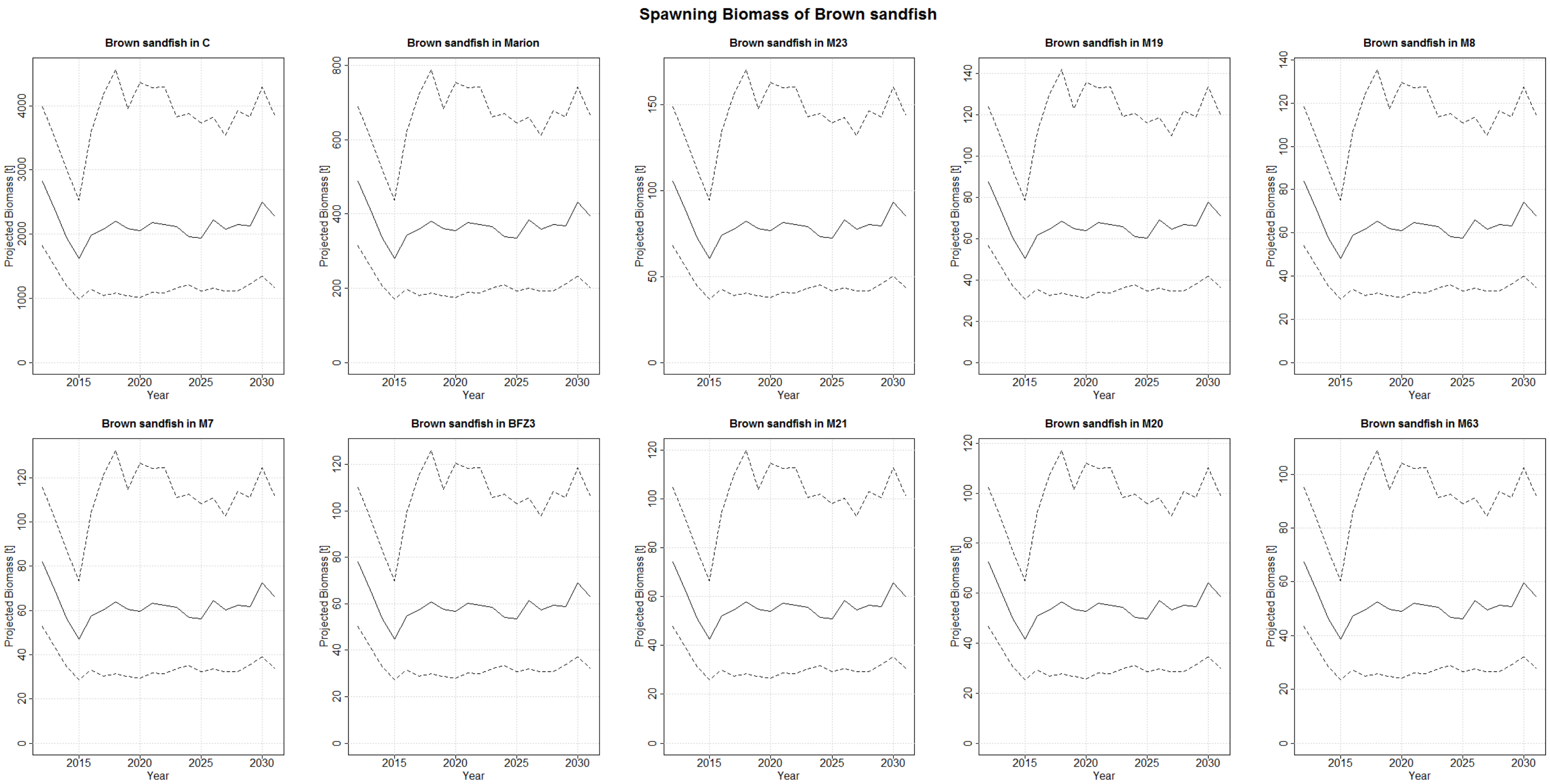


Figure 45. Projected spawning biomass (t) trajectories from 2012 to 2031 for Brown Sandfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

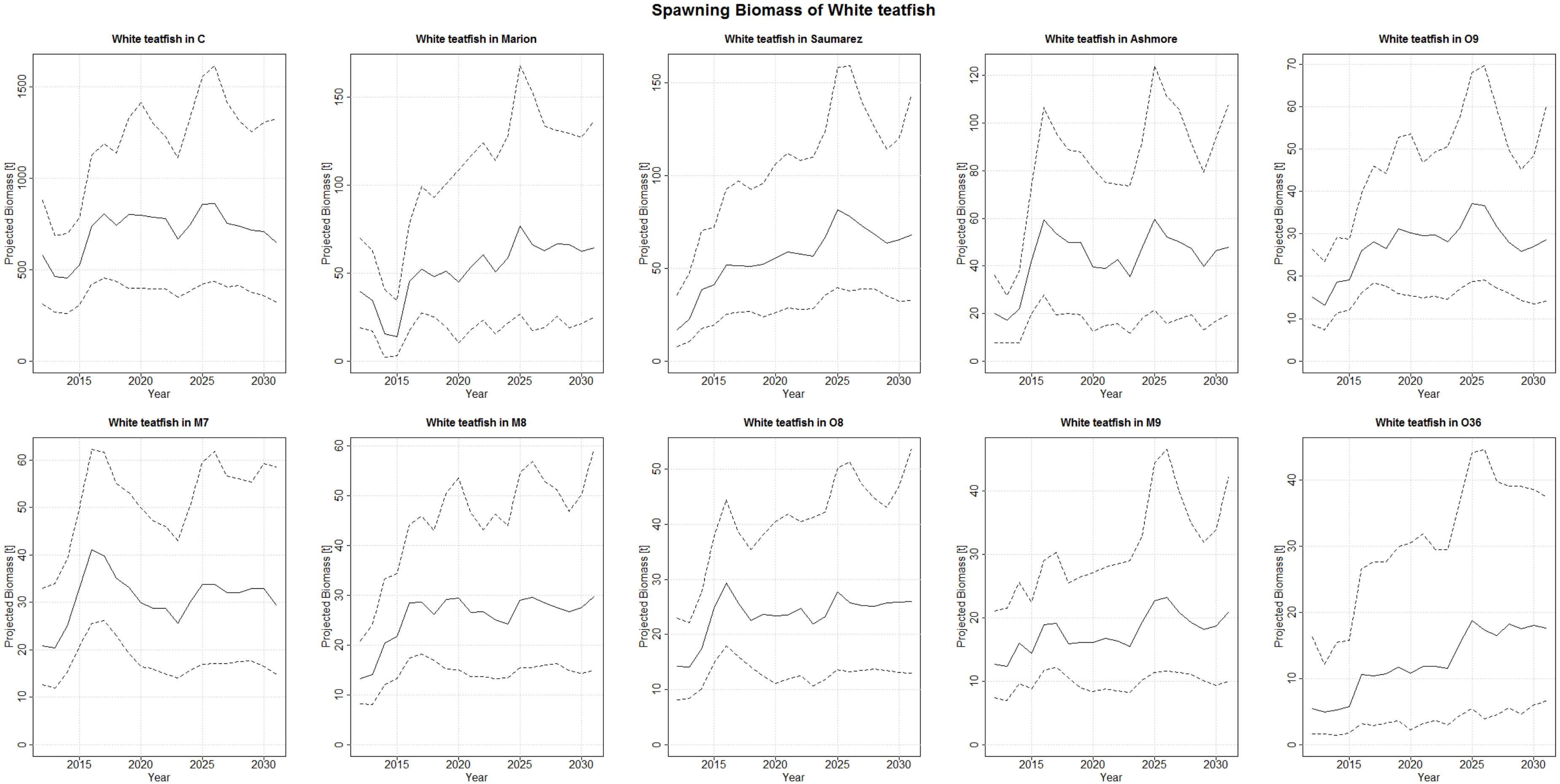


Figure 46. Projected spawning biomass (t) trajectories from 2012 to 2031 for White Teatfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

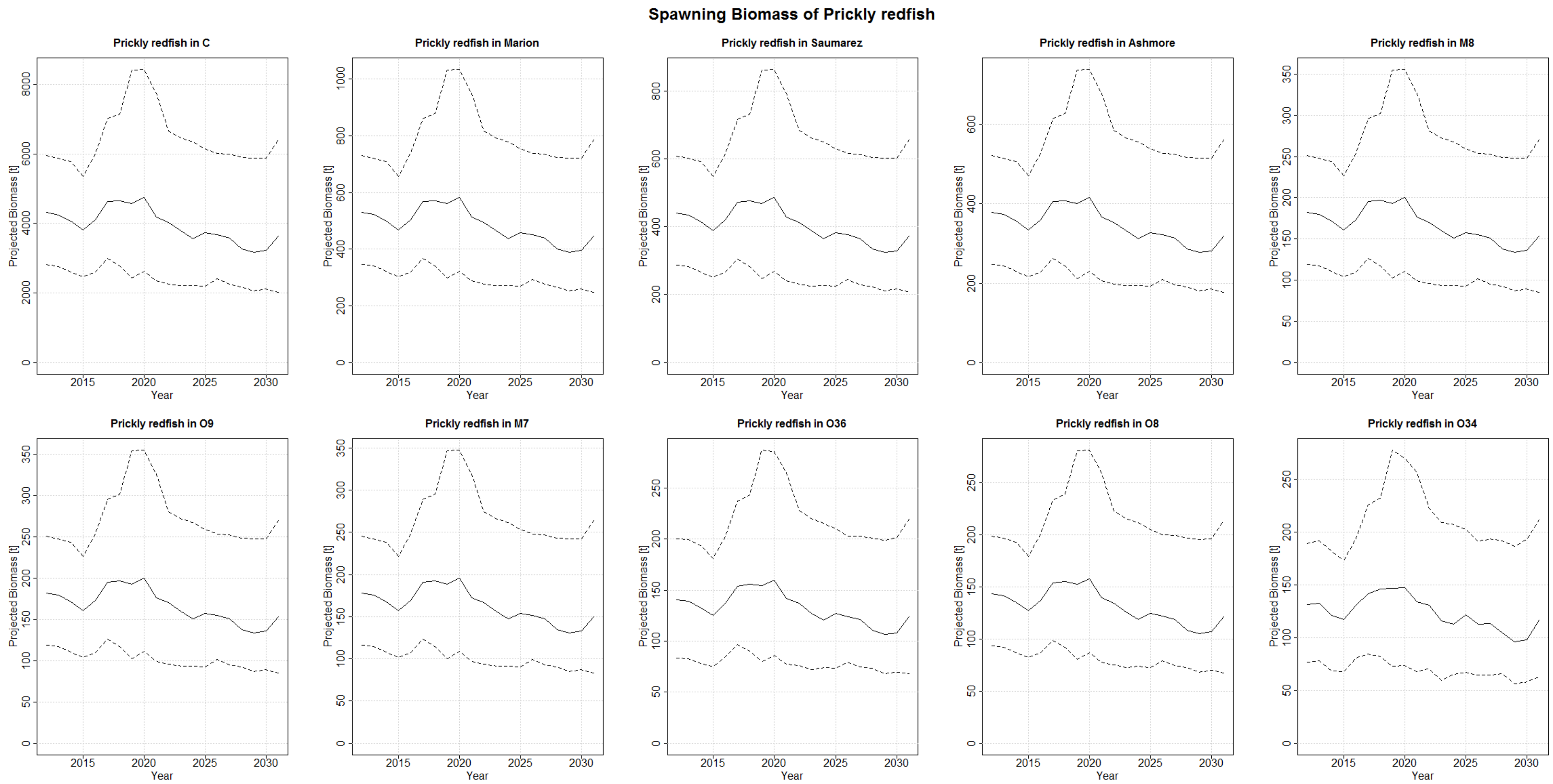


Figure 47. Projected spawning biomass (t) trajectories from 2012 to 2031 for Prickly Redfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

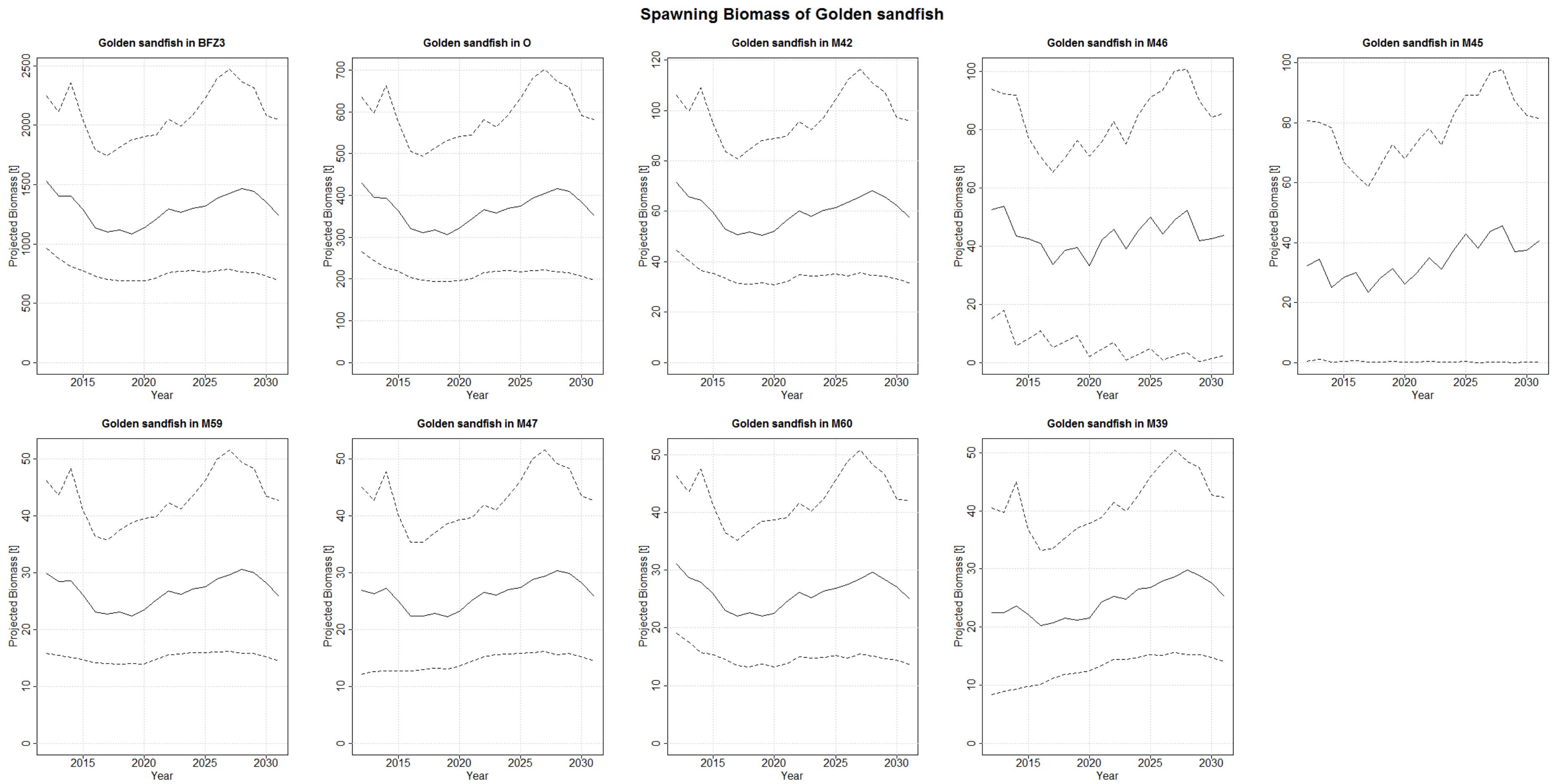


Figure 48. Projected spawning biomass (t) trajectories from 2012 to 2031 for golden Sandfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

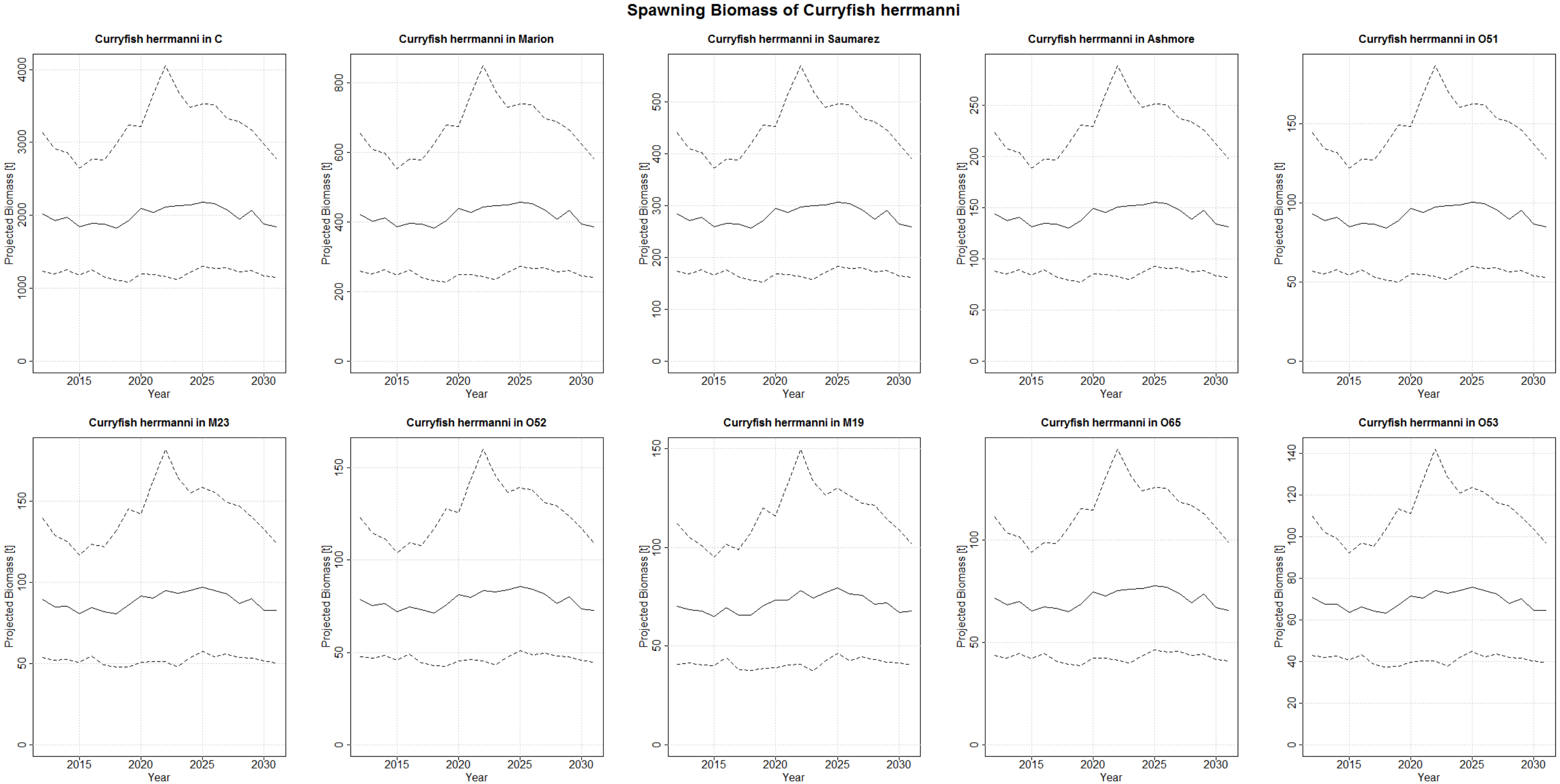


Figure 49. Projected spawning biomass (t) trajectories from 2012 to 2031 for Curryfish Herrmanni in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

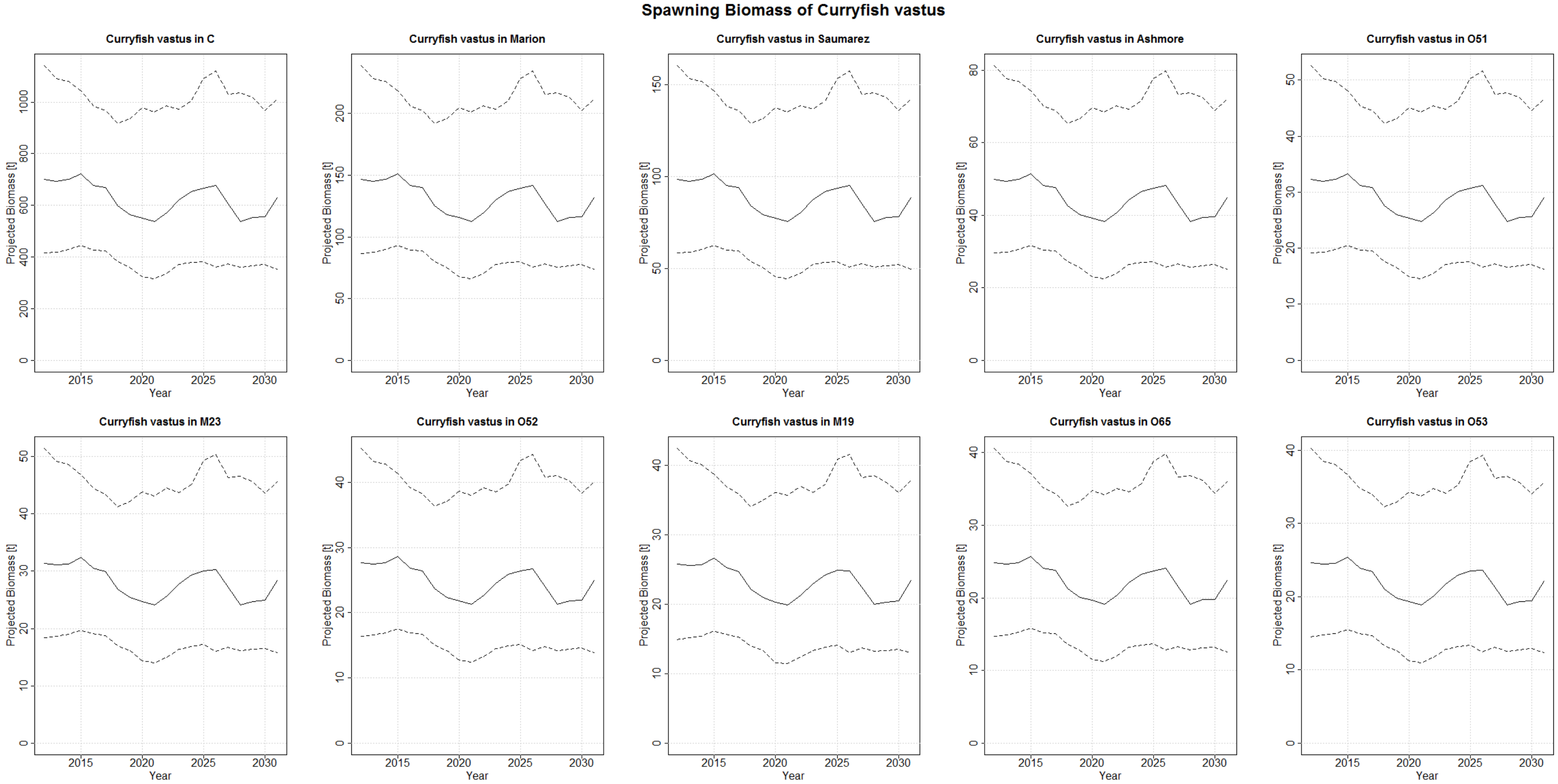


Figure 50. Projected spawning biomass (t) trajectories from 2012 to 2031 for Curryfish Vastus in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

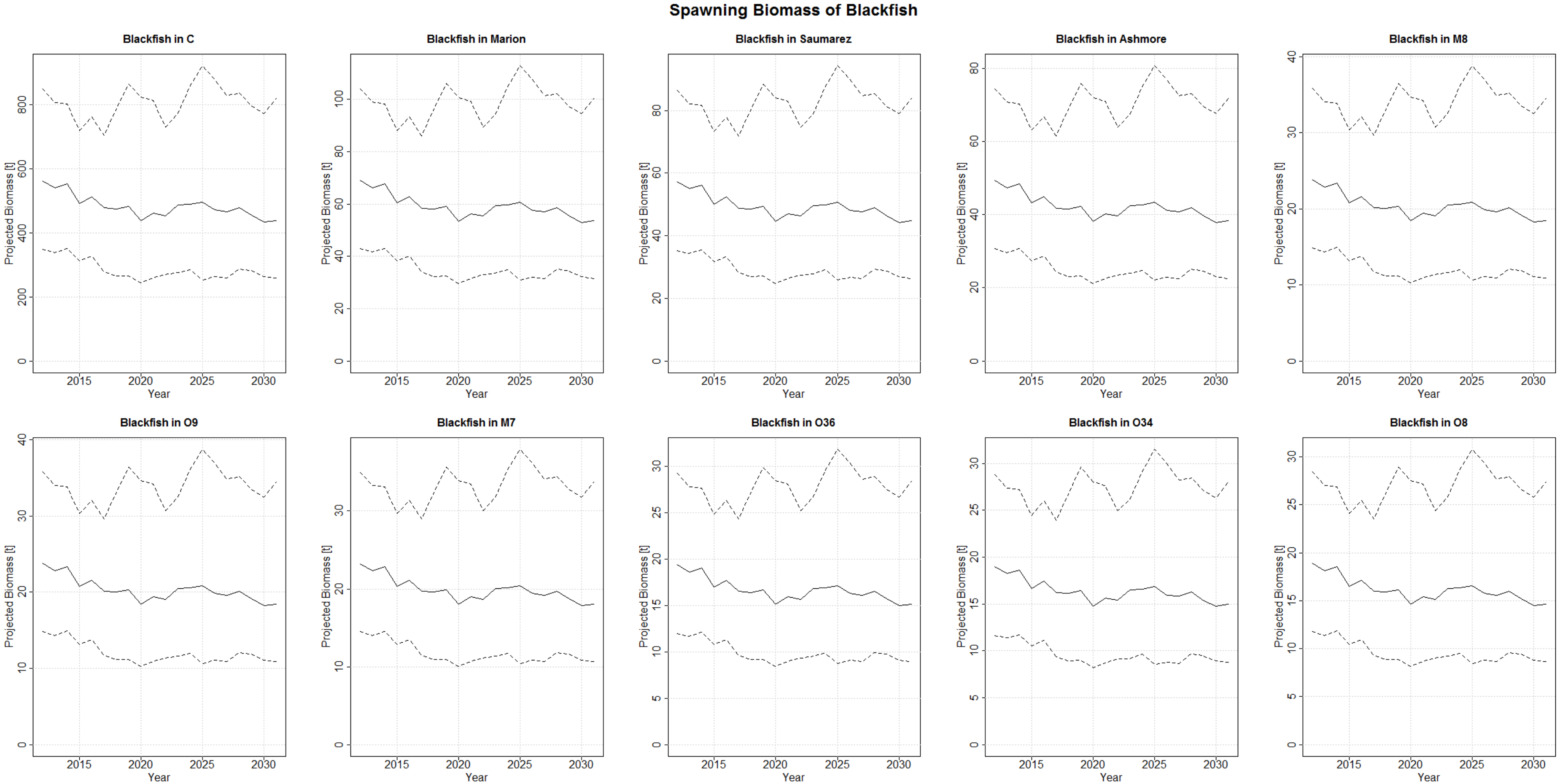


Figure 51. Projected spawning biomass (t) trajectories from 2012 to 2031 for blackfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

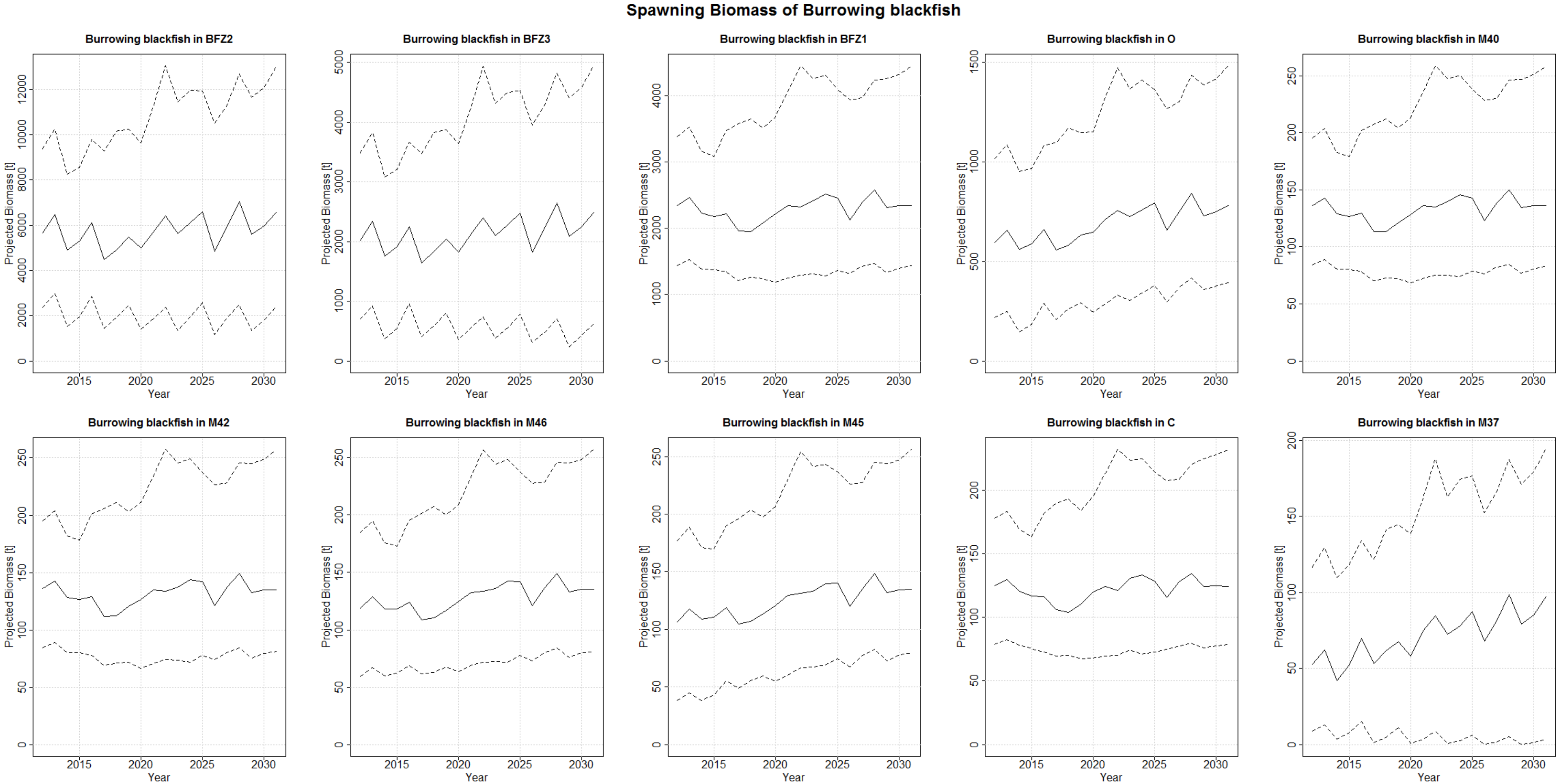


Figure 52. Projected spawning biomass (t) trajectories from 2012 to 2031 for Burrowing Blackfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

Appendix I Projected spawning biomass depletion with the revised base case RZS relative to no fishing, 2012 – 2031 (zones with highest abundance)

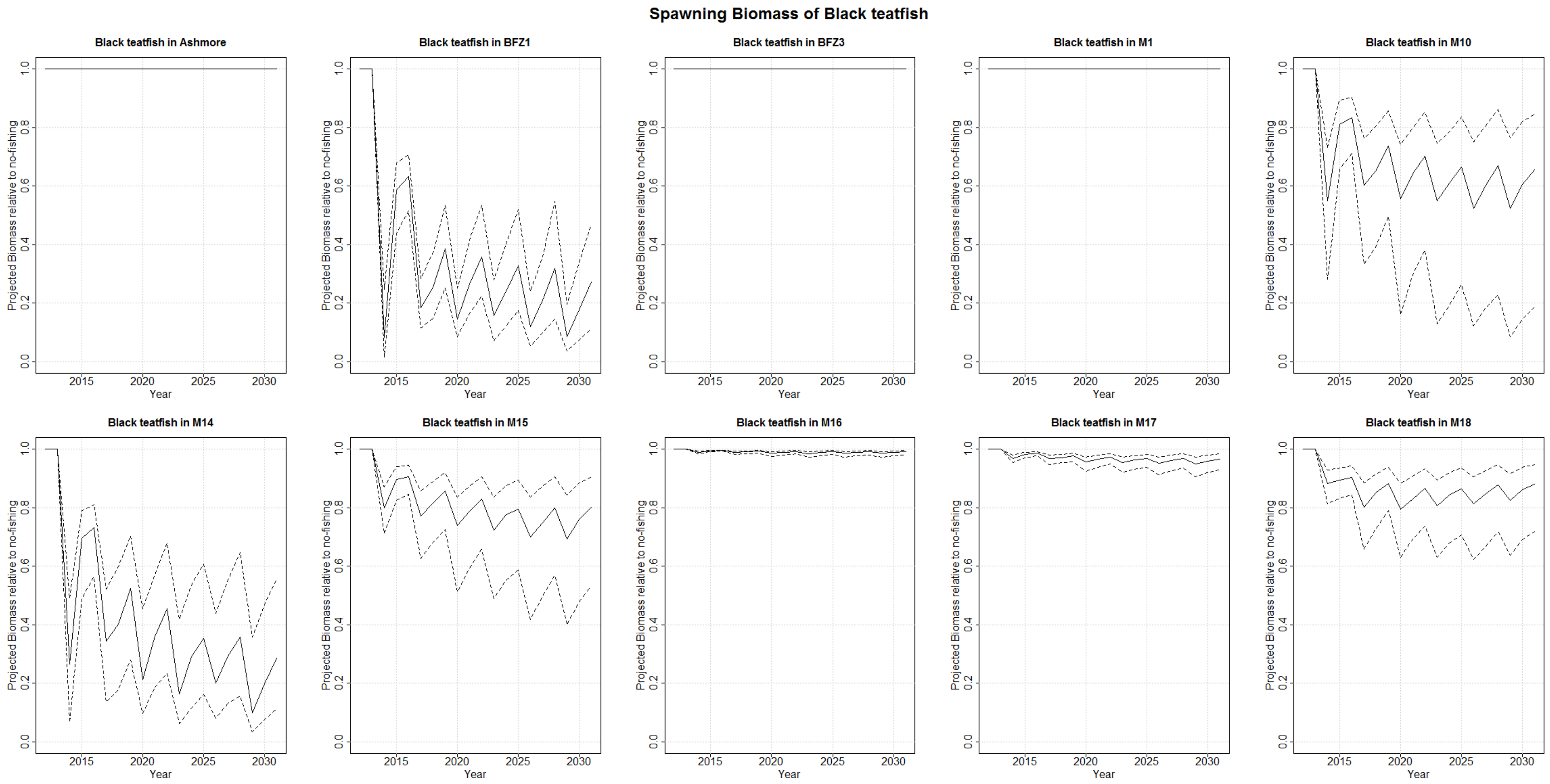


Figure 53. Revised base case RZS projected spawning biomass relative to the comparable no-fishing scenario from 2012 to 2031 for Black Teatfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels. Note the Black Teatfish TAC is currently zero, but for illustrative purposes the projections assume a future annual catch of 58t.

