NORTH WEST SHELF
JOINT ENVIRONMENTAL
MANAGEMENT STUDY

Management strategy evaluation results and discussion for Australia's North West Shelf

NWSJEMS
TECHNICAL REPORT No. 14

• R. Little • E. Fulton • R. Gray • D. Hayes • V. Lyne
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Final report

North West Shelf Joint Environmental Management Study Final Report.

List of technical reports

NWSJEMS Technical Report No. 1
Review of research and data relevant to marine environmental management of Australia's North West Shelf.
A. Heyward, A. Revill and C. Sherwood

NWSJEMS Technical Report No. 2
Bibliography of research and data relevant to marine environmental management of Australia's North West Shelf.
P. Jernakoff, L. Scott, A. Heyward, A. Revill and C. Sherwood

NWSJEMS Technical Report No. 3
Summary of international conventions, Commonwealth and State legislation and other instruments affecting marine resource allocation, use, conservation and environmental protection on the North West Shelf of Australia.
D. Gordon

NWSJEMS Technical Report No. 4
Information access and inquiry.
P. Brodie and M. Fuller

NWSJEMS Technical Report No. 5
Data warehouse and metadata holdings relevant to Australia's North West Shelf.
P. Brodie, M. Fuller, T. Rees and L. Wilkes

NWSJEMS Technical Report No. 6
Modelling circulation and connectivity on Australia's North West Shelf.
S. Condie, J. Andrewartha, J. Mansbridge and J. Waring

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Modelling suspended sediment transport on Australia's North West Shelf.
N. Margvelashvili, J. Andrewartha, S. Condie, M. Herzfeld, J. Parslow, P. Sakov and J. Waring

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Biogeochemical modelling on Australia's North West Shelf.
M. Herzfeld, J. Parslow, P. Sakov and J. Andrewartha

NWSJEMS Technical Report No. 9
Trophic webs and modelling of Australia's North West Shelf.
C. Bulman

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The spatial distribution of commercial fishery production on Australia's North West Shelf.
F. Althaus, K. Woolley, X. He, P. Stephenson and R. Little

NWSJEMS Technical Report No. 11
Benthic habitat dynamics and models on Australia's North West Shelf.
E. Fulton, B. Hatfield, F. Althaus and K. Sainsbury

NWSJEMS Technical Report No. 12
Ecosystem characterisation of Australia's North West Shelf.
V. Lyne, M. Fuller, P. Last, A. Butler, M. Martin and R. Scott

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Contaminants on Australia's North West Shelf: sources, impacts, pathways and effects.
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E. Fulton, K. Sainsbury, D. Hayes, V. Lyne, R. Little, M. Fuller, S. Condie, R. Gray, R. Scott, H. Webb, B. Hatfield, M. Martin, and D. McDonald

NWSJEMS Technical Report No. 16
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NWSJEMS Technical Report No. 17
Management strategy evaluations for multiple use management of Australia's North West Shelf – Visualisation software and user guide.
B. Hatfield, L. Thomas and R. Scott

NWSJEMS Technical Report No. 18
Background quality for coastal marine waters of the North West Shelf, Western Australia.
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ACRONYMS

ACOM	Australian Community Ocean Model
AFMA	Australian Fisheries Management Authority
AFZ	Australian Fishing Zone
AGSO	Australian Geological Survey Organisation now Geoscience Australia
AHC	Australian Heritage Commission
AIMS	Australian Institute of Marine Science
AMSA	Australian Maritime Safety Authority
ANCA	Australian Nature Conservation Agency
ANZECC	Australian and New Zealand Environment and Conservation Council
ANZLIC	Australian and New Zealand Land Information Council
APPEA	Australian Petroleum, Production and Exploration Association
AQIA	Australian Quarantine Inspection Service
ARMCANZ	Agricultural Resources Management council of Australia and New Zealand
ASIC	Australian Seafood Industry Council
ASDD	Australian Spatial Data Directory
CAAB	Codes for Australian Aquatic Biota
CAES	Catch and Effort Statistics
CALM	Department of Conservation and Land Management (WA Government)
CAMBA	China Australia Migratory Birds Agreement
CDF	Common data format
CITIES	Convention on International Trade in Endangered Species
CTD	conductivity-temperature-depth
CMAR	CSIRO Marine and Atmospheric Research
CMR	CSIRO Marine Research
COAG	Council of Australian Governments
ConnIe	Connectivity Interface
CPUE	Catch per unit effort
CSIRO	Commonwealth Science and Industrial Research Organisation
DCA	detrended correspondence analysis
DIC	Dissolved inorganic carbon
DISR	Department of Industry, Science and Resources (Commonwealth)
DEP	Department of Environmental Protection (WA Government)
DOM	Dissolved organic matter
DPIE	Department of Primary Industries and Energy
DRD	Department of Resources Development (WA Government)
EA	Environment Australia
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
EPP	Environmental Protection Policy
ENSO	El Nino Southern Oscillation
EQC	Environmental Quality Criteria (Western Australia)
EQO	Environmental Quality Objective (Western Australia)
ESD	Ecologically Sustainable Development
FRDC	Fisheries Research and Development Corporation
FRMA	Fish Resources Management Act
GA	Geoscience Australia formerly AGSO
GESAMP	Joint Group of Experts on Scientific Aspects of Environmental Protection
GIS	Geographic Information System
ICESD	Intergovernmental Committee on Ecologically Sustainable Development
ICS	International Chamber of Shipping
IOC	International Oceanographic Commission
IGAE	Intergovernmental Agreement on the Environment
ICOMOS	International Council for Monuments and Sites
IMO	International Maritime Organisation

IPCC	Intergovernmental Panel on Climate Change
IUNC	International Union for Conservation of Nature and Natural Resources
IWC	International Whaling Commission
JAMBA	Japan Australian Migratory Birds Agreement
LNG	Liquified natural gas
MarLIN	Marine Laboratories Information Network
MARPOL	International Convention for the Prevention of Pollution from Ships
MECO	Model of Estuaries and Coastal Oceans
MOU	Memorandum of Understanding
MPAs	Marine Protected Areas
MEMS	Marine Environmental Management Study
MSE	Management Strategy Evaluation
NCEP - NCAR	National Centre for Environmental Prediction – National Centre for Atmospheric Research
NEPC	National Environmental Protection Council
NEPM	National Environment Protection Measures
NGOs	Non government organisations
NRSMPA	National Representative System of Marine Protected Areas
NWQMS	National Water Quality Management Strategy
NWS	North West Shelf
NWSJEMS	North West Shelf Joint Environmental Management Study
NWSMEMS	North West Shelf Marine Environmental Management Study
ICIMF	Oil Company International Marine Forum
OCS	Offshore Constitutional Settlement
PFW	Produced formation water
P(SL)A	Petroleum (Submerged Lands) Act
PSU	Practical salinity units
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SOI	Southern Oscillation Index
SMCWS	Southern Metropolitan Coastal Waters Study (Western Australia)
TBT	Tributyl Tin
UNCED	United Nations Conference on Environment and Development
UNCLOS	United Nations Convention of the Law of the Sea
UNEP	United Nations Environment Program
UNESCO	United Nations Environment, Social and Cultural Organisation
UNFCCC	United Nations Framework Convention on Climate Change
WADEP	Western Australian Department of Environmental Protection
WADME	Western Australian Department of Minerals and Energy
WAEPA	Western Australian Environmental Protection Authority
WALIS	Western Australian Land Information System
WAPC	Western Australian Planning Commission
WHC	World Heritage Commission
WOD	World Ocean Database
www	world wide web

TECHNICAL SUMMARY

The management strategy evaluation (MSE) framework has been developed for scientific support of regional multiple-use management of marine and coastal resources. The MSE approach was used in the North West Shelf Joint Environmental Management Study to demonstrate the variation in possible outcomes from prospective and existing management strategies and development scenarios. In this report we provide an evaluation of the results of computer simulations designed to demonstrate the utility of the MSE framework. Relevant background and further elaboration can be found in three companion reports Gray et al. (2006), Fulton et al. (2006b) and Hatfield et al. (2006).

The key message from the simulations is that patterns in indicator variables under the integrated management strategy are clearly distinguishable from those under both the status quo and enhanced management strategies. Notwithstanding a few notable exceptions, this outcome is consistent across a range of uncertainties, including those treated explicitly in the alternative model specifications and development scenarios, and those treated as random variables in separate computer simulations. The outcome is consistent because the integrated strategy balances impacts across a range of sectoral activities that impact not only the sector itself, but also other sectors, or the human population and ecosystem as a whole. In contrast, the sectorally-based management strategies (i.e. the status quo and enhanced strategies) invoke broadly similar (to each other) patterns in the indicator variables, although the enhanced strategy has differential impacts on some conservation and social variables.

The integrated management strategy outcomes improves upon those from the sector-based strategies because it actively manages the region from a multiple-use perspective and simultaneously monitors, and responds to, indicator variables that represent social, environmental conservation, economic and safety considerations. With the exception of cases where uncertainty dominates the simulation results (notably prawn biomass and regional habitat coverage), the integrated management strategy (compared to the other, sector-based, management strategies) leads to:

- significant increases in the stocks and catch rates of high-value fish species;
- increased recreational fishing catch;
- improved abundance of species of high conservation value (particularly turtles, though the magnitude of this can be dependent on model type and assumptions);
- improved biodiversity;
- a reduction in commercial fishing effort;
- a reduction in commercial fishery gross margins;
- a decline in contaminant impact; and
- a decrease in the risk of ship collisions and catastrophic spills.

The two sector-based management strategies perform differently from each other according to only four indicator variables. The enhanced strategy leads to increased commercial catch and CPUE of high-value target species and greater recreational catch, as compared to the status quo management strategy. Enhanced management also leads to lower habitat fragmentation at local scales than status quo management.

These results provide a limited number of examples to demonstrate how alternative management strategies can alter natural resource use in a multiple-use setting. What they also demonstrate, however, is that the MSE framework is now developed sufficiently to provide robust evaluations of alternate management strategies, model specifications and development scenarios. Scientists and managers now have available powerful simulation tools that can assist in evaluating potential strategies, scenarios and model specification to help achieve better ecosystem level and sectoral outcomes and to guide scientific research and data collection, to best serve regional natural resource management.

The calibration of the model software using real-world data allows easy identification of shortcomings in both the model and available data. It also highlights the fact that particular indicators can be used to discriminate clearly among some, but not all, management strategies, depending on the magnitude of, and variation in, their relative impacts on indicator variables; showing why a suite of indicators, rather than a single indicator, should be used in comparative management analyses. The degree to which management strategies can be demonstrated to be substantially different from each other also depends on the uncertainties in present knowledge, existing data and scenarios for the future.

The simulation results demonstrate that differences in ecosystem evolution from alternative model specifications are predominantly robust to the choice of management strategy and development scenario combination. Compared to the pessimistic and base case specifications, the optimistic model specification consistently leads to greater recovery and resilience of the ecosystem, as measured by the chosen bio-physical indicator variables. Although not quite as clear-cut, the pessimistic specification leads to lesser recovery and resilience than that produced by the base case model specification.

Four important issues emerge from the comparison of model specifications. Firstly, the range of environmental outcomes produced by the alternative representations of the system appears to be relatively small. Whether this is a true reflection of reality is due to inadequate contrast among model specification or is a result of model calibration with patchy data, is open to both debate and to empirical testing in follow-up work. Secondly, the promising signs of recovery in species of high conservation value, notably turtles, appears to be consistently exaggerated across model specifications. Additional work has shown that this may be a symptom of model type dependency. The use of alternative model types (e.g. age-structured population models) indicate a much slower recovery (on the order of centuries) and very long-term dynamics. Ultimately, further model testing and empirical evidence from monitoring are required before one can be confident about which of the turtle population dynamics are closest to reality; and it is likely that species such as these will benefit from specialised representations. Thirdly, the alternative model specifications lead to a variety of interesting economic outcomes across management strategies and development scenarios. Of particular significance in this regard is the case of the pessimistic model specification in which the interplay between fish population dynamics and fisher decision-making leads to lower gross margins despite higher catch rates: this occurs because of the change in catch composition that results from a decline in high-valued species and a recovery of low-value species that exhibit weak habitat dependence.

The fourth important issue to arise from the comparison of model specifications is that of uncertainty. Obviously the faithfulness of the model in capturing the salient sources of uncertainty that truly exist is a critical issue. The results attributable to the various model specifications show clearly where the modelled uncertainty is greatest: notably in the banana prawn population dynamics (and, therefore, banana prawn catches) driven by rainfall events, and the benthic habitat dynamics. In these cases there is a good working knowledge of which drivers contribute to gross variation in the relevant variables. While other sources of uncertainty are included in the model their relationship to variables is less well understood and they ultimately have relatively little impact on the overall simulation results. In other applications of the MSE approach, either on the North West Shelf or elsewhere, model-induced variation will need further careful attention.

The results reported for the contaminant dynamics modelling provide an encouraging demonstration of capability that could be extended for direct use by government and industry managers. The modelled contaminant plumes provide an interesting perspective, not only on the surface and depth-averaged extent of detectable levels of contaminants released from point sources, but also on the quite restricted extent of toxic levels of contaminants near these point sources. For all contaminants examined, detectable levels extended to large plumes and only a small proportion of these plumes contained toxic levels of contaminants. The only exception to this is copper, for which toxic concentrations can persist for all but the fringe of the detectable-concentration plume if at historical levels. The spatial extent of toxic copper concentration is drastically reduced (to quite a small area) however, once the more rigorous guidelines now in place are enforced.

The results of contaminant modelling also shed light on the placement of monitoring stations. Monitoring activities must clearly be scaled and placed according to a balance among cost of monitoring, the faithfulness of the detected signal to true levels of contaminants, the impact of contaminants on the health of biota (including humans) and the likely response of industry and government to the data collected. The contaminant models used in the present study make use of oceanographic, tidal and wind data to advect and diffuse plumes emanating from point sources. Using the outputs from these models, it is relatively straightforward to show that the positioning of monitoring stations can influence both their cost and their effectiveness in accurately recording true contaminant levels.

The relative importance of factors affecting mortality due to contamination can also be evaluated within the MSE modelling framework. Lethal and sub-lethal effects of contamination are not simply a matter of contaminant concentration at point sources or the environmental persistence of particular contaminants. Contaminant toxicity is also affected differentially by various characteristics of biota: characteristics such as dietary and movement habits, location of preferred habitat, reproductive rates and contaminant excretion rates. As the results demonstrate, dispersion and dilution of contaminants is important, as is the temporally coincident location of susceptible biota and contaminant plumes. The simulation results also provide useful guidance on the issue of variability of impacts of contaminants. One observation worthy of emphasis in this regard is that localised effects from point sources can have highly variable impacts on small collective components of the population but these may have negligible impact on the population as a whole. In the case of schooling species, local impacts can be significant: for example some contaminants, if sufficiently concentrated locally, may be harmful to the predators (including humans) of affected species, whereas average concentration levels in plumes, and average contamination in the population, may appear to be quite safe. In assessing risks of, and adopting standards for, contaminants, therefore, managers may wish to modify the strategies used to achieve human and environmental health objectives in some cases.

Finally, of note from the contaminant modelling results is the (perhaps unsurprising) consistency of the patterns in contaminant dynamics across management strategies, model specifications and development scenarios. Contaminant dynamics are broadly similar for all five contaminants examined: in all cases there are stepwise reductions in simulated measures of contaminant concentration associated with development pulses. These stepwise reductions become progressively greater as enhanced and integrated management strategies are simulated, especially under the optimistic model specification.

It is worth reiterating, however, that the contaminant simulations are based on limited data and knowledge. Although baseline data, point-source flow data and oceanographic data were available for model calibration, there is very little information available about direct impacts of contaminants on adult and other active biota in the North West Shelf region (most information available is for larvae in the laboratory). Nonetheless, much has been achieved in establishing an analytical computer-based framework within which new data and knowledge can be used to improve our understanding of risks associated with contaminant flows, especially in the North West Shelf region.

Within the projection period of 15 years, distinct patterns in the spatial distributions of flora and fauna emerge from the MSE simulations across model specifications. These patterns are similar to what one would expect from an ecological viewpoint. Firstly, prawn distributions are more patchy under the pessimistic specification and, as biomass increases with more optimistic interpretations, they become more evenly distributed. This pattern also characterises the finfish species, including sharks. Secondly, under the pessimistic model specification, the turtle population is concentrated offshore in cases with little fishing pressure, or in favourable habitat around the Monte Bellos. Turtles are more widespread under the optimistic specification, however. Thirdly, sponge and reef habitat suffer greater depletion under the pessimistic specification (especially offshore), while recovery under the optimistic model tends to be greater in offshore and mid shelf areas. Fourthly, mangroves and seagrass maintain their distributions across model specifications. The seagrass result may be because of inadequate data for informing wider model distributions; but for the mangroves it is because there is little to disturb these species throughout much of their range.

The impact of development scenario on spatial distributions of flora and fauna is much less marked than that of model specification. Indeed changing the development scenarios makes virtually no difference. This is due to the fairly limited spatial extent of the potential impacts. Not surprisingly, the most significant impact is at fine scales on mangroves, which are affected directly in the vicinity of industrial developments. From a management perspective, fortunately, these impacts are localised and in many mangrove forests there is steady recovery.

Finally, the impact of management strategy on spatial distributions of fauna and flora is clearest when comparing the status quo and integrated management strategies. Broadly, there is very little impact of management strategy on the spatial distributions of prawns, mangroves and seagrass. More marked is the impact of management strategy on the spatial distributions of targeted finfish, sponge and reef habitat, sharks and turtles.

Under the status quo management strategy the populations of sharks and targeted finfish become depleted and their remaining distributions appear to be displaced from fishing grounds to outlying areas. Also under this strategy, sponge and reef habitat contract to the mid shelf area, again away from the trawl fishing zones, and turtles are reduced in all but offshore areas. Enhancement and integration of management leads to more even spatial distributions of these biota. Turtle populations recover inshore and become more evenly distributed. Sharks and targeted finfish also become more evenly distributed, although they remain relatively more concentrated outside fishing zones. Sponge and reef habitat also recover in a less patchy distribution, recolonising substrate in deeper water, particularly when the system is modelled as highly productive.

In conclusion, the overall impression gained from the results is that, given the available data and the limited number of management strategies, model specifications and development scenarios examined, much of the marine and coastal environment of the North West Shelf has retained its ecological integrity. The projection period of the simulations also indicates that there is a strong possibility of ecological recovery from existing impacts even under increased economic development, given time (in some cases decades) and provided suitable management strategies are put in place. Enhancement to existing sector-based management strategies has been demonstrated to yield some changes to projected outcomes. Integrated management, however, appears to offer the greatest rewards.

1. INTRODUCTION

Management Strategy Evaluation (MSE) is a simulation based methodology that can be used to test and compare the likely outcome of following alternative management strategies that are each directed at achieving specified management objectives. A management strategy in this context is a combination of a monitoring program, status assessment based on analysis of the monitoring data, selection of management measures in response to the findings of the status assessment, and implementation of the chosen management measures. MSE can be used to compare strategies that differ in any of these aspects.

The MSE approach allows comparison of management strategies using performance measures that are derived from management objectives, so that the comparisons are made in terms of the overall management performance rather than in terms of intermediate measures such as scientific accuracy of monitoring. MSE explicitly includes uncertainty at all levels: uncertainty, for example, in the dynamics of the system being managed, in the monitoring program, and in the implementation of management measures. Consequently one can examine the robustness of strategies to deliver management objectives despite uncertainties, as well as the gain in management performance from investment that resolves key uncertainties. In this context it is ideally suited to being used to develop and test adaptive management strategies which rely on feedback between detection of departures from intended outcomes and correction through a planned management response.

One of the aims of NWSJEMS was to develop scientific tools to support achievement of ESD for the NWS ecosystem as a whole, including management of the individual and cumulative effects of the various human uses and activities there. While MSE has been applied to management of different industry sectors individually, it has not been applied before to an ecosystem and all industry sectors as a whole.

There are significant challenges in applying MSE to the multiple use management of the NWS ecosystem, due to the high level of uncertainty about how ecosystems work and the complexity of representing the impacts, the benefits, the response of the sectors to management decisions, the future development and the management strategies of several industry sectors simultaneously. The basic approach remains the same as in simpler applications, however, and involves development of conceptual and computer models to represent:

- a range of ways the biophysical world is thought to work;
- the activities, impacts and benefits associated with the industry sectors; and
- possible monitoring and management strategies.

These models are used together to compare the range of outcomes expected under alternative management strategies.

The MSE framework is designed to emulate environmental, social and economic conditions associated with the state of an ecosystem, as it evolves in response to natural forcing and human use. Critical to integrated MSE is the clear definition of the three main elements *strategy*, *specification* and *scenario*.

1.1 Strategy

A *strategy* is a deliberate existing or planned course of action (in this case to do with management of resources) by one or more people. It may be:

- a management strategy that constrains human use in order to achieve environmental, social and economic objectives;
- a monitoring program designed to observe and measure the state of the ecosystem through time and space in order to build a set of environmental, social and economic *indicators*;
- a business or private strategy aimed at achieving business outcomes or personal advantage. It may be a particular set of policy instruments or governance arrangements;

or a combination of these and other measures.

1.2 Specification

A *specification* is either the system itself or a computer representation (or model) of the real system. Uncertainty in knowledge usually leads to several alternative specifications of the system, which include the natural ecosystem and relevant components of human society. These specifications represent alternative hypotheses about how the system evolves in response to natural events and human actions.

1.3 Scenario

A *scenario* is a future projection of various factors that impact on the system, but which are not included explicitly in any of the computer representations (models) of the system. The factors projected into the future are used as input data and include things such as human population growth patterns, industrial development, climate change and variability, and anticipated changes in recreational or industrial usage of natural resources.

1.4 MSE outputs

For each combination of a *strategy*, a *specification* and a *scenario*, the MSE provides output data in many forms, including: time series, both for overall totals and in the form of GIS layers (maps and images) for the various indicator variables. The display of these data may then be used to compare and contrast similar displays for different combinations of *strategy, specification* and *scenario*. Overlays of maps and images build up complete pictures of the spatial characteristics of the ecosystem at particular times. Such overlays can be updated through time to produce animated maps and images that allow the user to view the dynamical evolution of the real or modelled system under alternative combinations of strategy, specification and scenario. Just such a set of overlays and overall time series for the NWS MSE can be found on the DVD accompanying the comparison report by Hatfield et al. (2006).

1.5 The study area

The North West Shelf study area extends 1500 km along the Pilbara coast from North West Cape to Port Hedland, and out from the coast to the 200 metre depth contour, encompassing an area of 110000 square kilometres (figure 1.5.1). Of this area, 32000 square kilometres are in water depths less than 25 m and 25000 square kilometres are in Western Australian State waters.

This broad shelf is characterised as having a tropical hydrographic regime (Wyrtki, 1961; Condie et al. 2003; Condie et al. 2006), with a sharp distinction between naturally turbid inshore waters and clearer offshore waters. The seabed in this area is mostly calcareous sands and fine muds (Jones, 1973; McLoughlin & Young, 1985). There is also a patchy coverage of reef and sponge beds (CMR and DEP 2002; Althaus et al. 2006a).

Biologically the study region has reasonably high productivity (Tranter, 1962; Kabanova, 1968; Motoda et al. 1978), with diverse Indo-West Pacific fish fauna (Sainsbury et al. 1997), and crustacean populations (Sainsbury, pers. comm; Bulman, 2006). The form of the natural environment (in particular the biogenic habitat) has been shown to play a significant role in structuring the distribution of biological stocks in the area (Sainsbury et al. 1997; Althaus et al. 2006b).

A number of industries put pressure on the environment within the study area, including petroleum exploration and extraction, tourism, coastal development, salt production, port operations and fisheries. Not all sectors are equally intensive or have an equal historical span. For instance, while fisheries is not the biggest sector on the NWS economically it has had significant effects on the biota of the NWS during the past 36 years (Sainsbury, 1987, 1988). For further details on all sectors see the summaries below and further details in Fulton et al. (2006a).

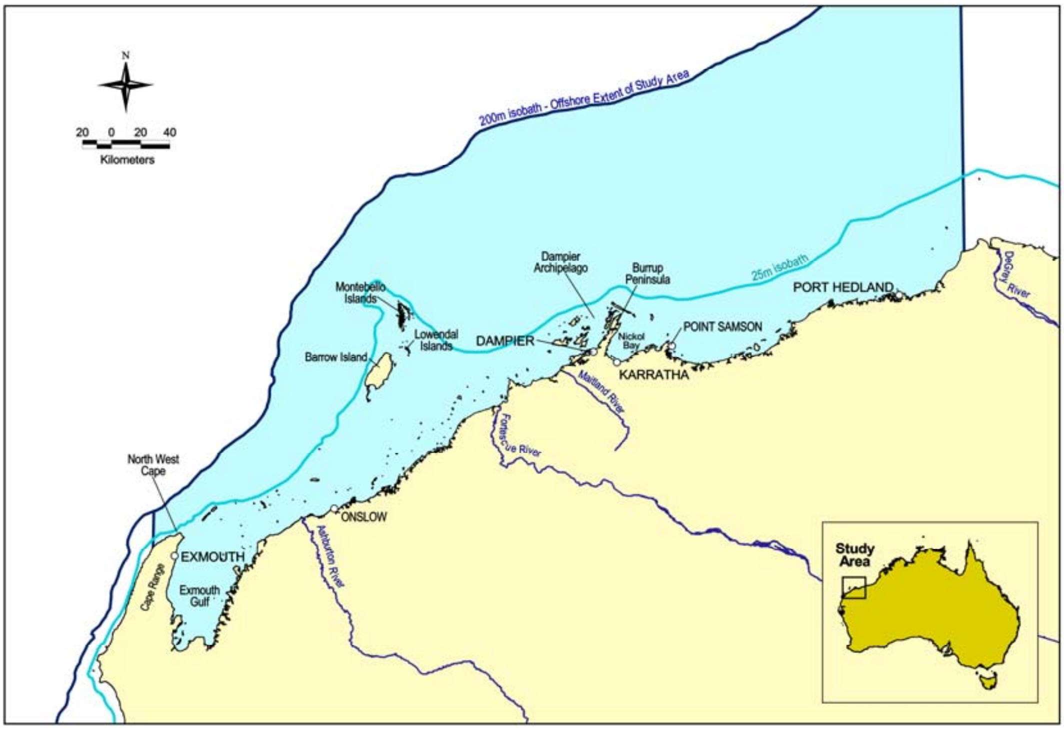


Figure 1.5.1: Map of the study area.

1.5.1 Fisheries

The three major commercial fisheries in the Pilbara are the Nickol Bay Prawn Fishery, the Onslow Prawn Fishery, and the Pilbara Finfish Trawl Fishery. Diving for pearl oyster is also carried out and there is a small finfish trap fishery. Established fishing operations are located at Onslow, Dampier, Point Samson and Port Hedland.

The major fishing operations (for finfish) during the last four decades have been:

- a Japanese trawl fishery targeting *Lethrinus* at 30 to 120 m depth from 116°E to 117°30’E (1959 to 1963);
- a Taiwanese pair trawl fishery that operated between 30 and 120 m depth (1972 to early 1990s) and took many species, mostly *Nemipterus*, *Saurida*, *Lutjanus* and *Lethrinus*;
- the current domestic Australian trap fishery (1984 onwards) that fishes to 80 m depth in areas that had previously seen little trawling and targets *Lethrinus*, *Lutjanus* and *Epinephelus*; and
- the domestic Australian trawl fishery (1989 onwards) that operates between 30 and 120 m depth, east of 116°45’E, targeting mainly *Lutjanus* and *Lethrinus*, but also capturing *Nemipterus* and *Saurida*.

The total catch for the region in the 1999/2000 season was 3356 tonnes and was estimated to have a value of A$18.6 million.

The three prawn fisheries in the North West Shelf study region are those of Exmouth Gulf, Onslow and Nickol Bay. Annual catches in these fisheries show quite large variations, averaging (in the late 1990s) approximately 1000 tones in Exmouth Gulf and 80 tonnes in the Onslow fishery (mainly king, tiger and endeavour prawns), and approximately 290 tonnes in the Nickol Bay fishery (mainly banana prawns). The combined value of the prawns from the region at this time exceeded $20 million per annum.

1.5.2 Oil and gas extraction

Oil was first discovered in Western Australia at Rough Range in 1953 with commercial exploration for crude oil and condensate beginning in 1962. The industry has grown substantially and by 2001 there were 44 fields producing in four sedimentary basins (figure 1.5.2). Thirty two of these fields are in the Northern Carnarvon basin, five are in each of the Canning and Perth basins and two are in the Bonaparte basin. During 2001 these fields collectively produced 26 Gm^3 of gas and 20 Gl of oil and condensate valued at A$9396 billion.

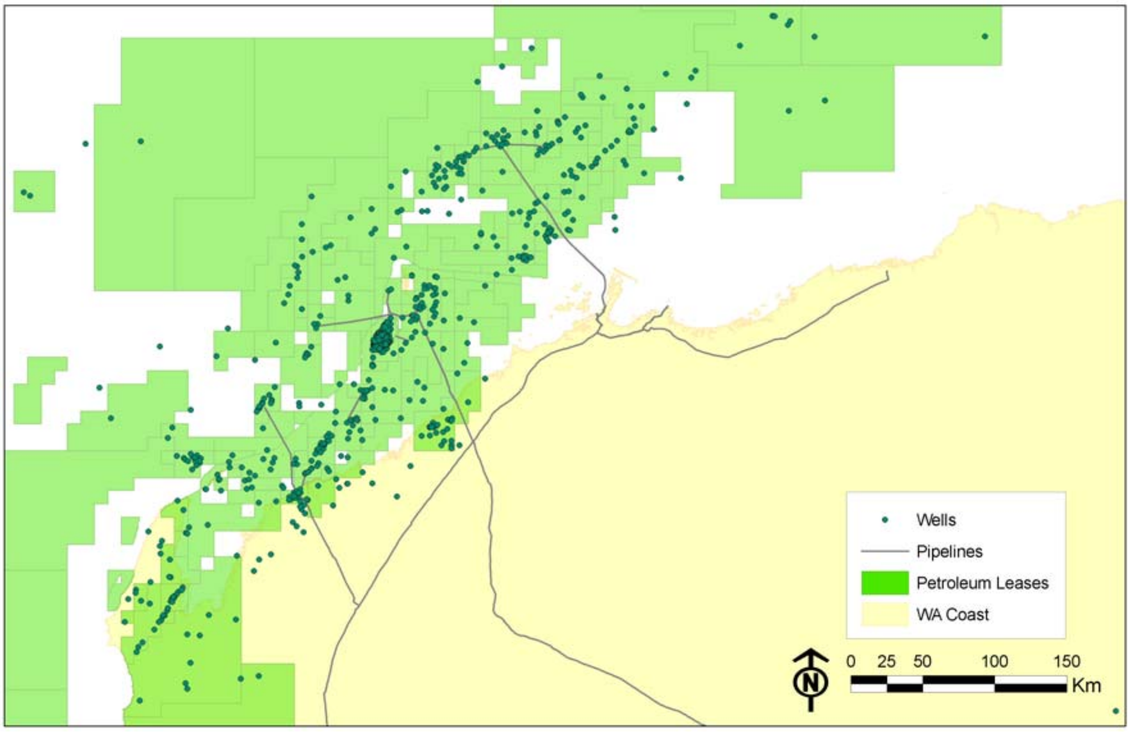


Figure 1.5.2: Map of the petroleum leases, wells and pipelines on the North West Shelf of Australia.

Woodside Energy Pty Ltd and BHP Billiton Petroleum Pty Ltd operations in the Pilbara region produced A$4.2 billion worth of crude oil, A$2.9 billion worth of LNG, A$1.7 billion worth of condensate, A$600 million worth of natural gas and over A$400 million worth of LPG products. The major oil and gas project in the Pilbara is the A$12 billion North West Shelf Joint Venture. This project is located on the Burrup Peninsula and currently has a production capacity of over 7.5 Mt/a of LNG that is primarily exported to Japan. The North West Shelf Joint Venture project is equally owned by Woodside Energy Pty Ltd; BP Developments Australia Ltd; Chevron Texaco Australia Pty Ltd; BHP Billiton Petroleum Pty Ltd; Shell Development (Australia) Pty Ltd; and Japan Australia LNG (MIMI) Pty Ltd.

1.5.3 Coastal industries and development

The major coastal industries in the study region are the Dampier Salt production ponds located at Dampier and Port Hedland, Hammersley Iron Parker Point and Western Power power stations, iron ore facilities, the onshore gas processing plant in King Bay and the Mermaid Marine slipway and supply base located at Mermaid Sound. These industries have contributed to the development of sea ports, international airports, major highways and roads, onshore and offshore pipelines and urban development in the region.

Oil and gas

Woodside's (http://www.woodside.com.au) onshore gas plant is located near Karratha and is Australia's largest gas processing plant. The plant produces natural gas, liquid petroleum gas and condensate.

A number of pipelines transport gas from the Pilbara to the WA domestic market:

- the 600 mm, 1530 km Dampier to Bunbury Natural Gas Pipeline transports gas from the Carnarvon Basin to customers in the Pilbara, Carnarvon, Geraldton, Perth and Bunbury areas.
- the Pilbara Energy Pipeline travels 219 km from Karratha to Port Hedland and delivers gas to the Port Hedland power station and BHP's Hot Briquetted Iron (HBI) plant (abandoned in 2005).
- the Goldfields Gas Transmission pipeline runs 1380 km from the Pilbara to the Northern and Eastern Goldfields areas.

Mermaid Marine Australia Limited at Dampier is a major service facility for the oil and gas industry. The organisation operates a fleet of fifteen tugs, workboats and barges undertaking all forms of offshore activity including exploration support, supply, survey and berthing assistance. Mermaid Marine also operates major slipway facilities.

Salt production

The two salt producers on the NWS are Dampier Salt Ltd and Onslow Salt Pty Ltd. Dampier Salt Ltd has two major operations located at Port Hedland and Dampier.

In 2002, the Pilbara produced over million tonnes of salt that represented 70 percent of the total salt produced in Western Australia for that year. The value of the Pilbara region's salt production over this period was estimated to be A$179.5 million.

Iron ore

Iron ore was discovered in the Pilbara region in the 1800s and the industry has now grown to include 22 iron ore mining and processing operations employing 9000 people. More than 95 percent of Australia's iron ore exports come from the region. In 2001 157 million tonnes of iron ore worth A$5.1 billion was produced.

There are currently three companies operating in the iron ore industry in the Pilbara region. These operators are BHP Iron Ore (now BHP Billiton Iron Ore), Hamersley Iron Pty Ltd (owned by Rio Tinto) and Robe River Mining Co Pty Ltd (owned by North Ltd, which is controlled by Rio Tinto). In early 2001, Rio Tinto completed a successful takeover of North Ltd and in June 2001, BHP Limited and Billiton Plc merged to form BHP Billiton.

Hammersley Iron is located at Karratha and is one of the world's leading iron ore producers supplying 76.5 million tonnes of iron ore per year. Hamersley Iron uses gas to fire its 120-megawatt Dampier power station, providing power to its port and processing operations at Dampier, the towns of Dampier, Tom Price and Paraburdoo, to its mine facilities and to Dampier Salt facilities. Some surplus power is sold to Western Power's western Pilbara grid.

Robe River Co Pty Ltd operates two open pit iron ore mines in the Pilbara region; Mesa J near Pannawonica and the new West Angelas mine. From these mines, iron ore is railed to a dedicated port at Cape Lambert. Robe currently exports over 40 million tonnes of iron ore per year.

Pilbara Rail Company, a joint venture between Robe and Rio Tinto Iron Ore, operates and maintains the joint rail assets of Robe and Hamersley Iron. Pilbara Rail services seven mines via a mainline system of approximately 1100 kilometres of track. The combined tonnage hauled by Pilbara Rail is approximately 110 million tonnes of ore per annum. Pilbara Rail operates the largest privately owned rail network in Australia.

BHP Billiton Iron Ore has six mining operations in the Pilbara – Mt Whaleback and nearby Satellite Orebodies 23, 25, 29 and 30, Jimblebar, Yandi, Area C and Yarrie. Altogether, the mines currently produce around 80 million wet tonnes of iron ore per annum. Processing and shipping facilities are located at Nelson Point and Finucane Island, Port Hedland. The two port facilities are located on opposite sides of Port Hedland harbour and are connected by a 1.4 km under-harbour tunnel conveyor and rail to the inland mines. Over 500 ships are loaded each year, the largest up to 230 metres long and carrying up to 260000 tonnes of ore. BHP Billiton Iron Ore operates two heavy haulage railroads to Port Hedland, one running 426 km from Newman and the Yandi and Area C mines, and the other 210 km from the Yarrie mine.

Electricity generation

The Western Power electricity production facility for the region is located at Port Hedland. This facility forms part of Western Power's extensive grid throughout Western Australia.

The growth of these major industries has had a direct impact on the human population size and structure on the NWS.

1.6 Specification of MSE for the North West Shelf region

MSE requires a computer representation of the natural ecosystem which influences, and is influenced by, human activity. This computer representation is made up of three components (which are detailed in the companion report by Gray et al. 2006):

1. an 'operating model' of the biophysical and human systems involved, including models of human impacts and the representation of uncertainty;
2. a range of important prospective social and industrial development scenarios; and
3. a group of feasible prospective management mechanisms and dynamics (i.e. monitoring, assessment of monitoring information, management response to the assessed information and implementation of the management response); alternative strategies are built from these mechanisms.

The MSE application to the North West Shelf region examines a 3 by 3 by 3 matrix of possibilities. This matrix is made up of three 'operating model' specifications, three development scenarios and three management strategies, giving 27 combinations for evaluation and comparison (see figure 1.6.1). This allows initial screening and examination of the behaviour that could be examined using a more complete MSE exploration of the options and possibilities. In particular it allows examination of the robustness of the different management strategies in delivering desired management outcomes, despite uncertainty about how the ecosystem works and what future socio-economic development might occur. Although clearly a great simplification of the full range of interactions among these three dimensions, the 27 combinations chosen are sufficient for bounding the primary issues and for demonstrating the utility of MSE as a science-based aid to regional and sector decision making.

Three operating models were chosen so that the first reflects an optimistic interpretation of the ecosystem's productivity and resilience, the second reflects a central or base case interpretation, and the third reflects a pessimistic interpretation. Each operating model consists of sub-models of various processes or entities in the ecosystem. These were individually modified to give the three operating models used in the MSE comparisons.

Three development scenarios were chosen so that the first represents current levels of infrastructure, residential and industrial development and environmental protection, with no further development. The second development scenario represents planned industrial development in the next five years with no further development: this is development under construction in December 2002 and envisaged in the following five years. The third development scenario represents a repeated cycle of development of the type planned for the next five years. Each development scenario consists of a component for each of the four industry sectors *oil and gas, coastal development, fishing* and *conservation*, although there was little change to the commercial fishing sector.

Three management strategies were chosen so that the first reflects the situation as at December 2002. The mix of management measures used by the sectoral regulators at this time are referred to here as the *status quo* management strategy. The second reflects enhancements of the sectoral measures in place in December 2002 so that they moved to industry best practice (though these are still executed independently sector-by-sector). The third management strategy reflects increased collaboration and coordination among sectoral regulators, so that decisions in one sector are reflected in associated decisions in the other sectors.

A full description of the MSE specifications, input data and performance indicators is given in the companion report by Fulton et al. (2006b).

Figure 1.6.1 represents the three dimensions of the *strategy*, *specification* and *scenario* as a cube which exists in a four dimensional space. The fourth dimension represents stochastic elements (i.e. uncertainty) in the system, e.g. variation in climate, weather and reproduction rates, random components in the movement of water masses and organisms, and randomness necessary for programming the synchronised actions of many biological, physical and institutional entities represented in the computer software. The clouds of points illustrate the outcomes of various simulation runs across these stochastic elements for each of the 27 discrete combinations of *strategy*, *specification* and *scenario*.

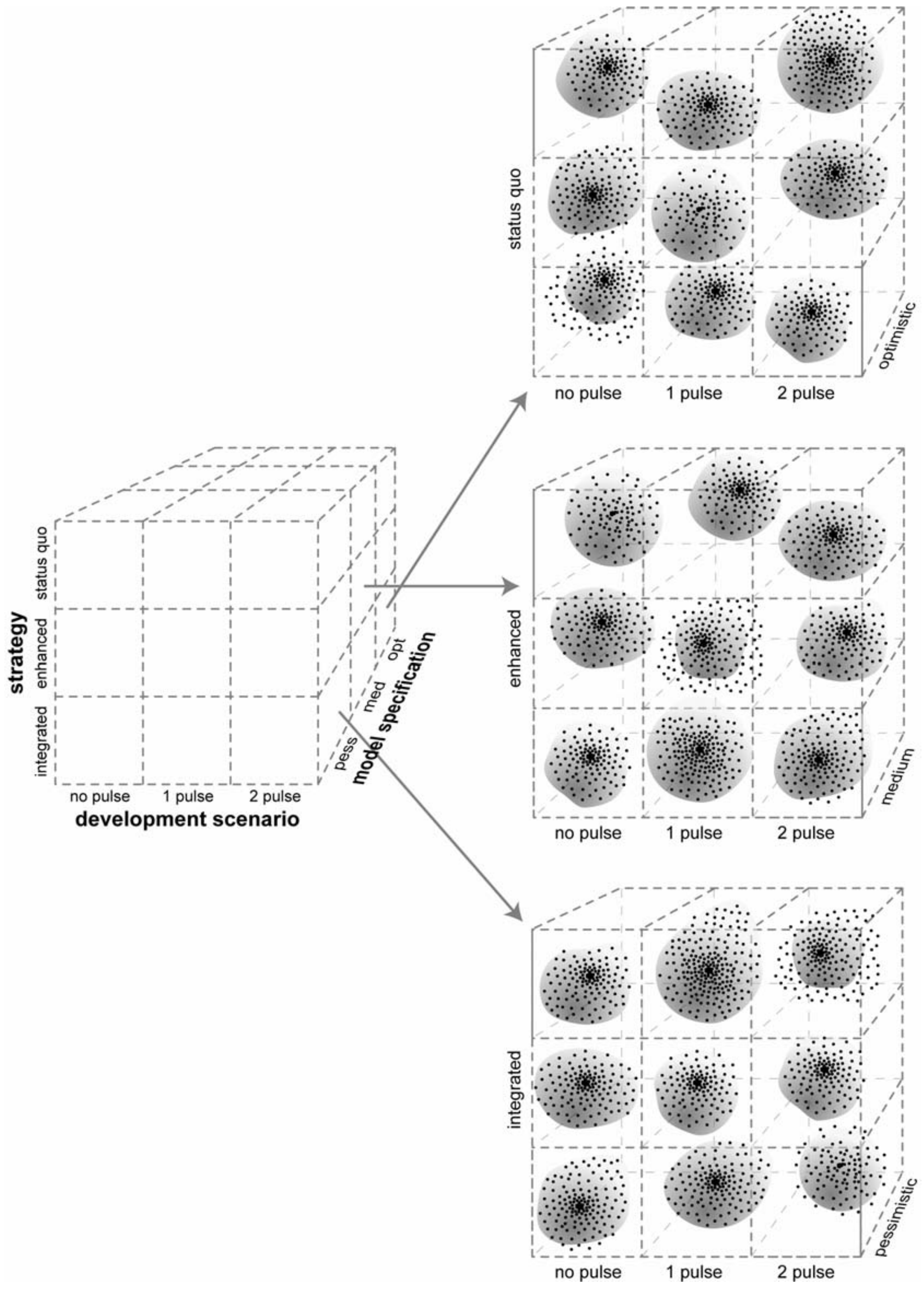


Figure 1.6.1: Schematic diagram of 3 by 3 by 3 matrix showing the stochastic nature of the solution space.

1.7 Performance indicators and triplet nomenclature

A large number of indicators and performance measures were calculated for each of the 27 combinations of management strategy, development scenario and model specification. To help describe the results of the simulations each combination of management strategy, development scenario and model specification is labelled using the triplet (management strategy, development scenario, model specification). In this triplet:

- The management strategy maybe S (status quo or in place in December 2002), E (enhanced sectoral) or I (integrated);
- The development scenarios may be 0 (no change from December 2002), 1 (a single pulse of planned five year development) or 2 (two 5 year pulses of development);
- The model specifications may be P (pessimistic), M (medium or base case) and O (optimistic).

For example (E, 1, O) refers to a set of simulations under the enhanced management strategy, the single-pulse development scenario, and optimistic model specification.

This triplet is also represented visually on many of the graphs and figures as an icon (e.g. figure 1.7.1) with a small square representing each of the 27 possible combinations of management strategy, development scenario and model specification. The square relating to the combination being applied in the particular case is shaded (e.g. figure 1.7.1). If the same icon is used to indicate results from several different combinations, all shown in the same figure, then the shading in the icon is coloured to match the colour used for that combination in the figure (e.g. figure D.1).

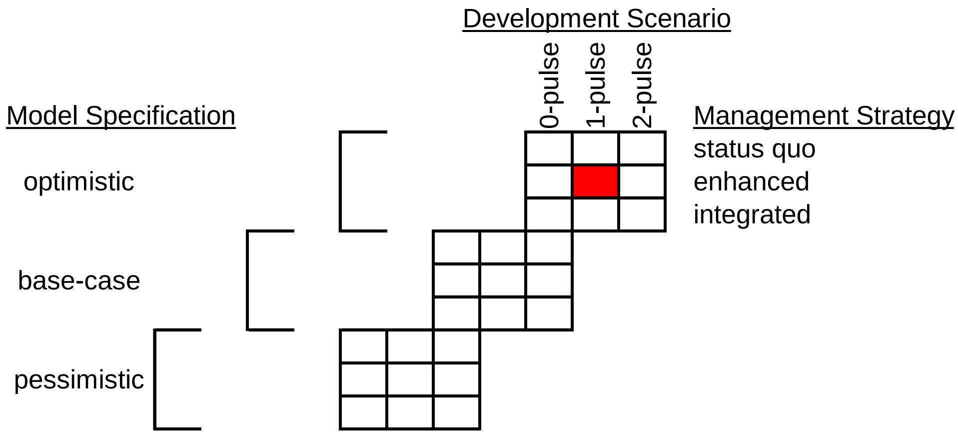


Figure 1.7.1: Icon for the triplet (E, 1, O) representing enhanced sectoral management, 1-pulse development and optimistic model specification.

Because of the complex nature of the simulation results they are summarised in three sections, each of which compares the different elements of the triplet (management strategies, development scenarios, model specifications). So that each of the following sections refers to the model results that are represented in a single plot for a single indicator, for the three levels of the chosen element, while holding the other two elements constant.

2. COMPARISON OF MODEL SPECIFICATIONS

In this section the results are grouped to examine the implications of the different model specifications. These model specifications essentially represent alternative representations of the productivity and resilience of the regional ecosystem and so account explicitly for uncertainty in scientific knowledge about how the system evolves through space and time.

2.1 Finfish trawl fisheries

Different model specifications attempt to capture uncertainty in bio-physical knowledge about the state of the world. In the case of the North West Shelf fisheries model, this uncertainty is addressed by specifying alternative values for the Beverton-Holt growth parameters. These alternative growth parameter values determine the optimistic, pessimistic and base case model specifications (see Gray et al. 2006 and Fulton et al. 2006b for details). For different finfish species in the region, the implications of the three model specifications can be seen in figures D.1 to D.3. Figure D.1 shows the modelled time series of Spawning Stock Biomass (SSB) in kg, for three species groups: *Lutjanus sebae*, large lutjanids (*L. erythropterus*, *L. malabaricus*) and other species (small lutjanids [*L. vitta*], lethrinids, nemipterids, and saurids), under three development scenarios and the status quo management strategy. Figures D.2 and D.3 show the SSB under the enhanced and integrated management strategies, respectively. Great differences arise from the different model specifications. Not surprisingly, the optimistic model specification has a correspondingly high SSB for each species group, the pessimistic model specification a corresponding low SSB, and the base case model specification has an intermediate level of SSB. This is replicated for each combination of development scenario and management strategy. These SSB levels correspond well with the best and bounding estimates of biomass for those groups from other studies (Bulman, 2006).

Also apparent from figures D.1 to D.3 is the historical period of the model, prior to 2000, in which the finfish populations are constrained and depleted by historical catches. In the period after 2000, the model projects forward for 15 years under the imposed management strategies and decision procedures. The results for the finfish show that large lutjanids and the combined species group recover to near pre-exploitation levels by 2015. The greatest depletion of the populations occurred prior to 1990, but afterwards populations increased steadily to recover by 2015. These recoveries occurred regardless of management strategy or development scenario.

In contrast to the more productive species, *L. sebae* did not recover to pre-exploitation levels by 2015. Under the pessimistic model specification *L. sebae* SSB continued to decline slightly throughout the projection period. The base case and pessimistic model specifications showed either slight recovery or no recovery of the *L. sebae* SSB. Again the results were roughly the same regardless of management strategy or development scenario.

2.2 Finfish CPUE

The trawl CPUE (kg per trawl hour) in the projection period of the simulations for the different species of finfish comparing different model specifications are shown in figure D.4 for the status quo management strategy and all development scenarios. Figure D.5 displays results for the enhanced management strategy and figure D.6 displays results for the integrated management strategy. There is little difference among development scenarios and management strategies. For large lutjanids there is little difference among model specifications, though the variability of the CPUE drops as the productivity of the system increases (i.e. CPUE variation is highest for the pessimistic model specification and lowest for the optimistic specification). The small lutjanids also show a decrease in the variability of their CPUE with an increase in system productivity that is reflected in the optimistic specification. While the confidence intervals for the small lutjanid CPUE under the pessimistic model specification overlap with those from the other specifications, the CPUE under the optimistic model specification is significantly larger than under the base case specification (even though both increase through time).

For the red emperor (*L. sebae*) the pessimistic model specification is associated with the lowest CPUE, as would be expected, with little or no difference among the base case and optimistic model specifications. In contrast, the other three species group (saurids, lethrinids and nemipterids) all have higher catch rates under the pessimistic model specification. The CPUE under the optimistic and base case specifications show little separation for the saurids and lethrinids. The nemipterids, however, show a clear ordering in the CPUE trajectories (in inverse order to system productivity). These species are the most productive species of the finfish species modelled. They also benefit the most from habitat damage because of their modest habitat requirements. The reason for their elevated biomass under the pessimistic model specification, and the increased decline of slower growing species like *L. sebae*, is due to the slow recovery of highly-damaged habitat that results from the pessimistic model specification.

The annual trap CPUE (kg per trap soak hour) for the different species of finfish across different model specifications are shown in figure D.7 for the status quo management strategy and all development scenarios. Figure D.8 displays results for the enhanced management strategy and figure D.9 displays results for the integrated management strategy. Under the status quo management strategy, trap CPUE of red emperor is highest (and stable at about 2000 levels) under the optimistic model specification and lowest (and declining) under the pessimistic model specification (figure D.7). For the other species, there is less clear difference among model specifications. There tend to be more small lutjanids under the optimistic model specification, but more nemipterids under the pessimistic model specification, although the variability is high and the pattern is not consistent among different development scenarios. The lethrinid time series are also highly variable, although all model specifications project an increasing trend in trap CPUE.

Under the enhanced management strategy (figure D.8), again inter-simulation variability is high but there seem to be more *L. sebae* under the optimistic model specification, and fewer *L. sebae* under the pessimistic model specification. The more opportunistic species (saurids, nemipterids and lethrinids) all tend to have higher catch rates under the pessimistic model specification. The pattern is similar under the integrated management strategy (figure D.9).

2.3 Prawn biomass and CPUE

Because of the large number of prawn agents and the intensive computer time needed to run them, the prawn results start in 1995. Comparisons of model specification for king prawn (the category of king prawns presents king, tiger and endeavour prawns) and banana prawn biomass (kg) and CPUE (kg per trawl hour) under the three development scenarios are shown in figure D.10 for the status quo management strategy. Figure D.11 displays the results for the enhanced management strategy and figure D.12 displays results for the integrated management strategy. Across all management strategies and development scenarios, for king prawn, the variation across model specifications is high and the inter-annual variability is low. There is a clear ordering of the biomass trajectories based on model specification, from lowest under the pessimistic specification to highest under the optimistic specification, but in each case the time series is relatively flat (remaining at about year 2000 levels). The relatively unresponsive nature of these time series suggests that the dynamics of this stock have probably not been captured completely. Given the historical decline in the time series of CPUE for this fishery, the projected recovery should probably have been more responsive to interannual fishing activities.

The biomass time series for the banana prawns are much more variable. The different model specifications are apparent in some years, but not all. The high inter-annual variability, induced by the environmental forcing (rainfall data) used in the model, obscures the differences induced by the different model specifications in some years when environmental conditions are not conducive to strong year classes.

The inter-simulation variability in the biomass of both prawn species (represented by the error bars), is small because the prawn agent population dynamics are not heavily impacted by any of the randomised environmental conditions of the operating model. This may not be the case in a food-web model or if cyclones had wider footprints. The main force influencing the variability in banana prawn biomass is the rainfall time series data.

King prawn catch rates are more variable than the king prawn biomass (figures D.10 to D.12), though they remain at about (or exceed) the 2000 catch rates. The king prawn CPUE under the pessimistic model specification is clearly lower than for the other specifications (which periodically coincide) when status quo or enhanced management strategies are used. Under the integrated management strategy the CPUE under the optimistic specification is an order of magnitude higher than for the base case specification, which is significantly higher than for the pessimistic specification.

The banana prawn catch rates also differ somewhat from the banana prawn biomass, showing strong “boom and bust” dynamics. While the rates are generally around year 2000 levels, or higher, there is little to distinguish any of the trajectories in the poorest years (when they can all fall to very low levels). Overall the magnitude of the boom-bust fall is much smaller under the pessimistic specification, implying that catches are more consistent in this case; whereas the catch rates are more erratic in the more productive (optimistic) model specifications. The difference between the trajectory of the biomass and the CPUE represents the measurement uncertainty of the prawn vessels as they respond to the moving prawn agents.

2.4 Fishing effort

Overall effort

The data available for describing fishing effort vary in temporal extent across fisheries on the North West Shelf. The time series data for the prawn fishery begins in 1995, the trap fishery in 1983 and the trawl fishery in 1972.

Trajectories of trawl, trap and prawn fishing effort (measured in fishing hours) across the different model specifications are shown in figures D.13 to D.15. There is almost no change in fishing effort for any fleet when the status quo management strategy is in place (figure D.13), with all trajectories remaining at about the year 2000 level. Similarly, there is little change in fishing effort in the trap and prawn fisheries under an enhanced management strategy (figure D.14), again staying about year 2000 levels. The trawl fishery effort under an enhanced management strategy and a pessimistic model specification (figure D.14), however, is substantially lower than for the other model specifications, declining to about half of year 2000 levels, as the resource is depleted and the shifting of effort between zones provides decreasing returns, forcing fishery effort reductions overall.

Under the integrated management strategy (figure D.15) there are differences among model specifications for the trawl and prawn fleets. The main difference in these fleets is that the optimistic model specification allows more fishing effort than do the pessimistic and base case model specifications (where effort falls to negligible levels). This is not surprising because, in the pessimistic and base case model specifications, fish, prawns and the reduced biomasses of conservation species (i.e. turtles) are triggering management actions – specifically effort reduction in the trawl fishery, and area closures in the prawn fishery.

Effort per fishing zone

Model specification comparisons of the projected finfish trawl effort applied in each of the six trawl areas (marked in figure 2.4.1) through time are displayed in figures D.16 to D.24. No effort is seen in areas 3 and 6 as these are closed to fishing. Under the status quo management strategy, effort tends to be removed from area 1, and displaced to area 2, under the pessimistic model specification (figures D.16 to D.18), mainly as a result of the Fisheries Management Authority (FMA) agent moving quota to area 2 to conserve fish stocks in area 1. Under the base case and optimistic model specifications area 1 consistently has the most effort, with little or no effort displacement to other areas.

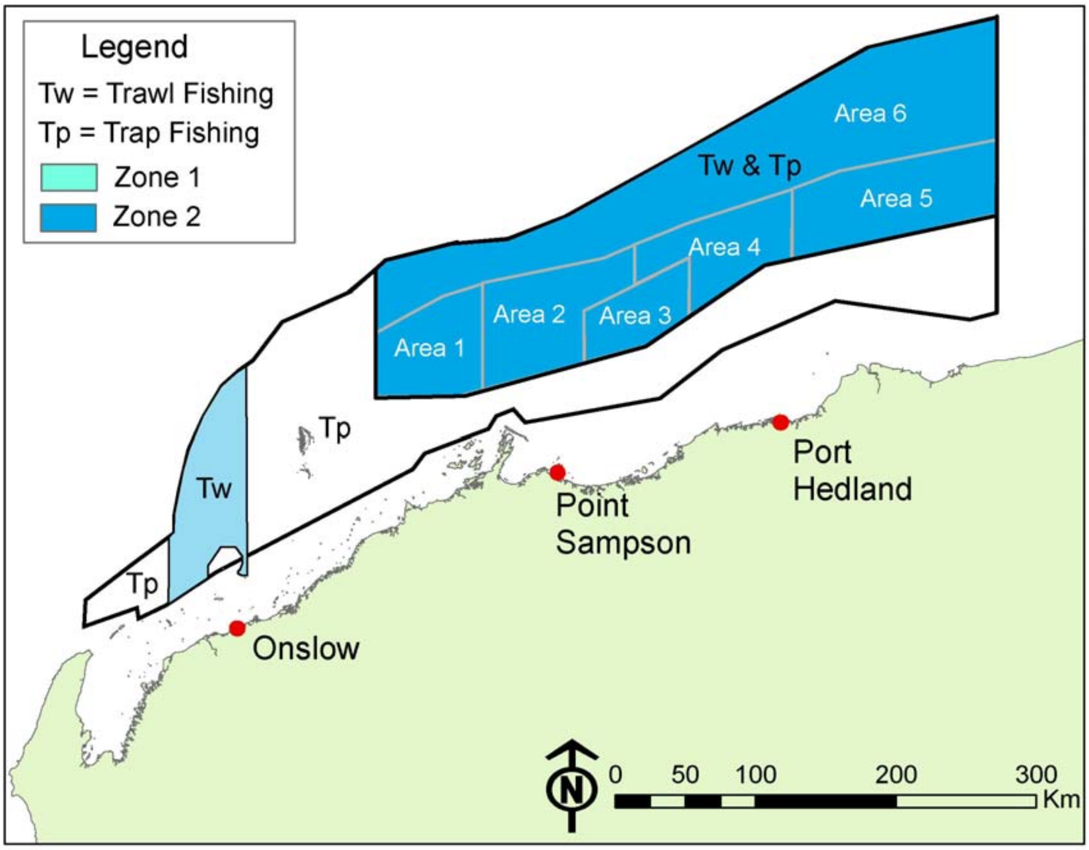


Figure 2.4.1: Commercial finfish fishing zones.

Under the enhanced management strategy, effort is displaced from both areas 1 and 2, to area 4 under the pessimistic model specification (figures D.19 to D.21), as a result of the Fisheries Management Authority's (FMA's) concern for the stock status in areas 1 and 2; the FMA deeming this displacement acceptable with regard to risks to the stock in area 4. No effort was displaced to area 4 under the base case and optimistic model specifications, however. Under these, effort in area 4 actually declines. Instead the effort in area 2 increases, as a result of the FMA deeming the stock in area 2 capable of handling increased effort; and the smaller economic costs of accessing that area make it preferable to area 4.

Under the integrated management strategy, effort was often effectively set on the basis of the state of other species, principally sharks and turtles (figures D.22 to D.24). Under this management strategy, when the pessimistic model specification is used, area 1 is closed to fishing, and effort is also reduced considerably in areas 2 and 4. Even under the more productive base case and optimistic model specifications, trawl effort is initially reduced in all areas (1, 2, 4 and 5) under the integrated management strategy. Later rises occur, but these do not see effort returning to year 2000 levels at any time in the projection period.

2.5 Habitat

The habitat types examined in the MSE for NWSJEMS are small and large benthic (sponge and reef) communities, seagrass and mangroves. The condition or health of these habitat types is characterised by their biomass, height and patchiness (or degree of fragmentation). In this section the habitat dynamics are assessed according to these characteristics, based on historical data and model simulations.

2.5.1 Proportional cover

Comparison of model specifications for spatial extent of seagrass, mangrove and small and large benthic habitat under the alternative development scenarios is shown for the status quo management strategy in figure D.25, for enhanced management in figure D.26 and for the integrated management strategy in figure D.27.

Spatial extent of a particular type of habitat is measured by the proportion of seabed covered by that habitat within a defined regular grid cell. Grid size for each habitat discussed in this report is determined mainly by the resolution of available data. The grid for large and small benthos on the continental shelf is 10 minutes latitude by 10 minutes longitude (cells of approximately 100 n mile^2). The grid for seagrass is 12 minutes latitude by 12 minutes longitude (cells of approximately 144 n mile^2). The grid for mangroves is 3 minutes latitude by 3 minutes longitude (cells of approximately 9 n mile^2).

There is no systematic difference in the seagrass extent across model specifications, development scenarios or management strategies, and the variability among and within simulations is very large (figures D.25 (a) to D.27 (a)). The main reason for both the consistency of seagrass extent and variability across all strategy, specification and scenario combinations is that the indicator statistic is calculated over the entire inshore area, not just those cells consistently containing substantial seagrass meadows. There is a slight decline in seagrass meadows through time in all cases, although the majority of physical damage was done in the early years of the simulation. Overall, these impacts are relatively weak (considering the large spatial area being examined) and have not been replicated at any time since because the seagrass meadows have stabilised under the current disturbance regime. A more detailed consideration of the seagrass dynamics appears below in the spatial results section.

The inter-simulation variability for the small benthos extent is also high but for this habitat type there are significant differences among the median trajectories for different model specifications. The optimistic model specification tends to give rise to greater extent of small benthos than the base case and pessimistic model specifications (figures D.25 to D.27). This is consistent across all development scenarios and management strategies. Most damage was done to the small benthos as a result of the foreign trawl fleet operating in the early 1970s. The decline is greatest with the pessimistic and base case model specifications. No specification yielded any appreciable regional-scale recovery of the overall extent of small benthos. Consideration of the spatial results below indicates there is some local recovery in the benthos groups through time, but this is not seen at the regional level due to high variability and slow recruitment dynamics.

The results for the large benthos are quite similar to those for small benthos. These habitats were also severely depleted by the historical fishing of the foreign trawl fleets – to the point that the remaining coverage is so small that regionally there is little difference in the mean dynamics under the different model specifications, development scenarios and management strategies. Local recovery is greater under the optimistic model specifications and that is what is leading to the higher variability in those cases.

The dynamics of the total mangrove forest cover are quite similar in all cases (figures D.25 (b) to D.27 (b)). The mangroves continue to expand until an equilibrium forest structure is reached in each coastal cell. There are some local differences due to disturbances such as cyclones, but overall there is little to distinguish any of the alternative model specifications. The most notable features of the overall mangrove cover dynamics are the dips coinciding with major clearing and development. While the coarse resolution of the mangrove model means that reestablishment of early forest stages happens very quickly (and so the dips are short-lived) in reality (or for a more finely resolved forest model) these localised effects would be expected to be more substantial and prolonged.

2.5.2 Habitat fragmentation

Fragmentation of habitat is the degree to which habitat patches are broken into smaller patches by the impact of cyclones, dredging, fishing and other physical disturbance. This is measured by a proxy for the number of discernible patches in a given grid cell.

Comparison of model specifications for the habitat fragmentation index of seagrass, benthos and mangroves under the alternative development scenarios is shown for the status quo management strategy in figure D.28, for the enhanced management strategy in figure D.29 and for the integrated management strategy in figure D.30.

Although the seagrass extent changes very little over the simulated period (figures D.25 to D.27), the habitat appears to have become more fragmented (figures D.28 to D.30). There is little difference among model specifications, development scenarios and management strategies. In all cases the majority of the fragmentation occurred prior to 1980, with little recovery or patch agglomeration occurring in the remaining time. Locally (see spatial results below), the fragmentation is marginally higher under the base case and pessimistic model specifications.

Benthos fragmentation has increased more strongly than seagrass fragmentation throughout the projection period, although the majority of this increase also occurred prior to 1980. There is a difference in the fragmentation trajectories among model specifications, though there is little, if any, difference among the development scenarios or management strategies. Optimistic and base case model specifications indicate slightly more fragmentation than does the pessimistic model specification (figures D.28 to D.30). This is mainly a result of the higher benthic habitat cover under these model specifications (figures D.25 to D.27) – i.e. the presence of more benthos to fragment.

As seen in the overall benthic cover, the different model specifications, development scenarios and management strategies did not alter the mangrove habitat quality to any great extent. Although there is some suggestion of higher fragmentation rates when the pessimistic model specification is used, which equates to more-vulnerable mangrove stands. The historical data indicate only slightly disturbed mangrove habitat prior to 1980, and afterwards there is little extra effect. This result follows from the existence of the relatively large stands of mangroves throughout the Pilbara region coincident with relatively little disturbance as development and cyclones cover only small areas of the coast.

2.5.3 Habitat height

Comparison of model specifications for average habitat height (in cm) of seagrass, benthos and mangroves under the alternative development scenarios is shown for the status quo management strategy in figure D.31, for the enhanced management strategy in figure D.32 and for the integrated management strategy in figure D.33.

As with seagrass cover (see above), there are no observable differences among the alternative model specifications, development scenarios or management strategies. In every case seagrass height declined throughout the first ten years of the historical period and then tended to remain at the same level for the remainder of the simulation period.

Benthos height varied a little among the different model specifications, but not among the different development scenarios or management strategies. The benthos height was greatest, and recovered most quickly, under the optimistic model specification; and in the pessimistic specification benthic recovery was slow. The large reduction in benthos height in the historical period prior to 1980 was caused by the foreign trawl fleet. In all model specifications the regional-scale average benthos height did not recover from this damage during the simulation period. The spatially resolved results (see below) indicate that there was some recovery locally, but this is patchy and so overall this growth occurs so slowly that the majority of sites do not reach prior-to-fishing levels again during the simulation period.

There is no difference in the mangrove height observed across the various model specifications, development scenarios and management strategies. Moreover, the variability is very large (see figures D.31 to D.33). There is also very little trend in the mangrove height through the historical and projection periods, as any damage done by land clearing or cyclone strikes is very localised and thus weak on regional scales, given the large spatial area being examined.

2.5.4 Relative habitat cover

Comparisons of seagrass, large and small benthos and mangrove habitat cover, relative to initial conditions (habitat cover in 1970) for the different model specifications are shown in figure D.34 for the status quo management strategy and all development scenarios, in figure D.35 for the enhanced management strategy and in figure D.36 for the integrated management strategy. Among the different model specifications there is no discernible difference in the seagrass or mangrove coverage. Seagrass coverage in all model specifications declines through the historical period and continues to do so throughout the projection period, regardless of the management strategy. The coverage of small mangroves was mainly affected in the period prior to 1980, but thereafter mangroves recover steadily for the remainder of the historical period and throughout the projection period.

Both the large and small benthos are affected strongly, though mainly in the period prior to 1980 by the foreign trawl. The effect was greater on the slower-growing large benthos than on the more productive small benthos. The magnitude of this effect is determined by the model specification. In general, the pessimistic model specification leads to lower coverages and the optimistic model specification to higher coverages and less damage. Under the optimistic model specification the small benthos began to recover (slightly) following the initial damage.

2.6 Catch and biomass of high valued and low valued species

The biomass and catch of different species of finfish is of economic interest to fishers and fish consumers and also of conservation interest to the community more generally. In this section the finfish species have been grouped into those of high value and those of low value in the fish market. These species groups invoke different targeting behaviour by fishers and also exhibit different habitat preferences. The ecological condition of these groups is characterised by their natural mortality, and the state of their spawning stocks biomass.

2.6.1 Absolute catches of high and low valued species

Comparisons of total catches of the high valued species (*L. sebae*, large lutjanids) and low valued species (letherinids, small lutjanids, nemipterids and saurids) across model specifications are shown in figures D.37 to D.39. These show the catch trajectories for the entire simulation period. The finfish catches late in the projection period are relatively small compared to those in the early years of the simulation period. Figures D.40 to D.42 show the catch trajectories for only the projection period of the simulation.

For the status quo management strategy the catches of high value species are roughly the same among model specifications (the high value catch at about 65% of year 2000 levels). For the enhanced management strategy catches of the high value species tend to be lower under the pessimistic model specification, in particular under the 2-pulse development scenario, where they decline to half the year 2000 catch levels. Under the integrated management strategy catches of high valued species tend to be higher under the optimistic model specification (though still only about half of the year 2000 levels) and lower under the base case model specification. This pattern reflects the non-linear effects of productivity and habitat. When productivity is high (optimistic) the catches are high, but when productivity is low overall (the pessimistic model specification) then the species habitat requirements lead them into small areas and make them more vulnerable to the small amount of fishing allowed under the integrated management strategy (causing the pessimistic catches to be greater than in the slightly more productive base case). Notably, the high value catch trajectories drop under the integrated management strategy (in comparison to historical levels) regardless of the specification used.

Catches of the low value species, under the status quo management strategy, are much higher under the pessimistic model specification (up to twice the year 2000 levels) than under the other model specifications, regardless of the development scenario (figure D.40). Under the enhanced management strategy the catches of low valued species are more variable. While the centroid of the time series under the pessimistic model specification may sit along, above or below the other time series, the confidence bars for the pessimistic case always overlap the other cases (figure D.41). Under the integrated management strategy the optimistic model specification leads to higher catches of low valued species in a pattern similar to that of the high valued species. For these low value species, less specific habitat preferences allow them to flourish under the pessimistic model specification and so contribute more to the total catch.

Under the status quo management strategy, higher catches of the low valued species under the pessimistic model specification, compared to the base case or optimistic model specifications, may seem unexpected initially. However, this is the result of the highly productive saurid and nemipterid species groups being advantaged by the poor state of the habitat. The free-moving trawlers under the status quo management strategy cause the benthic habitat under a pessimistic model specification to be continuously damaged, with minimal (and localised) recovery. As the restriction on the trawl effort increases with the enhanced and integrated management strategies (figures D.13 to D.15), the catches (as well as CPUEs and biomasses) of these opportunistic species decreases because the resulting improvement in habitat favours the high-valued species.

2.6.2 Relative catches of high and low valued species

The ratios of total catch of high valued species to total catch of low valued species among the different model specifications are shown in figure D.43 for the status quo management strategy (under the three development scenarios). Figure D.44 displays this catch ratio for the enhanced management strategy and figure D.45 shows the catch ratio for the integrated management strategy. Under the status quo and enhanced management strategies the contribution of low valued species to the total catch tends to be significantly higher than the contribution from the high valued species under the pessimistic model specification. The reason for this is the poor response of habitat in the pessimistic model specification due to benthic habitat disruptions caused by trawlers. When trawl effort is more restricted, such as under the integrated management strategy, the contribution of the high-valued species is greater, even under the pessimistic model specification. In the case of integrated management there is no difference between the pessimistic and optimistic model specifications as the low effort levels yield high returns. The higher contribution of high-valued species in the base case model specification under the integrated management strategy results from the potential for strong effects being counteracted by management-induced substantial habitat recovery.

2.6.3 Biomass of high and low valued species

Comparisons in the projection period of the simulation of the ratio of total spawning stock biomass of high valued species (*L. sebae*, large lutjanids) to the total spawning stock biomass of low valued species (letherinids, small lutjanids, nemipterids and saurids) across model specifications are shown in figures D.46 to D.48. For all management strategies the low-valued species biomass is higher under the pessimistic model specification than under the other model specifications. This reflects the greater abundance of the lower valued species in that case. There is no significant difference in the ratio of high to low valued species biomass between the base case and optimistic model specifications, particularly at the beginning and end of the period. Notably, in every case, there is an initial drop in the value of the ratio as the heaviest historical fishing pressure impacts upon, the fish populations and then a slight recovery as that pressure is relaxed. The trend is then reversed and there is a very slow decline in the value of the ratio throughout the rest of the simulation period.

2.7 Biomass of r-selected and K-selected species

Comparisons among model specifications of the ratio of biomass of r-selected species (king and banana prawns, nemipterids, saurids and small lutjanids) to K-selected species (*L. sebae*, large lutjanids, lethrinds, sharks and turtles) are shown in figure D.49 for the status quo management strategy. Figure D.50 displays similar results for the enhanced management strategy and figure D.51 deals with the integrated management strategy. Under all management strategies and development scenarios there is greater r-selected species biomass than K-selected species biomass in the optimistic model specification, compared to the other model specifications. The pessimistic model specification shows the smallest ratio indicating that, despite the poor habitat conditions, the community composition has a larger percentage of K-selected species. The reason for these differences in relative community composition is that the increased productivity of r-selected species in the optimistic (versus pessimistic) model specification is greater than the increase in productivity of the K-selected species. Consequently, the optimistic specification results in a system that is more heavily weighted toward r-selected species. Despite these differences all the trajectories in the status quo and enhanced management strategies show a similar pattern: an initial large drop in the relative contribution of the r-selected species, but a strong increase from the early 1980s onward. This indicates an increasing dominance of r-selected species as the simulations progress. While this rise is fastest in the optimistic model specification, it flattens out in that case. By contrast, the slower rise in the pessimistic model specification continues throughout the simulation period. The time series under integrated management are similar, except that the dominance of the r-selected species stabilises or declines through the projection period. This is a direct result of the conservation actions taken as part of this management strategy to protect habitat and vulnerable (K-selected) species.

2.8 Indices of species diversity

Three measures of species diversity were used to examine model output. These are:

1. the summed relative biomass or proportional cover;
2. Shannon’s diversity index across the relative proportions of all species in the model; and
3. Renyi’s generalised diversity index of order 12.

The simplest diversity index, summed relative biomass, is computed for the different model specifications and displayed as the diversity proxy in figure D.52 for the status quo management strategy. Figure D.53 displays the diversity proxy for the enhanced management strategy and figure D.54 displays it for the integrated management strategy. In all development scenario and management strategy combinations the optimistic model specification has the highest diversity measure, while the pessimistic one has the lowest. Nevertheless, in all model specifications the loss of diversity was greatest during the 1970s, followed by an ongoing recovery for the rest of the model simulation, albeit at different rates depending on the model specification. Notably, under the integrated management strategy, the different model specifications approach each other by the end of the simulation period, with the optimistic and base case specifications converging to the point at which they are statistically indistinguishable.