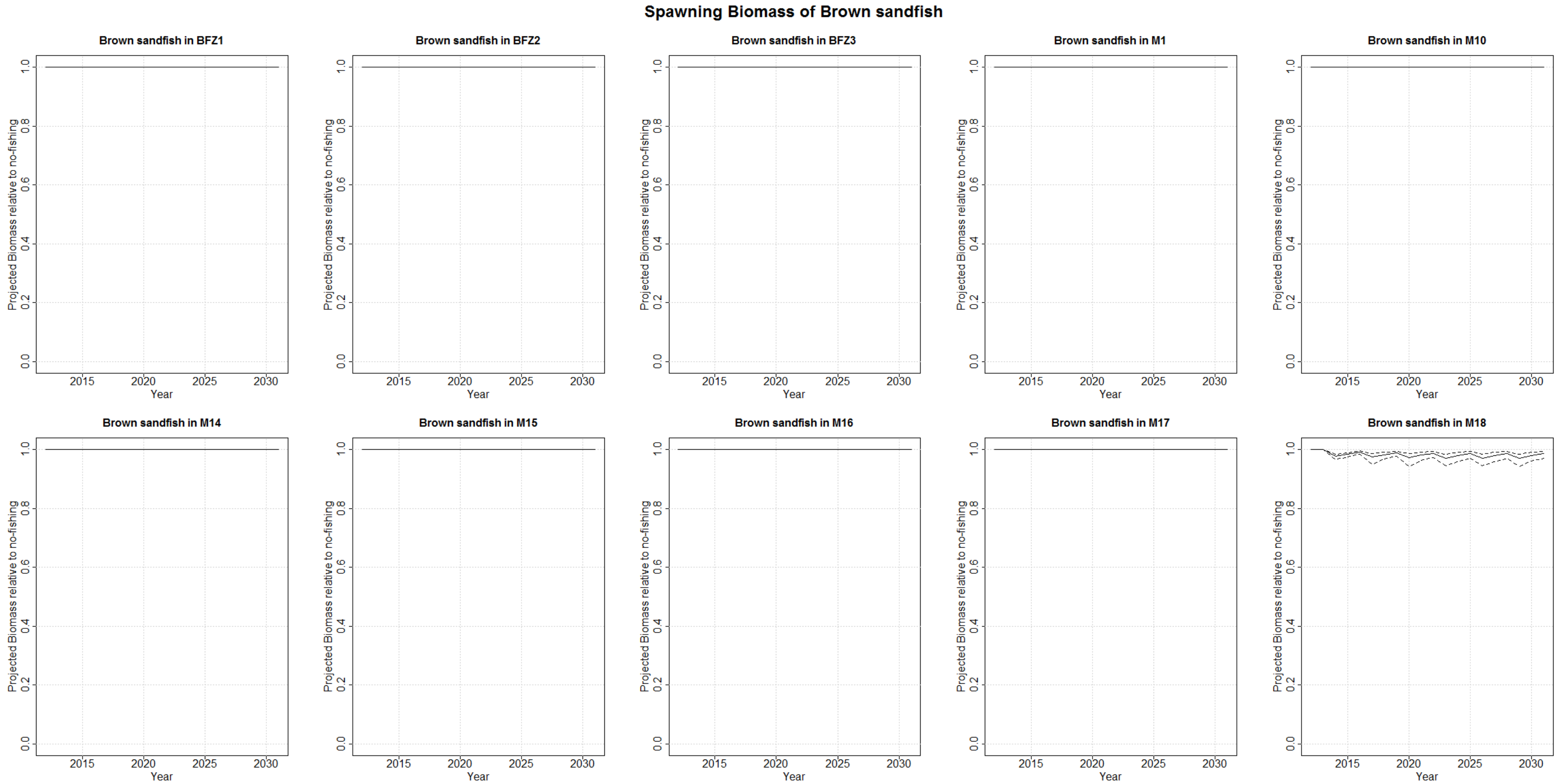


Figure 54. Revised base case RZS projected spawning biomass relative to the comparable no-fishing scenario 2012 to 2031 for Brown Sandfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

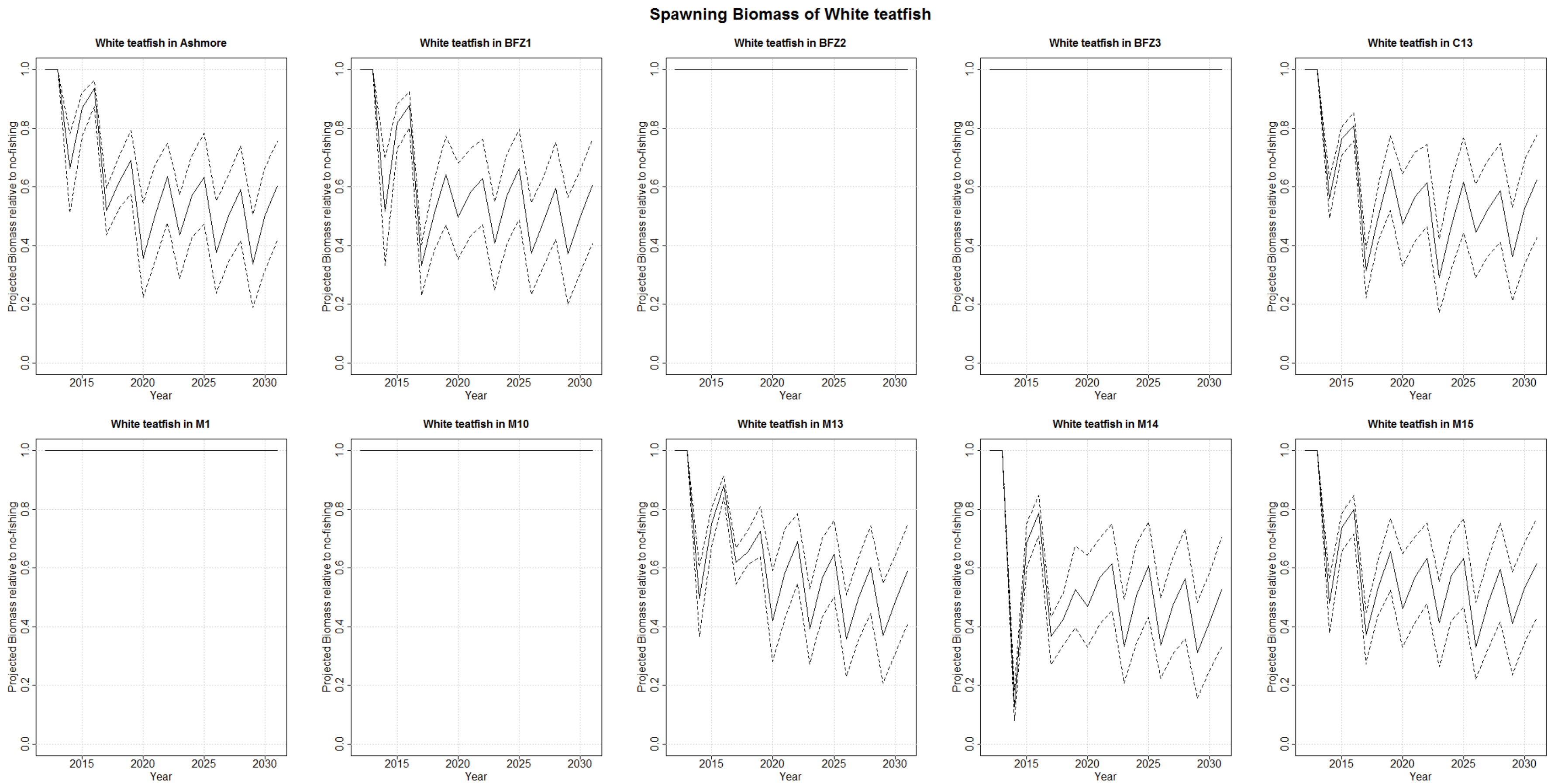


Figure 55. Revised base case RZS projected spawning biomass relative to the comparable no-fishing scenario 2012 to 2031 for White Teatfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

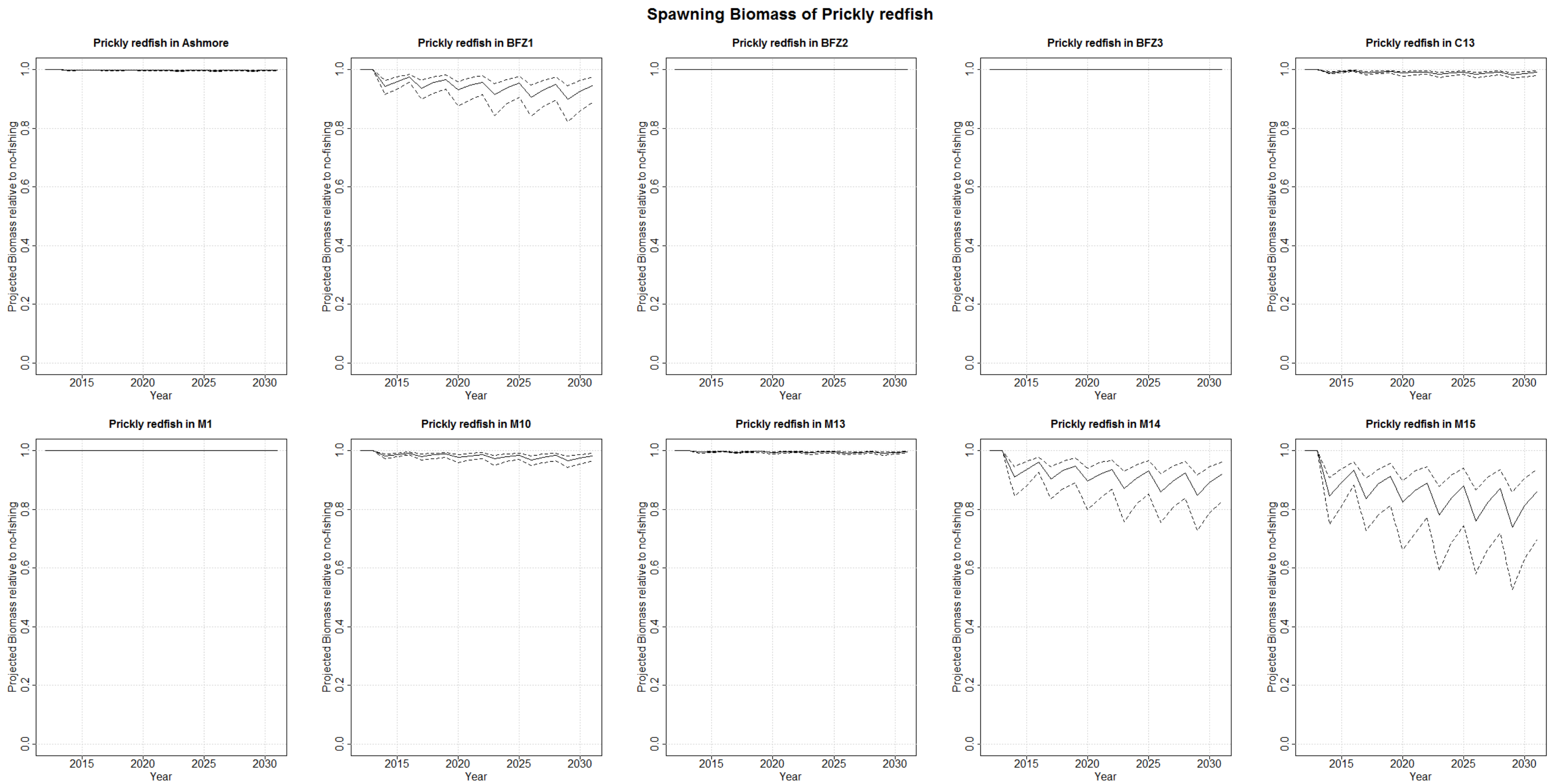


Figure 56. Revised base case RZS projected spawning biomass relative to the comparable no-fishing scenario 2012 to 2031 for Prickly Redfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

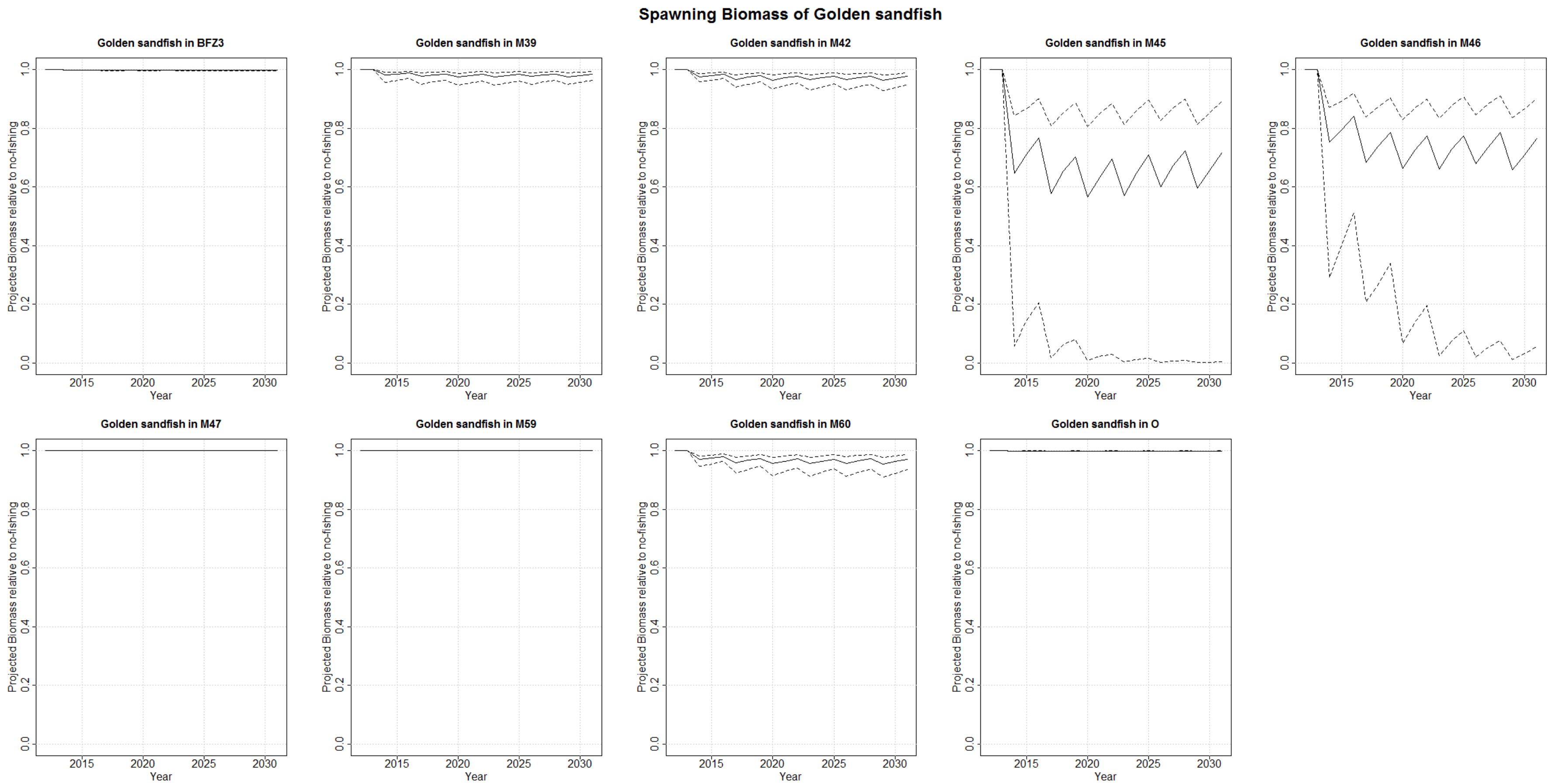


Figure 57. Revised base case RZS projected spawning biomass relative to the comparable no-fishing scenario 2012 to 2031 for golden Sandfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

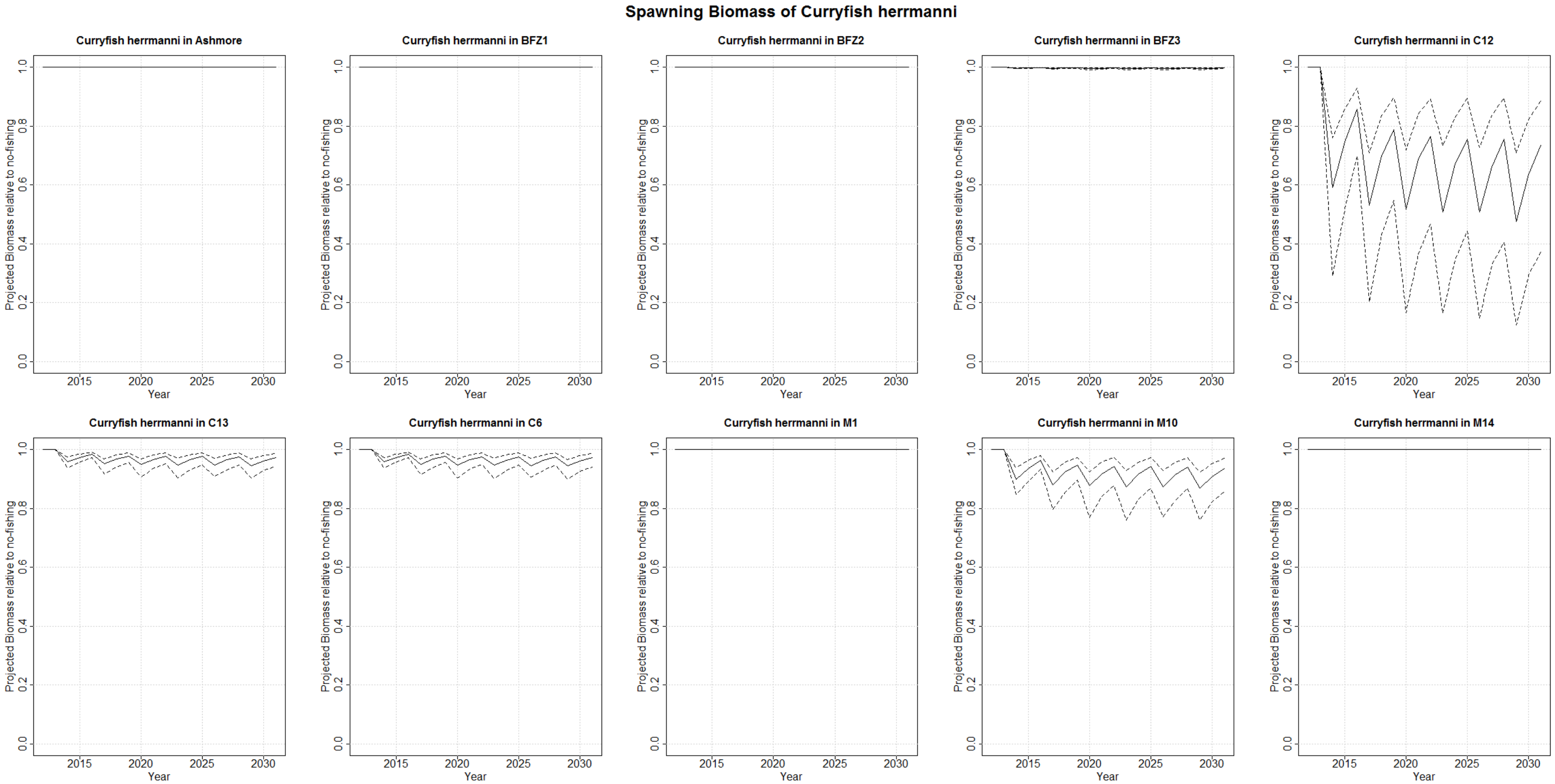


Figure 58. Revised base case RZS projected spawning biomass relative to the comparable no-fishing scenario 2012 to 2031 for Curryfish Herrmanni in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

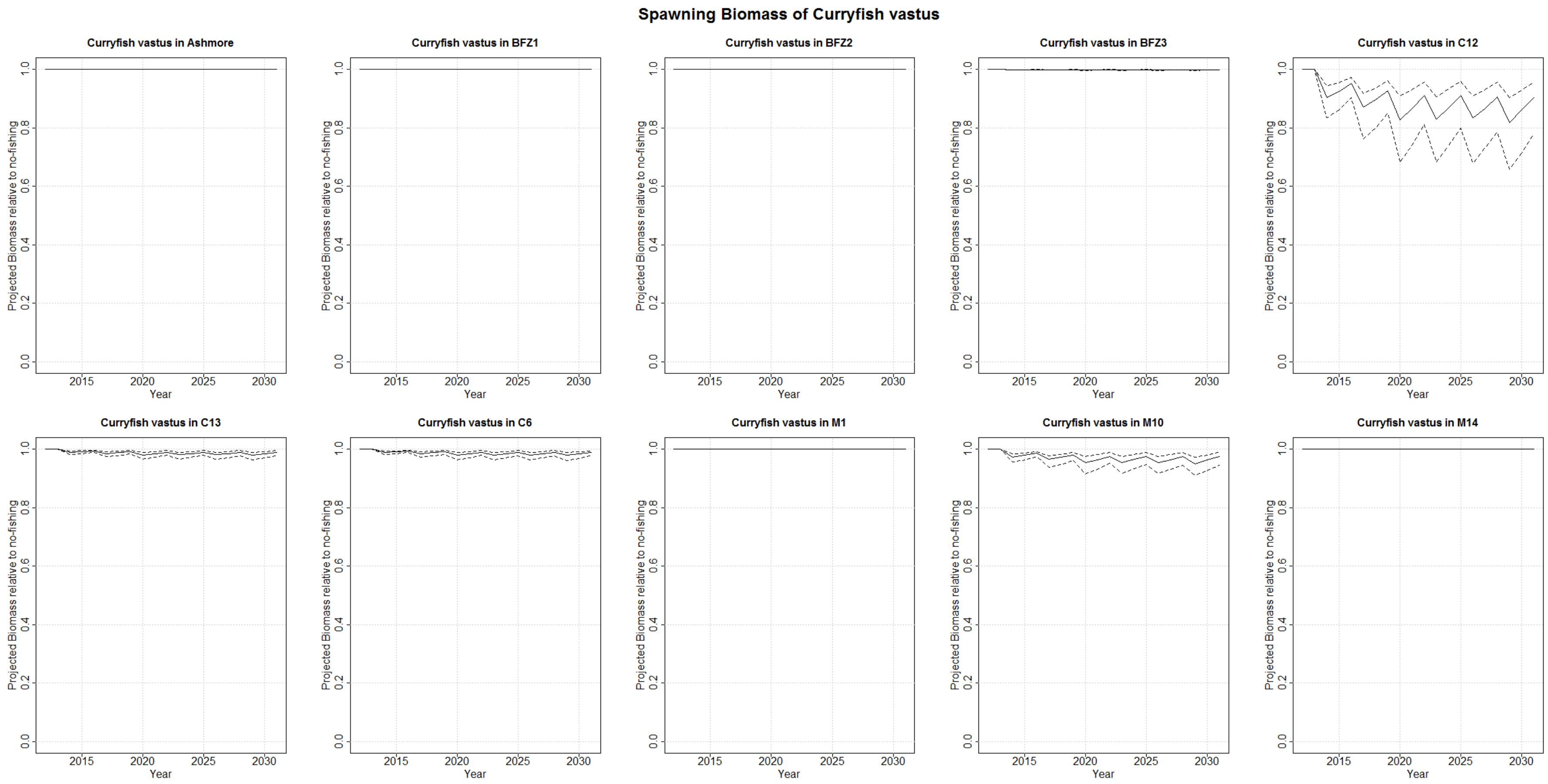


Figure 59. Revised base case RZS projected spawning biomass relative to the comparable no-fishing scenario 2012 to 2031 for Curryfish Vastus in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

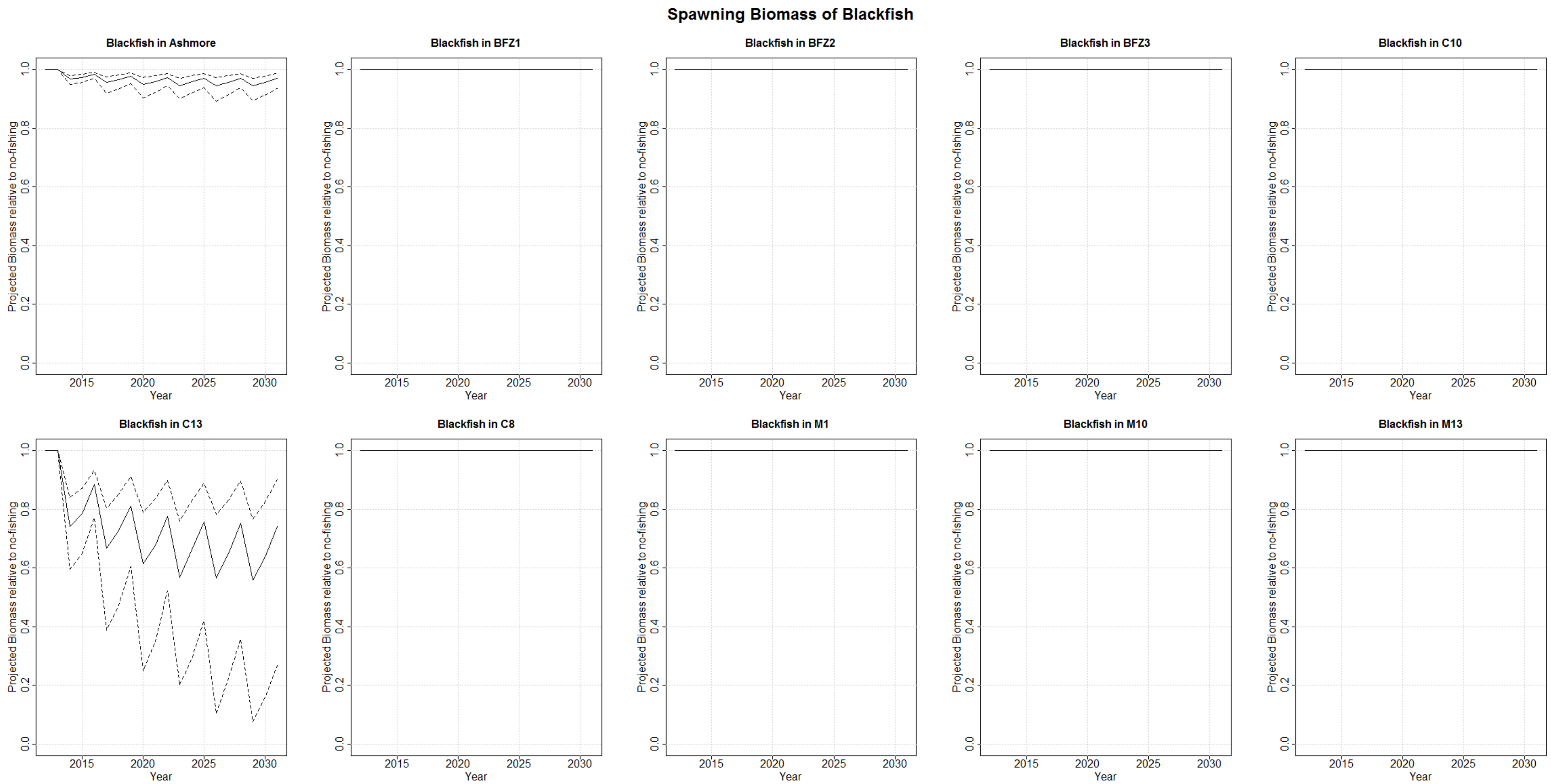


Figure 60. Revised base case RZS projected spawning biomass relative to the comparable no-fishing scenario 2012 to 2031 for blackfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

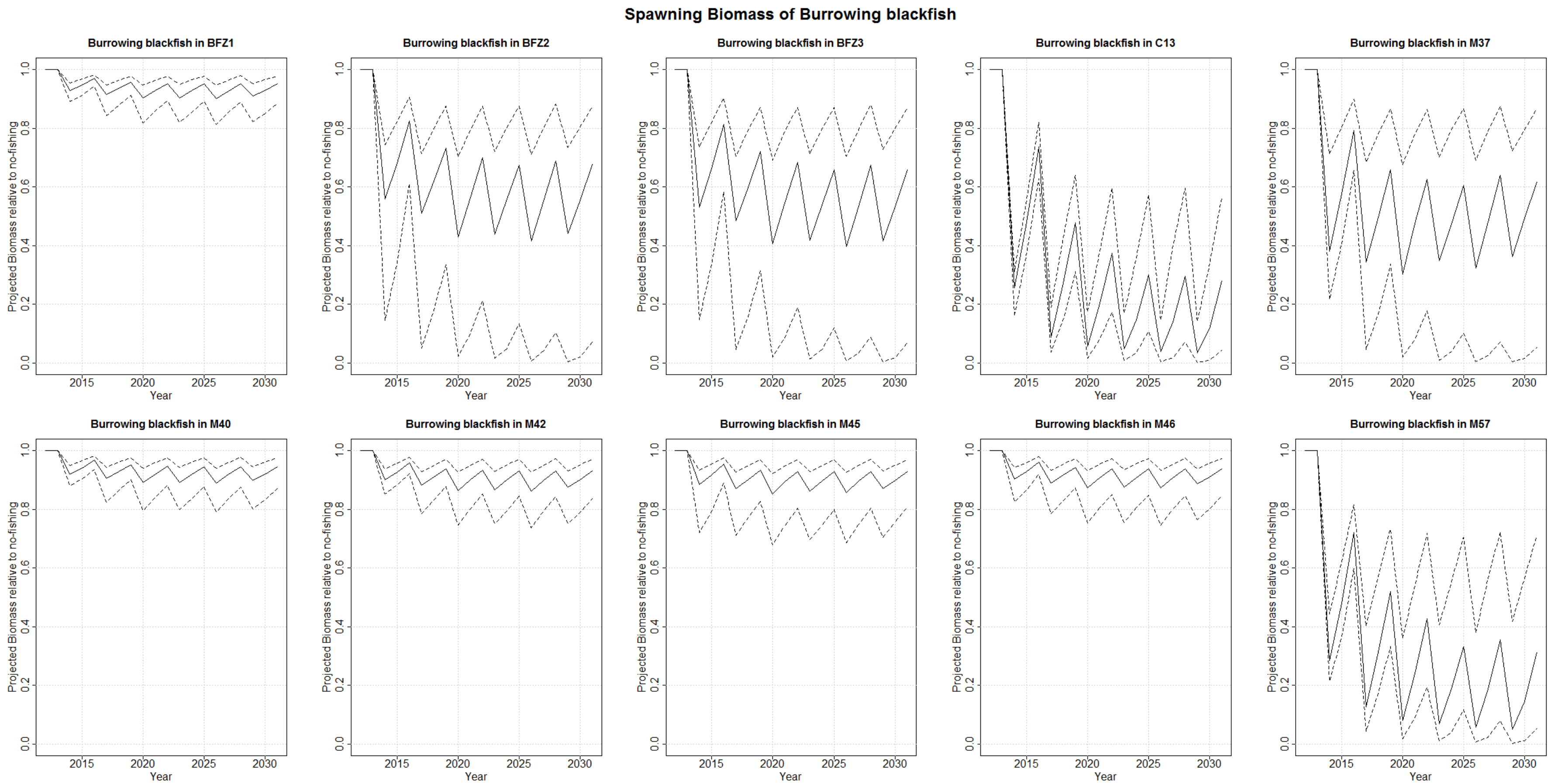


Figure 61. Revised base case RZS projected spawning biomass relative to the comparable no-fishing scenario 2012 to 2031 for Burrowing Blackfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

Appendix J Projected spawning biomass depletion with the revised base case RZS relative to no fishing, 2012 – 2031 (zones with highest fishing mortality)

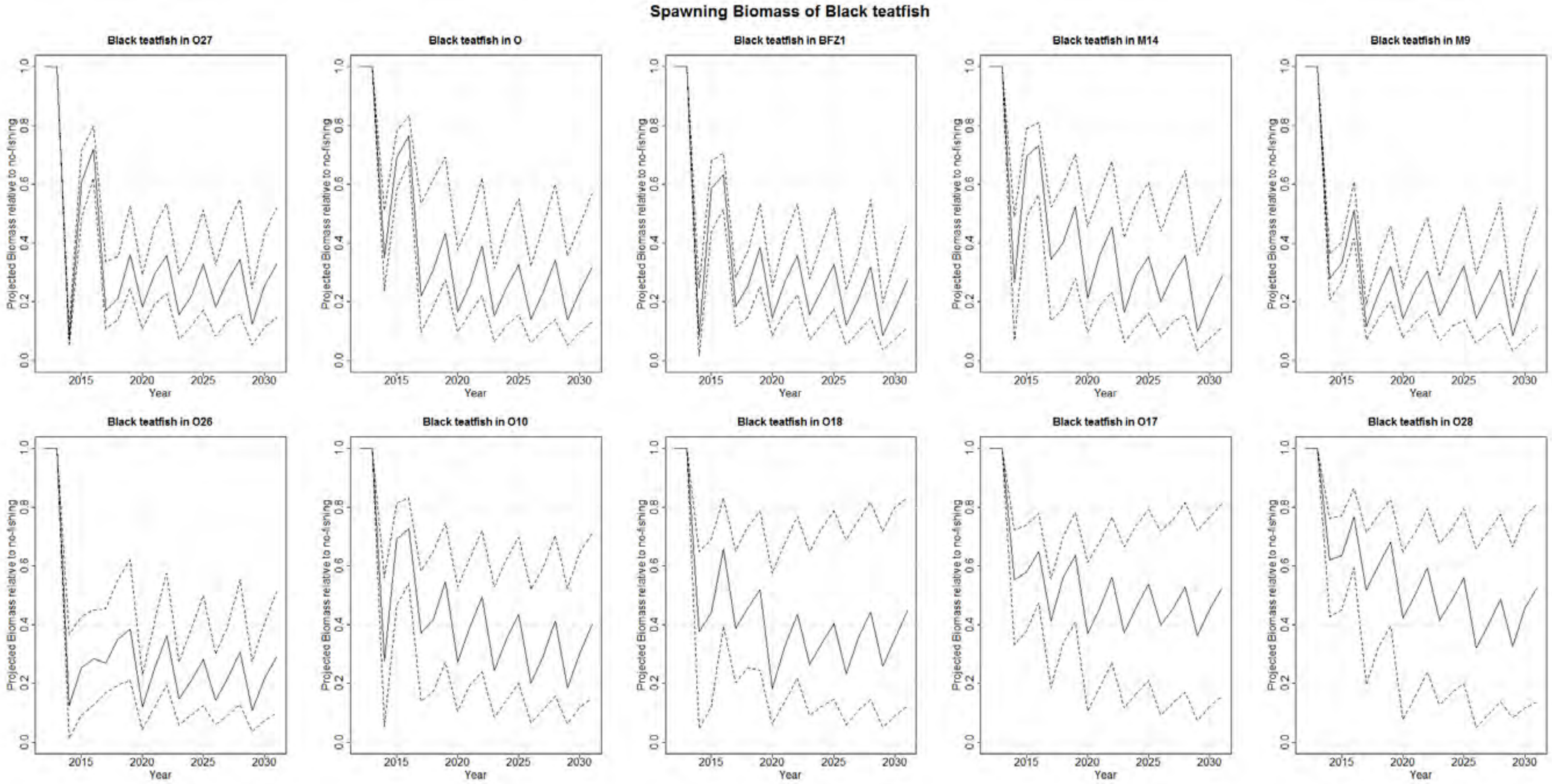


Figure 62. Revised base case RZS projected spawning biomass relative to the comparable no-fishing scenario 2012 to 2031 for Black Teatfish in 10 of the 162 zones selected based on having the highest average fishing mortalities. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels. Note the Black Teatfish TAC is currently zero, but for illustrative purposes the projections assume a future annual catch of 58t.

Spawning Biomass of Brown sandfish

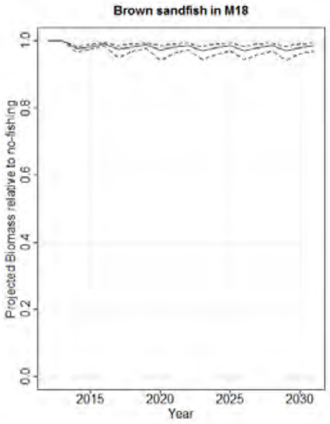


Figure 63. Revised base case RZS projected spawning biomass relative to the comparable no-fishing scenario 2012 to 2031 for Brown Sandfish in 10 of the 162 zones selected based on having the highest average fishing mortalities (fished in a single zone only for this species). The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

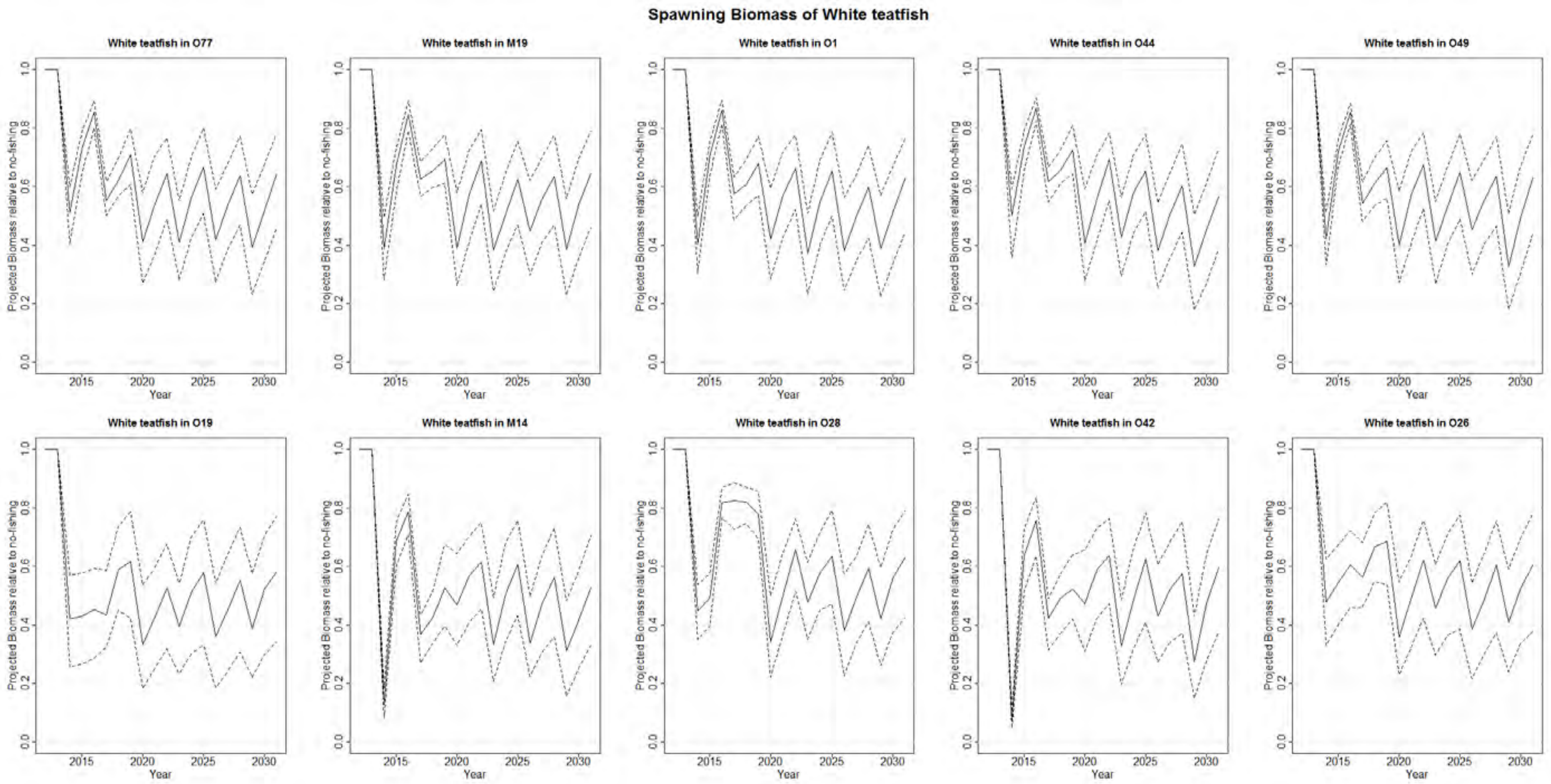


Figure 64. Revised base case RZS projected spawning biomass relative to the comparable no-fishing scenario 2012 to 2031 for White Teatfish in 10 of the 162 zones selected based on having the highest average fishing mortalities. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

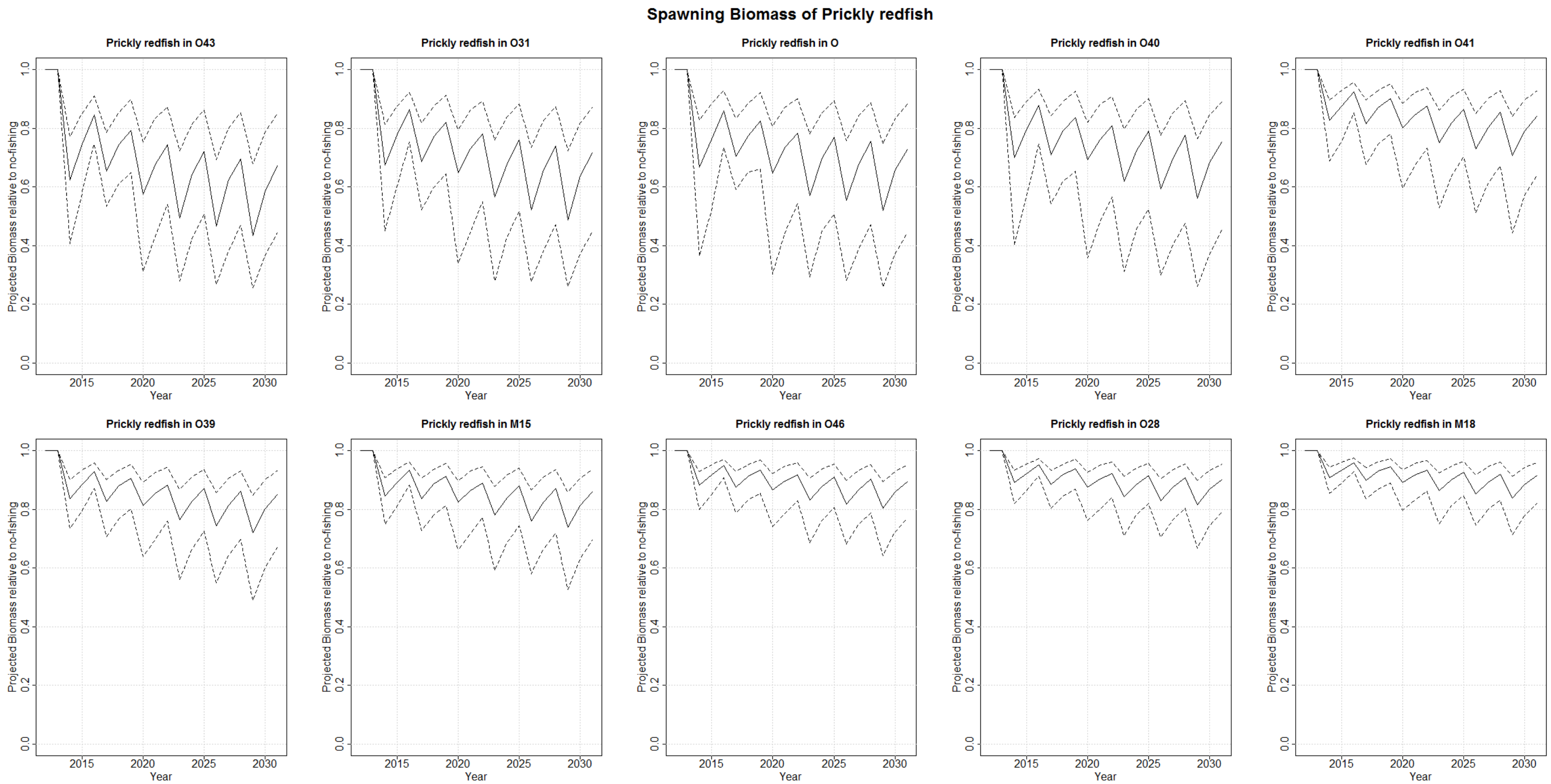


Figure 65. Revised base case RZS projected spawning biomass relative to the comparable no-fishing scenario 2012 to 2031 for Prickly Redfish in 10 of the 162 zones selected based on having the highest average fishing mortalities. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

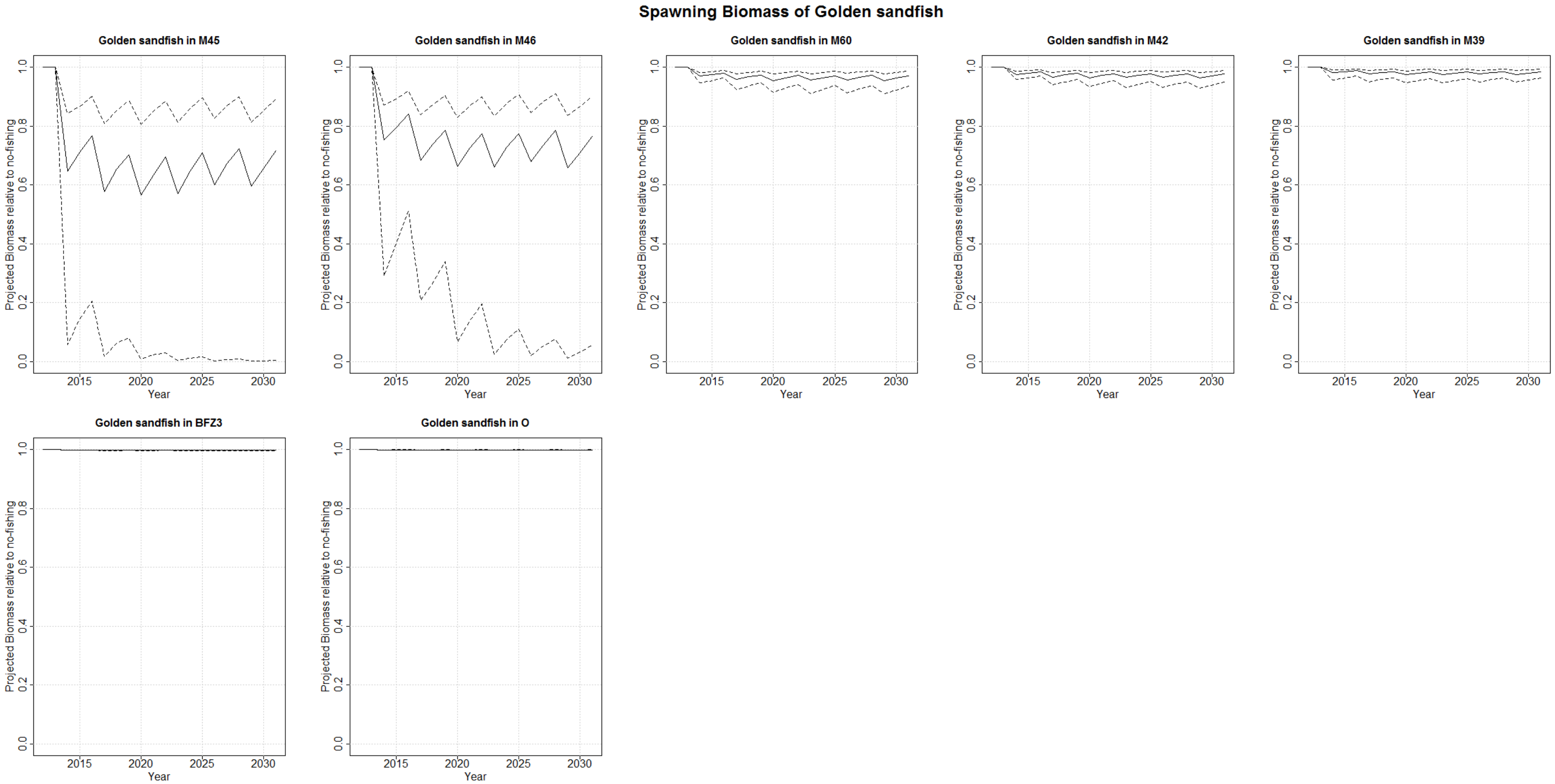


Figure 66. Revised base case RZS projected spawning biomass relative to the comparable no-fishing scenario 2012 to 2031 for golden Sandfish in 10 of the 162 zones selected based on having the highest average fishing mortalities (fished in only 7 zones for this species). The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

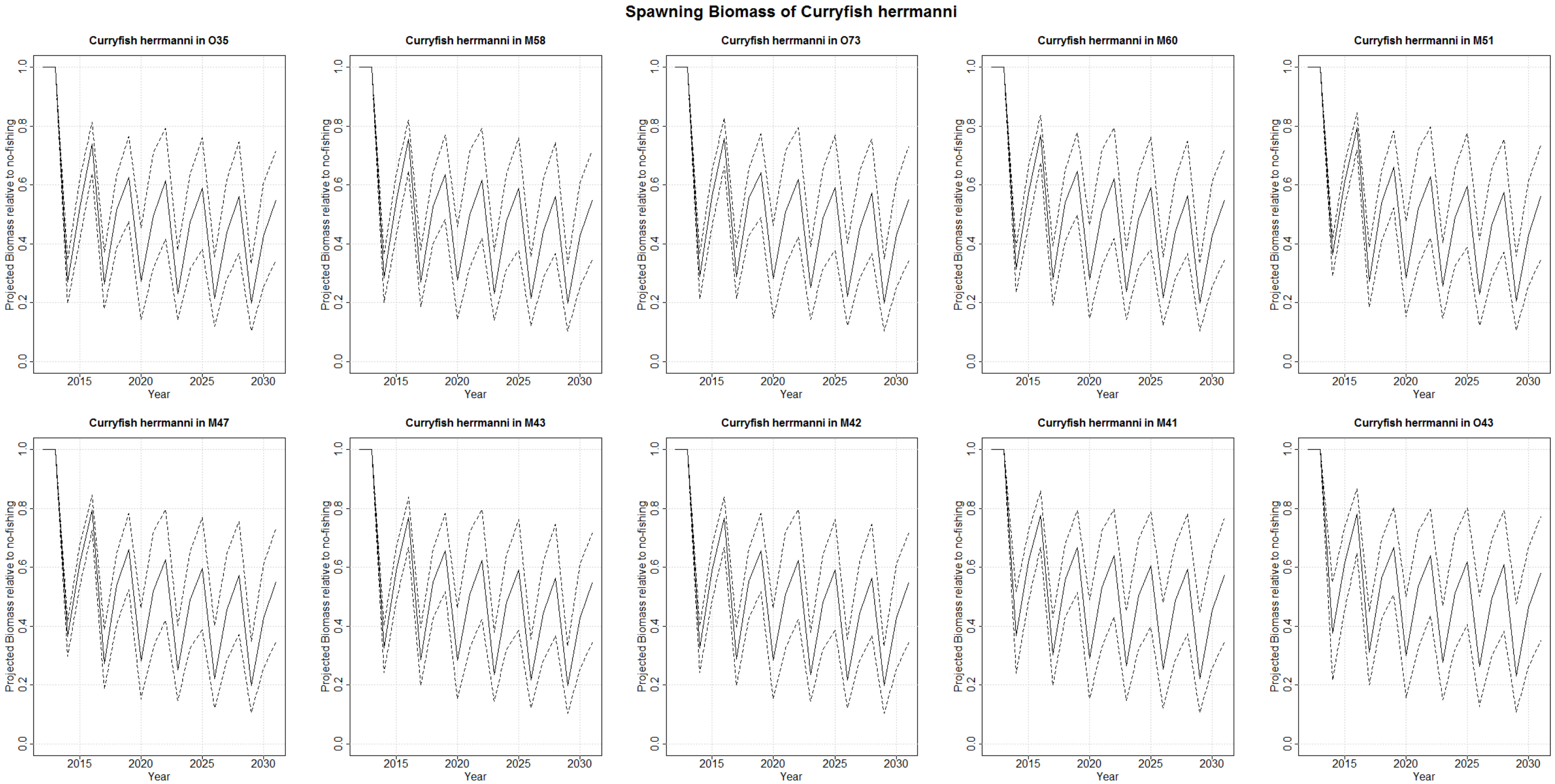


Figure 67. Revised base case RZS projected spawning biomass relative to the comparable no-fishing scenario 2012 to 2031 for Curryfish Herrmanni in 10 of the 162 zones selected based on having the highest average fishing mortalities. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

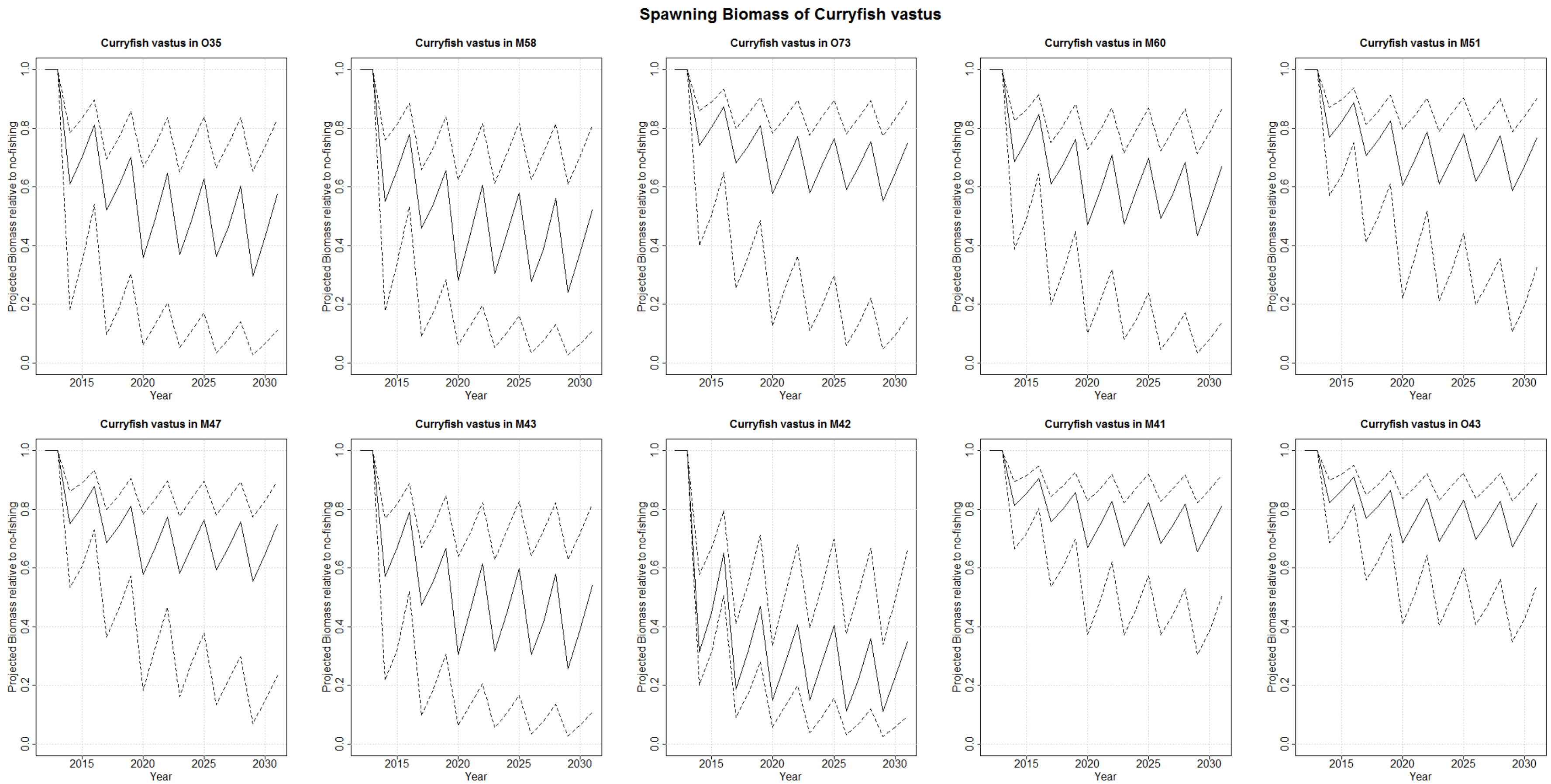


Figure 68. Revised base case RZS projected spawning biomass relative to the comparable no-fishing scenario 2012 to 2031 for Curryfish Vastus in 10 of the 162 zones selected based on having the highest average fishing mortalities. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

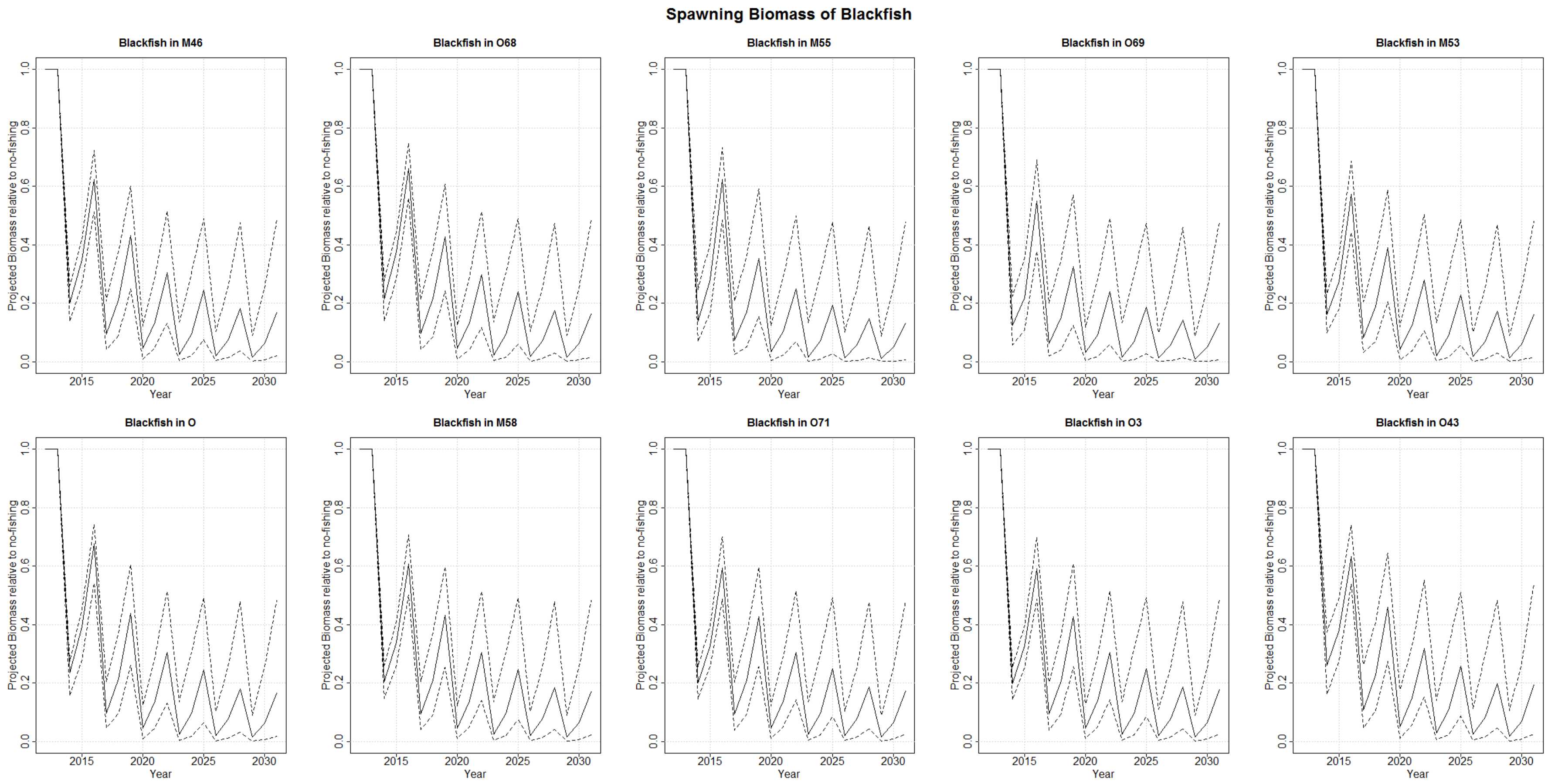


Figure 69. Revised base case RZS projected spawning biomass relative to the comparable no-fishing scenario 2012 to 2031 for blackfish in 10 of the 162 zones selected based on having the highest average fishing mortalities. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