The results for the Shannon diversity index (figures D.55 to 57) tend to decrease throughout the entire period, with no great difference among management strategies, development scenarios or model specifications. This is due to the large variability in the index, which is a result of the large variability in the benthic cover components. There is some suggestion that the central tendency of the index is lower under the base case model specification, probably because this specification does not include localised habitat-productivity interactions that feature in the other model specifications.

The results for Reyni's diversity index are much less variable and more stable than Shannon's index, as has been shown in past studies (Kindt, 2002). This pattern follows much the same trend as the summed relative biomass index – in that there is little difference among the management strategies and development scenarios, while there are strong differences in the magnitude of the index across the model specifications. The optimistic model specification always sees a faster recovery (sometimes even over shooting unfished levels) and leads to the highest final value. Under the pessimistic specification Reyni's index drops further, recovers later and ends with the lowest value. The difference between this diversity index and the summed relative biomass is that the later weighs each species equally, whereas the Renyi index (figures D.58 to D.60) weighs each species according to the logarithm of their relative proportion. The Renyi index is more sensitive to changes in species relative proportion, as indicated in figure D.60, which shows comparisons among different model specifications and development scenarios for the integrated management strategy. The diversity under the base case model specification declines quickly in the last ten years of the simulation. This is caused by a large turtle recovery which skews the species-evenness distribution. Under the optimistic model specification the turtle levels may be as high as in the base case model specification, but their relative amounts are lower and closer to the other species, so the decline in the index is not as precipitous. It is interesting that the values of the Reyni index are also heavily impacted by environmental variation towards the end of these time series.

2.9 Recreational fishing

The recreational fishing catches of four species (*L. sebae*, large lutjanids, lethrinds and nemipterids) under the different model specifications are shown in figure D.61 for the status quo management strategy. Figure D.62 provides a similar display for the enhanced management strategy and figure D.63 displays recreational catches for the integrated management strategy. Because no data were available for historical recreational fishing catches the trajectories are shown only for the projection period. The recreational catches follow a pattern very much like the commercial catches (figures D.40 to 42) in that the catches of the high-valued, less productive species (*L. sebae*) are lower under the pessimistic model specification because their habitat is damaged. This damaged habitat is beneficial to the lower-valued, more productive species like the nemipterids, however. This pattern is followed under all three management strategies, although the increasing trend in catches of trophy fish (e.g. *L. sebae*) is stronger under integrated management. Fish such as the large lutjanids, which have some degree of habitat association tend to occur more often in the recreational catch under the pessimistic model specification as they have moved inshore towards more suitable habitat, as offshore habitat is depleted.

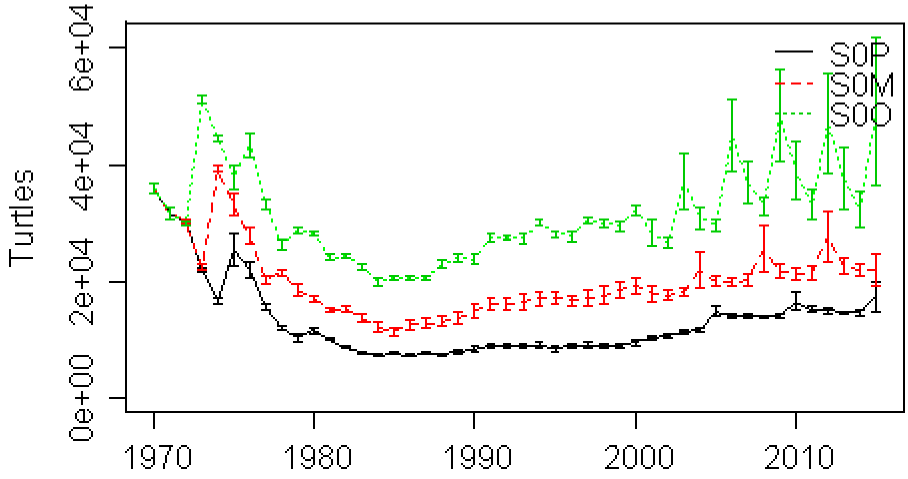
The effect of development scenario can be seen clearly in the recreational catches. The effect is most obvious in the recreational catches of *L. sebae*, but there is also an effect on the other species. For example, under the pessimistic model specification, recreational catches tend to increase over time under the 0-pulse development scenario. Under the 1-pulse and 2-pulse development scenarios there are corresponding pulses in the magnitude of the recreational fishing catches. Although there may be local depletion of the fish species, there is little effect of these pulses on the total fish biomass (figure D.1) mainly because the recreational catches are small relative to the trawl catch (~1%) (figure D.40).

2.10 Species of high conservation value

The species of high conservation value included in the simulations are sharks and turtles. Comparisons of their population dynamics over different model specifications are shown in figure D.64 for the status quo management strategy. Figure D.65 applies to the enhanced management strategy and figure D.66 applies to the integrated management strategy. There is little difference among the development scenarios, but strong differences among the specifications and management strategies. All cases show a strong impact of historical events, including the directed turtle fishery, but also incidental impacts of the finfish and prawn fisheries. Under the status quo and enhanced management strategies there are clearly more turtles under the optimistic model specification, with the abundance recovering to almost virgin levels by the end of the simulation period. Abundance under the pessimistic model specification is considerably lower, dropping to as little as 10% of undisturbed levels, although turtle populations have recovered to slightly less than 50% of initial levels by the end of the projection period. The situation is better still under the integrated management strategy, where all model specifications see a recovery as strong as (or stronger than) that seen under the optimistic model specifications for the other management strategies. Note that this expansion of the turtle population under the integrated management strategy and base case model specification is the reason the species diversity index drops so quickly in figure D.60, as the species distribution is influenced more by turtles than by many other species. More importantly, this rate of recovery is probably too high in reality, as it assumes a relatively short pre-reproductive phase (see Fulton et al. 2006b for the parameterisation used). Work with an alternative population agent-based version of the turtle model produces a similar initial decline but the recovery in all cases is, at the very least, much slower (if not absent) – see figure 2.10.1 (b). This suggests much more attention must be given to species with long and complex life histories (like turtles) if they are to become conservation triggers in integrated management.

The difference in patterns for sharks is less strong. In each case there is a historical depletion after the first years of the fishery. In the more productive model specifications, smaller individuals benefit from the removal of their large conspecifics by fishing due to density-dependent mortality. The depletion is followed by a long, slow recovery period, with some short-term reversals as fishing pressure varies. The differences among the trajectories are smaller for sharks than turtles, but the pessimistic model specification still clearly yields a lower biomass trajectory and the more productive model specifications yield highly-variable trajectories.

(a)



(b)

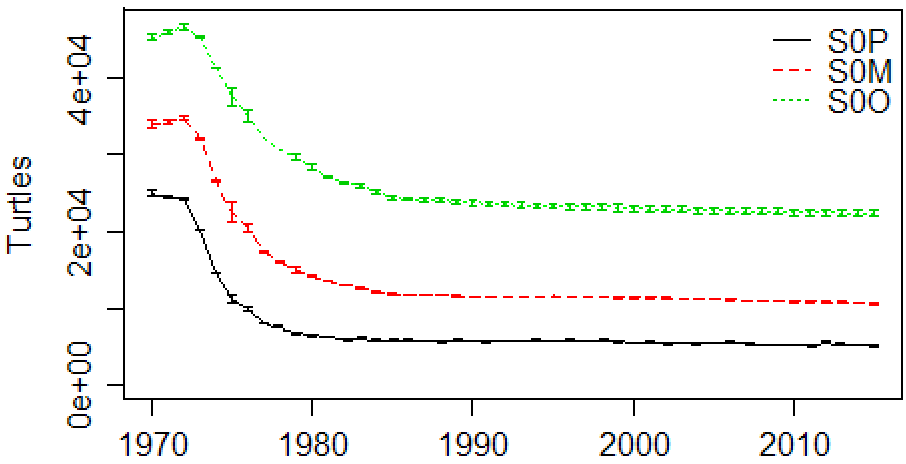


Figure 2.10.1: Alternative turtle biomass trajectories produced with (a) individual-based and (b) population-based turtle models.

2.11 Economic indicators

The economic indicators for the trawl fishery were based on costs from the South East Trawl Fishery (Appendix E) as there were no available data for the NWS at the time simulations commenced. These indices allow for the comparison of the gross margin of fishing (total revenue less the total variable costs) across all vessels in the fishery to the fixed costs (capital and gear costs). Figure D.67 compares the gross margin of the trawl fishery for different model specifications under the three development scenarios and for the status quo management strategy. Figure D.68 makes the comparison under the enhanced management strategy and figure D.69 makes the comparison under the integrated management strategy. There is an increase in this index throughout the projection period, though it is very slight under the integrated management strategy. Under the status quo management strategy the economic performance of the fishery tends to be better under the pessimistic model specification than under the optimistic specification (figure D.67). This is due to the enhanced catches (figure D.40) and biomass (figure D.1) experienced with the less valuable, but more numerous, nemipterid and lethrind species. Under more restrictive management strategies the economic performance among the different model specifications becomes more similar. The economic condition of the trawl fishery changes little across the management strategies and development scenarios under the base case and optimistic model specifications. It is noteworthy that it seems very hard for the trawl fishery to cover fixed costs for most of the period, regardless of the model specification or management strategy.

Comparisons of the economic performance for the prawn trawl fishery among model specifications are shown in figure D.70 for all three development scenarios and the status quo management strategy, in figure D.71 for the enhanced management strategy and in figure D.72 for the integrated management strategy. In contrast to the finfish trawlers, the prawn trawl seems to be capable of covering fixed costs. Under the status quo management strategy the economic performance of the prawn fishery is proportional to the productivity of the model specification. That is, under the optimistic model specification the economic performance is highest, and under the pessimistic model specification the economic performance is lowest. This pattern is repeated under the enhanced management strategy (figure D.71). Under the integrated management strategy, however, there is a strong contrast across fisheries in that the pessimistic and base case model specifications yield net returns from finfish that are frequently close to zero (and below or concordant with the fixed cost line) while the prawn biomasses under the optimistic model specification are high enough to produce fishery gross margins well above the level of fixed cost (figure D.72).

2.12 Implications for science and management

The discussion above confirms the differential dynamics across the pessimistic, base case, and optimistic model specifications. The differences in ecosystem evolution expected from these alternative specifications are predominantly robust to the choice of management strategy, development scenario combination. Compared to the pessimistic and base case specifications, the optimistic model specification consistently leads to greater recovery and resilience of the ecosystem, as measured by the chosen bio-physical indicator variables. Although not quite as clear-cut, the pessimistic specification leads to lesser recovery and resilience than that produced by the base case model specification.

The model specifications highlight four major issues. The first is that the range of environmental outcomes produced by the alternative system representations appears to be relatively small. It is open to debate whether this is true of the actual NWS system, whether it is due to inadequacies in the breadth of contrast that the model specifications can generate and remain numerically stable, or is an artefact generated by model calibration with sparse and patchy data. Only further empirical testing and follow-up work would settle the issue, as it is likely to be a complex mix of answers depending on which part of the model system is being considered. This is demonstrated in the second issue raised by the comparison of specifications.

The promising signs of recovery in species of high conservation value, notably turtles, appears to be consistently exaggerated across model specifications. This is a critical concern as it has implications for the potential severity of management decisions, their success and trade-offs under the alternative management strategies. Further model testing using alternative model representations for turtles has already shown that much slower rates of recovery result under alternative model formulations (e.g. use of age-structured population agents) – see figure 2.10.1. This modelling exercise made it painfully obvious that for species with long and complex life cycles, such as turtles, that targeted and specific modelling exercises are required. Moreover, these modelling efforts need to be paired with monitoring if there is to be an improvement in knowledge about the true form of the long-term population dynamics.

Putting these concerns regarding turtles aside, the third point raised by the comparison of model specifications is that the alternative model specifications lead to a variety of interesting economic outcomes across the management strategies and development scenarios. Of particular note is, in the case of the pessimistic model specification, where the interplay between fish population dynamics and fisher decision-making leads to lower gross margins despite higher catch rates. This is a direct result of changes in catch composition, resulting from a decline in the biomass of higher valued species simultaneous with a recovery of low-value species that exhibit weak habitat dependence.

The fourth issue to arise from the comparison of model specifications is that of uncertainty. The ability of the model to faithfully capture the salient sources of uncertainty that exist in reality is a critical issue if the alternative management strategies are to be tested to the point necessary for them to be employed in the real system. The results of the various model specifications show that the modelled uncertainty is greatest for the banana prawn population dynamics (and, therefore, banana prawn catches), which is driven by rainfall events, and the benthic habitat dynamics. This is at least partly a reflection of our greater grasp of drivers and responses for these system components. In the present application, other sources of uncertainty (where known) are included in the model but they have relatively little impact on the overall simulation results. In other applications of the MSE approach, either on the North West Shelf or elsewhere, model-induced variation will need further careful attention.

3. COMPARISON OF MANAGEMENT STRATEGIES

Comparisons of the different management strategies determine the relative performance of each of them in achieving management objectives. When a management strategy performs equally well in achieving a particular set of objectives across different model specifications and development scenarios that bracket the uncertainty of the system, then that management strategy is considered to be robust.

3.1 Finfish biomass

Comparisons of Spawning Stock Biomass (SSB) of finfish (*L. sebae*, large lutjanids and the other species) under the different management strategies are shown in figure D.73 for the pessimistic model specification, in figure D.74 for the base case model specification and in figure D.75 for the optimistic model specification. Integrated management is the best strategy for maintaining high SSB of the different species. The improvement is better under the pessimistic (figure D.73) and base case (figure D.74) model specifications than under the optimistic model specification. This is because the populations are not as depleted under the optimistic model specification (figure D.75). Regardless of the management strategy used there is a decline in the biomass of *L. sebae* under the pessimistic model specification, whereas the time series are flat under the other specifications. In contrast, the large lutjanid and other species SSBs increase in all cases, though the trend is strongest under integrated management when the model specifications have lower productivity (base case and pessimistic model specification).

3.2 Finfish CPUE

Comparisons of finfish trawl CPUE under different management strategies are shown across all development scenarios for the pessimistic model specification in figure D.76, and for the base case and optimistic model specifications in figures D.77 and D.78, respectively. Catch rates of *L. sebae* and large lutjanids under the integrated management strategy tend to be higher than under the status quo management strategy, because their populations recover more under this strategy than under the status quo. There is little difference among management strategies for the other more productive and less habitat specific finfish species (in particular the nemipterids, saurids and lethrinids). Overall however, the CPUE for *L. sebae,* declines under status quo management, remains stable longer under enhanced management and remains at year 2000 levels under the integrated management strategy. The trend in CPUE for the large lutjanids tends to be increasing through time (especially under integrated management), although it is highly variable (particularly under status quo management). The CPUE for small lutjanids shows the strongest increase under the optimistic model specification, as one might expect, and is marginally higher under the integrated management strategy.

Comparisons of finfish trap CPUE under different management strategies are shown across all development scenarios for the pessimistic model specification in figure D.79, while the base case and optimistic model specification results are shown in figures D.80 and D.81, respectively. Like the trawl catches rates, trap catch rates of red emperor (*L. sebae*) and large lutjanids tend to be higher under the integrated management strategy, especially under the pessimistic model specification. The variability of the time series tend to swamp other signals but it appears that the trend in CPUE for *L. sebae* is declining in all cases, though not as strongly under integrated management. Variability is overwhelming in all cases, but it is still possible to detect a general trend in the CPUE trajectories for the large lutjanids, where there is a general increase regardless of the management strategy. The trends for the small lutjanids are more mixed, though again dominated by the variability. Under the pessimistic model specification the trend is increasing and tends to be higher under the more restrictive management strategies. The benefit of the more intensive management is not as evident under the more productive model specifications. The same is true for the other finfish groups.

As was the case in section 2.2 above, the total catches are not discussed here as they do not provide any additional insight beyond that already gained from considering the CPUE.

3.3 Prawn biomass and CPUE

Prawn biomass and CPUE trajectories under all three management strategies are shown in figure D.82, for the pessimistic model specification, in figure D.83 for the base case model specification and in figure D.84 for the optimistic specification. There is little or no effect of management strategy on the biomass of both species, but the absolute value of biomass differs among the model specifications (this is seen more clearly in figures D.10, D.11 and D.12). Management strategies mainly affect the king prawn catch rates. They are lower under the integrated management strategy under both the pessimistic and base case model specifications, but are unaffected by the management strategy under the optimistic model specification.

Variability evident across CPUE trajectories in particular is of similar magnitude and timing, except for those corresponding to pessimistic and base case model specifications under the integrated management strategy. In these exceptional cases the mean and variation are significantly lower. The reason for this is that the best prawn areas are closed when the integrated management strategy decision procedure is triggered (mainly as a result of actions to protect high-conservation value species). Under the optimistic model specification there is enough prawn biomass across the entire region for the closure of a particular prawn trawl area to have little effect on the fishery, but this is not the case under the other model specifications.

Potentially the most notable impact of the integrated management strategy under all development scenarios and model specifications is that it increases the catch rate variability. This is even true for banana prawns, where the environmental signal drives the shape of the time series irrespective of the management strategy in place. The strongest impact of the alternative management strategies on the banana prawn catch rates is that the magnitude of the response is higher under the enhanced and, particularly, under the integrated management strategy.

3.4 Fishing effort

Overall effort

Fishing effort rates of different fleets under different management strategies are compared in figure D.85 for the pessimistic model specification and all three development scenarios, in figure D.86 for the base case model specification, and in figure D.87 for the optimistic model specification. The integrated management strategy reduced prawn trawl effort to low levels under the pessimistic and base case model specifications, but not under the optimistic model specification (where it stayed at about year 2000 levels). There is some suggestion that the prawn effort under the enhanced strategy may fall below that under status quo, but only marginally.

The integrated management strategy also sees reduced finfish trawl effort, under all model specifications, but trap effort remains at historical levels. While the enhanced management strategy did not produce results substantially different to those from status quo management for the prawn or trap fisheries, for the finfish trawl fishery, where enhanced management means independent surveys are used in the stock assessment, the trawl effort was reduced under the pessimistic model specification. This result was not repeated under more optimistic model specifications, where use of the enhanced management strategy actually leads to higher levels of effort than under either of the other management strategies.

Effort per fisheries zone

Management strategy comparisons of the finfish trawl effort applied in each of the six trawl areas (as defined in figure 2.4.1) through time are displayed in figures D.88 to D.96. No effort is seen in areas 3 and 6 as these are closed to fishing. Under the pessimistic model specification, all three management strategies reduced the effort in area 5 at roughly the same rate (see figures D.88 to D.90); notably, however, the integrated management strategy tends to reduce effort in a more step-like path than the more continuous decline under the other strategies. In the other fished areas, the integrated management strategy decreased the effort generally to negligible levels, in response to the status of the high-conservation value species (sharks and turtles). The enhanced management strategy did not lead to such sweeping changes, though it did reduce effort in areas 1 and 2 in addition to area 5 – displacing effort from these areas into area 4. In contrast, the status quo management strategy maintained high levels of effort in area 1, and lower levels in areas 2 and 4.

Under the base case model specification, effort was not reduced in area 1 under either status quo or enhanced management strategies (see figures D.91 to D.93). The effort in areas 4 and 5 however, was reduced substantially under all management strategies. Such a consistent result did not occur in area 2 where the enhanced management strategy deemed the fish stock to be sufficient to support the effort displaced from areas 4 and 5. Again the integrated management strategy tended to make the greatest effort reductions across model specifications and development scenarios although the reductions were not as great as under the pessimistic model specification; the integrated strategy yields effort reductions of a similar magnitude to those from status quo management in area 5, and less severe reductions than resulted from status quo management in area 2.

The results under the most optimistic model specification were similar to those under the base case model specification (see figures D.94 to D.96), though of a smaller absolute magnitude.

3.5 Habitat

The habitat types examined in the MSE for NWSJEMS are small and large benthic (sponge and reef) communities, seagrass and mangroves. The condition or health of these habitat types is characterised by their biomass, height and patchiness (or degree of fragmentation). In this section the habitat dynamics are assessed according to these characteristics, based on historical data and model simulations.

3.5.1 Proportional cover

A comparison of habitat extent (proportional cover) of seagrass, small and large benthos under different management strategies for the various development scenarios is shown for the pessimistic model specification in figure D.97, for the base case model specification in figure D.98 and for the optimistic model specification in figure D.99. There is no significant difference in the mean seagrass, small benthos or large benthos extent across management strategies. The variability is very large, for the same reasons as discussed in section 2.5. That is, because major impacts tend to be local and habitat is patchy, regional-scale statistics exhibit noisy behaviour. As previously stated there was also very little trend in the extent of seagrass through the historical and projection periods, in contrast to the stronger impacts of historical fishing activities on the benthic habitat. This is due to the relatively weak strength of the disturbances on the seagrass given the large spatial area being examined. This is also the case for mangroves, but not the case for the benthos, which were heavily impacted across much of their range by trawl fishing.

Consideration of the spatial results (see below) indicates that these regional trends and gross results do not always hold at finer spatial scales. Locally there are patches of higher habitat cover for small and large benthos under the enhanced management strategy and, particularly, under the integrated management strategy.

3.5.2 Habitat fragmentation

The comparison of management strategies for the indices of habitat fragmentation for seagrass, benthos and mangroves under the different development scenarios is shown for the pessimistic model specification in figure D.100, for the base case model specification in figure D.101 and for the optimistic model specification in figure D.102. Although the seagrass extent changed very little over the course of the simulation period (see figures D.97 to D.99), the meadows became much more fragmented (figures D.100 to D.102). The pattern is almost identical across model specifications, development scenarios and management strategies; with most fragmentation occurring prior to 1980 and little recovery or patch agglomeration occurring after that. Benthos fragmentation also increased throughout the simulation period and was consistent across alternative management strategies. For both seagrass and benthos the variability of these regional results masks finer-scale differences between the strategies. Locally the integrated management strategy leads to lower fragmentation, while the enhanced strategy produced more heavily fragmented habitats.

Mangrove habitat was affected little by the different management strategies, development scenarios or model specifications. Human activities only slightly disturbed the mangrove habitat prior to 1980. Since 1980 mangroves have been affected little, owing to the relatively large coverage of mangroves throughout the Pilbara region, and by comparison the relatively small amount of disturbance through economic development and cyclones.

3.5.3 Habitat height

Comparison of the effect of the different management strategies on average habitat height (in cm) of seagrass, benthos and mangroves under the various development scenarios is shown for the different model specifications in figures D.103 to D.105. There are no notable differences in the time series of habitat height indices among the different model specifications, development scenarios or management strategies. There is almost no change in average mangrove height for any of the displayed trajectories. In contrast, seagrass and benthos declined under historical pressures. The seagrass height declined by half throughout the first ten years of the historical period in each case and tended to remain at that reduced level for the remainder of the simulation period. The large reduction in benthos height in the historical period prior to 1980, caused by the foreign trawl fleet, is the same in all cases, though there is some suggestion of a recovery (at least a reduction in variability across the region) under the optimistic model specification. Nevertheless the pattern does not differ across the management strategies at this regional scale. Again, locally (see the spatial results below) there is more recovery in some patches under the integrated management strategy.

3.5.4 Relative habitat cover

Time series projections of the effect of the different seagrass, large and small benthos and mangrove habitat cover relative to initial conditions (in 1970) for the different management strategies under the alternative model specifications and development scenarios are shown in figures D.106 to D.108. There is little variability among management strategies and development scenarios. Seagrass coverage under all management strategies declines through the historical period and continues to do so throughout the projection, regardless of model specification. The overall relative coverage of mangroves is mainly affected in the historical period prior to 1980, but thereafter recovers steadily through the simulation period. Both the large and small benthos were affected primarily in the historical period (prior to 1980) by the foreign trawl fleet. The effect was larger on the slower growing large benthos than on the more productive small benthos, the latter showing some recovery towards the end of the projection period under the base case and optimistic model specifications.

3.6 Catch and biomass of high valued and low valued species

The biomass and catch of different species of finfish is of economic interest to fishers and fish consumers and also of conservation interest to the community more generally. In this section the finfish species have been grouped into those of high value and those of low value in the fish market. These species groups invoke different targeting behaviour by fishers and also exhibit different habitat preferences. The ecological condition of these groups is characterised by their mortality rates, and the state of their spawning stocks biomass.

3.6.1 Absolute catches of high and low valued species

The total catches of high valued species and low valued species across different management strategies are shown for the pessimistic model specification in figure D.109, and under base case and optimistic model specifications in figures D.110 and D.111, respectively. Under all model specifications the integrated management strategy results in substantially decreased catches of the high valued species (*L. sebae* and large lutjanids) to half historical levels or less. The other two strategies lead to catches closer to historical levels. The confidence intervals for the time series of high value catch tend to overlap across management strategies, but the plots suggest that the enhanced management strategy may lead to lower total catches of high valued species under a pessimistic model specification and higher catches may result from such a strategy in more productive systems (i.e. the base case and optimistic model specifications).

Similar patterns occur for the total catch of low-valued species; catches are lower under integrated management (this time remaining at about the levels in the year 2000), while there is less separating the time series under enhanced or status quo management, where catches reach 150% or more of historical levels.

3.6.2 Relative catches (high value/low value)

The ratio of the catch of high-valued species (*L. sebae* and large lutjanids) relative to low-valued species (lethrinds, small lutjnaids, nemipterids and saurids) are shown in figure D.112 for the pessimistic model specification, figure D.113 for the base case model specification and figure D.114 for the optimistic model specification. In each case the ratio remained relatively stable through the projection period. The integrated management strategy resulted in relatively high catches of high valued species in all cases, though the effect was more pronounced under the less productive model specifications.

3.6.3 Biomass of high and low valued species

The biomass of high-valued species relative to the low-valued species was also higher under the integrated management strategy for all model specifications (see figures D.115 to D.117); although this result is marginal under the optimistic model specification. Compared to the other management strategies, the integrated management strategy does best under the pessimistic model specification (figure D.115). This is also the only model specification for which the enhanced management strategy leads to higher relative biomass of high-valued species than under status quo management (figure D.115). As the productivity of the system increases from pessimistic to base case to optimistic model specifications, the benefit of the integrated management strategy at conserving high-valued species biomass (in comparison with conservation of high-value biomass under the other management strategies), decreases because the stocks are less depleted at the beginning of the projection period. It is only under the integrated management strategy that recovery of high-value species occurs, thus improving community composition. Under the other management strategies the population of high-valued species stabilises at best.

3.7 Biomass of r-selected and K-selected species

The effects of management strategy on the biomass of r-selected species (king and banana prawns, nemipterids, saurids and small lutjanids) relative to K-selected species (*L. sebae*, large lutjanids, lethrinids, shark and turtles) are shown in figures D.118 to D.120. The integrated management strategy favours the K-selected species more than the other management strategies under the pessimistic and base case model specifications. There are no notable differences among management strategies under the optimistic model specification. Under pessimistic and base case model specifications, the status quo and enhanced management strategies result in levels of r-selected species that rise above the levels in the unexploited system at the beginning of the simulation (i.e. during the early 1970s). In contrast, the integrated management strategy results in stabilised biomass ratios of r- and K-selected species under the pessimistic model specification and a decrease in the contribution by r-selected species under a base case model specification. This is due to the recovery of turtles in these simulations. Under the optimistic model specification (figure D.120) there is little effect of the management strategy because the species are sufficiently productive that the system has recovered to the approximate pre-exploitation levels before the projection period begins: this means that the management strategy used through the projection period has little impact on the community composition, as there is little to trigger the different decision procedures. Note that the divergences between integrated and other management strategies are not as pronounced under alternative model implementations where turtles do not recover so strongly.

Towards the end of the simulation period under more intensive anthropogenic disturbance (the 2-pulse development scenario) there is the suggestion that the trend under the enhanced management strategy may lead to a system more heavily weighted toward r-selected species. This is due to the combination of recreational fishing pressure (which increases with each developent pulse) depleting inshore stocks and unrelenting commercial fishing pressure on offshore stock components.

3.8 Indices of species diversity

Species diversity measured as summed relative biomasses is compared for different management strategies in figures D.121 to D.123. As previously stated, the loss of diversity was greatest during the 1970s, with a slow recovery for the rest of the model simulation, the rate of recovery being dependent on the model specification used. The integrated management strategy resulted in greater levels of this diversity measure under the pessimistic and base case model specifications (figures D.121 and D.122), but not significantly different to that under the other management strategies when an optimistic model specification was employed (figure D.123). While the increased diversity does not approach pre-exploitation levels under the pessimistic model specification, even with integrated management, the increase in diversity is so marked under the base case model specification that it approaches pre-exploitation levels by simulations' end (figure D.123). These levels are also comparable to those under an optimistic model specification.

The results for the Shannon diversity index (see figures D.124 to D.126) show very high variability (as indicated by the error bars). In every case the measure decreases consistently through time and, like the summed relative biomass, there is no effect of management strategy under the optimistic model specification. In contrast, the impact of the management strategy on the Shannon diversity index is the opposite to that on the summed relative biomass measure of species diversity. That is, the Shannon diversity is lower than the relative biomass measure of diversity under integrated management for the pessimistic and base case model specifications (figures D.124 and D.125). The reason for the difference in diversity measures is the contribution of turtle recovery under the integrated management strategy. As turtle relative biomass increases, so too does its contribution to the summed relative biomass, but the dominance of turtle biomass in the species distribution leads to a decreased value for the Shannon diversity index, which is maximised when there are equal amounts of each species.

The results for Renyi's diversity index are a mix of the other diversity indices (see figures D.127 to D.129). Under the pessimistic model specification (figure D.127) the integrated management strategy increases this diversity measure the most, in much the same way it increases the summed relative biomass measure of diversity (figure D.121). Under the base case model specification, the integrated management strategy initially causes the Reyni diversity measure to increase more strongly than do the other strategies, but then it causes a sharp decline (figure D.128). As mentioned above, this was caused by the large recovery of turtles that dominates the species distribution. There is much less effect of management strategy on the Renyi's diversity measure under the optimistic model specification although that specification represents a highly-productive system which seems to be more susceptible to environmental forcing.

As for the other turtle-associated results, the differences between the values of these diversity indices under integrated management and the other management strategies is much less pronounced when other turtle models are used, as turtle recovery is not as strong.

3.9 Recreational fishing

The effects of management strategy on the recreational fishing catches of *L. sebae*, lethrinids, large lutjanids and nemipterids are shown in figure D.130 for the pessimistic model specification, in figure D.131 for the base case model specification and in figure D.132 for the optimistic model specification. The enhanced and integrated management strategies, which regulate the trawl fishing effort fairly heavily, lead to higher recreational catches of red emperor and large lutjanids (*L. sebae* and large lutjanids) than under the status quo management strategy. This is particularly true for the pessimistic and base case model specifications. In contrast, the catch of the less-desirable species does not differ significantly under the alternative management strategies.

Again the effect of development scenario is apparent. Under the pessimistic model specification, there are distinct pulses and step changes in recreational fishing catches of *L. sebae*, matching the timing of the corresponding development scenario pulses. These have little effect on the overall total fish biomass because they represent a relatively small portion removed from the finfish populations.

3.10 Species of high conservation value

The effects of management strategy on the species of high conservation value (turtles and sharks) are shown in figure D.133 for the pessimistic model specification, in figure D.134 for the base case and in figure D.135 for the optimistic model specification. Integrated management results in increased turtle abundances under pessimistic and base case model specifications (figures D.133 and D.134), with population sizes matching (or even exceeding) pre-exploitation levels by the end of the simulated period. Similar levels of recovery are seen under all management strategies when employing an optimistic model specification. Again, it is the very high levels of turtle recovery relative to other species that causes a drop in the Renyi and Shannon diversity indices (figures D.125 and D.128), and the increase in the summed relative biomass measure of diversity (figure D.122). Such strong recoveries suggest that some of the lags in the real system are not captured in this model implementation. Further consideration of those species with an age-structured population agent representation shows that such lags can produce very long-term dynamics and very slow rates of recovery (with the impacts of historical events still being felt throughout the projection period, resulting in little difference between the biomass trajectories under the alternative management strategies). Nevertheless, the results for the species of conservation concern show that there is the potential for strong direct and indirect effects of alternative management strategies on many of the indicators. This is a very informative result given that a positive change in one conservation index (biomass of turtles) can lead to such strong changes of a potentially undesirable nature in another index (diversity). This reinforces the practical notion that ecosystem management will never be straightforward.

The form of the management strategy has much less impact on the shark time series. In all cases there was no difference between the shark populations under each strategy, with the same general form being followed in each case: an initial marginal increase, then strong decline, followed by a long (and sometimes erratic) recovery.

3.11 Economic indicators

The economic indicators for the trawl fishery, across the different management strategies and development scenarios, are shown in figure D.136 for the pessimistic model specification, in figure D.137 for the base case and in figure D.138 for the optimistic model specification. All trajectories of gross margin were less than the level of fixed cost (capital and gear costs). Admittedly these were based on South East Fishery data (Appendix E), which were the only cost data available to the authors at the time these indicators were assessed, but they should still be indicative of the costs faced on the NWS (Tom Kompas, ABARE, pers. comm.). The general trend, however, is for a slight increase through the projection period (approaching the fixed cost level by the end of the simulated period). Under the pessimistic and base case model specifications, the integrated management strategy tends to give smaller gross margins than the status quo or enhanced management strategies. The reason for this lies in the reduced effort of the finfish trawl fishery (figures D.85 and D.86), which outweigh the increased benefit of higher catch rates under the integrated management strategy (figures D.76 and D.77).

Under the optimistic model specification (figure D.138), the economic performance of the trawl fishery is worse than under the other, less productive, model specifications (figures D.137 and D.136). This is the case regardless of the management strategy employed. The reason for this somewhat unexpected result is the unresponsiveness of catch rate (figure D.78) or biomass (figure D.75) of the targeted species *L. sebae*, to changes in management strategy. Since the finfish biomass was close to pre-exploitation levels in the optimistic model specification, little management intervention is applied during the projection period. As such, the catches, catch rates and fish biomasses were similarly unaffected. The bioeconomic interaction between the finfish populations and the vessels was designed so that the catch rates of the vessels in the projection period mimic that of the historical data under the same biomass and effort, by using the average historical catchability factor q. Under the optimistic model specification q is low because the historical catches took only a small proportion of the populations, compared to the pessimistic model specification which historically took a larger portion of the population. As a result the catch rates change little under the optimistic model specification because the biomass remains close to pre-exploitation levels, thus causing gross margins to remain low.

The economic indicators for the prawn trawl fishery, comparing the different management strategies and development scenarios are shown in figure D.139 for the pessimistic model specification, in figure D.140 for the base case and in figure D.141 for the optimistic model specification. The results are different from that of the finfish trawl fishery. Most combinations of management strategy, development scenario and model specification yield gross margins that are above the level of fixed costs (again based on data from the Southeast fishery Appendix E). The only exception to this is under the integrated management strategy for the pessimistic and base case model specifications (figures D.139 and D.140) where returns are well below the values for the enhanced and status quo management strategies (and often coincident with the level of fixed costs, suggesting that the fishery would be troubled economically in these cases). The gross margin resulting from the integrated management strategy under the optimistic model specification (figure D.141) does not drop as it does under the other two model specifications, mainly because prawns are abundant relative to the restrictions imposed by management. While there is not much to separate the enhanced and status quo management strategies under base case and pessimistic model specifications, it seems that the status quo prawn fishery management strategy performs better economically under the base case specification, while the enhanced management strategy yields highest gross margins when the pessimistic specification is in place.

3.12 Implications for multiple-use management

The dominant message from the discussion above is that the integrated management strategy leads to patterns in the indicator variables that are clearly distinguishable from the patterns resulting from the status quo and enhanced management strategies. Notwithstanding a few notable exceptions, this outcome is consistent across a range of uncertainties, including those treated explicitly in the alternative model specifications and development scenarios, and those treated as random variables in the computer simulations. This is an important result given that the enhanced management strategy represents best or most-efficient practice for each independent sector. The reason for such a consistent outcome is that the integrated strategy provides checks and balances across the impacts of a range of sectoral activities. These sector activities have direct impact on the sector itself and may have spillover effects on other sectors or the human population and ecosystem as a whole. In contrast, the sectorally-based management strategies need not pay attention to anything but their own focus resources. As a result, while their details differ, the sectorally-based management strategies invoke broadly-similar patterns in the indicator variables; although the enhanced strategy, as compared to the status quo strategy, does have differential impacts on some conservation and social variables.

The integrated management strategy differs from the sector-based strategies in that its multiple-use perspective requires simultaneous attention to indicator variables that represent social, environmental conservation, economic and safety considerations. With the exception of cases where uncertainty dominates the simulation results (notably prawn biomass and regional habitat coverage), the integrated management strategy (compared to the other, sector-based, management strategies) leads to significant increases in the stocks and catch rates of high-value fish species, increased recreational fishing catch, improved abundance of species of high conservation value (particularly turtles), an improved state of the overall system and biodiversity (in general), a reduction in commercial fishing effort and a reduction in commercial fishery gross margins. Integrated management also leads to a decline in contaminant impact and a decrease in the risk of ship collisions and catastrophic spills (see below).

For the NWS analysis presented here, the two sector-based management strategies perform differently according to only four indicator variables. The enhanced strategy leads to increased commercial catch and CPUE of high-value target species and greater recreational catch, as compared to the status quo management strategy. Enhanced management also leads to lower habitat fragmentation at local scales than does status quo management.

Clearly these results provide a limited number of examples to demonstrate how alternative management strategies can alter natural resource use in a multiple-use setting. They go beyond that, however, because they illustrate that the MSE framework is now developed sufficiently to provide analyses of how well potential strategies, scenarios and model specification can be used and improved to help the achievement of management objectives and to guide scientific research and data collection to best serve regional and ecosystem-level natural resource management.

The calibration of the model software using real-world data allows for easy identification of both model and data shortcomings. It also highlights that particular indicators can be used to discriminate clearly among some, but not all, management strategies, depending on the magnitude of, and variation in, their relative impacts on indicator variables and depending on the uncertainties in present knowledge, existing data and scenarios for the future. This can give useful insights into effective monitoring schemes.

4. COMPARISON OF DEVELOPMENT SCENARIOS

Alternative development scenarios potentially have differential impacts on the biophysical and socio-economic dynamics of a region. They also have the potential to harm or enhance the effectiveness of competing management strategies in achieving management objectives. In this section a comparison is made among the 0, 1 and 2 pulse development scenarios, taking into account alternative model specifications and management strategies.

4.1 Human population, vessels and production

The different number of cargo vessels, total population and total production under the different economic development scenarios are shown in figure D.142. These data are not model outputs but rather are used as inputs to the model as forcing variables on various components. For example, the number of cargo vessels in the model effects the vessel congestion, the need for ports to expand existing facilities and the probability of a collision or an oil spill. The total population is assumed to affect the recreational fishing catches, and the total production is assumed to affect the effluent or contaminant levels.

Under the 0-pulse development scenario the number of vessels in the model moving among ports and rigs is static at 60; the total human population through the projection period is maintained at 30 000; and the total value of production index fluctuates at about a factor of five. Under the 1-pulse development scenario the number of vessels in the model increases linearly to a maximum of 90 in 2005; the population increases to about 60 000 before dropping back to 50 000, and the total production index rises to a factor of six. Under the 2-pulse development scenario, the number of vessels in the model does not stop at the level seen under 1-pulse but continues to increase linearly to 140 by 2010; the population also increases, reaching 60 000 before plateauing a little lower in 2010, and the total production follows the 1-pulse development scenario until 2010 before climbing to a factor of eight.

4.2 Recreational fishing

The effects of development scenario are shown in figures D.130 to D.132. Under all model specifications and management strategies, the recreational fishing catches of *L. sebae* and, to a lesser degree the other species, correspond to the human population trajectory (figure D.120). These have little effect on the total fish biomass because they represent a relatively small portion of the catch removed from the population. Under the optimistic model specification there is little difference among recreational catches for different management strategies (figure D.132). Although the catch of *L. sebae* and large lutjanids is as high as 5 t, this is almost insignificant compared to the trawl catches of 500 t for the two species (figure D.111). Consequently recreational fishing, as modelled here, has little overall impact on the total finfish biomass (figure D.75).

4.3 Port and vessel traffic

The effect of alternative development scenarios on the performance of the ports of Dampier and Port Hedland, and on the number of vessel near-misses and evasions, is shown in figure D.143 for the status quo management strategy and in figure D.144 for the enhanced management strategy. A comparison of the strategies is given in figure D.145.

There is no systematic difference among the different model specifications because the productivity of the ecosystem has little effect on the economic activities associated with deep sea freight traffic. The effect of the 1- and 2-pulse development scenarios, in the form of increased vessel traffic and demand for port facilities, decreased net revenues in the status quo management strategy (net revenue was scaled to the first year of the projection period). This profitability may be better considered as an inverse index of the risk of collision inside the port. Consequently figure D.143 shows that there is a substantial risk of collision inside the port under increased development if the status quo management strategy is maintained.

The revenue function for the ports (or inverse port collision function) is quadratic in form so, as the capacity of port facilities is exceeded, the net revenue of the port agent decreases (and the risk of a major accident inside the port significantly increases). Under the enhanced management strategy, when the port usage exceeds a threshold, the port capacity is expanded, thus enabling the port authority to handle more vessels and increase annual net revenue (and reduce the risk of a catastrophic collision). This can be seen in figure D.144, particularly for Dampier. As the vessel traffic increases and exceeds the port's capacity, the net revenue decreases, until an expansion is triggered in 2003. At this point the net revenue increases with the increasing number of vessels using the port. Potentially more importantly, this also shows that under this management strategy the risk of collision inside the port can decrease despite the higher number of vessels serviced. Under the 1-pulse development scenario this increase in traffic continues until 2005, at which point port net revenue is maximal. Under the 2-pulse development scenario, the vessel traffic continues to increase further, resulting once again in a decrease in port net revenue (and an increase in the chance of a collision inside the port's confines). Note that the improvement in performance of the ports under the enhanced management strategy is only realised under the 1-pulse and 2-pulse development scenarios (figure D.145).

The risk of collision is not only restricted to the waters within the ports. It is also possible that ships in the inshore waters may collide as they move to and from the local ports. Essentially the only real trend in the number of evasions outside the ports is that there is an increase, matching the increase in vessel traffic under the alternative development scenarios. There is no effect of management strategy for the port on the number of these near collisions (or evasions) because they occur outside the area under the port authority's control.

4.4 Mangrove cover

As mentioned above for figures D.25 to D.36 and figures D.97 to D.108, there is little difference among the mangrove habitat indices under the alternative management strategies, model specifications or development scenarios. The only difference observed is that there is more depletion with more periods of development. Considering local dynamics immediately around human settlements (see the spatial results discussed below), there is extensive depletion where trees are cleared during development. As may be expected, this is more severe with more development pulses. Generally, however, unless this land remains cleared (i.e. is built upon) then there is some understorey (small tree) recovery in a fairly short period; although full forest formations take quite long periods to be re-established (in the order of a decade or more).

4.5 Acid sulphate soils

A comparison of the levels of an index of acid sulphate soil exposure is given in figure D.146. This coarse index does not really show any difference due to model specification, when considered at the regional scale. However, like so many habitat indices, more differences are apparent at the local scale, especially under more pessimistic model specifications where the impacts are higher. The impacts of development scenarios is quite clear in this index: the more development pulses imposed on the system, the more acid sulphates persist as they are re-disturbed and the “recovery” process must be reset.

4.6 Implications for management

The results under the alternative development scenarios highlight the finding mentioned in passing under both the model specification and management strategy discussions. On the regional scale there is little that proposed industrial and residential development can do to impact the natural system more than has already occurred. There are too few humans to cause widespread impacts under the development scenarios examined. The same is not true on local scales around settlements or ports. At that scale the system is very sensitive to the form and extent of development and to the management strategy employed.

5. CONTAMINANT RESULTS

The model's contaminant-ecosystem interaction is present as a demonstration of capability, more than a rigorous treatment of the mortality which can be attributed to contaminant release on the North West Shelf. This is primarily due to an almost complete lack of local data on which to base the simulations, especially with respect to the toxicity of the released contaminants to active (especially adult and juvenile) life stages of the various organisms. All available data deal with larvae in laboratory conditions (and then only for a subset of species types).

One of the central problems with contaminant impact representation is that it is not possible to determine which toxins in a mix of contaminants are responsible for what proportions of mortality in the modelled populations, since the mortality associated with a contact is determined in an order-independent way. Attempting to impose an order to the way mortality is calculated would systematically over-estimate or under-estimate the mortality associated with the different toxins which comprise the contaminant plume. Though Könemann and Pieters (1996) note that partial dose additivity is a common occurrence in aquatic systems, no specific data were found to inform a dose additive model of the mixtures' toxicities to the simulated organisms. Lacking such data, the authors took, as a first approximation, a model of toxicity which assumed the independent action of the components of the mixture (response additive) rather than a dose additive or ameliorating model. The mortalities associated with distinct outfalls were differentiated since these mortalities are applied to the populations in a non-deterministic order.

The contaminants represented in the model were taken from the North West Shelf contaminant inventory (Fandry et al. 2006) which details the amount released and the flow rates at the outfalls. Mortality associated with several contaminants listed for outfall sites (notably total petroleum hydrocarbons and tin) was not simulated because no non-zero levels of these were reported in the contaminants register.

With the exception of mortality associated with bitterns contact, the lethal concentration levels were taken from the ASEAN Marine Water Quality Criteria document (McPherson, 1999). This document provided a consistent set of recommended levels which address the effects of the contaminants simulated in a tropical, marine environment for species represented, or closely related to those present, in the simulation (e.g. *P. monodon,* and *C. commercialis*).

The simulated mortality of the bitterns discharge at Nickol Bay is likely to be substantially different from what would be expected from current practice. In reality, bitterns are released from the salt works in discrete pulses timed to minimise their effect on the local system. The simulated release of bitterns into the bay was as a continuous plume rather than discrete releases, so the chance of encounter was likely to be much greater than current practice would suggest. This limitation was a result of computer runtime constraints.

The reader will notice that the results reported in this section are essentially deterministic. Stochastic elements of containment outflows, transport and ecosystem impacts were necessarily minimised because of computer runtime constraints and the need to process large amounts of numerical data. Nonetheless, the results presented are informative, provided they are interpreted as being an average representation of the distribution of results that could be produced from multiple simulations.

5.1 Plumes

The model for contaminant interaction uses plumes generated by a simulated outfall under the influence of currents derived from the output of MECO (Condie et al. 2006). The MECO currents were processed as described in Fulton et al. (2006b) to produce a series of snapshots of the proportion of the initial outfall concentration at each location in the region. This index-field and the outfall's flow were used to scale the concentration of a contaminant at the outfall to yield its concentration at locations within the full extent of the plume in the simulated environment (further details can be found in Gray et al. 2006).

5.1.1 Total footprint

The potential spread of the plumes from contaminated outfalls can extend considerable distances on the sea surface, as displayed in figure 5.1.1 (a). The extent of the depth averaged plume (displayed in figure 5.1.1 (b)) is much smaller than (approximately half as wide as) at the surface, but it still covers a considerable area.

The bulk of this footprint comes from the Hammersley and Mermaid Sound outfalls (see figure 5.1.2 (b) and (c)); the plumes of which both extend from west of the Burrup Peninsula through to Barrow Island and the Monte Bellos. The plume from the Nickol Bay outfall is not as extensive, though it still spreads across the entire bay east of the Burrup and sweeps back west once it clears the top of the peninsula and is caught by longshore flows.

(a) (b)

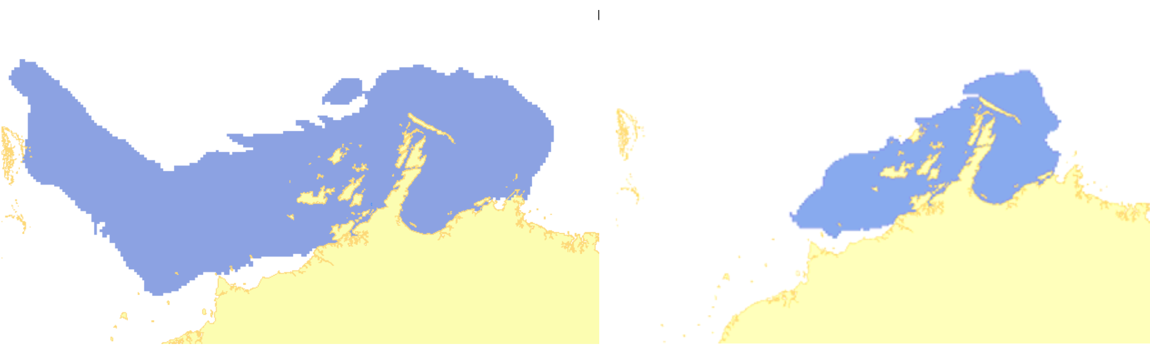


Figure 5.1.1: Total footprint of the combined plumes from the Nickol Bay, Mermaid Sound and Hammersley outfalls (a) at the surface, (b) depth averaged.

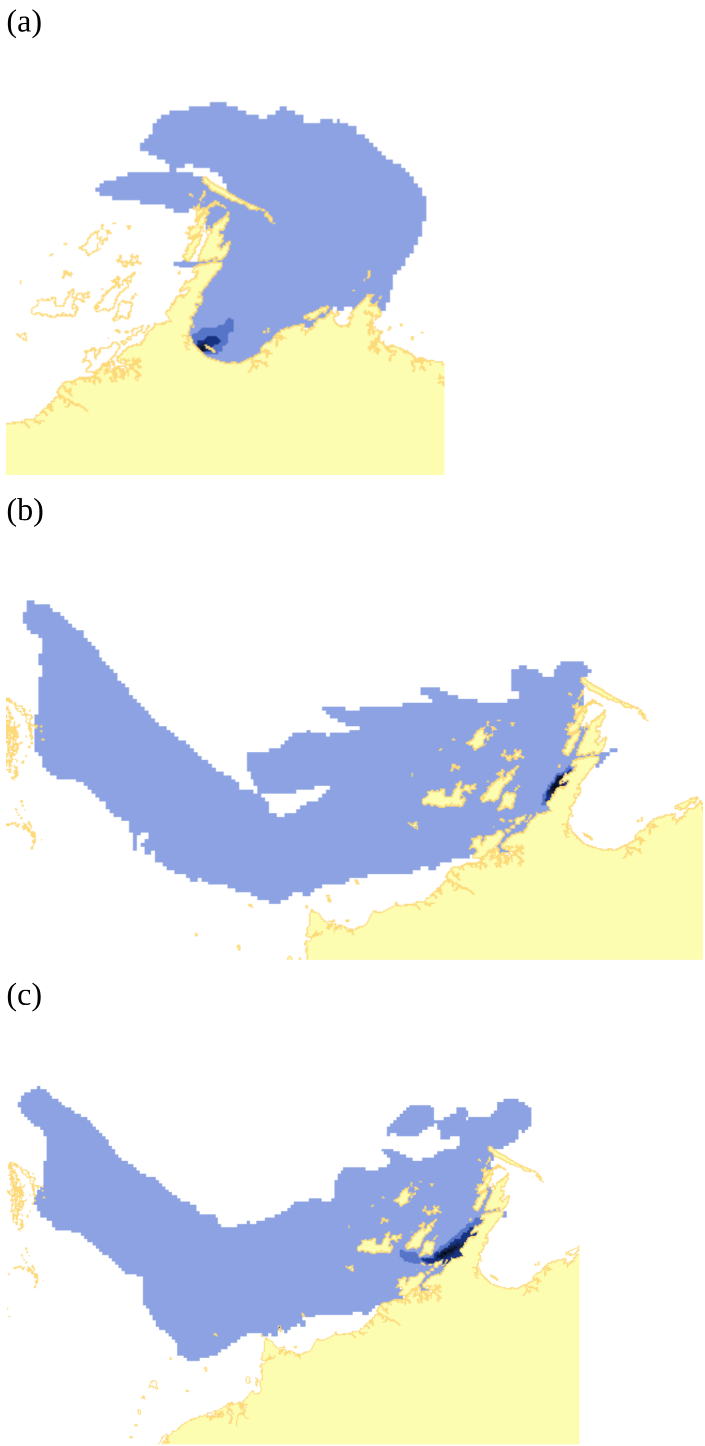


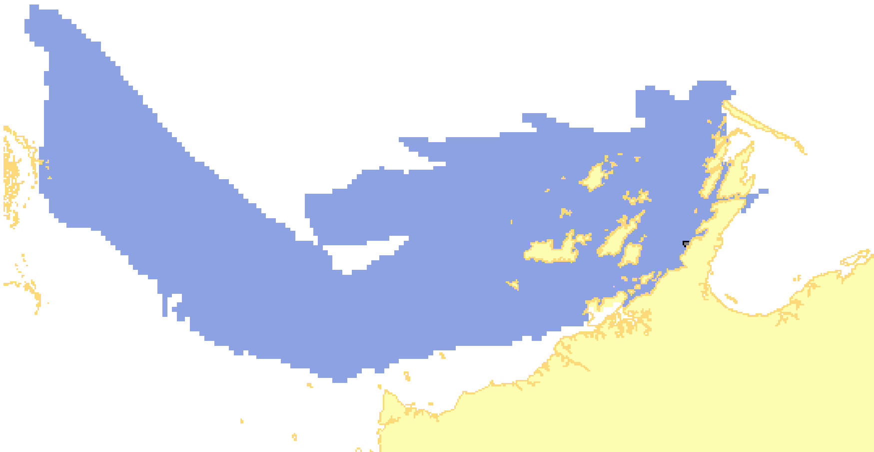
Figure 5.1.2: Maximal extent of the plumes from each of the outfalls (a) Nickol Bay, (b) Mermaid Sound and (c) Hammersley.

Toxin specific threshold points

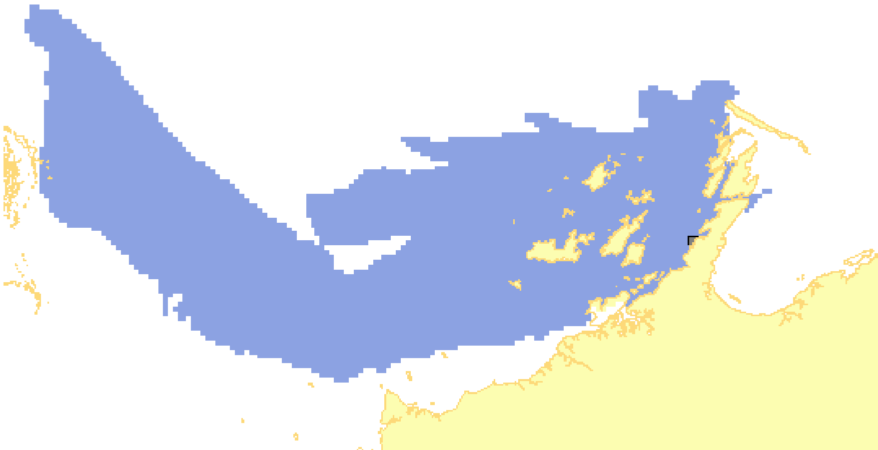
While the potential footprints can be extensive the areas where the concentrations can exceed ANZECC limits are much smaller. For oil, tin and the petrochemical hydrocarbons the concentrations are below the limits even at the outfall mouth. Cadmium is potentially the most troubling of the toxicants in the inventory, but the maps in figure 5.1.3 show that the critical area (marked in grey), where concentrations may exceed ANZECC guidelines, is a small fraction of the total potential footprint (shown in blue). The critical area grows through to the mid 1990s before it stabilises, but it can grow again in the projection period if flows aren't tightly controlled.

Copper has potentially the widest critical footprint (see figure 5.1.4), due to the low flow rates but high concentrations at the Hammersley outfall. The timeseries for copper is not as long as cadmium so there are no footprints before 1994. The spatial coverage of the plume is also so large initially that it does not undergo noticeable extensions during the projection period. It does, however, contract. Once current more stringent guidelines (in comparison with historical allowances) are enforced, the footprint drops to a relatively small area (see figure 5.1.4 (b)).

There were no ANZECC standards for sulphate or bitterns, but given their potential to impact upon larvae (Dampier Salt, pers. comm.) hypothetical standards were created (set to 8000 ppm for sulphates and 700000 ppm for bitterns). With these settings both of these contaminants have critical areas within Nickol Bay. The critical area for bitterns (see figure 5.1.5) is highly variable (at least in the period before 2000), but remains fairly small throughout the entire time series (never extending more than a third of the way across Nickol Bay). In contrast the critical area for sulphates changes substantially through time. The critical area for sulphate (in grey in figure 5.1.6) starts out as a very small proportion of the entire footprint (in blue) and is situated on the western side of the Burrup Peninsula. Through time the critical area grows substantially, especially in the late 1990s when the Nickol Bay source becomes significant. After that it continues to extend (by a small amount) through the projection period.

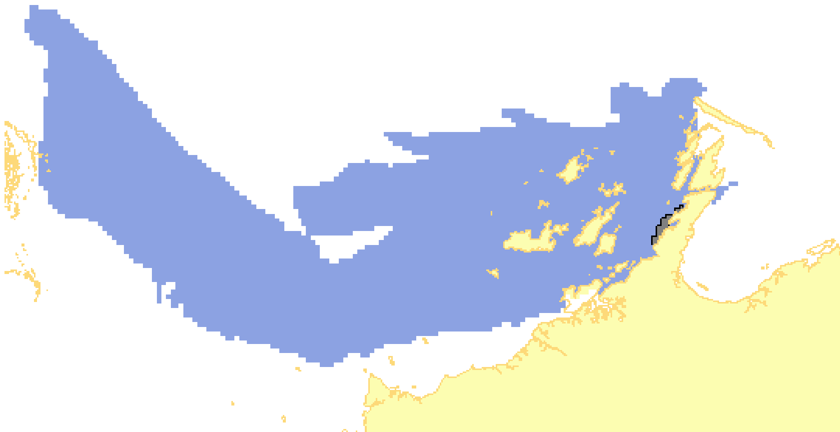


1985 to 1988

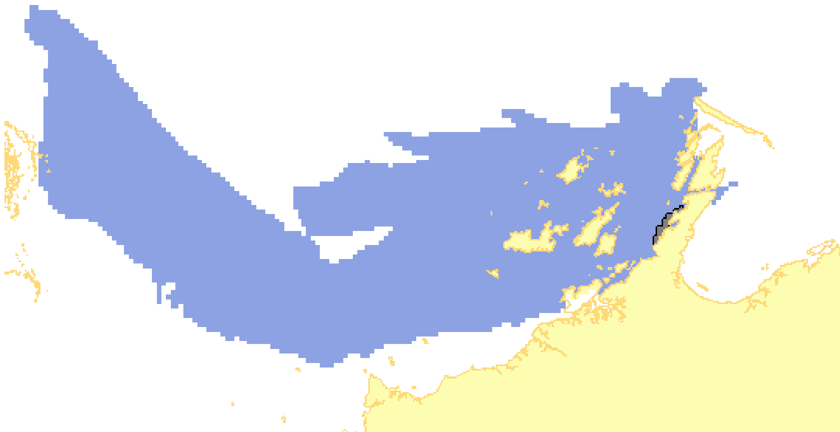


1989

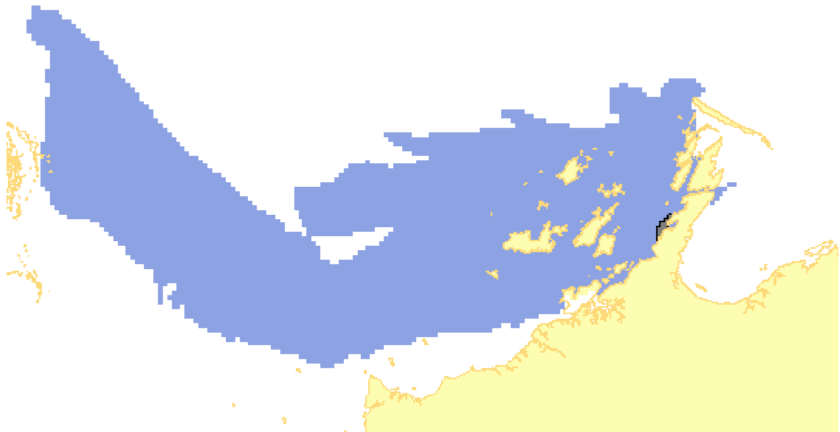
Figure 5.1.3: Cadmium footprint through time (blue is the total potential footprint in the water column and the grey indicates the area where the concentrations may exceed ANZECC guidelines).



1990

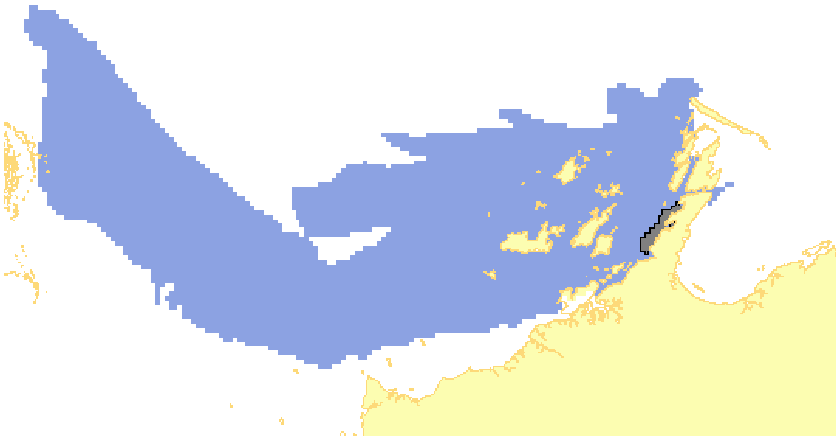


1991

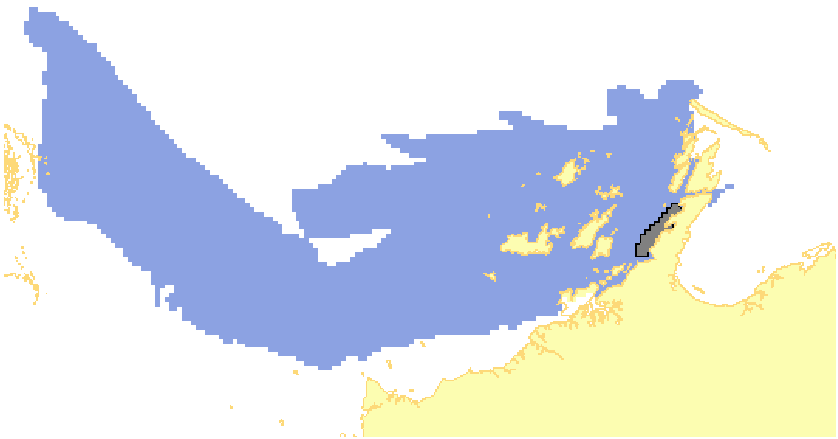


2000 to 2008

Figure 5.1.3: Continued. Cadmium footprint through time (blue is the total potential footprint in the water column and the grey indicates the area where the concentrations may exceed ANZECC guidelines).



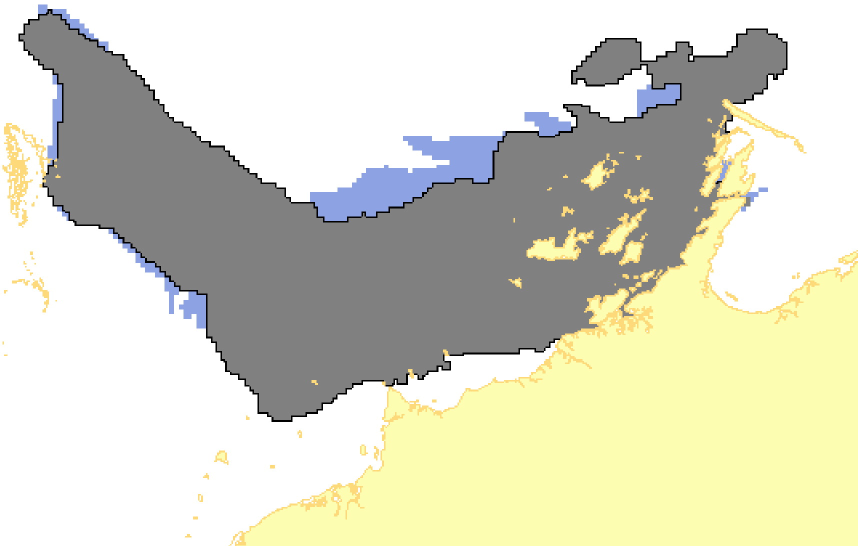
2009 to 2013



2014

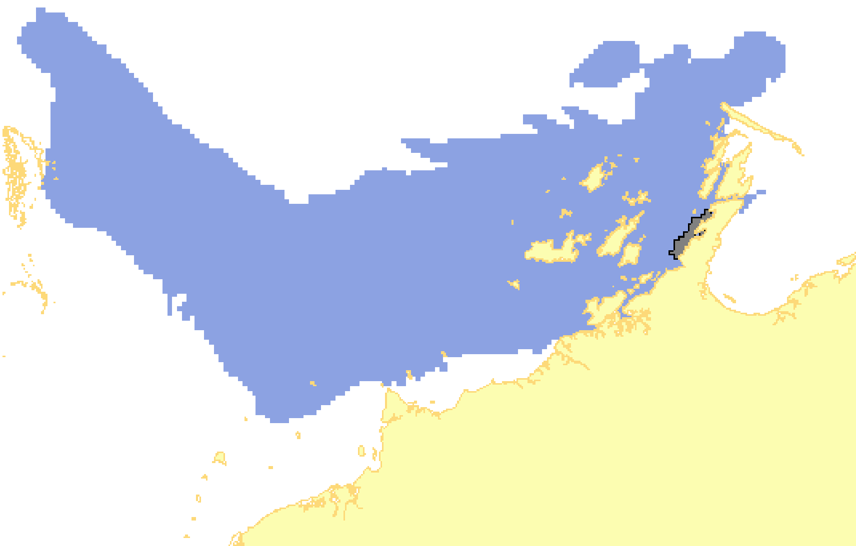
Figure 5.1.3: Continued. Cadmium footprint through time (blue is the total potential footprint in the water column and the grey indicates the area where the concentrations may exceed ANZECC guidelines).

(a)



Historical maximum footprint

(b)



Footprint 2000 onward

Figure 5.1.4: Critical footprint for copper (blue is the total potential footprint and the grey indicates the area where the concentrations may exceed ANZECC guidelines); (a) historical maximum and (b) under current more stringent guidelines.

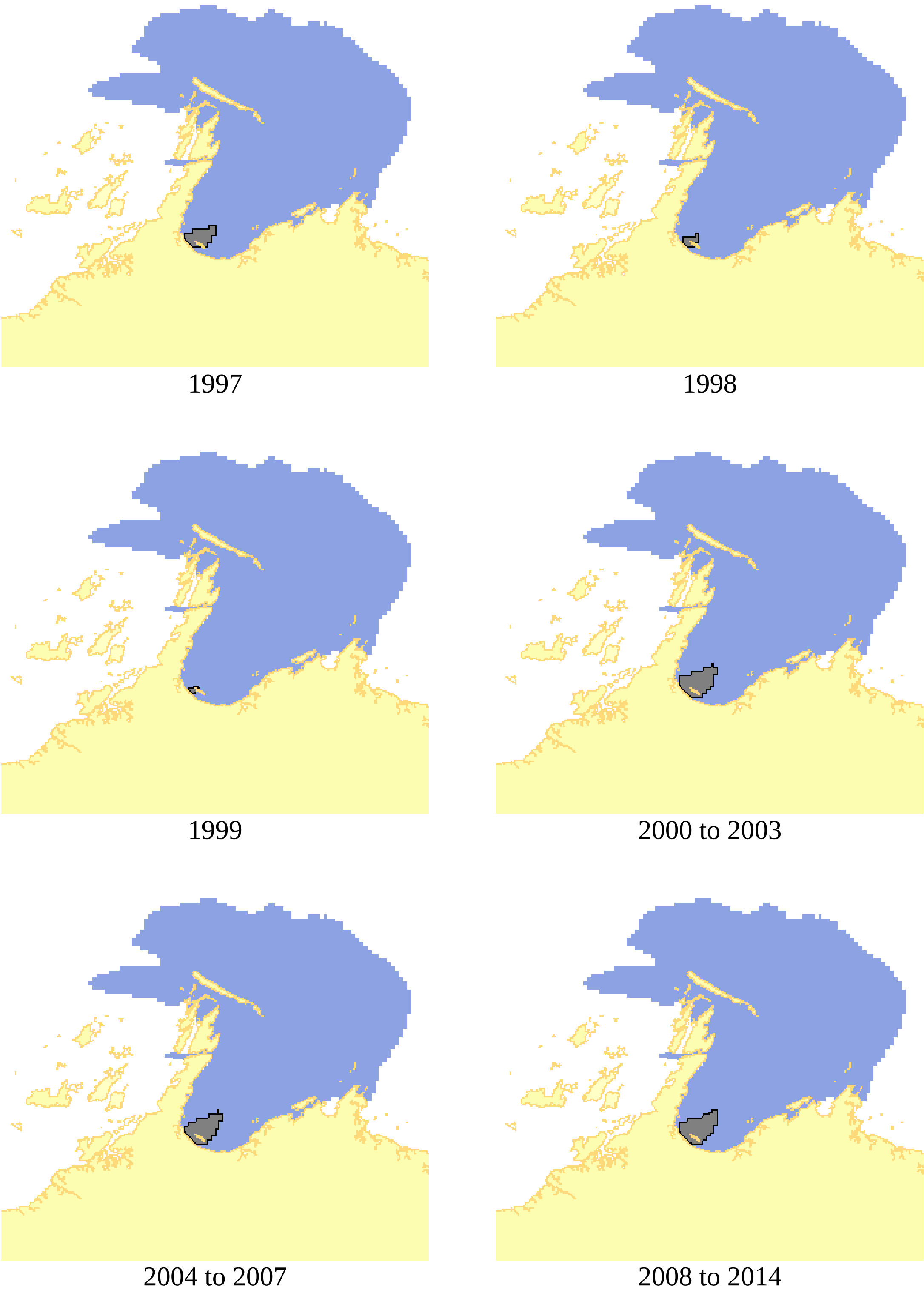


Figure 5.1.5: Critical areas for bitterns on the NWS (blue is the total potential footprint and the grey indicates the area where the concentrations may exceed hypothetical ANZECC guidelines).

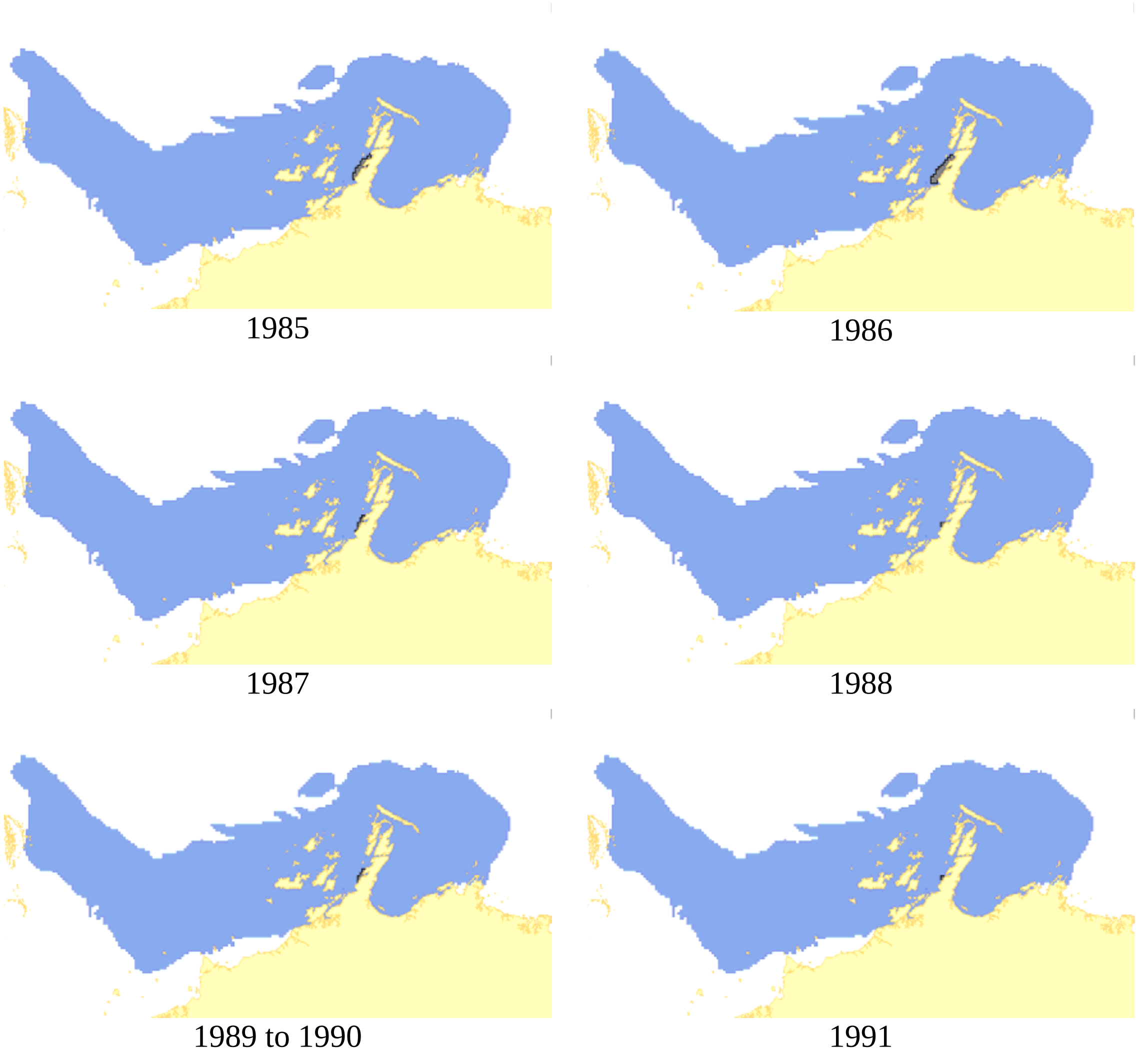


Figure 5.1.6: Critical areas for sulphates through time (blue is the total potential footprint and the grey indicates the area where the concentrations may exceed hypothetical ANZECC guidelines).