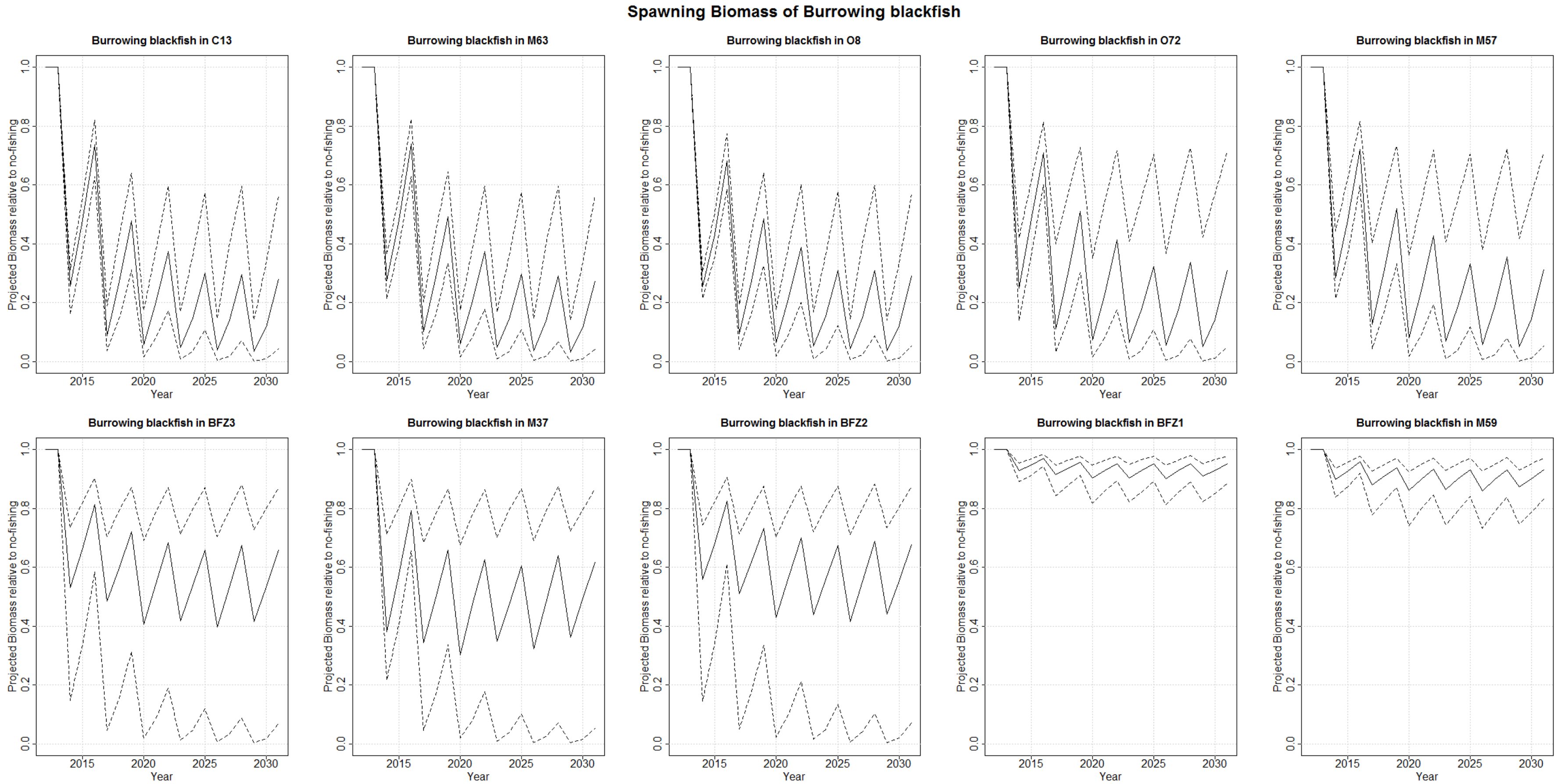


Figure 70. Revised base case RZS projected spawning biomass relative to the comparable no-fishing scenario 2012 to 2031 for Burrowing Blackfish in 10 of the 162 zones selected based on having the highest average fishing mortalities. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

Appendix K Projected spawning biomass – no RZS and current catch, 2012-2031

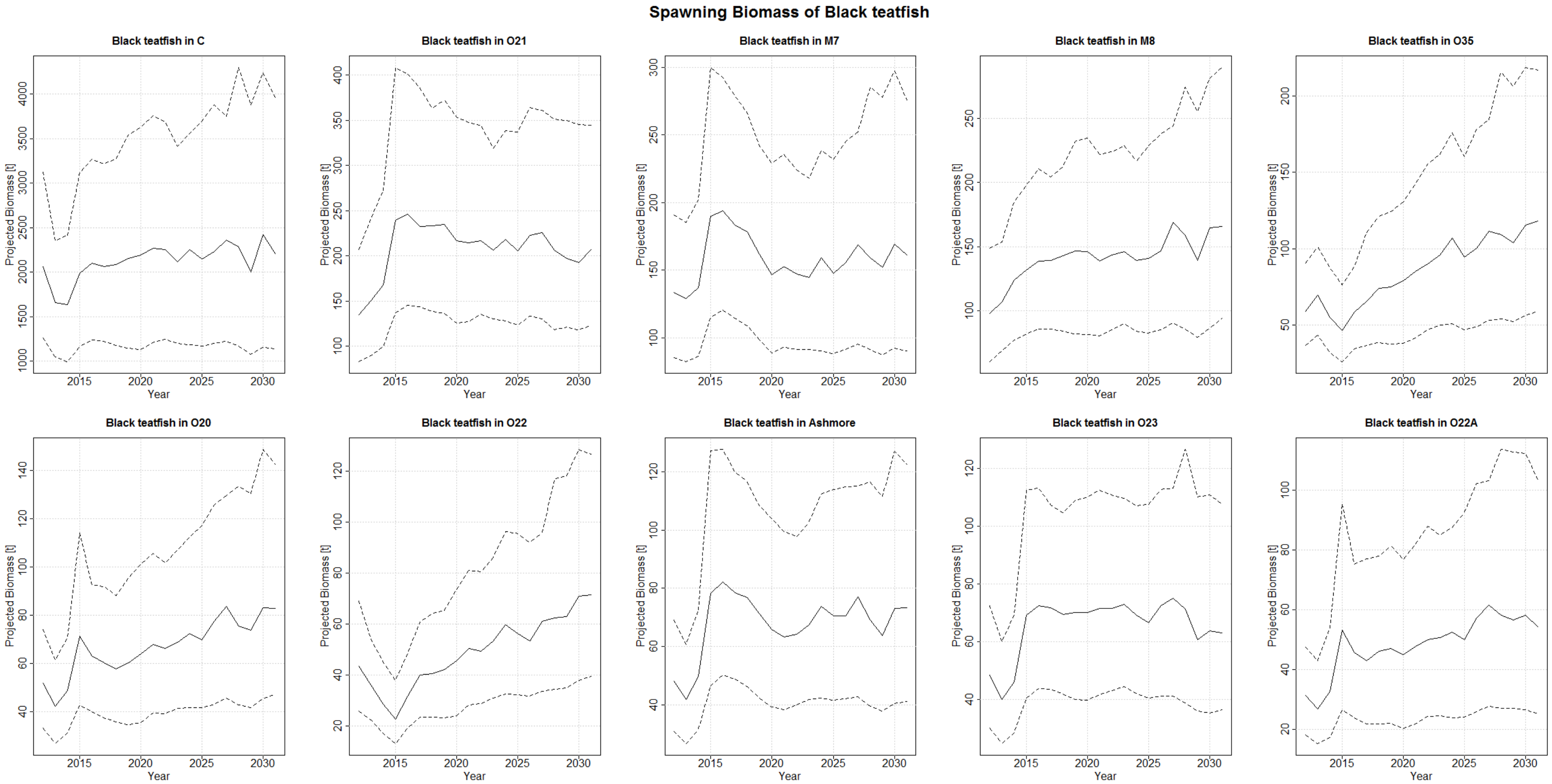


Figure 71. Projected spawning biomass (t) trajectories from 2012 to 2031 for Black Teatfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume a future TAC of 58 tons for the Black Teatfish but no RZS. (Note: y axis does not always include zero).

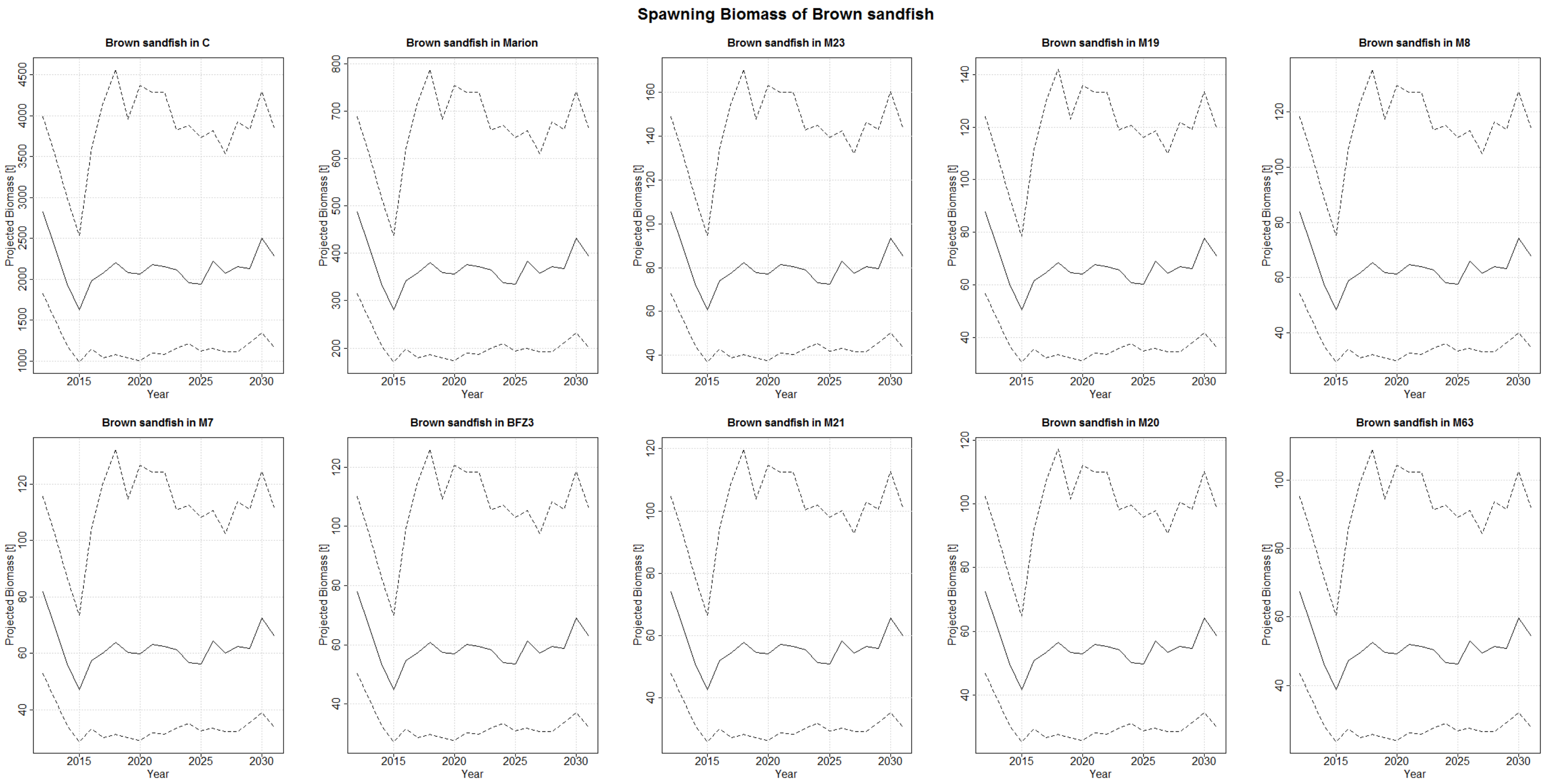


Figure 72. Projected spawning biomass (t) trajectories from 2012 to 2031 for Brown Sandfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume no future RZS but with TACs similar to current levels. (Note: y axis does not always include zero).

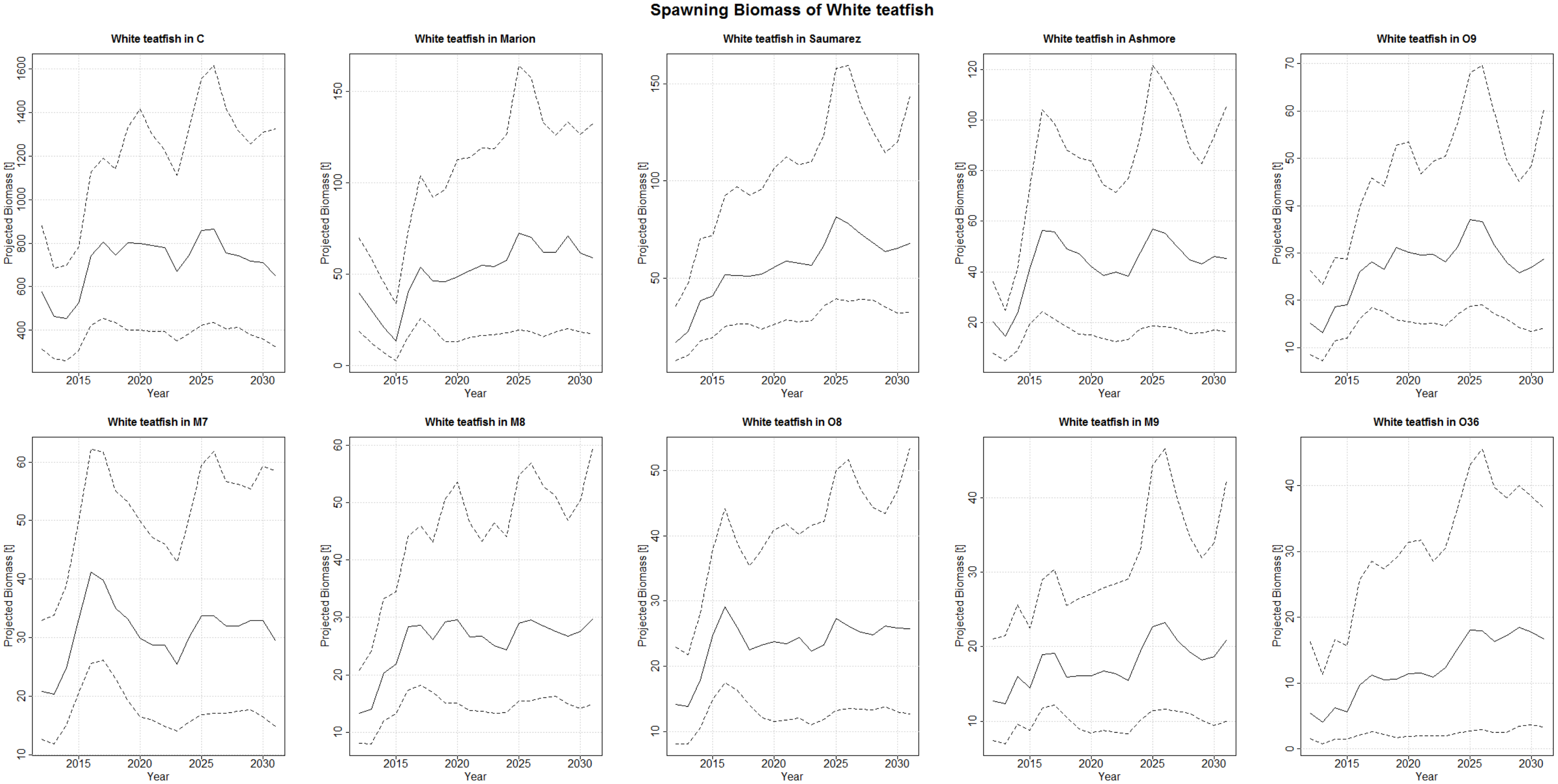


Figure 73. Projected spawning biomass (t) trajectories from 2012 to 2031 for White Teatfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume no future RZS but with TACs similar to current levels. (Note: y axis does not always include zero).

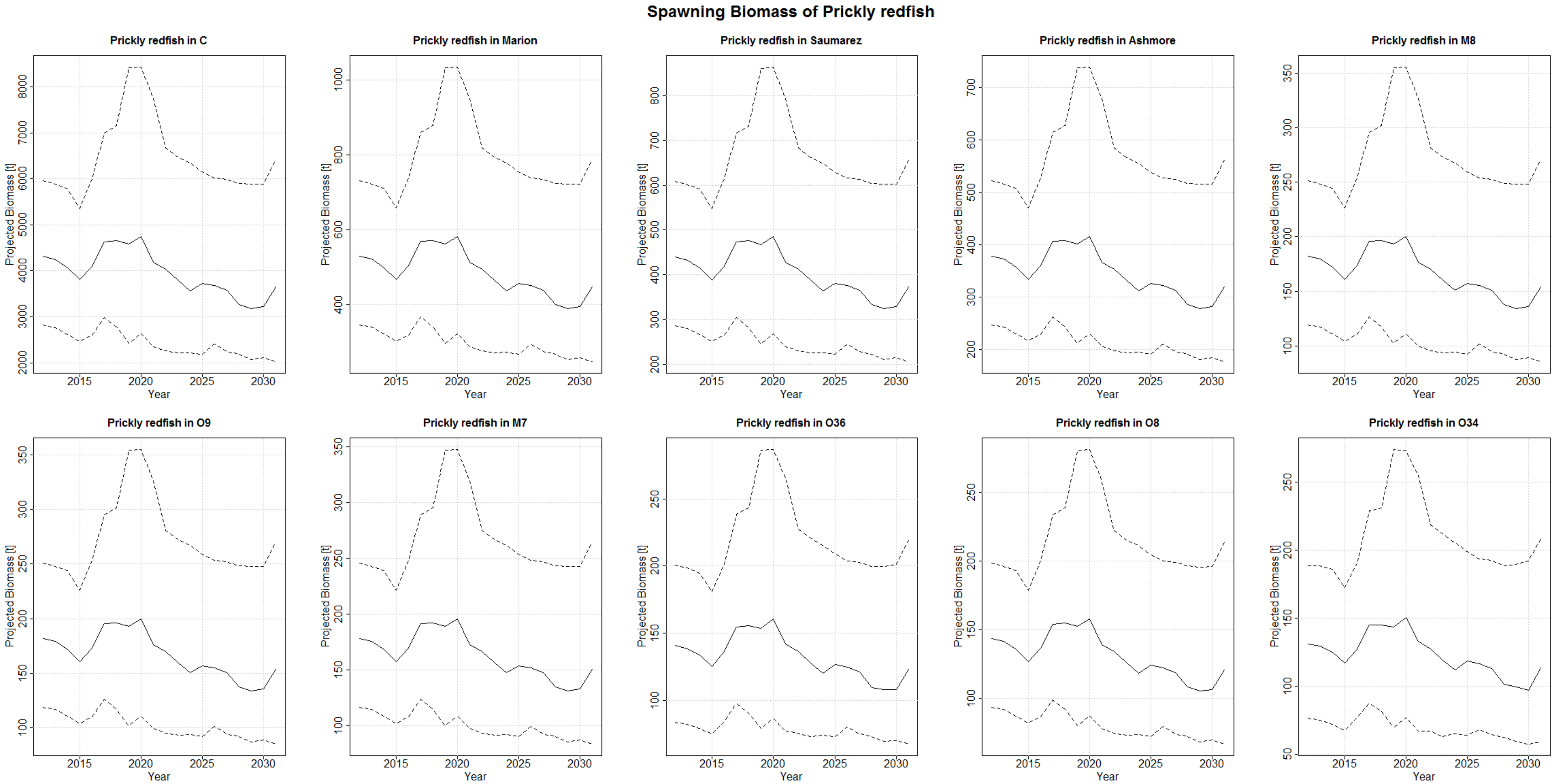


Figure 74. Projected spawning biomass (t) trajectories from 2012 to 2031 for Prickly Redfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume no future RZS but with TACs similar to current levels. (Note: y axis does not always include zero).

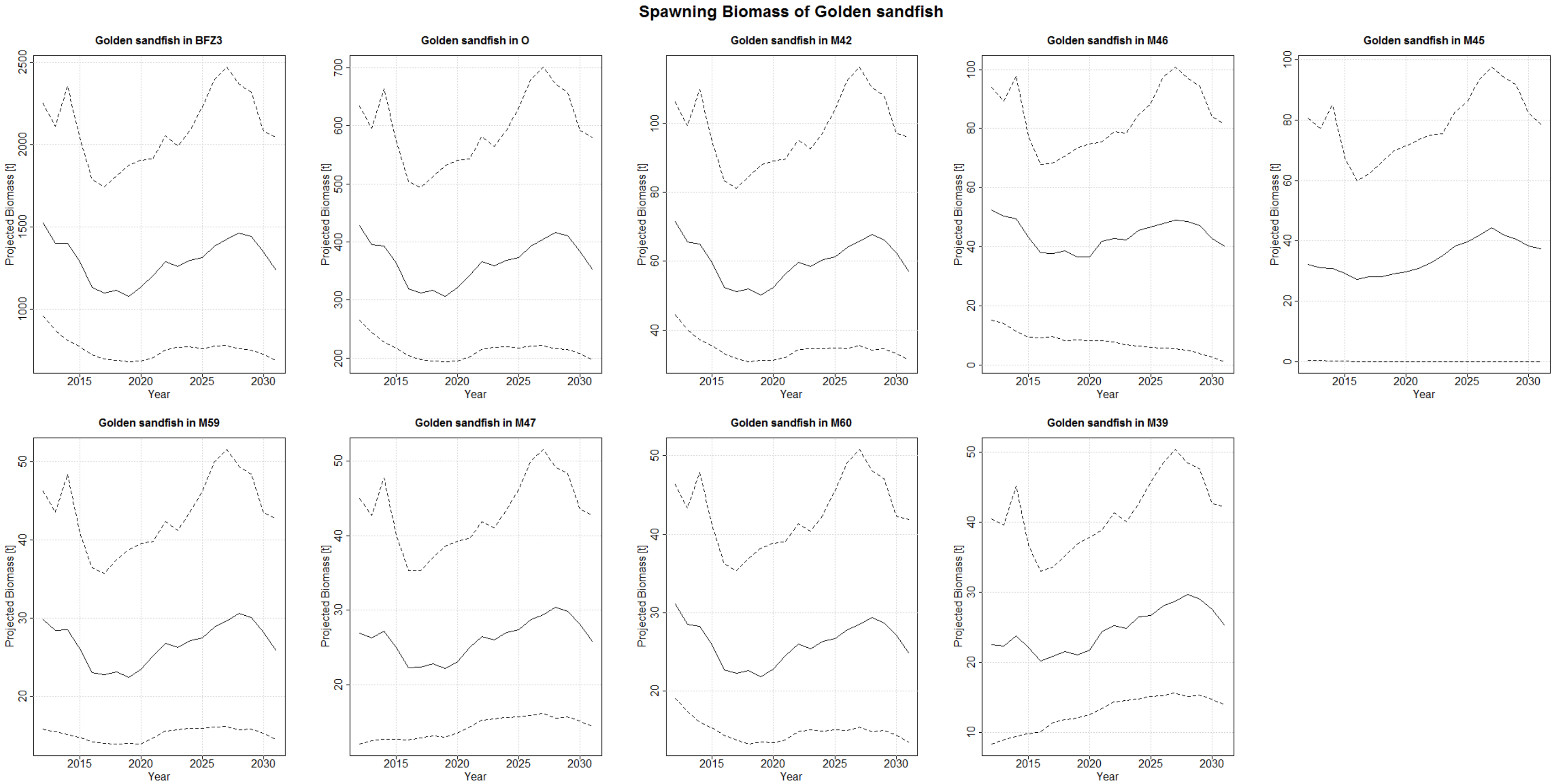


Figure 75. Projected spawning biomass (t) trajectories from 2012 to 2031 for golden Sandfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume no future RZS but with TACs similar to current levels. (Note: y axis does not always include zero).

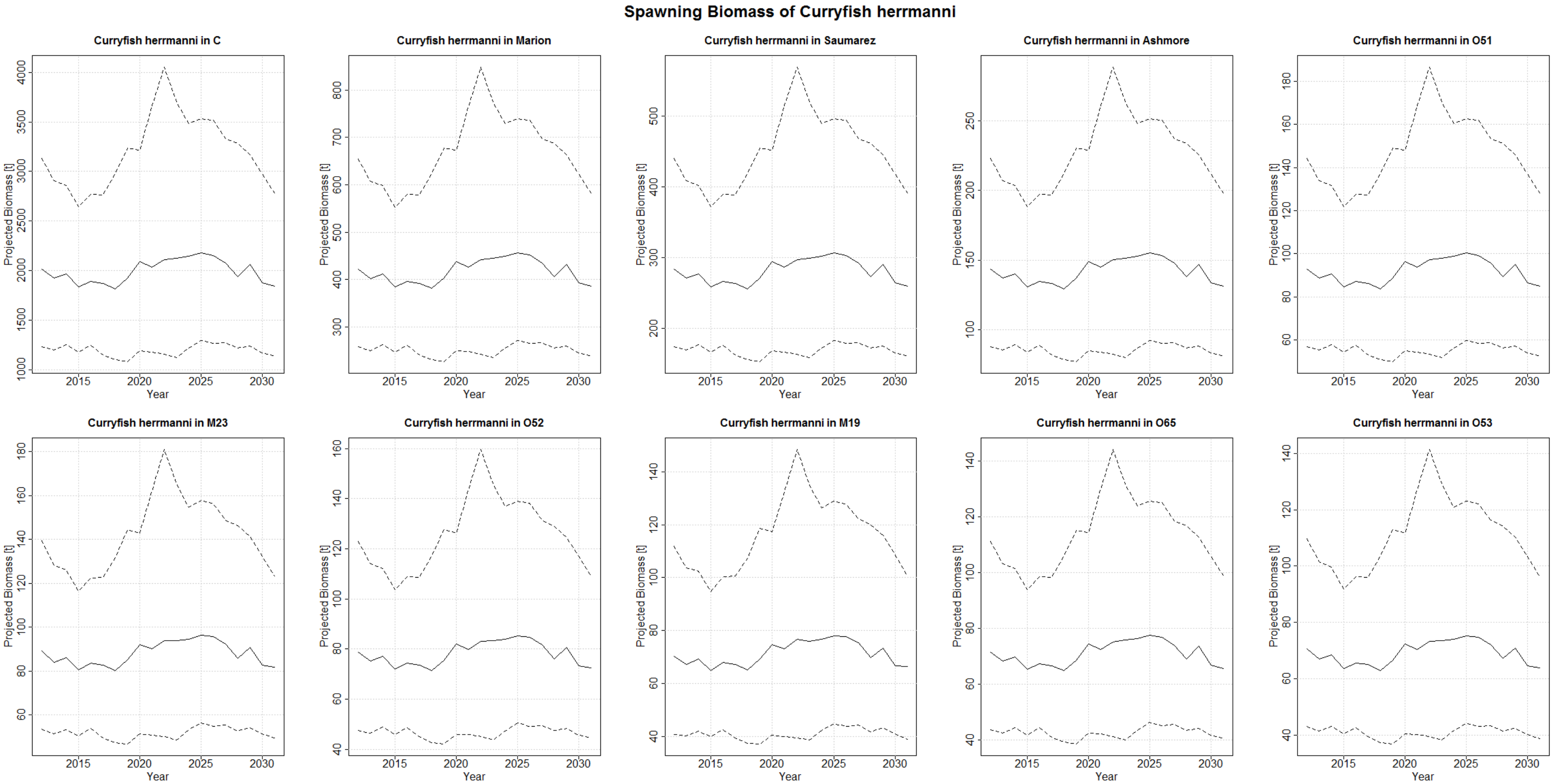


Figure 76. Projected spawning biomass (t) trajectories from 2012 to 2031 for Curryfish Herrmanni in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume no future RZS but with TACs similar to current levels. (Note: y axis does not always include zero).

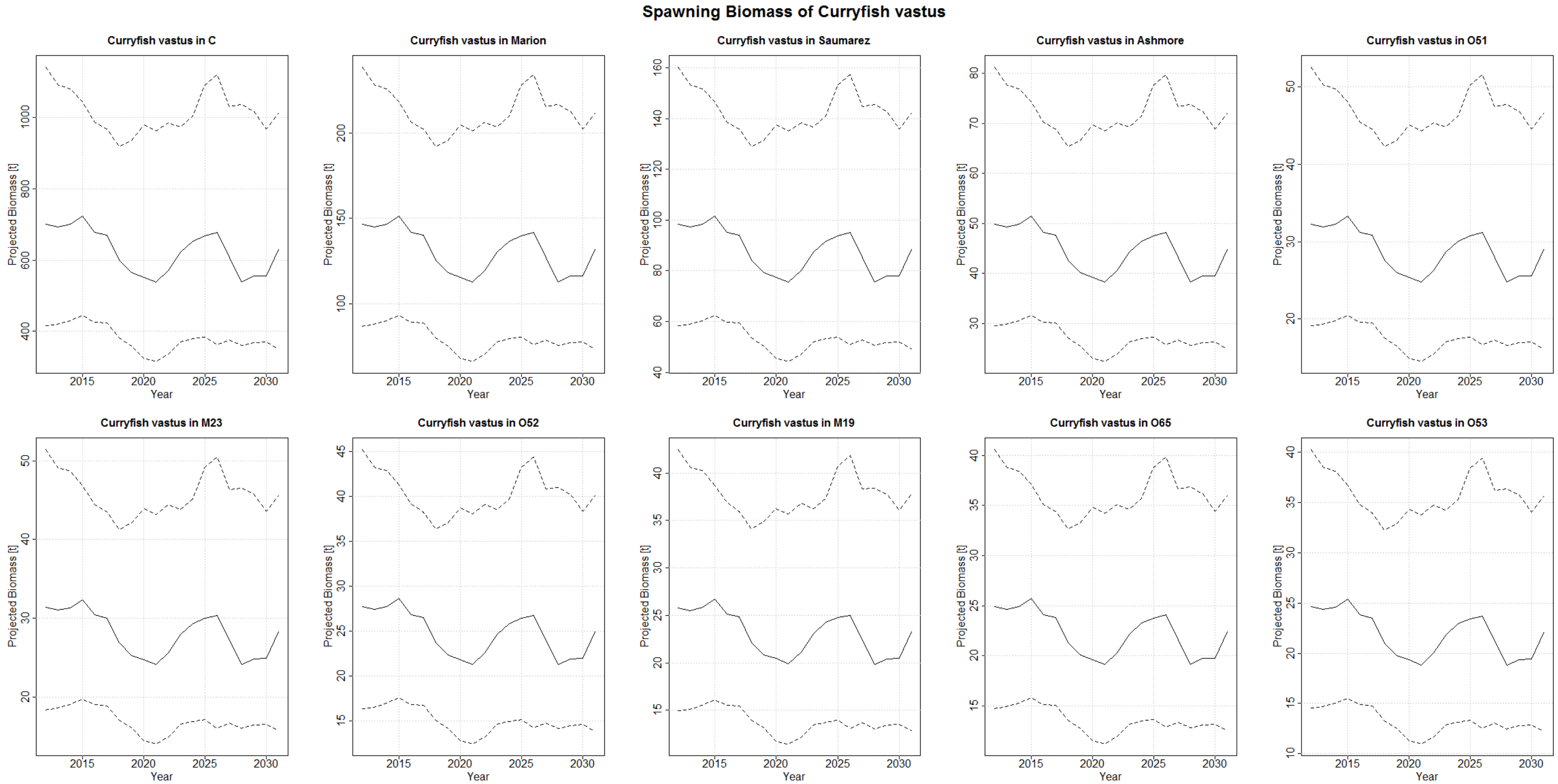


Figure 77. Projected spawning biomass (t) trajectories from 2012 to 2031 for Curryfish Vastus in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume no future RZS but with TACs similar to current levels.

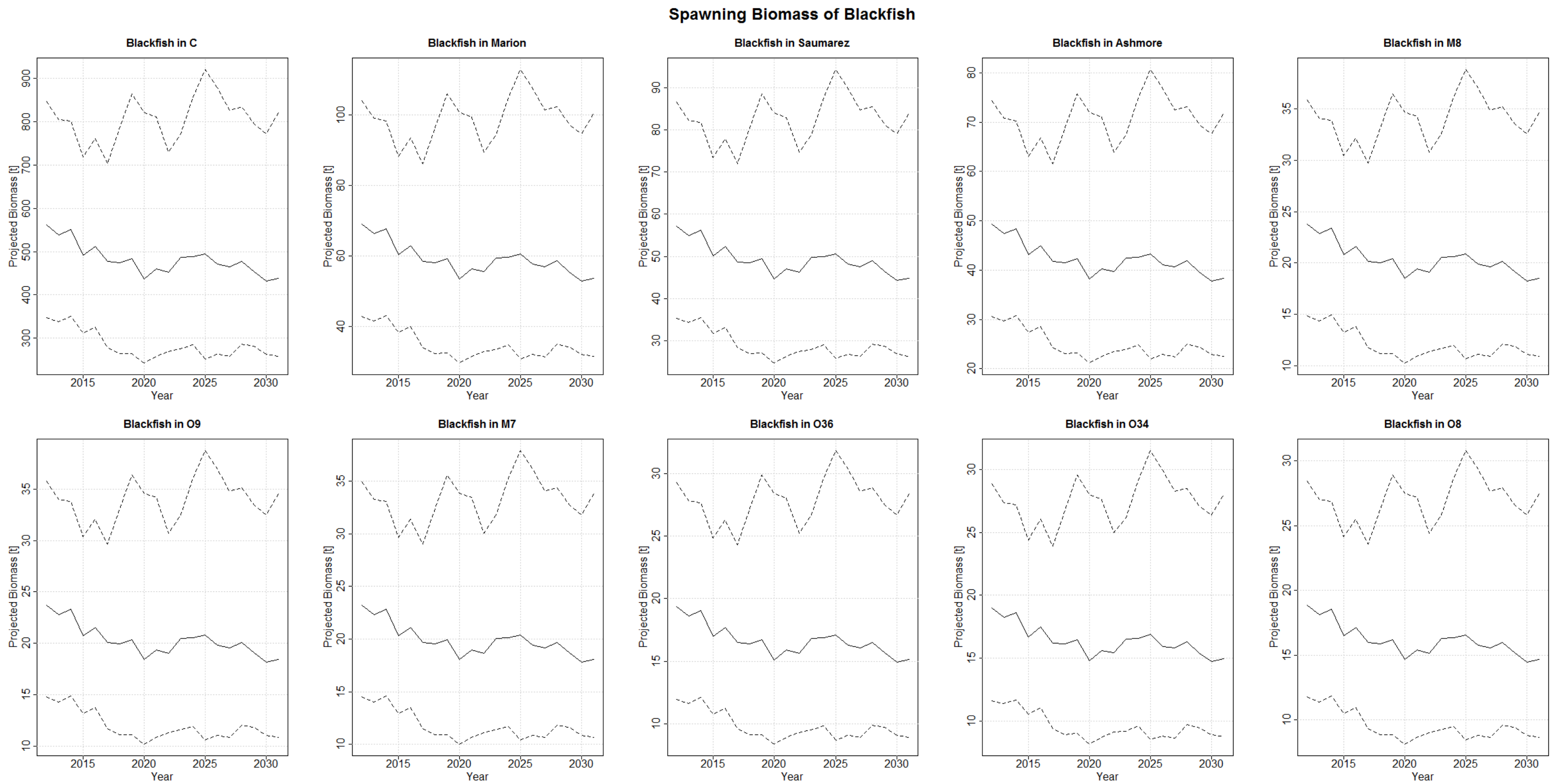


Figure 78. Projected spawning biomass (t) trajectories from 2012 to 2031 for blackfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume no future RZS but with TACs similar to current levels. (Note: y axis does not always include zero).

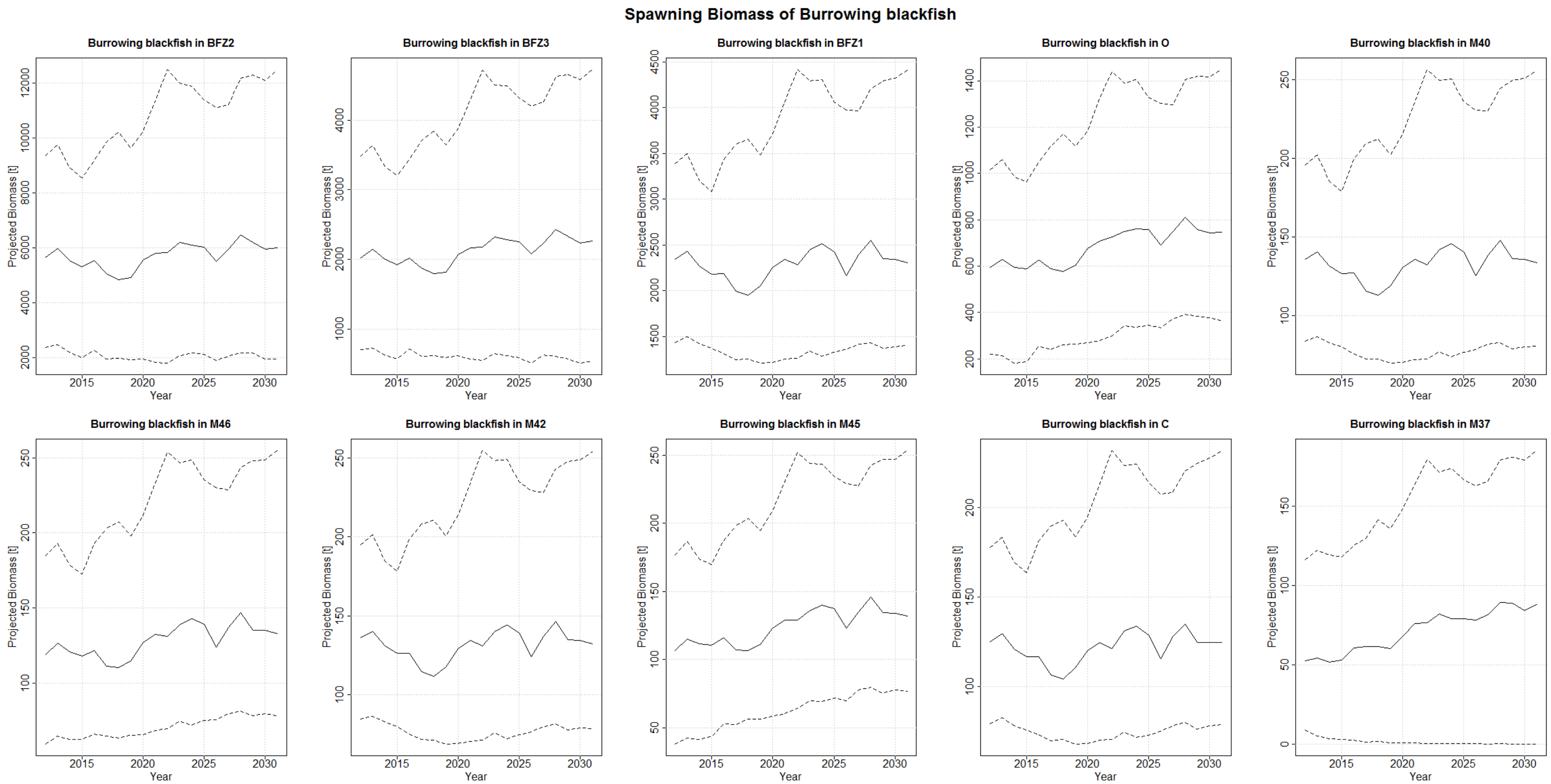


Figure 79. Projected spawning biomass (t) trajectories from 2012 to 2031 for Burrowing Blackfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume no future RZS but with TACs similar to current levels. (Note: y axis does not always include zero).

Appendix L Projected spawning biomass depletion with the revised base case no-RZS relative to comparable revised RZS case, 2012 - 2031

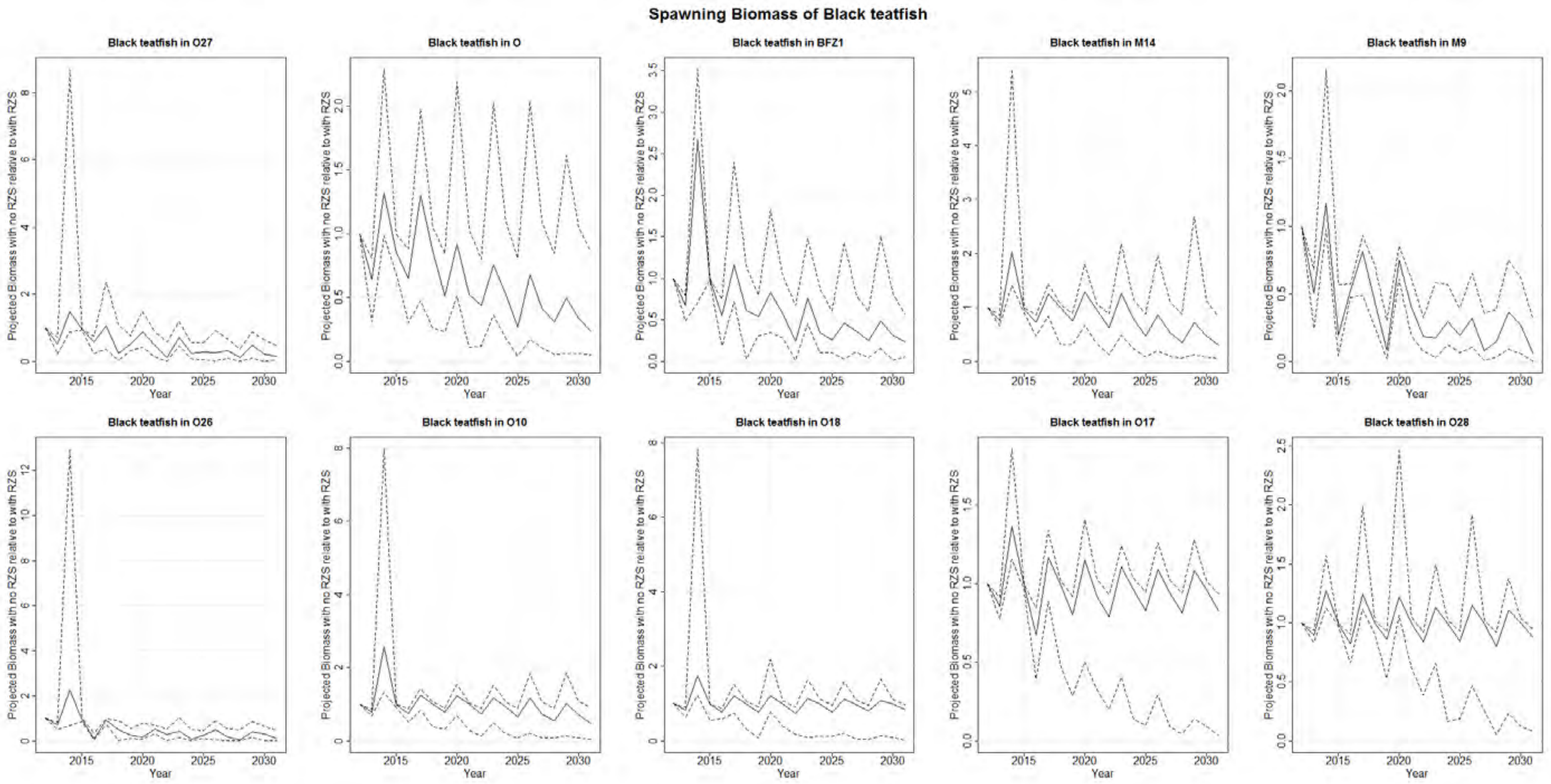


Figure 80. **Revised base case no-RZS projected spawning biomass relative to the comparable revised RZS scenario from 2012 to 2031 for Black Teatfish in 10 of the 162 zones selected based on having the highest average fishing mortalities. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels. Note the Black Teatfish TAC is currently zero, but for illustrative purposes the projections assume a future annual catch of 58t.**

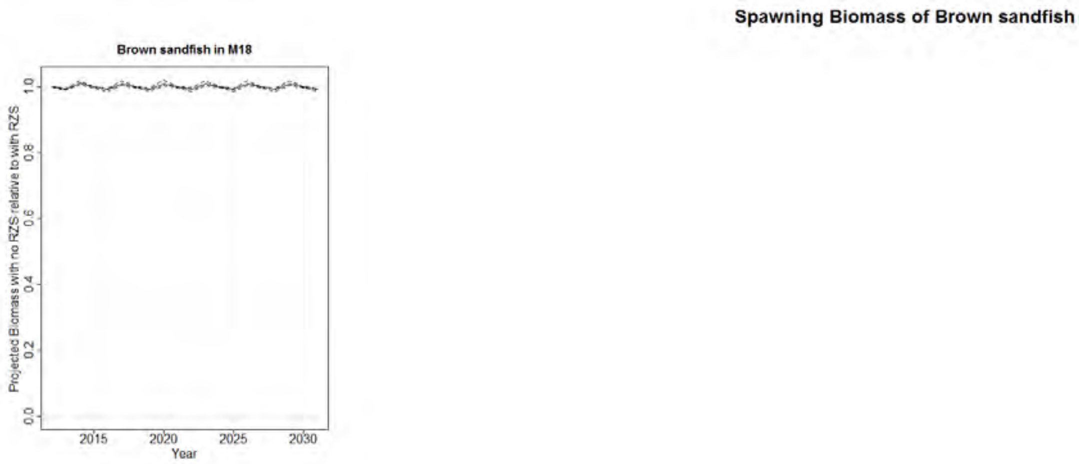


Figure 81. Revised base case no-RZS projected spawning biomass relative to the comparable revised RZS scenario from 2012 to 2031 for Brown Sandfish in 10 of the 162 zones selected based on having the highest average fishing mortalities (fished in a single zone only for this species). The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

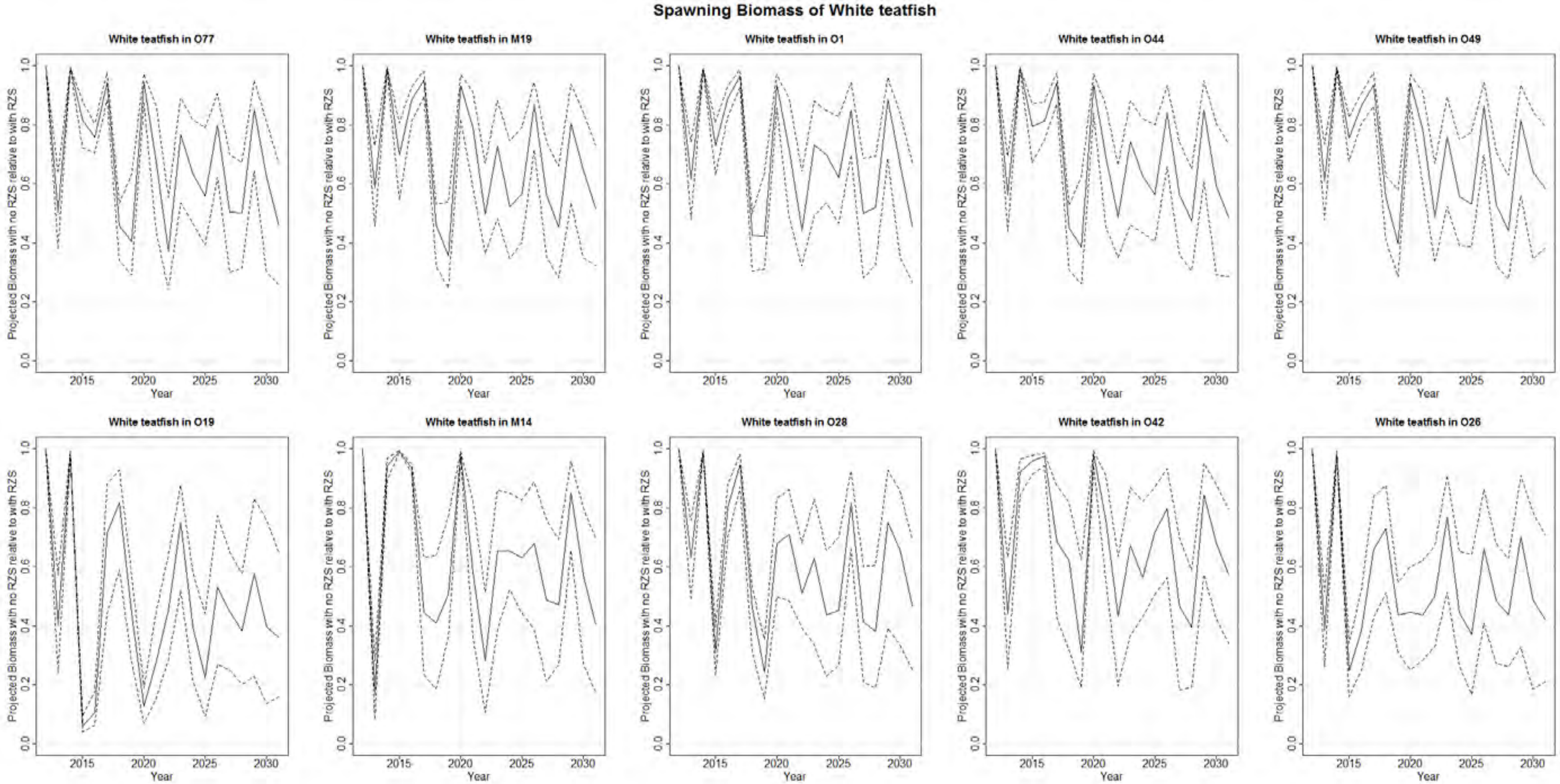


Figure 82. Revised base case no-RZS projected spawning biomass relative to the comparable revised RZS scenario from 2012 to 2031 for White Teatfish in 10 of the 162 zones selected based on having the highest average fishing mortalities. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

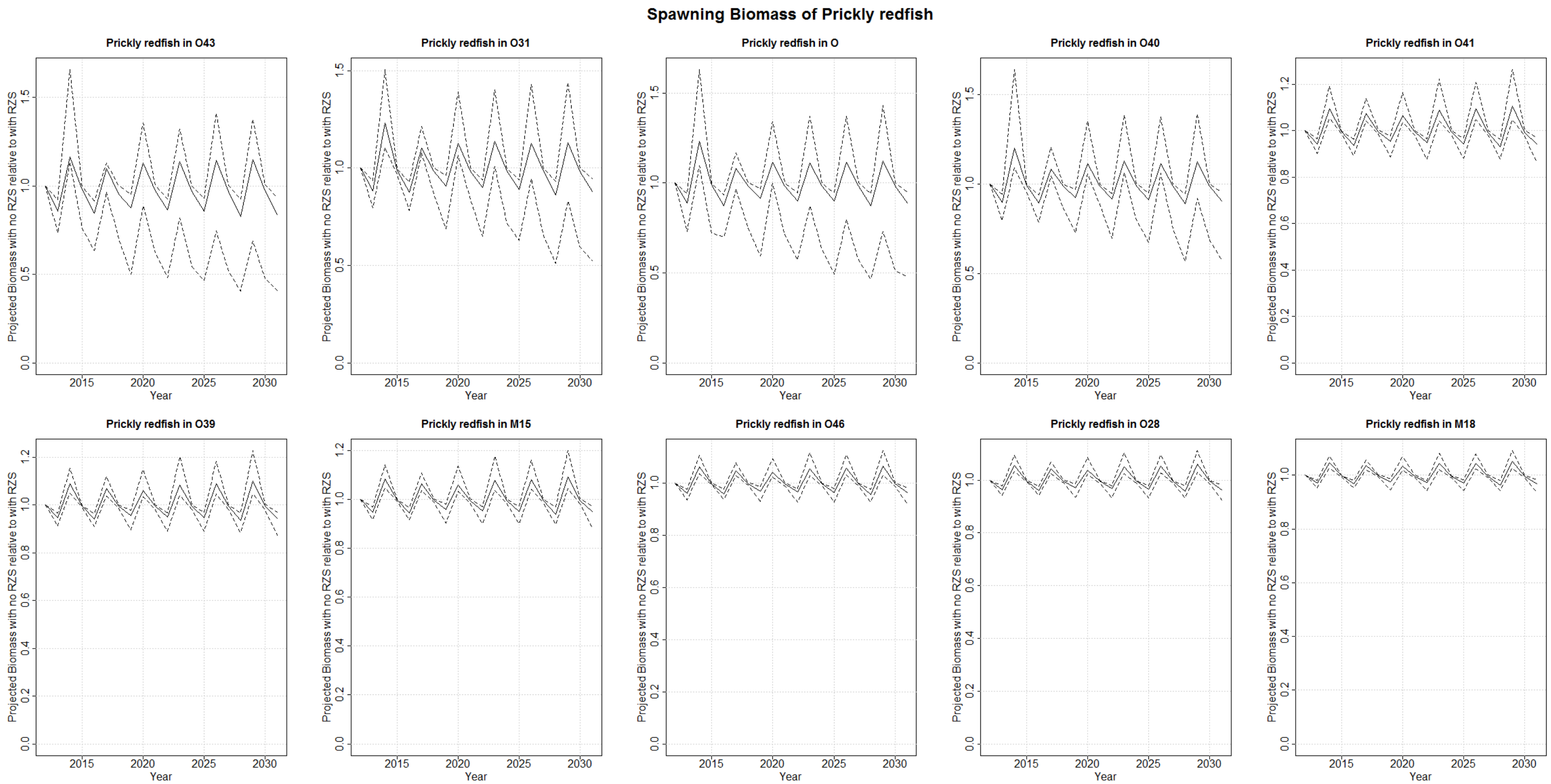


Figure 83**. Revised base case no-RZS projected spawning biomass relative to the comparable revised RZS scenario from 2012 to 2031 for Prickly Redfish in 10 of the 162 zones selected based on having the highest average fishing mortalities. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.**

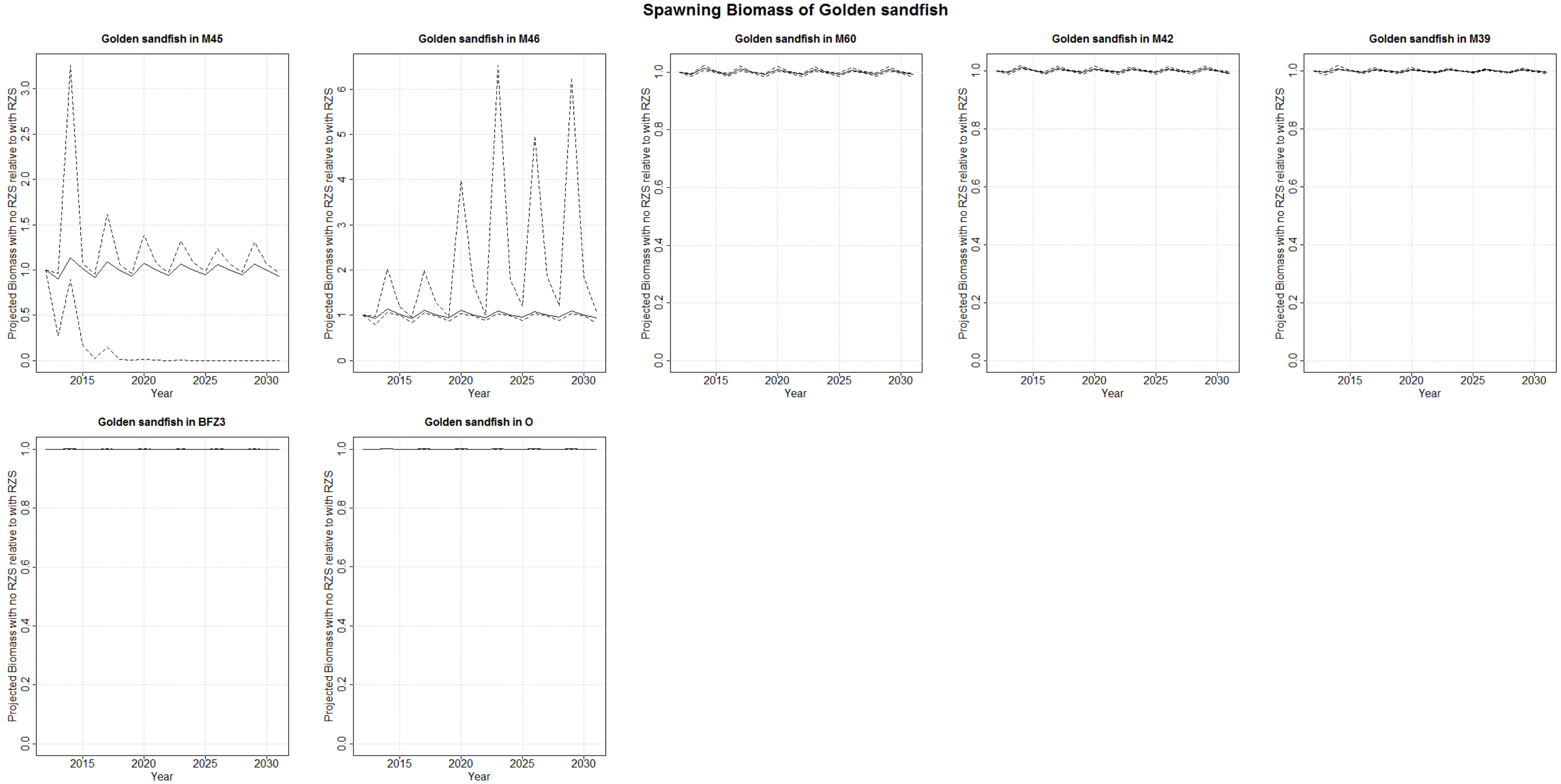


Figure 84. Revised base case no-RZS projected spawning biomass relative to the comparable revised RZS scenario from 2012 to 2031 for golden Sandfish in 10 of the 162 zones selected based on having the highest average fishing mortalities (fished in only 7 zones for this species). The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

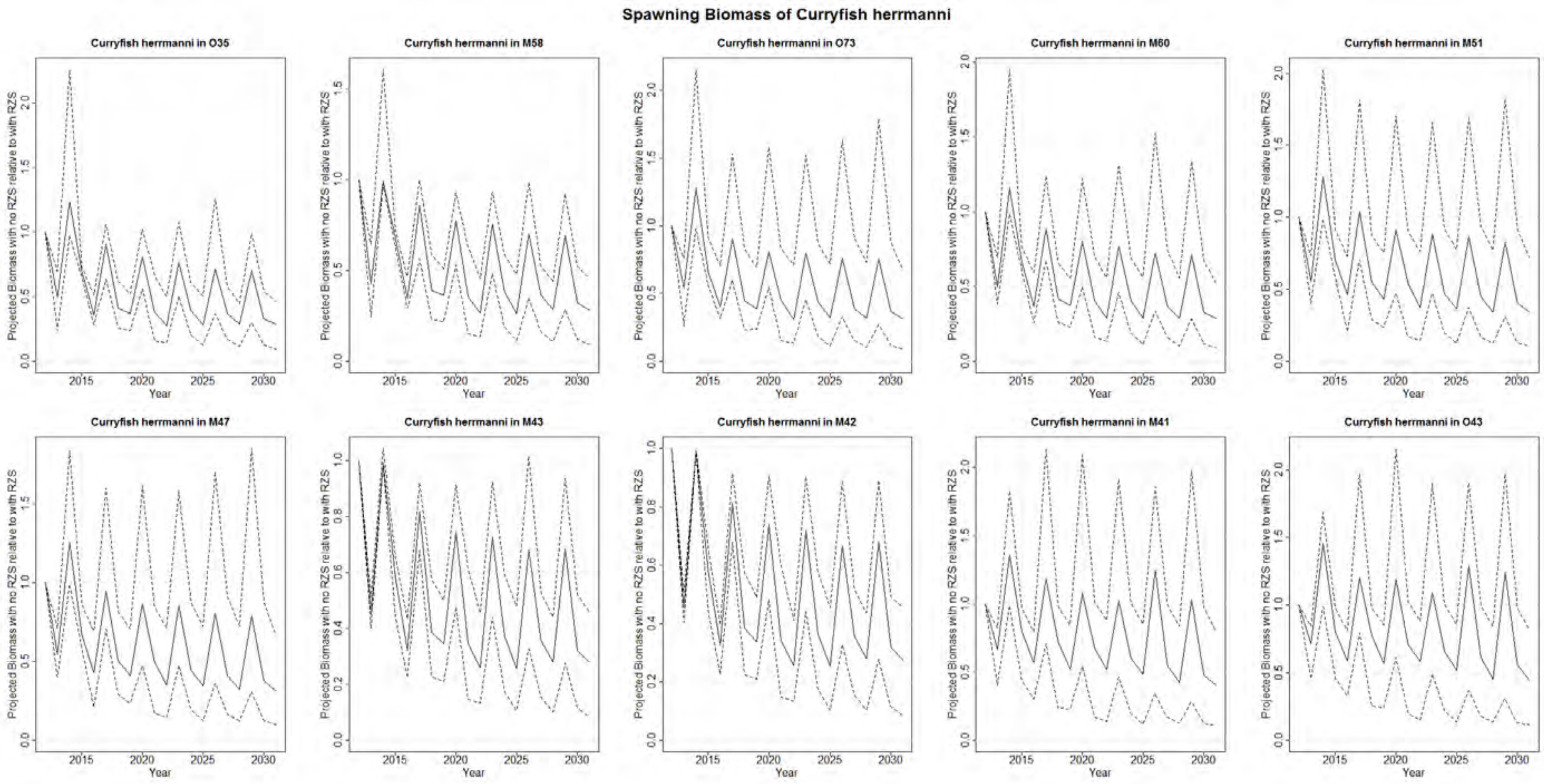


Figure 85. Revised base case no-RZS projected spawning biomass relative to the comparable revised RZS scenario from 2012 to 2031 for Curryfish Herrmanni in 10 of the 162 zones selected based on having the highest average fishing mortalities. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