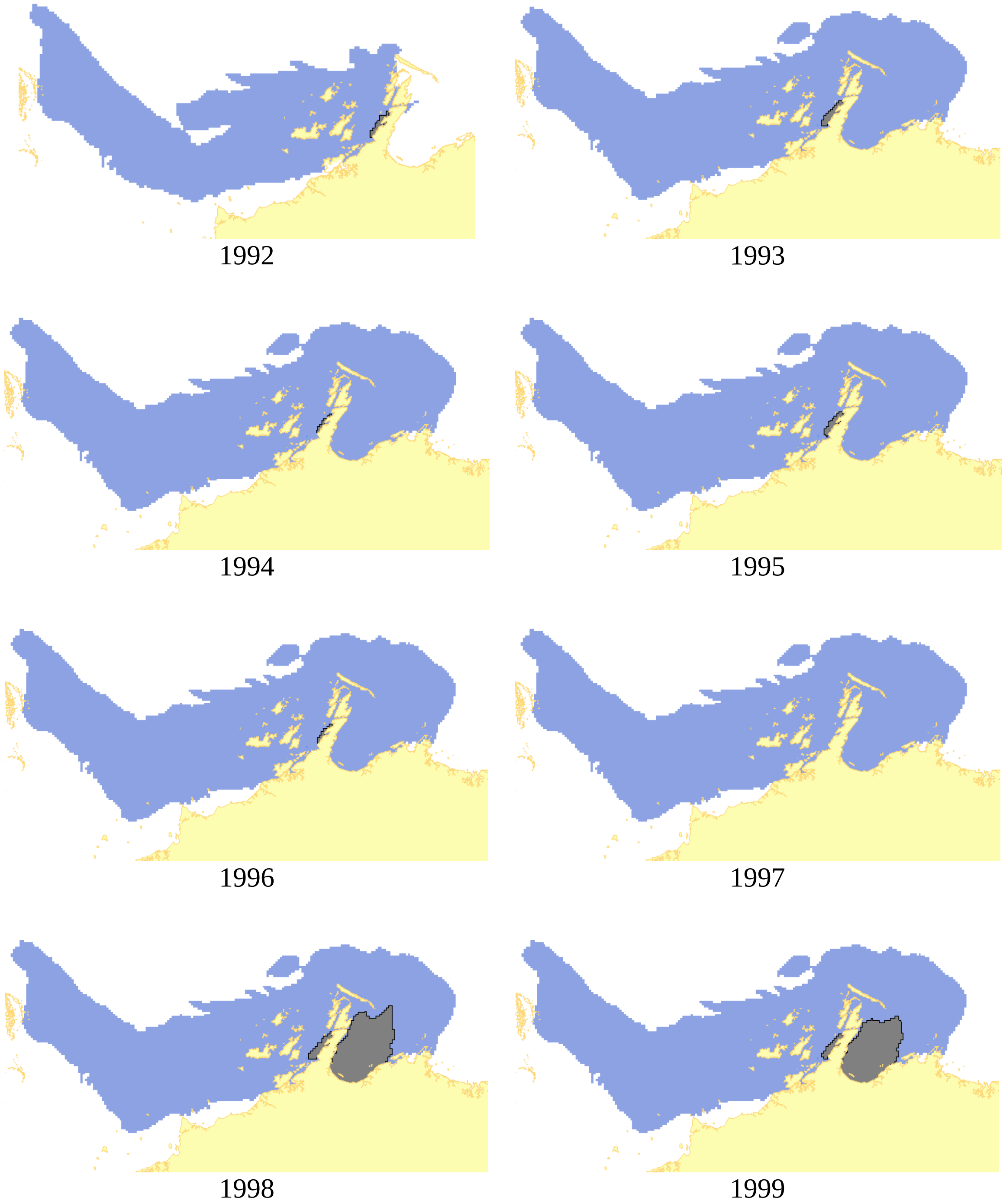


Figure 5.1.7: Critical areas for sulphates through time (blue is the total potential footprint and the grey indicates the area where the concentrations may exceed hypothetical ANZECC guidelines).

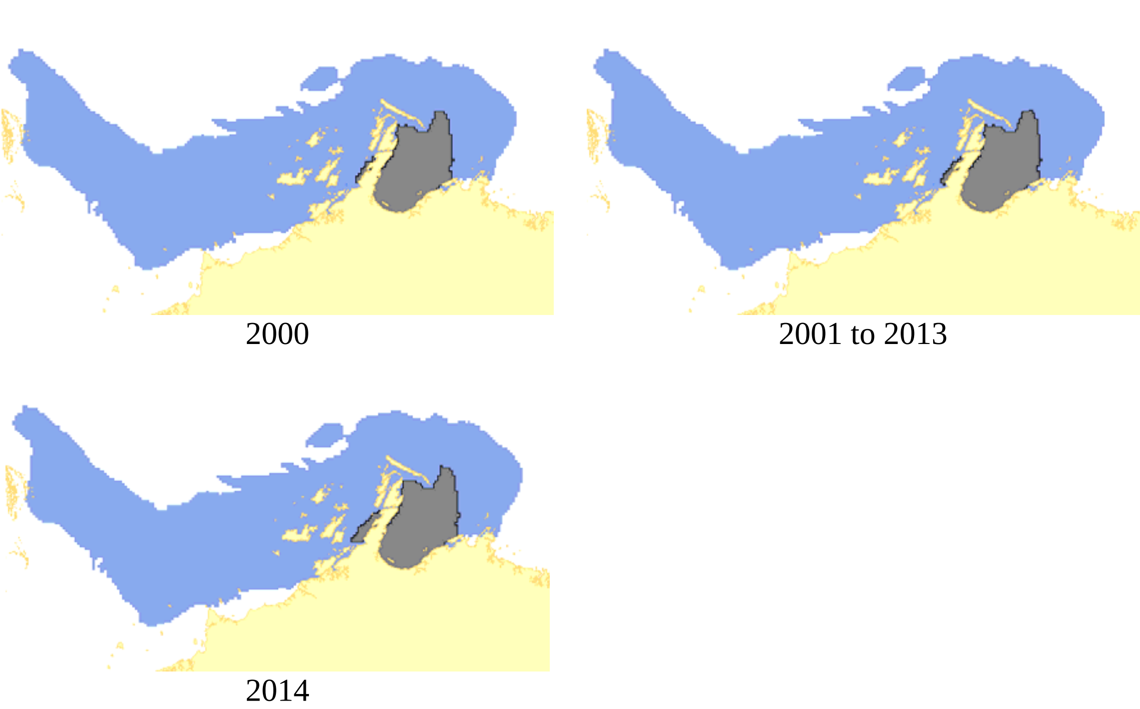


Figure 5.1.8: Critical areas for sulphates through time (blue is the total potential footprint and the grey indicates the area where the concentrations may exceed hypothetical ANZECC guidelines).

5.2 Logger station locations

The location of logger stations can have a significant impact on the signal returned. If loggers at critical distances from the outfall are required for monitoring purposes, then careful attention must be given to where they are placed if they are to return representative profiles that can be used for management purposes.

Three logger stations trialled in the MSE are shown below in figure 5.2.1. Sections of their time series records are shown in figures 5.2.1 to 5.2.4. Figure 5.2.2 shows that station A is ineffective, missing all the major peak plume concentrations and providing downwardly biased measurements at half the actual outfall values. The record at station B (figure 5.2.3) is a much better reflection of outfall levels. It is still not a perfect match, but does have peaks of about the same magnitude as the outfall. Station B misses some peaks, but in general it would give a sufficient warning of dangerous levels spreading from the outfall. The placement of station B out in the bay, however, means it may have high maintenance costs. Another logger position at station C (marked in purple in figure 5.2.1) would be easier to service and still provides a representative signal (figure 5.2.4). The record doesn't capture some of the highest peaks but it is more faithful to the outfall concentrations than is station A and it captures much of the desirable signal at station B. Station C looks to be a good compromise between signal reliability and support costs.

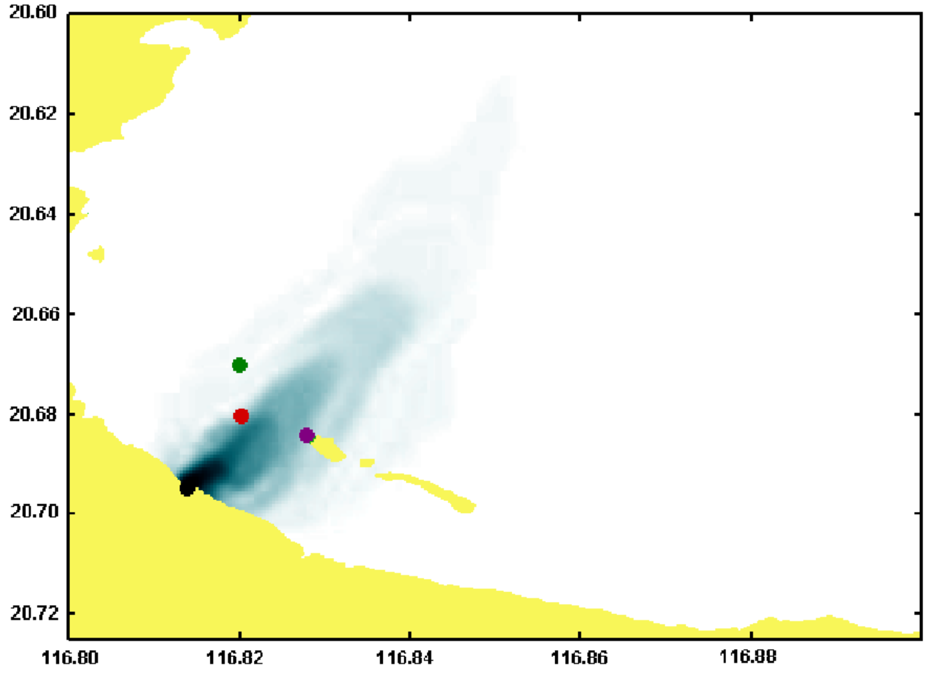


Figure 5.2.1: Location of three logger stations and a representative plume in Nickol Bay (green is station A, red is station B and purple is station C).

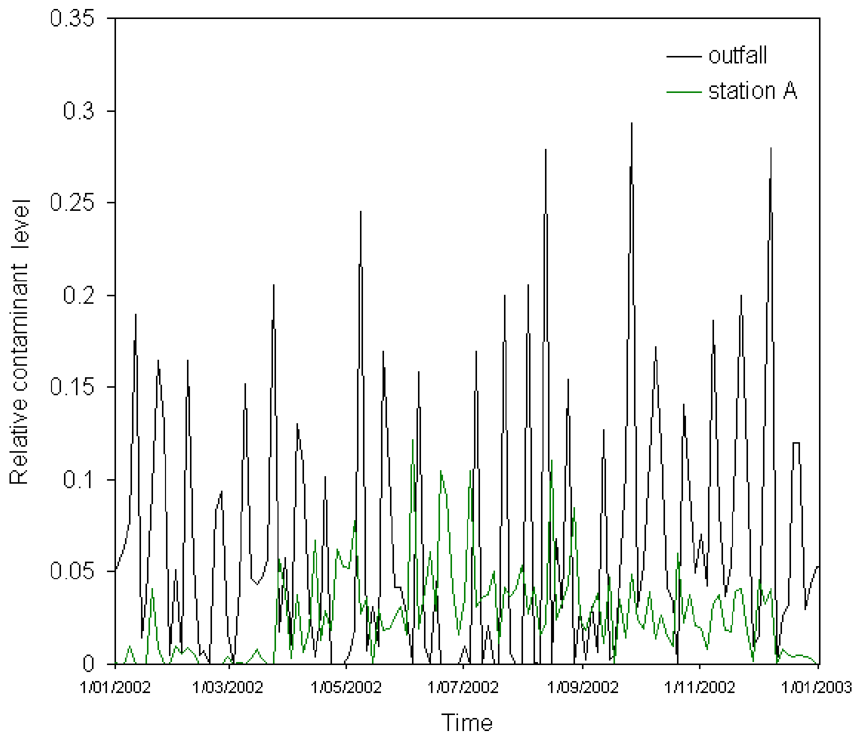


Figure 5.2.2: Relative contaminant signal strength at Nickol Bay outfall (black) and logger station A (green).

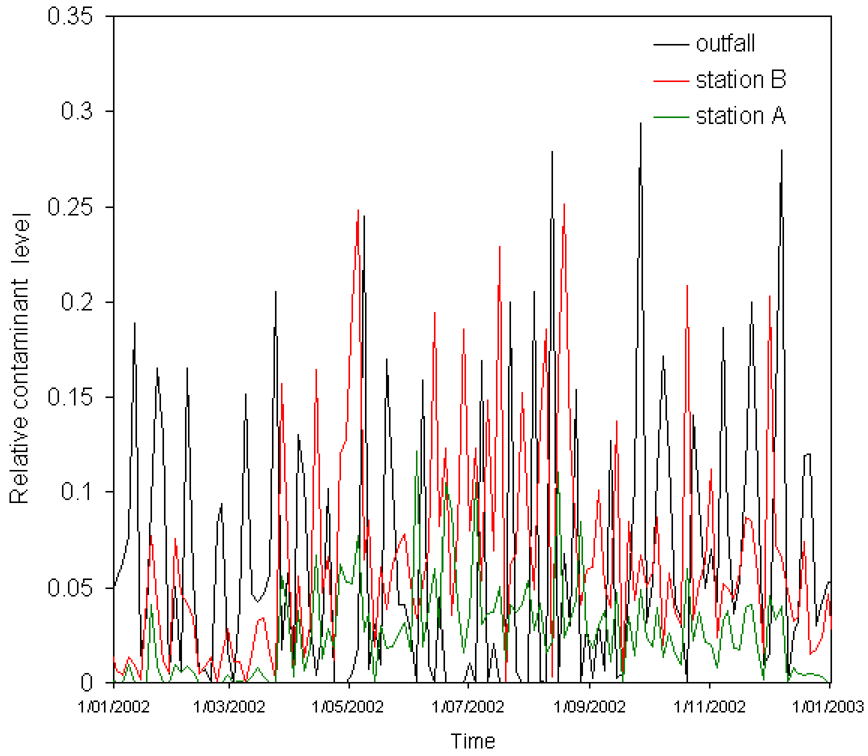


Figure 5.2.3: Relative contaminant signal strength at Nickol Bay outfall (black) and logger stations A (green) and B (red).

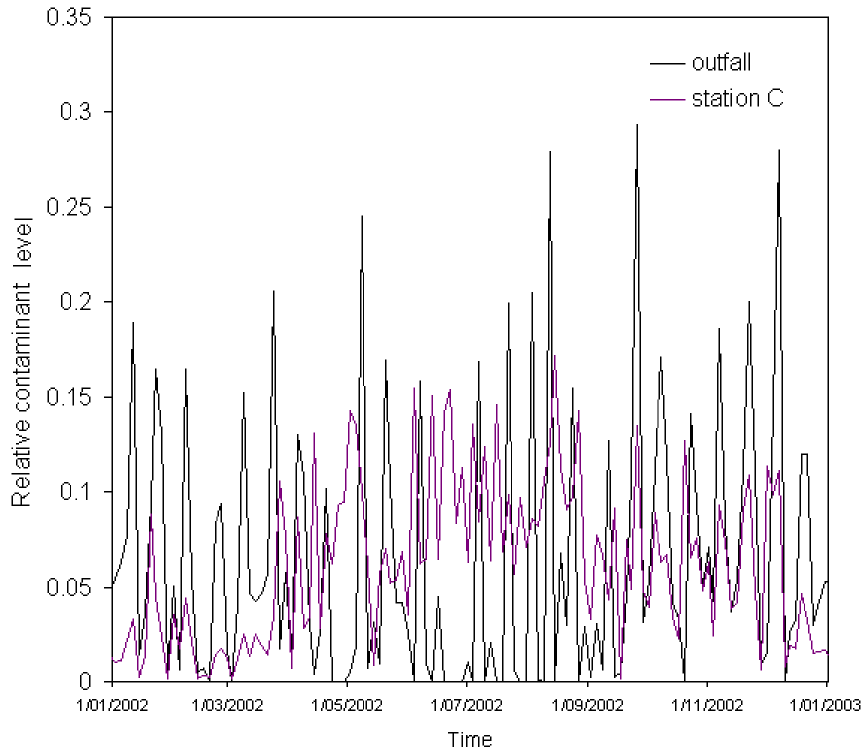


Figure 5.2.4: Relative contaminant signal strength at Nickol Bay outfall (black) and logger station C (purple).

5.3 Contaminant mortality

The most computationally intensive simulations for MSE were those including the analysis of contaminants and their impacts. This limited what could be achieved in this analysis. The lack of information about contaminant effects on biota also heavily constrained the range of possible mechanisms, simulations and analyses. The results reported here are therefore restricted to lethal effects of a subset of contaminants.

No detectable tissue loads were recorded in farmed oysters, turtles or sharks during the MSE simulations for the NWSJEMS. This is no surprise because these animals are typically outside the critical areas of the lethal contaminants. Therefore only the results for king prawns and banana prawns will be discussed here.

The total mortality (biomass lost) over the entire simulation period due to releases from each outfall is given in figure 5.3.1 for king prawns and figure 5.3.2 for banana prawns. There is a discernible increase in the biomass lost when the system is productive (that is, under the optimistic model specification). There is less of a difference (if any) between the biomass lost under the alternative management strategies and development scenarios.

For king prawns the Mermaid Sound outfall has the greatest impact (by close to an order of magnitude greater than the Nickol Bay outfall and two orders of magnitude greater than the Hammersley outfall). The pattern for banana prawns is similar, but the biomass lost is only half the size in absolute terms.

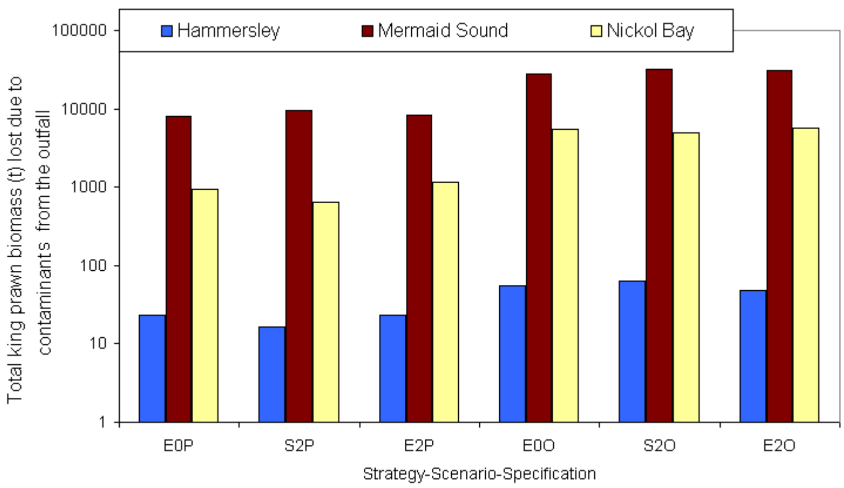


Figure 5.3.1: Total biomass of king prawns lost due to contaminants from outfalls.

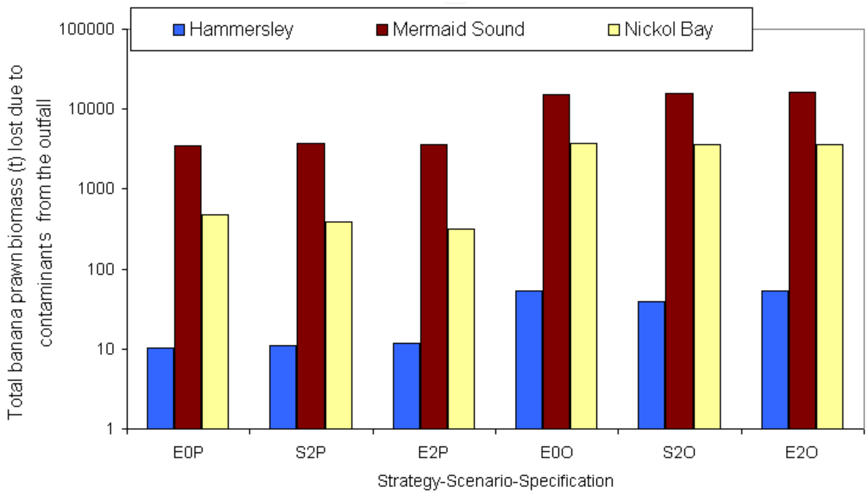


Figure 5.3.2: Total biomass of banana prawns lost due to contaminants from outfalls.

5.3.1 Annual contaminant induced mortality at the population level

The average annual population mortality rate due to contaminant poisoning is quite low for both king prawns and banana prawns (see figure 5.3.4). The king prawn rate shows some variability but is approximately 0.0045 in a highly productive system and 0.008 in the less productive systems. There also seems to be little difference between the rates realised under the alternative strategies and development scenarios.

The banana prawn rates are much more variable through time ranging from 0.001 to 0.05 in the highly productive system specification and from approximately 0.01 to 0.06 when the specified system is less productive. This degree of variability means there is much less difference between king and banana prawns with respect to the mortality rates seen under the alternative model specifications. As for the king prawns, there does not seem to be a consistent difference between the rates observed for banana prawns under the alternative management strategies or development scenarios.

The oyster leases in the Pilbara region were represented within the model as polyorganism and logger agent types (Gray et al. 2006). This means that while their active growth and other dynamics are not tracked directly, because it was assumed they would be tended adequately to ensure their continued operation, any contact with contaminants was recorded. While there were some oyster lease locations within the potential contaminant footprint (see figure 5.3.3), no actual oyster contaminant events were logged. That is, no oyster lease was contacted by detectable levels of contaminants during the course of the simulation. This is due to two factors. Firstly, while the potential footprint extended over a few oyster lease locations, individual plume snapshots quite often did not. Therefore there were only a relatively few days when leases were in anyway under threat from plume contact. Secondly, even when potentially in contact with a plume, the leases were at the margins of the plume where concentrations are minimal, so the probability of uptake of detectable levels is exceptionally small. Consequently, while the potential exists, it was never actually realised.

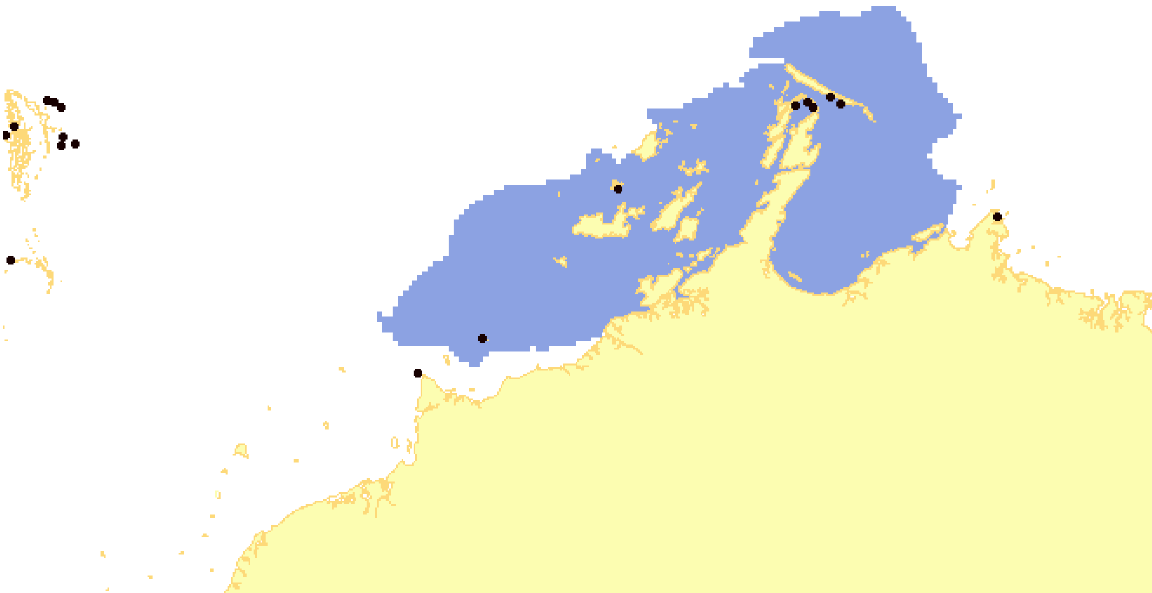


Figure 5.3.3: Map of total depth averaged plume footprint and the location of oyster leases in the immediate area (more leases exist beyond this area, but they were well beyond the plume footprint).

5.3.2 Annual contaminant induced mortality at the school level

The school (or boil) level annual mortality rates presented in figure 5.3.5 are much higher than the population-level rates for both prawn species (by as much as an order of magnitude or more). The king prawn rates for schools are also more variable than at the population level. The king prawn rate varies from 0.05 to 0.2 and the banana prawn rates range from 0.04 to 0.25. While there is little overall difference under alternative model specifications or development scenarios, there does seem to be a decreasing trend in boil-level mortality rates for both species under enhanced management that is not seen under the status quo strategy.

At a general level, it appears that only a small proportion of the prawn population comes into contact with parts of the contaminant plumes sufficiently concentrated to cause damage. Nevertheless, when a boil does contact concentrated parts of the plume it quickly succumbs.

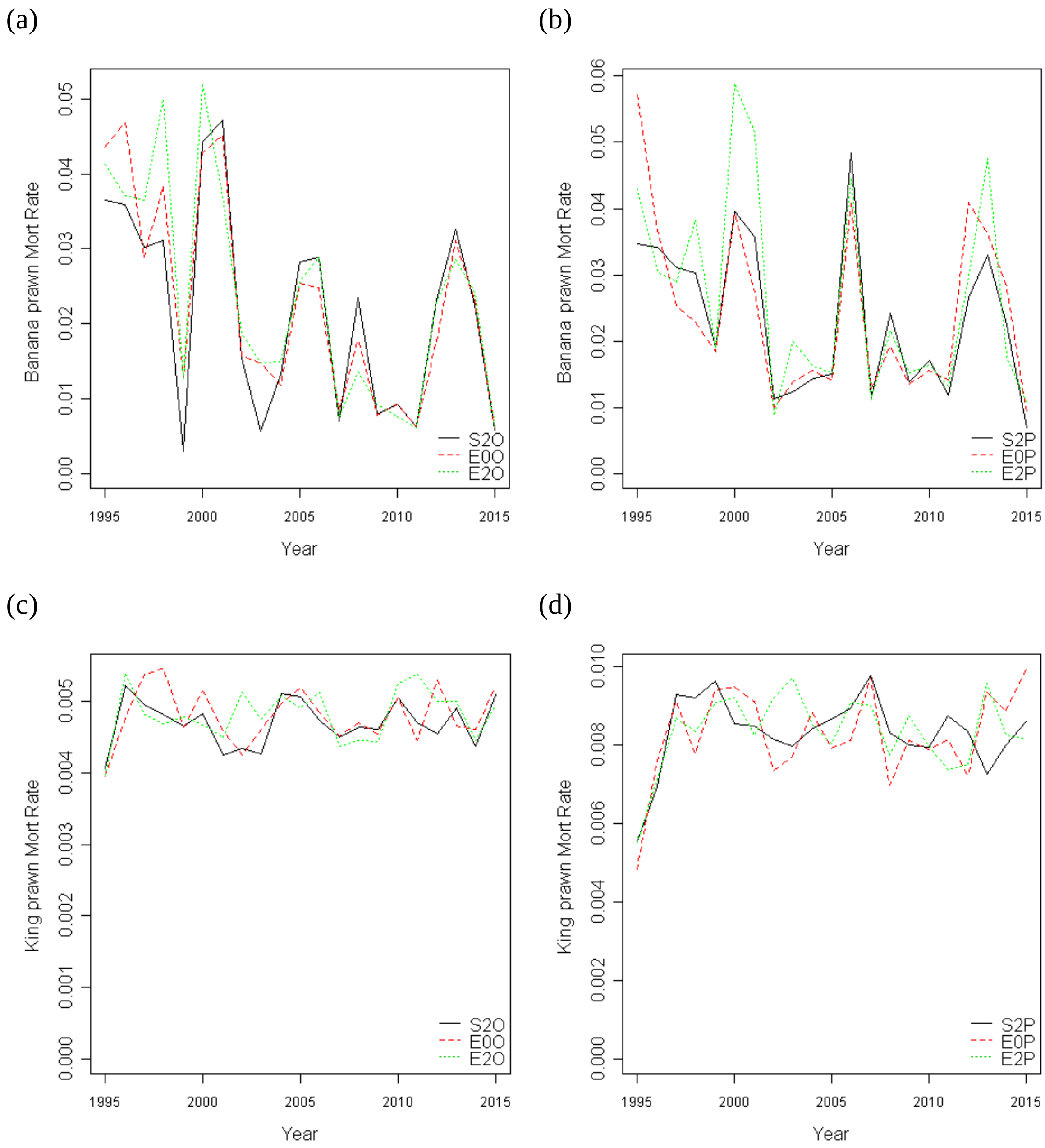


Figure 5.3.4: Annual average population-level mortality rate due to contaminant poisoning (a) banana prawns in productive systems (optimistic model specification), (b) banana prawns in systems with low productivity (pessimistic model specification), (c) king prawns in highly productive systems and (d) king prawns in systems with low productivity (pessimistic model specification).

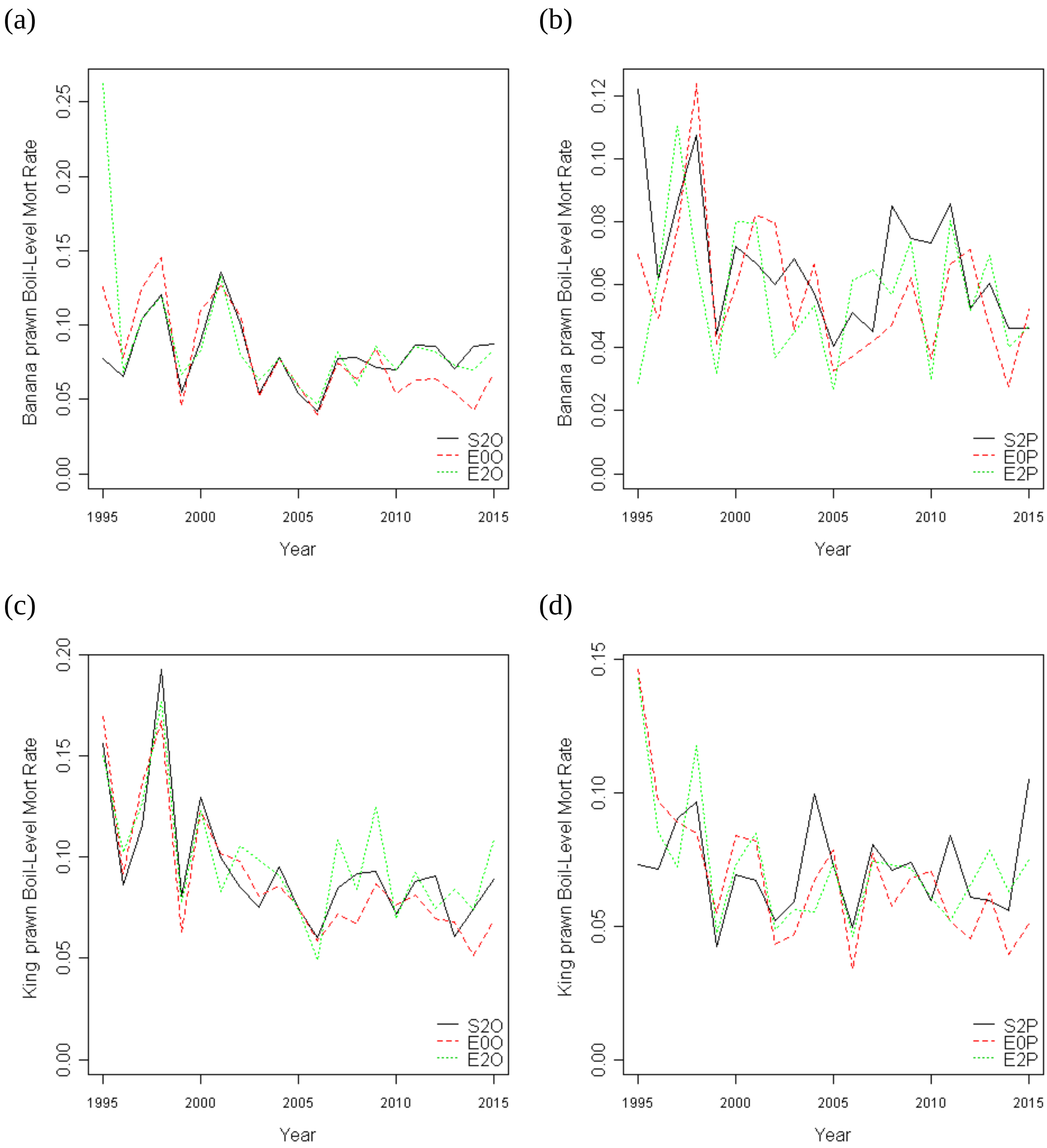


Figure 5.3.5: Annual average school-level mortality rate due to contaminant poisoning (a) banana prawns in productive systems (optimistic model specification), (b) banana prawns in systems with low productivity (pessimistic model specification), (c) king prawns in highly productive systems and (d) king prawns in systems with low productivity (pessimistic model specification).

5.4 Tissue loads

The pattern of tissue loads for banana prawns for each contaminant is essentially the same for all model specifications (see figures 5.4.1 and 5.4.2). In contrast the pattern is very different across contaminants. There is little gross level change through time in the tissue loads for cadmium and oil, whereas sulphate, copper, lead and bitterns tail off in the final decade of the simulation, as management restrictions begin to take effect (see the following section). Potentially the only unifying feature of all the tissue load time series for banana prawns is that the mean value is low (less than a third and often less than a tenth of the maximum values), with occasional high values.

The patterns in the tissue load results for king prawns (see figures 5.5.1 and 5.5.2) are like those for banana prawns (essentially the same across model specifications, but with different patterns across contaminants). Cadmium and oil tissue loads are quite consistent through time, but the other contaminant loads tail off in the latter parts of the time period. The loads are not consistently higher in one species than the other and are of a similar magnitude in both species.

5.5 EPA actions

Figures 5.5.1 and 5.5.2 summarise the EPA management actions for all contaminants that had their outflows modified in any way (in response to monitoring triggers). These figures display the EPA management release scalar for each contaminant. The release scalar is contaminant outflow in any given year scaled (divided) by the outflow in the reference year 1985. Notice that tin and oil at Mermaid Sound and calcium at Nickol Bay are not discussed below as their outflows were not modified at any point in any simulation. To maximise the period of contaminant dynamics considered it was necessary to use flows and potential footprints beginning in 1985 rather than 2001 (which was the end of the “historical period” and beginning of the “projection period” for the other sectors). This was appropriate because the stability of plumes improves with use of longer time series.

Cadmium

Cadmium was only released from the outfall at Mermaid Sound and the EPA actions are shown in figure 5.5.3. Under the pessimistic model specification there was a reduction in cadmium outflows in 1986 (when they decreased from base year level 1.0 to 0.65), 1990 (decrease to 0.425), 1991 (falling further to 0.275) and 1992 (reaching a plateau of 0.179). Under the enhanced management strategy, 0-pulse development and pessimistic model specification the flow of cadmium was again reduced in 1995 (to 0.116).

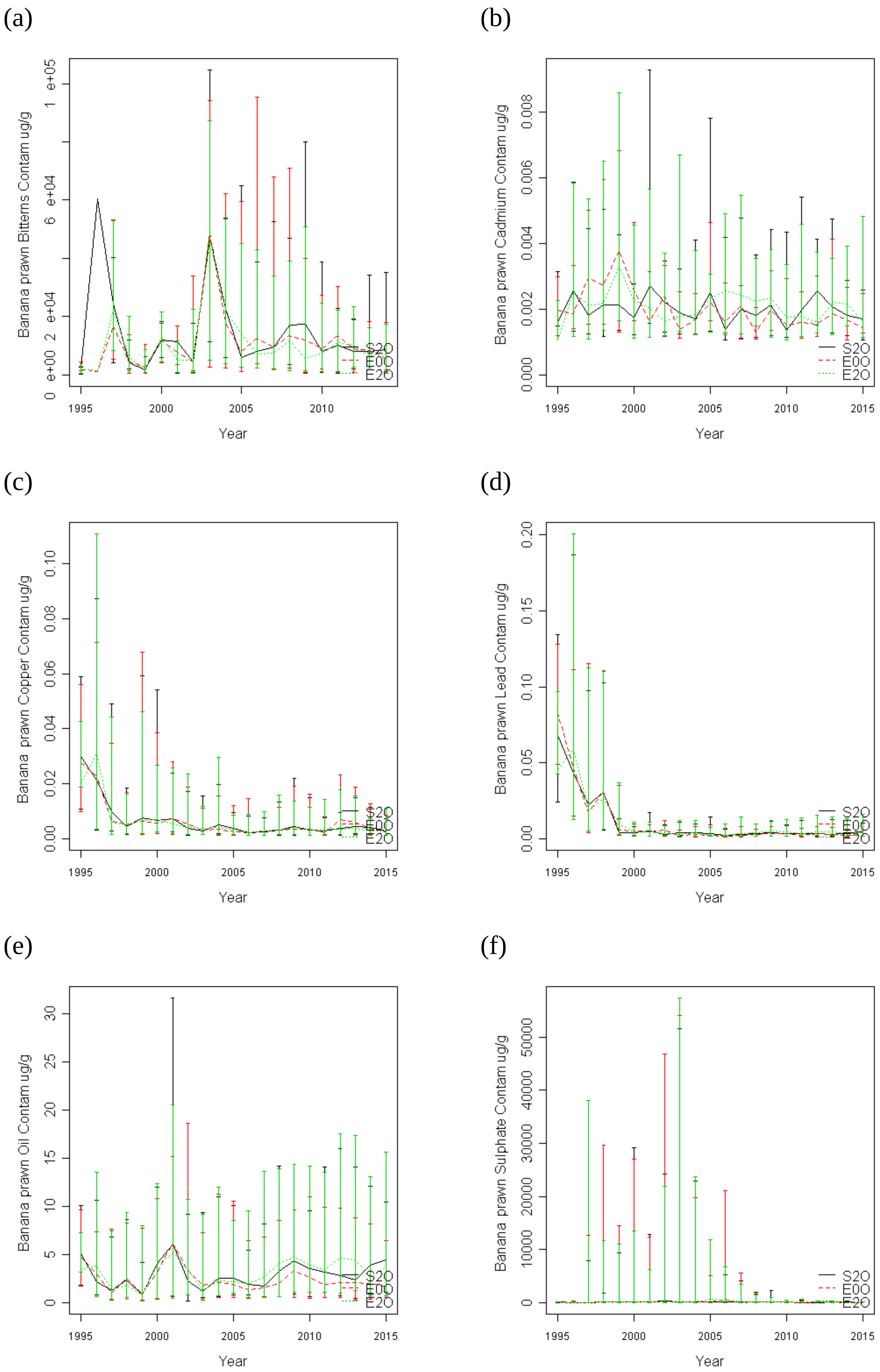


Figure 5.4.1: Contaminant tissue loads in banana prawns under the optimistic model specification.

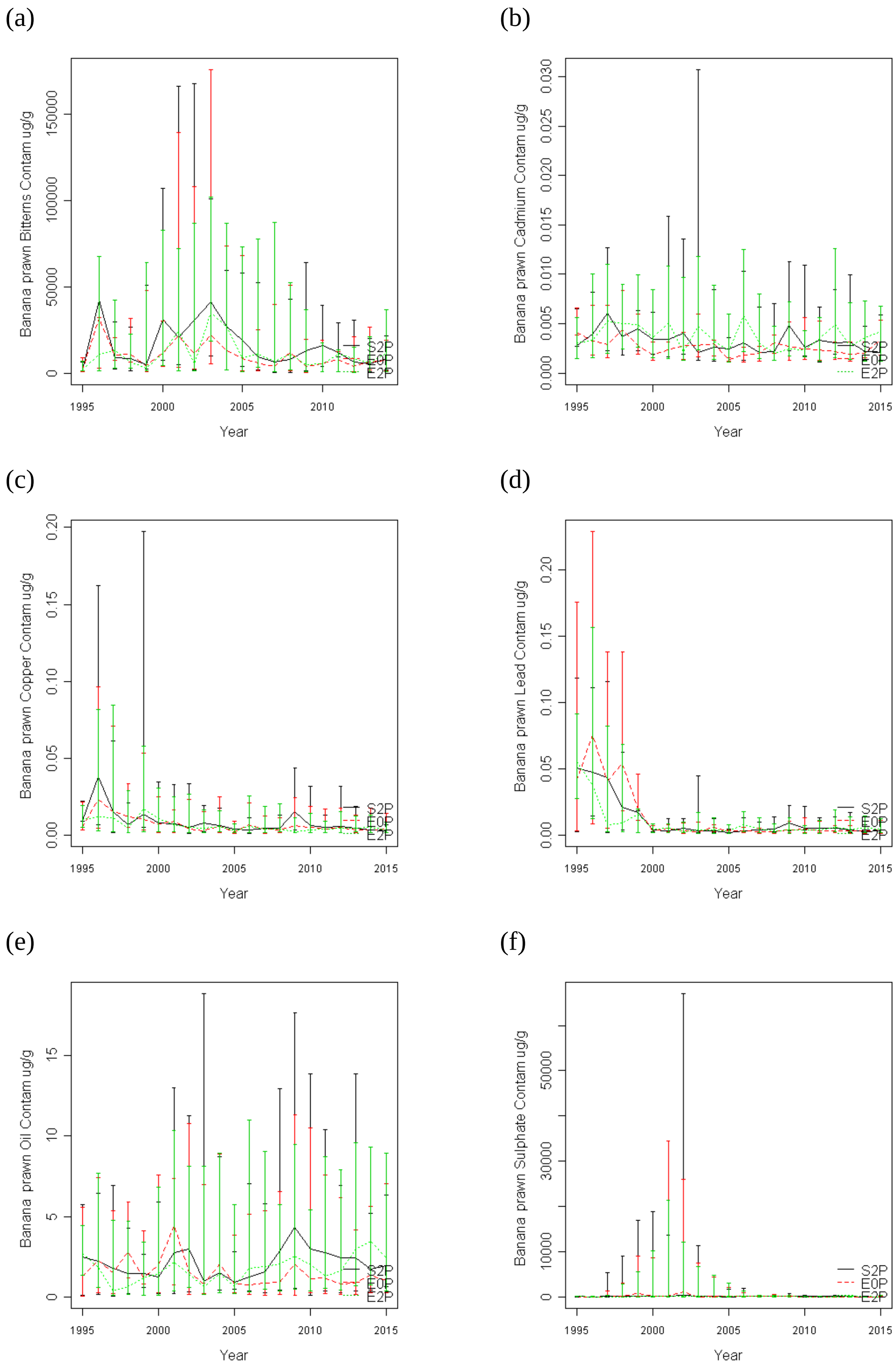


Figure 5.4.2: Contaminant tissue loads in banana prawns under the pessimistic model specification.

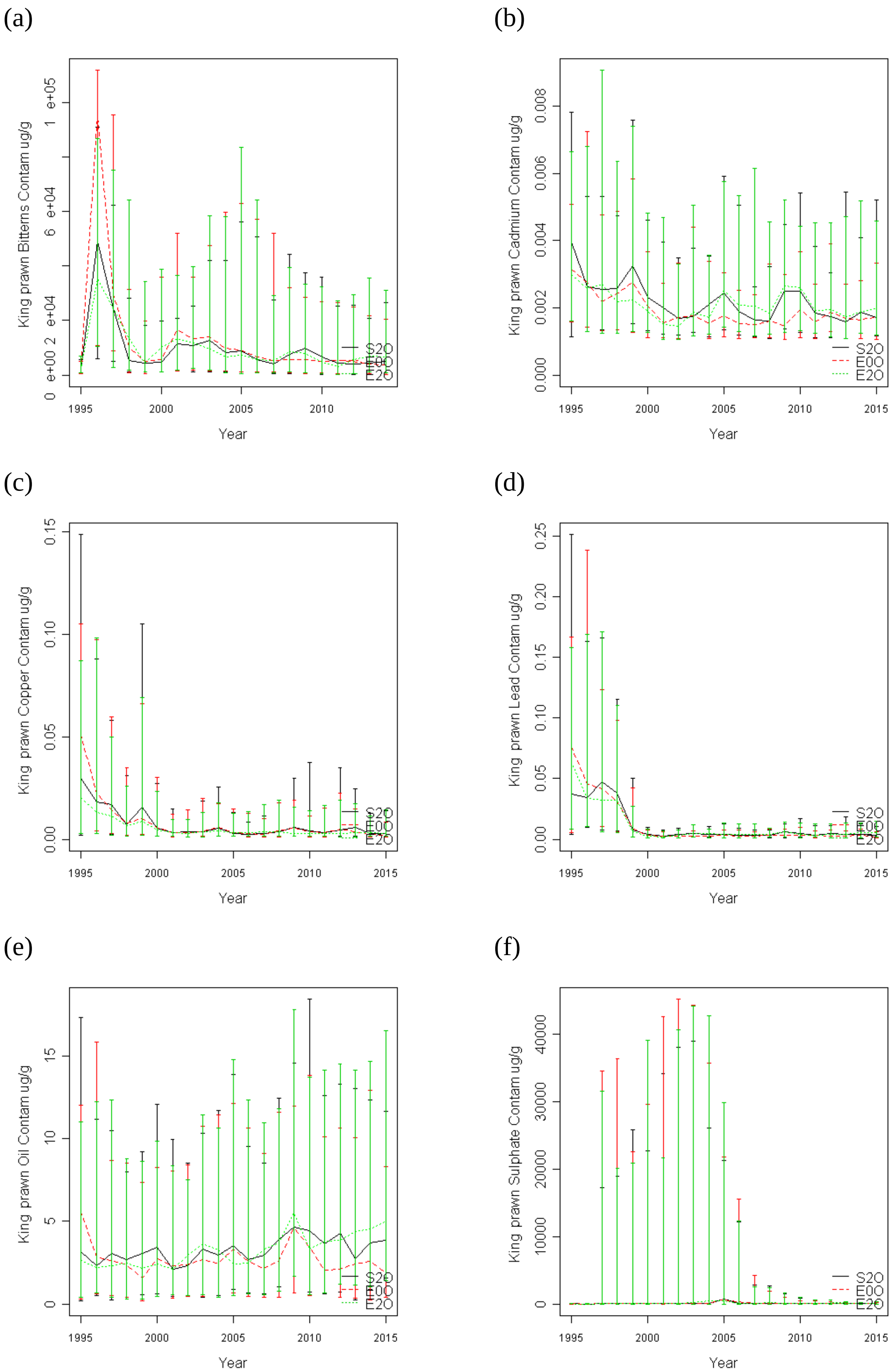


Figure 5.5.1: Contaminant tissue loads in king prawns under the optimistic model specification.

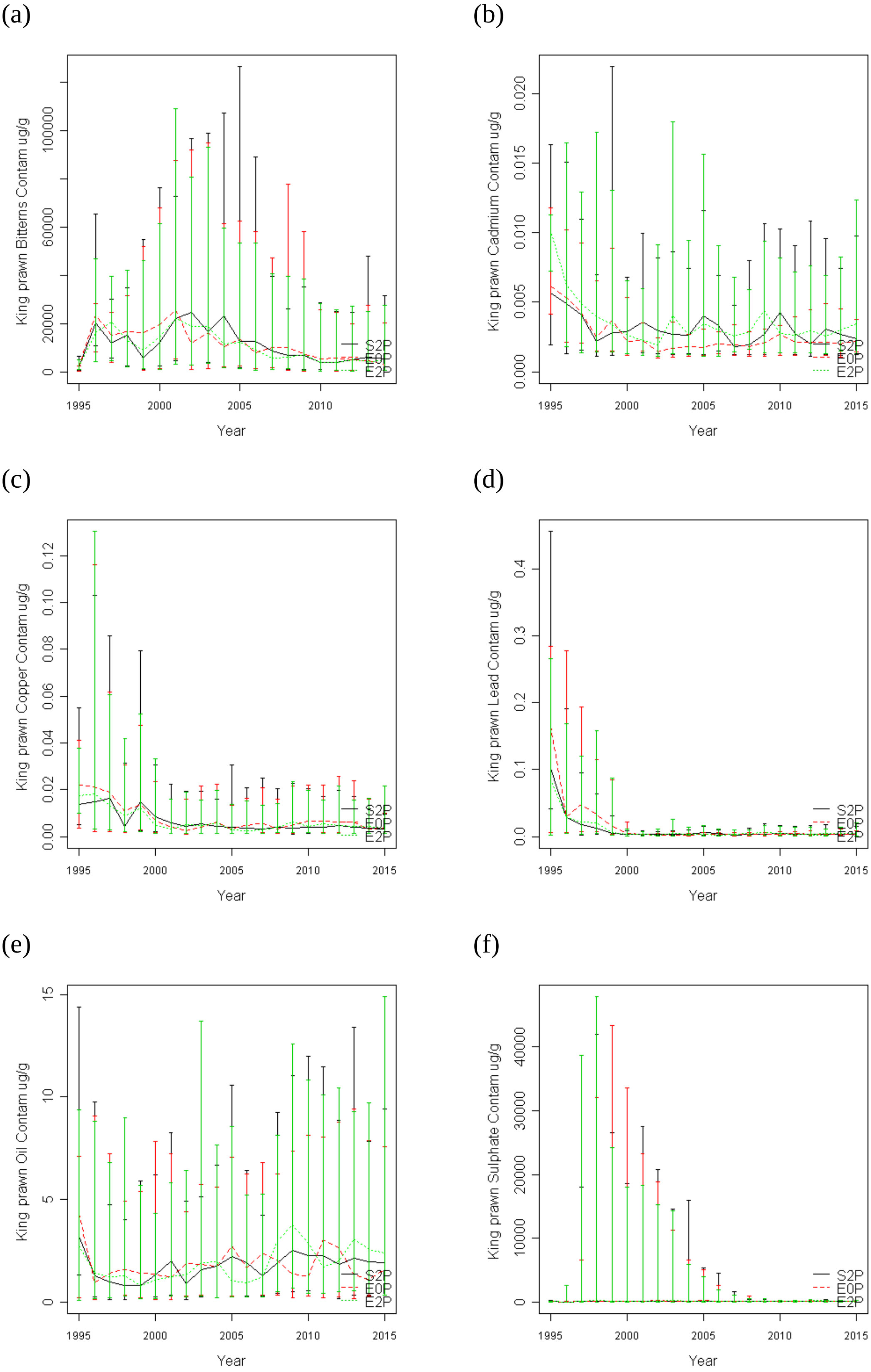


Figure 5.5.2: Contaminant tissue loads in king prawns under the pessimistic model specification.

Under an optimistic model specification cadmium outflows begin with falls in 1986 (to 0.65) and 1987 (to 0.423). This is much faster than with a pessimistic model specification as the EPA responds to a higher biomass of prawns, so the chance of contact with a plume occurring and being detected by the monitoring is much higher. At this point there is a slight divergence between the trajectories under the three optimistic cases considered. For the status quo management, 2-pulse development combination there are further reductions in cadmium outflow in 1988 (to 0.275), 1989 (down to 0.179), 1990 (0.116), 1991 (0.075), 1995 (stabilising at 0.049 for 15 years) and 2009 (ending at 0.032). The trajectory under enhanced management and 0-pulse development is very similar, except that the final decrease to 0.032 does not occur. The general trend under the enhanced management and 2-pulse development is also similar. Although the drop to 0.275 is delayed, the rest of the decline happens as quickly and all three trajectories are realigned in 1995 when they all drop to 0.049. Like the status quo management, 2-pulse development combination, the enhanced management and 2-pulse development combination drops to 0.032 in 2009.

In all cases there was a fairly rapid drop in outflows (by 82 to 92%) followed by a long period of stability, with few modifications in the final two decades of the simulated period. The reduction is much larger under the optimistic model specifications as the system is more productive, so there is more chance of interactions that may be detected, which in turn triggers management responses.

Copper

While the exact trajectory followed for the reduction in the outflows of copper in Mermaid Sound under the various MSE combinations is not an exact match for the cadmium trajectories, there are many similarities (see figure 5.5.1). The biggest differences between the trajectories are between those under a pessimistic and those under an optimistic model specification. The reductions are larger under an optimistic model specification and the initial decrease (when it occurs) is rapid, followed by a long more stable period.

In comparison with the cadmium outflows the reduction in copper outflow in Mermaid Sound does not happen as early in the simulation. The first drop (to 0.65) does not occur until 1993 or 1994, which is then followed by reductions every year (or even quicker) through a four year period under the pessimistic model specification, stabilising briefly at 0.179 before dropping again in 1999 to 0.116. The reduction in outflow begins at the same time under the optimistic model specification, but continues year after year until 1999 where it reaches a plateau of 0.049 for the remainder of the simulation.
Copper is also released at the Hammersley outfall (see figure 5.5.4). The pattern of reductions in the outflow scalar at Hammersley is much like those at Mermaid Sound. In all cases the outflows are reduced at Hammersley in 1994 and following years, until the final reduction in 1999. Also as in Mermaid Sound, the final value under the pessimistic model specification (0.075) is roughly twice that under the optimistic model specification (0.032).

Lead

As with copper and cadmium the biggest difference in the outflows at Mermaid Sound (figure 5.5.3) is between trajectories under the pessimistic and optimistic model specifications. Under the pessimistic model specification the first reduction in outflow is in 1995 to 1996 (where it drops to 0.65), followed by reductions in the final two years before the scalar stabilises at 0.275. Under the optimistic model specification the reductions start much earlier, in 1988, followed by another fall in 1989. There is then a long period of stability before another series of reductions in 1997 and 1998. The 1998 reduction is the last, leaving the scalar at 0.179 for the remaining 18 years of the simulated period. As with all other contaminants, the final scalar under the optimistic model specification is only about half the magnitude of that under the pessimistic model specification.

Sulphate

Sulphate is released at both the Mermaid Sound and Nickol Bay outfalls. At Mermaid Sound (figure 5.5.3) the pattern of reductions under the alternative model specifications are similar in form, though different in ultimate magnitude. All the trajectories for the EPA scalar of sulphate at Mermaid Sound begin with an initial reduction in 1986 (to 0.65), followed by further reductions in 1987 (to 0.422) and 1988 (to 0.275). Under the pessimistic model specification there is no further reduction until 1992 when the scalar is reduced to 0.179, dropping further the next year to 0.116. This scalar is then unchanged for the rest of the simulation for the enhanced management, 0-pulse development combination. For the other two cases under a pessimistic model specification there is a final reduction to 0.075 in 1998.

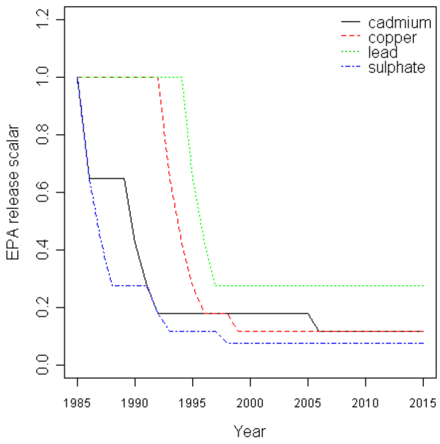
The pattern of reductions at Mermaid Sound is similar for the optimistic model specification. The second wave of reductions begins in 1991 and runs through every year until 1994 when it stabilises at 0.049. This value persists unchanged for the remainder of the simulation for the enhanced management, 0-pulse development, but is reduced further to 0.032 in 2001 in the other two cases with an optimistic model specification.

At Nickol Bay (figure 5.5.5) the reductions in the outflows begin much later (not commencing until 1997) and continuing much longer – nearly every year until 2012 under a pessimistic model specification and until 2014 under an optimistic specification. The magnitude of the reductions is also much higher at this outfall (in comparison with the reductions at Mermaid Sound). The final scalar is only 0.0003 under the pessimistic model specification and 0.0001 to 0.0002 under the optimistic model specification.

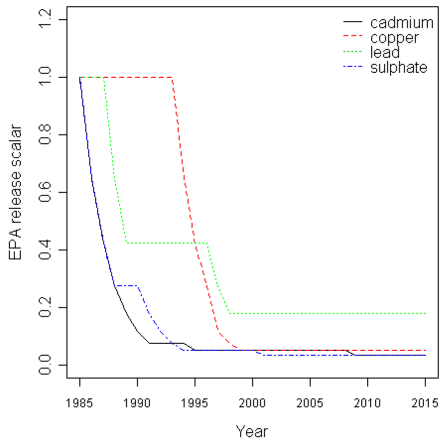
Bitterns

This contaminant was only present in the Nickol Bay outfall (figure 5.5.5). The pattern of reductions is fairly consistent across all cases for bitterns. An initial wave of reductions begins in 1996 and extends through until 2001, with a sequence of periodic reductions every two to three years after that, until the final value is reached in 2010 – except for the enhanced management, 0-pulse development combination where the final reduction is delayed from 2010 to 2012. As in all other cases, the magnitude of the reduction is slightly larger for the optimistic model specification (dropping by a little over 98.6%) than the pessimistic model specification (which dropped by 96.8%).

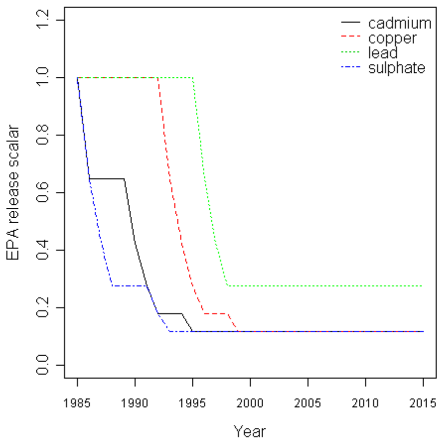
(a)
(Status Quo, 2-pulse, Pessimistic)



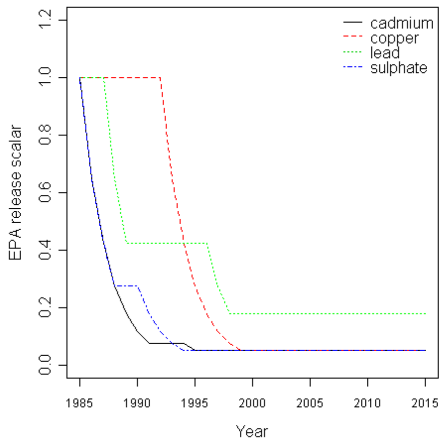
(b)
(Status Quo, 2-pulse, Optimistic)



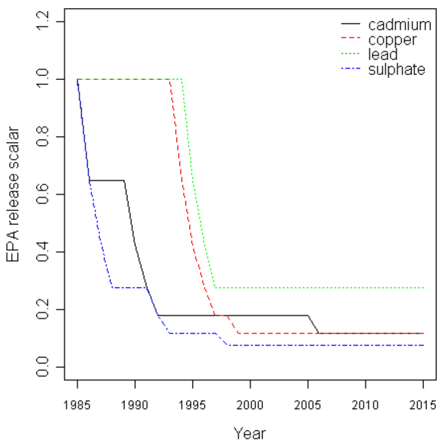
(c)
(Enhanced, 0-pulse, Pessimistic)



(d)
(Enhanced, 0-pulse, Optimistic)



(e)
(Enhanced, 2-pulse, Pessimistic)



(f)
(Enhanced, 2-pulse, Optimistic)

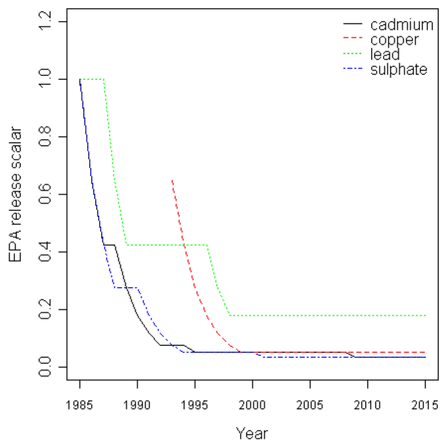


Figure 5.5.3: EPA management scaling of contaminant outflows through time at the Mermaid Sound outfall for (a) (status quo management, 2-pulse development, pessimistic model specification), (b) (status quo management, 2-pulse, optimistic model specification), (c) (enhanced management, 0-pulse, pessimistic model specification), (d) (enhanced management, 0-pulse, optimistic model specification), (e) (enhanced management, 2-pulse, pessimistic model specification) and (f) (enhanced management, 2-pulse, optimistic model specification) MSE combinations.

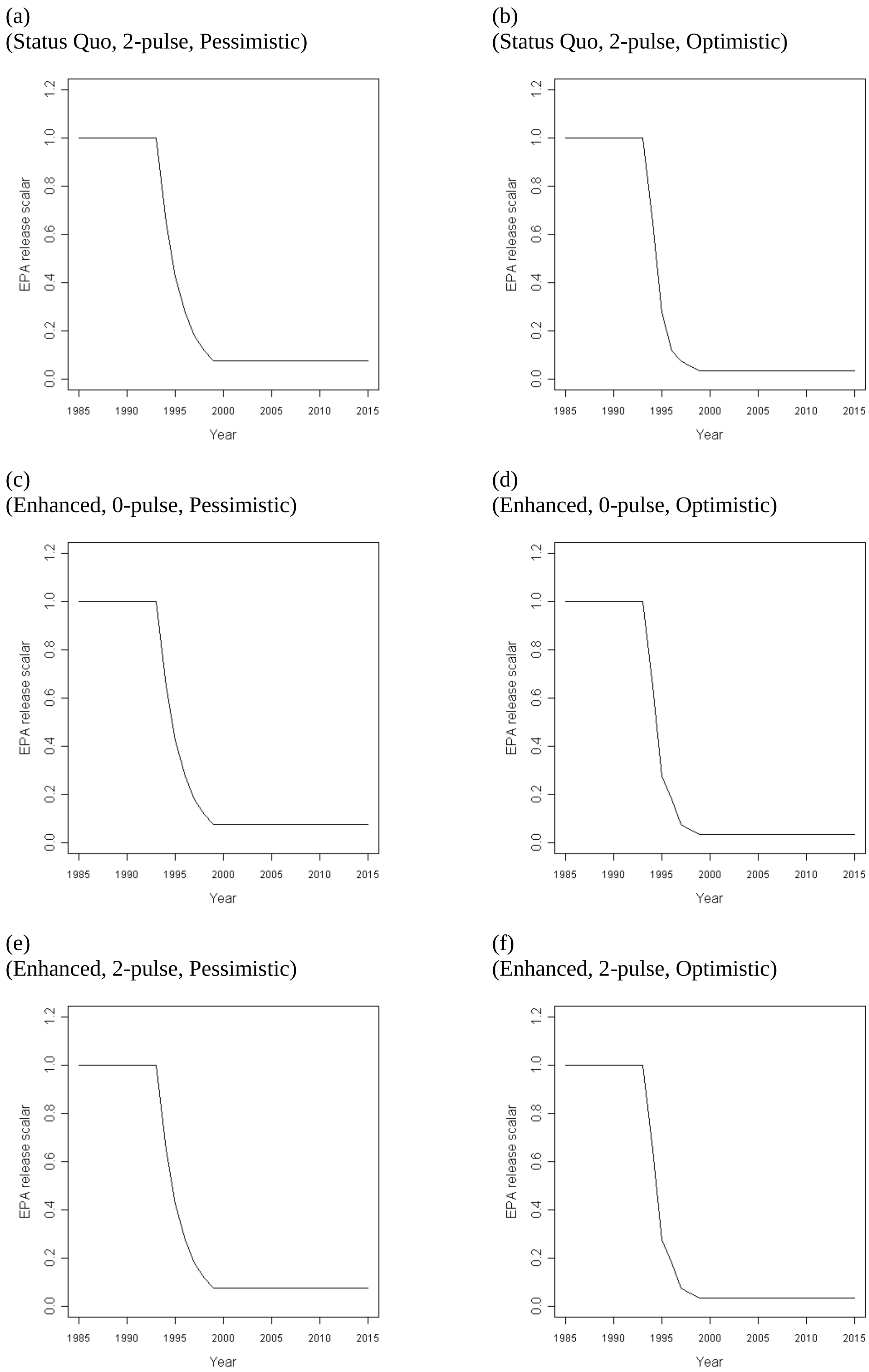
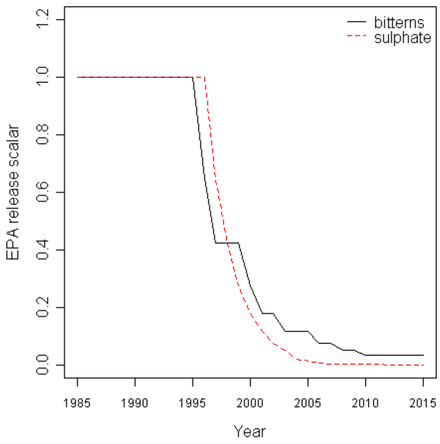
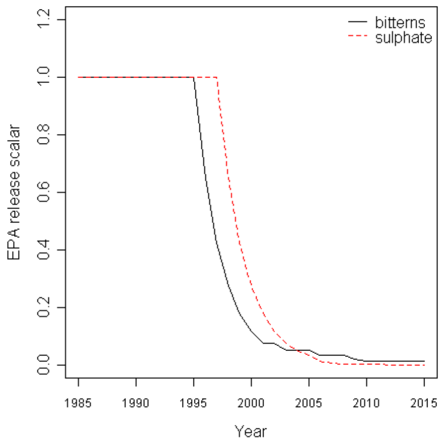


Figure 5.5.4: EPA management scaling of copper outflows through time at the Hammersley outfall for (a) (status quo management, 2-pulse development, pessimistic model specification), (b) (status quo management, 2-pulse, optimistic model specification), (c) (enhanced management, 0-pulse, pessimistic model specification), (d) (enhanced management, 0-pulse, optimistic model specification), (e) (enhanced management, 2-pulse, pessimistic model specification) and (f) (enhanced management, 2-pulse, optimistic model specification) MSE combinations.

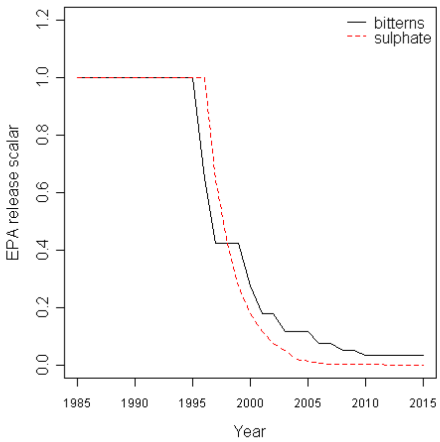
(a)
(Status Quo, 2-pulse, Pessimistic)



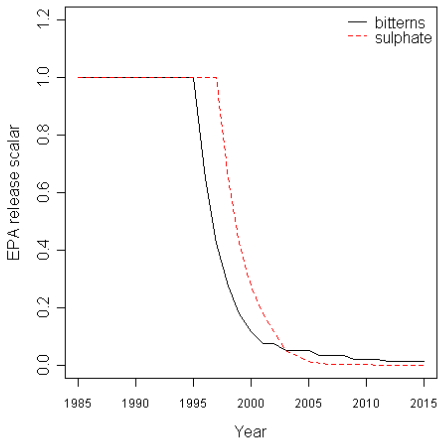
(b)
(Status Quo, 2-pulse, Optimistic)



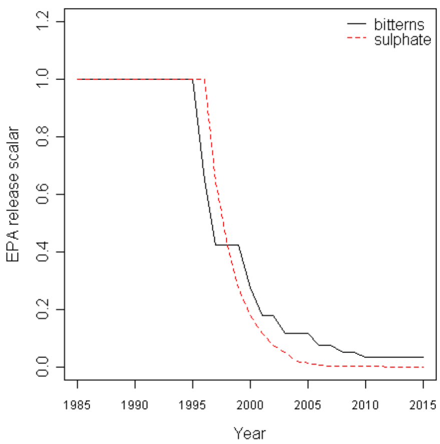
(c)
(Enhanced, 0-pulse, Pessimistic)



(d)
(Enhanced, 0-pulse, Optimistic)



(e)
(Enhanced, 2-pulse, Pessimistic)



(f)
(Enhanced, 2-pulse, Optimistic)

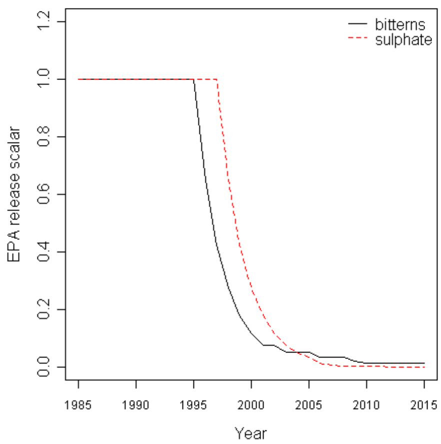


Figure 5.5.5: EPA management scaling of bitterns and sulphate outflows through time at the Nickol Bay outfall for (a) (status quo management, 2-pulse, pessimistic model specification), (b) (status quo management, 2-pulse, optimistic model specification), (c) (enhanced management, 0-pulse, pessimistic model specification), (d) (enhanced management, 0-pulse, optimistic model specification), (e) (enhanced management, 2-pulse, pessimistic model specification) and (f) (enhanced management, 2-pulse, optimistic model specification) MSE combinations.

5.6 Implications of contaminant modelling for management

Despite the need for a more deterministic approach to modelling contaminant dynamics, the results reported provide an encouraging demonstration of capability that could be extended for direct use by government and industry managers. The modelled contaminant plumes provide an interesting perspective not only on the surface and depth-averaged extent of detectable levels of contaminants released from point sources, but also on the quite restricted extent of toxic levels of contaminants near these point sources. For all contaminants examined, while detectable levels extended to large plumes, only a small proportion of these plumes contained toxic levels of contaminants. The only exception to this is copper, for which potentially toxic concentrations persist for all but the fringe of the detectable-concentration plume, at least historically. The footprint is reduced quite markedly once the more stringent guidelines currently in place have been instituted.

The results also shed light on the placement of monitoring stations. Monitoring activities must clearly be scaled and placed according to a balance among cost of monitoring, the faithfulness of the detected signal to true levels of contaminants, the impact of contaminants on the health of biota (including humans) and the likely response of industry and government to the data collected. The contaminant models used in the present study make use of oceanographic, tidal and wind data to advect and diffuse plumes emanating from point sources. Using the outputs from these models it is relatively straightforward to show that the positioning of monitoring stations can influence both their cost and their effectiveness in accurately recording true contaminant levels.

The relative importance of factors affecting mortality due to contamination can also be evaluated within the MSE modelling framework. Lethal and sub-lethal effects of contamination are not simply a matter of contaminant concentration at point sources and the environmental persistence of particular contaminants. Contaminant toxicity is also affected differentially by various characteristics of biota: for example dietary and movement habits, location of preferred habitat, reproductive rates and contaminant excretion rates. As the results demonstrate, dispersion and dilution of contaminants is important, as is the coincident location of susceptible biota and contaminant plumes. The simulation results also provide useful guidance on the issue of variability of impacts of contaminants. One observation worthy of emphasis in this regard is that localised effects from point sources can have highly variable impacts on small collective components of the population but these may have negligible impact on the population as a whole. In the case of schooling species, local impacts can be significant: for example some contaminants, if sufficiently concentrated locally, may be harmful to the predators (including humans) of affected species, whereas average concentration levels in plumes and average contamination in the population may appear to be quite safe. The differences between these approaches would become even broader if sub-lethal effects and bioaccumulation through the trophic chain were to be taken into account. In assessing risks of, and adopting standards for, contaminants, therefore, managers may wish to modify the strategies used to achieve human and environmental health objectives in some cases.

Finally, of note from the above results, is the (perhaps unsurprising) consistency of the patterns in contaminant dynamic across management strategies, model specifications and development scenarios. Contaminant dynamics are broadly similar for all five contaminants examined: in all cases there are stepwise reductions in simulated measures of contaminant concentration associated with development pulses. These stepwise reductions become progressively greater as enhanced and integrated management strategies are simulated, especially under the optimistic model specification (where higher biomasses make contact both more likely, but also more easily detectable).

In conclusion, it is worth reiterating that the contaminant simulations are based on limited data and knowledge. Although baseline data, point-source flow data and oceanographic data were available for model calibration, there is very little information available about direct impacts of contaminants on biota in the North West Shelf region. Nonetheless, much has been achieved in establishing an analytical computer-based framework within which new data and knowledge can be used to improve our understanding of risks associated with contaminant flows, especially in the North West Shelf region.

6. SPATIAL DISTRIBUTIONS OF FAUNA AND FLORA THROUGH TIME

The spatial distributions of North West Shelf flora and fauna through time on the coarse scale grid (1 degree latitude by 1 degree longitude) were compared using Kolmogorov-Smirnov tests. The results of these tests were verified and interpreted using cumulative distributions, frequency histograms of relative biomass and the distribution of average relative biomass per cell. Cells have been rank ordered inshore to offshore, west to east, so that one may readily discern locations with unusual densities of biota. Where particularly interesting patterns emerge, the time series of maps for the species of interest are also consulted. Relative biomasses are used so that the absolute magnitude (which could vary strikingly among the model specifications) do not obscure the signal from the underlying distributions. The relative biomass was calculated by standardising against the maximum value in each individual geo-time series (i.e. each strategy-scenario-specification combination) for each species.

For the fine scale grid (6 minutes latitude by 6 minutes longitude) a similar set of analyses was performed, except for the Kolmogorov-Smirnov tests. It was inappropriate to perform Kolmogorov-Smirnov tests for this fine scale data set due to the patchy data structure and the resulting high number of data-free cells for some species in some of the MSE combinations. The distributions suggest that, for many species groups, analysis at more aggregated levels is appropriate, and this is what the analysis of coarse scale results provides.

6.1 Coarse scale distributions

For ease of interpretation, immediately below is a summary of the coarse scale spatial results and representative maps that illustrate important aspects of the distributions. Appendix A has also been included to display the associated tables of Kolmogorov-Smirnov tests and the various plots (cumulative distributions and average relative biomass per cell) used to aid interpretation and analysis of the coarse scale spatio-temporal distributions.

6.1.1 Banana prawns

The only significant differences among the spatio-temporal distributions of banana prawns are related to the different system productivity implied by alternative model specifications (see figure 6.1.1). After fishing, the banana prawn distribution under the pessimistic model specification is focused around sites close to major nursery grounds. While the same general pattern persists under the base case specification, it is not as peaked and the banana prawn biomass is spread along the coast. This trend to wider dispersion persists under the optimistic model specification where the biomass is almost uniformly distributed along the coast, rather than being primarily aggregated around nursery areas.

6.1.2 King prawns

There are no significant differences among the spatiotemporal distributions of relative king prawn biomass for any of the strategies, scenarios and specifications, except for the comparison between the pessimistic and optimistic model specifications (see figure 6.1.2). The distributions under the pessimistic (and base case) specification are patchy, being concentrated around favourable habitat and nursery grounds. In contrast, under the optimistic model specification the relative biomass of king prawns is higher and more evenly spread throughout the inshore waters of the North West Shelf.

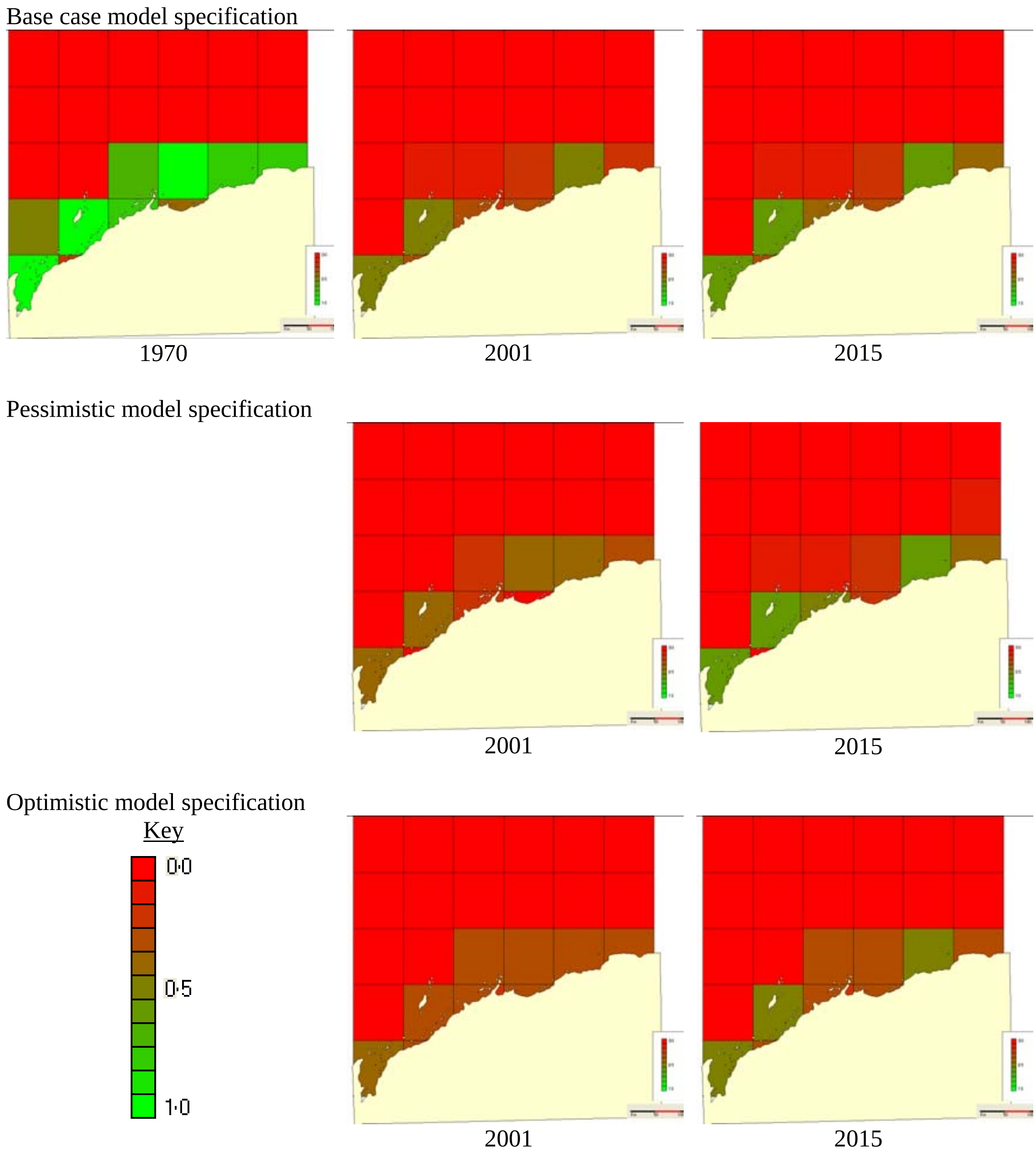


Figure 6.1.1: Representative maps of coarse scale distribution of relative biomass of banana prawns through time. Relative biomass is defined as the ratio of biomass in a given year to estimated initial biomass (in 1970).

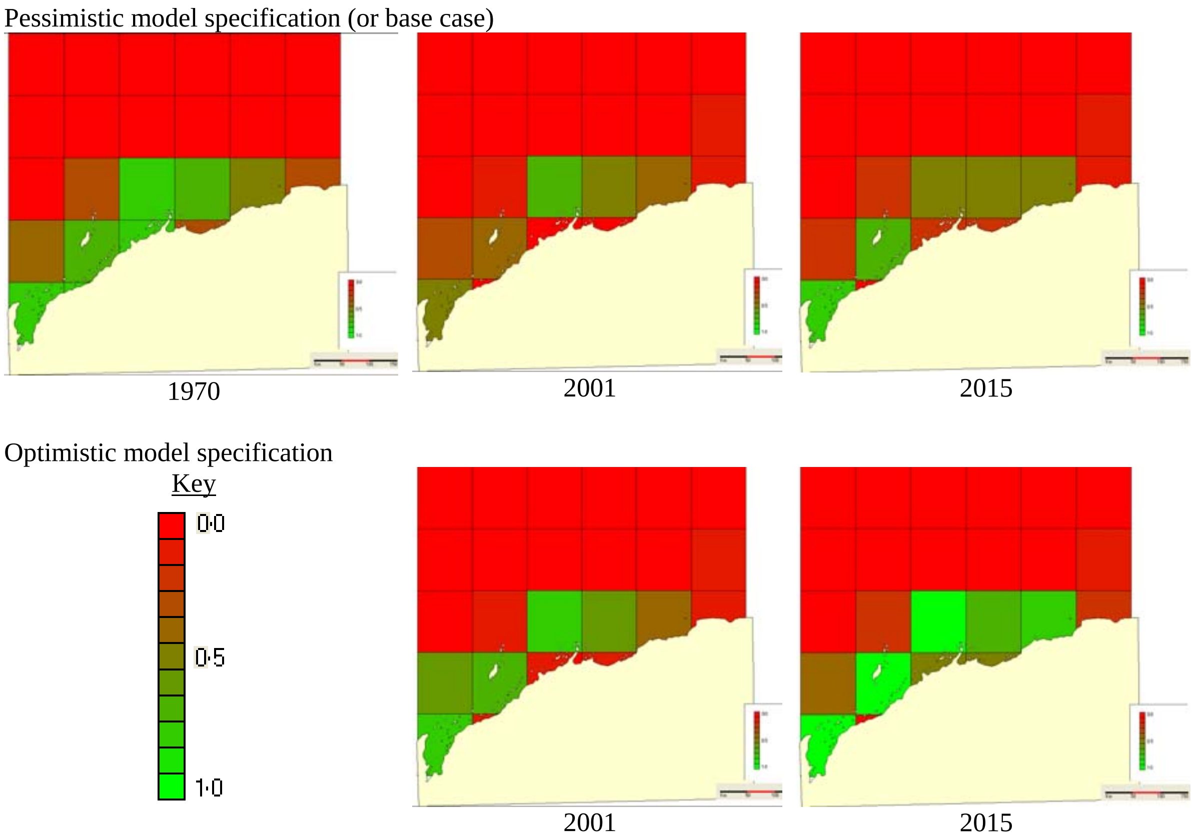


Figure 6.1.2: Representative maps of coarse scale distribution of relative biomass of king prawns through time. Relative biomass is defined as the ratio of biomass in a given year to estimated initial biomass (in 1970).

6.1.3 Turtles

The widespread depletion in turtles due to the historical fisheries (those directly targeting turtles as well as those impacting upon them incidentally) means that many of the spatio-temporal distributions are fairly similar. Quite a few of the distributions are not statistically significant (e.g. there is no difference among development scenarios). There are some notable results displayed in figure 6.1.3, however, particularly in the contrast between the integrated and other management strategies. Under the status quo management strategy the turtles are greatly reduced but they are still found offshore in the zones that do not see as much fishing pressure. Under the enhanced management strategy the offshore areas are also depleted with more of the turtle biomass concentrated in the inshore waters. With integrated management the offshore areas see a recovery, as does the entire system, with the relative biomass of turtles rising in every cell. Such a widespread recovery is not seen under any other management strategy, although localised increases can be seen under status quo and enhanced management with the optimistic model specification. With the other model specifications the biomass drops and the distributions increasingly contract to favourable habitats inshore or around Barrow Island and the Monte Bellos.

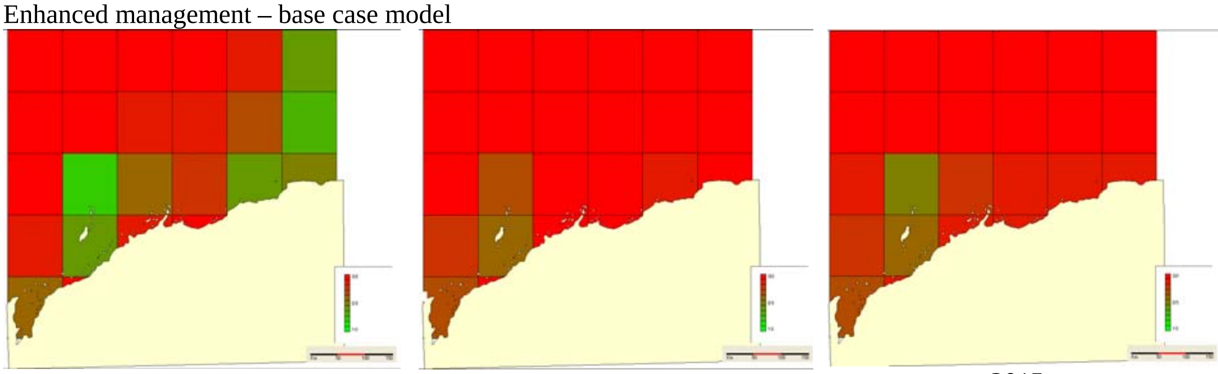
Note that further work with an alternative model type for turtles sees a much wider recovery of turtles and the resulting spatial distributions are more heavily centred around favourable habitats.

6.1.4 Sharks

While many of the distributions of relative biomass of sharks on the North West Shelf are not significantly different from each other, the Kolmogorov-Smirnov tests and cumulative distributions displayed in Appendix A indicate that there are some notable differences between the distributions under the alternative model specifications. The analysis also indicates that when the system is highly productive the alternative management strategies could also lead to significantly different spatio-temporal distributions for sharks.

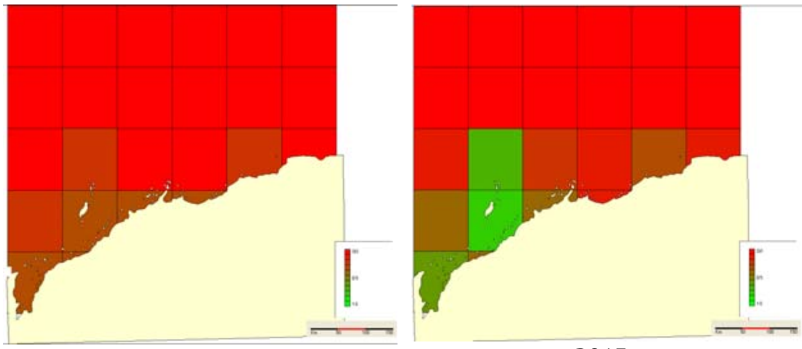
Under the base case model specification the peak of the shark relative biomass distribution is displaced, through time, from the trawl grounds to the areas around the southern and eastern edges of the fishing zones and the Dampier Archipelago. There is some recovery during the projection period (post year 2000), but full recolonisation of the offshore waters does not take place. With the pessimistic model specification even limited recolonisation does not appear to occur and the sharks become more concentrated around the Monte Bellos and the eastern boundary of the modelled area. While these areas are also sites of higher relative biomass under the optimistic specification, the relative biomass of sharks in that case is universally higher and the overall distribution much more evenly spread. When an enhanced management strategy is employed the offshore recovery of the shark biomass is not observed, at least not to the same extent. In contrast, when an integrated management strategy is used the relative biomass levels are higher across the region, leading to higher relative biomasses offshore and a flatter overall distribution; although the shark population is still more dense towards the inshore waters and the Barrow and Monte Bello islands.

Enhanced management – base case model



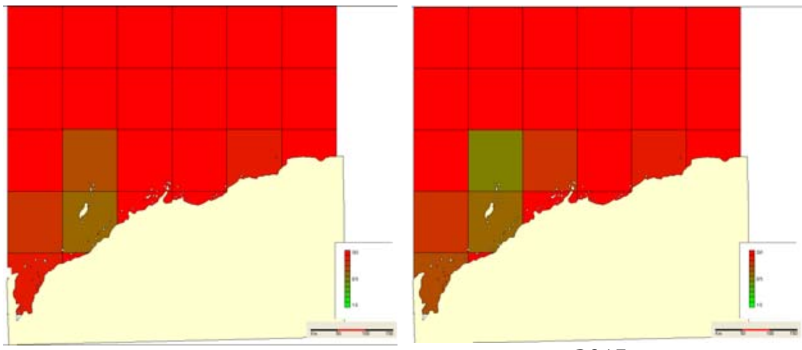
1970 2001 2015

Enhanced management – optimistic model



2001 2015

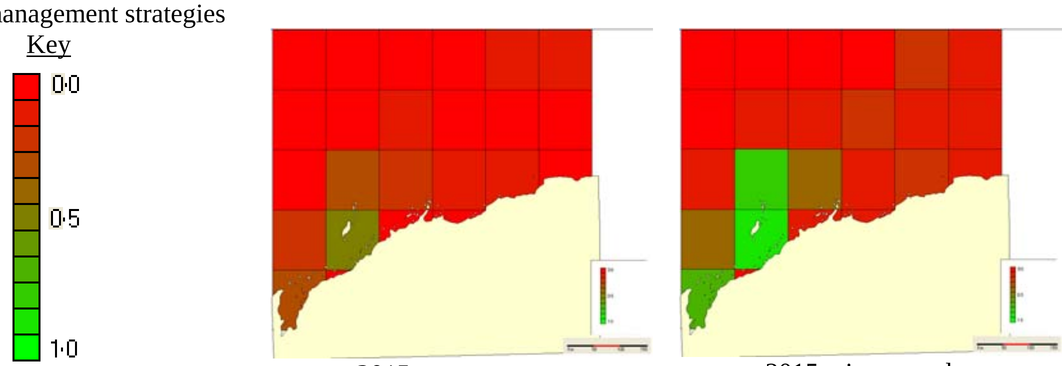
Enhanced management – pessimistic model



2001 2015

Alternative management strategies

Key



2015 – status quo – pessimistic model

2015 – integrated – pessimistic model

Figure 6.1.3: Representative maps of coarse scale distribution of relative biomass of turtles through time. Relative biomass is defined as the ratio of biomass in a given year to estimated initial biomass (in 1970).

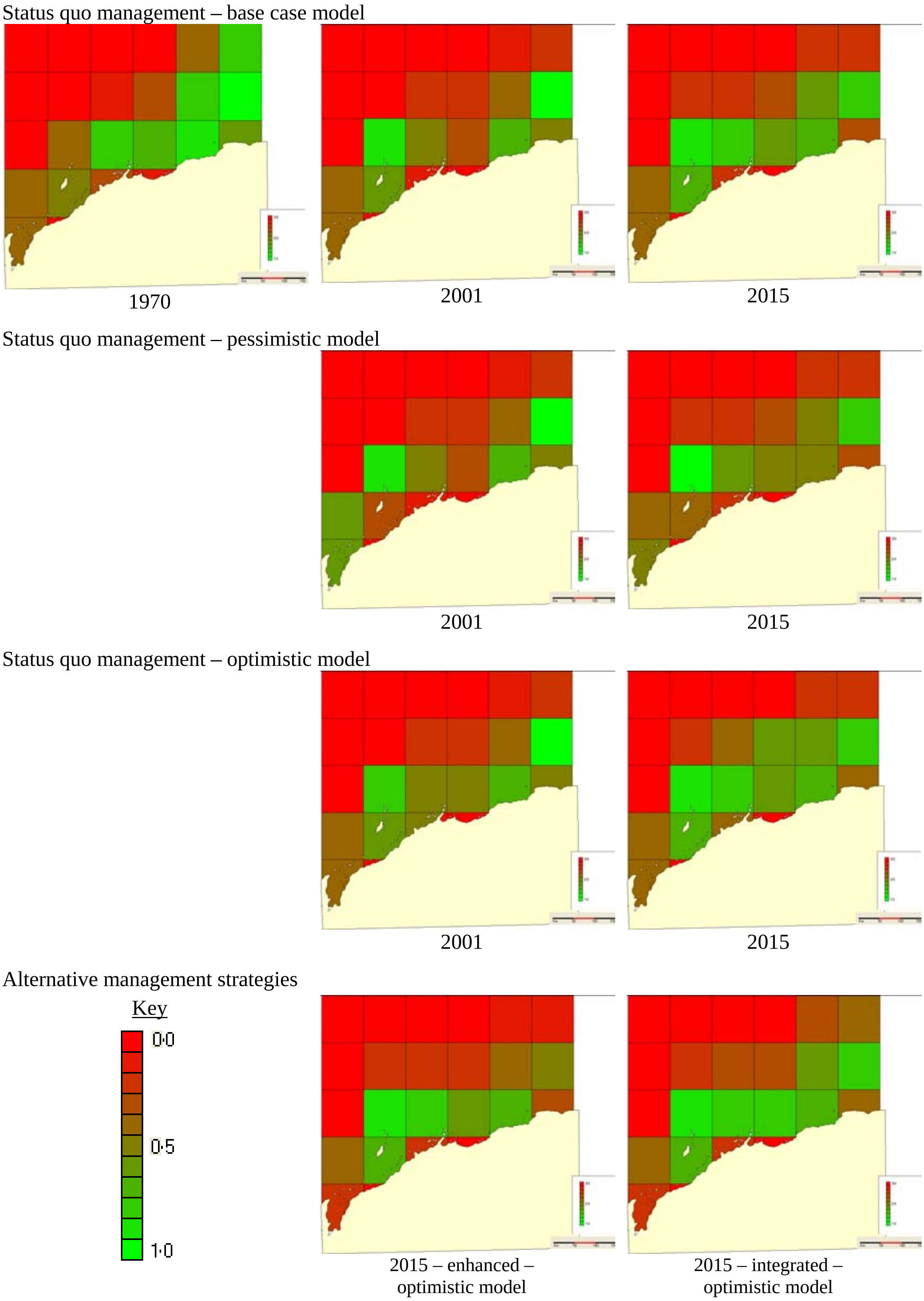


Figure 6.1.4: Representative maps of coarse scale distribution of relative biomass of sharks through time. Relative biomass is defined as the ratio of biomass in a given year to estimated initial biomass (in 1970).

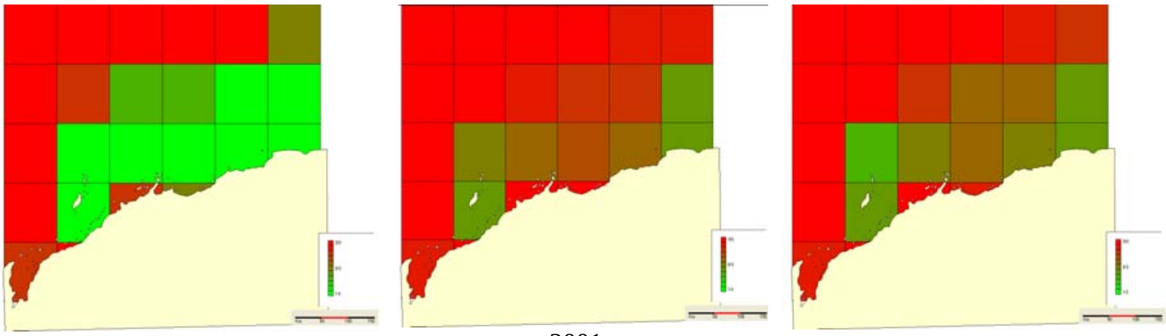
6.1.5 Small lutjanids

The only significant differences amongst the distributions of small lutjanid relative biomasses are among the alternative model specifications (see figure 6.1.5). Under the base case specification the depletion of the stock on the trawl fishing grounds sees the relative biomass concentrated along the lightly fished eastern boundary, inshore waters and around Barrow Island and the Monte Bellos. During the projection period there is some recovery back onto the trawl grounds, but this does not approach the unfished levels. Under the pessimistic model specification the pattern of depletion is almost identical, but the subsequent recovery is more concentrated in the inshore waters and the relative biomass on the trawl grounds stays lower than in the base case specification. Under the optimistic model specification the inshore depletion and patchiness is not as great and there is a flatter inshore distribution (with the biomass spread throughout the inshore waters rather than being concentrated primarily around the Barrow-Monte Bellos to the west, and the edge of the fished area to the east). The recovery during the projection period is also more widespread and by the end of the period there is a fairly even distribution over the shelf area north of Exmouth. This means there are much higher relative biomasses on the trawl grounds and less of an inshore-offshore gradient.

6.1.6 Large lutjanids

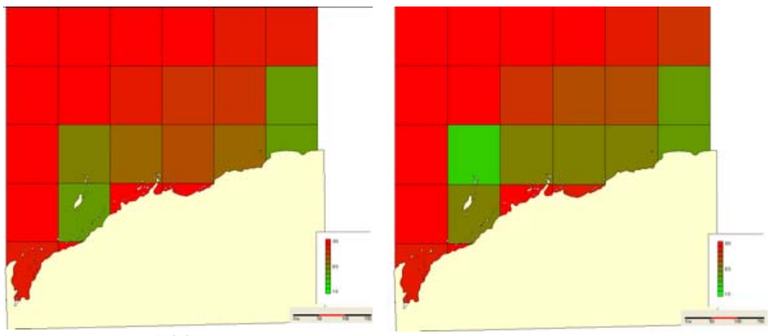
There is no significant difference between the distributions of large lutjanid relative biomasses under the alternative management strategies and development scenarios, although there are differences between the pessimistic and more optimistic model specifications (see figure 6.1.6). The base case model specification sees the large lutjanid distribution contract and become focused around the Dampier Archipelago, Monte Bellos and the eastern edge of the modelled area by the end of the historical period, and then expand back out into the fishing zones (particularly areas 3 and 4) as the effects of management lead to localised stock rebuilding. Under the pessimistic model specification the initial historical depletion leads to an almost identical relative biomass distribution. During the projection period however, the fishing grounds are not extensively recolonised and the relative biomass remains concentrated around the eastern border and the Monte Bellos. In contrast, under the optimistic model specification, the initial contraction is not as patchy (the trawl grounds do not become as depleted as in the other two cases). Moreover, in the projection period, the relative biomass becomes fairly evenly spread, although it still doesn’t approach the magnitude of the most heavily stocked areas of the unfished system.

Status quo management – base case model



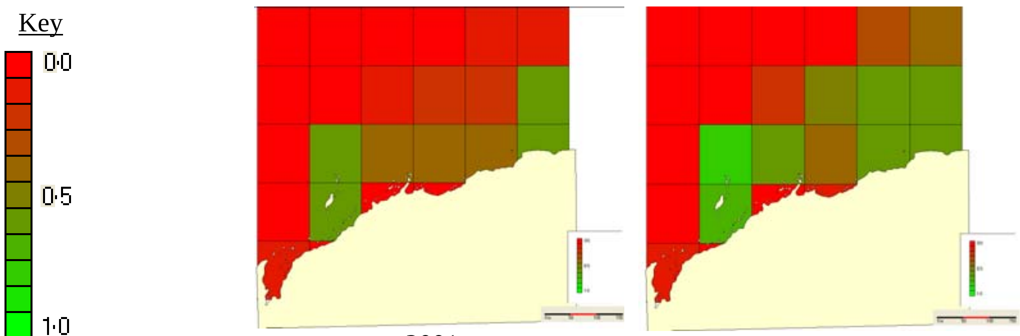
1970 2001 2015

Status quo management – pessimistic model



2001 2015

Status quo management – optimistic model



2001 2015

Figure 6.1.5: Representative maps of coarse scale distribution of relative biomass of small lutjanids through time. Relative biomass is defined as the ratio of biomass in a given year to estimated initial biomass (in 1970).

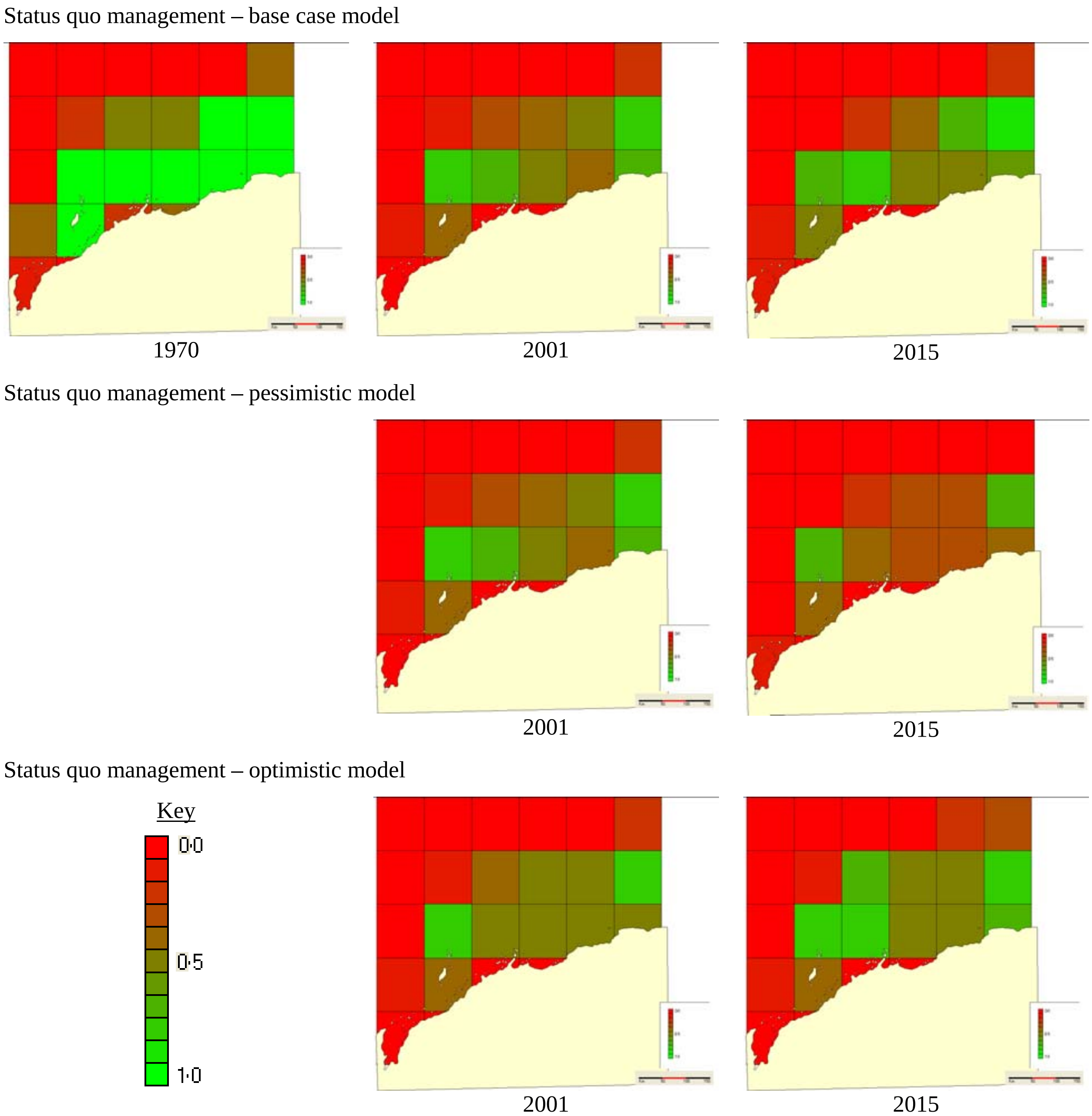


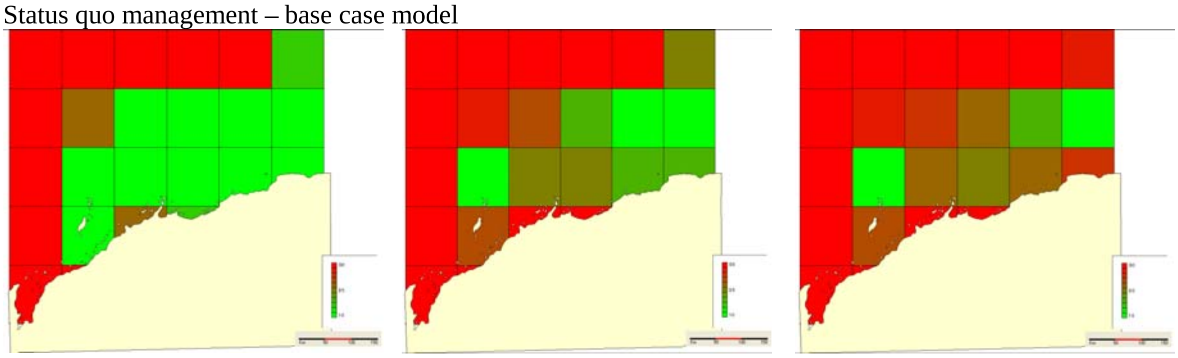
Figure 6.1.6: Representative maps of coarse scale distribution of relative biomass of large lutjanids through time. Relative biomass is defined as the ratio of biomass in a given year to estimated initial biomass (in 1970).

6.1.7 *Lutjanus sebae*

As with many other finfish the significant differences in the relative biomass distributions of *Lutjanus sebae* are between the distributions under the alternative model specifications and between the integrated and other two management strategies (see figure 6.1.7). Under the base case model specification and status quo management, the relative biomass on the trawl grounds is depleted steadily through the historical and into the projection period. Ultimately the biomass becomes concentrated on the edges of the fishing grounds and in the zones designated trawl free. Under the pessimistic model specification the historical depletion and redistribution is almost identical to that under the base case. Into the projection period, however, the relative biomass is depressed further in any area within or bordering the intensively-fished zones. By the end of the period there is a single peak in the distribution around the Monte Bellos. The distribution of relative biomass under the optimistic model specification is not nearly as peaked at the end of the period. With an optimistic model specification, at the end of the historical period the relative distribution of *L. sebae* is steeper than for the pessimistic and base–case model specifications and is concentrated around the Monte Bellos and the edges of the fished area; during the projection period, however, the partial recovery of stocks along the southern edge of the trawl ground means that the inshore distribution is smoother, although there is still a strong inshore-offshore gradient, making it similar in general form to that under the base case model specification.

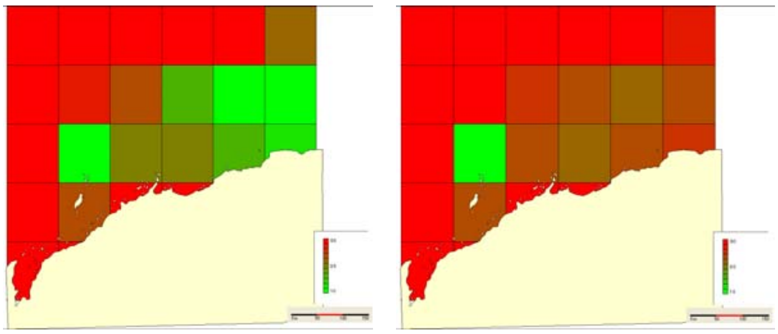
The redistribution of effort under the enhanced management strategy has a marked effect on the relative distribution of the target species *L. sebae*. Under the status quo management strategy the relative biomass on the trawl grounds is depressed, so there are peaks along the edges of the fished area. In contrast, under the enhanced management strategy, the relative biomass is more evenly distributed across the fished area. There is no increase in relative biomass: it is simply more evenly distributed across the fished area, though it is still depleted in those areas under the heaviest pressure. It is only under integrated management that the relative distribution of *L. sebae* is widespread, resulting in a largely uniform distribution across the eastern shelf, typical of the unfished system.

Status quo management – base case model



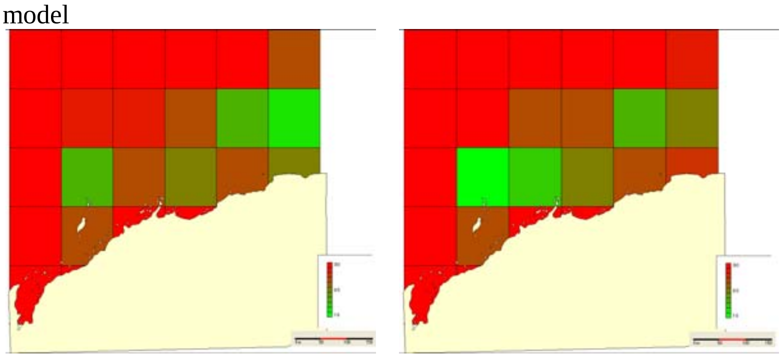
1970 2001 2015

Status quo management – pessimistic model



2001 2015

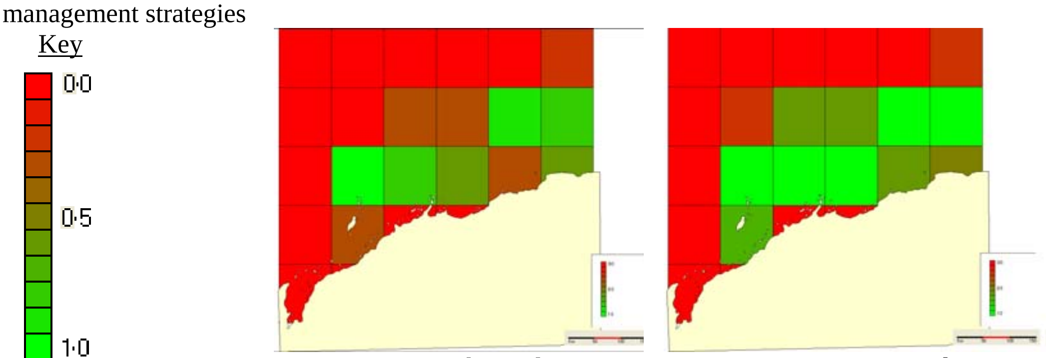
Status quo management – optimistic model



2001 2015

Alternative management strategies

Key



2015 – enhanced 2015 – integrated

Figure 6.1.7: Representative maps of coarse scale distribution of relative biomass of *Lujanus sebae* through time. Relative biomass is defined as the ratio of biomass in a given year to estimated initial biomass (in 1970).

6.1.8 Lethrinids

The significant differences between the distribution of lethrinid relative biomasses lie among the model specifications and between management strategies under specific conditions, particularly in the more productive systems. As can be seen in figure 6.1.8 under the base case model specification the edges of the lethrinid range are depleted during the historical period, but the core remains quite robust. The same is true for the optimistic model specification: during the projection period the biomass spreads out again and is more even across the lethrinids' preferred habitat areas. This spread is not as even under the optimistic model specification when an enhanced management strategy is used. In that case the redistribution of fishing effort leads the lethrinids to continue to be depleted at the edge of their range. In contrast, under the pessimistic model specification, the lethrinids remain evenly spread throughout the area because their preferred habitat is equally degraded elsewhere, so there are no preferred habitat patches to which to retreat. The condition of the habitat also seems to dictate the generally uniform distribution of lethrinids under the status quo management strategy. Under integrated management the distribution of lethrinids is also more evenly distributed at the end of the projection period than at the end of the historical fishing period. Lethrinid distribution is not as even under the other management strategies: rather, a fairly strong inshore-offshore gradient almost brings it back to the unfished distribution.

6.1.9 Nemipterids

The Kolmogorov-Smirnov tests and the cumulative distributions displayed in figure 6.1.9 indicate that there is a difference between the spatial distributions under the optimistic model specification and the other specifications (particularly the pessimistic). This has less to do with the end points than the transitional dynamics. The final maps are identical, but the fact that nemipterids are not as tied to habitat means that maps at other times can have the values in adjacent cells swapped, thus magnifying the statistical differences. The only real visual difference in the distributions is between integrated management and the other strategies under the base case model specification: integrated management encourages more biomass in the inshore and fisheries areas and, as a result, a stronger inshore-offshore gradient.

6.1.10 Saurids

The significant differences between the distributions of relative biomass of saurids are all based on the model specifications. There are no significant differences among the development scenarios or management strategies (see figure 6.1.10). Under the pessimistic model specification there is large-scale depletion across the region, with minor peaks left on the eastern and western edges of the fished area. Under the base case model specification there is depletion, but it isn't as large and a strong inshore-offshore gradient persists. With this specification the depletion does not plateau (as in the pessimistic case), but continues to increase into the projection period. Under the optimistic model specification the depletion in the fisheries area is much smaller, there is a slight inshore-offshore gradient in relative biomass, and a stronger gradient running from the edge to the centre of the fishing area. This new pattern is strengthened during the projection period, as the relative biomass of saurids in the Monte Bellos and the eastern end of the fished area, rises back toward unfished levels, while the central cells remain depressed.

This depletion may seem to be in contradiction to observed increases in the proportion of the catch made up by saurids. This needn’t be the case however, as a lower absolute biomass can remain undetected if there is a masking shift in catch composition – which there is within the simulations.

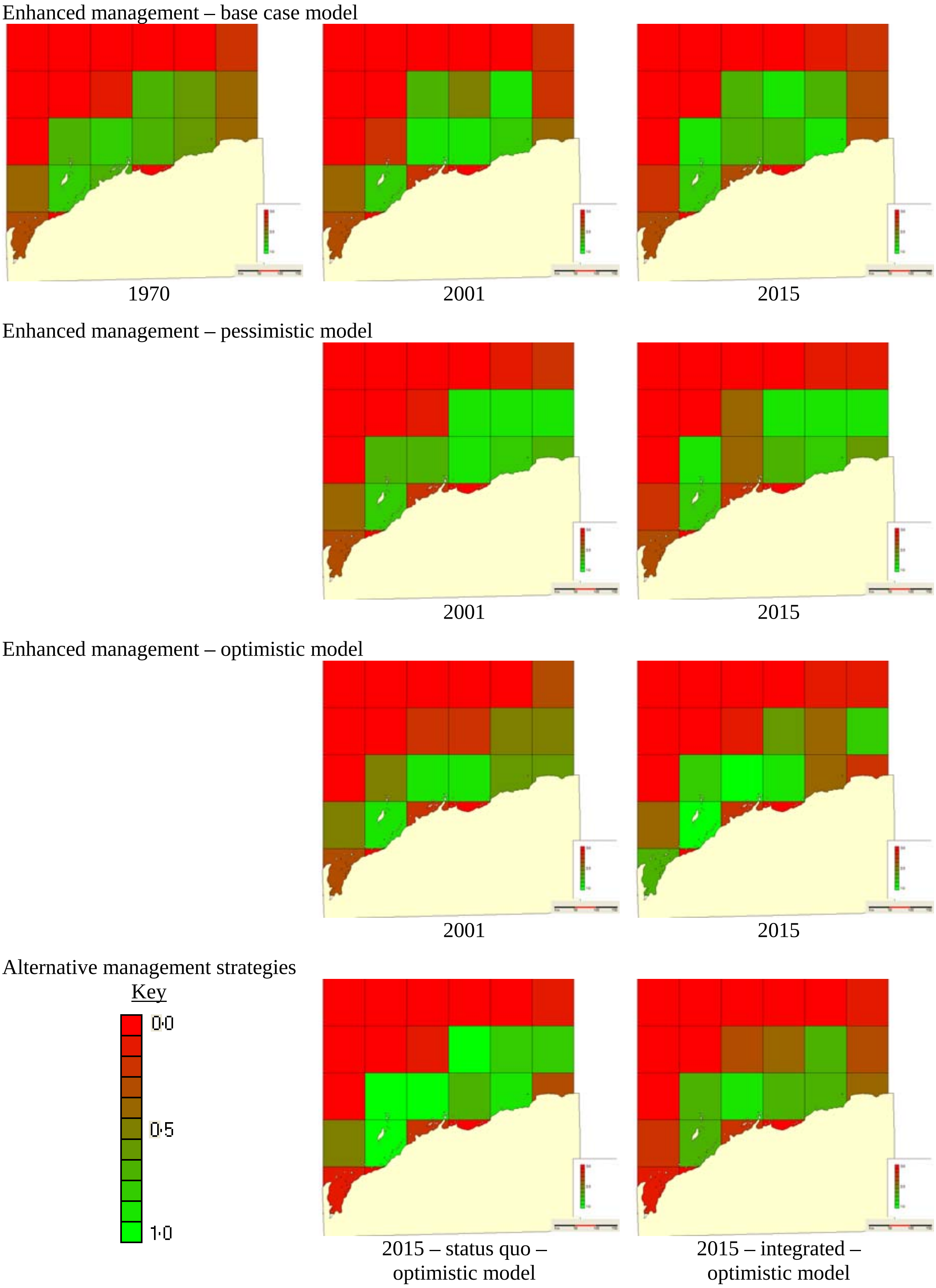


Figure 6.1.8: Representative maps of coarse scale distribution of relative biomass of lethrinids through time. Relative biomass is defined as the ratio of biomass in a given year to estimated initial biomass (in 1970).

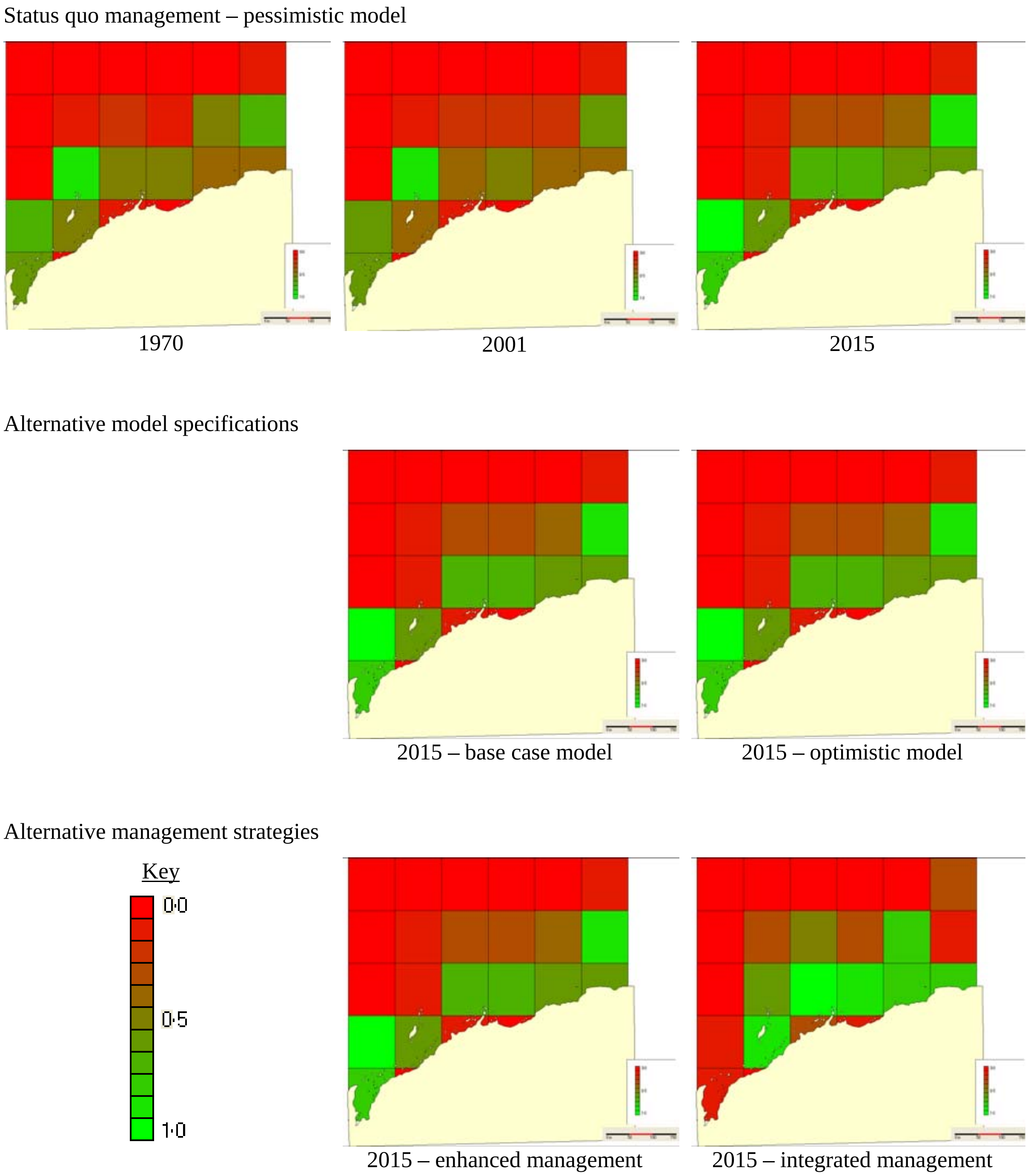
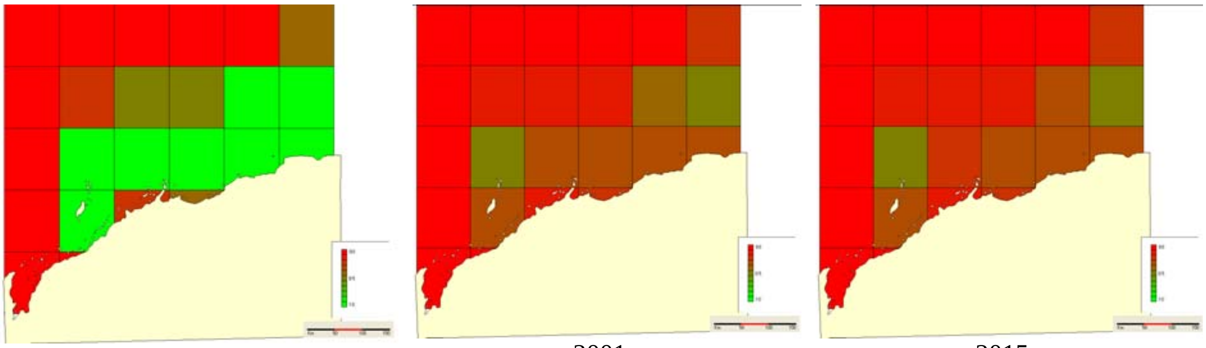
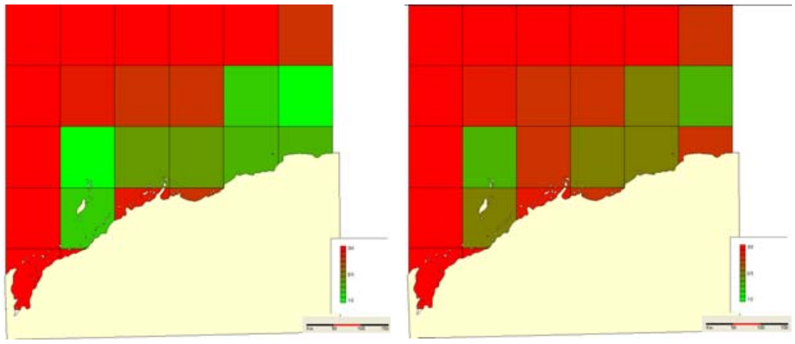


Figure 6.1.9: Representative maps of coarse scale distribution of relative biomass of nemipterids through time. Relative biomass is defined as the ratio of biomass in a given year to estimated initial biomass (in 1970).

Status quo management – pessimistic model



Status quo management – base case model



Status quo management – optimistic model

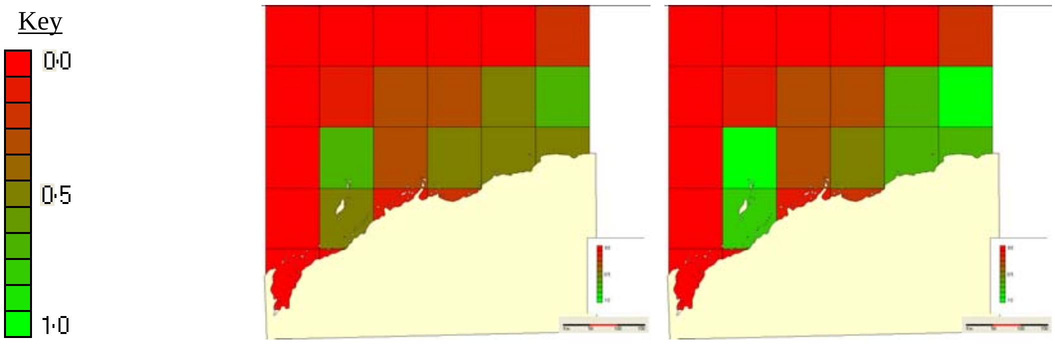
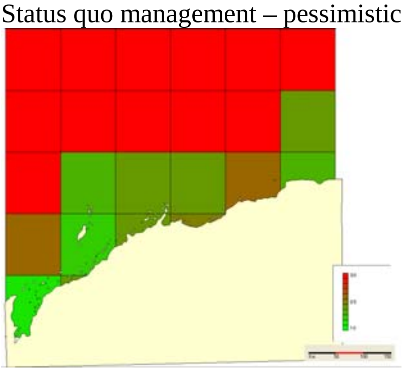


Figure 6.1.10: Representative maps of coarse scale distribution of relative biomass of saurids through time. Relative biomass is defined as the ratio of biomass in a given year to estimated initial biomass (in 1970).

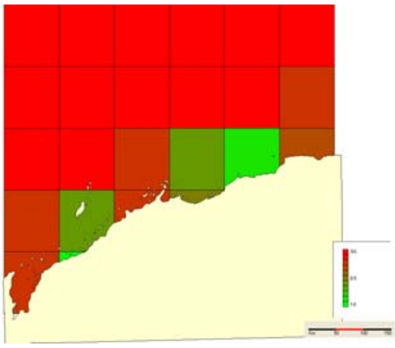
6.1.11 Seagrass

There were no significant differences in the relative distribution of seagrass between any of the management strategies, development scenarios and model specifications. The pattern observed in all cases in figure 6.1.11 is that the biomass in the seagrass meadows, in the areas trawled by the prawn fishery, is drastically reduced and remains depleted for as long as the fishery remains active in that area. The substantial reduction of fishing pressure under the integrated management strategy means that recovery could be marked in some areas, the resulting map being similar to the unfished state in 1970.

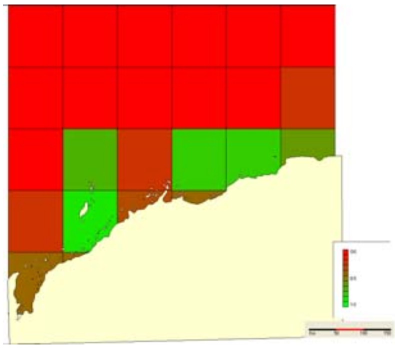
Status quo management – pessimistic model



1970



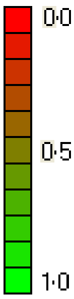
2001

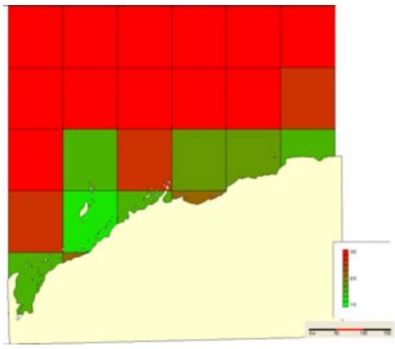


2015

Integrated management – pessimistic model

Key





2015

Figure 6.1.11: Representative maps of coarse scale distribution of relative biomass of seagrass through time. Relative biomass is defined as the ratio of biomass in a given year to estimated initial biomass (in 1970).

6.1.12 Sponge and reefs

There are no significant differences between the distributions of sponge and reef habitat under the alternative development scenarios. In contrast, there are some differences between the management strategies and all of the model specifications. The basic pattern of all sponge and reef distributions (figure 6.1.12) display moderate levels inshore, decreasing offshore (particularly in cells that see intensive fishing pressure), and to a smaller concentration on the eastern edge of the fishing zones (where pressure has typically been much lighter). Under the pessimistic model specification the distribution offshore is more depleted than in the base case, while under the optimistic model specification the distribution is more evenly spread both inshore-offshore and west-east. Integrated and enhanced management also lead to more even distributions, at least across the fished areas. Under the integrated management strategy the relaxation of fishing pressure allows substantial recovery of habitat across the entire area; whereas under enhanced management the shuffling of fishing effort between areas results in the entire region being more evenly impacted, leading to less recovery in general and less patchiness.

6.1.13 Mangroves

There are no significant differences among the various management strategies, development scenarios and model specifications examined. The spatial pattern in mangrove biomass observed in all cases (see figure 6.1.13) is that the mangroves varied along shore only as a direct result of destruction due to cyclones or coastal development (a relatively minor pressure that impacted only a few cells). Cells spanning cyclone paths or coastal development in the previous decade (or so) have lower relative biomass of mangroves than surrounding cells.

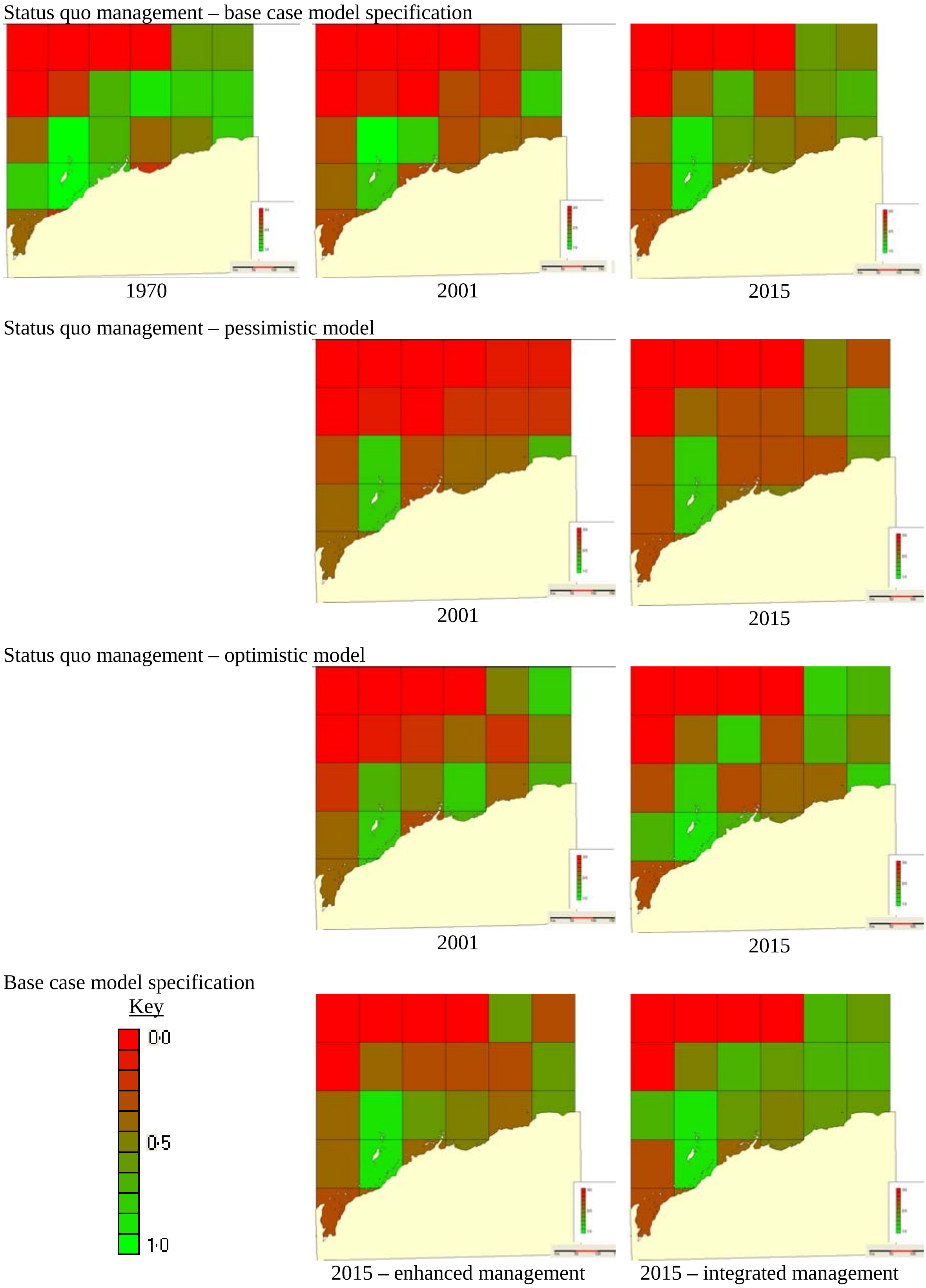


Figure 6.1.12: Representative maps of coarse scale distribution of relative biomass of sponge and reef through time. Relative biomass is defined as the ratio of biomass in a given year to estimated initial biomass (in 1970).

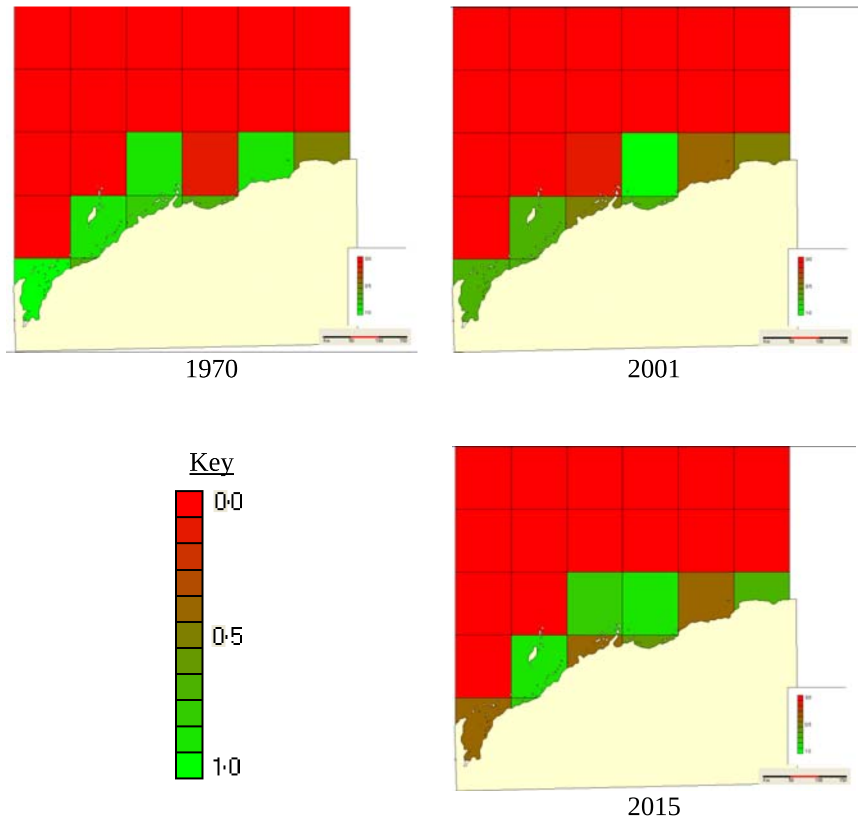


Figure 6.1.13: Representative maps of coarse scale distribution of relative biomass of mangroves through time. Relative biomass is defined as the ratio of biomass in a given year to estimated initial biomass (in 1970). Note that due to the coarse resolution it may appear that cells over water contain mangroves: this is obviously not the case and it is only the coastline of bodies of land within those cells that are lined by mangroves.

6.2 Fine scale distributions

For clarity, a summary of the fine scale spatial results and the average relative biomass per cell for each of the MSE combinations (strategy-scenario-specification) are given immediately below. The associated frequency histograms and cumulative distribution plots, also used in the analysis of the fine scale spatio-temporal distributions, are given in Appendix B. The mapping of grid cells to map locations is given in figure 6.2.1 to make interpretation of the average biomass per cell plots easier.

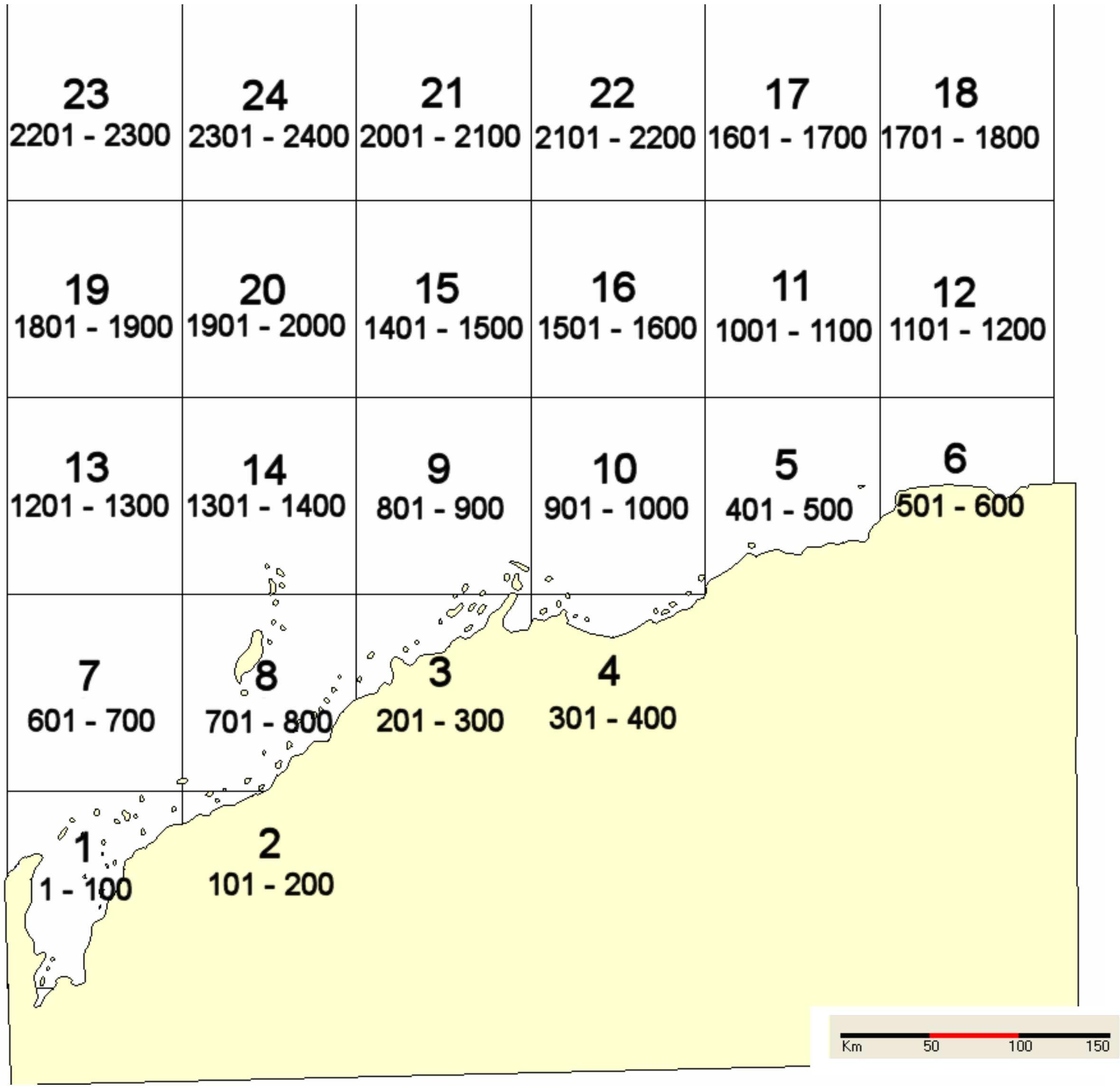


Figure 6.2.1: Mapping of grid cell identification numbers to map locations (coarse scale identification numbers appear in the larger font and the fine scale below that in small font).

6.2.1 Banana prawns

The cumulative distribution plots in Appendix B (figures B.1 to B.3) show that there is a discernible difference between the relative biomass distributions of banana prawns at the fine scale when comparing model specifications, but that no such difference exists when comparing among management strategies or development scenarios. The average relative biomass per cell plots are given in figures 6.2.2 to 6.2.4. These figures show that the bulk of the banana prawn biomass is distributed evenly throughout the inshore waters in all cases. The differences between the distributions under the various model specifications arises as a result of a higher relative biomass inshore under the pessimistic specification, particularly off the eastern part of the coast of Nickol Bay, where the relative biomass is three times greater than in the more optimistic model specifications.

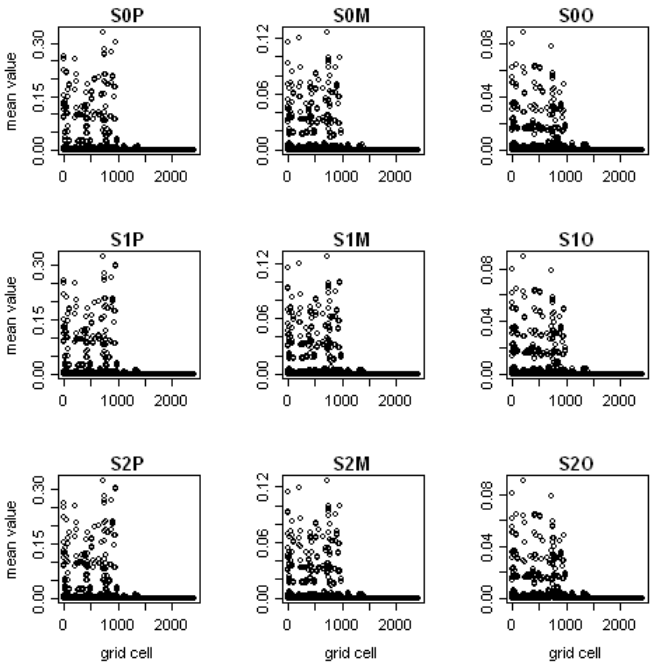


Figure 6.2.2: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for banana prawns under status quo management for each combination of development scenario and model specification.

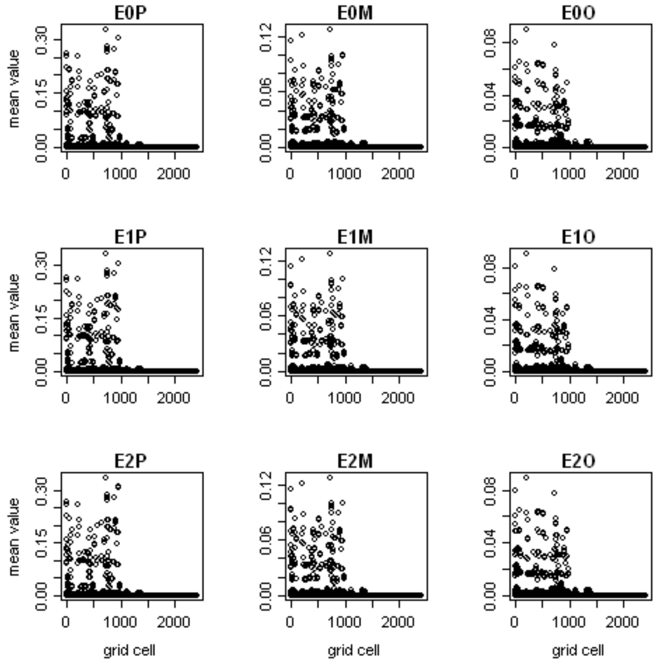


Figure 6.2.3: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for banana prawns under enhanced management for each combination of development scenario and model specification.

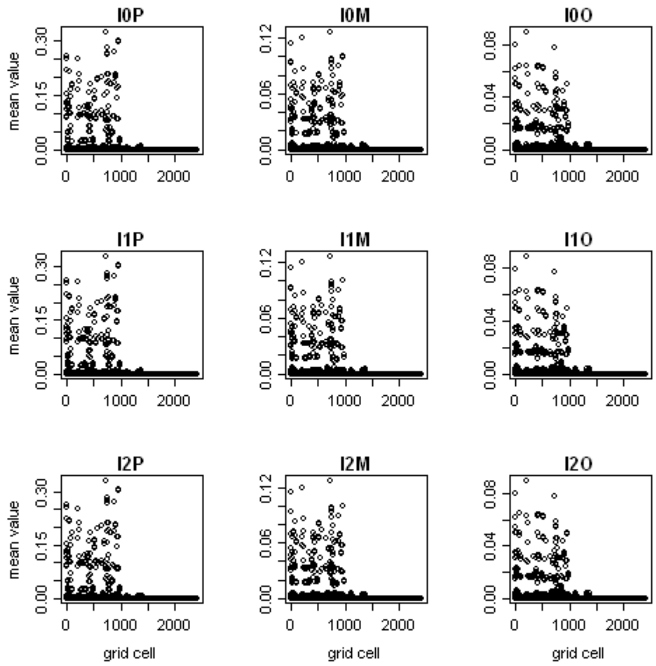


Figure 6.2.4: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for banana prawns under integrated management for each combination of development scenario and model specification.

6.2.2 King prawns

The difference between the king prawn fine scale distributions is again due to the model specification rather than management strategy or development scenario (according to the cumulative distribution plots provided in Appendix B – see figures B.7 to B.9). While the base case and optimistic specifications have a peak north of Exmouth, the pessimistic specification has two peaks. The first peak is in the same location as for the other specifications, but is not as large. The second peak is further east, in the inshore waters between Nickol Bay and Port Hedland (similar to the banana prawns). Apart from these peaks, all of the average biomass plots (figures 6.2.5 to 6.2.7) show that the king prawn biomass is concentrated close to the coastline, with a slight gradient with depth and distance along the shore from west to east.

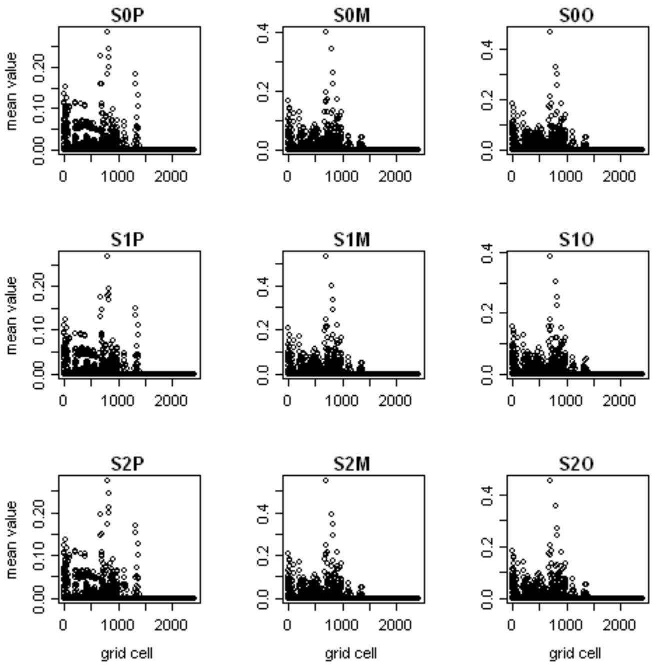


Figure 6.2.5: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for king prawns under status quo management for each combination of development scenario and model specification.

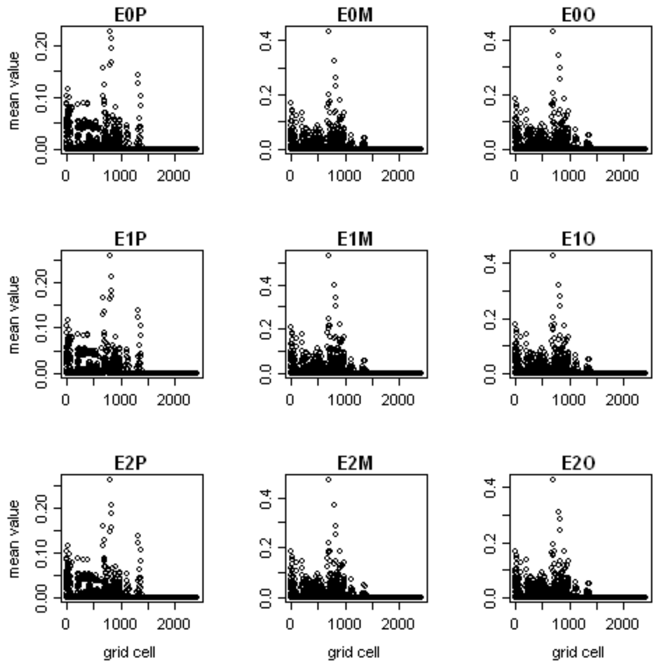


Figure 6.2.6: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for king prawns under enhanced management for each combination of development scenario and model specification.

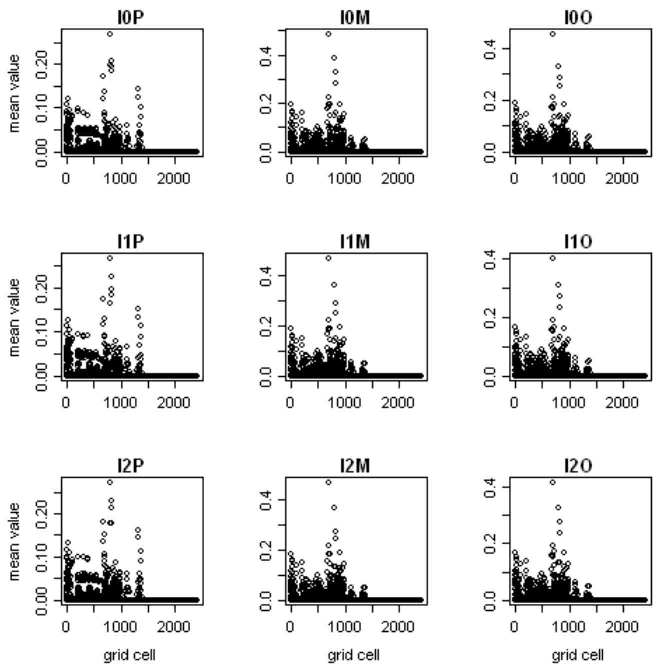


Figure 6.2.7: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for king prawns under integrated management for each combination of development scenario and model specification.