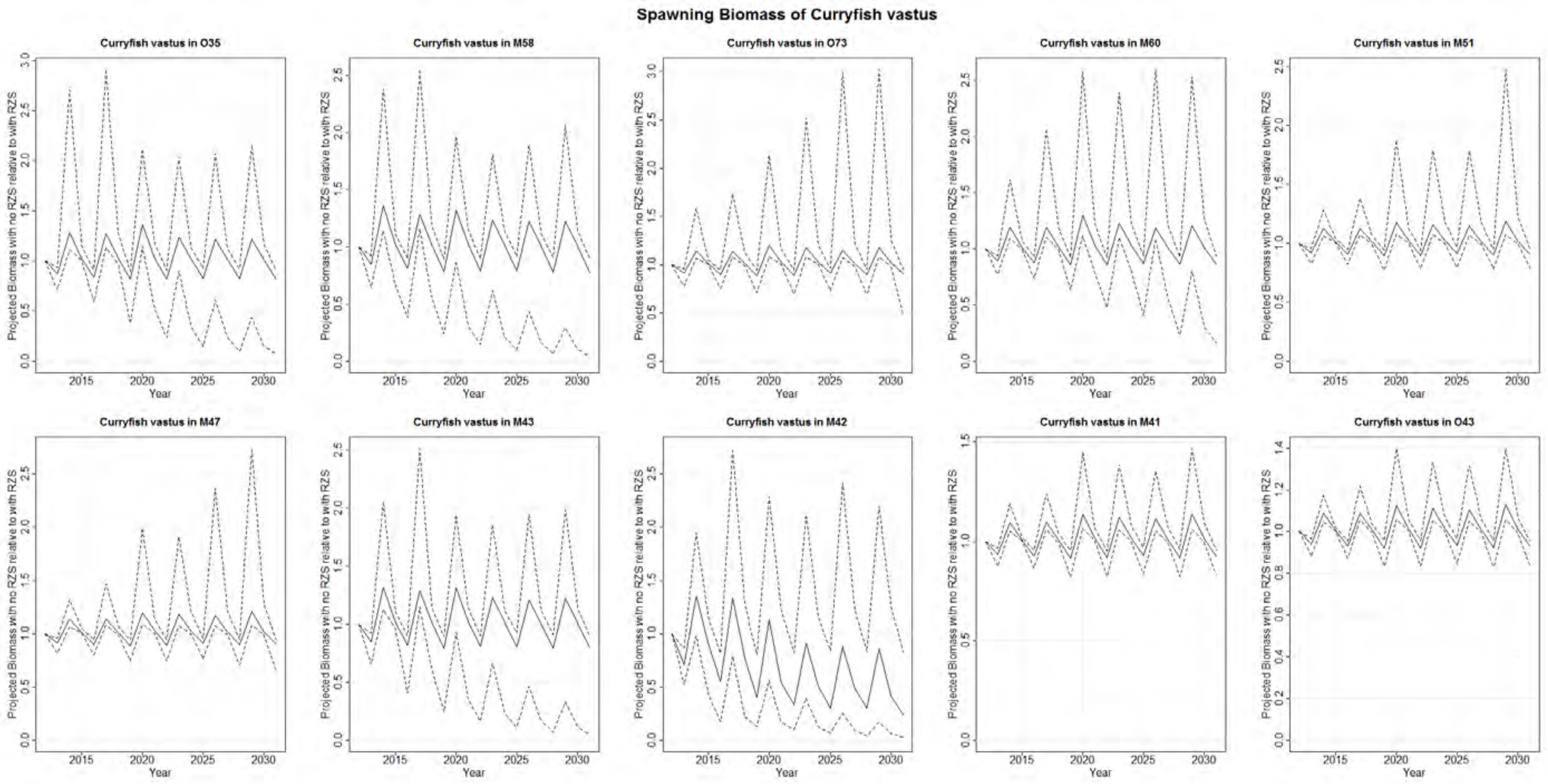


Figure 86. Revised base case no-RZS projected spawning biomass relative to the comparable revised RZS scenario from 2012 to 2031 for Curryfish Vastus in 10 of the 162 zones selected based on having the highest average fishing mortalities. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

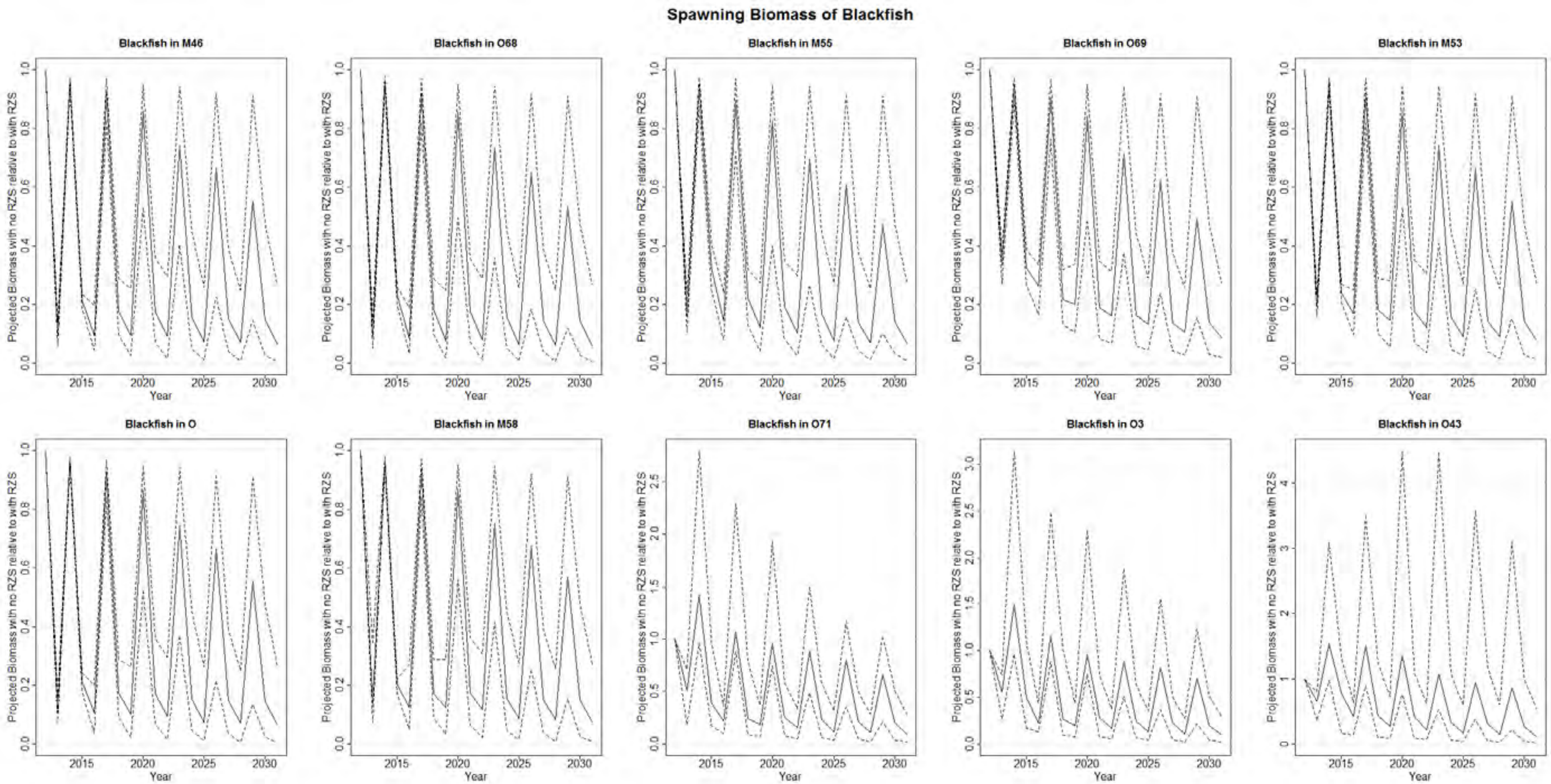


Figure 87. Revised base case no-RZS projected spawning biomass relative to the comparable revised RZS scenario from 2012 to 2031 for blackfish in 10 of the 162 zones selected based on having the highest average fishing mortalities. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

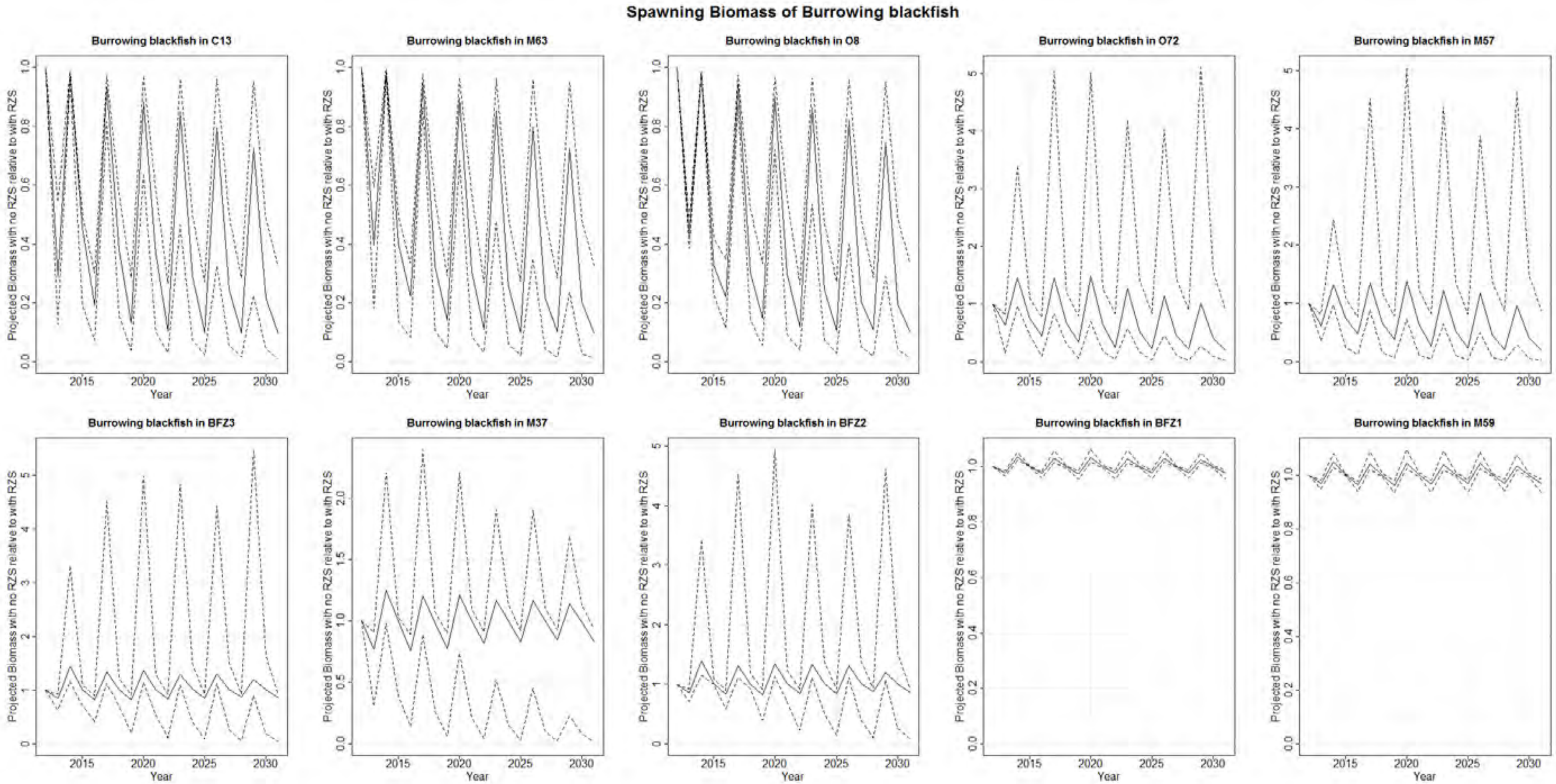


Figure 88. Revised base case no-RZS projected spawning biomass relative to the comparable revised RZS scenario from 2012 to 2031 for Burrowing Blackfish in 10 of the 162 zones selected based on having the highest average fishing mortalities. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels.

Appendix M Projected spawning biomass – RZS and 3X catches, 2012 - 2031

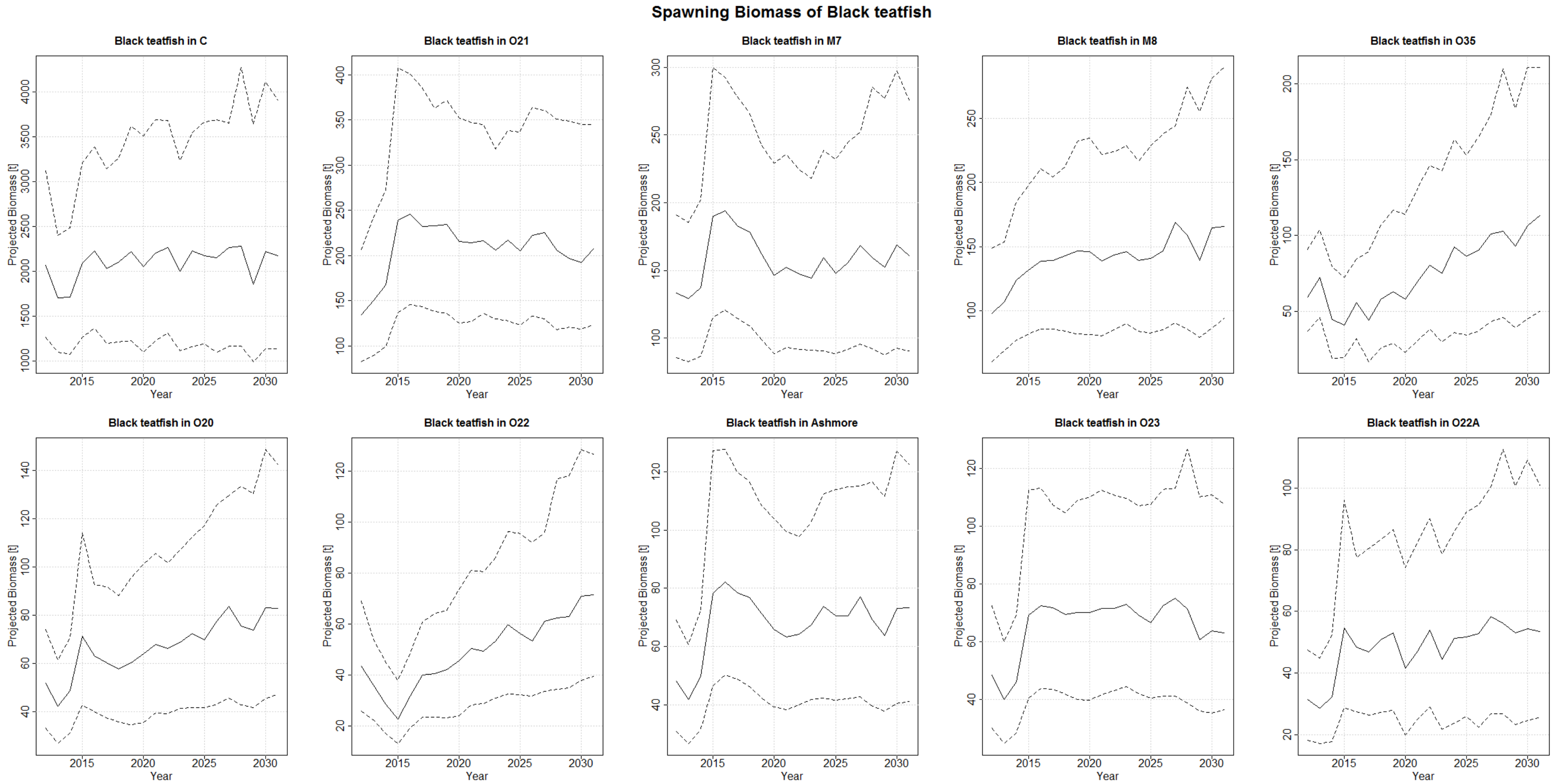


Figure 89. Projected spawning biomass (t) trajectories from 2012 to 2031 for Black Teatfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections continued future implementation of the RZS and a future TAC of 170 tons for the Black Teatfish (Note: y axis does not always include zero).

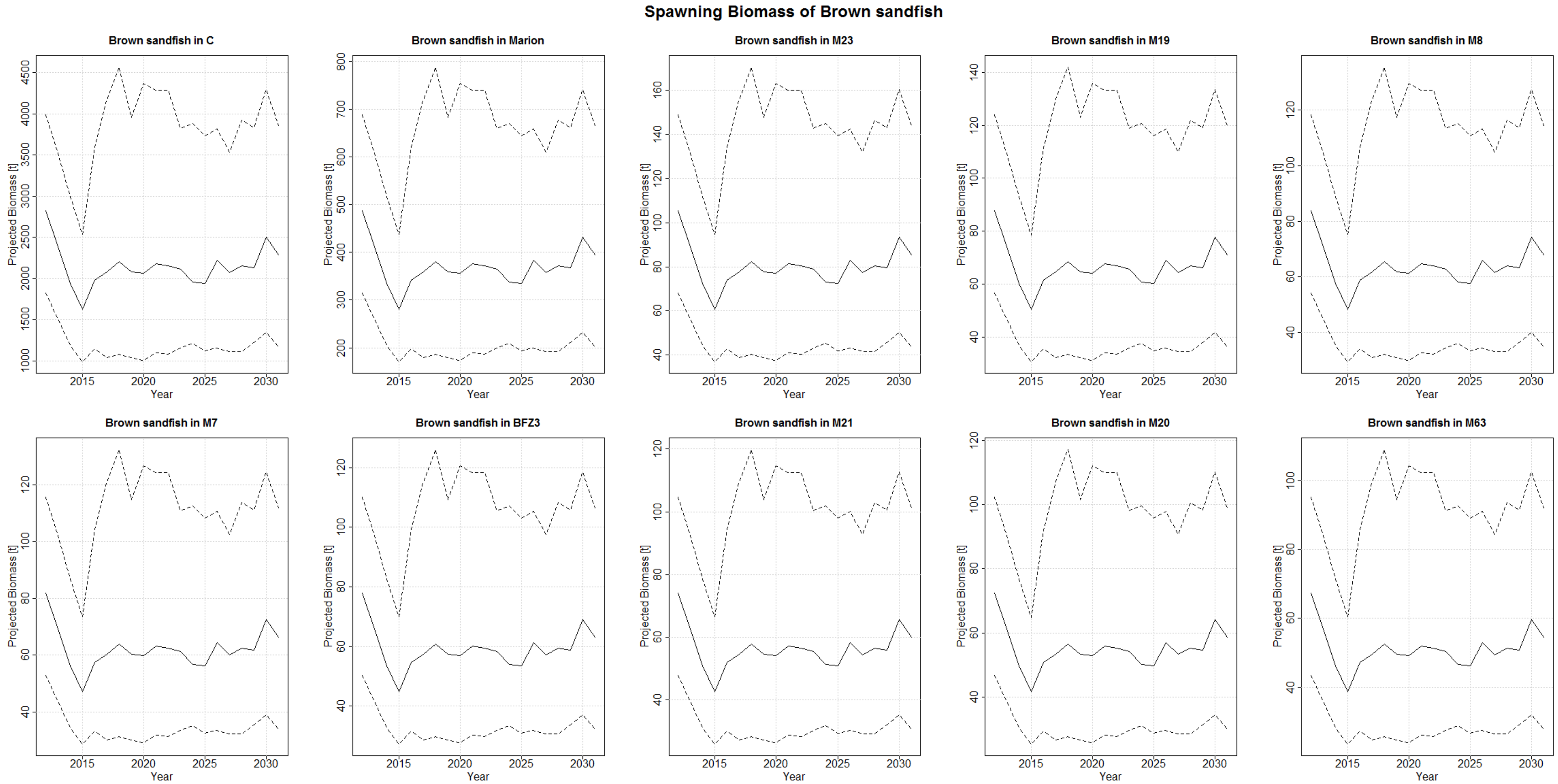


Figure 90. Projected spawning biomass (t) trajectories from 2012 to 2031 for Brown Sandfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS but with TACs set to three times higher levels.(Note: y axis does not always include zero).

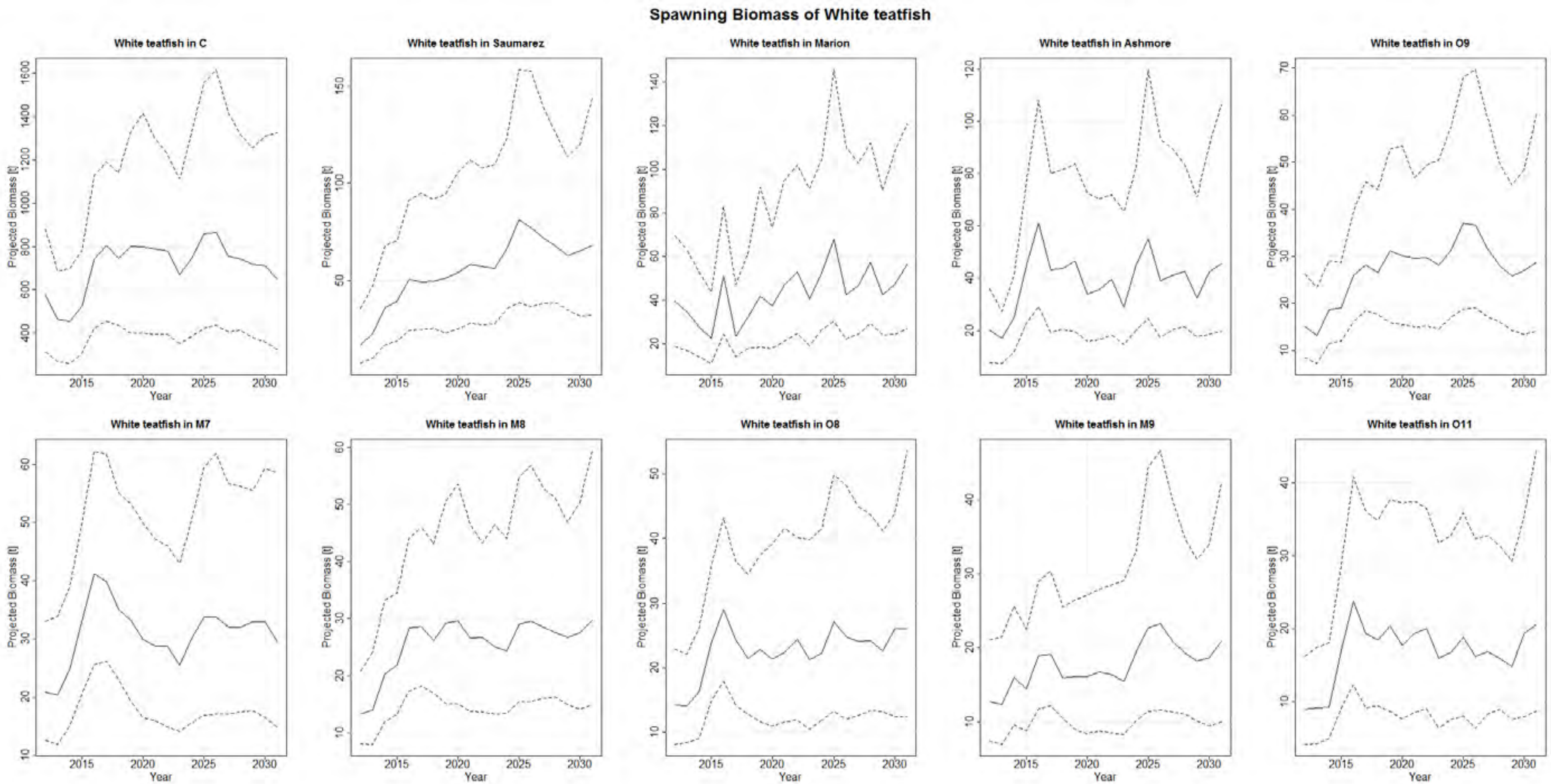


Figure 91. Projected spawning biomass (t) trajectories from 2012 to 2031 for White Teatfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS but with TACs set to three times higher levels. (Note: y axis does not always include zero).

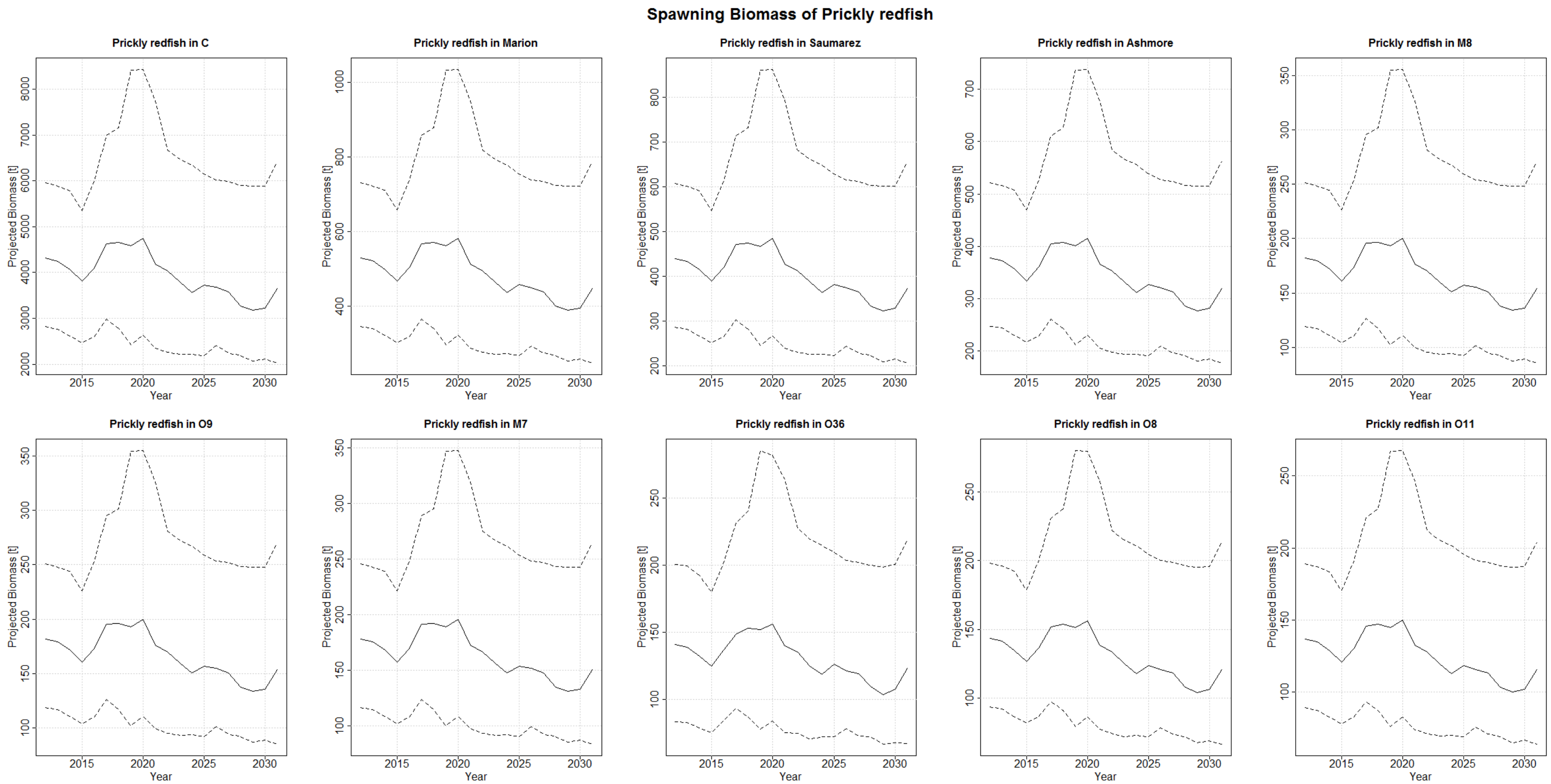


Figure 92. Projected spawning biomass (t) trajectories from 2012 to 2031 for Prickly Redfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS but with TACs set to three times higher levels. (Note: y axis does not always include zero).

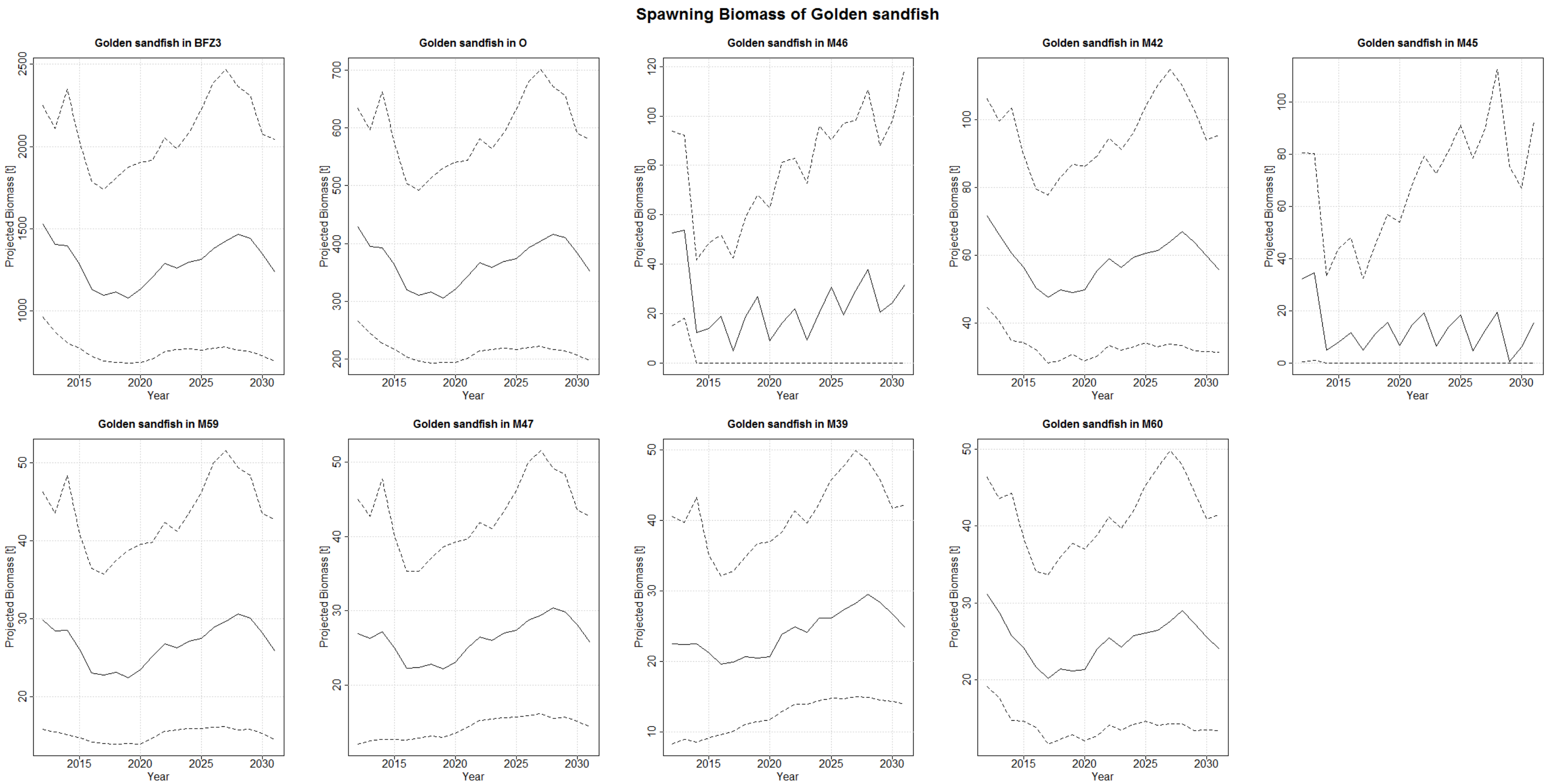


Figure 93. Projected spawning biomass (t) trajectories from 2012 to 2031 for golden Sandfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS but with TACs set to three times higher levels. (Note: y axis does not always include zero).