6.2.3 Turtles

The cumulative distribution plots for turtles (see figures B.13 to B.15 in Appendix B) show that there is little difference among the development scenarios and, where there are differences among the management strategies or model specifications, they are small. The average biomass plots (figures 6.2.8 to 6.2.10) also suggest there is little to separate the various cases. Every combination shows a largely flat mean value, with a handful of much higher concentrations inshore. The small differences that may exist between the management strategies is that the size of these peaks inshore is smaller for integrated management, suggesting a more even distribution than is given under the other management strategies. This holds true even when alternative model types are used for this species.

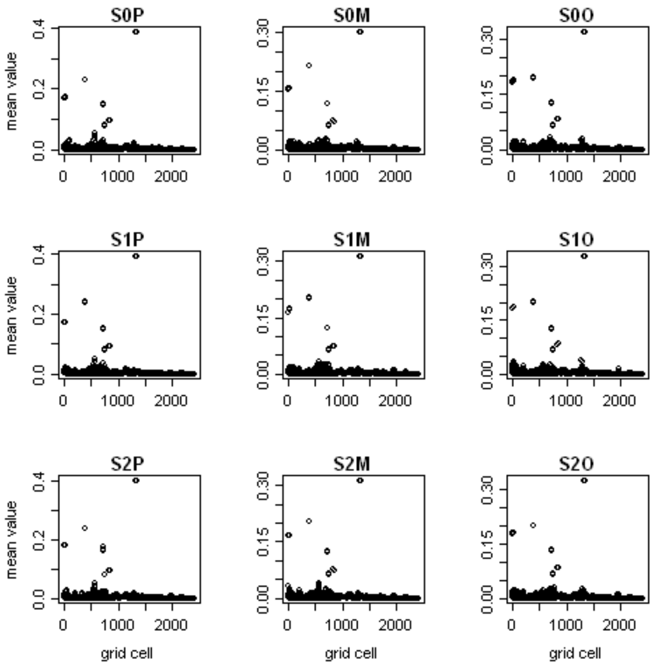


Figure 6.2.8: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for turtles under status quo management for each combination of development scenario and model specification.

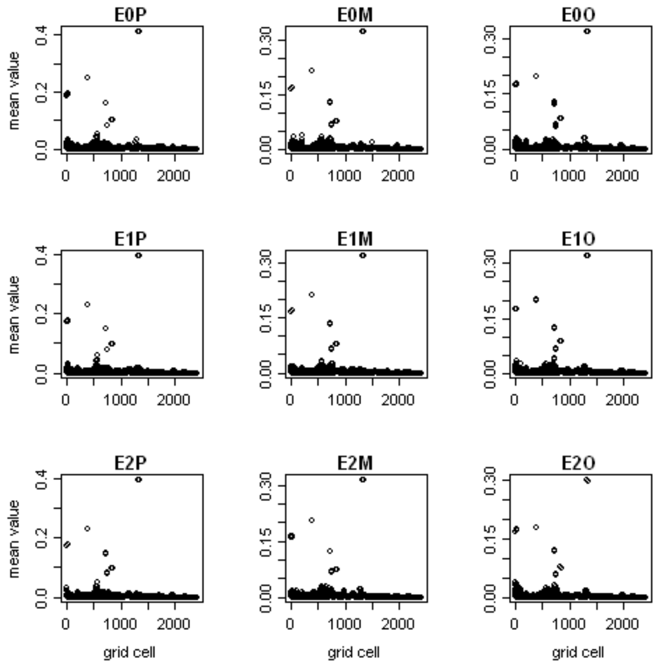


Figure 6.2.9: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for turtles under enhanced management for each combination of development scenario and model specification.

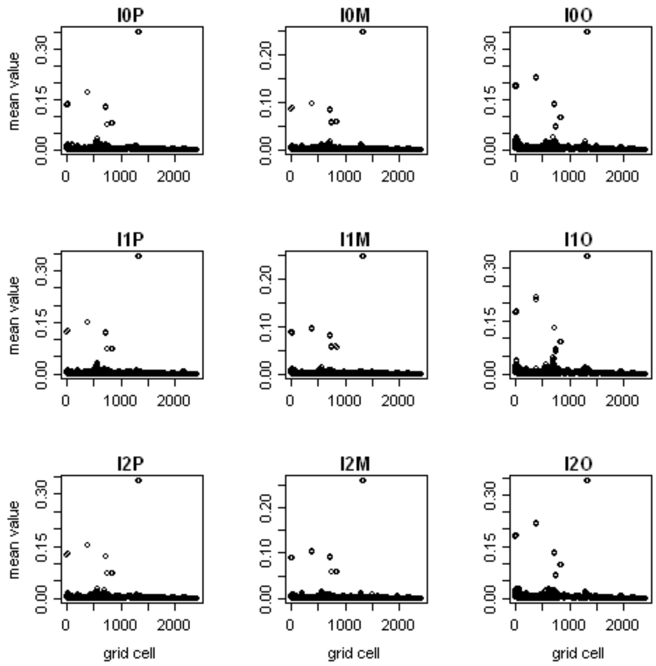


Figure 6.2.10: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for turtles under integrated management for each combination of development scenario and model specification.

6.2.4 Sharks

The cumulative distribution plots for the relative biomass of sharks on the North West Shelf, shows that there is a difference between model specifications, but no apparent difference between the management strategies or development scenarios (see figures B.19 to B.21 in Appendix B). The average biomass plots (figures 6.2.11 to 6.2.13) show that this is due to the strength of inshore peaks in biomass and the steepness of the inshore-offshore gradient in relative biomass in each case. As system productivity increases (from pessimistic to base case to optimistic model specifications), the relative biomass spreads further offshore. Under the pessimistic specification the biomass is spread relatively evenly through the inshore waters (peaking on the eastern end of the model domain) before tailing off in the deeper waters. The base case model specification shows a similar pattern, though the inshore values are higher and slightly more even, making the tail into the deeper waters much steeper. Under the optimistic model specification this general pattern is strengthened with a steep drop off in maximum relative biomass with depth. When an enhanced management strategy is used the patchiness is accentuated, while it is smoothed out under integrated management, although this does not seem to be of sufficient magnitude to produce striking results in the cumulative distribution.

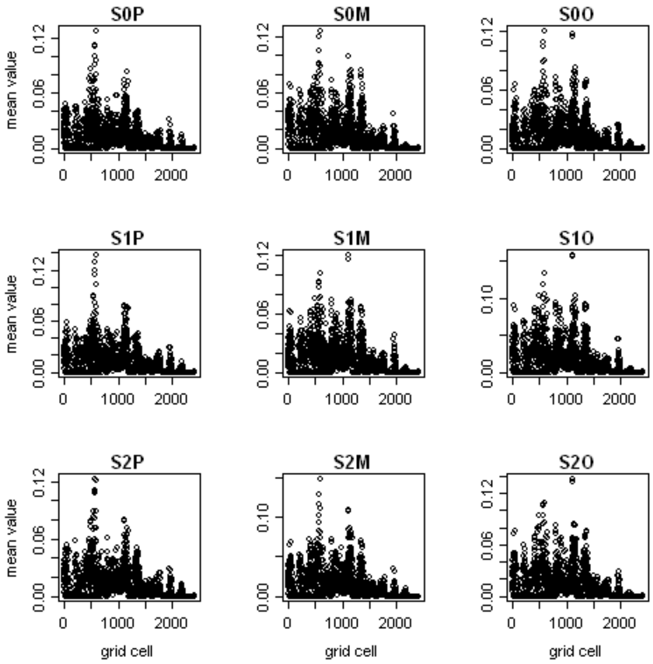


Figure 6.2.11: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for sharks under status quo management for each combination of development scenario and model specification.

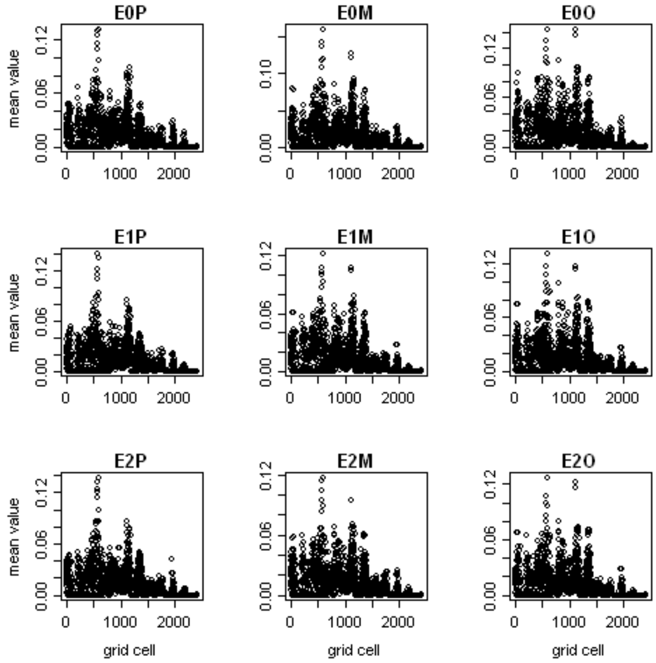


Figure 6.2.12: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for sharks under enhanced management for each combination of development scenario and model specification.

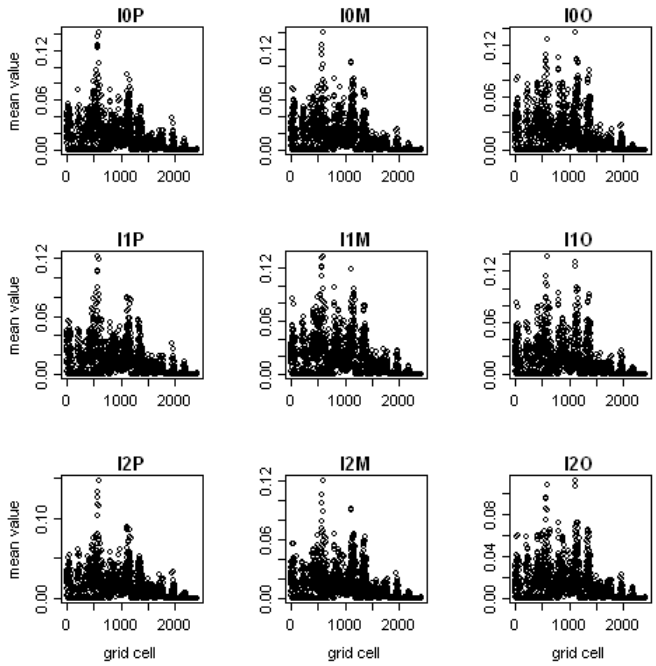


Figure 6.2.13: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for sharks under integrated management for each combination of development scenario and model specification.

6.2.5 Small lutjanids

The cumulative distribution plots for the relative biomass of small lutjanids (figures B.31 to B.33) show that there is a difference among the model specifications, but no detectable differences among the management strategies and development scenarios. The basic form of the fine scale relative biomass distributions for the small lutjanids is of a similar form in all cases: low biomass levels close inshore, increasing with depth until the offshore waters are reached, after which the biomass drops off again (see figures 6.2.14 to 6.2.16). The difference between the model specifications is that the inshore band is large in magnitude with increasing system productivity and there is less patchiness within that area. In the pessimistic case there is a clear peak, which persists in the other cases, though the difference between that peak and the other inshore cells is smaller under the more optimistic model specifications. The values in this inshore band also increase marginally when the status quo management strategy is replaced by enhanced and integrated management. However, this increase is much smaller in size than the difference among the model specifications and thus does not show marked pattern differences in the cumulative distributions.

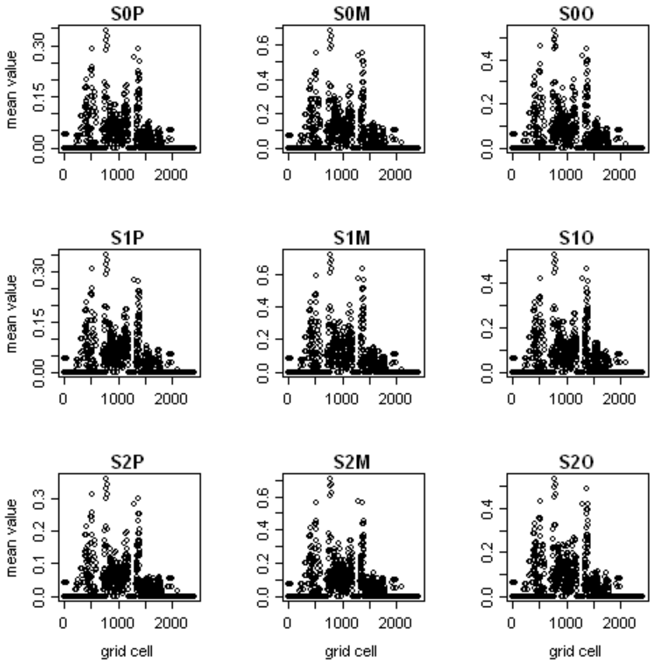


Figure 6.2.14: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for small lutjanids under status quo management for each combination of development scenario and model specification.

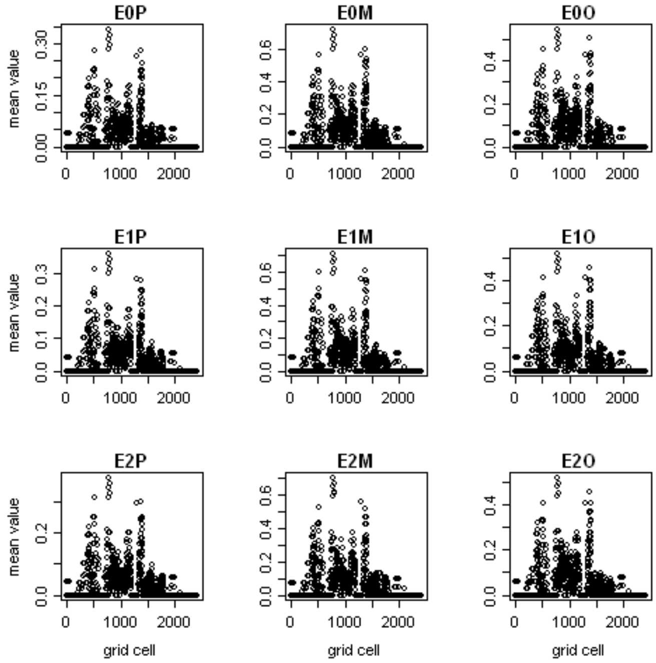


Figure 6.2.15: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for small lutjanids under enhanced management for each combination of development scenario and model specification.

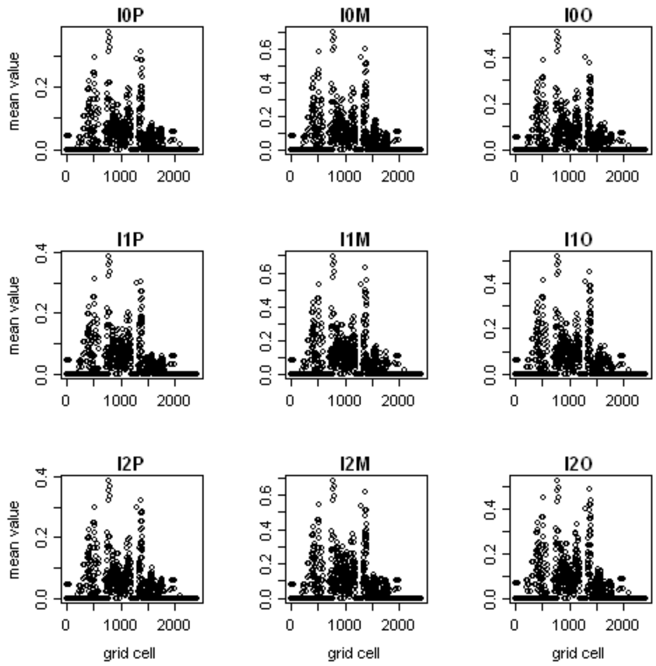


Figure 6.2.16: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for small lutjanids under integrated management for each combination of development scenario and model specification.

6.2.6 Large lutjanids

The model specifications and some of the management strategies yield differences in the cumulative distributions of the relative biomass of large lutjanids (see figures B.25 to B.27 of Appendix B). The difference between the management strategies is due to a spike in relative biomass at either end of the shelf around the eastern boundary and off the Monte Bellos. The spike is much larger relative to surrounding cells under status quo management. Both spikes are present for the other management strategies but the difference between the values at those sites and surrounding cells is much smaller because of a general increase in biomass in those cells, particularly under integrated management. Similarly, the relative strength of the spikes and inshore band of biomass also distinguishes the distributions under the various model specifications, as is apparent in figures 6.2.17 to 6.2.19.

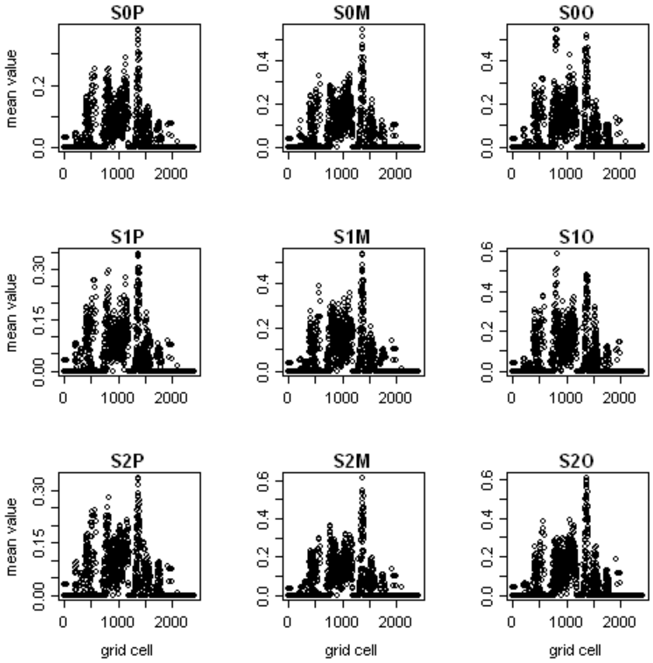


Figure 6.2.17: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for large lutjanids under status quo management for each combination of development scenario and model specification.

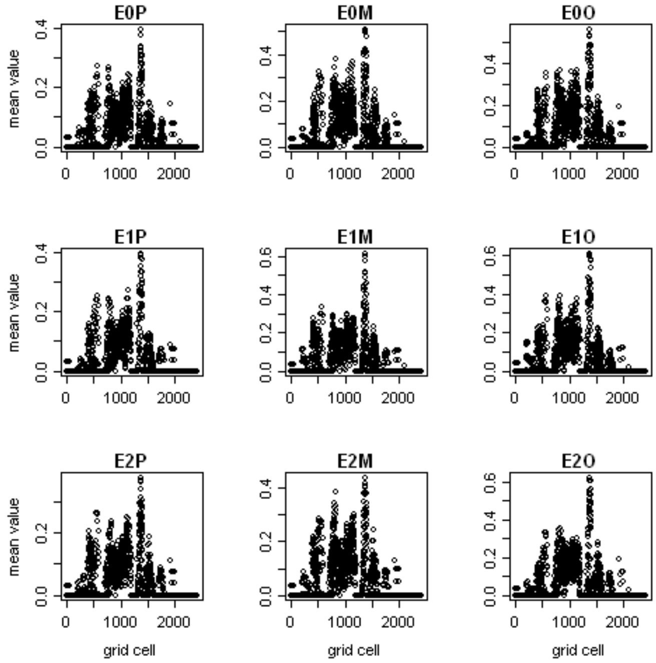


Figure 6.2.18: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for large lutjanids under enhanced management for each combination of development scenario and model specification.

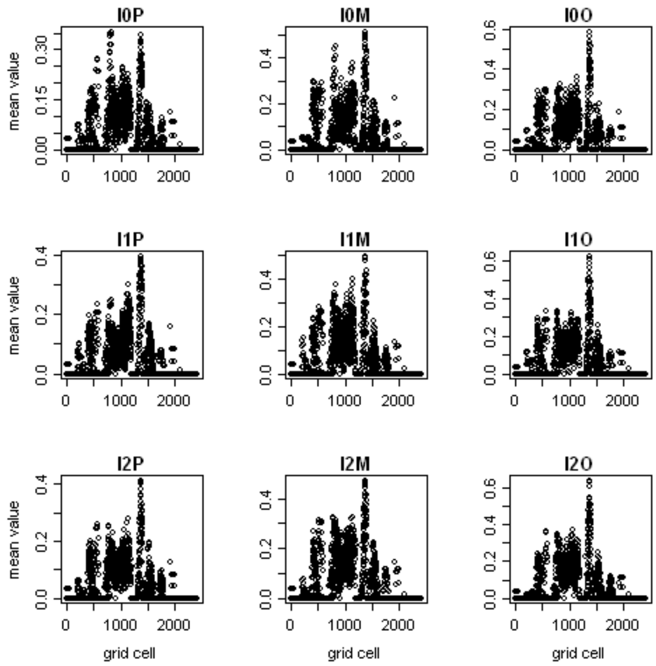


Figure 6.2.19: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for large lutjanids under integrated management for each combination of development scenario and model specification.

6.2.7 *Lutjanus sebae*

As with the other finfish the strongest differences among the cumulative distribution plots is due to the alternative model specifications (see figures B.38 to B.40 in Appendix B). These differences are due to the magnitude of the inshore biomass band, which is nearly twice as large, and much more even, under the optimistic and base case model specifications in comparison with the pessimistic specification. The average biomass plots also indicate that there are some differences between the fine scale relative biomass distributions of *L. sebae*. The spatial distributions under enhanced management are much more patchy than they are under status quo management, while the integrated strategy gives rise to a more even distribution of the species throughout its preferred habitat (see figures 6.2.20 to 6.2.22).

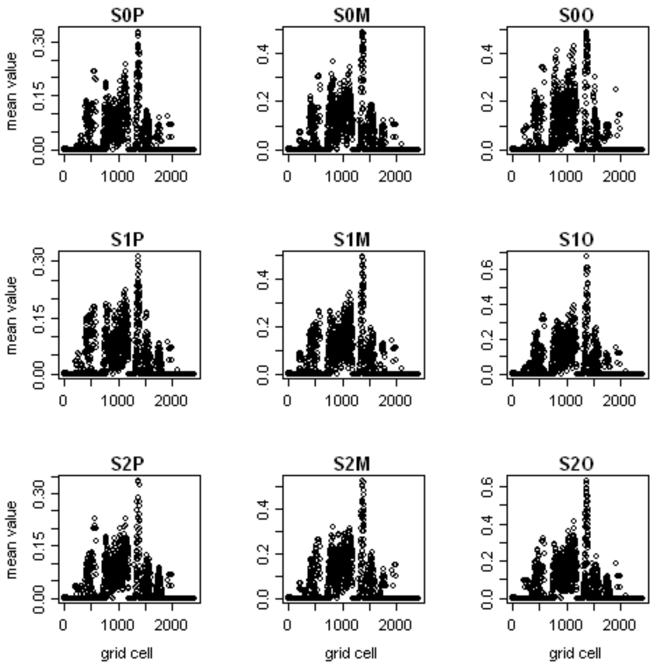


Figure 6.2.20: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for *Lutjanus sebae* under status quo management for each combination of development scenario and model specification.

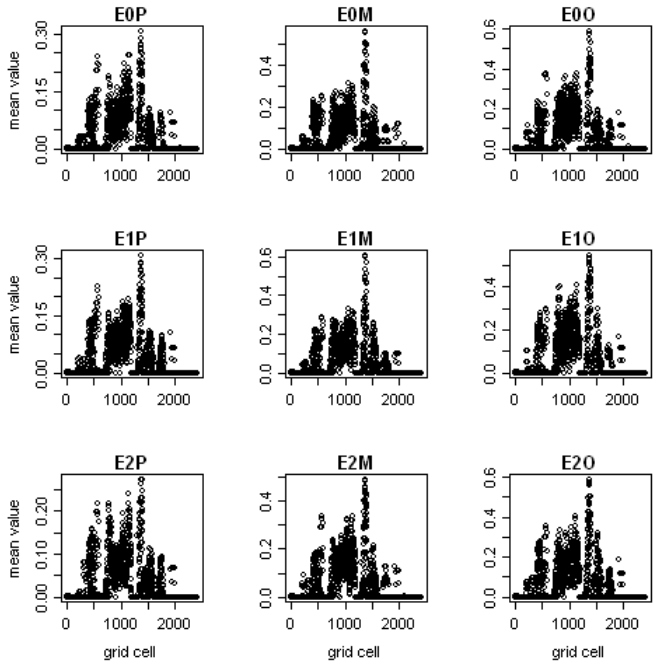


Figure 6.2.21: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for *Lutjanus sebae* under enhanced management for each combination of development scenario and model specification.

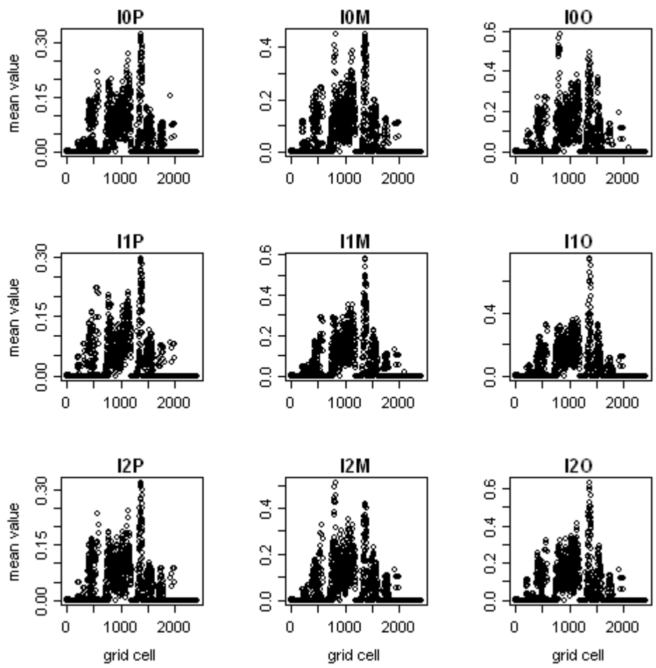


Figure 6.2.22: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for *Lutjanus sebae* under integrated management for each combination of development scenario and model specification.

6.2.8 Lethrinids

The cumulative distribution plots for lethrinids in figures B.43 to B.45 of Appendix B show that there are some differences between the management strategies, but more between the model specifications, with no real differences between the development scenarios. The differences between the model specifications relates to the spread of the relative biomass into deeper water in more productive systems (see figures 6.2.23 to 6.2.25). The enhanced strategy yields much patchier distributions than do the other management strategies because the lethrinid's preferred habitats are poor in the centre of the inshore waters leading to a marked gap in the average biomass plots. Status quo management leads to an intermediate degree of patchiness, but the population is denser towards the inshore cells, with maximum average biomass dropping off fairly smoothly with depth.

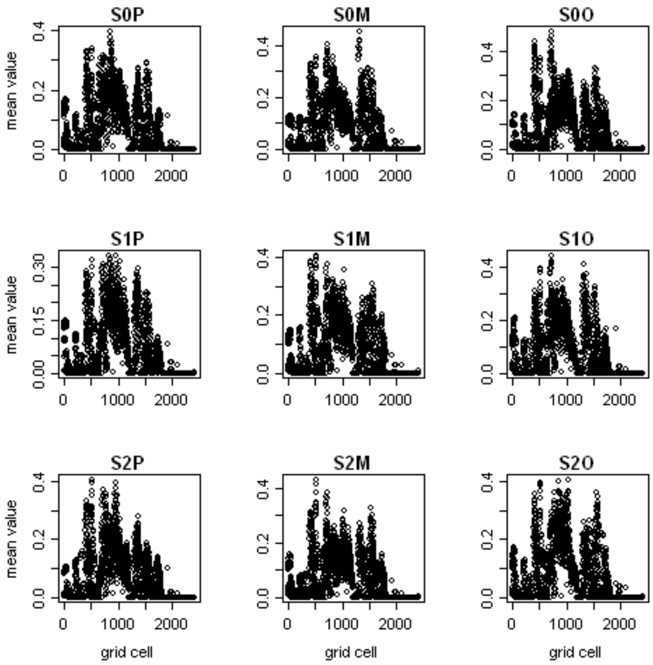


Figure 6.2.23: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for lethrinids under status quo management for each combination of development scenario and model specification.

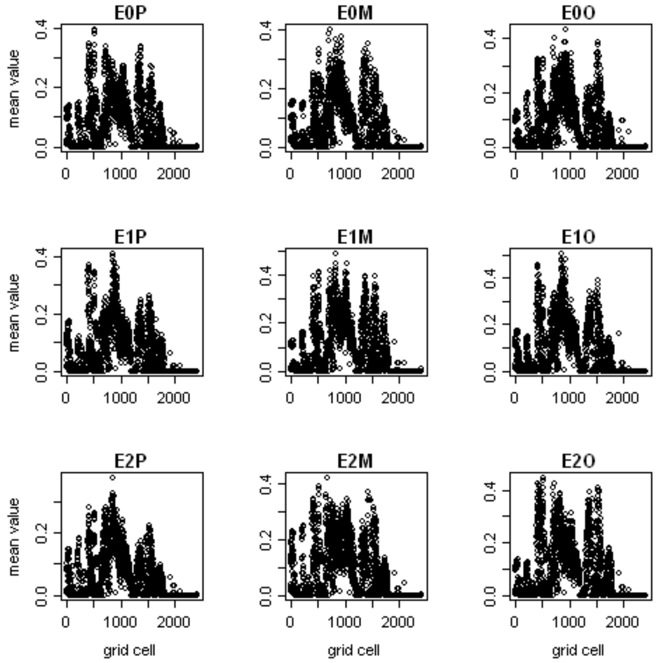


Figure 6.2.24: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for lethrinids under enhanced management for each combination of development scenario and model specification.

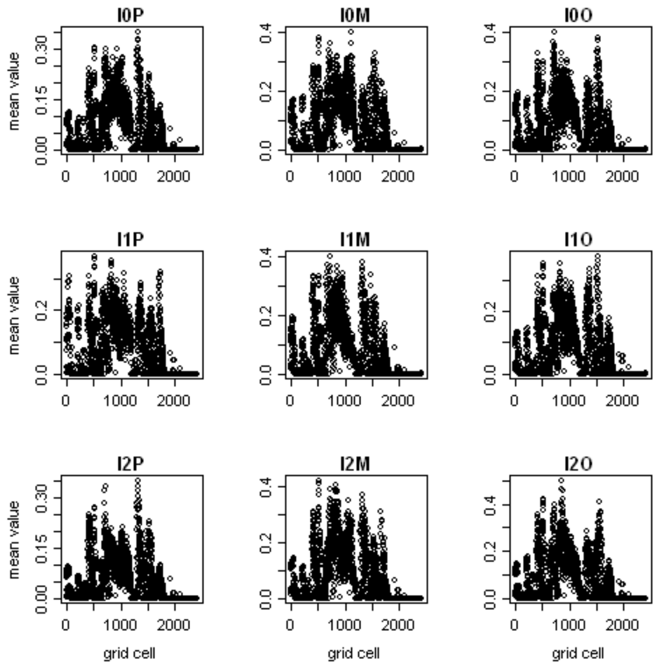


Figure 6.2.25: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for lethrinids under integrated management for each combination of development scenario and model specification.

6.2.9 Nemipterids

The cumulative distributions in Appendix B show little real difference between any of the fine scale relative biomass distributions for nemipterids (figures B.49 to B.51). This is also clear in the average biomass plots of figures 6.2.26 to 6.2.28. In all cases the distributions have strongly patchy distributions from the shoreline to the edge of the inshore waters, peaking around the Monte Bellos and dropping off quickly into the deeper water. The size of these peaks varies between management strategies and model specifications, but the overall form is consistent across all cases.

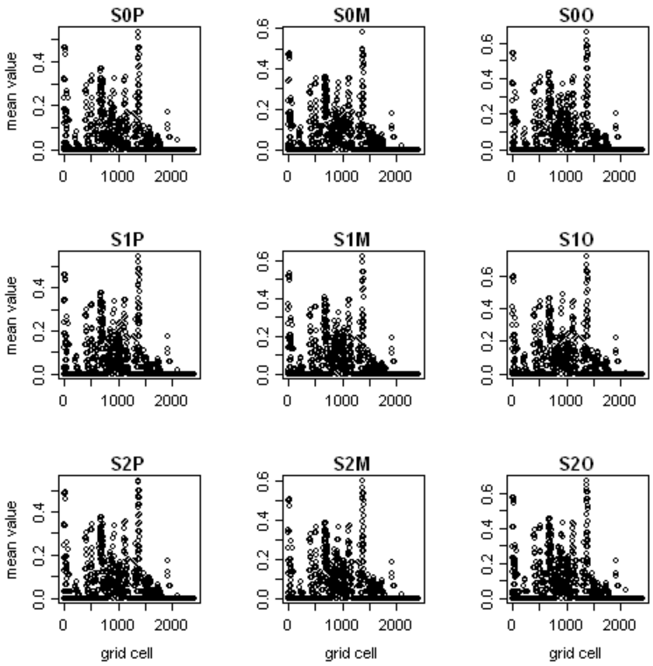


Figure 6.2.26: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for nemipterids under status quo management for each combination of development scenario and model specification.

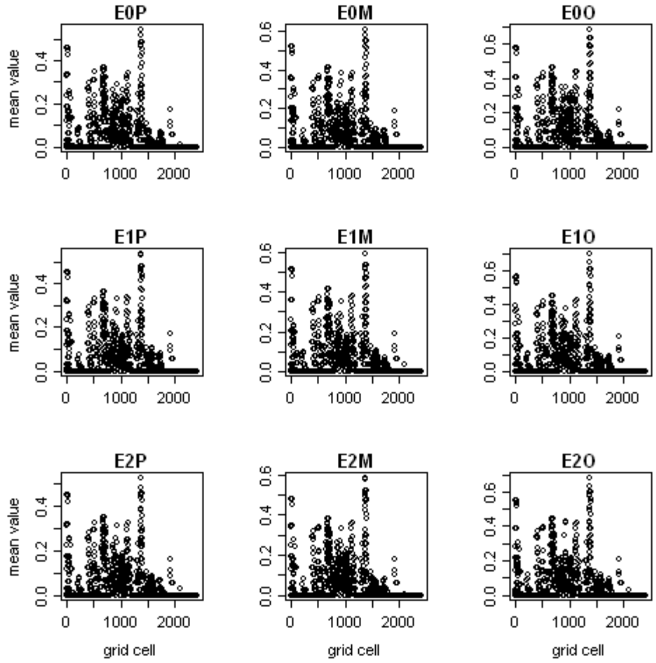


Figure 6.2.27: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for nemipterids under enhanced management for each combination of development scenario and model specification.

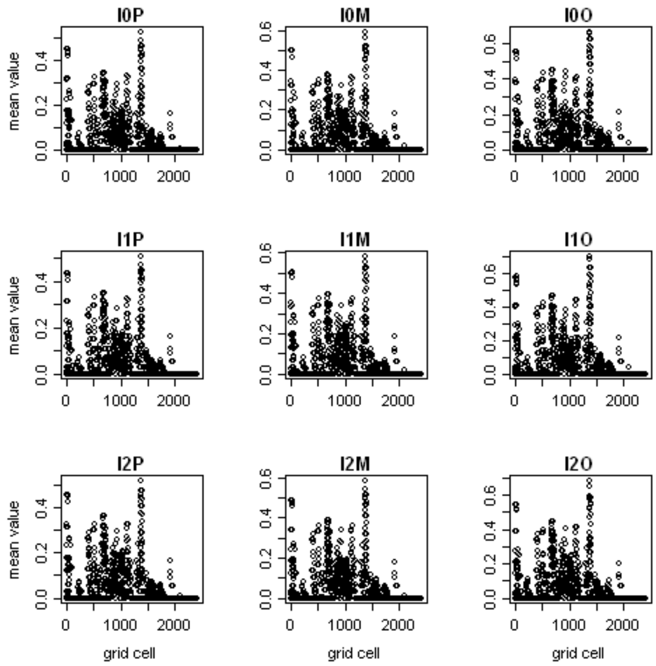


Figure 6.2.28: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for nemipterids under integrated management for each combination of development scenario and model specification.

6.2.10 Saurids

The cumulative distribution plots for the fine scale relative biomass of the saurids shows some small differences in the model specifications (see figures B.55 to B.57 in Appendix B). There are no notable differences between any of the management strategies or development scenarios in these plots. This is supported by the distributions given in the average biomass plots in figures 6.2.29 to 6.2.31. The pattern doesn't change from strategy to strategy, but does become more peaked with increasing system productivity. In all cases the biomass is concentrated in an inshore band, dropping off near the shoreline and again towards the shelf edge. The magnitude of the values in this band (and particularly the values at the two hotspots, one around Barrow Island and the other at the eastern edge of the system) increase from a maximum of a little over 0.4 under the pessimistic model specification to a high of 0.7 under the optimistic model specification.

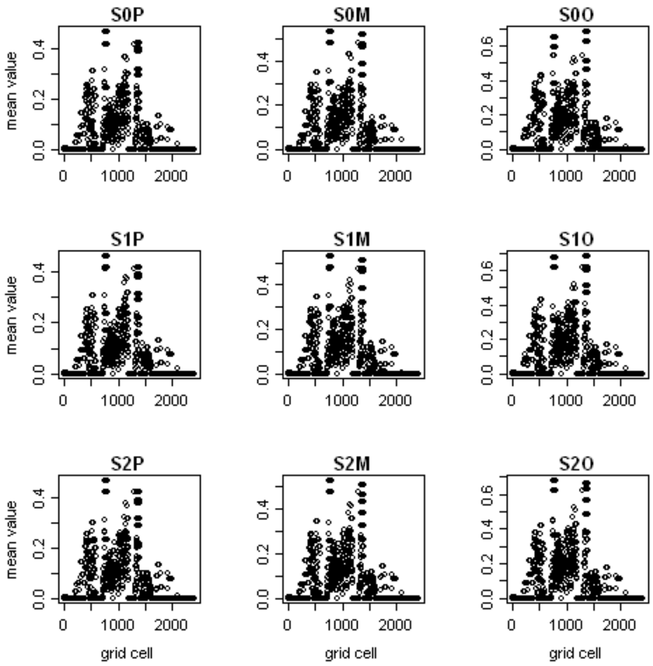


Figure 6.2.29: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for saurids under status quo management for each combination of development scenario and model specification.

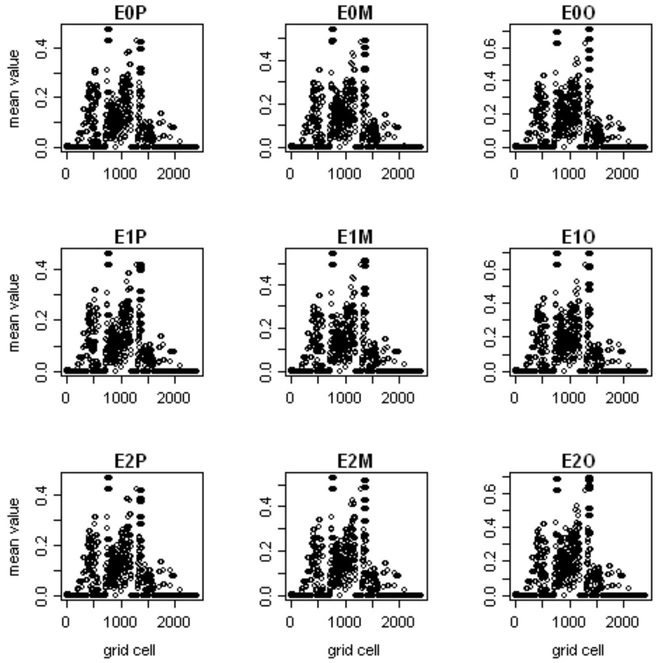


Figure 6.2.30: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for saurids under enhanced management for each combination of development scenario and model specification.

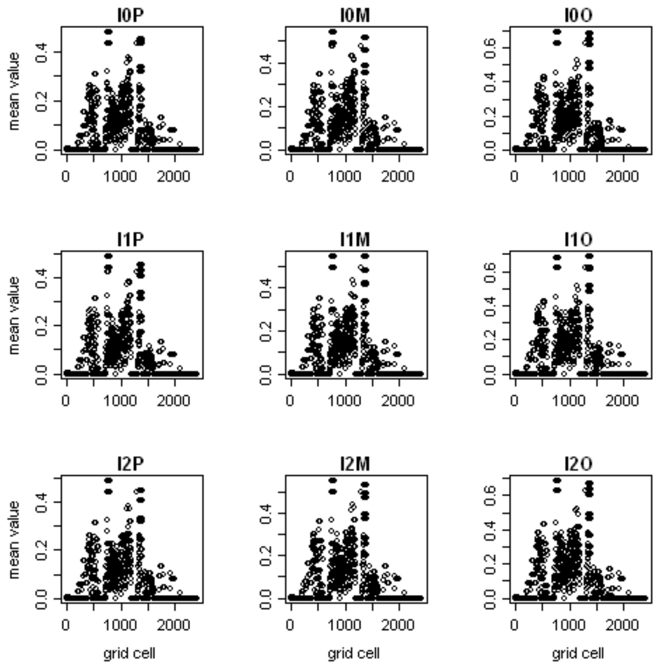


Figure 6.2.31: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for saurids under integrated management for each combination of development scenario and model specification.

6.2.11 Seagrass

There are no significant differences among any of the cumulative distributions (see figures B.61 to B.63 in Appendix B), histograms (figures B.64 to B.65) or average biomass plots (figures 6.2.32 to 6.2.34 below) for the fine scale relative biomass of seagrass under any of the development scenario, model specification, management strategy combinations.

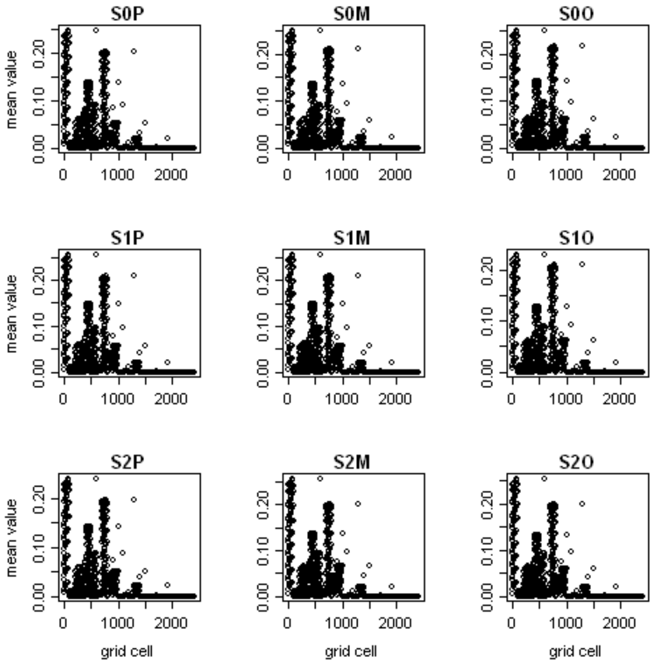


Figure 6.2.32: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for seagrass under status quo management for each combination of development scenario and model specification.

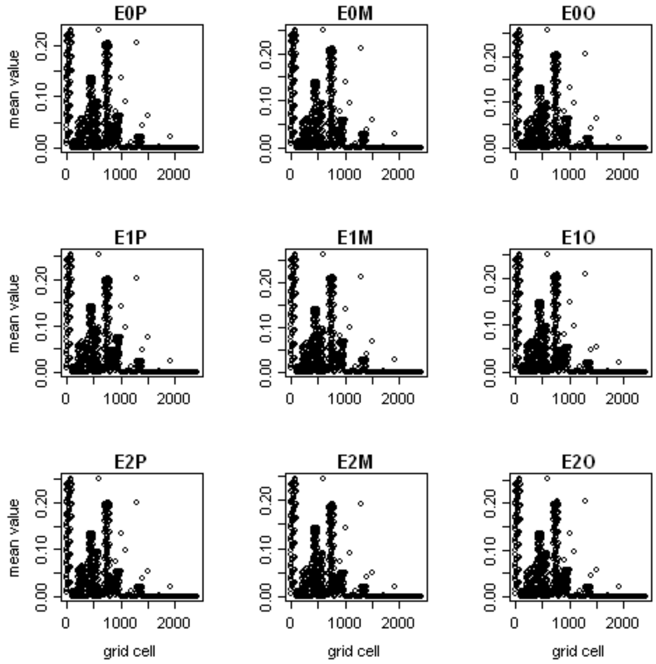


Figure 6.2.33: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for seagrass under enhanced management for each combination of development scenario and model specification.

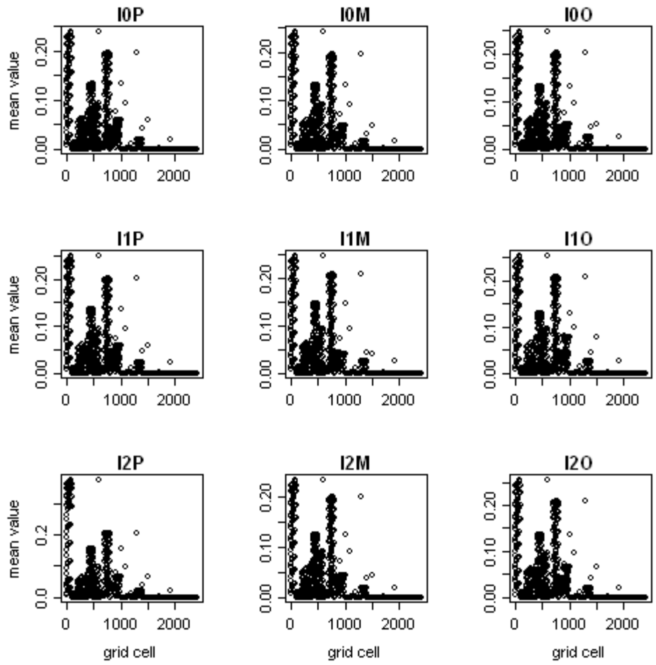


Figure 6.2.34: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for seagrass under integrated management for each combination of development scenario and model specification.

6.2.12 Sponge and reef habitat

The cumulative distributions for the relative biomass of sponges and reef habitat indicate significant differences between the alternative model specifications (figures B.67 to B.69). Consideration of the average biomass plots also indicates a marked difference between the distributions under the alternative management strategies (see figures 6.2.35 to 6.2.37 below). In all cases the relative biomass of the sponge and reef habitat peaks mid shelf, tailing off inshore (due to the sediments there) and again in deeper water. The difference between the model specifications is due to an increase in relative biomass overall, and especially in deeper waters, under the increasingly-optimistic model specifications. This is mainly a reflection of the respective vulnerabilities to fishing and the realised rates of recovery. The difference between the management strategies is due to the location of the biomass peaks in each case. Under status quo management the peak is along the southern edge of the fished area. In contrast, the distribution under the integrated management strategy is more even, though in some cases it does still peak in the areas of hard bottom (e.g. through Barrow Island, the Monte Bellos and the Dampier Archipelago). Under the enhanced management strategy the peaks are closer inshore, with the offshore areas being depressed much further than they are inshore, which produces a stronger inshore-offshore gradient than in the other strategies.

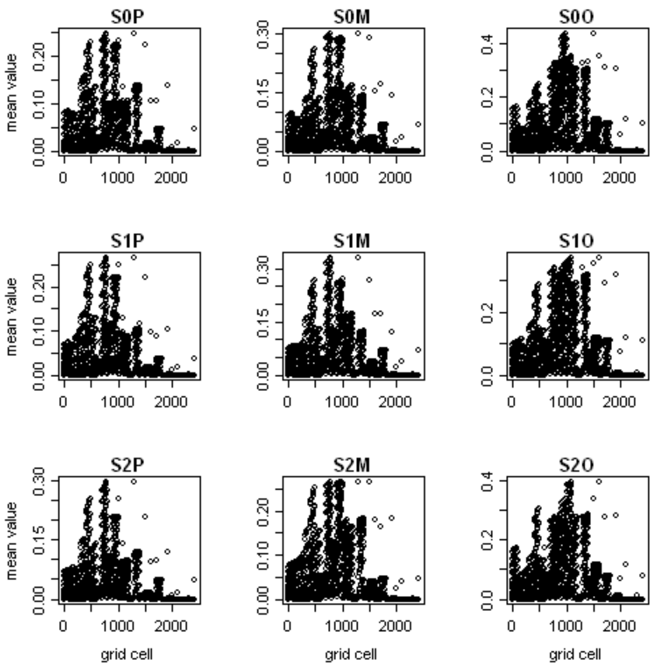


Figure 6.2.35: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for sponge and reef habitats under status quo management for each combination of development scenario and model specification.

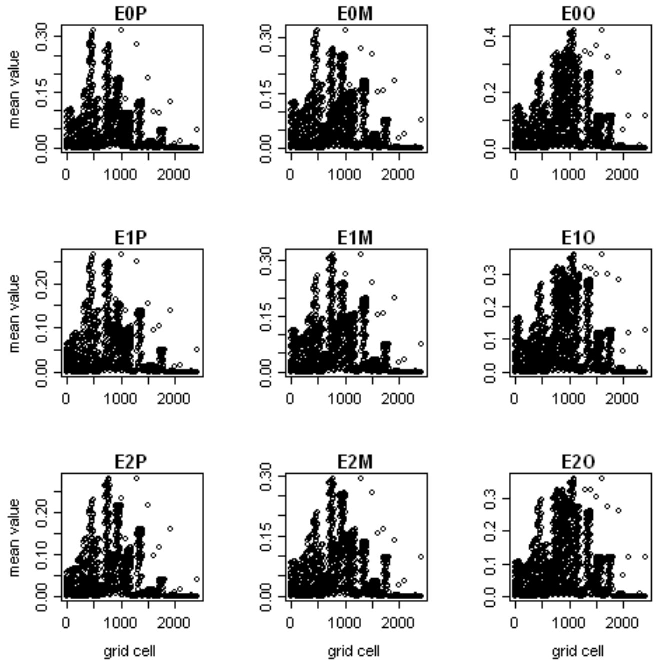


Figure 6.2.36: Average fine -cale relative biomass per cell (ordered inshore to offshore, west to east) for sponge and reef habitats under enhanced management for each combination of development scenario and model specification.

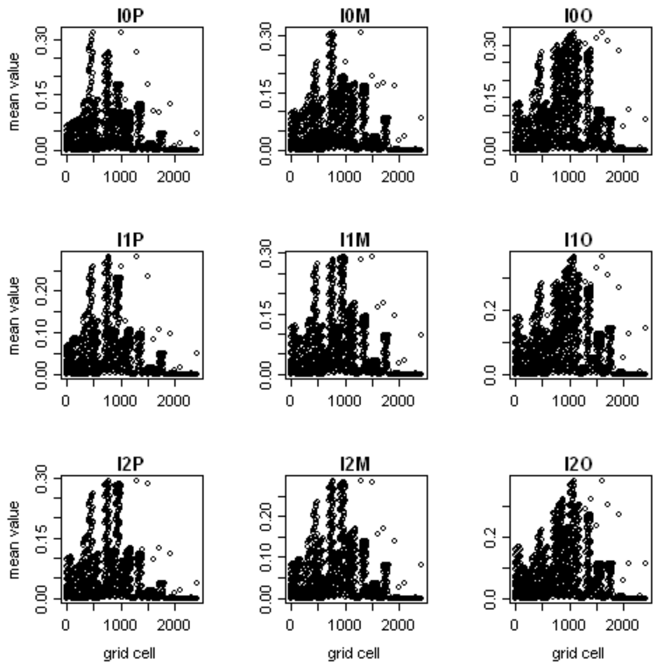


Figure 6.2.37: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for sponge and reef habitats under integrated management for each combination of development scenario and model specification.

6.2.13 Mangroves

According to the relative biomass distributions of the mangroves represented in the cumulative distributions of figures B.73 to B.75, the frequency histograms in figures B.76 to B.78 and average biomass plots given in figures 6.2.38 to 6.2.40, there are no differences among any of the development scenario, management strategy and model specification combinations.

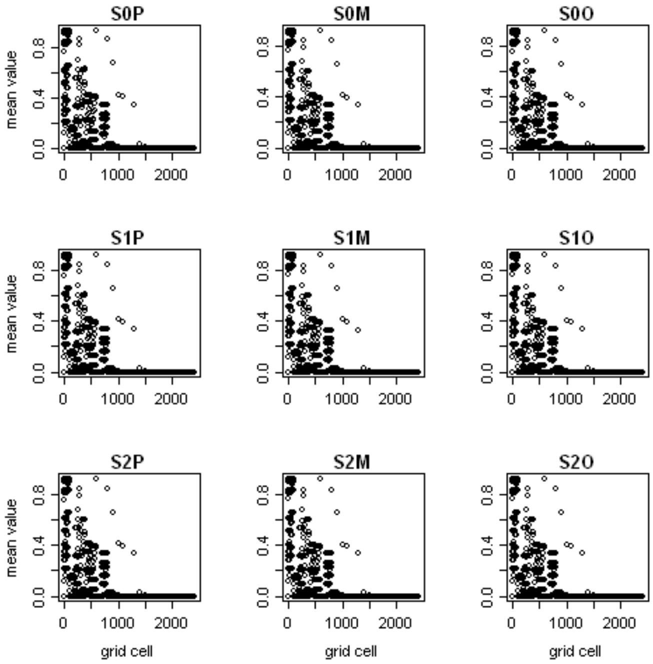


Figure 6.2.38: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for mangroves under status quo management for each combination of development scenario and model specification.

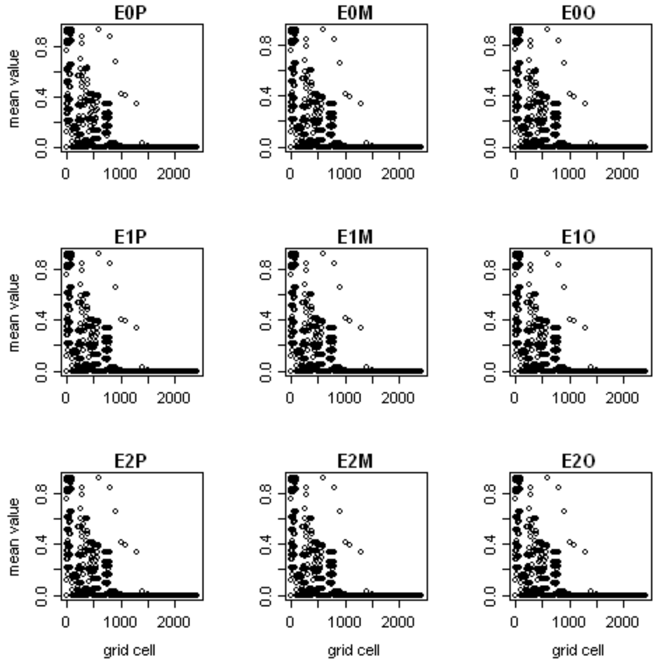


Figure 6.2.39: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for mangroves under enhanced management for each combination of development scenario and model specification.

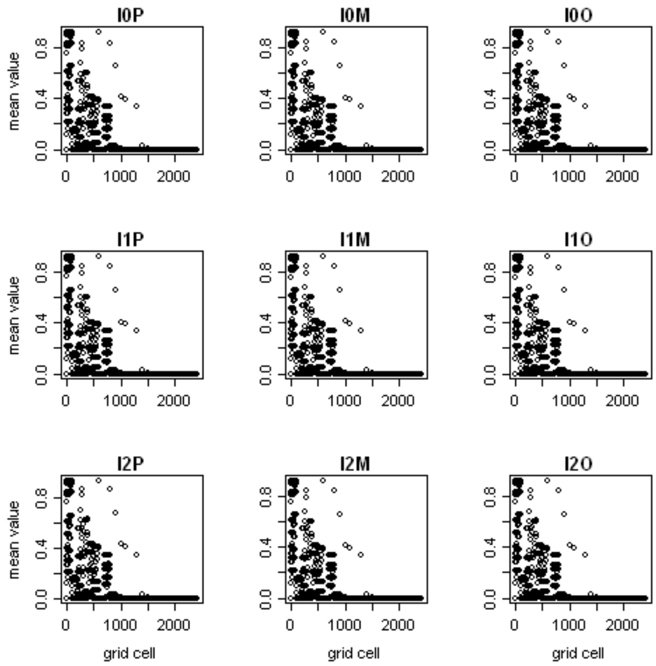


Figure 6.2.40: Average fine scale relative biomass per cell (ordered inshore to offshore, west to east) for mangroves under integrated management for each combination of development scenario and model specification.

6.3 Implications of spatial dynamics for management

Within the projection period of 15 years, distinct patterns in the spatial distributions of flora and fauna emerge from the MSE simulations across model specifications:

- prawn distributions are more patchy under the pessimistic specification and, as biomass increases with more optimistic interpretations, they become more evenly distributed. This pattern also characterises the finfish species, including sharks;
- the remnants of the turtle population are concentrated offshore under the pessimistic model specification but are closer inshore under the optimistic specification;
- sponge and reef habitat suffer greater depletion offshore under the pessimistic specification and recovery under the optimistic model tends to be greater in offshore and mid shelf areas; and
- mangroves and seagrass maintain their distributions across model specifications.

These patterns all make sense from an ecological viewpoint. What they reflect ecologically is that depletion occurs in the areas of greatest pressure. When the system is not particularly productive the remnant populations are only found in the most favourable habitat. Under more productive conditions the greater biomass spills out into more marginal habitats, leading to more even distributions.

The impact of development scenario on spatial distributions of flora and fauna is much less marked than that of model specification. Indeed, changing the development scenarios makes virtually no difference. This is because development scenarios present only limited local-scale pressures and so the system is unaffected at the regional scale. The most significant impact is at fine scales on mangroves, which are affected directly in the vicinity of industrial developments. From a management perspective, fortunately, these impacts are localised and in many mangrove forests there is steady recovery.

Finally, the impact of management strategy on spatial distributions of fauna and flora is clearest when comparing the status quo and integrated management strategies. Broadly, there is very little impact of management strategy on the spatial distributions of prawns, mangroves and seagrass. More marked is the impact of management strategy on the spatial distributions of targeted finfish, sponge and reef habitat, sharks and turtles.

Under the status quo management strategy the populations of sharks and targeted finfish become depleted, with the distribution of the remnant populations making it appear as if the population has been displaced from fishing grounds to outlying areas. Also under this strategy, sponge and reef habitat contracts to the mid shelf area, again away from the trawl fishing zones, and turtles retreat to offshore areas. As with the finfish this does not represent intelligent evasion, but rather a shift in the centre of gravity as those parts of the populations overlapping fishing grounds are stripped away (primarily by trawl fisheries). Enhancement and integration of management leads to more even spatial distributions of these biota, although for different reasons: it is due to a total reduction in effort for integrated management, and a shift of effort for the enhanced management strategy. Turtle populations recover inshore and become more evenly distributed. Sharks and targeted finfish also become more evenly distributed, although they remain relatively more concentrated outside fishing zones. Sponge and reef habitat also recover in a less patchy distribution, recolonising substrate in deeper water, particularly when the system is modelled as highly productive.

7. CLUSTER ANALYSIS OF COARSE SCALE SPATIAL OUTPUT

The relative biomass for each of the 27 MSE combinations (strategy-scenario-specification) was evaluated using the hierarchical cluster analysis, with complete linkage, in the R software package (R Development Team, 2003). Basically, this clustering algorithm uses a set of dissimilarities for the objects being clustered (i.e. the distance between the objects in multi-dimensional space) to find groups that clump together. Initially, each object is assigned to its own singleton cluster (i.e. the tips of the branches) and then the algorithm iteratively joins the two most similar clusters until there is just one cluster containing all of the objects (the root of the dendrogram). The “complete” method used means that the focus is on finding compact spherical clusters. The orientation of the branches in the tree (what is left and what is right) can also be informative. The R software package uses the convention that the subtree (branch) which represents the tighter cluster is always positioned on the left.

The purpose of such a cluster analysis is to check the consistency of simulation output and to detect any major flaws in implementation of the MSE framework or any of its components.

Considering all the cluster trees produced, there are some large-scale structures that are common over many of the MSE combinations. Using this cluster analysis it is possible to identify three basic tree types:

- pessimistic system state – showing a strong inshore-offshore split, sensitivity of the vertebrates to the remaining distribution of habitat, and correlation of the dynamics of the habitat-dependent species and the more generalist saurids (this relationship exists because they are responding to the environment in inverse ways).
- the optimistic system state – again showing the strong inshore-offshore split; habitat dependency and condition (which are much more evident in this set).
- the mixed system state – similar in form to the optimistic, but with considerable variation, particularly inshore.

These basic tree types conform quite closely with the pessimistic, base case and optimistic model specifications. This improves the confidence one might have in the implementation of the MSE framework. The cluster analysis verifies that the ecological integrity of NW Shelf region is captured well and is robust to the defined alternative management strategies and development scenarios. An example of each of the basic tree forms is given below, and all trees can be found in Appendix C.

7.1 Pessimistic system state

The majority of cluster trees in this section are from MSE combinations using the pessimistic model specification. The only exception is the tree from the case with the enhanced management strategy, 2-pulse development scenario, and base case model specification case.

All trees in this set have the mangroves, seagrass and prawns in one arm (figure 7.1.1) and the other taxa (sponges, sharks, turtles, lethrinids (leth), large lutjanids (llut), small lutjanids (slut), nemipterids (nemip), saurids (saur) and *Lutjanus sebae* (lsebae)) in the other arm. The structure of the left arm is identical in all cases, with mangroves branching off first, then seagrass, with the prawn groups clustering together at the tip of that arm. Details in the right arm are more mixed. Sponges and turtles are grouped together; as are lethrinids, sharks and nemipterids; with the remaining groups in a single lower order branch (large lutjanids and saurids typically grouped together and small lutjanids and *L. sebae* usually making up the other pair).

This cluster tree structure suggests that there is a strong inshore-offshore divide with little ontogenetic or migratory "cross contamination". It also indicates that while the vertebrate stocks are being influenced to some degree by the state of the reef and sponge bed habitat, the effect is being expressed in different ways. The nemipterids and lethrinids are distributing quite similarly (despite having very different habitat requirements) while the remaining habitat-dependent finfish form a single group. Surprisingly the saurids, which have little habitat preference, are also in this group. This is due to two factors. The first is that the habitat is so poor in general that the habitat dependent fish tend to move between extensive patches of poor habitat. Secondly, and probably more importantly, the saurids are depleted by fishing. They are not impacted to the same degree as other groups (and so can come to dominate catch composition), but they are still relatively depleted on the trawl grounds and so their overall relative distribution shows the same peaks along the edges of the fished grounds that are associated with the habitat-dependent target species.

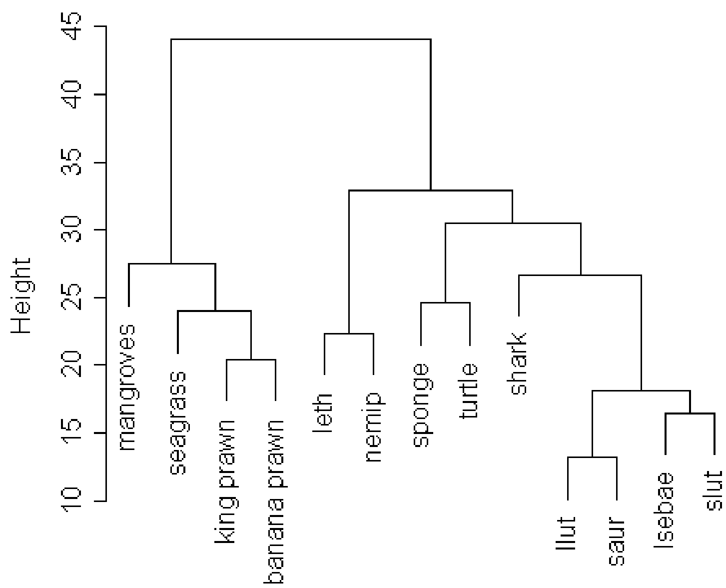


Figure 7.1.1: Representative dendrogram for the pessimistic system state set of clustering trees (taken from the status quo management, 0-pulse development, pessimistic model specification case).

7.2 Optimistic system state

The second set of clustering trees is drawn almost exclusively from the MSE combinations using the optimistic model specification. The only exceptions are for the cases with enhanced or integrated management, the 2-pulse development scenario and base case model specification.

In all cases in this cluster set, the mangroves, seagrass, turtles and prawns are found in the right arm; nemipterids (nemip), sharks, lethrinids (leth), small lutjanids (slut), large lutjanids (llut), saurids (saur), *L. sebae* (lsebae) and sponges are all in the other (left) arm (see figure 7.2.1). Once again the arm containing the coastal groups (prawns, seagrass and mangroves) is stable across cases. For the optimistic model specifications (figure 7.2.1 (a)), the seagrass and turtles are paired and the mangroves are grouped with the two prawn species, the latter occupying the terminal positions of the final branch in the right arm. In the two trees from the base case model specifications (figure 7.2.1 (b)) turtles are the first branch of the right arm, then mangroves and seagrass, with the prawns in the final (tight) cluster.

The clustering in the left arm is more variable. While some pairs are (reasonably) stable in this arm, the location of the lethrinid and sponge groups varies. In contrast, the nemipterids and sharks are consistently paired together, as are the large lutjanids and *L. sebae*; with small lutjanids typically grouped with the saurids. This pattern among the shelf species seems to be due to their habitat preferences and the state of desirable habitat such as sponge beds and reefs.

The form of tree clustering in this set reinforces the impression of disjunct inshore and offshore systems given in the pessimistic set above. While sponges are found in the inshore branches of some of these trees, due to their preference for shallow waters with suitable substrate, they tend to be grouped with the offshore finfish that are dependent upon them for habitat. This dependency does not lead to a universal grouping because the habitat is of sufficient quality over a wide area to allow some freedom for fish movement. Again the saurids are the interesting group, as they have little habitat dependence, yet they are strongly paired with the mildly habitat-dependent small lutjanids. This similarity in distributions appears to be due to the lack of habitat preferences for the saurids and relaxation of constraints for the small lutjanids (due to the prevalence of good quality habitat in preferable water depths) leading to free roaming movements (and broad distributions) for both groups.

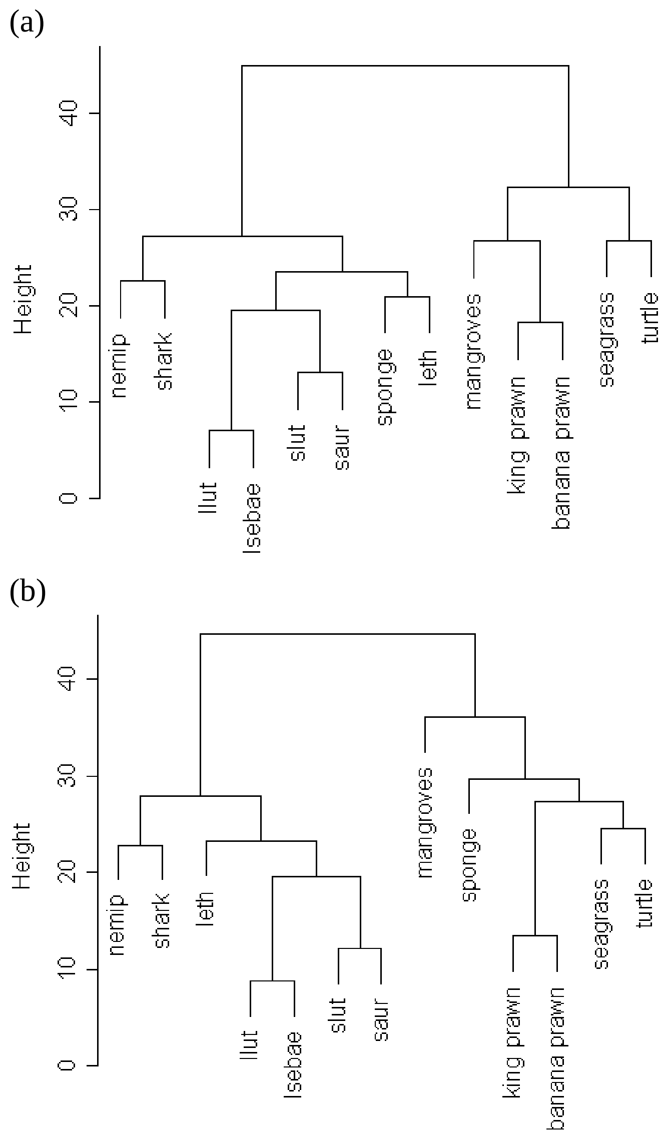


Figure 7.2.1: Representative dendrograms for the optimistic system state set of clustering trees: (a) is an example under the optimistic model specification (taken from the enhanced management, 0-pulse, optimistic model specification case) and (b) is the tree from a base case model specification (taken from the enhanced management, 2-pulse development scenario, base case model specification).

7.3 Mixed system state

All of the cluster trees in this set come from pessimistic or base case model specifications, but every scenario and management strategy option is represented. In all cases the right arm of the tree is made up of the habitat defining groups (mangroves, seagrass and sponges) along with turtles and the prawn species (figure 7.3.1). The species in the left arm consist of lethrinids (leth), large lutjanids (llut), *L. sebae* (lsebae), small lutjanids (slut), saurids (saur), nemipterids (nemip) and sharks. The right arm is more variable in this set than in the other sets. In all cases the mangroves are the first branch in the arm, followed by one of the other habitat-defining groups, and the prawns are the terminating (lowest-order) branch of this arm. Turtles are also typically found on a branch close to the seagrass branch.

In this case the right arm is quite stable. The nemipterids and sharks are paired and branch off first on this arm, followed closely by lethrinids, which are in their own branch. The final lower-order branches consist of two pairs: the saurids and small lutjanids in one, and *L. sebae* and the large lutjanids in the other. This is a much harder cluster tree structure to interpret. The inshore-offshore split is a persistent feature, showing the disjunct nature of the system irrespective of its state. Beyond that, the general tree structure seems to be governed by depth preferences. While habitat preferences seem to be governing the general pattern within the finfish and for the turtles and prawns, the distribution of the other groups seems to be governed by their response to depth (via light attenuation, substrate presence or suitable depth ranges). This reinforces the ecological notion that the distribution of any group is not usually a simple single-factor issue.

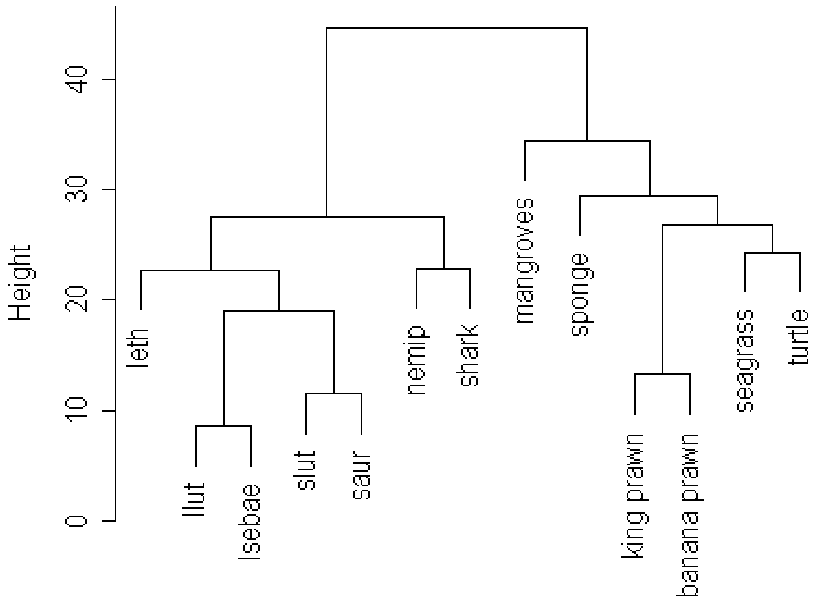


Figure 7.3.1: Representative dendrograms for the mixed system state set of clustering trees (taken from the status quo management, 0–pulse development scenario, base case model specification).

8. A NOTE ON THE ASSESSMENT MODEL

One result that is noteworthy, but does not fit in easily in the MSE comparison above, is that when using the current fisheries stock assessment protocol it is possible for the assessment model to become ill informed and diverge from the actual stock size (as defined in the biophysical model). To illustrate this finding, consider the case when the stock assessment is applied under the base case and pessimistic model specifications for the status quo and enhanced management strategies. Under the status quo strategy the assessment uses commercial catch data only, but under the enhanced strategy, fisheries independent survey data are used to supplement the commercial catch data in the assessment.

A comparison of the biomass estimates of *Lutjanus sebae* produced by the assessment model versus the actual biomass trajectory in the operating model in these four cases is given in figure 8.1 to 8.4. In each case the first stock assessment performed in the simulation is in the year 2000. This assessment is based entirely on the historical catch and effort data and not on data generated from the fishing boat agents in the model. As this first assessment is based solely on historical catch data, the biomass estimates are identical across model specifications and management strategies. Note that, even at this stage, the stock assessment estimate is closer to the actual biomass under the base case model specification than the biomass under the pessimistic specification. This suggests that the performance of the assessment model may be system dependent.

Looking at the subsequent assessments (those using catch data generated by the fishing boat and survey agents), under the base case model specification, the use of fisheries independent data in the assessment (i.e. the enhanced management strategy) results in estimates that better match the actual biomass trajectory from the operating model. The initial estimates are progressively tightened with each extra year of simulated data and converge to the actual trajectory. In contrast, the series of assessments given without fisheries independent data do not converge and certainly do not progressively improve in their information content.

The situation is only worse under a pessimistic model specification. In a system with low productivity, the status quo management strategy consistently over-estimates the actual biomass. The addition of fisheries independent data under the enhanced management strategy results in the biomass estimates from the assessment model achieving a significantly closer fit to the actual trajectory. Even then the assessment model still over-estimates the projected biomasses, making them very unreliable predictions of future stock status. In all, this makes the assessment model results (and any management based upon it) over-optimistic in ecosystems with low productivity.