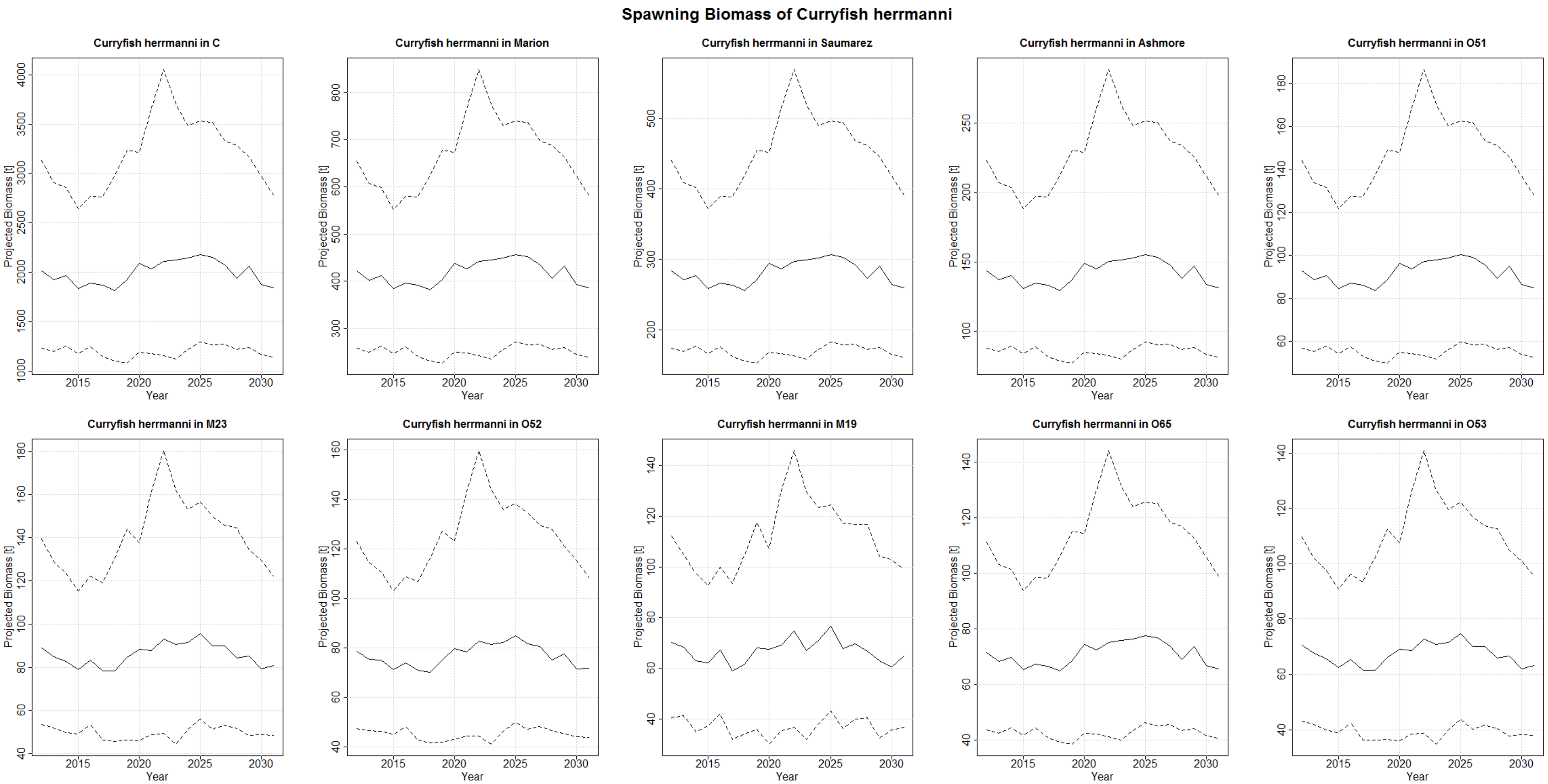


Figure 94. Projected spawning biomass (t) trajectories from 2012 to 2031 for Curryfish Herrmanni in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS but with TACs set to three times higher levels. (Note: y axis does not always include zero).

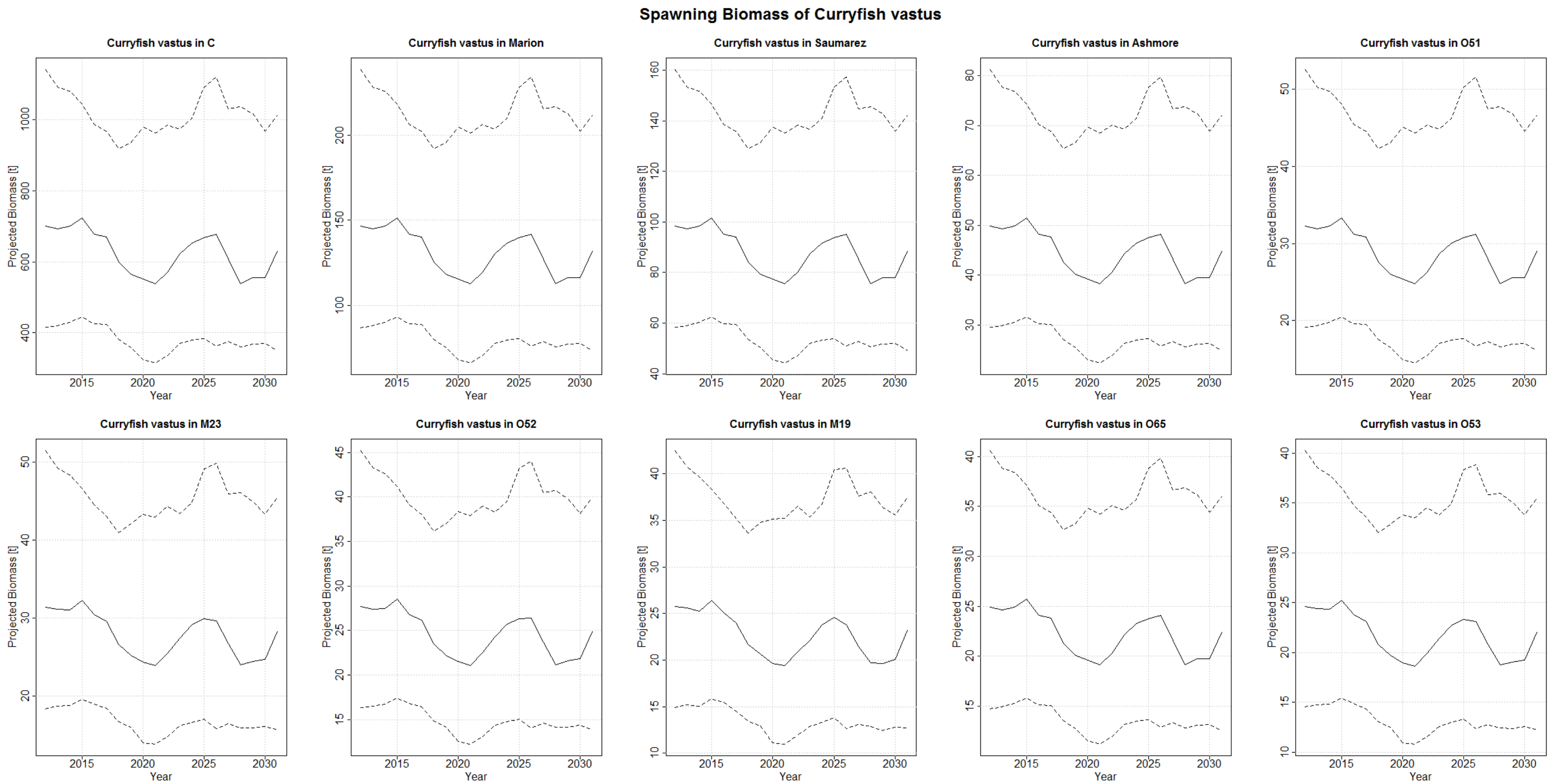


Figure 95. Projected spawning biomass (t) trajectories from 2012 to 2031 for Curryfish Vastus in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS but with TACs set to three times higher levels. (Note: y axis does not always include zero).

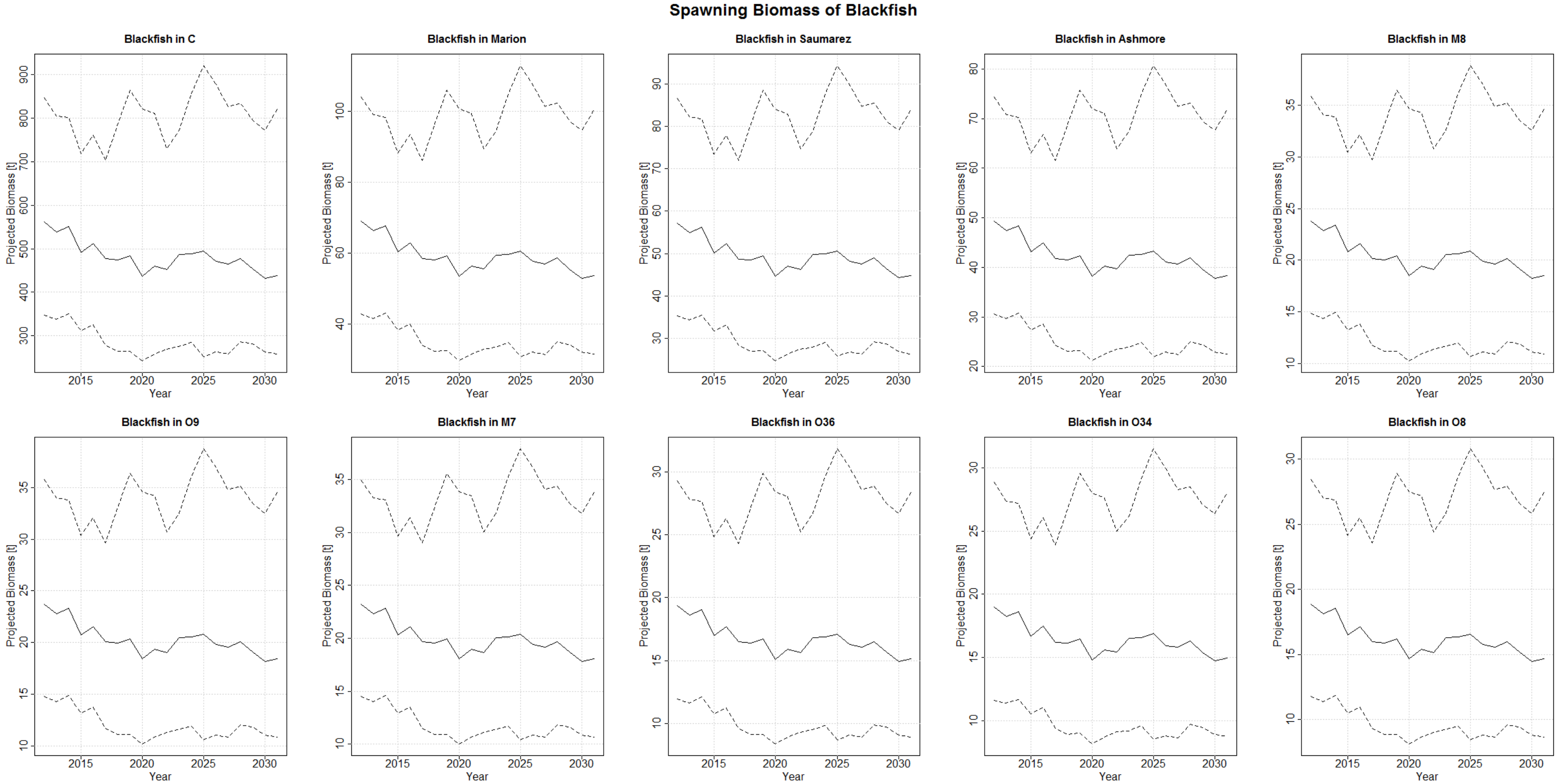


Figure 96. Projected spawning biomass (t) trajectories from 2012 to 2031 for blackfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS but with TACs set to three times higher levels. (Note: y axis does not always include zero).

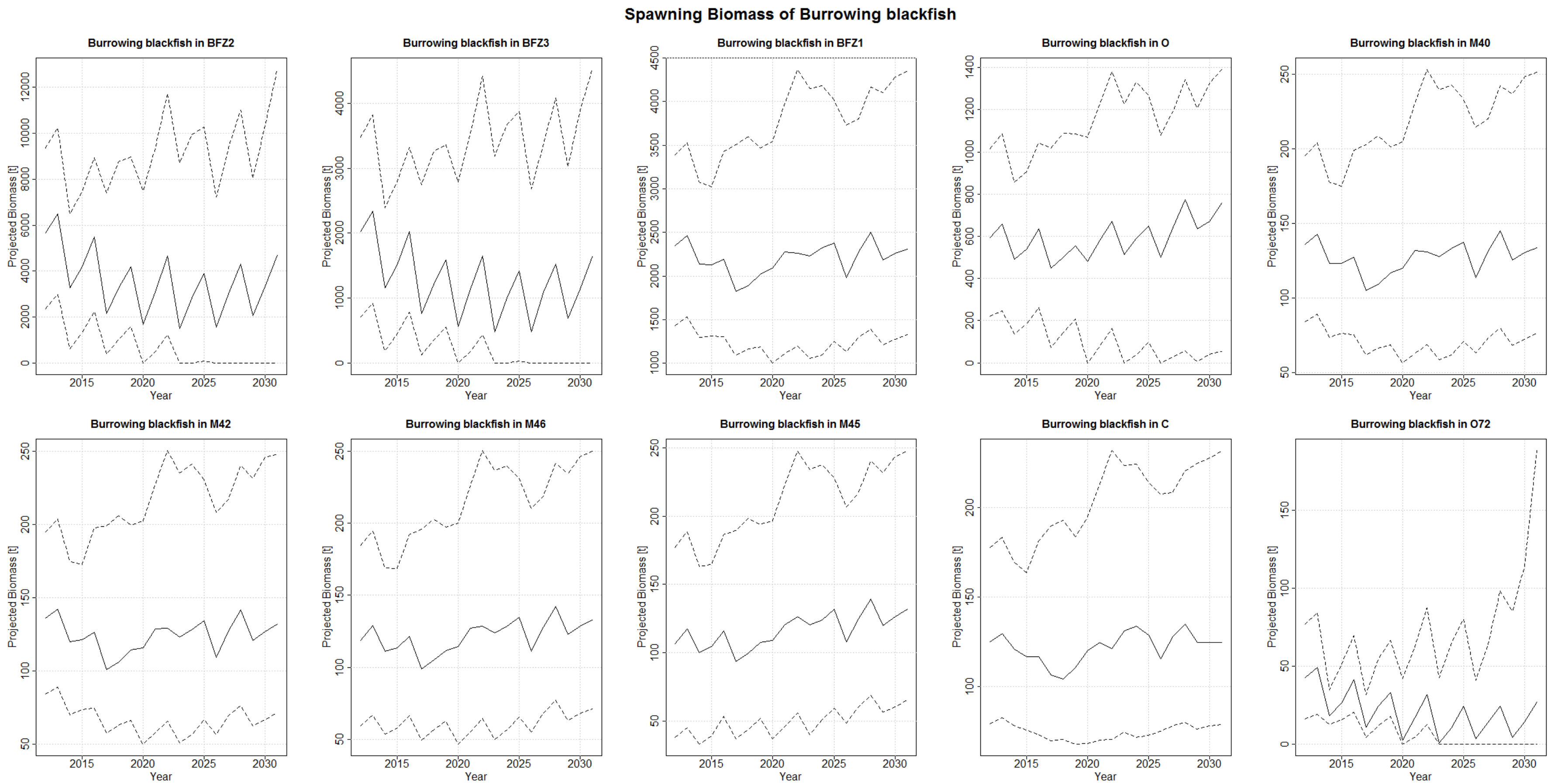


Figure 97. Projected spawning biomass (t) trajectories from 2012 to 2031 for Burrowing Blackfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS but with TACs set to three times higher levels. (Note: y axis does not always include zero).

Appendix N Projected spawning biomass – no RZS and constant F

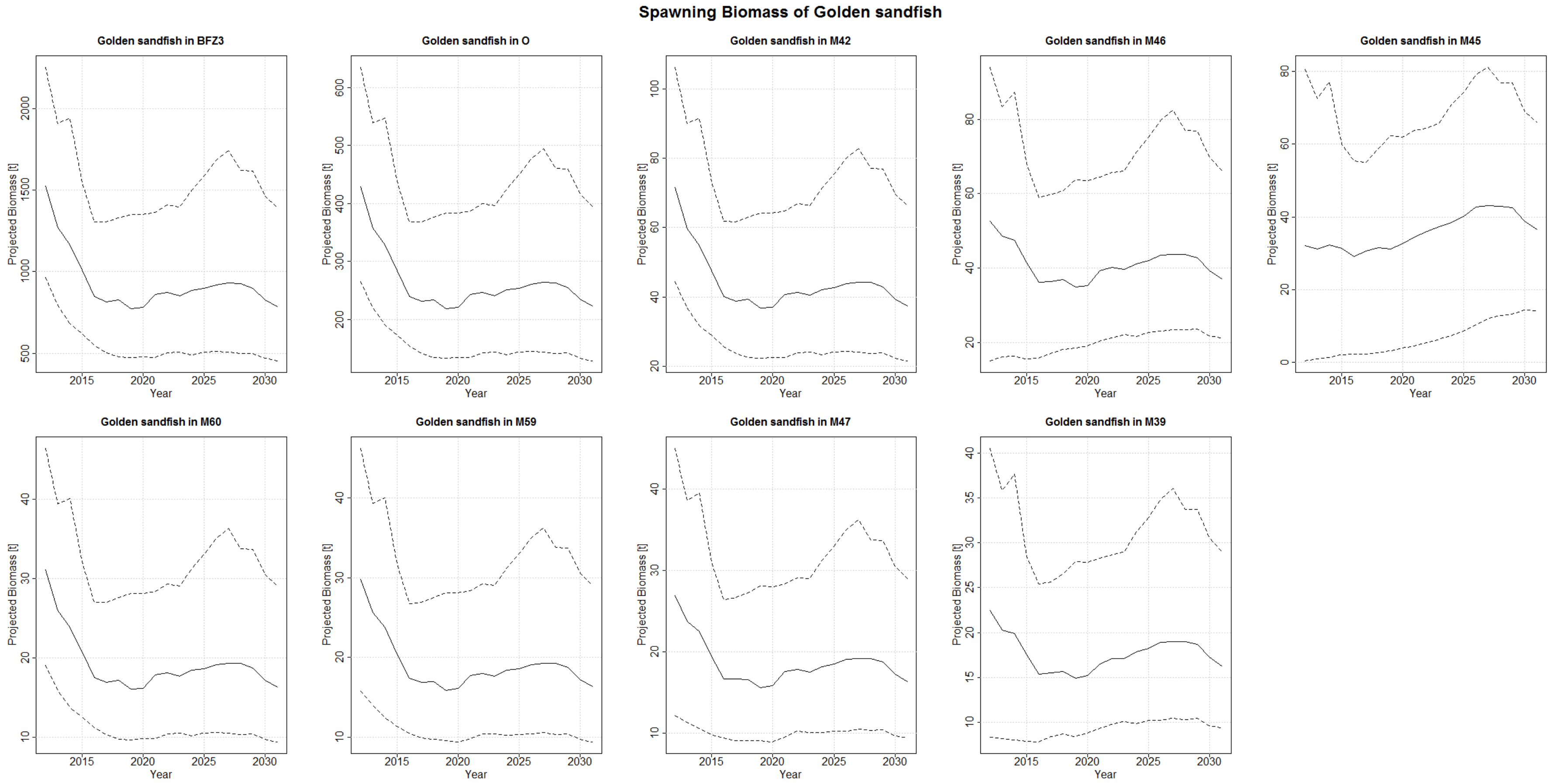


Figure 98. Projected spawning biomass (t) trajectories from 2012 to 2031 for golden Sandfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume no future RZS and a constant fishing proportion of 10% per annum applied to all zones. (Note: y axis does not always include zero).

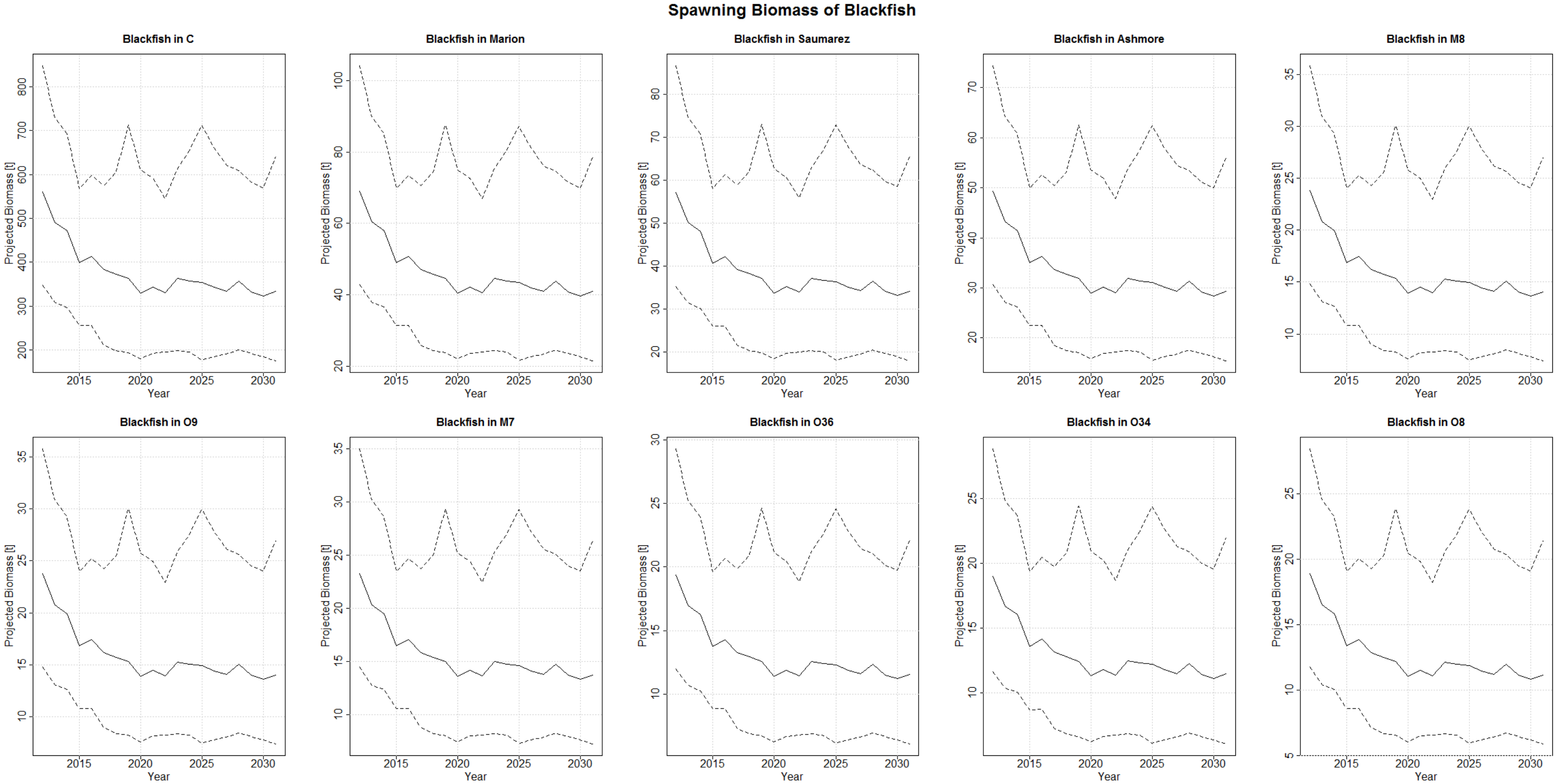


Figure 99. Projected spawning biomass (t) trajectories from 2012 to 2031 for blackfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume no future RZS and a constant fishing proportion of 10% per annum applied to all zones. (Note: y axis does not always include zero).

Appendix O Sensitivity analysis

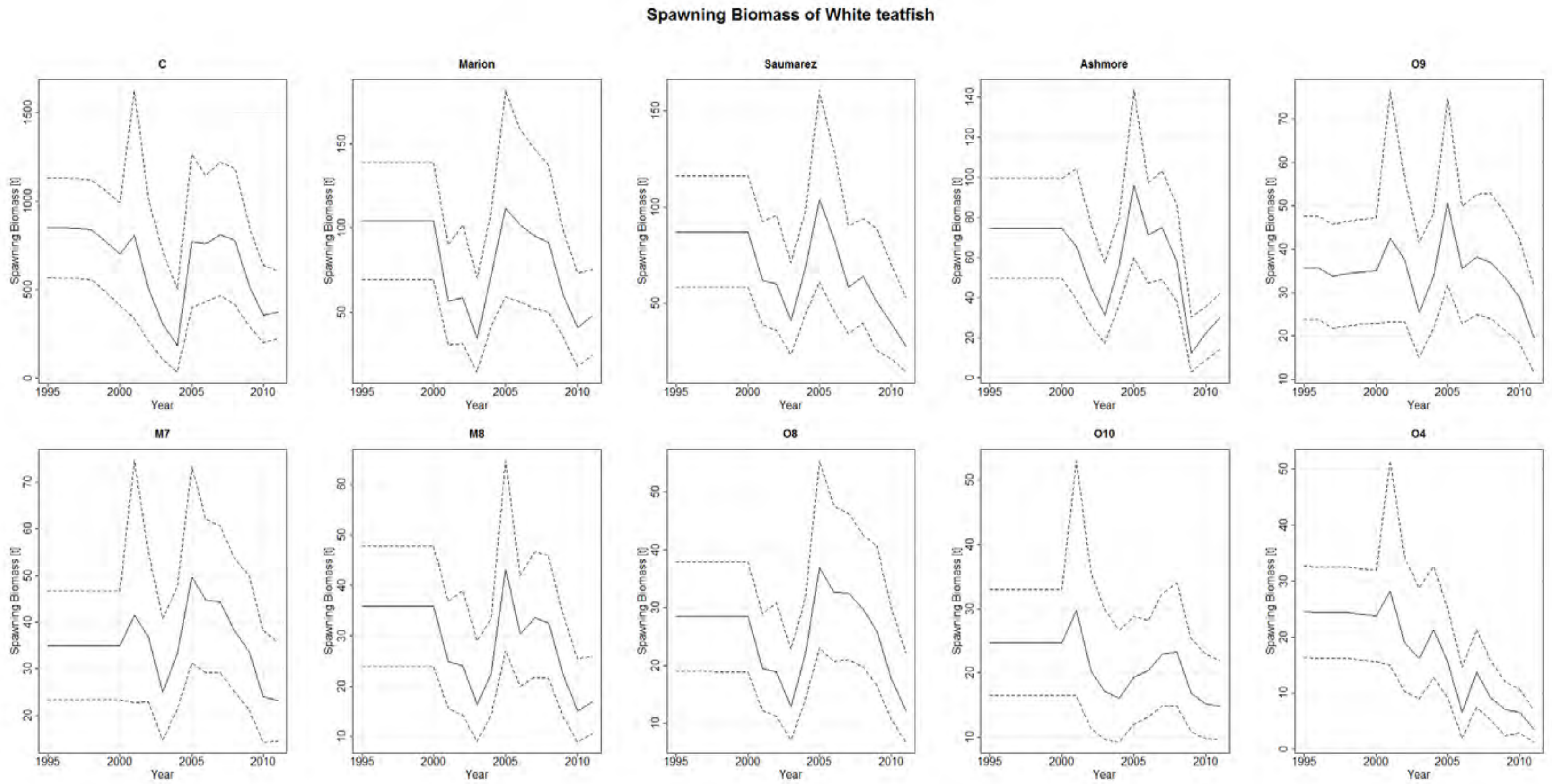


Figure 100. Age-at-maturity sensitivity scenario (age-at-maturity increased one year), and illustrative impact shown on spawning biomass (t) trajectories from 1995 to 2012 for White Teatfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the dashed lines bound 90% of the 16 simulations. (Note: y axis does not always include zero).

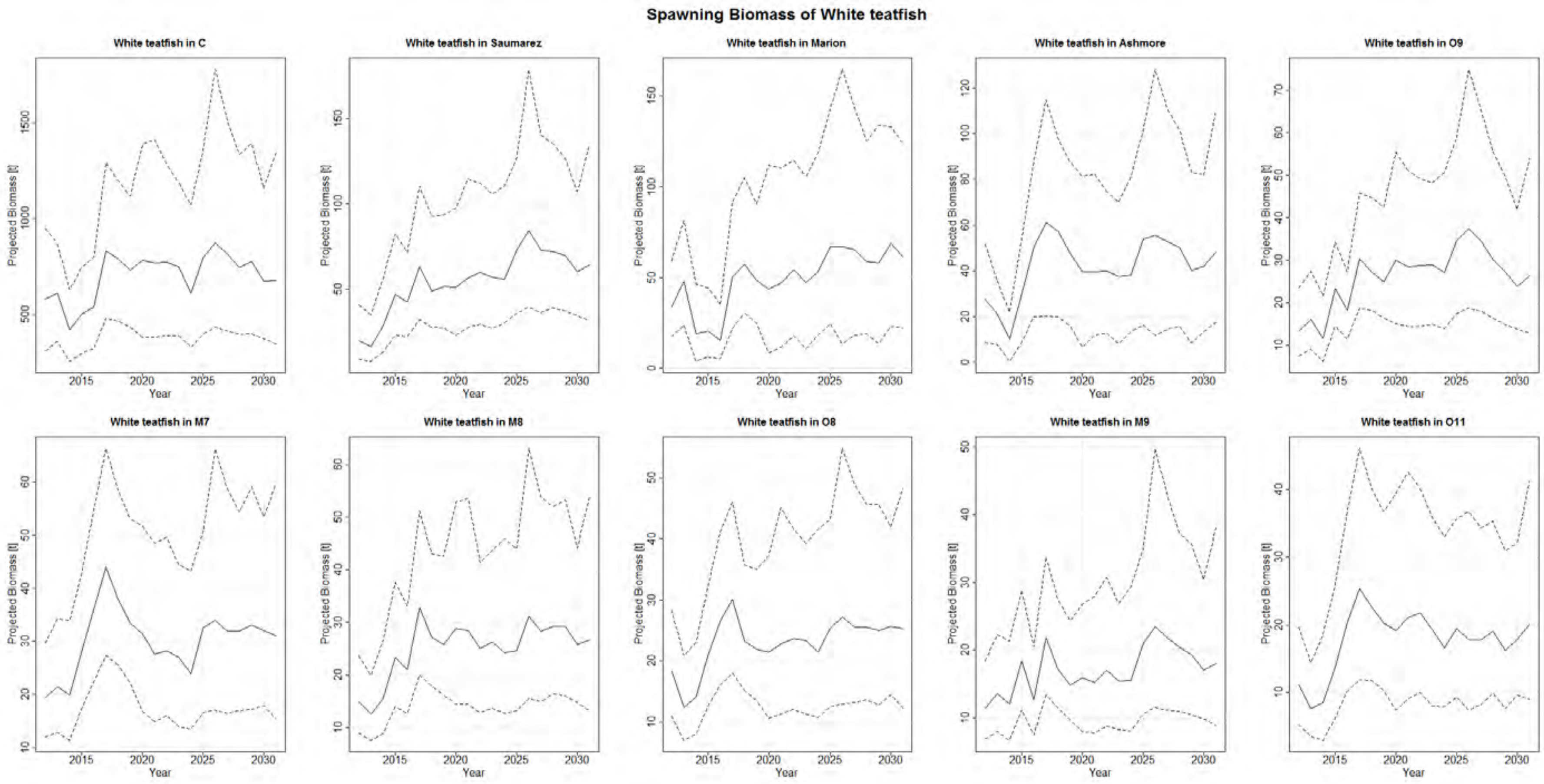


Figure 101. Age-at-maturity sensitivity scenario (age-at-maturity increased one year), and illustrative impact shown on projected spawning biomass (t) trajectories from 2012 to 2031 for White Teatfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the dashed lines bound 90% of the simulations from a total of 16 simulations with 10 replicates of each. Projections assume the RZS with current TACs. (Note: y axis does not always include zero).

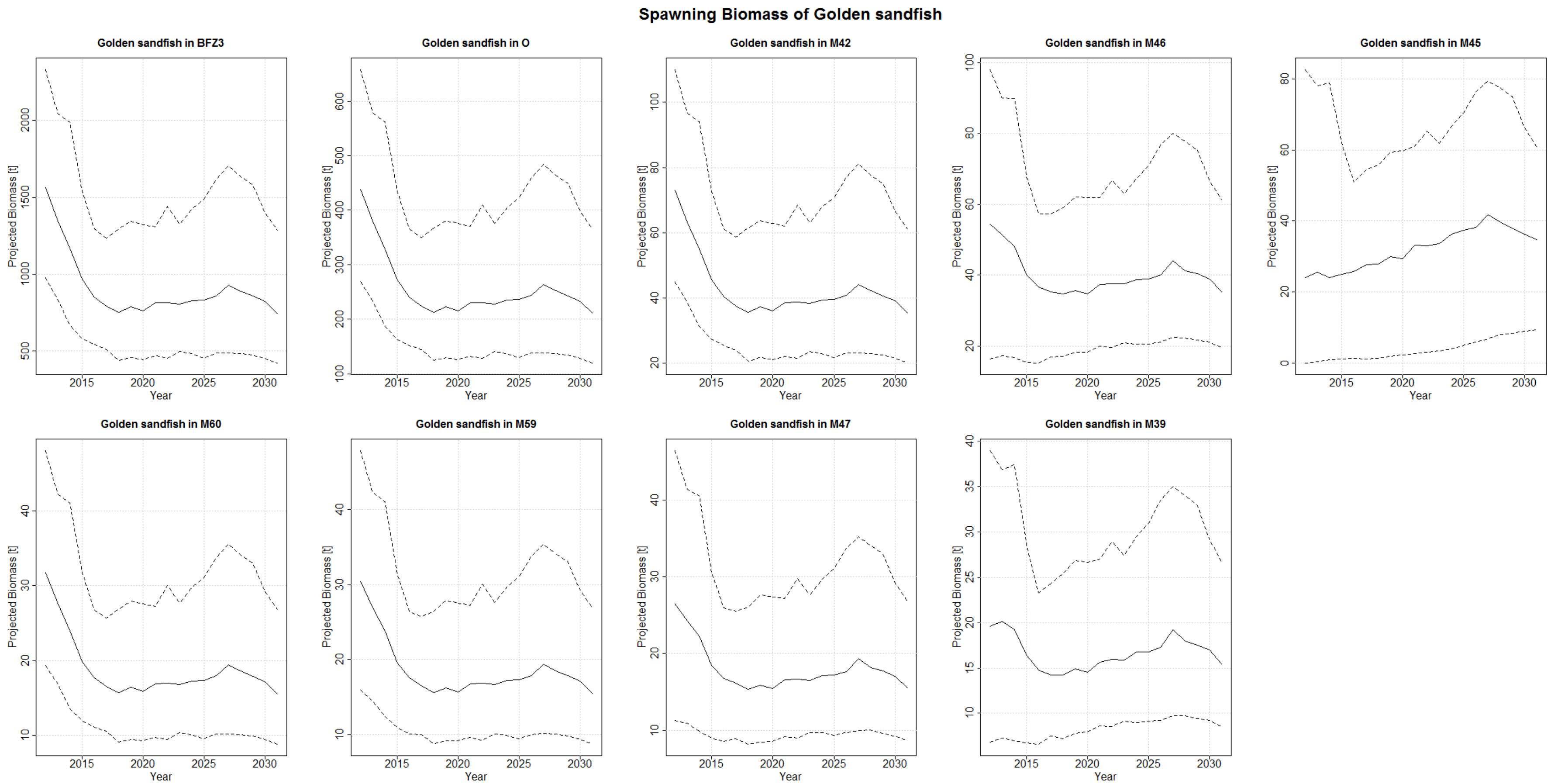


Figure 102. Age-at-maturity with higher TACs sensitivity scenario (age-at-maturity increased one year, catches multiplied by 3), and illustrative impact shown on projected spawning biomass (t) trajectories from 2012 to 2031 for golden Sandfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the dashed lines bound 90% of the simulations from a total of 16 simulations with 10 replicates of each. Projections assume the RZS with current TACs. (Note: y axis does not always include zero).

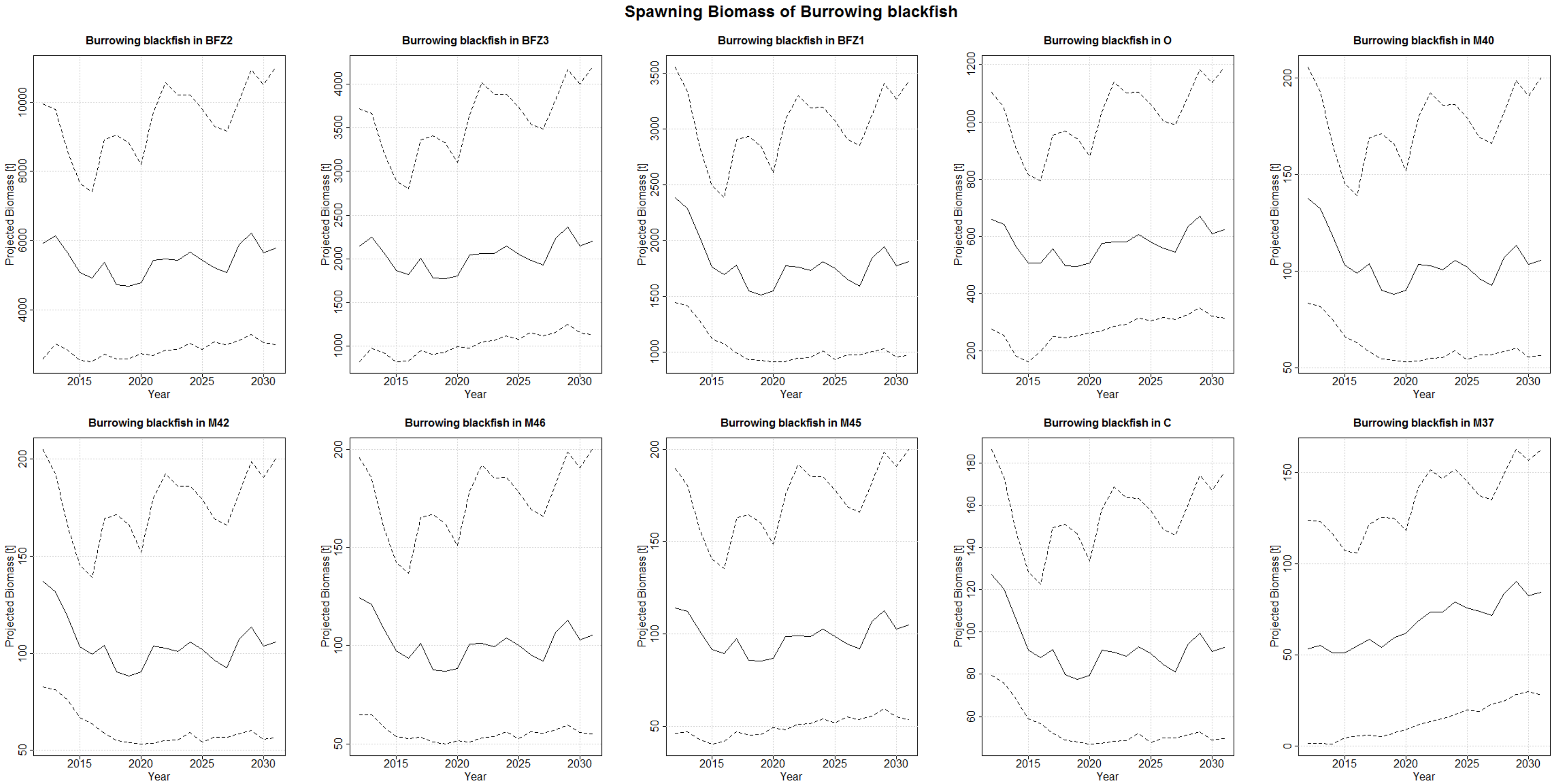


Figure 103. Age-at-maturity with higher TACs sensitivity scenario (age-at-maturity increased one year, catches multiplied by 3), and illustrative impact shown on projected spawning biomass (t) trajectories from 2012 to 2031 for Burrowing Blackfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the dashed lines bound 90% of the simulations from a total of 16 simulations with 10 replicates of each. Projections assume the RZS with current TACs. (Note: y axis does not always include zero).

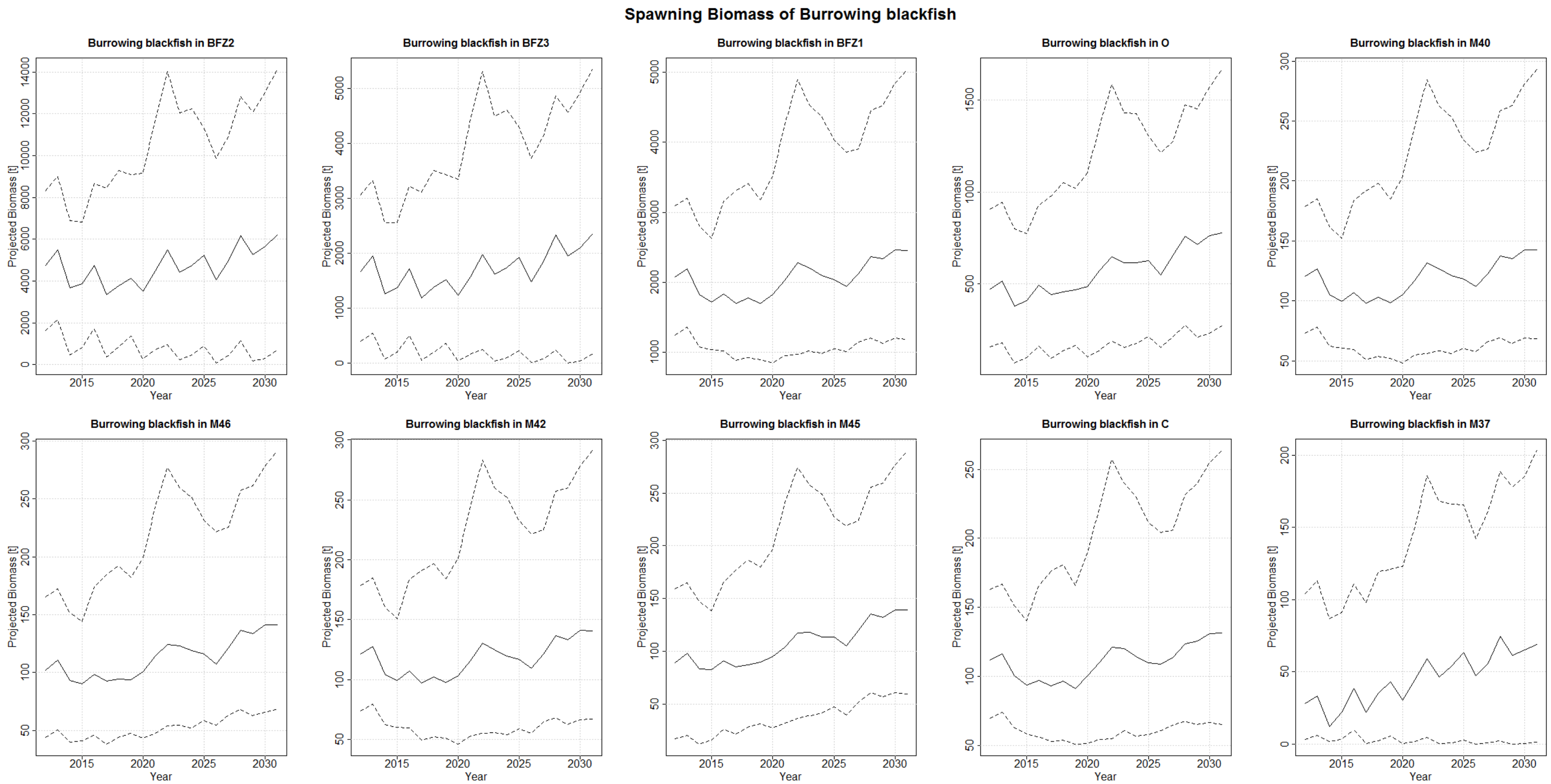


Figure 104. Recruitment variability sensitivity scenario (larger recruitment fluctuations), and illustrative impact shown on projected spawning biomass (t) trajectories from 2012 to 2031 for Burrowing Blackfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the dashed lines bound 90% of the simulations from a total of 16 simulations with 10 replicates of each. Projections assume the RZS with current TACs. (Note: y axis does not always include zero).

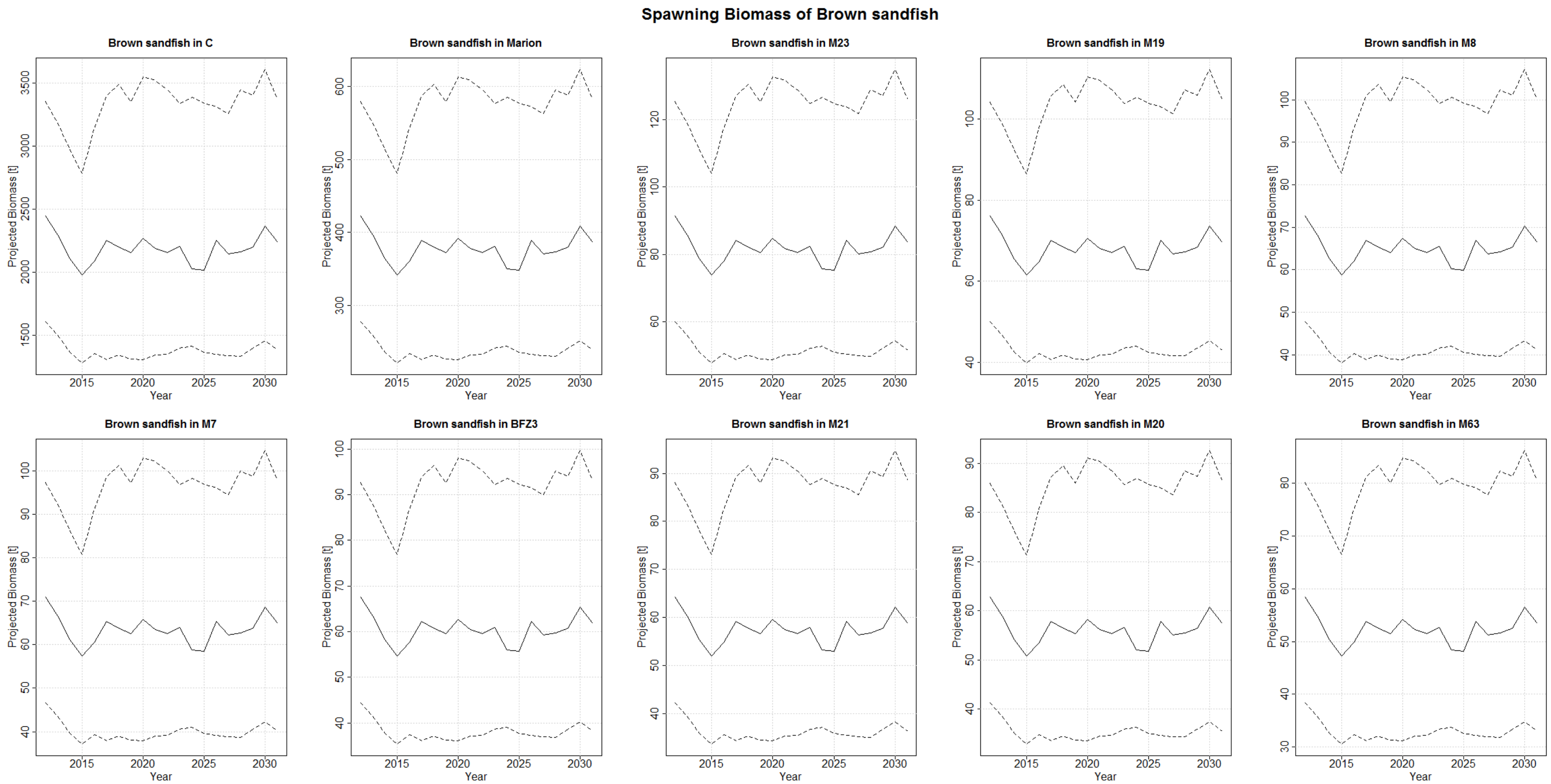


Figure 105. Recruitment variability sensitivity scenario (smaller recruitment fluctuations), and illustrative impact shown on projected spawning biomass (t) trajectories from 2012 to 2031 for Brown Sandfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the dashed lines bound 90% of the simulations from a total of 16 simulations with 10 replicates of each. Projections assume the RZS with current TACs. (Note: y axis does not always include zero).

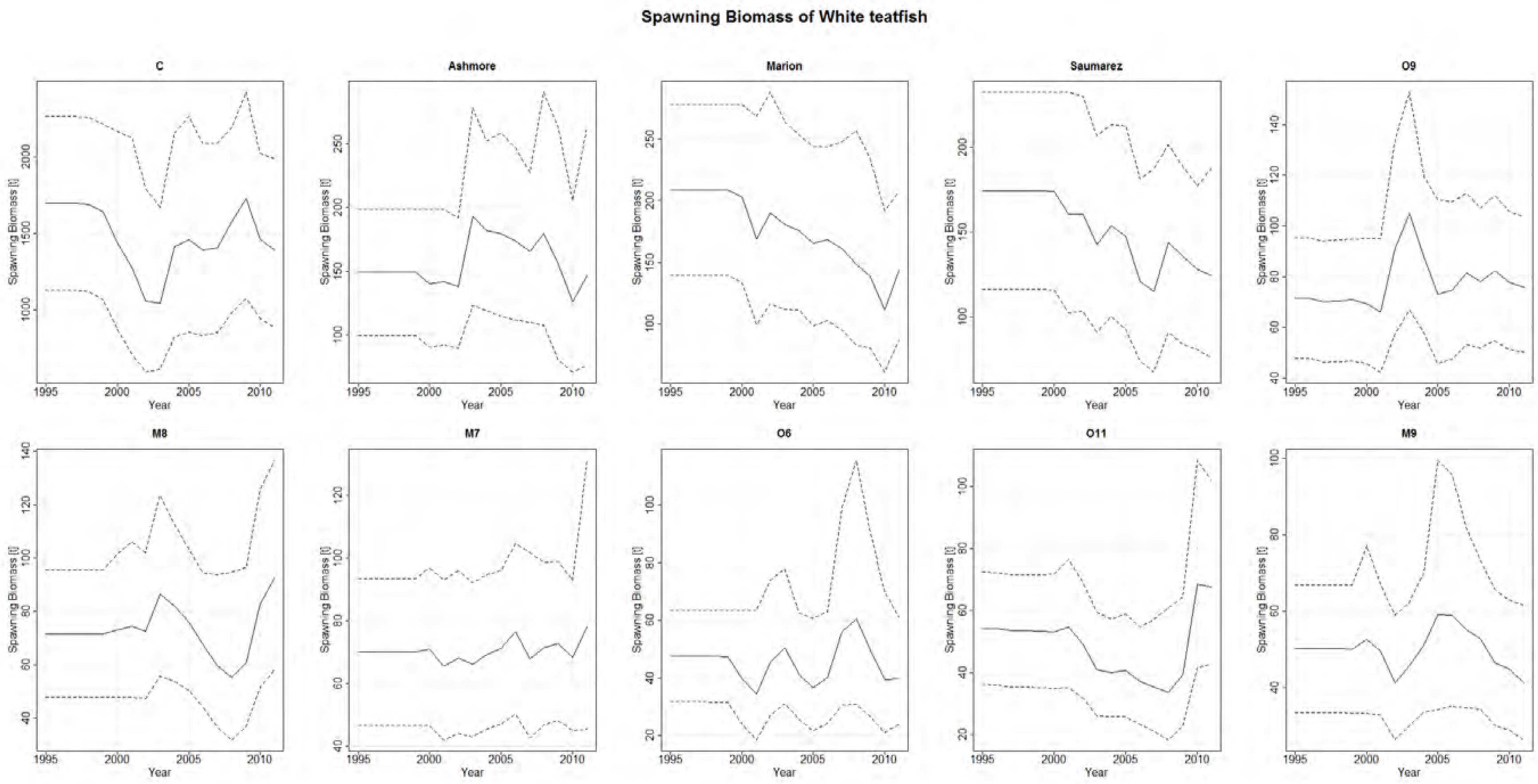


Figure 106. Locally-variable recruitment sensitivity scenario (different recruitment residuals per zone), and illustrative impact shown on spawning biomass (t) trajectories from 1995 to 2011 for White Teatfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines bound 90% of the 16 Reference case simulations. (Note: y axis does not always include zero).

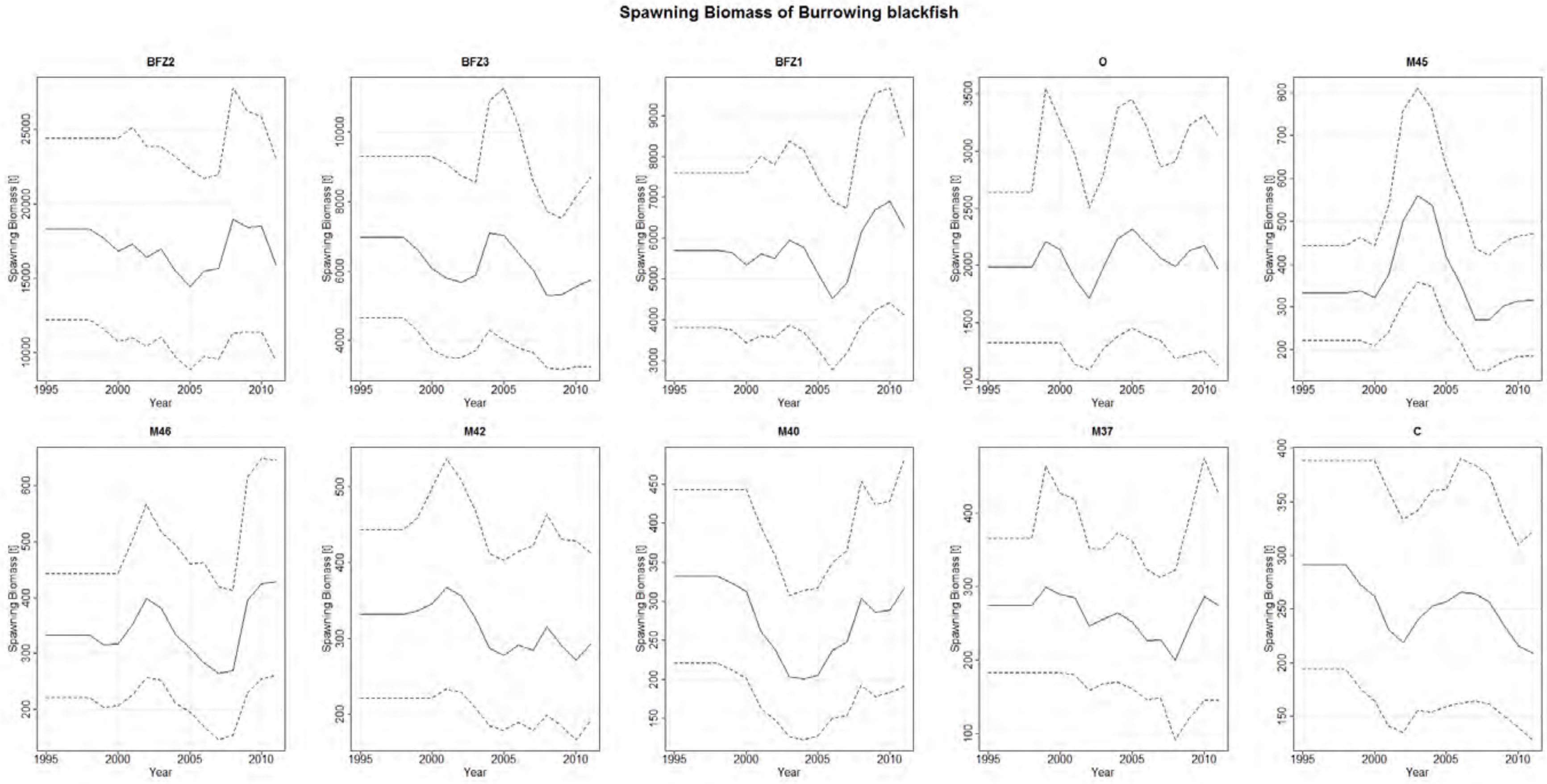


Figure 107. Locally-variable recruitment sensitivity scenario (different recruitment residuals per zone), and illustrative impact shown on spawning biomass (t) trajectories from 1995 to 2011 for Burrowing Blackfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines bound 90% of the 16 Reference case simulations. (Note: y axis does not always include zero).

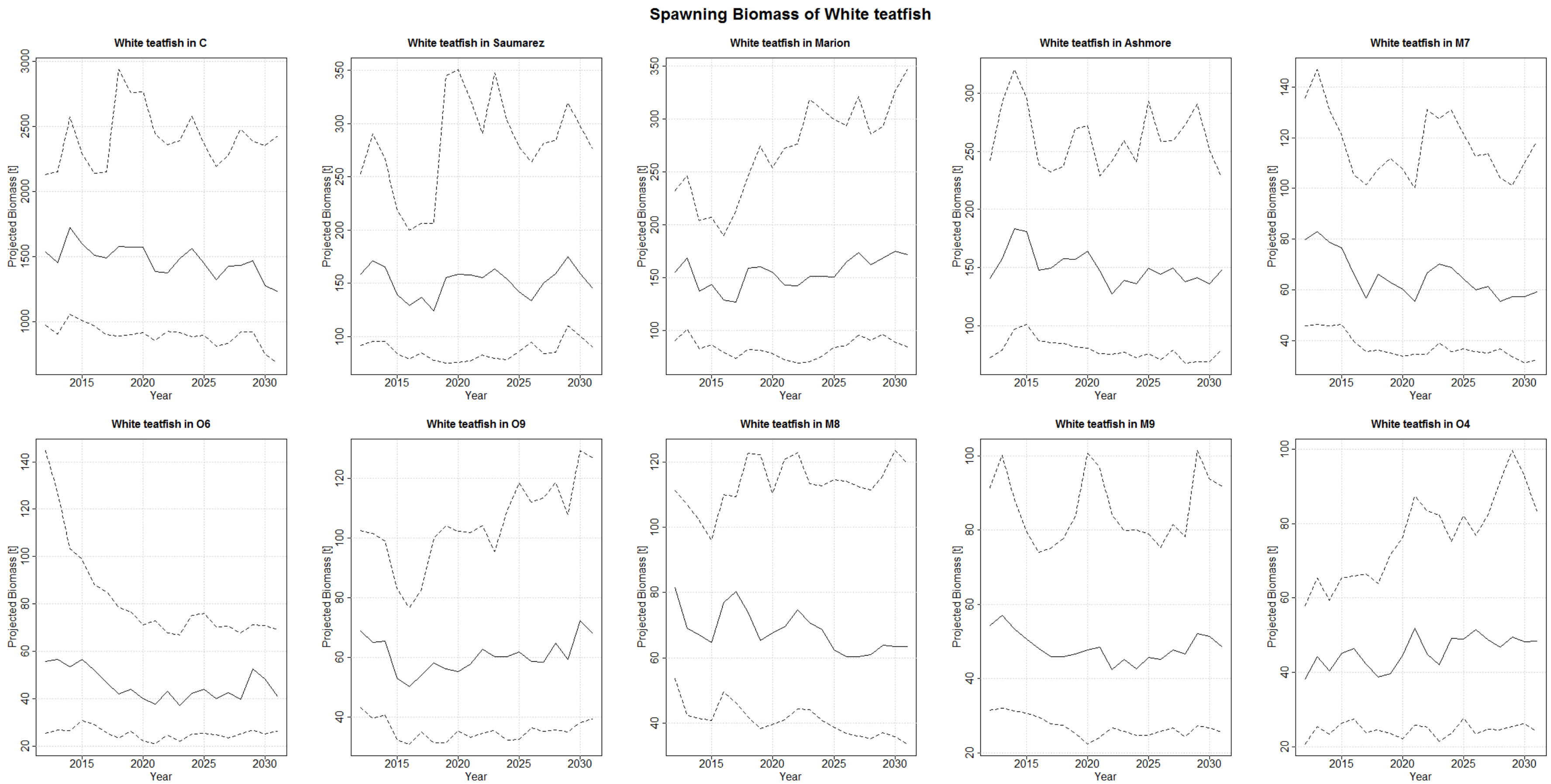


Figure 108. Locally-variable recruitment sensitivity scenario (different recruitment residuals per zone), and illustrative impact shown on projected spawning biomass (t) trajectories from 2012 to 2021 for White Teatfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels. (Note: y axis does not always include zero).

Figure 109. Locally-variable recruitment sensitivity scenario (different recruitment residuals per zone), and illustrative impact shown on projected spawning biomass (t) trajectories from 2012 to 2021 for Burrowing Blackfish in 10 of the 162 zones where it is most abundant. The central solid line is the median and the dashed lines the 90th percentile from a total of 16 simulations with 10 replicates of each. Projections assume continued future implementation of the RZS and TACs similar to current levels. (Note: y axis does not always include zero).

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