It is unlikely that the ecosystem is as unproductive as given by the bounding pessimistic model specification. Nevertheless, a cautionary note must be drawn regarding the use of assessment models, such as the one discussed here, without fisheries independent data. The introduction of a vessel survey, which provides additional information on stock status, produces a substantial improvement in the stock assessment estimates. Whether the fishery is of sufficient economic importance to warrant the expense of such a survey is a matter that deserves wider discussion.

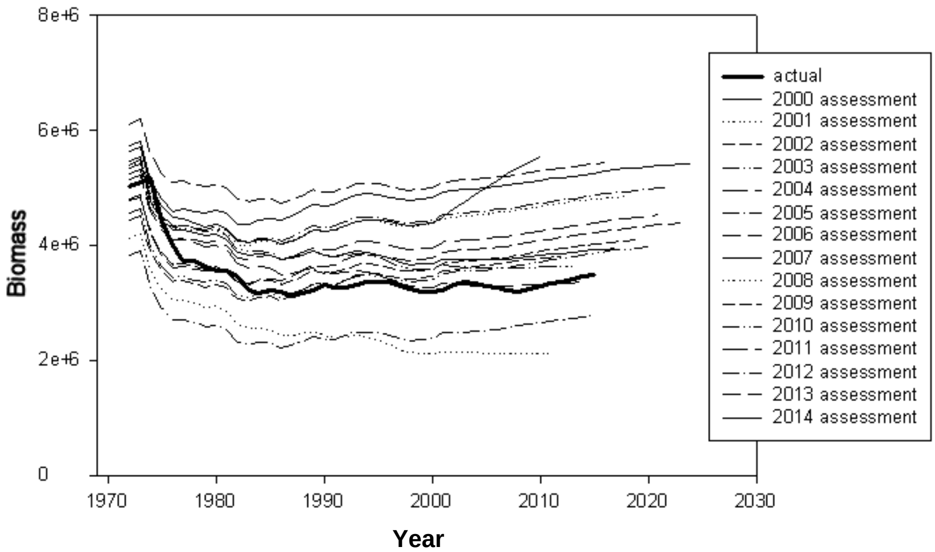


Figure 8.1: Biomass trajectories of *Lutjanus sebae* from the stock assessment model and operating models for the status quo management strategy under the base case model specification.

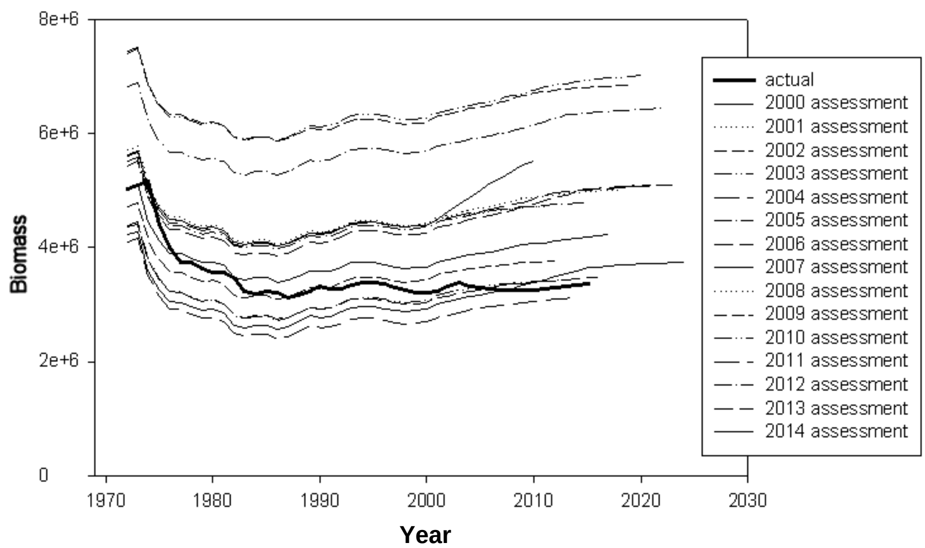


Figure 8.2: Biomass trajectories of *Lutjanus sebae* from the stock assessment and operating model for the enhanced management strategy under the base case model specification.

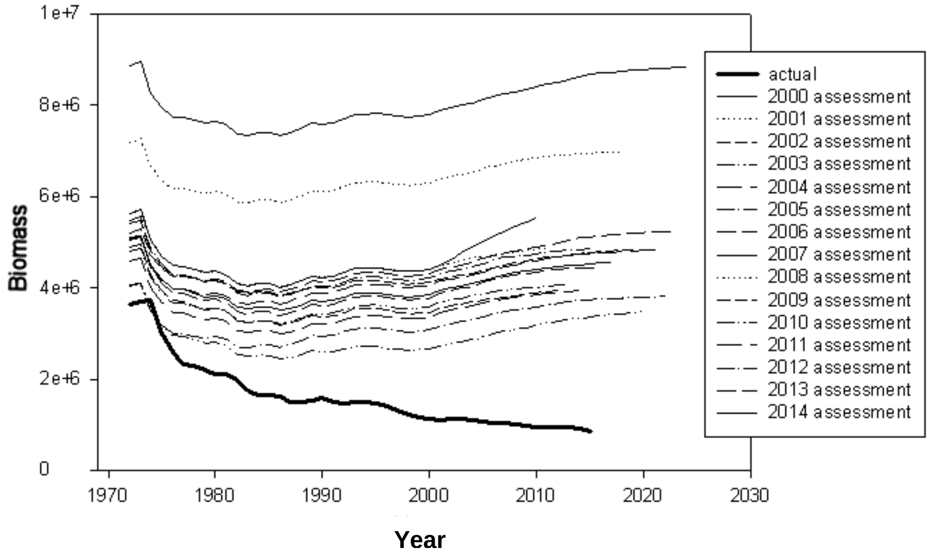


Figure 8.3: Biomass trajectories of *Lutjanus sebae* from the stock assessment and operating models for the status quo management strategy under the pessimistic biomass model specification.

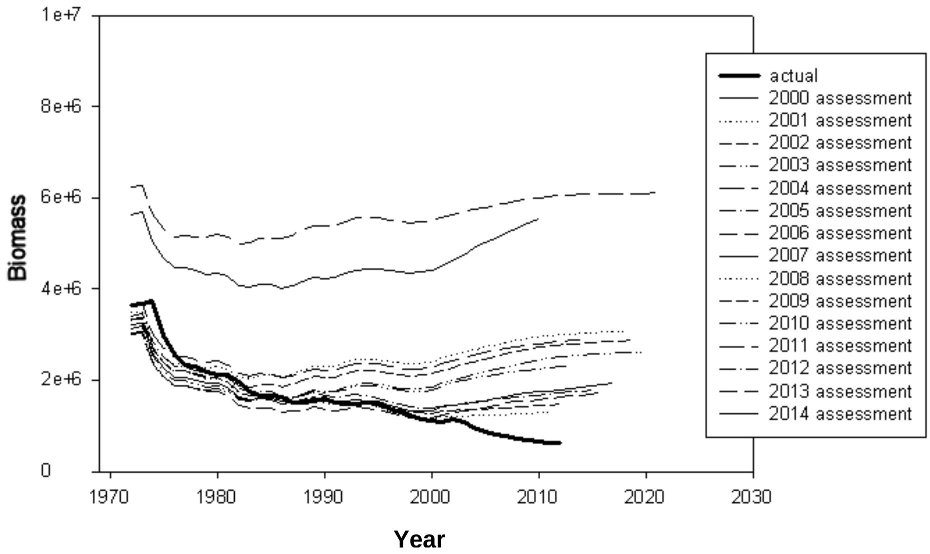


Figure 8.4: Biomass trajectories of *Lutjanus sebae* from the stock assessment and operating models for the enhanced management strategy under the pessimistic biomass model specification.

9. DISCUSSION AND SUMMARY

This concluding section is included to present an overview of the main findings of the MSE for the NWSJEMS. The discussion is divided into five main topics related to commercial fisheries, social values, conservation, management trade-offs and some shortcomings of the study.

9.1 Commercial fisheries

As the reader is aware, there are five commercial fisheries in the North West Shelf region. There are three prawn fisheries (Exmouth, Onslow and Nickol Bay), a finfish trawl fishery and a trap fishery. These fisheries differ in their responses to management strategies, especially in regard to conservation measures.

9.1.1 Fishing effort

With status quo and enhanced management strategies there is little difference in absolute total trawl effort, the magnitude of which is constrained by the stock assessment and decision procedure adopted by the fisheries management authority (FMA) and the absolute underlying biomass. Management response is really only limiting if biomass estimates are pessimistic.

The enhanced management strategy, which involves a fishery-independent survey, leads to a redistribution of effort rather than any significant reductions in overall effort. This means that there are localised effects on stock size and the extent of benthic habitat. There are also some CPUE benefits, but overall (and especially in the long-term) there is no discernible gain from enhanced management as the effort is simply displaced to other areas and a result of the decision procedure and the overall stocks do not benefit from significant recovery. If the individual finfish stocks were more localised and there was the ability to instigate more broad-sweeping changes in spatial management (e.g. close zones other than zone 3) these results may change.

The trap fishery, at its current level, has little impact, especially relative to the trawl fisheries, and so remains unchanged in all circumstances.

The prawn fishery management regime of only opening and closing areas, rather than directly controlling effort or catch quotas, means that the management tends to be very blocky in effect (almost an on/off form). Thus the prawn fisheries are most heavily impacted by effort reductions when conservation concerns, regarding habitats and species such as turtles, are explicitly considered. However, this conclusion is based on sparse data regarding the actual interactions and more information is required to verify that these conclusions match the real situation on the North West Shelf. Existing information in documents such as the ESD assessment (WA Department of Fisheries, 2002) may not faithfully match reality. While that document states that slow trawl speeds mean that there will be little potential threat to turtles posed by NWS fisheries, the simple fishing rules employed in the model, for example, suggest that turtles can be caught when trawling at four knots and that juvenile turtles suffer mortality when they pass through fishing nets at this speed.

The integrated management strategy as implemented here leads to a more conservation centred approach, leading to substantial reductions in trawl effort for finfish and prawns, unless the system is highly productive. This reduction in effort leads to better catch composition, but lower absolute catch, and this can impose a high opportunity cost on fishers. If the system is productive, however, the integrated management strategy performs well, as it can lead to more stable returns (for the finfish trawlers) or higher returns (for the prawn trawlers) than do the other strategies.

The cost structure available for use in this study suggests that the prawn fishery is more lucrative economically than the finfish trawl fishery. Arguably, a strategy that presents a compromise between the increased rate of return associated with recovered stocks and the loss of revenue associated with the almost complete cessation of fishing in the integrated management strategy might provide a real boon to the NWS finfish trawl fishery.

9.1.2 Catch and CPUE

Trawl catches dominate the total catches for all combinations of management strategy, development scenario and model specification. It is clear from the results for catch and CPUE indicators that there are strong implications of the alternative model specifications for commercial viability and that there will be potential trade-offs of significance between CPUE and absolute catch, depending on the form of explicit management objectives that are put forward within the fisheries and conservation sectors.

Integrated management leads to higher CPUE (but often only marginally) for the preferred species, and lower CPUE for the secondary and bycatch species, but with greatly reduced absolute catches of all species. Despite the improved practices and efficiency put forward under the enhanced strategy, there is often little to distinguish the mean enhanced and status quo strategies. Catches may be marginally higher for the preferred species (and slightly lower for the secondary and bycatch species) under the enhanced strategy, but only when the system is highly productive (i.e. under the optimistic model specification). There is not much to recommend the status quo management strategy however, as it tends to lead to highly variable, and declining, catches and CPUE, particularly when the ecosystem is less productive or when it is highly susceptible to incidental impacts of fishing.

The trap fishery has much less of an impact on the system, although trap catches and CPUE are much more variable than trawl catches and CPUE. This is perhaps the strongest feature of the trap fishery’s trajectories. CPUE for the preferred species is tighter the more productive and robust the system, but the CPUE of the secondary and bycatch species always remains high. This variability is not ameliorated under the alternative strategies. There is some evidence that when the system has low productivity and is vulnerable to the impacts of trawling operations, trap fishery catches and CPUE are higher under the integrated management strategy, particularly late in the time series and especially for the preferred species, but the variability remains unaffected. The reduced level of impact on the other system components can make the trap fishery attractive, especially given the potential for high economic costs when the state of other system components causes a reduction in effort for the trawl fishery.

The prawn fisheries appear to be more economically viable under the crude indices available in this study. This does not necessarily provide fishers with stable incomes or make them easily managed. The dependency of banana prawn dynamics on rainfall means the catch trajectories for this species under the various model specifications overlap in the “poor years” and are only differentiated in the good years. The catches of king prawns, however, are more clearly separable across the model specifications. In productive systems there is little difference between the CPUE predicted under all of the management strategies. For systems at lower levels of productivity the catches under integrated management are lower than for other strategies and, in this case, they are almost at negligible levels. Banana prawn CPUE is effectively the same under all strategies, although potentially more variable under the integrated management strategy. This reinforces the potential tension between fisheries and conservation management objectives. Economically fisheries could potentially benefit from stock recoveries that occur due to reductions in fishing effort or fishery zone access that results from management actions which are triggered by conservation objectives. Catches with a higher proportion of high-value species may go a long way to mitigating the reduction in total catch. This is not a given, however, as annual net revenue is also dependent on the overall state and productivity of the system. In truly integrated management, such issues must be faced directly and transparently, often calling for strategies that represent compromises between the various sectors.

Poor productivity and sensitivity to disturbance (i.e. the pessimistic model specification) leads to a system that is most suited to those species that don’t have strong habitat requirements and which are capable of adjusting well to changing habitat conditions. This in turn has implications for species composition under the various strategies. Under the status quo management strategy the increase in low-value species is reflected in their higher proportion of catch. In the enhanced strategy a more even catch composition is maintained, mainly by avoiding severe depletion of any one location. The fact that stocks as a whole are not seeing a drop in fishing pressure, however, means that catch composition can be highly variable: low-value species can still make up a significant proportion of the catch under enhanced management because the total stock patterns are still much the same as under status quo management.

Under the integrated management strategy absolute catch of low-value species is high for both pessimistic and optimistic model specifications: in the former because they make up more of the biomass and in the latter because all biomasses are higher. The relative proportion of the catch made up of low-value species is lower for the integrated strategy than for the other strategies, however. There is little difference in the proportion of the catch made up of high-value species between the model specifications under status quo management, but under the enhanced strategy solid returns for the high-value species occur only when the system is more productive. Economic performance can drop significantly when environmental conditions are poor. The catch of high-value species is only substantially higher with the optimistic model specification under the integrated management strategy. While the absolute catches are lower under the integrated management strategy (showing little difference among the different productivity and system sensitivity levels) the high-value to low-value species ratio shows that the catch composition tends much more toward the high-value species when this strategy is used.

9.2 Social values

While there are relatively few people on the NWS they (and the public at large) can form strong opinions on system state based on the few indicators they are familiar with. Recreational fishing is perhaps the leading form of recreation on the NWS. It typically occurs within 50 km of boat ramps, jetties and wharves. Catches of the preferred species are higher under the integrated management strategy for the pessimistic and base case model specifications, but there is little difference in preferred-species catches among management strategies for very productive and resilient systems. There is also little variation in recreational catch of secondary species under all circumstances. The absolute value of the recreational catches of the preferred species is lower in less productive and sensitive systems, though the opposite is true for the secondary (less habitat associated) species, which exhibit habitat indifference. As trophy fish are a prominent indicator for recreational fishers, it is likely that this important stakeholder group would see significant benefits from a switch to something like the integrated management strategy.

Risk of collision between vessels, both inside and outside the ports, is a major management concern within Australian waters. This study found collision risk increases with the number of production pulses associated with alternative development scenarios. While management strategy has little impact on the chance of collision outside the ports, the introduction of an additional navigation channel significantly decreases the risk of collision within and at the mouth of the ports. This would come at the cost of local degradation in environmental values due to dredging.

Dredging impacts on local habitat quality in ports are small, mainly because natural environmental conditions on the NWS give rise to turbid waters. Despite this, recreational fishermen, for example, would notice the effect of increased dredging. There is a strong trade-off between the immediate decline in value of recreational fishing (due to the degradation of the habitat as a result of dredging) and the long-term risk of catastrophic degradation should a vessel collision occur (a risk that is drastically reduced by the dredging of an overflow channel).

The last management concern of resource managers addressed in NWSJEMS is acid sulphate leaching from disturbed soil, which can be a significant environmental issue in Western Australian coastal regions (Department of Environment and Conservation, 2006). Our results suggest however, that, overall, the NWS doesn’t have much to fear from acid sulphate leaching because soil disturbances are localised and restricted to areas that have human settlements. Locally, however, acid sulphates could become a significant persistent issue, particularly if development is continual or undergoes pulses that are not sufficiently separated in time and space to allow recovery in the short to medium term.

9.3 Conservation

Biomass of marine flora and fauna is one of the most widely accepted indicators of the health of the regional marine ecosystem (Fulton et al. 2006a). The biomass of a suite of indicator species, and the relative contribution of these species, provide a meaningful specification of the biodiversity, state and structure of the region. In this section we examine the results for a selection of species.

The environmental influences on banana prawns means that they are in their time series trajectories, and are not as clearly differentiated across management strategies as are the king prawns. As such they are of less use in defining system health than they are in simply indicating system state. More is known of finfish dynamics on the NWS and this has allowed for verification as a regional ecosystem indicator. Of the management strategies considered, the integrated management strategy leads to higher finfish biomasses, particularly for the main target species in systems that are specified as pessimistic. The finfish biomasses are less sensitive to management strategy in more productive (optimistic) systems than are the biomasses of the secondary and bycatch species.

While management strategy has a much smaller effect on the shark biomass trajectory, management has a significant effect on the turtles, which only see recovery under the integrated management strategy when the system is less productive or less robust. Work with other model formulations indicates that this result may be somewhat model dependent. Nevertheless it does serve to highlight that a firmer understanding of these species, based on a long-term data collection program, is a necessity if the ecosystem is to be managed well and confidently.

Once that confidence is in place the recovery of protected K-selected species under integrated management (reflected in the biomass ratios) shows the potential to move away from sector-specific management. The ratios show that the system is more heavily weighted towards K-selected species under the integrated strategy than under other strategies, particularly for systems with low productivity and low sensitivity to disturbance (i.e. the pessimistic model specification). This makes such ratios useful for assessing objectives stated under policies such as the Federal EPBC act.

The effect of the disproportionate recovery of conservation species also highlights some interesting conservation quandries. This skew in structure produced by conservation of charismatic species is reflected in the diversity indices: positively or negatively, depending on the degree of weighting for evenness versus richness. Simple indices indicate improvement because many species appear to be rebounding to starting positions, while higher-order diversity indices indicate declining biodiversity due to the disproportionate rates of recovery and the influence of environmental forcing. This contradiction would need careful interpretation and communication, or interest groups could point to it as a failure to reach conservation objectives.

The disjointed nature of the NWS ecology and rather restricted extent of human sector interactions in the region imply that there are few examples of real cross sector clashes. Despite this, illustrative examples can be found. Potentially the most interesting interaction of multiple sectors, alternative management strategies, distinct development scenarios and competing model specifications for stocks (inshore and offshore) is shown through the biomass ratio of r to K selected species under the enhanced versus status quo management strategies. Under higher human population levels the enhanced strategy leads to a high proportion of r-selected species in the long-term. By comparison there is either no difference, or the enhanced strategy may even lead to slightly more K-selected species in the short-term. This is due to a combination of increasing recreational fishing pressure inshore (due to growing human population) depleting inshore stock components, while commercial fishing pressure stresses offshore stock components. As enhanced fisheries management shuffles the commercial fishing pressure around, more of the offshore components are affected, thus preventing overall stock recovery. This leads to pressure from recreational and commercial fishing impact and so higher exploitation of larger K-selected finfish, without any compensating drop in impacts on the “protected” species.

9.4 Management trade-offs

The integrated ecosystem-based management strategies evaluated in the MSE is a small subset of what is possible. Despite this, the suite of 3 by 3 by 3 combinations of management strategies, development scenarios and model specifications has highlighted some important trade-off decisions that need to be made as integrated management of multiple uses is implemented. The most important of these trade-offs are discussed below.

9.4.1 The cost of integrated management

As sectors not traditionally considered in management are brought onto an equal footing with long-managed industrial sectors, it is inevitable that there will be a rebalancing of expectations and focus. Unless this process is handled with care, some sectors will be more heavily impacted than others. For instance, in the integrated management scheme used here, the fisheries saw drastic reductions in operation as a result of conservation objectives related to vulnerable “iconic” species. This has a significant economic impact on individual fisheries operations, though this could have been mitigated by the use of alternative management methods (and by paying some fishers to leave the fishery rather than retaining all at reduced effort levels). Wherever policies, management objectives and management strategies change, there is an opportunity cost involved, and where this falls must be carefully considered before imposing any form of broad cross-sectoral management scheme.

When making decisions regarding the form of integrated management, equally careful attention must be given to the criteria chosen to judge or set objectives. There has always been potential tension between competing sectors (such as recreational and commercial fisheries), but with a move to integrated management these potential conflicts multiply. It is a simple exercise within the MSE framework to show that, in a system like the NWS, if economics is used as the sole decision criterion, then it is quite easy to find a single sector (such as oil and gas production) dominating the decisions made in the region, with all other sectors potentially allocated lower priority. Whether this is considered socially acceptable needs to be addressed transparently and with on-the-ground stakeholder consultation.

Beyond the issue of balancing the interests of multiple sectors there is the simple question of “who pays?” It is conceivable that this form of management will transfer costs among management agencies or among industrial sectors, both through additional monitoring and maintenance of the decision-making infrastructure. How this is best managed, how it is structured (whether it is some form of mandated cooperative interaction or via some form of new purpose-built institution) and how it is funded are open questions, especially given that not all sectors have access to the same resources.

9.4.2 The cost of enhanced management

Whether integrated management is implemented or not, even enhanced sectoral management can be associated with changes in the magnitude of management costs and who bears them. Enhanced fisheries management, for example, involves the collection of fisheries independent data for inclusion in stock assessments. Whether this is reflected by an increase in the reliability of the assessments associated with these data is something that should be evaluated before such data collection begins. The MSE shows that in this case the scientific benefit of the fisheries independent data is extensive (removing bias and problems with uninformative biomass estimates). However, as far as actual industry management is concerned, the increase in management effectiveness may still only be marginal in some circumstances. This may mean that a short-term intensive scientific exercise may be needed to assess the baseline productivity of the system, thus determining whether the inclusion of fisheries independent data will be a net benefit for both fishery and conservation management.

In those sectors that require extra monitoring, whether enhanced or integrated management is implemented, it may be that a short-term intensive sampling exercise can guide the form of long-term management. An example of just such a case is the placement of water quality monitoring stations. If they are placed without considering system hydrodynamics, then they may be located in sites that give erroneous signals or are overly expensive to maintain. Some light may be shed on this issue by MSE simulations without necessarily involving expensive field monitoring programs, especially if local hydrodynamics are well understood.

9.4.3 Short-term reversible damage versus long-term risk

As may be expected the most contentious and delicate trade-offs will occur around human settlements. This is demonstrated by the decreased risk of collision brought by dredging navigation channels to cope with high shipping traffic levels. While this may lead to some localised habitat degradation it may be considered worthwhile because of the avoidance of catastrophic collisions (and spills) that give rise to extensive environmental and economic damage. Fortunately, this trade-off may not be as contentious in areas such as the NWS as it would be elsewhere. The natural highly-disturbed state of coastal waters on the NWS means that the extra dredging may only have a marginal effect on local turbidity and so have only minor impact on local habitat. In less turbid locations the impacts would be greater.

9.5 Some shortcomings of the study

In order to develop the MSE beyond its current prototypical form to the point where it can be used for assisting the formulation and implementation of management strategies in practice, a number of gaps must be filled. In this section a few of these gaps are briefly examined and invite the reader to suggest ways of filling them and to point out additional omissions.

9.5.1 Model shortcomings

The first aspect of this study that can be improved is the model, which has a few notable shortcomings. The first of these gaps is with respect to habitat. For all habitat types the results show more responsiveness locally, although this is overwhelmed by variation at the regional scale. While a fair amount is known about the sponge and reef forming benthos on the NWS, little is known about the dynamics of the other biogenic habitat forming groups. What the crude representations included here demonstrated is that there is the potential for local recovery under the integrated management strategy, but that regional recovery could take considerable time (in the order of decades). Looking at development associated impacts, there is localised depletion of mangroves immediately around human settlements, which is more severe with each development pulse. There is too little information on non-natural perturbation, however, to allow the model to show much differentiation between the effects of the various management strategy, development scenario, model specification combinations on seagrass, macroalgae and mangroves, even locally.

The second shortcoming of the model relates to contaminant impacts. Contaminant feedback controls reduce substantially the impacts of contamination on biota. Moreover, careful placement of buoys may make the monitoring relatively simple and inexpensive. Unfortunately detailed information about the toxicity of contaminants and their uptake and depuration rates for the North West Shelf biota at appropriate ages will be required before stronger conclusions can be drawn from contaminant simulations. Treatment of food-web associated contaminant impacts is also a must in any future study, as these have the potential to make contaminant impacts more far reaching. Similarly, sub-lethal effects may play a significant role in reducing the viability of local populations, either by increasing vulnerability to predation or by reducing reproductive success.

Thirdly, the most effective form of representing species with long and complex life histories (e.g. turtles) has already been addressed by some additional work. Comparison of completely individual-based representations (the standard form reported here) with an age-structure population agent based representation shows quite strikingly that these species must be treated carefully. It is apparent that a good deal of information and specifically formulated models are required to capture the long-term dynamics and many pressures on these species of intense conservation concern.

The fourth model shortcoming is related to the issue with turtles, but is more to do with system understanding and model complexity than with simple model shortcomings per se. To improve the faithfulness of the model to the real environment, more information is required on the following aspects of ecological models:

- interactions of fishing gears (and other processes) with turtles (particularly juvenile turtles); in particular the rate of incidental mortality on turtles that are caught in a trawl (whether they escape via an excluder or are caught and released by hand);
- habitat types other than reef and sponge communities;
- stock structure of the main species on the North West Shelf, indicating how localised are their dynamics; and
- food web connections and dynamics (this would be the ultimate test of the assumption used here that the condition of the preferred habitat is a good proxy for the condition of the web as a whole).

There are also shorcomings associated with the human behaviour and industry sub-models used. In general these kinds of models are less well developed and the dynamics less well understood. As a result the specific shortcomings in those areas are not as obvious.

While some (indirect) cross-sectoral effects are evident from the results, these were far from complete, given the rudimentary treatment of trophic dynamics in the model and only low degrees of connectivity between the inshore and offshore systems. Lack of trophic structure and low internal connectance created model calibration difficulties, thus making it much riskier to take information from the scientific literature and use it as a simple basis for calibration. Without explicit trophic dynamics and linkages, the model lacks sensitivity to impacts on lower trophic levels and shows a lack of inertia when shocked. It often implies that the ecosystem recovers too quickly and it often indicates that the ecosystem is too “robust” to disturbance. It was possible to correct for these patterns, but only by taking parameter estimates beyond ranges typical in the literature and by introducing additional mortality terms or more complex representations to try to capture the effect of the trophic links that had not been included. It is the experience of the authors in other research that it is often easier to calibrate a trophic web model (which imposes its own constraints, sensitivities and buffering) than to calibrate the present model, even though the present model has fewer groups and uses the justifiable assumption that the condition of the “habitat” could represent the condition of all “supporting system groups”. There may be a salient point here for all natural resource modelling (from ecosystem models through to the most complicated assessment models) – a representation of the basic system structure and processes may be much easier to complete than trying to fit together increasingly intricate representations of a few specific components. Work is continuing on the MSE *InVitro* framework to address this issue.

The agent-based approach comprising a mix of individual and classical dynamical approaches does well, but where in that spectrum is most appropriate depends on the scale of interest; if considering a single bay then an individual-level representation may be better but at regional scales, a classical representation may be both sufficient for, and the most effective way of, representing the system for computer based analysis. The *InVitro* software has been designed to incorporate the flexibility required to encompass multiple scales and is currently being improved for easier implementation.

9.5.2 Strategy and status quo management shortcomings

Beyond the representational shortcomings associated with the actual model formulation used, there are some knowledge and inferential deficiencies, where the model can’t completely answer some management questions. For instance, in the case of finfish stocks, most of the population decline occurred several decades ago and the ecosystem has been on a slow recovery path ever since. Little is known about what will lead to faster recovery. There are many ways habitat recovery can be harmed and results suggest that current management practices may not be adequate to allow recovery in time scales of less than many decades. Systems need long periods to rebuild internal resilience, even if they appear to be robust. Further careful monitoring is needed to verify whether the use of fishing data can be adequate for assessing the long-term health of the ecosystem. Fishery independent surveys help make the stock assessments more reliable and may also be necessary from a “strategic” ecosystem-based fisheries management standpoint.

Sponge and reef habitat, much like the finfish, suffered most of their losses in the 1960s and 1970s and have been on a recovery path ever since. The model doesn’t capture the fine scale well but it does capture the general recovery trend, particularly in protected shallower areas just outside the turbid inshore waters. Current fishing retards recovery, particularly in zones 1 and 5. What the model cannot tell with certainty is exactly how long regional scale recovery will take. The model seems to be overly pessimistic (i.e. recovers too slowly) based on local recovery estimates, but it may be on the mark for regional scale recovery (Fulton et al. 2006b). More information is required to assess this adequately.

Even more information is needed to be sure about the state and dynamics of the other biogenic habitats. It is apparent that mangroves and seagrass are dominated by environmental conditions on a regional scale. Trawling obviously has an impact on seagrass in places like Exmouth Gulf but the environment is generally poor for seagrass at the scales specified on the NWS as a whole and seagrass is established in relatively small areas. The endemic seagrass species are impacted physically by the prawn trawls, but they are apparently unaffected by shading, as would be expected elsewhere. Likewise, human activity is too small and localised to affect mangroves significantly on a regional scale. Endemic mangrove species are accustomed to forest-scale disturbance by cyclones which, since 1920, have effected an almost complete coverage of the coastline. The huge gaps in knowledge mean that important impacts or management responses may have been missed.

One aspect of management that could do with more explicit investigation using the model is spatial zonation. Limited conclusions are drawn here regarding spatial management, but that has more to do with little contrast in the spatial management used in the alternative strategies. Even so the model results do allow for some general conclusions to be drawn. Recently declared MPAs and fishery zoning allow for some recovery of habitat, but the effectiveness of these measures is less than one might expect because their current positions are not necessarily ideal for habitat preservation or recovery. Their impact on the highly mobile species, which move in and out of such areas, is also moderate because these animals tend to move off the fishing grounds altogether as habitat is degraded. The exclusion zones around pipelines indicate that spatial zoning can help localised increases in habitat cover and associated fish biomass. Better conditions for habitat recovery and greater overlap of species ranges exist in fishing zone 1 so this zone might be worthy of conservation.

While all of the shortcomings mentioned above hamper in one way or another the final strategy comparison, it is not a paralysis. Comments regarding the effectiveness of the alternative strategies can be made. Overall the status quo management strategy seems to be forming a holding pattern, but will not necessarily lead to better ecological or economic endpoints in the long-term. The enhanced management strategy, in contrast, is more effective from a long-term resource extraction point of view; although this result is dependent on whether pessimistic or optimistic model specifications are in place. This can mean that ecological values remain at depressed values regionally, though locally there may be some recovery as fisheries change their centre of operation. Economically, some short-term gains occur but there is little difference between enhanced management and the status quo strategy.

The integrated management strategy is not much different from the other strategies for some sectors and species but, in other cases, it is much more ecologically conservative, essentially because it reduces commercial fishing. This produces higher CPUEs etc, but when conditions are of moderate or low productivity, the drop in absolute catches means that the industries are under immense economic strain if all operators are forced to reduce individual effort. Economic viability may be improved if some operators leave the fishery, thus allowing remaining vessels to continue at economically-viable effort levels. In contrast, if conditions are productive and resilient, the integrated management strategy can lead to more stable and higher economic return, as well as improved ecological and economic conditions across all sectors explicitly considered.

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APPENIDX A: COARSE SCALE SPATIAL ANALYSIS TABLES AND PLOTS

Table A.1: Two-sample Kolmogorov-Smirnov test scores correspond to coarse scale spatial analysis of the average relative grid cell biomass, for each combination of management strategy, model specification and development scenario, for all species simulated in NWSJEMS. Those values in *italics* correspond to p-value of 0.01 and those in bold correspond to a p-value of 0.05. Note that this test shows that the two data sets are not from the same distribution if the p-value is non-significant (i.e. p=0.01 or p=0.05): that is, bolded and italicised entries indicate significant difference whereas other entries indicate no significant difference between the 2 cells being compared.

Comparison of grid cells	Banana prawn	King prawn	Large lutjanids	Small lutjanids	Lethrinids	*Lutjanus sebae*	Nemipterid	Saurid	Shark	Turtle	Mangroves	Seagrass	Sponge and reef
111 vs 112	*0.0671*	*0.0694*	0.1435	0.2245	**0.0613**	0.169	**0.0567**	*0.0775*	0.103	0.1609	**0.022**	**0.0197**	0.1539
111 vs 113	0.1481	0.0995	0.1713	0.1898	0.1435	0.2083	0.1157	0.1701	**0.0451**	0.1713	**0.0197**	**0.0127**	0.2778
112 vs 113	0.1493	**0.0532**	**0.0451**	0.0926	0.1377	*0.0706*	0.0938	0.1181	*0.0775*	**0.0625**	**0.0046**	**0.0093**	0.228
211 vs 212	*0.0694*	**0.0648**	0.1505	0.2407	*0.0683*	0.1481	**0.059**	*0.0706*	**0.0532**	0.1076	**0.022**	**0.0243**	0.1447
211 vs 213	0.1493	*0.0741*	0.169	0.2037	**0.0486**	0.1829	0.1088	0.1655	**0.0498**	0.1898	**0.0243**	**0.0301**	0.2488
212 vs 213	0.1516	**0.0463**	**0.0475**	0.1169	**0.0637**	0.0787	*0.0741*	0.1169	*0.0718*	0.088	**0.0046**	**0.022**	0.1863
311 vs 312	*0.0729*	**0.0579**	0.1343	0.2083	0.1667	0.1597	**0.0532**	**0.0637**	**0.0405**	0.1377	**0.0058**	**0.0359**	0.1771
311 vs 313	0.1481	*0.0741*	0.1516	0.147	0.1424	0.1887	0.0984	0.1539	0.1308	0.2014	**0.0081**	**0.0185**	0.2662
312 vs 313	0.1458	**0.0486**	**0.044**	0.1238	**0.0463**	*0.0729*	*0.0729*	0.1111	0.1169	0.2813	**0.0035**	**0.0359**	0.2303
111 vs 211	**0.0058**	**0.0104**	**0.0394**	**0.0162**	0.0787	**0.0394**	**0.0208**	**0.0162**	**0.0394**	**0.0417**	**0.0046**	**0.0359**	0.0868
111 vs 311	**0.0104**	**0.0116**	**0.0347**	**0.0394**	**0.0428**	0.0845	**0.0185**	**0.0278**	**0.0231**	**0.0382**	**0.0197**	**0.0174**	**0.0613**
211 vs 311	**0.0116**	**0.0127**	**0.037**	**0.0451**	*0.0694*	**0.0602**	**0.0162**	**0.0208**	**0.0382**	**0.0417**	**0.022**	**0.022**	*0.066*
112 vs 212	**0.0266**	**0.0104**	**0.0359**	**0.037**	0.0995	**0.0289**	**0.0521**	**0.022**	0.0995	**0.0521**	**0.0058**	**0.0139**	0.1065
112 vs 312	*0.0729*	**0.0174**	**0.0231**	**0.0197**	0.1273	**0.0324**	**0.0255**	**0.0243**	0.0914	0.2639	**0.0069**	**0.0359**	0.0822
212 vs 312	*0.0752*	**0.0127**	**0.0312**	**0.022**	**0.0648**	**0.044**	**0.0312**	**0.0208**	**0.0301**	0.2269	**0.0023**	**0.0382**	*0.0706*
113 vs 213	**0.0301**	**0.037**	**0.0162**	**0.0139**	*0.0718*	**0.0359**	**0.0208**	**0.0197**	**0.0451**	**0.0428**	**0.0058**	**0.0312**	*0.0718*
113 vs 313	**0.0289**	**0.0359**	**0.0324**	**0.0382**	**0.0567**	**0.0313**	**0.0394**	**0.0197**	0.0926	**0.0336**	**0.0058**	**0.0289**	0.1111
213 vs 313	**0.0278**	**0.0313**	**0.0336**	**0.037**	0.0949	**0.0289**	**0.0324**	**0.0127**	**0.0625**	**0.0567**	**0.0035**	**0.0197**	0.1308
111 vs 121	**0.0104**	**0.0104**	**0.0394**	**0.0231**	**0.0567**	**0.0382**	**0.0185**	**0.0104**	**0.0382**	**0.0394**	**0.0197**	**0.0301**	*0.0694*
111 vs 131	**0.0081**	**0.0116**	**0.0463**	**0.0301**	0.0926	**0.0394**	**0.0278**	**0.0104**	*0.0671*	**0.0475**	**0.022**	**0.0394**	**0.044**
121 vs 131	**0.015**	**0.0104**	**0.0359**	**0.022**	0.1065	**0.0185**	**0.0289**	**0.0093**	**0.0475**	**0.059**	**0.0058**	**0.0278**	**0.0486**
112 vs 122	**0.0475**	**0.015**	**0.0382**	**0.0312**	0.1227	**0.0266**	**0.0208**	**0.0174**	**0.0567**	**0.0347**	**0.0046**	**0.0324**	0.0799
112 vs 132	**0.0278**	**0.0116**	**0.0289**	**0.0231**	0.0903	**0.0382**	**0.0313**	**0.015**	0.1204	**0.0243**	**0.0069**	**0.0312**	*0.0752*

Comparison of grid cells	Banana prawn	King prawn	Large lutjanids	Small lutjanids	Lethrinids	*Lutjanus sebae*	Nemipterid	Saurid	Shark	Turtle	Mangroves	Seagrass	Sponge and reef
122 vs 132	**0.0475**	**0.0104**	**0.0266**	**0.0301**	**0.037**	**0.0579**	**0.0208**	**0.0127**	*0.0683*	**0.0394**	**0.0046**	**0.0197**	0.088
113 vs 123	**0.0278**	**0.0255**	**0.0336**	**0.0231**	*0.0694*	**0.0579**	**0.0417**	**0.0093**	0.1204	**0.0289**	**0.0046**	**0.0255**	*0.0775*
113 vs 133	**0.0266**	**0.0359**	**0.0637**	**0.0231**	0.088	**0.0336**	**0.0532**	**0.0185**	0.0845	**0.0266**	**0.0046**	**0.0312**	*0.0764*
123 vs 133	**0.0266**	**0.0336**	**0.059**	**0.0324**	**0.044**	**0.0394**	**0.0301**	**0.0127**	**0.0486**	**0.0324**	**0.0046**	**0.0289**	0.1065
221 vs 222	*0.0706*	**0.0637**	0.1424	0.2269	0.088	0.1632	**0.0567**	*0.0718*	**0.0347**	0.1794	**0.0035**	**0.0197**	0.1817
221 vs 223	0.1481	0.0787	0.1539	0.1713	**0.0521**	0.191	0.11	0.1701	0.081	0.2373	**0.0058**	**0.0162**	0.3194
222 vs 223	0.1481	**0.0486**	**0.0532**	0.1227	**0.0475**	*0.0741*	*0.0764*	0.1192	**0.0556**	*0.0718*	**0.0046**	**0.0093**	0.1898
321 vs 322	*0.0671*	**0.0625**	0.1343	0.2095	*0.0706*	0.1748	*0.0706*	*0.0741*	*0.0718*	0.0914	**0.0046**	**0.022**	0.1701
321 vs 323	0.1493	*0.0752*	0.184	0.1551	0.1262	0.2014	0.1111	0.162	0.0845	0.1736	**0.0023**	**0.0243**	0.3854
322 vs 323	0.1481	**0.0451**	**0.0648**	0.1181	*0.0718*	**0.0602**	*0.0718*	0.1088	*0.066*	0.2558	**0.0046**	**0.0243**	0.2743
231 vs 232	*0.0729*	**0.0637**	0.1377	0.1956	*0.0775*	0.1505	*0.0683*	*0.0729*	**0.037**	0.1308	**0.0035**	**0.0255**	0.1991
231 vs 233	0.147	*0.0706*	0.1528	0.1655	0.1563	0.228	0.103	0.1667	0.1111	0.1424	**0.0046**	**0.0162**	0.2951
232 vs 233	0.1516	**0.0463**	**0.0544**	0.1042	0.1273	0.0903	**0.0613**	0.1157	0.1019	**0.0289**	**0.0046**	**0.0255**	0.2072
331 vs 332	*0.0694*	**0.0637**	0.1204	0.2049	0.1204	0.1667	*0.066*	**0.0637**	**0.0428**	**0.0637**	**0.0208**	**0.044**	0.1389
331 vs 333	0.1516	*0.0694*	0.1458	0.1655	0.1887	0.2014	0.1227	0.1551	*0.0729*	0.2095	**0.0197**	**0.0394**	0.2778
332 vs 333	0.1505	**0.0417**	**0.044**	0.1053	0.081	**0.0602**	0.0845	0.103	**0.0463**	0.2234	**0.0035**	**0.037**	0.2199
121 vs 221	**0.015**	**0.0116**	**0.0428**	**0.0197**	**0.0648**	**0.0289**	**0.0185**	**0.0081**	0.0787	**0.0347**	**0.0058**	**0.0174**	*0.0694*
121 vs 321	**0.0174**	**0.015**	**0.0428**	**0.0359**	**0.059**	**0.0382**	**0.0243**	**0.0174**	**0.0312**	**0.0394**	**0.0058**	**0.022**	**0.0475**
221 vs 321	**0.0162**	**0.0104**	**0.0463**	**0.0301**	**0.0347**	**0.0579**	**0.0289**	**0.0185**	*0.0775*	**0.0532**	**0.0058**	**0.022**	*0.0706*
122 vs 222	**0.0266**	**0.0127**	**0.0417**	**0.0231**	*0.0683*	**0.044**	**0.0255**	**0.0127**	**0.0336**	**0.0625**	**0.0058**	**0.0185**	0.1076
122 vs 322	**0.0463**	**0.0104**	**0.0428**	**0.0197**	**0.0498**	**0.0567**	**0.015**	**0.0185**	**0.0255**	0.2419	**0.0058**	**0.0197**	**0.0613**
222 vs 322	**0.0255**	**0.0127**	**0.0394**	**0.0162**	**0.0509**	**0.0347**	**0.0313**	**0.0197**	**0.0243**	0.2118	**0.0081**	**0.0231**	0.0938
123 vs 223	**0.0278**	**0.0336**	**0.0347**	**0.0301**	*0.0775*	**0.0312**	**0.0231**	**0.0127**	0.103	**0.0255**	**0.0035**	**0.0301**	0.1157
123 vs 323	**0.0266**	**0.0405**	**0.0359**	**0.0278**	**0.0637**	**0.0428**	**0.0162**	**0.0185**	0.0891	**0.0394**	**0.0046**	**0.037**	0.1262
223 vs 333	**0.0255**	**0.0394**	**0.0405**	**0.0324**	0.1042	**0.0255**	**0.0278**	**0.0174**	**0.0637**	**0.0289**	**0.0081**	**0.0197**	0.0972
131 vs 231	**0.0127**	**0.0093**	**0.0405**	**0.0266**	0.0961	**0.0266**	**0.0278**	**0.0116**	0.0833	**0.0417**	**0.0035**	**0.0266**	0.0833
131 vs 331	**0.0104**	**0.0104**	**0.044**	**0.0266**	**0.0602**	**0.0359**	**0.0336**	**0.0185**	0.088	0.0903	**0.0231**	**0.044**	0.0868
231 vs 331	**0.0127**	**0.0093**	**0.0394**	**0.0197**	0.081	**0.037**	**0.0174**	**0.0243**	**0.022**	*0.0694*	**0.0231**	**0.044**	0.0891
132 vs 232	**0.0521**	**0.0116**	**0.0382**	**0.0324**	*0.0683*	**0.037**	**0.0255**	**0.0093**	*0.0764*	**0.037**	**0.0046**	**0.0266**	*0.0764*
132 vs 332	**0.0475**	**0.0116**	**0.037**	**0.022**	**0.0312**	**0.0486**	**0.0243**	**0.0197**	**0.0405**	0.2037	**0.0058**	**0.037**	0.0856
232 vs 332	**0.0498**	**0.0093**	**0.0312**	**0.0336**	**0.0521**	**0.0463**	**0.0243**	**0.0208**	**0.0648**	0.1921	**0.0046**	**0.0313**	**0.059**
133 vs 233	**0.0289**	**0.0359**	**0.0278**	**0.0243**	0.0938	**0.0532**	**0.0289**	**0.0127**	0.14	**0.0359**	**0.0058**	**0.0058**	0.088

Comparison of grid cells	Banana prawn	King prawn	Large lutjanids	Small lutjanids	Lethrinids	*Lutjanus sebae*	Nemipterid	Saurid	Shark	Turtle	Mangroves	Seagrass	Sponge and reef
133 vs 333	**0.0266**	**0.0382**	**0.0602**	**0.037**	0.0961	**0.037**	**0.0301**	**0.0116**	0.125	**0.0255**	**0.0046**	**0.0104**	0.0891
233 vs 333	**0.0255**	**0.0336**	**0.0394**	**0.0231**	**0.0463**	**0.0417**	**0.0301**	**0.0174**	**0.0486**	**0.0463**	**0.0058**	**0.0081**	*0.0775*

A.1 Banana prawns

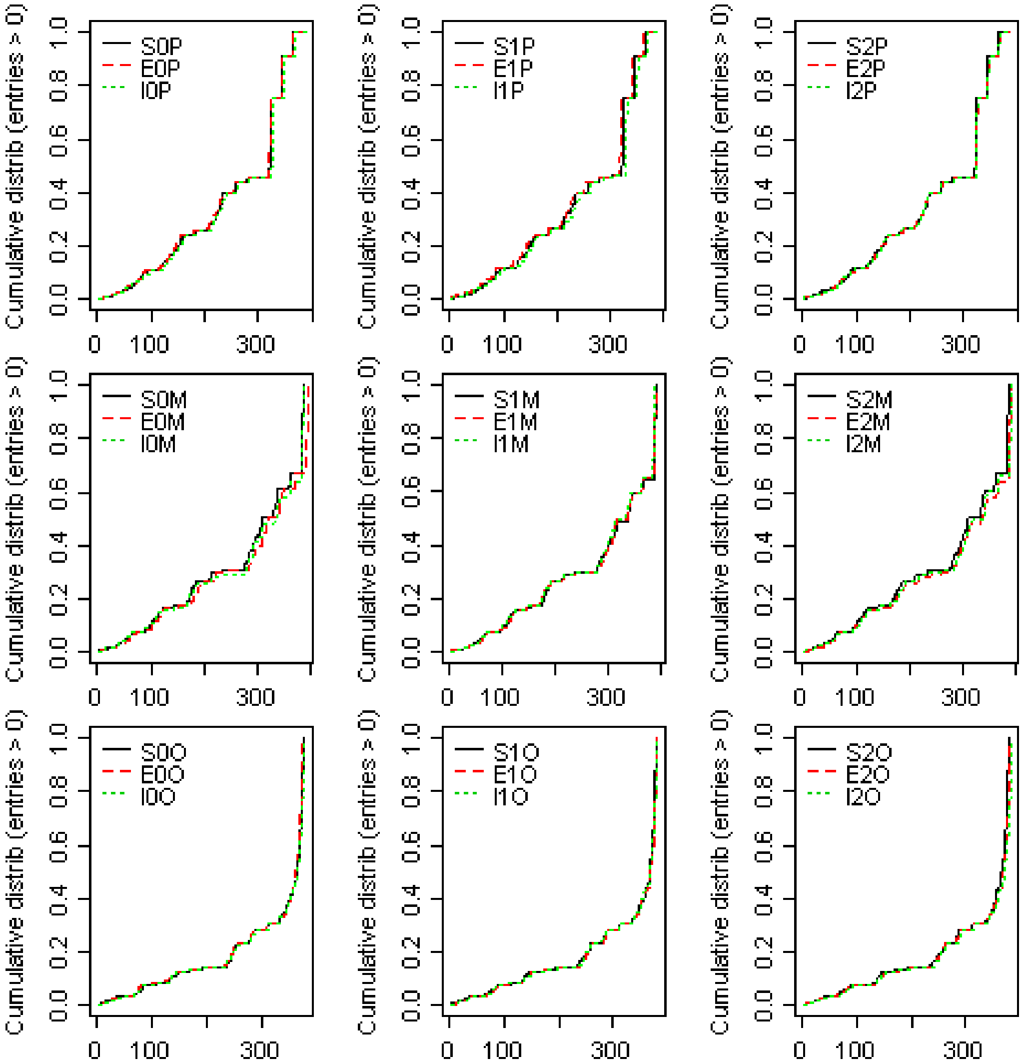


Figure A.1: Cumulative distribution plot for coarse scale spatial analysis of banana prawn average grid-cell relative biomass, comparing management strategies (each box contains the cumulative distributions for status quo [black], enhanced [red] and integrated [green] management for a given combination of model specification and development scenario).

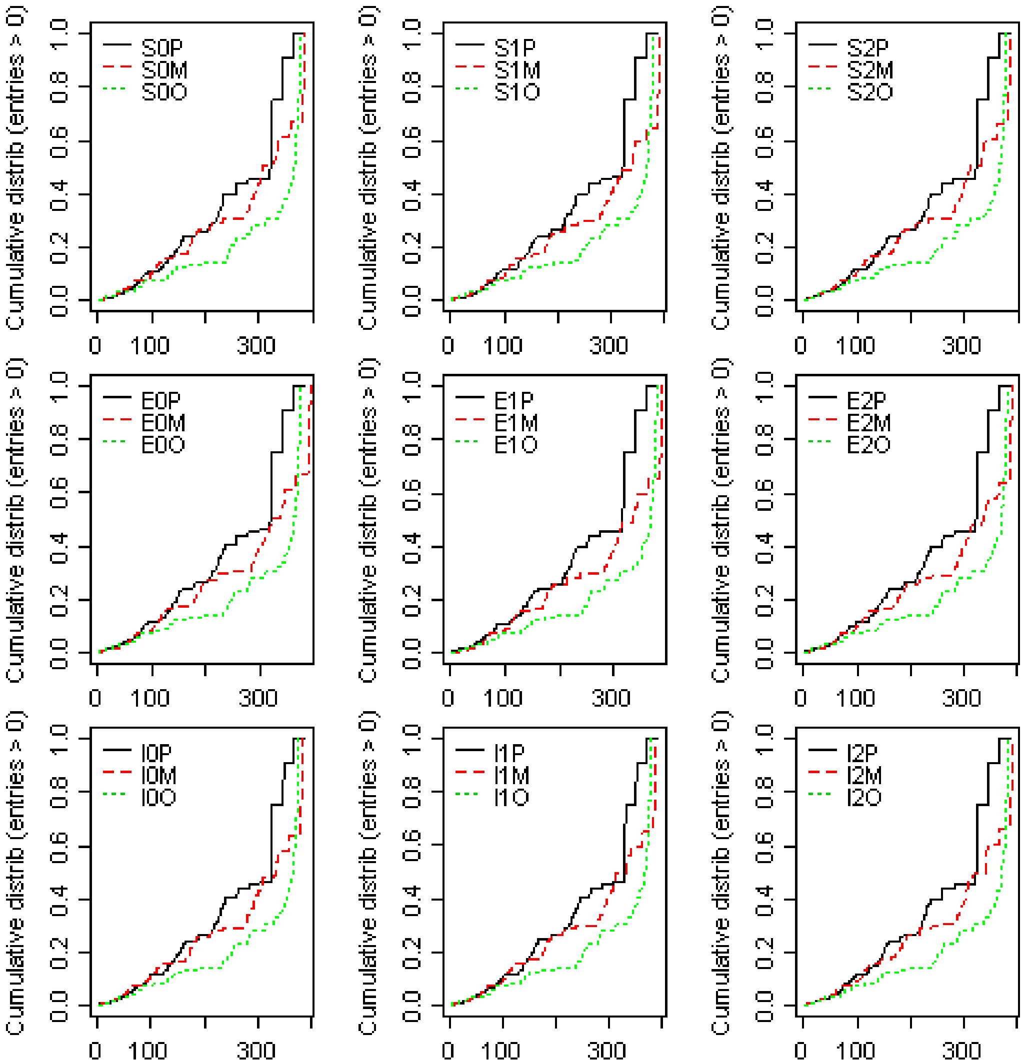


Figure A.2: Cumulative distribution plot for coarse scale spatial analysis of banana prawn average grid-cell relative biomass, comparing model specifications (each box contains the cumulative distributions for pessimistic [black], base case [red] and optimistic [green] specifications for a given combination of management strategy and development scenario).

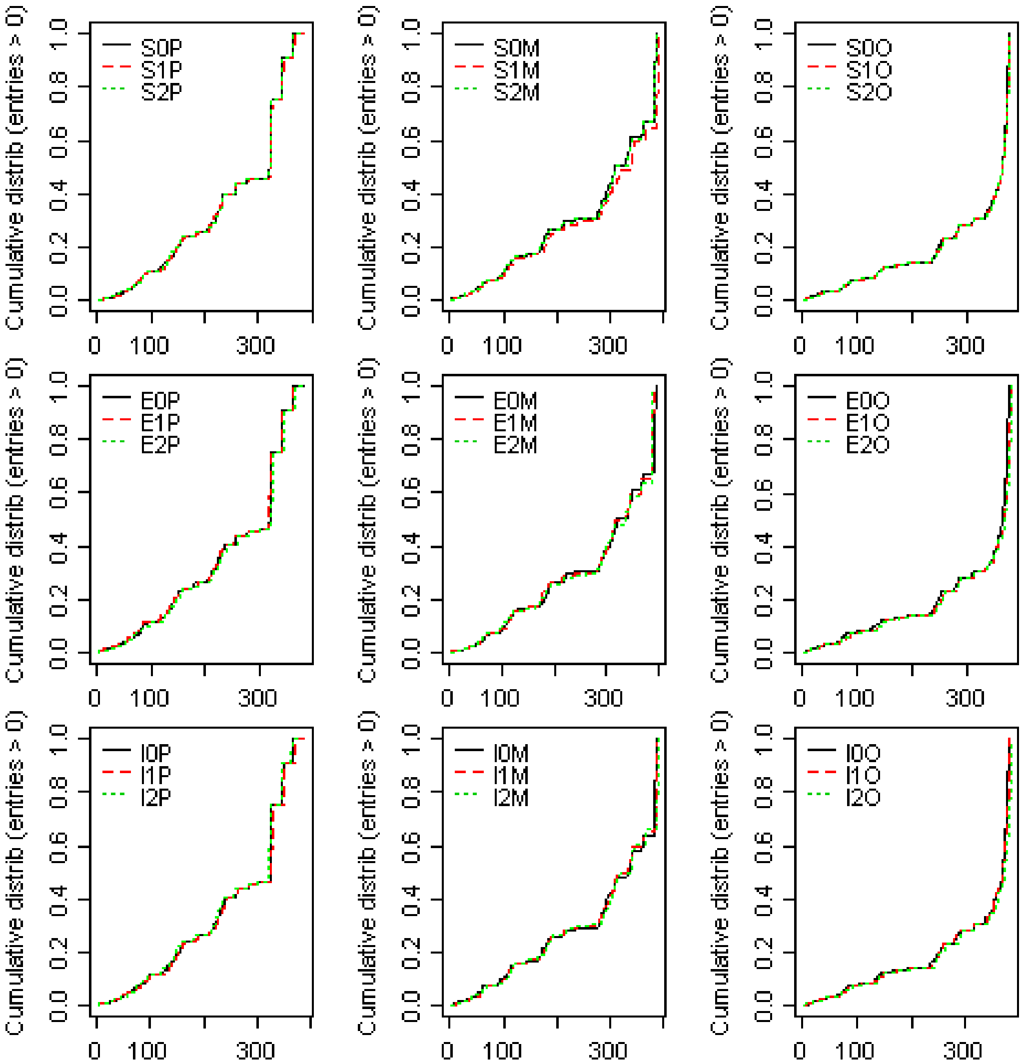


Figure A.3: Cumulative distribution plot for coarse scale spatial analysis of banana prawn average grid-cell relative biomass, comparing development scenarios (each box contains the cumulative distributions for 0-pulse [black], 1-pulse [red] and 2-pulse [green] development scenarios for a given combination of management strategy and model specification).

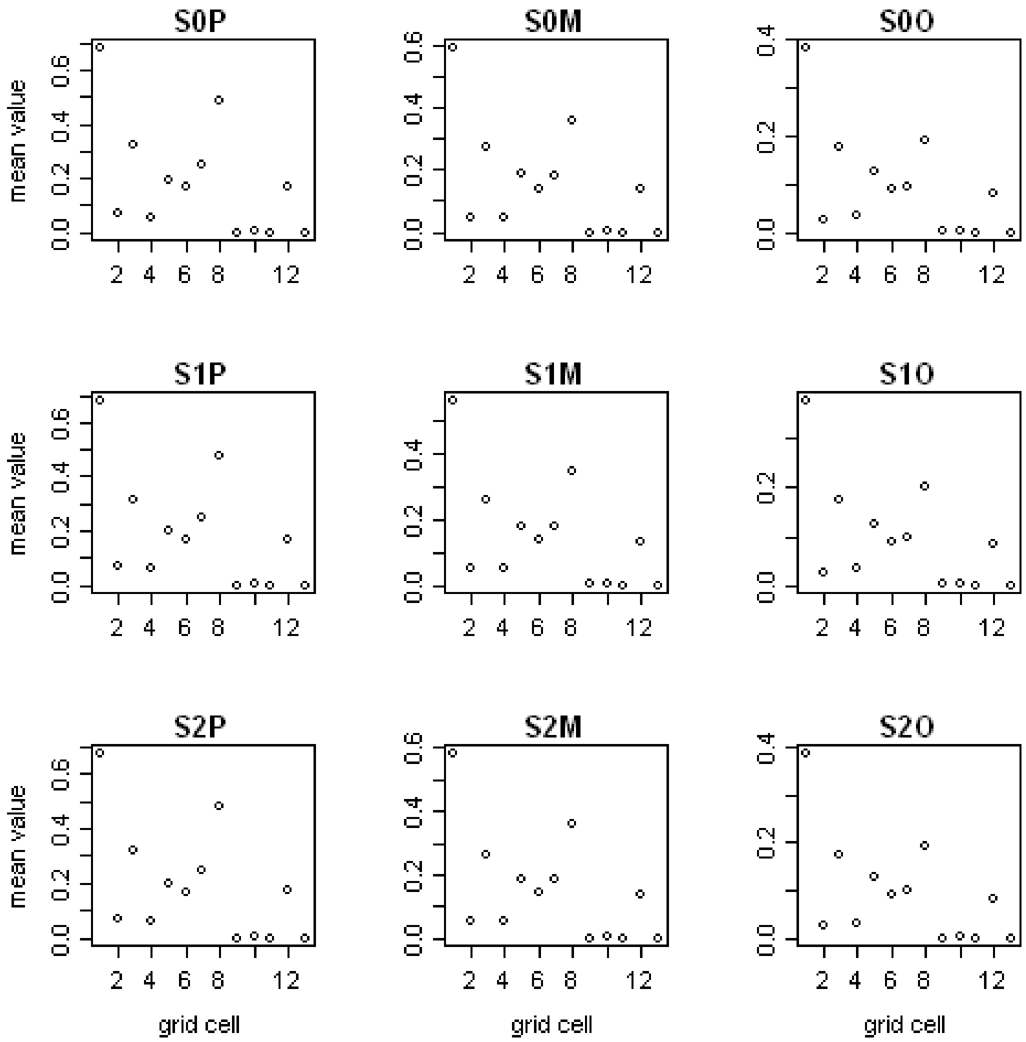


Figure A.4: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for banana prawns under status quo management for each combination of development scenario and model specification.

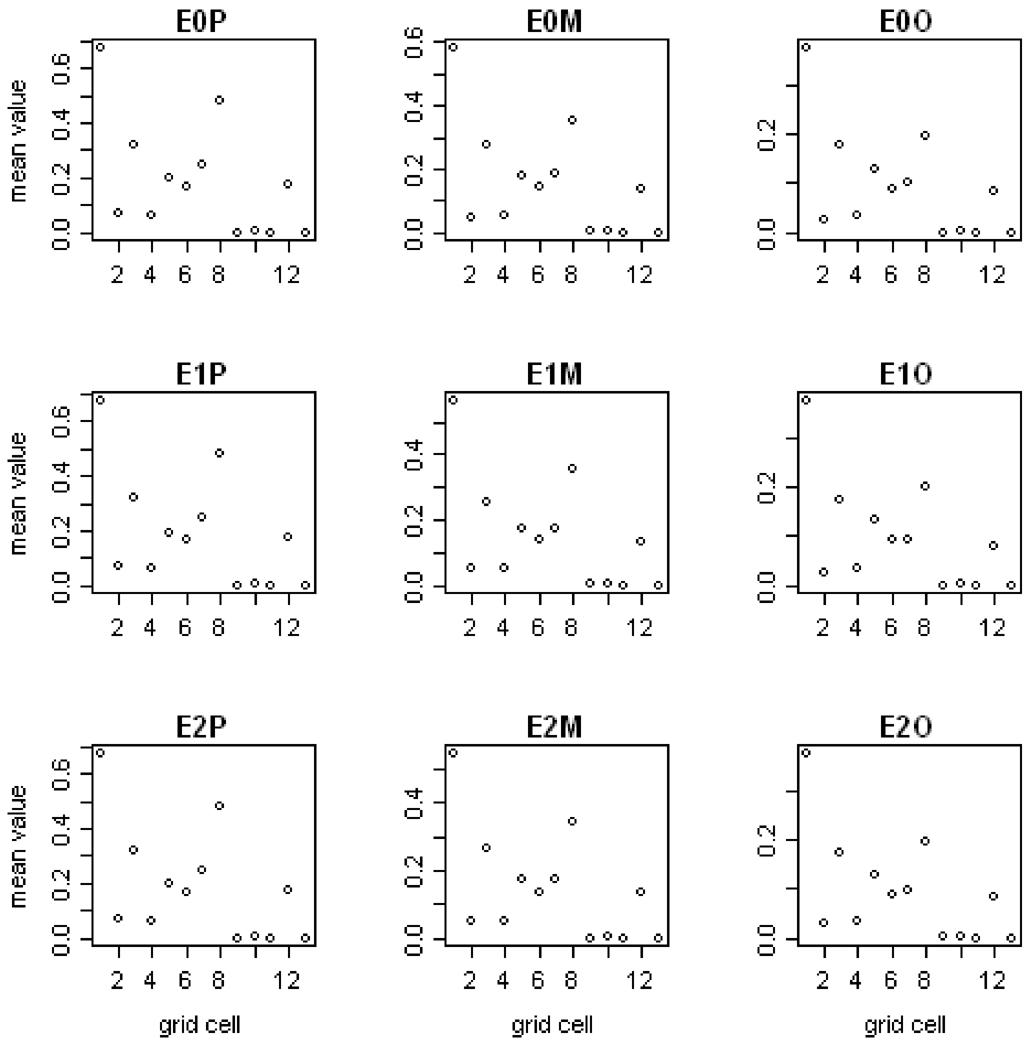


Figure A.5: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for banana prawns under enhanced management for each combination of development scenario and model specification.

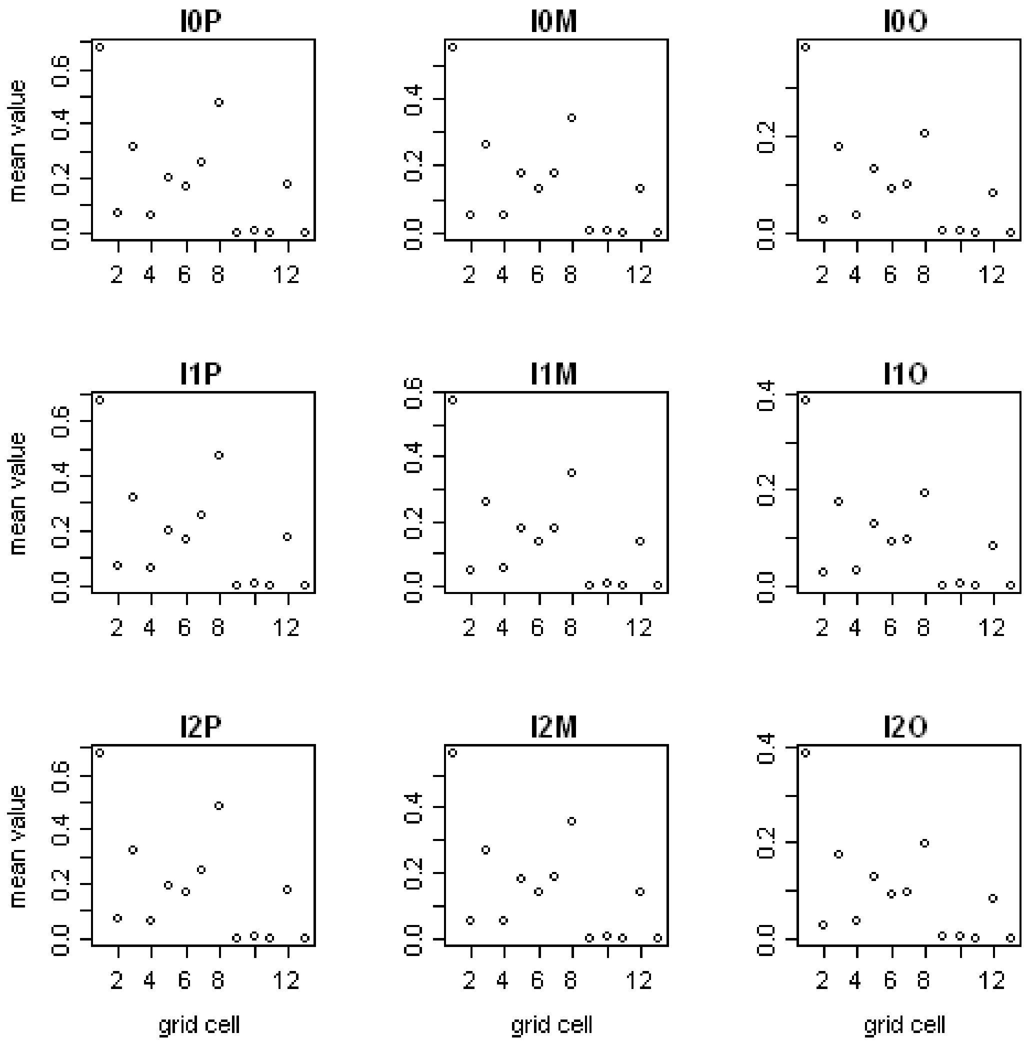


Figure A.6: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for banana prawns under integrated management for each combination of development scenario and model specification.

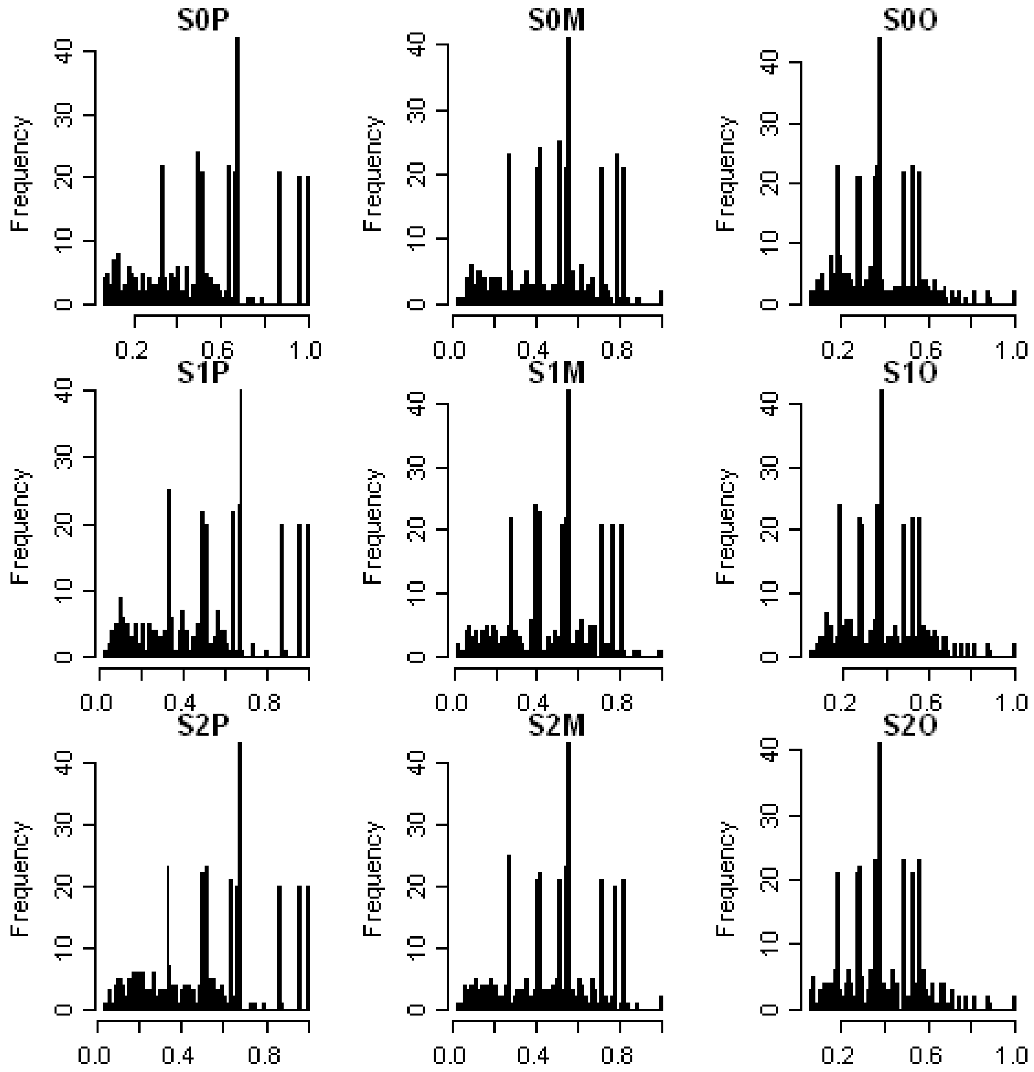


Figure A.7: Frequency histogram of coarse scale relative biomass (over time) for banana prawns under status quo management for each combination of development scenario and model specification.

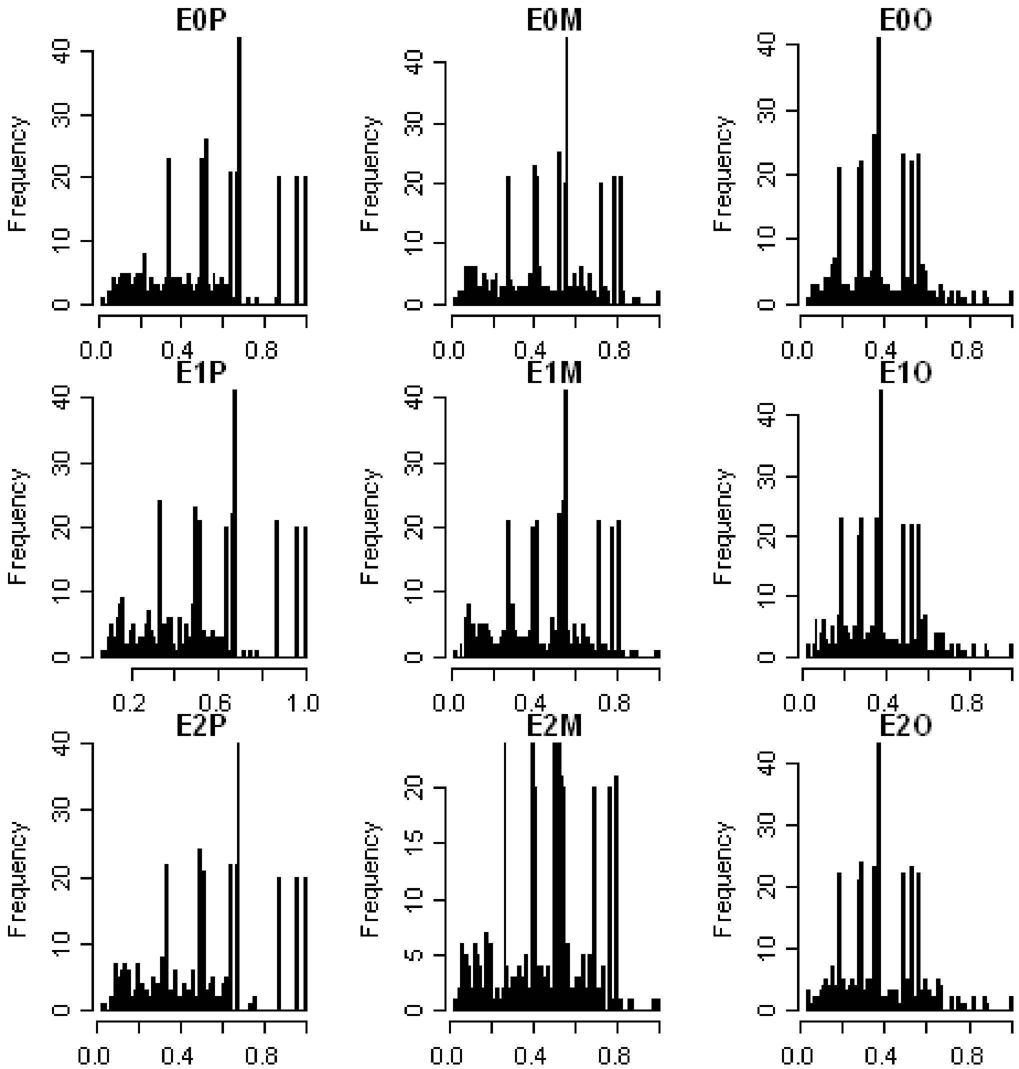


Figure A.8: Frequency histogram of coarse scale relative biomass (over time) for banana prawns under enhanced management for each combination of development scenario and model specification.

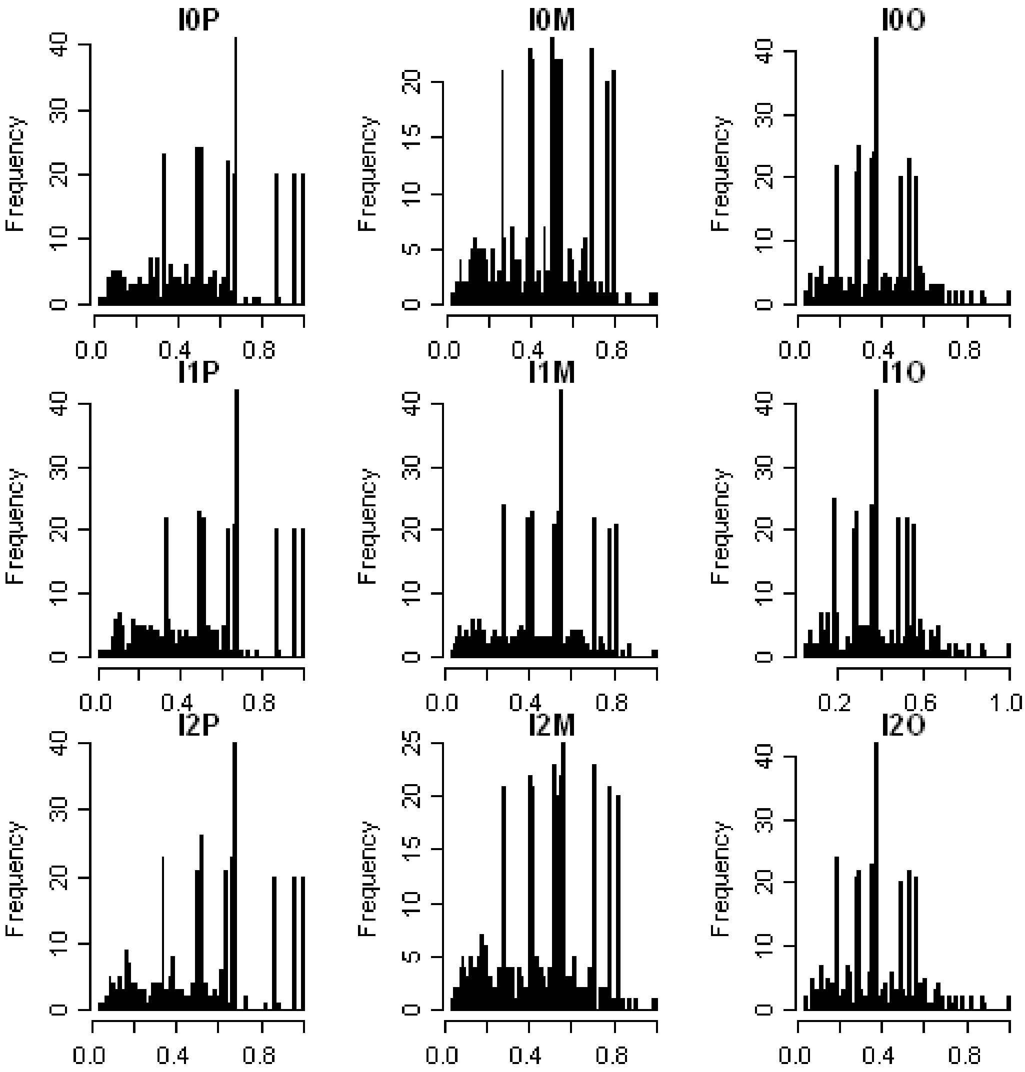


Figure A.9: Frequency histogram of coarse scale relative biomass (over time) for banana prawns under integrated management for each combination of development scenario and model specification.

A.2 King prawns

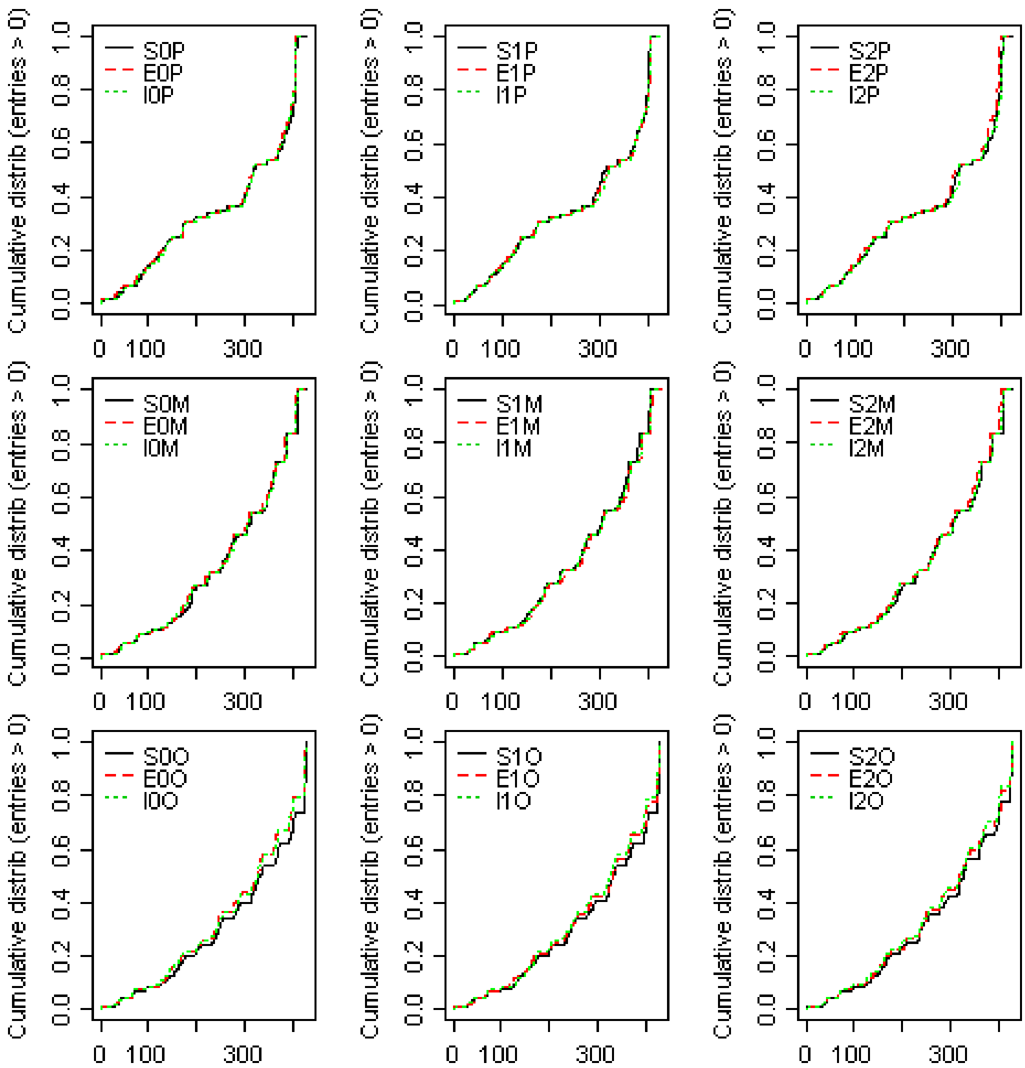


Figure A.10: Cumulative distribution plot coarse scale spatial analysis of king prawn average grid-cell relative biomass, comparing management strategies (each box contains the cumulative distributions for status quo [black], enhanced [red] and integrated [green] management for a given combination of model specification and development scenario).

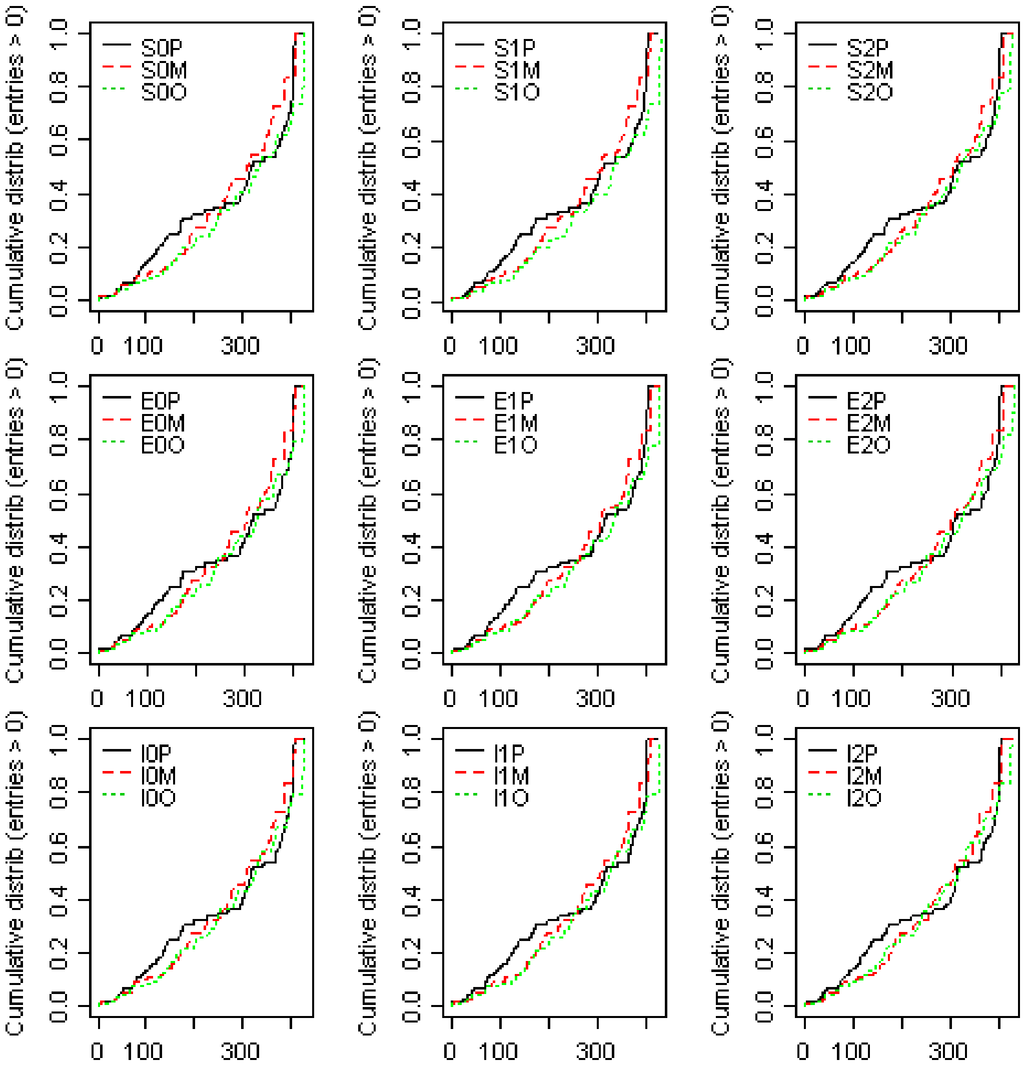


Figure A.11: Cumulative distribution plot for coarse scale spatial analysis of king prawn average grid-cell relative biomass, comparing model specifications (each box contains the cumulative distributions for pessimistic [black], base case [red] and optimistic [green] specifications for a given combination of management strategy and development scenario).

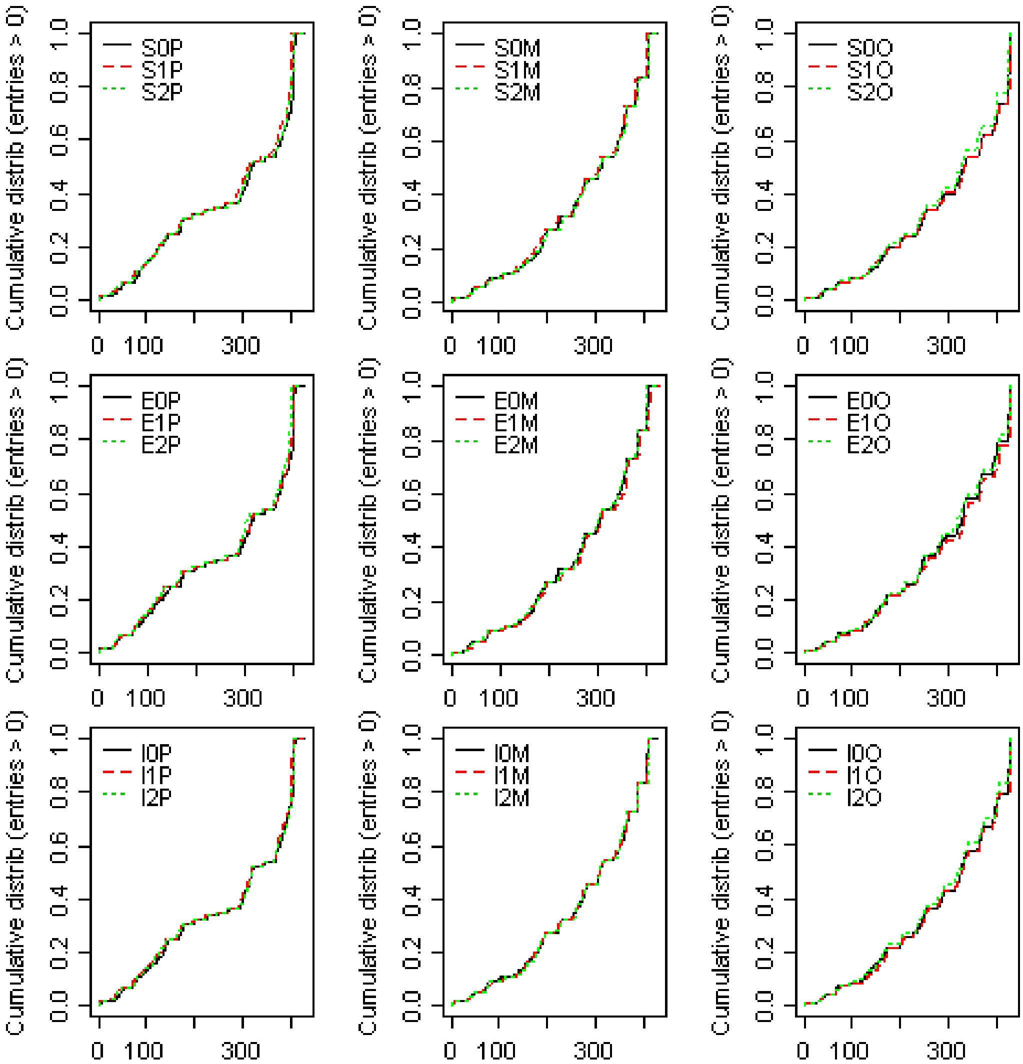


Figure A.12: Cumulative distribution plot for coarse scale spatial analysis of king prawn average grid-cell relative biomass, comparing development scenarios (each box contains the cumulative distributions for 0-pulse [black], 1-pulse [red] and 2-pulse [green] development scenarios for a given combination of management strategy and model specification).

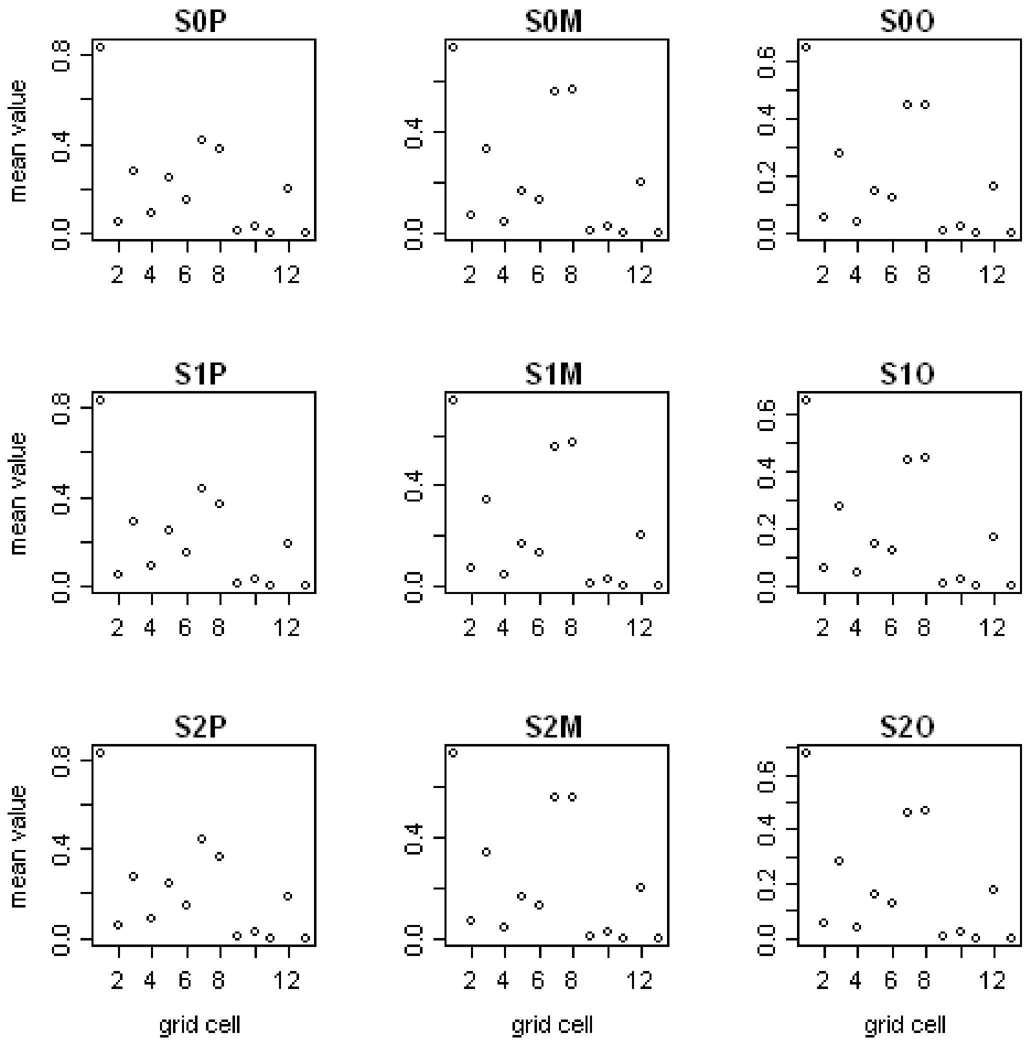


Figure A.13: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for king prawns under status quo management for each combination of development scenario and model specification.

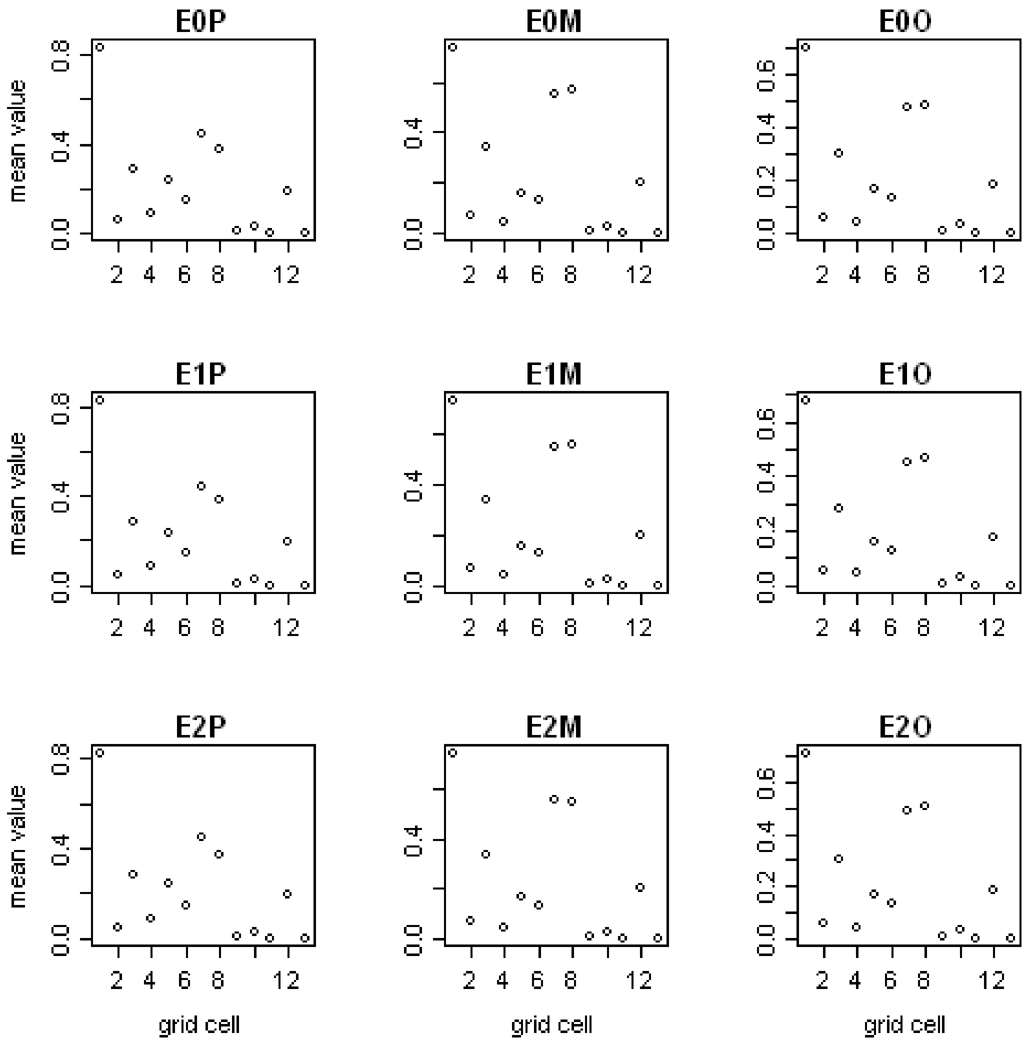


Figure A.14: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for king prawns under enhanced management for each combination of development scenario and model specification.

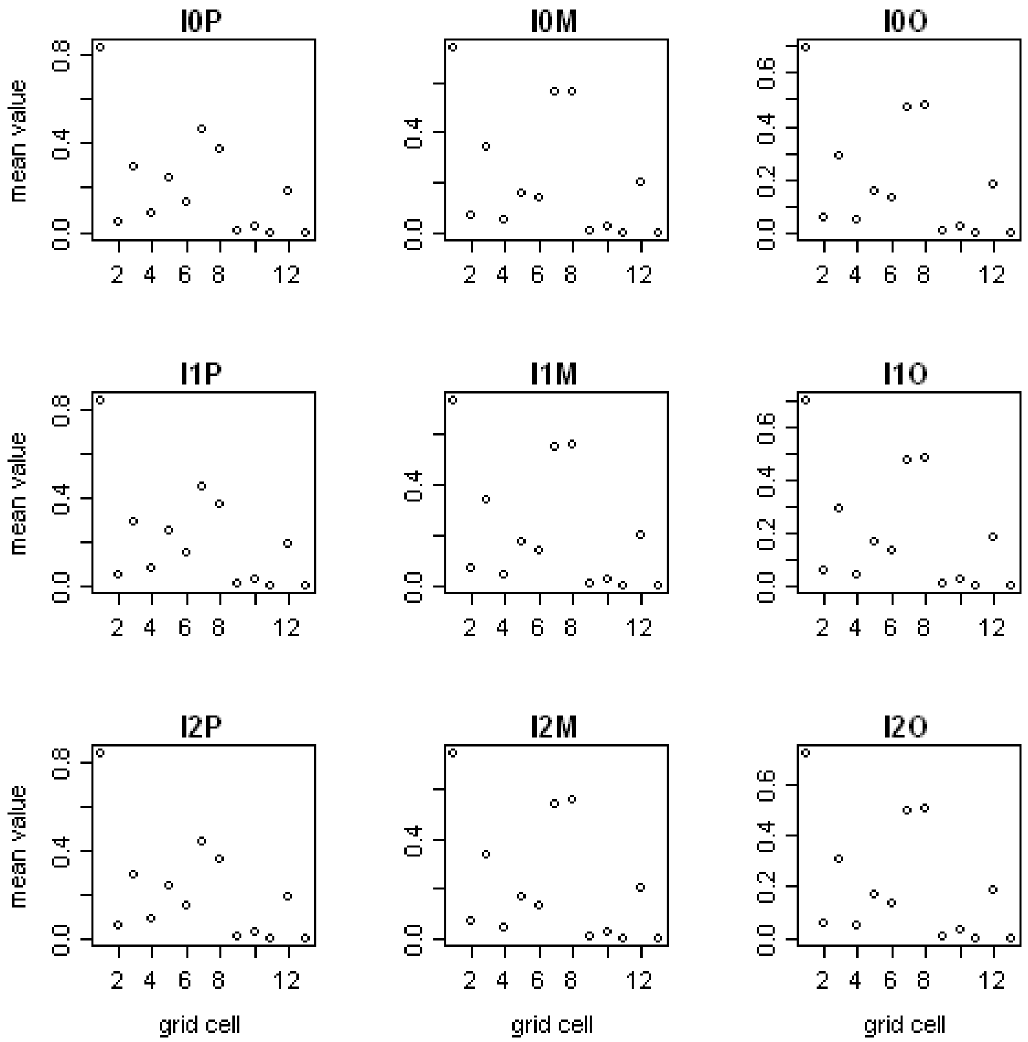


Figure A.15: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for king prawns under integrated management for each combination of development scenario and model specification.

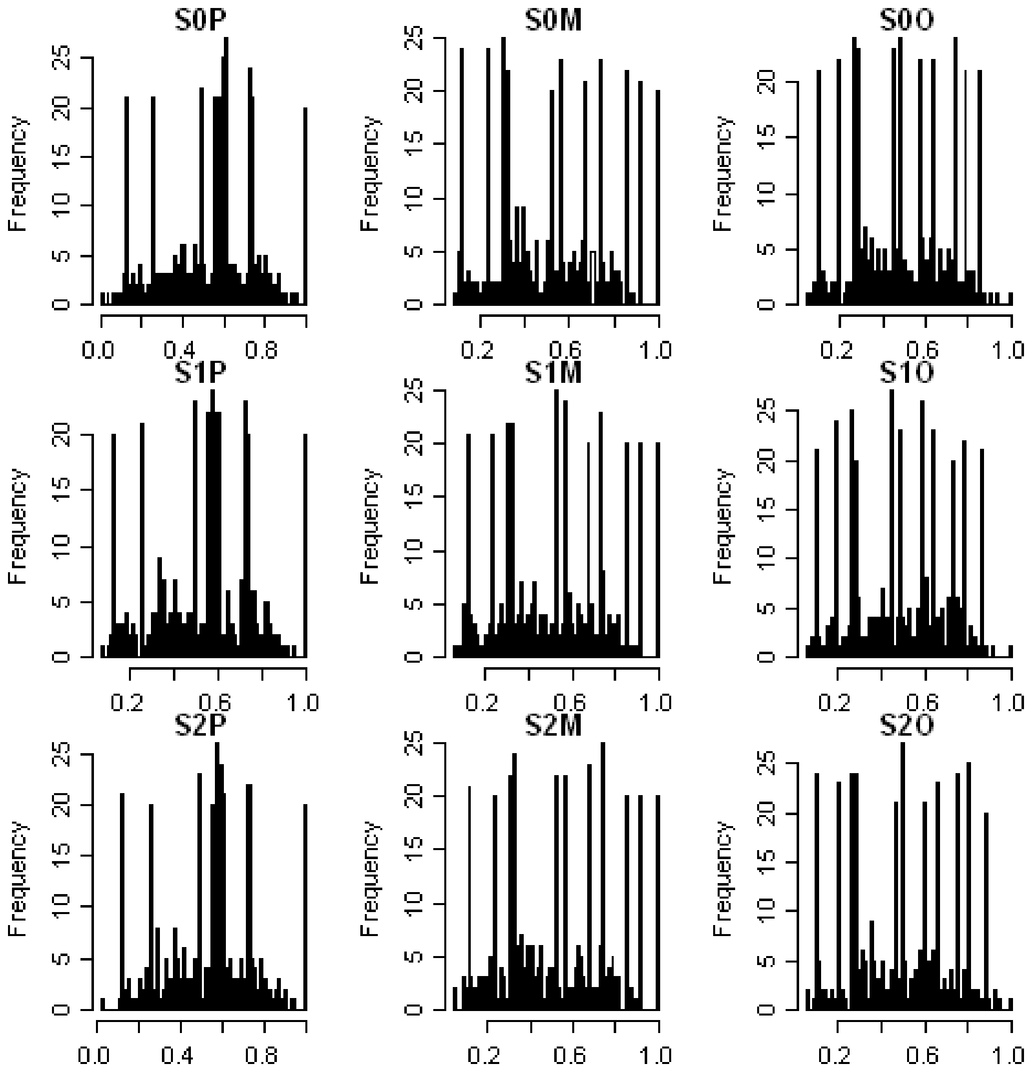


Figure A.16: Frequency histogram of coarse scale relative biomass (over time) for king prawns under status quo management for each combination of development scenario and model specification.

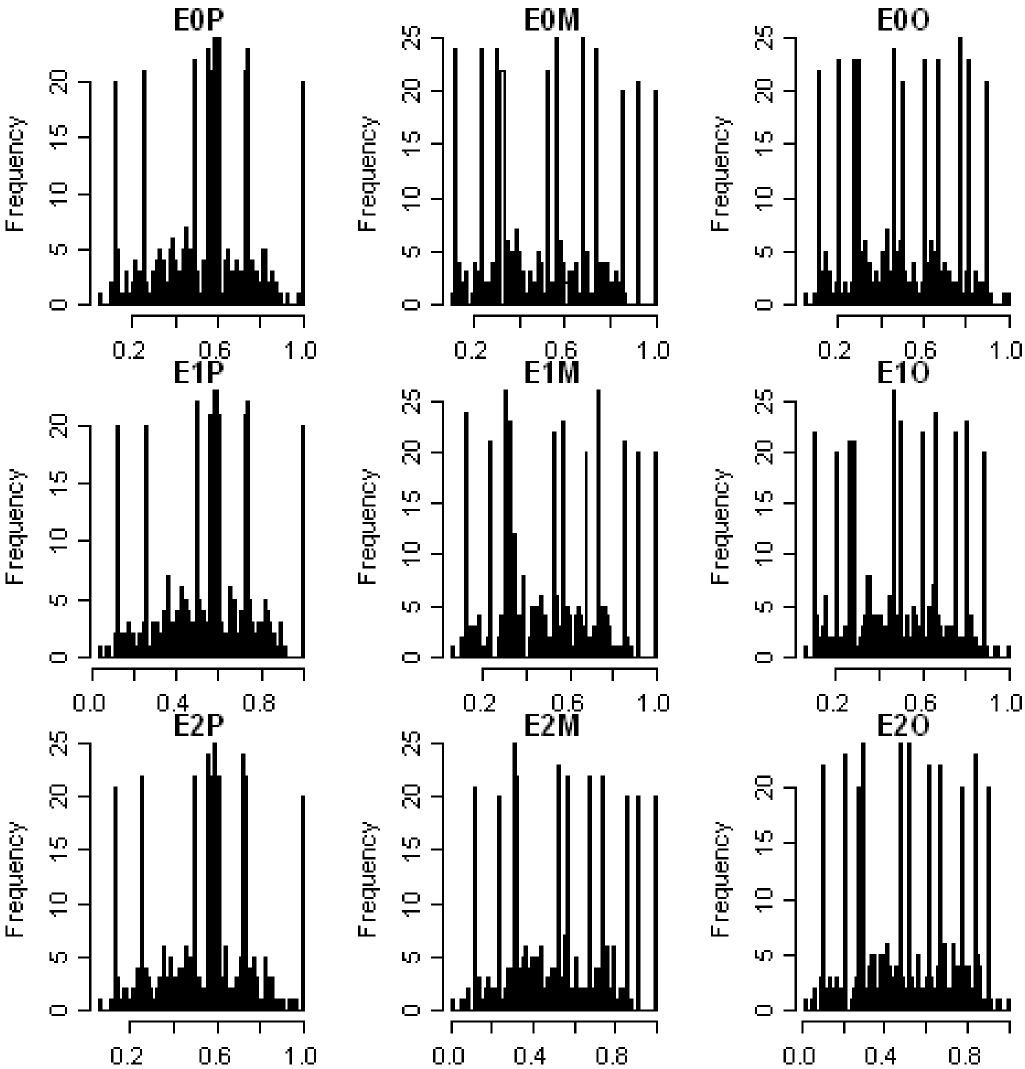


Figure A.17: Frequency histogram of coarse scale relative biomass (over time) for king prawns under enhanced management for each combination of development scenario and model specification.

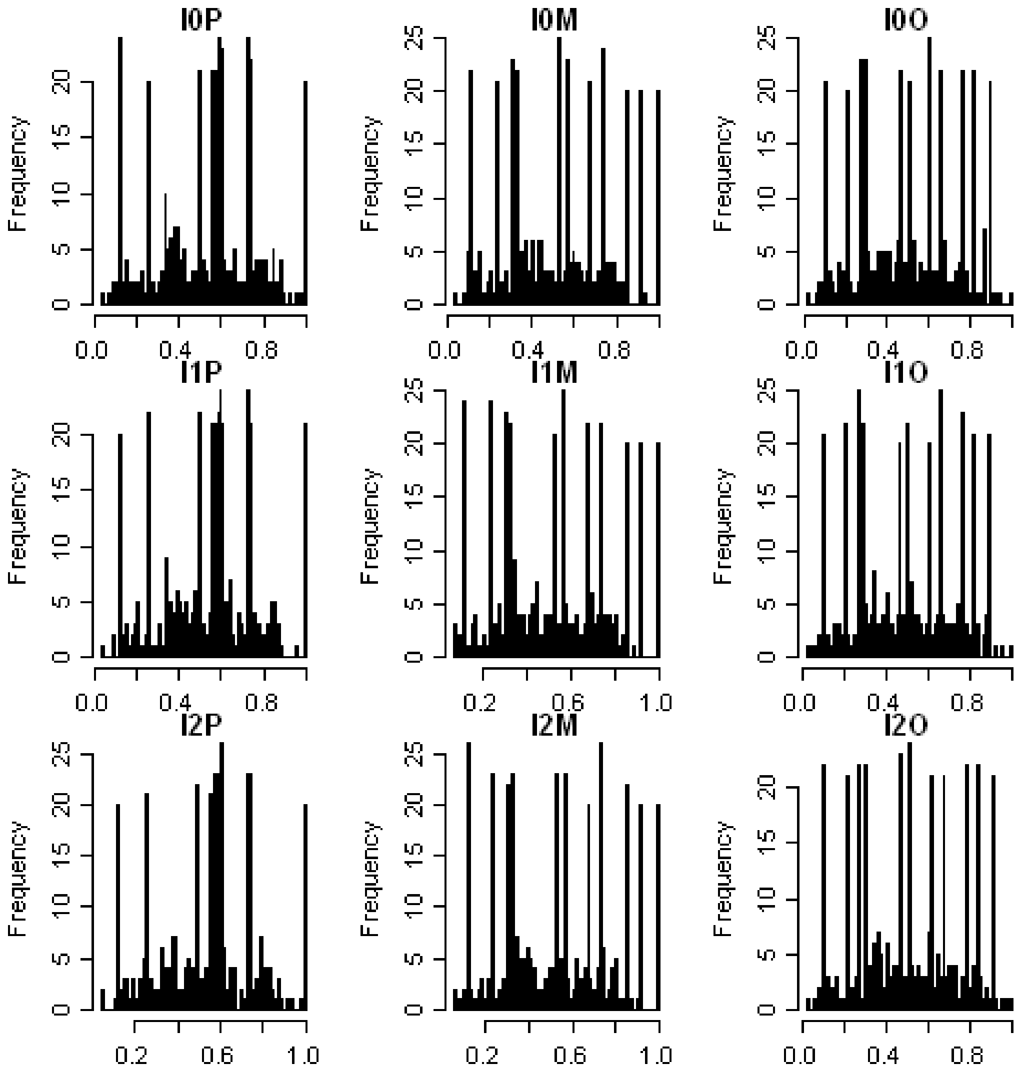


Figure A.18: Frequency histogram of coarse scale relative biomass (over time) for king prawns under integrated management for each combination of development scenario and model specification.

A.3 Turtles

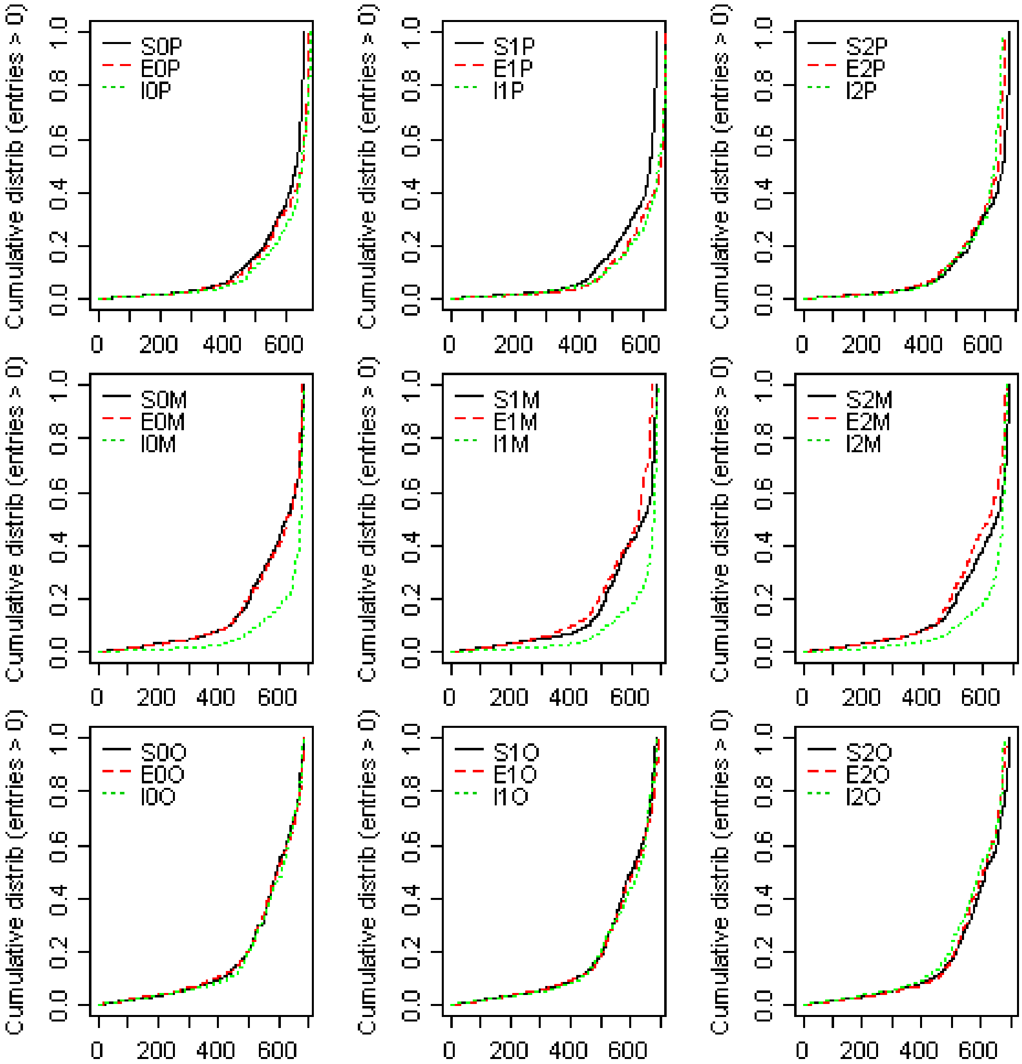


Figure A.19: Cumulative distribution plot for coarse scale spatial analysis of turtle average grid-cell relative biomass, comparing management strategies (each box contains the cumulative distributions for status quo [black], enhanced [red] and integrated [green] management for a given combination of model specification and development scenario).

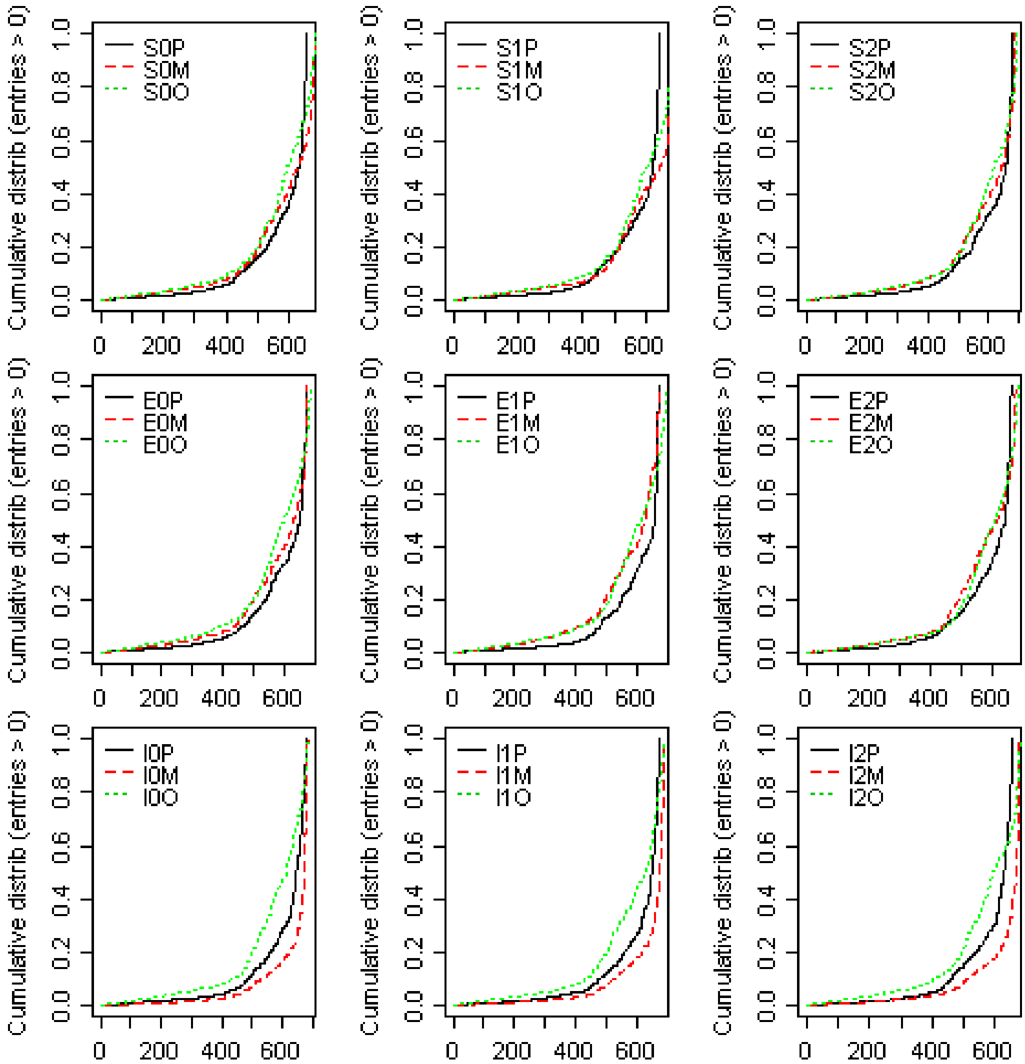


Figure A.20: Cumulative distribution plot for coarse scale spatial analysis of turtle average grid-cell relative biomass, comparing model specifications (each box contains the cumulative distributions for pessimistic [black], base case [red] and optimistic [green] specifications for a given combination of management strategy and development scenario).

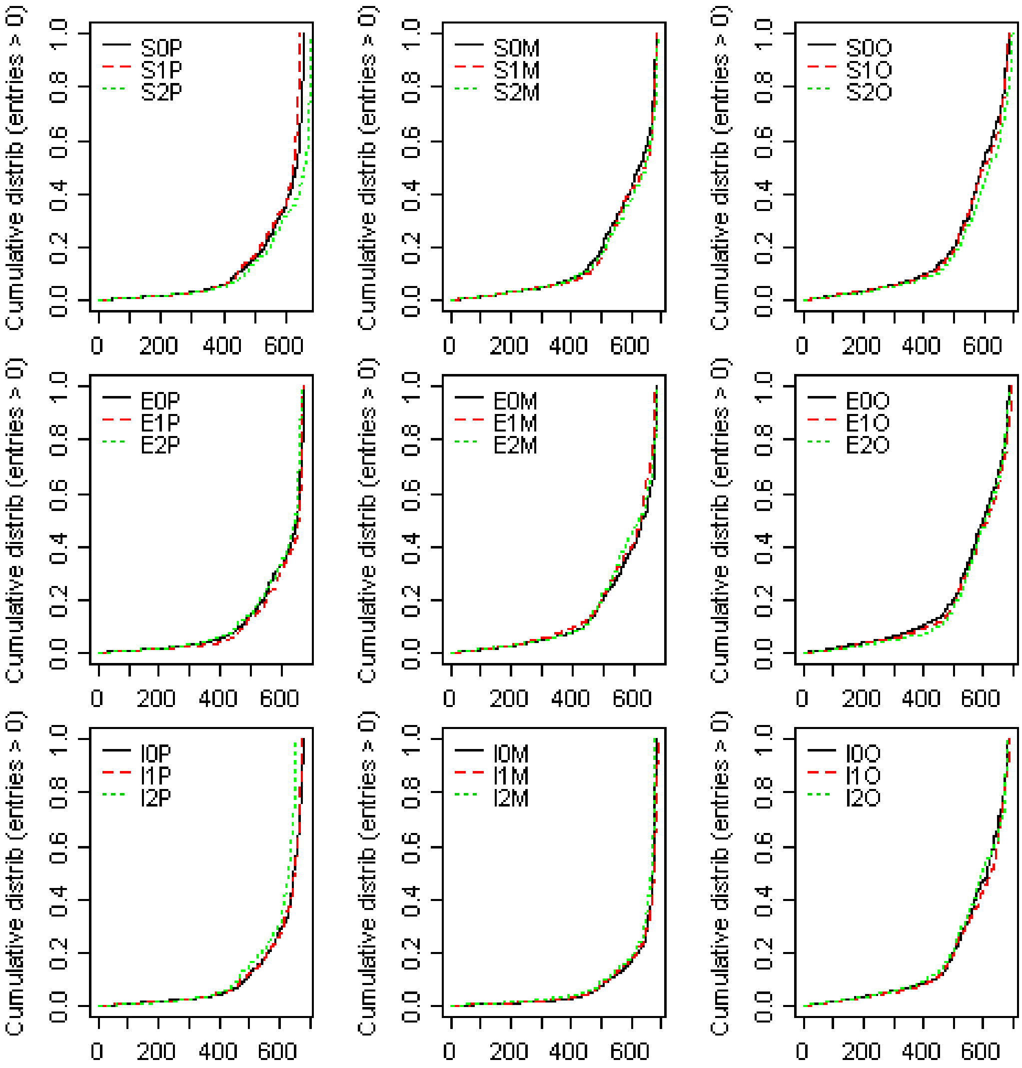


Figure A.21: Cumulative distribution plot for coarse scale spatial analysis of turtle average grid-cell relative biomass, comparing, comparing development scenarios (each box contains the cumulative distributions for 0-pulse [black], 1-pulse [red] and 2-pulse [green] development scenarios for a given combination of management strategy and model specification).

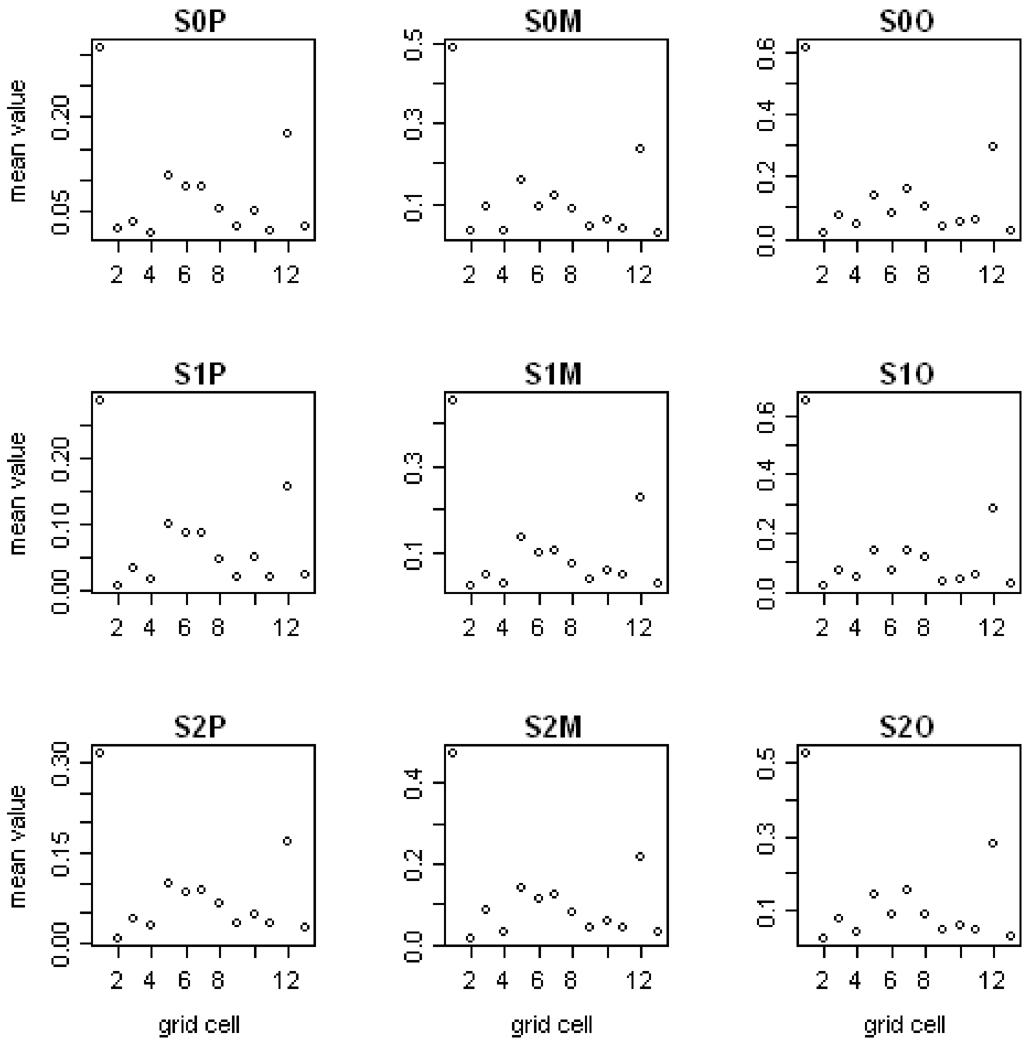


Figure A.22: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for turtles under status quo management for each combination of development scenario and model specification.

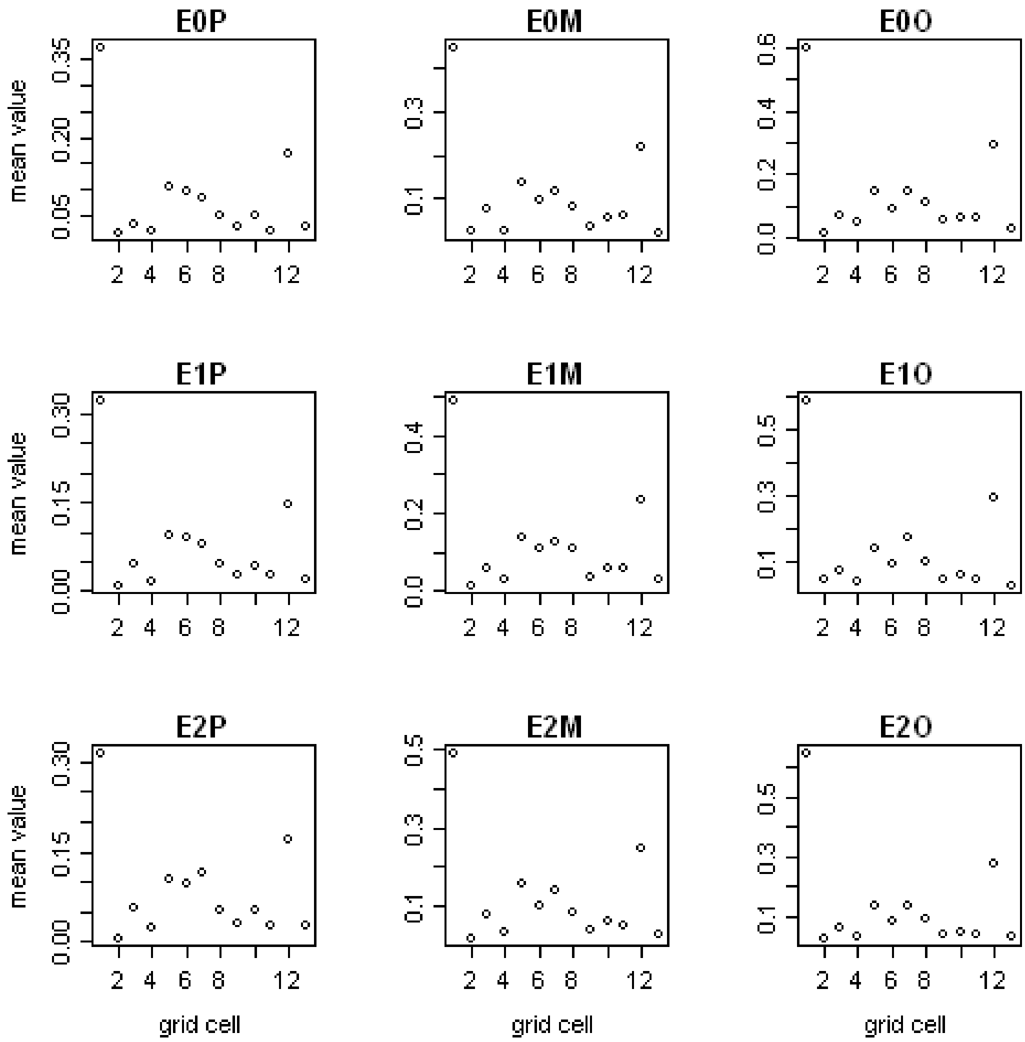


Figure A.23: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for turtles under enhanced management for each combination of development scenario and model specification.

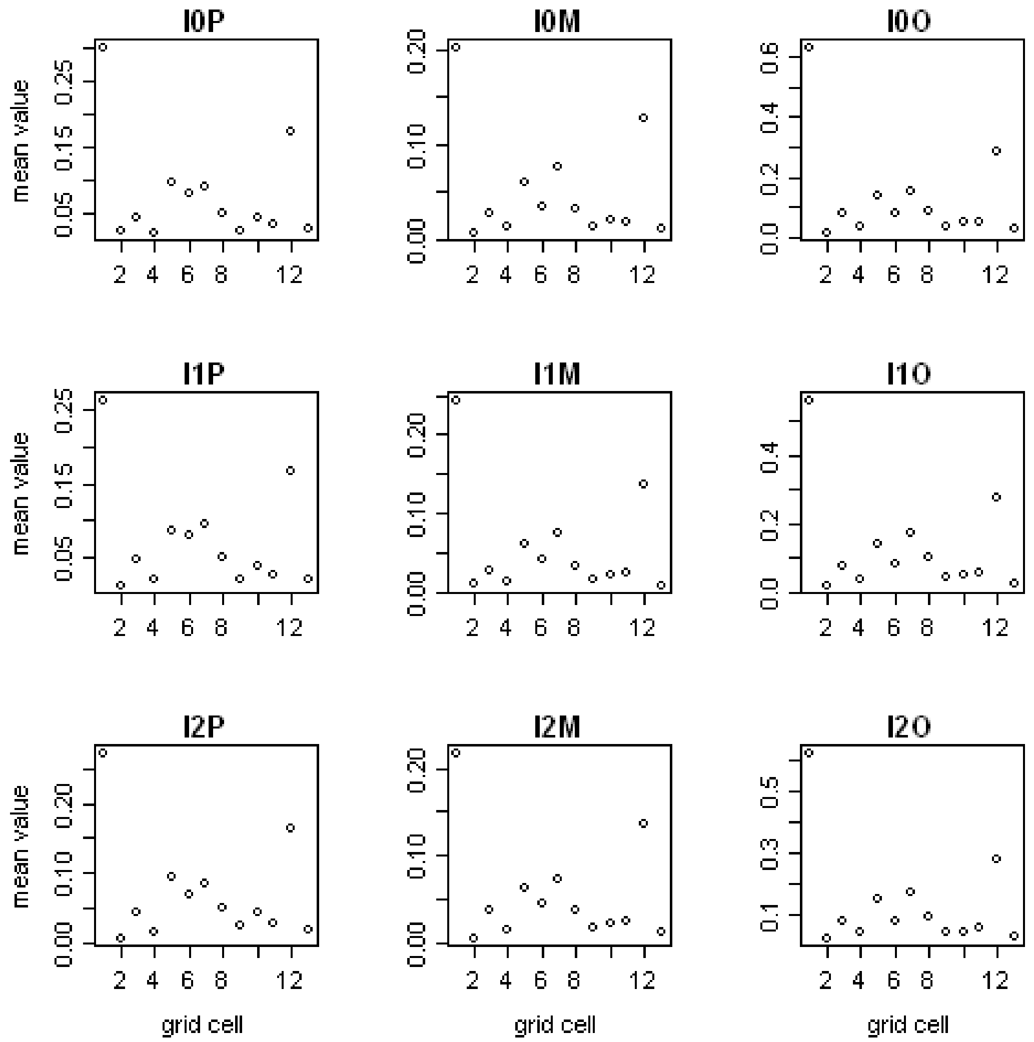


Figure A.24: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for turtles under integrated management for each combination of development scenario and model specification.

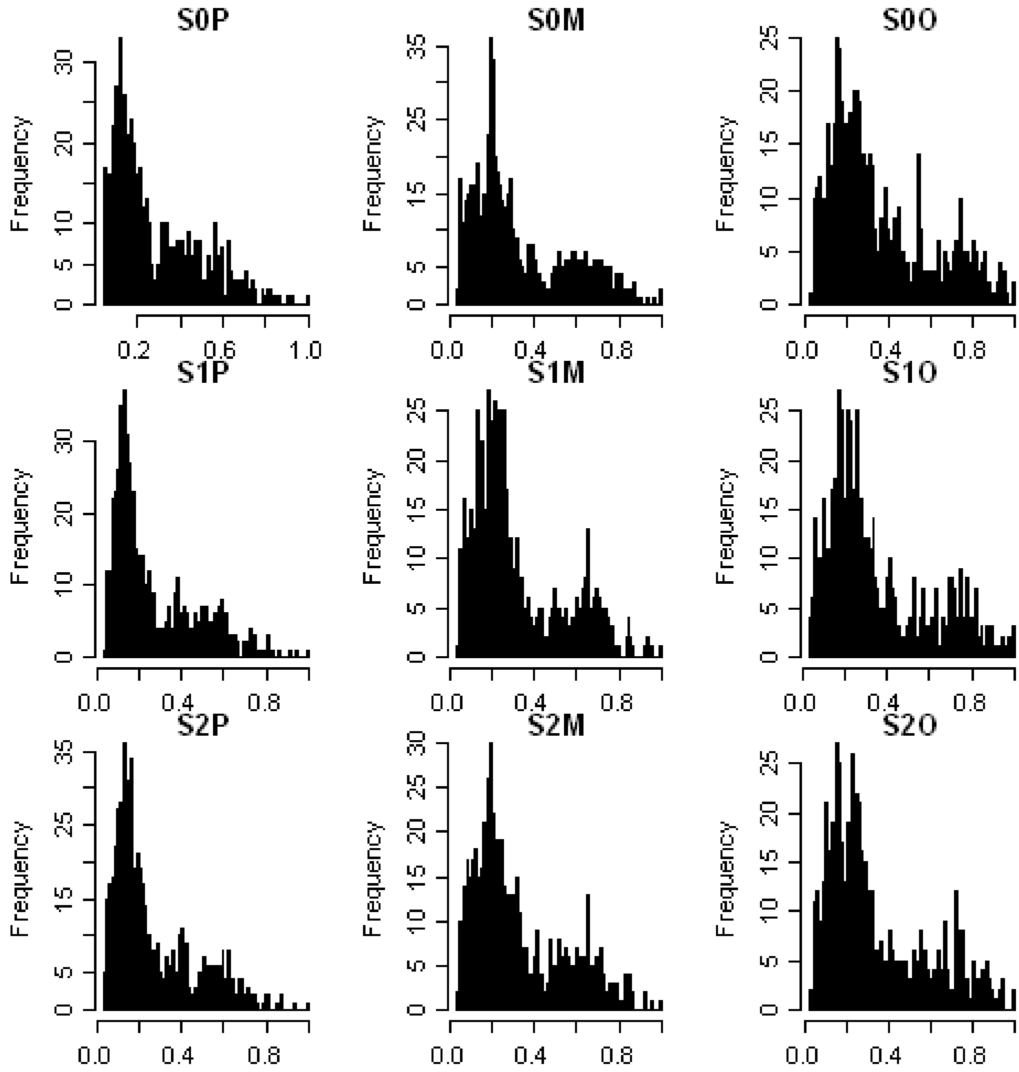


Figure A.25: Frequency histogram of coarse scale relative biomass (over time) for turtles under status quo management for each combination of development scenario and model specification.

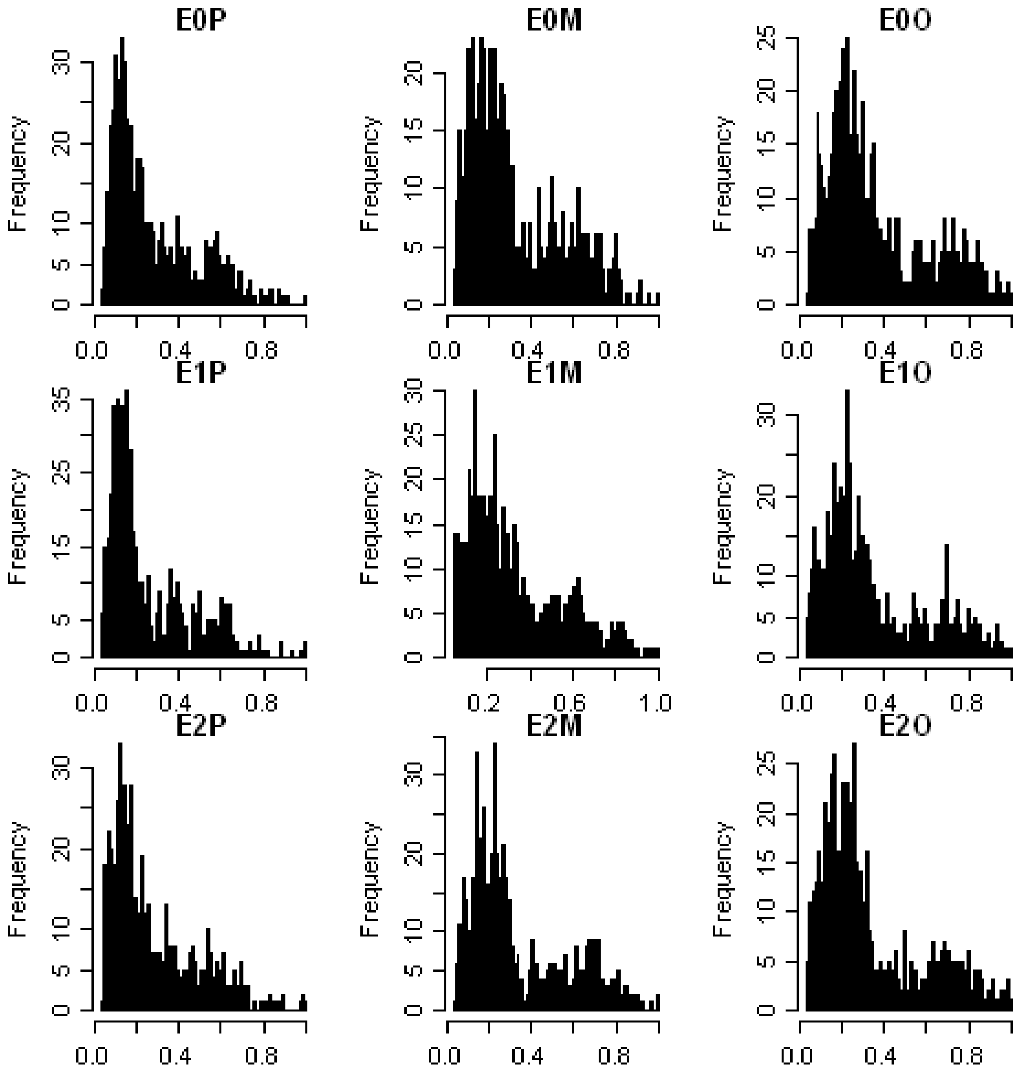


Figure A.26: Frequency histogram of coarse scale relative biomass (over time) for turtles under enhanced management for each combination of development scenario and model specification.

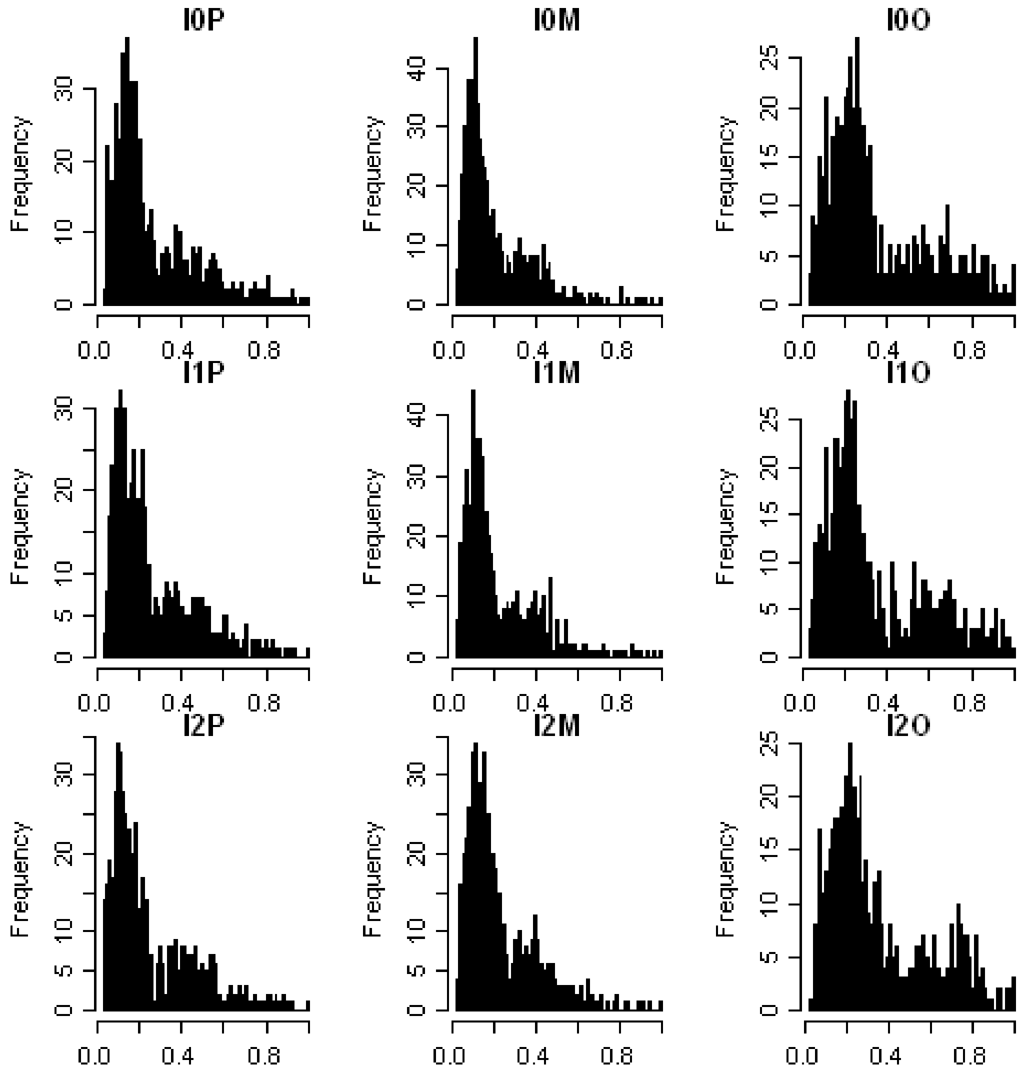


Figure A.27: Frequency histogram of coarse scale relative biomass (over time) for turtles under integrated management for each combination of development scenario and model specification.

A.4 Sharks

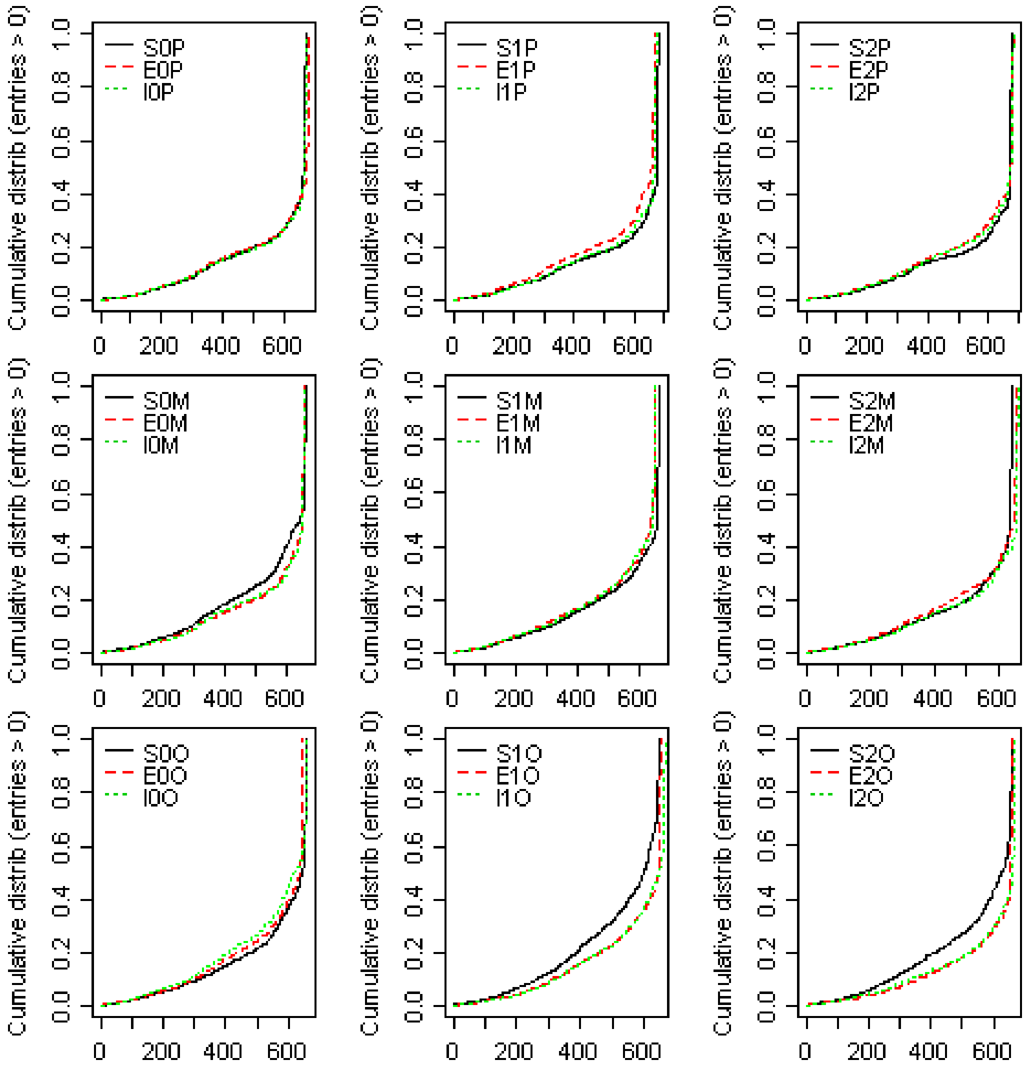


Figure A.28: Cumulative distribution plot for coarse scale spatial analysis of shark average grid-cell relative biomass, comparing management strategies (each box contains the cumulative distributions for status quo [black], enhanced [red] and integrated [green] management for a given combination of model specification and development scenario).

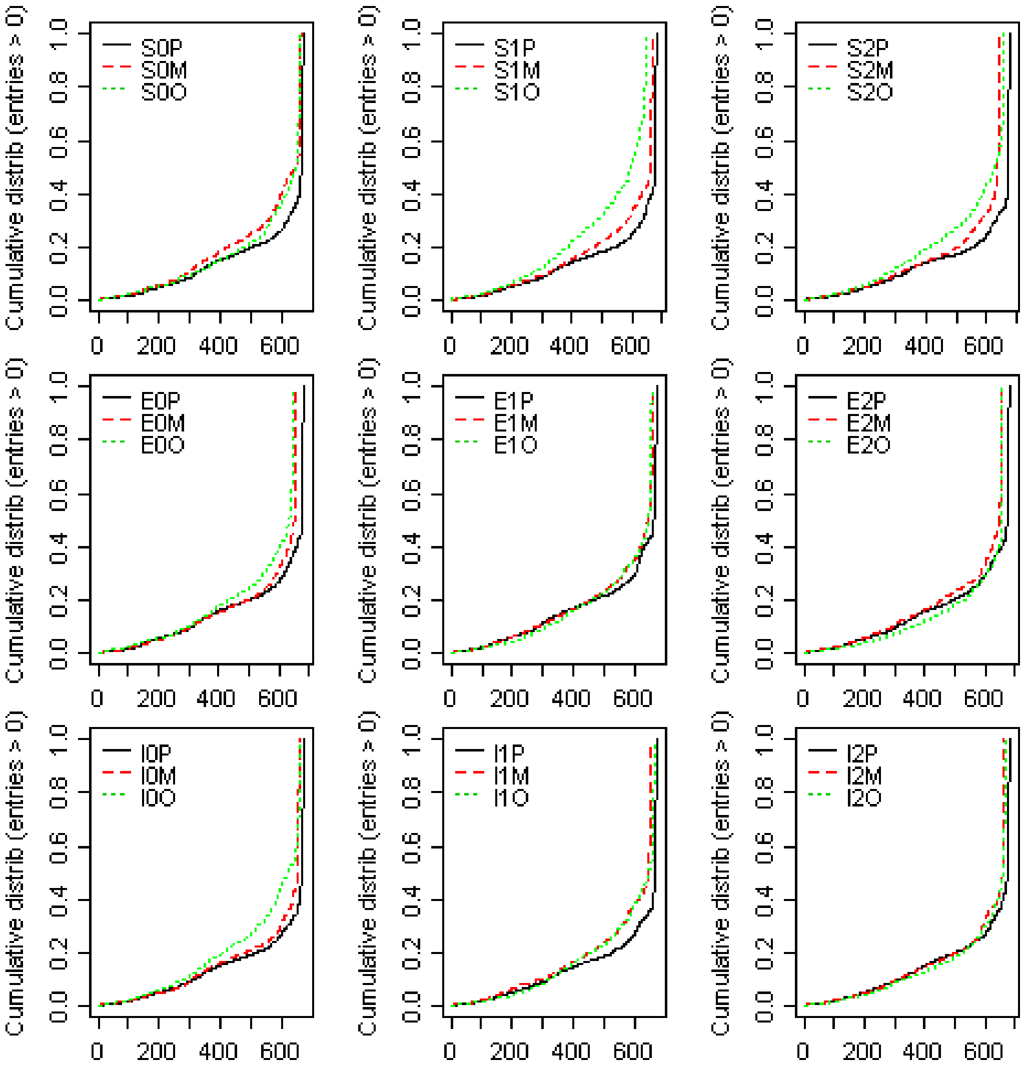


Figure A.29: Cumulative distribution plot for coarse scale spatial analysis of shark average grid-cell relative biomass, comparing model specifications (each box contains the cumulative distributions for pessimistic [black], base case [red] and optimistic [green] specifications for a given combination of management strategy and development scenario).

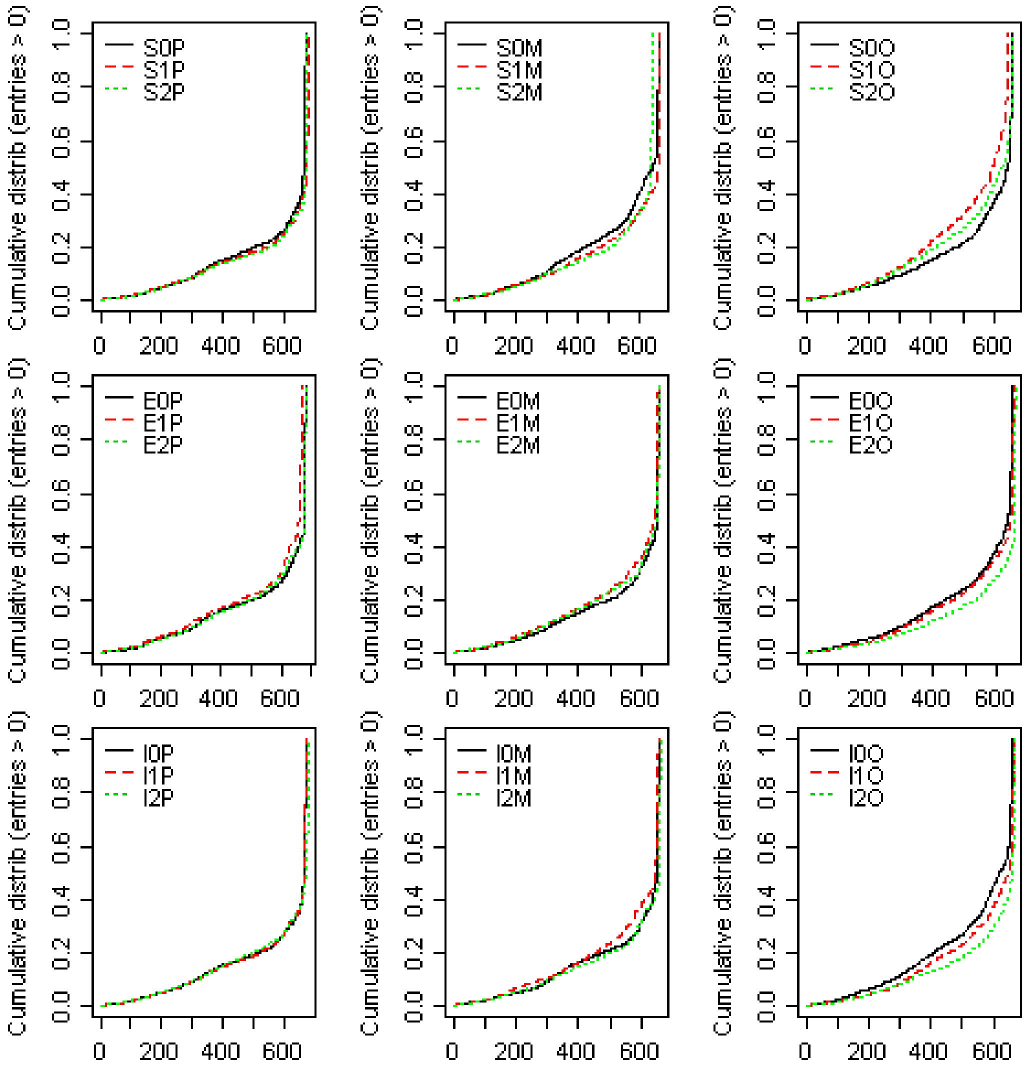


Figure A.30: Cumulative distribution plot for coarse scale spatial analysis of shark average grid-cell relative biomass,, comparing development scenarios (each box contains the cumulative distributions for 0-pulse [black], 1-pulse [red] and 2-pulse [green] development scenarios for a given combination of management strategy and model specification).

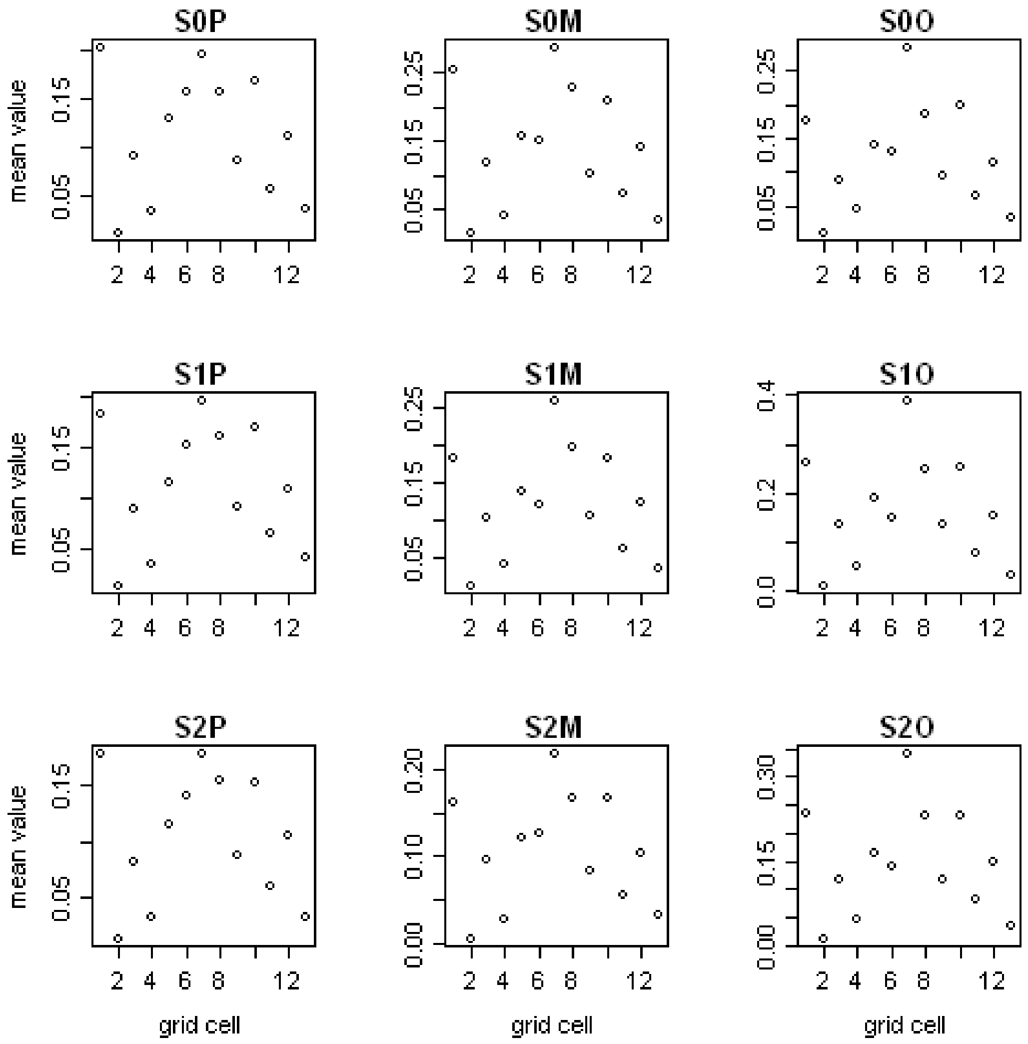


Figure A.31: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for sharks under status quo management for each combination of development scenario and model specification.

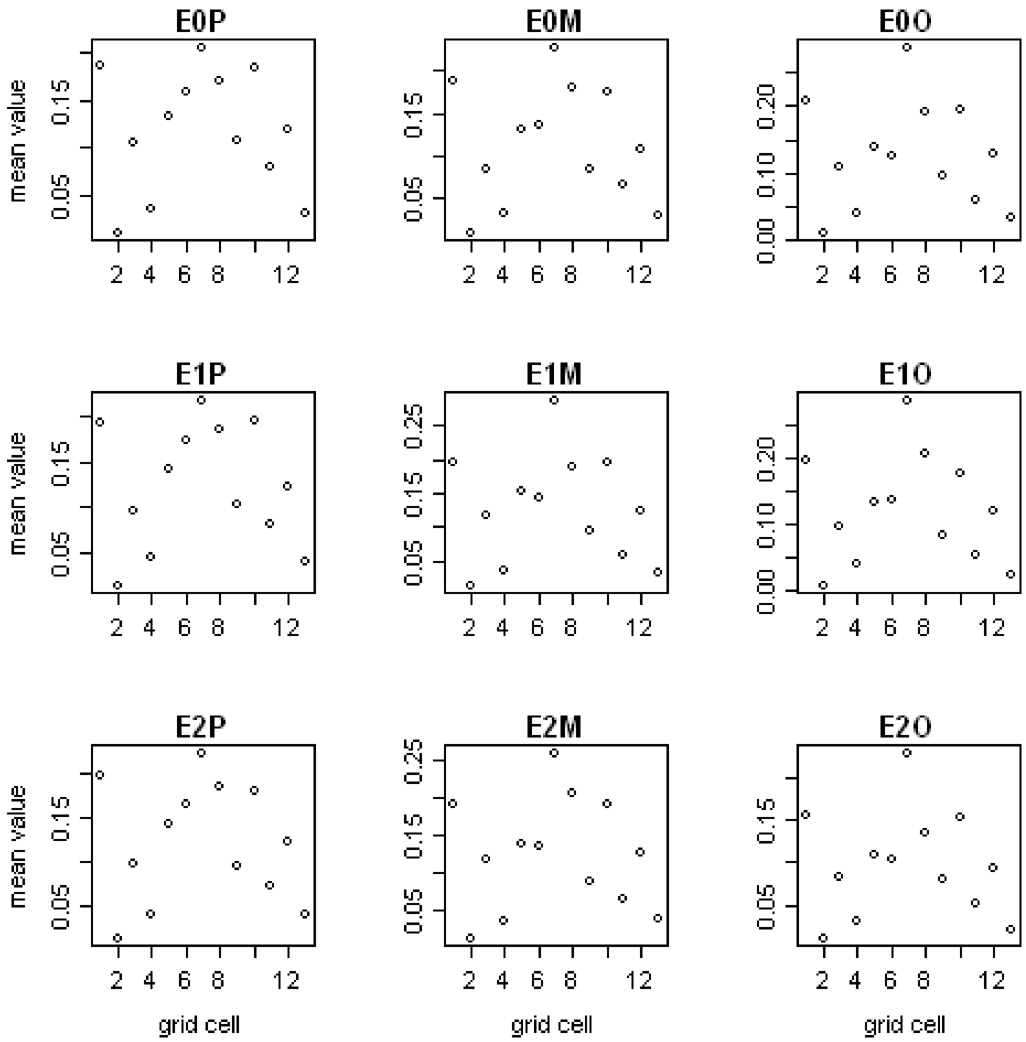


Figure A.32: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for sharks under enhanced management for each combination of development scenario and model specification.

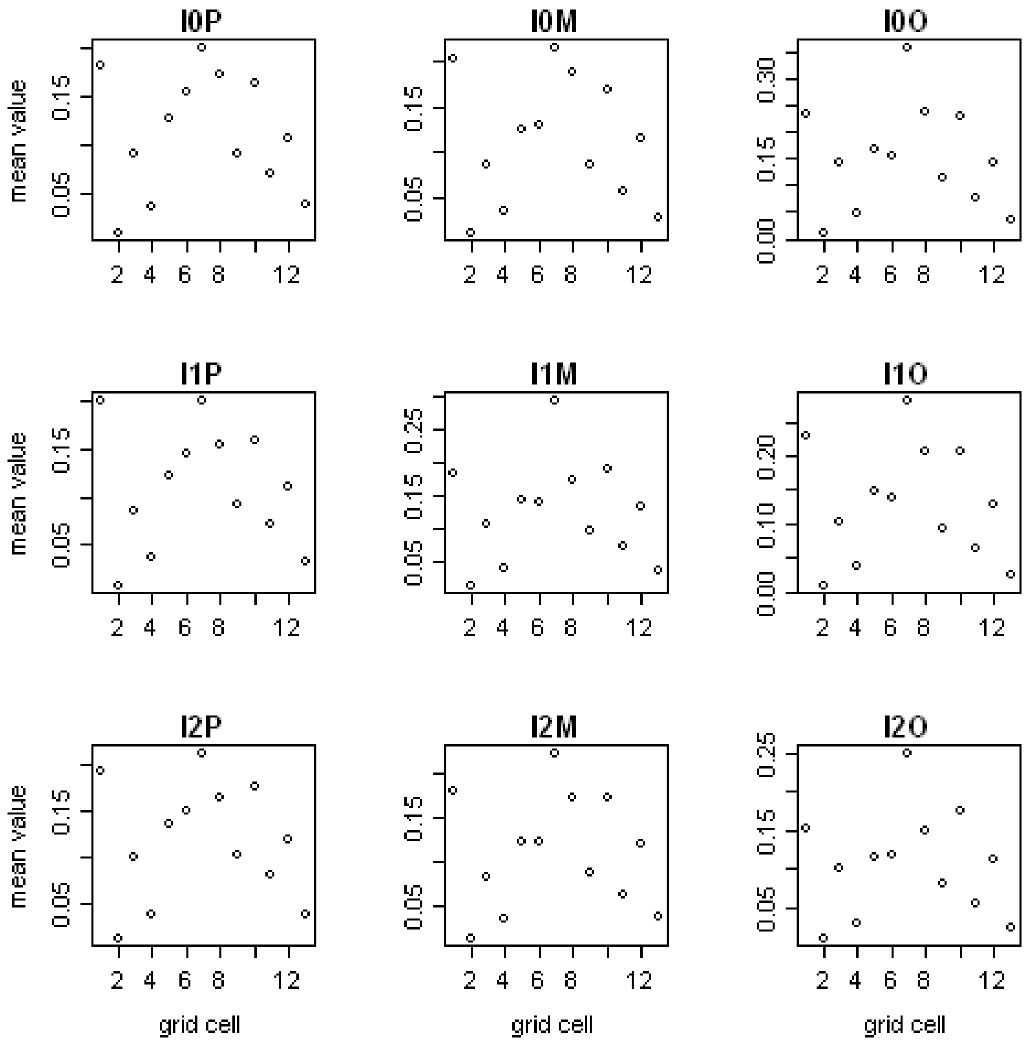


Figure A.33: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for sharks under integrated management for each combination of development scenario and model specification.

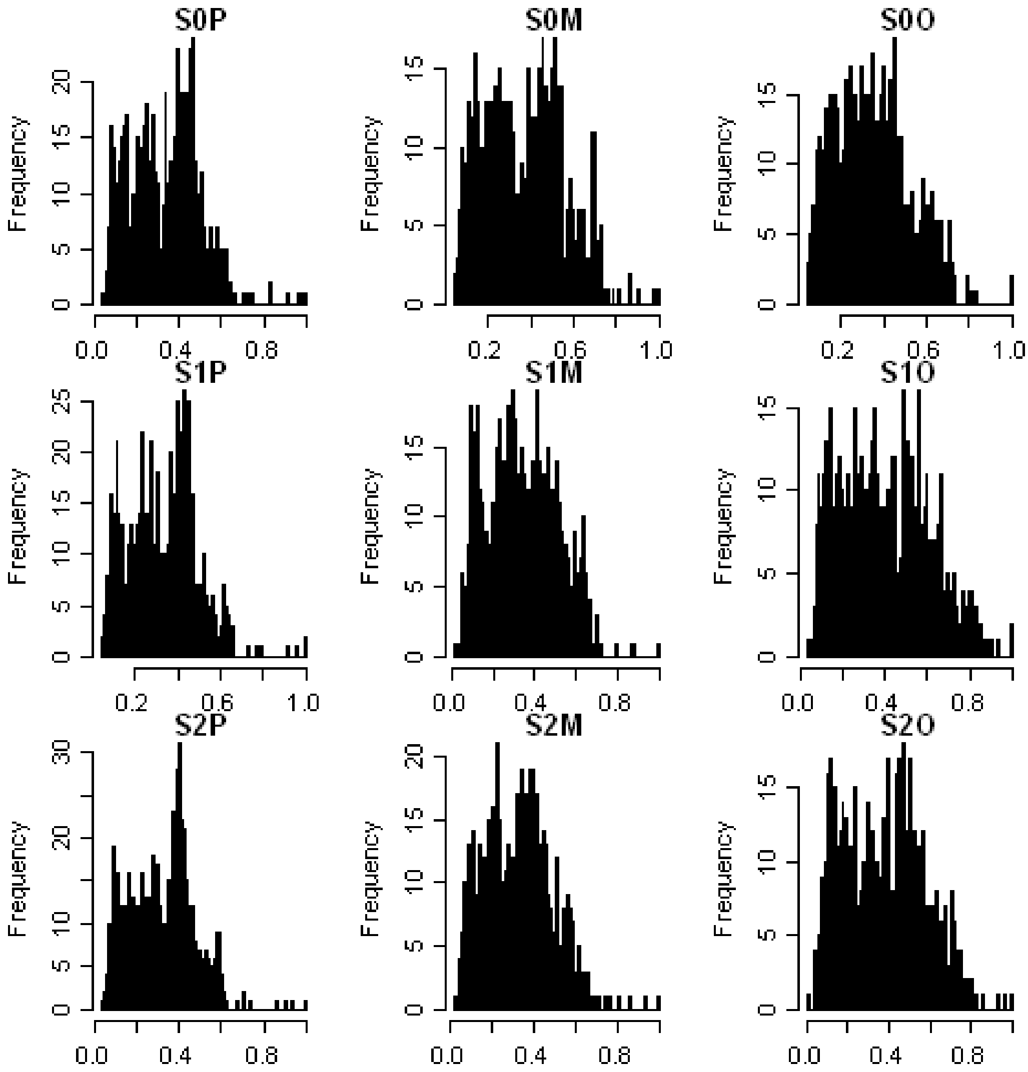


Figure A.34: Frequency histogram of coarse scale relative biomass (over time) for sharks under status quo management for each combination of development scenario and model specification.

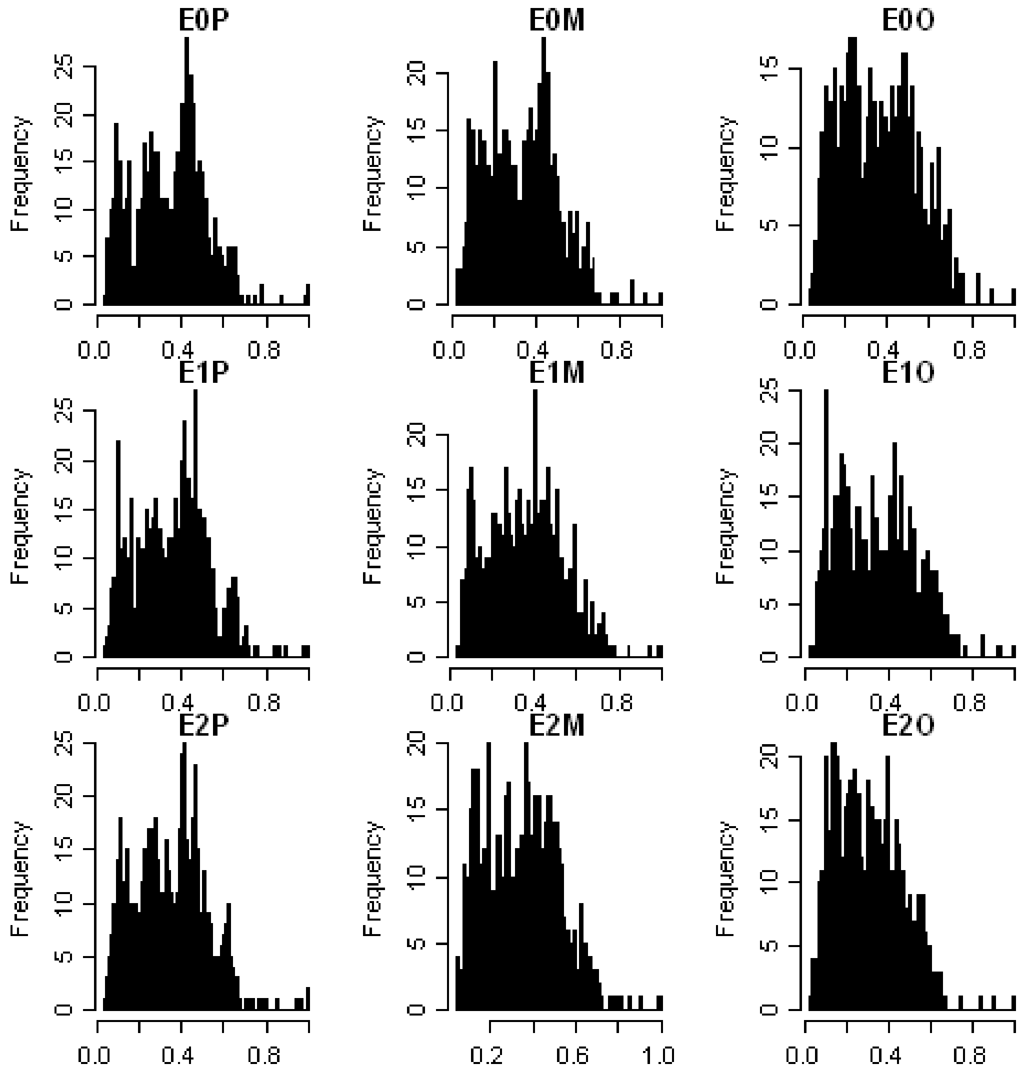


Figure A.35: Frequency histogram of coarse scale relative biomass (over time) for sharks under enhanced management for each combination of development scenario and model specification.

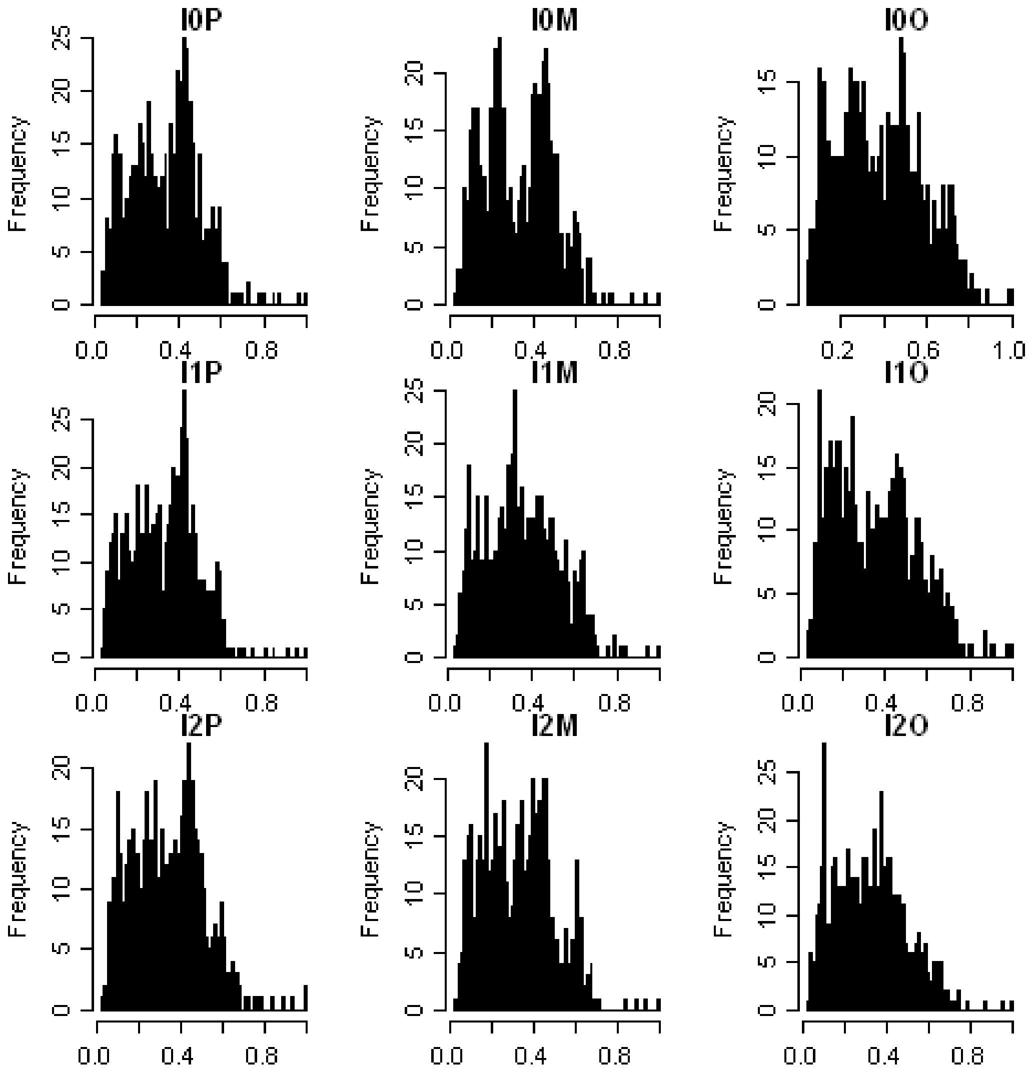


Figure A.36: Frequency histogram of coarse scale relative biomass (over time) for sharks under integrated management for each combination of development scenario and model specification.

A.5 Large lutjanids

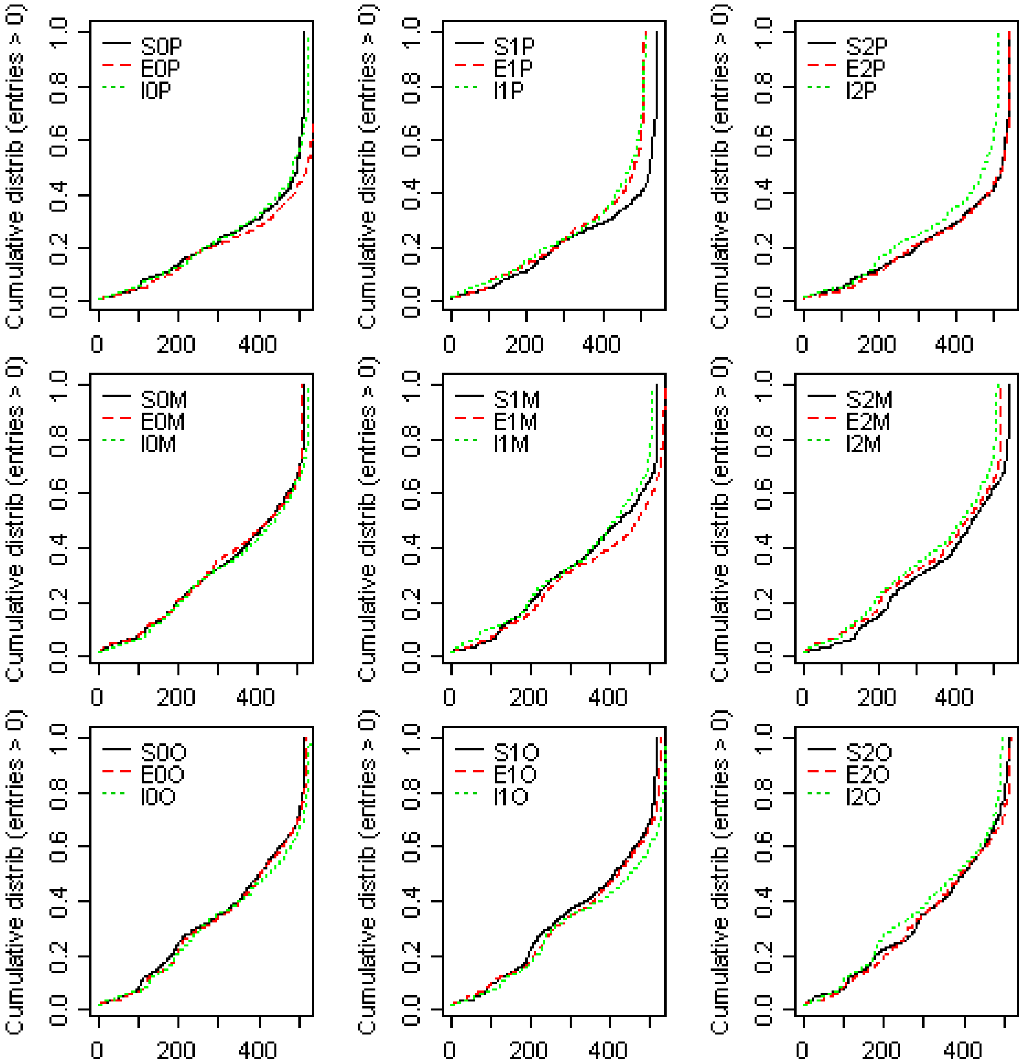


Figure A.37: Cumulative distribution plot for coarse scale spatial analysis of large lutjanid average grid-cell relative biomass, comparing management strategies (each box contains the cumulative distributions for status quo [black], enhanced [red] and integrated [green] management for a given combination of model specification and development scenario).

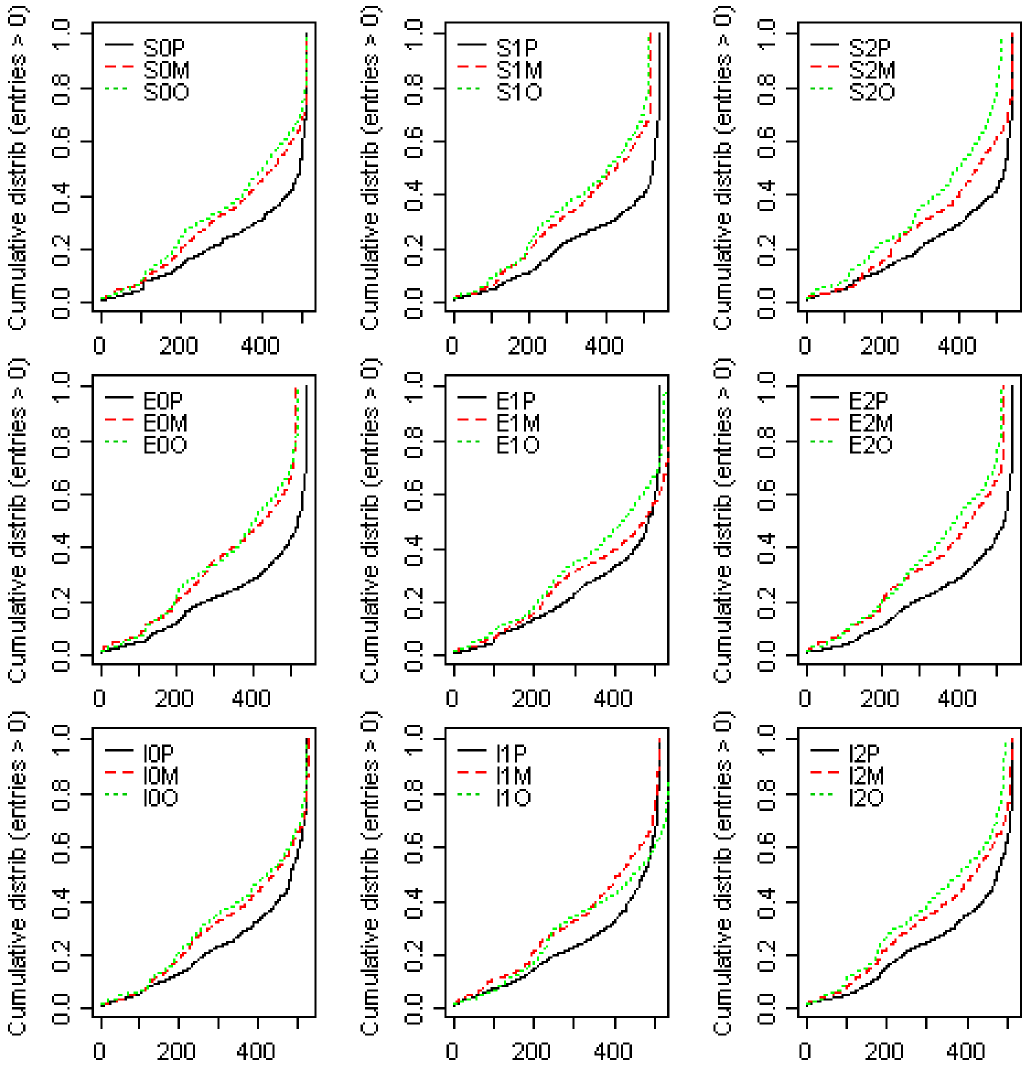


Figure A.38: Cumulative distribution plot for coarse scale spatial analysis of large lutjanid average grid-cell relative biomass, comparing model specifications (each box contains the cumulative distributions for pessimistic [black], base case [red] and optimistic [green] specifications for a given combination of management strategy and development scenario).

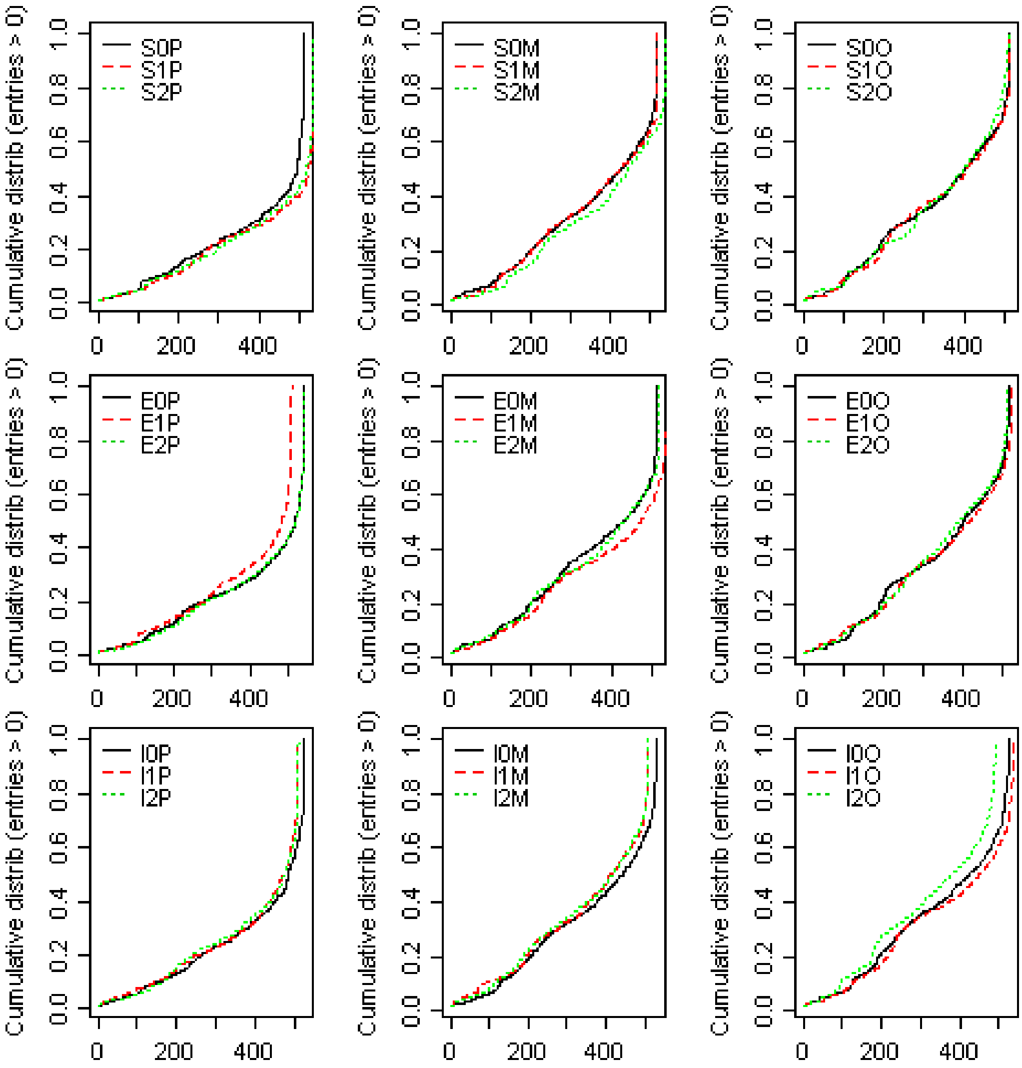


Figure A.39: Cumulative distribution plot for coarse scale spatial analysis of large lutjanid average grid-cell relative biomass, comparing development scenarios (each box contains the cumulative distributions for 0-pulse [black], 1-pulse [red] and 2-pulse [green] development scenarios for a given combination of management strategy and model specification).

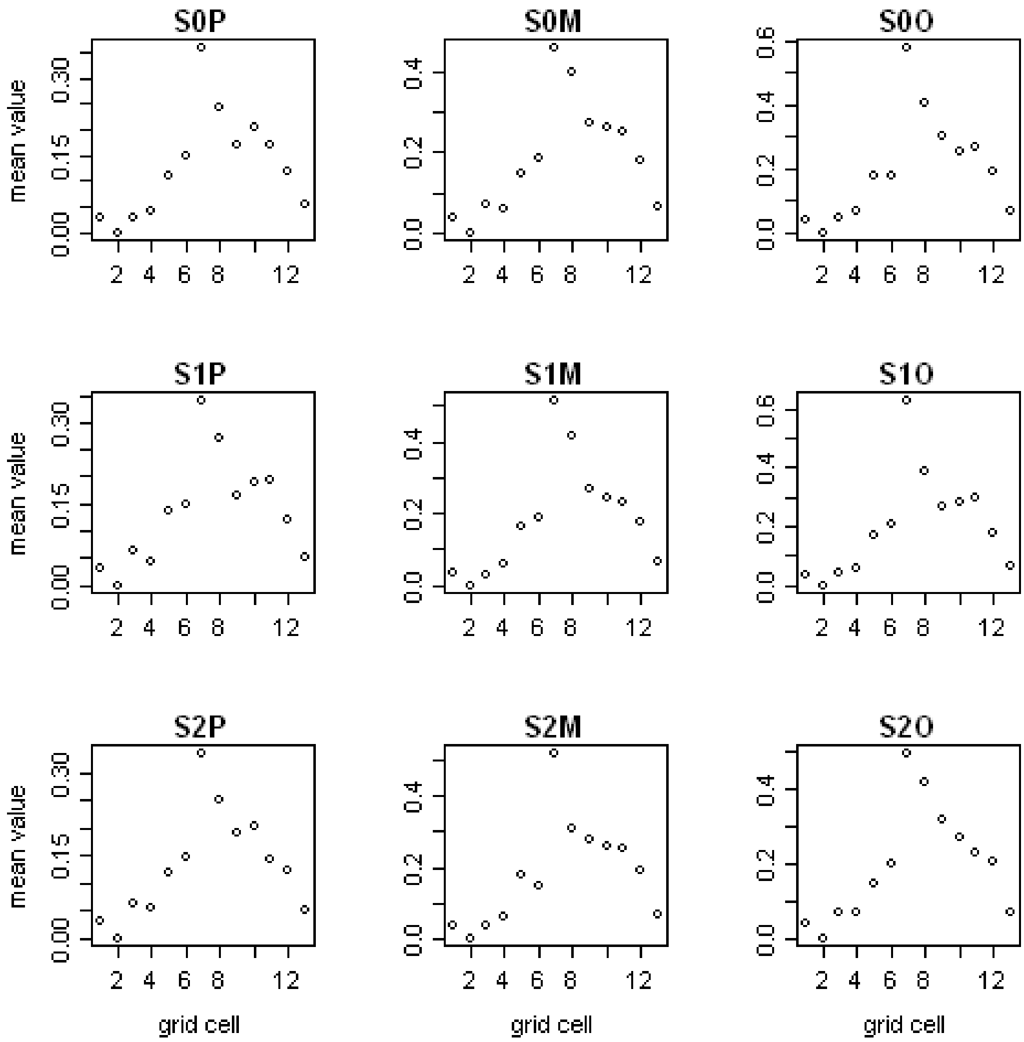


Figure A.40: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for large lutjanids under status quo management for each combination of development scenario and model specification.

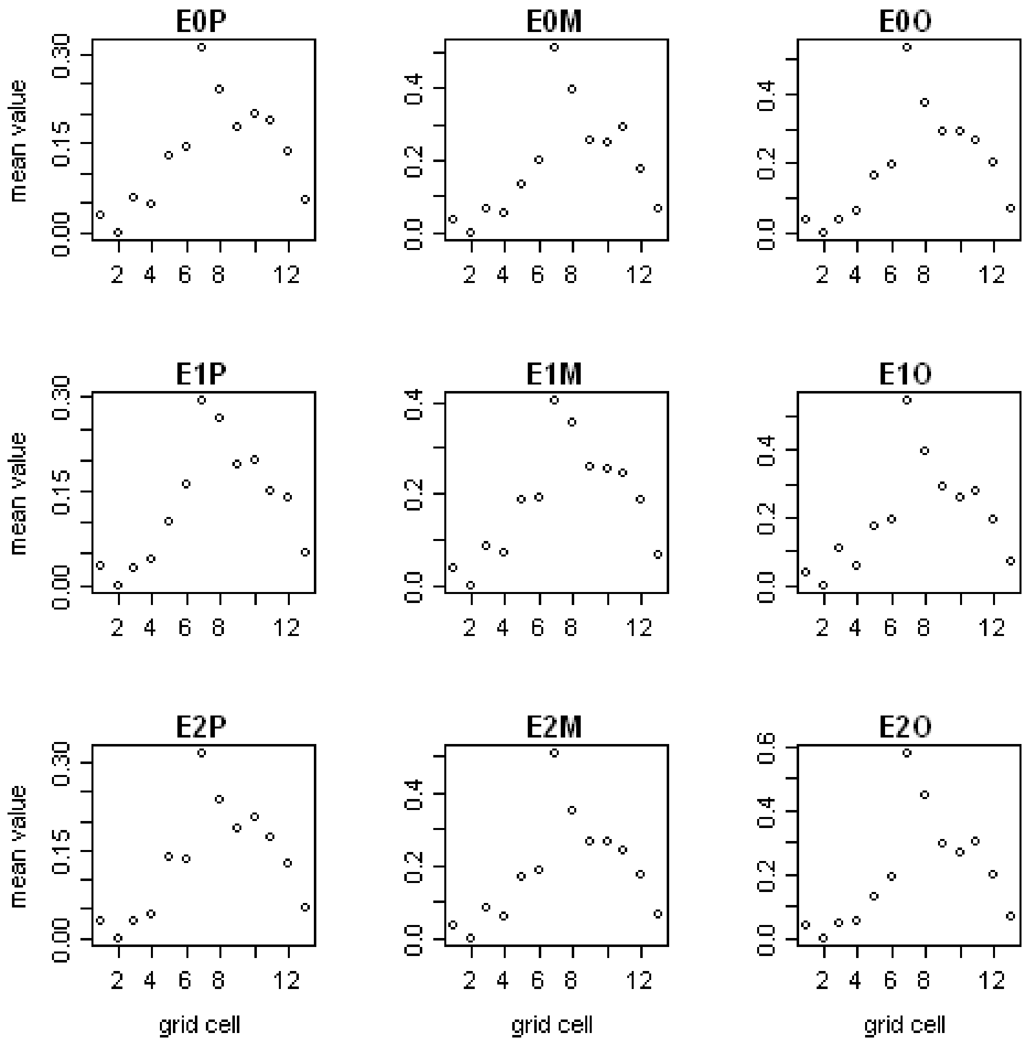


Figure A.41: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for large lutjanids under enhanced management for each combination of development scenario and model specification.

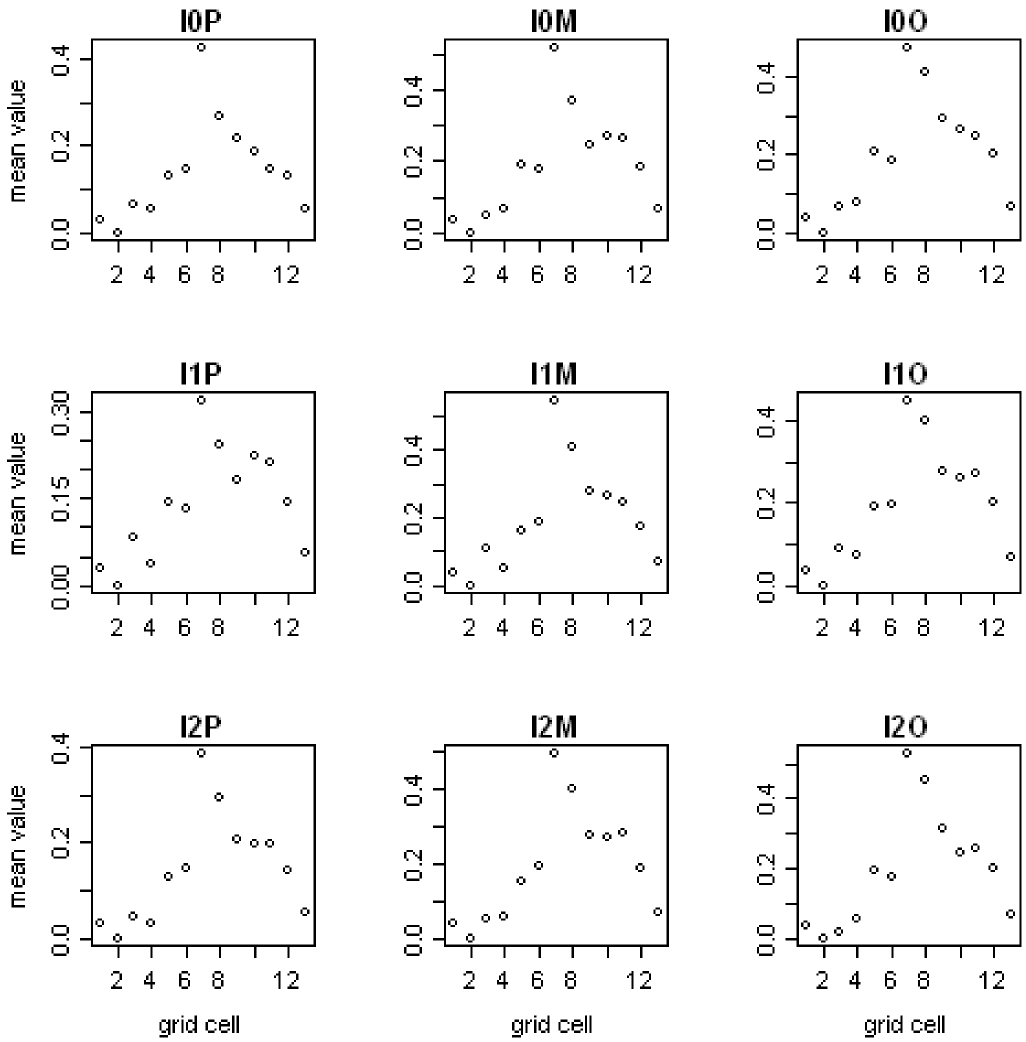


Figure A.42: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for large lutjanids under integrated management for each combination of development scenario and model specification.

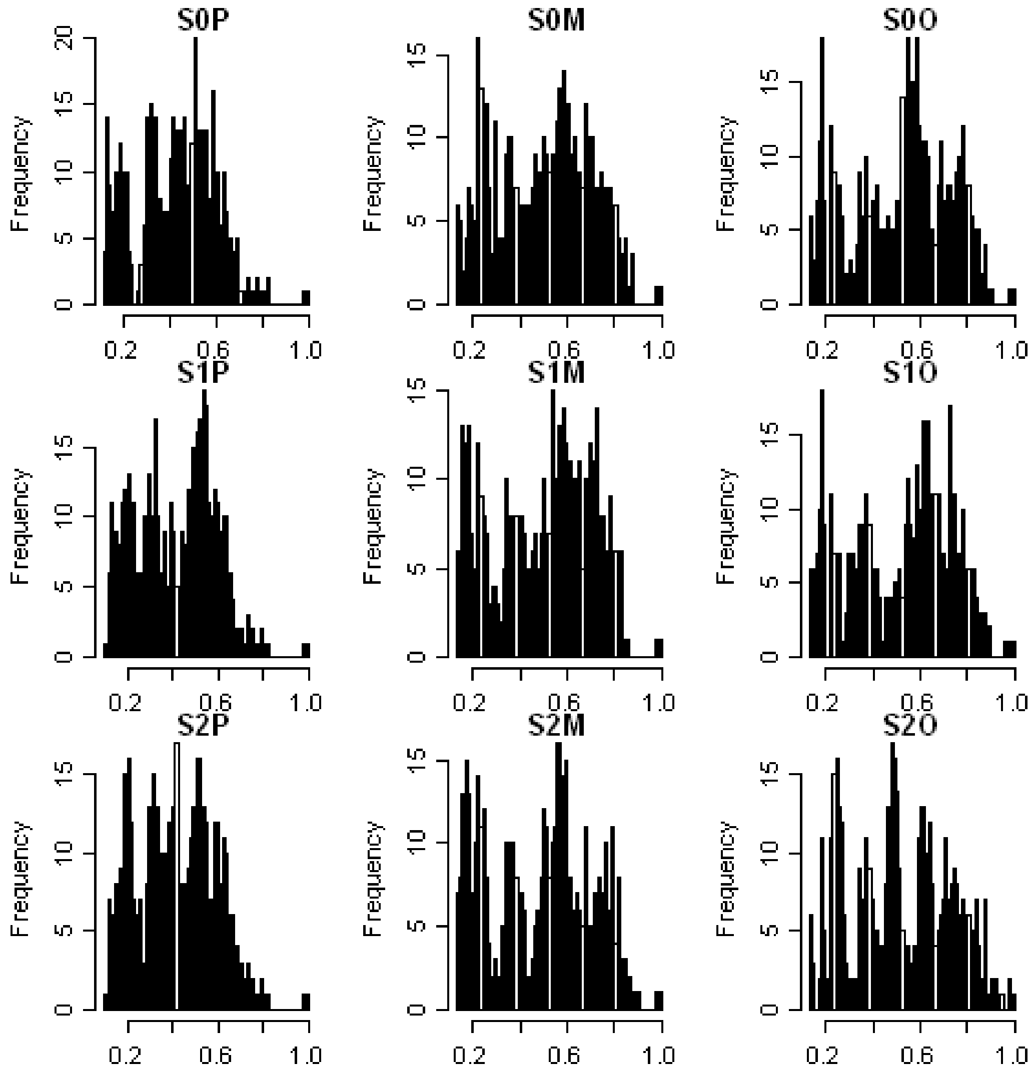


Figure A.43: Frequency histogram of coarse scale relative biomass (over time) for large lutjanids under status quo management for each combination of development scenario and model specification.

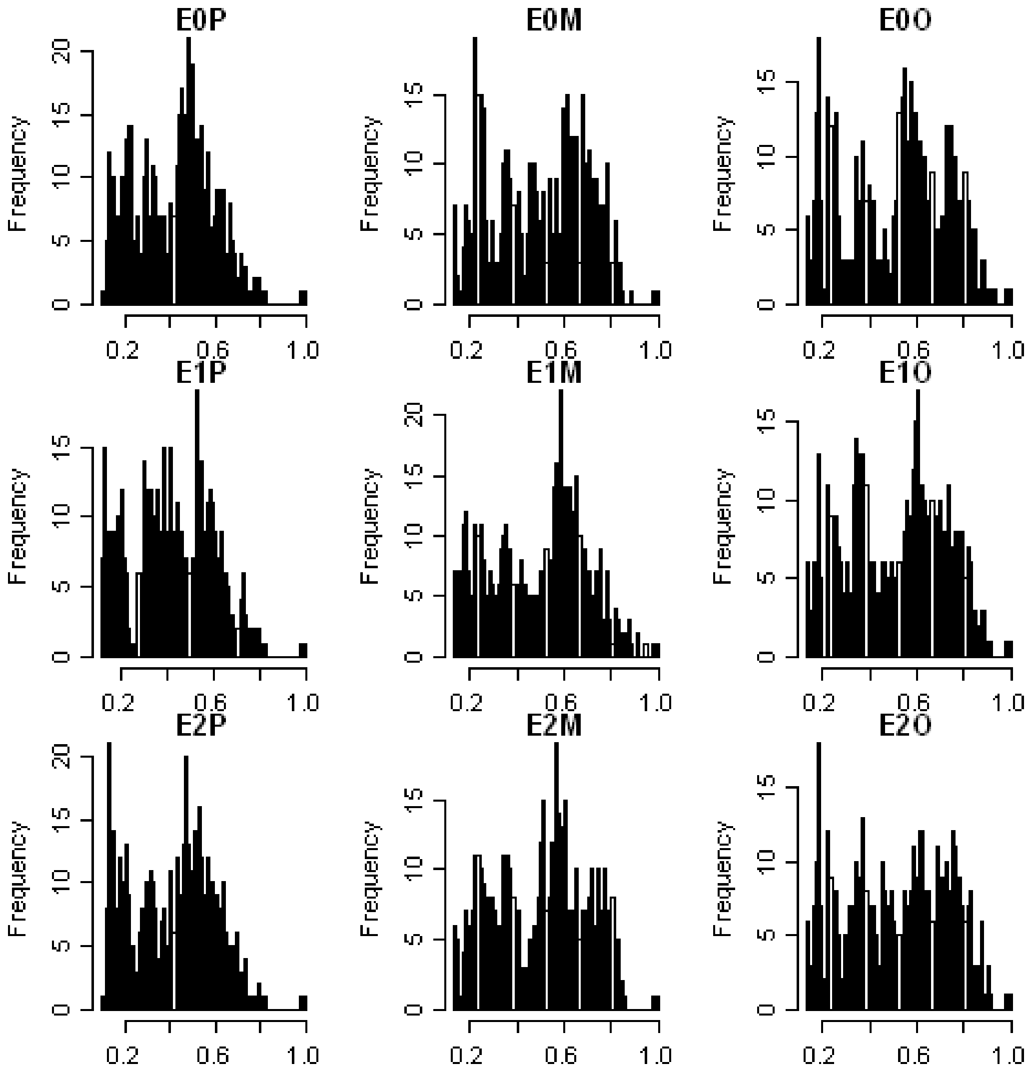


Figure A.44: Frequency histogram of coarse scale relative biomass (over time) for large lutjanids under enhanced management for each combination of development scenario and model specification.

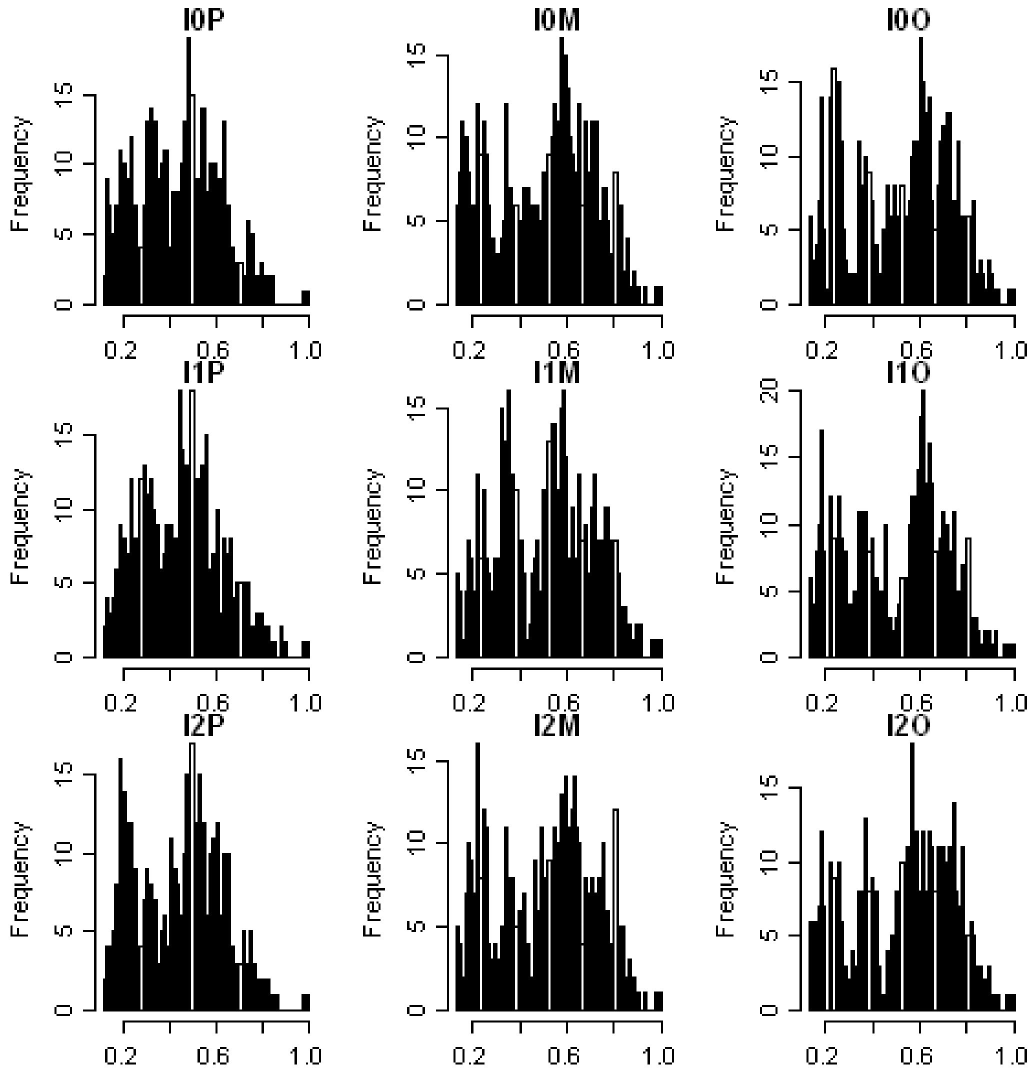


Figure A.45: Frequency histogram of coarse scale relative biomass (over time) for large lutjanids under integrated management for each combination of development scenario and model specification.

A.6 Small lutjanids

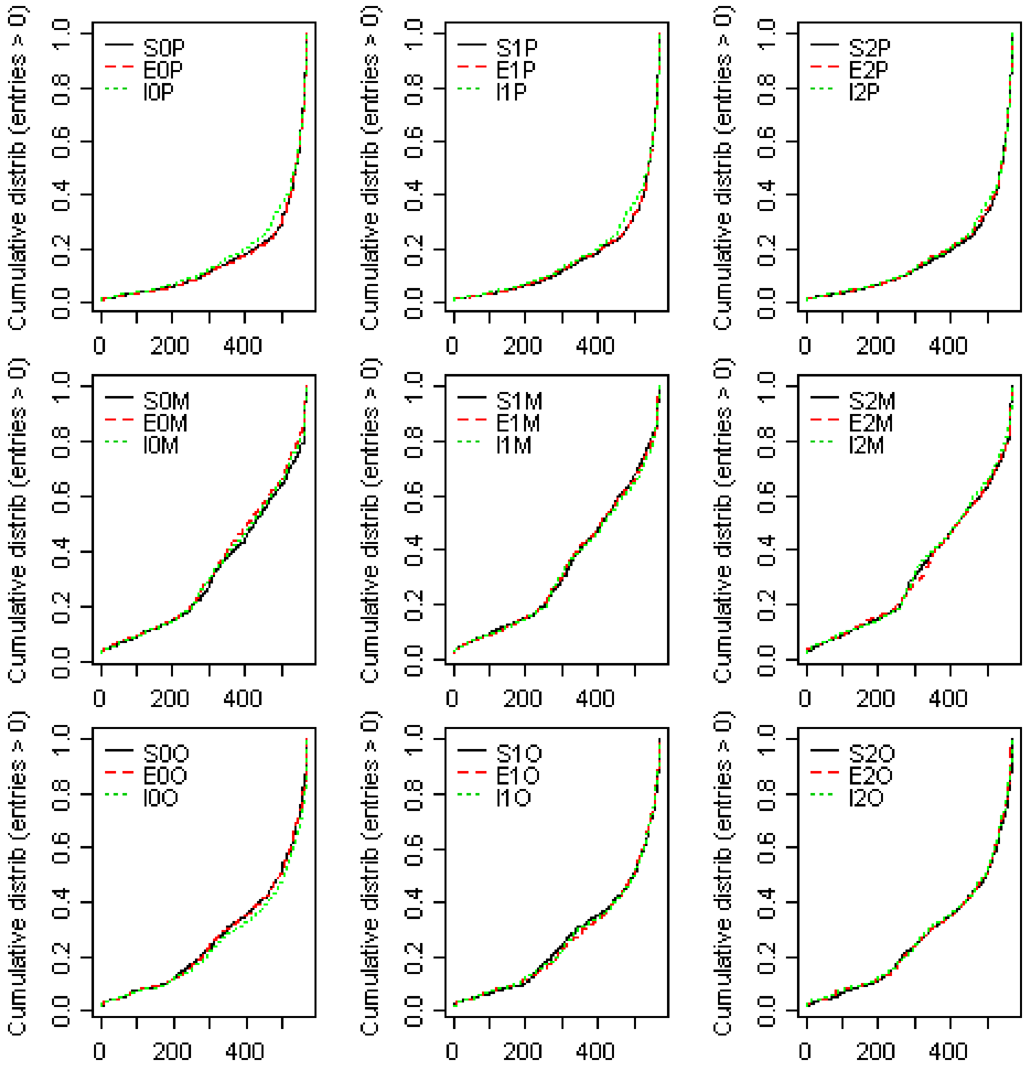


Figure A.46: Cumulative distribution plot for coarse scale spatial analysis of small lutjanid average grid-cell relative biomass, comparing management strategies (each box contains the cumulative distributions for status quo [black], enhanced [red] and integrated [green] management for a given combination of model specification and development scenario.

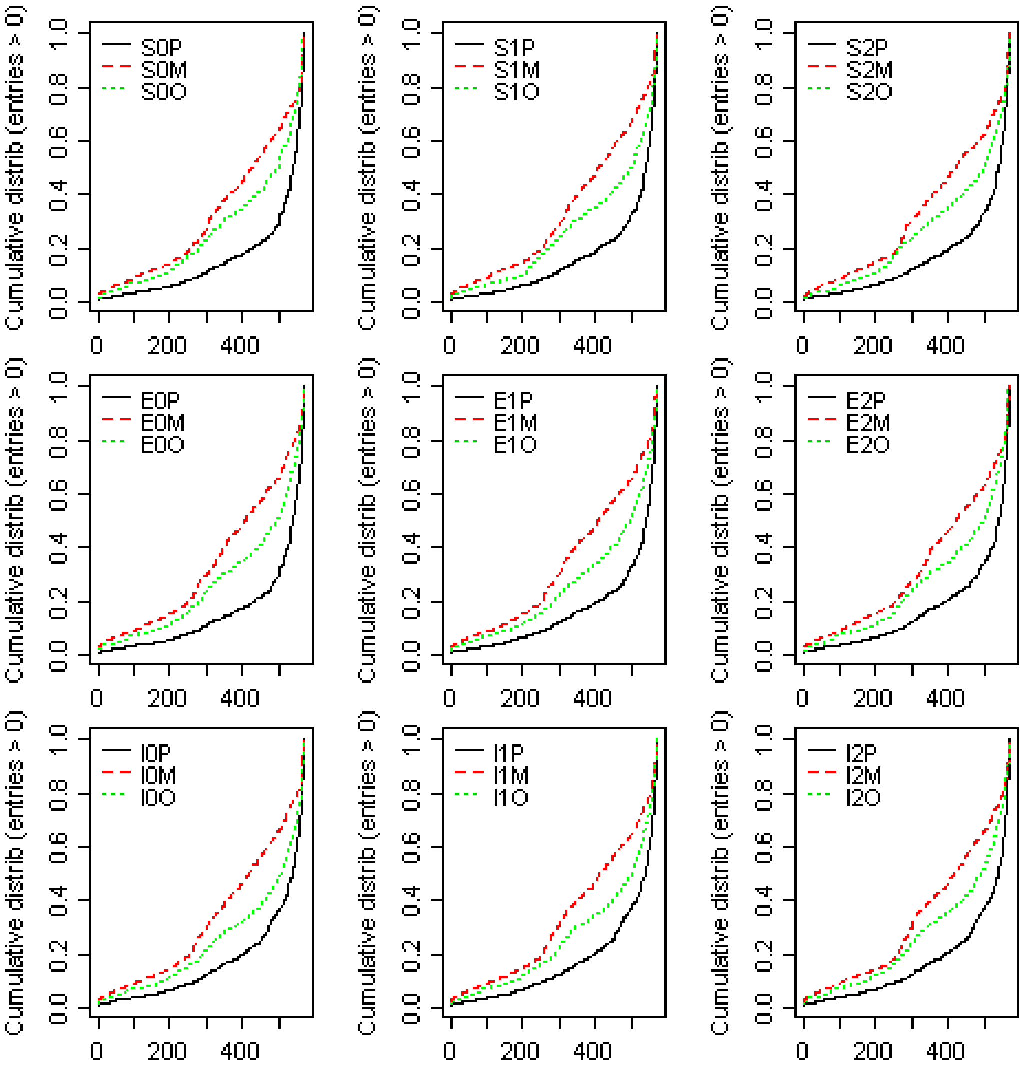


Figure A.47: Cumulative distribution plot for coarse scale spatial analysis of small lutjanid average grid-cell relative biomass, comparing model specifications (each box contains the cumulative distributions for pessimistic [black], base case [red] and optimistic [green] specifications for a given combination of management strategy and development scenario).

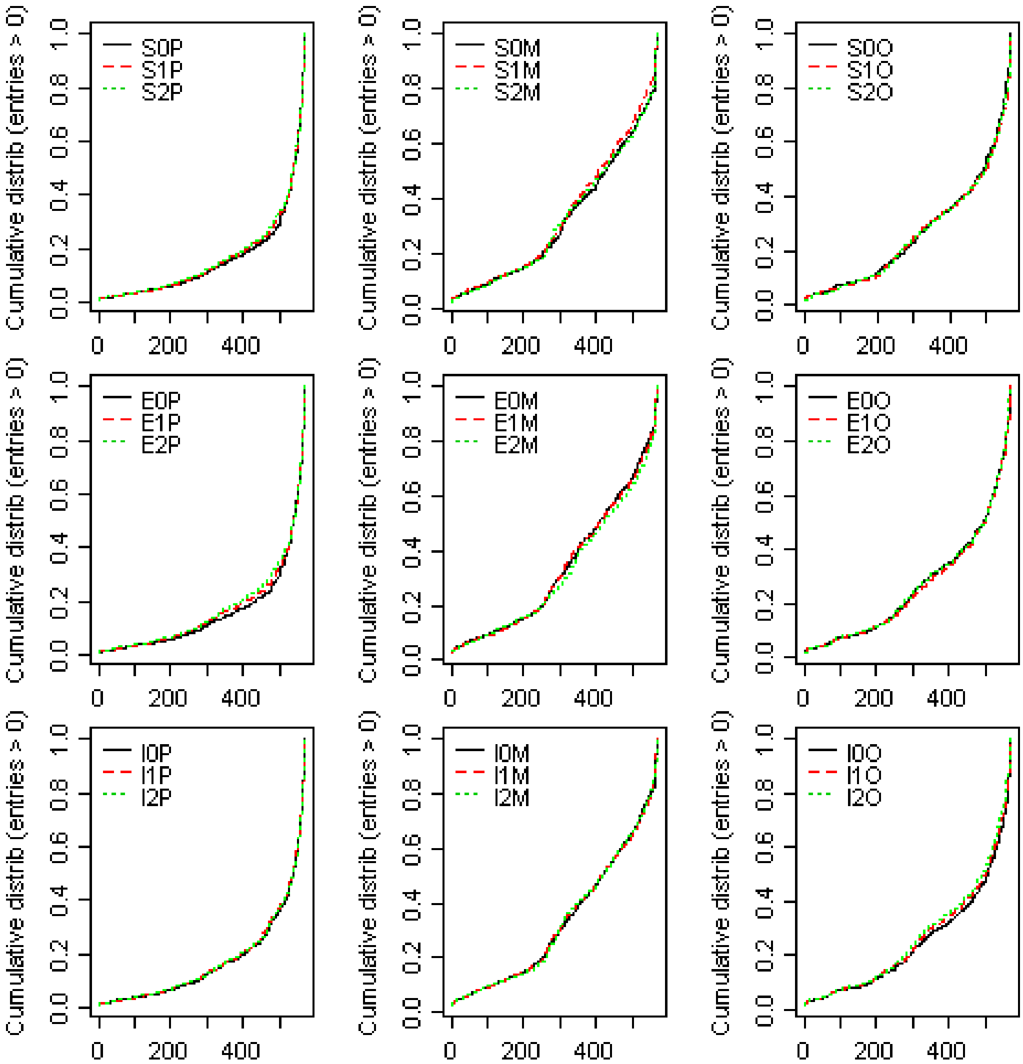


Figure A.48: Cumulative distribution plot for coarse scale spatial analysis of small lutjanid average grid-cell relative biomass, comparing development scenarios (each box contains the cumulative distributions for 0-pulse [black], 1-pulse [red] and 2-pulse [green] development scenarios for a given combination of management strategy and model specification).

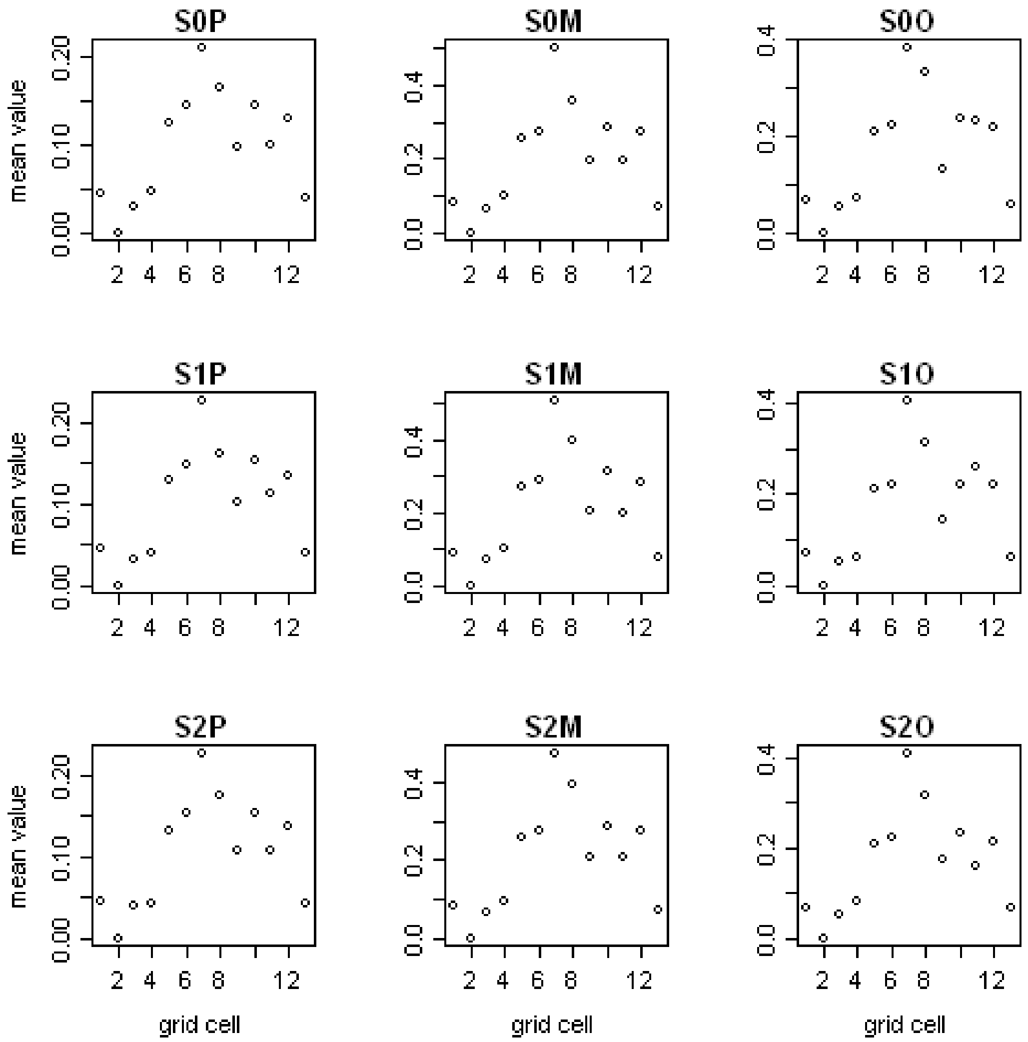


Figure A.49: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for small lutjanids under status quo management for each combination of development scenario and model specification.

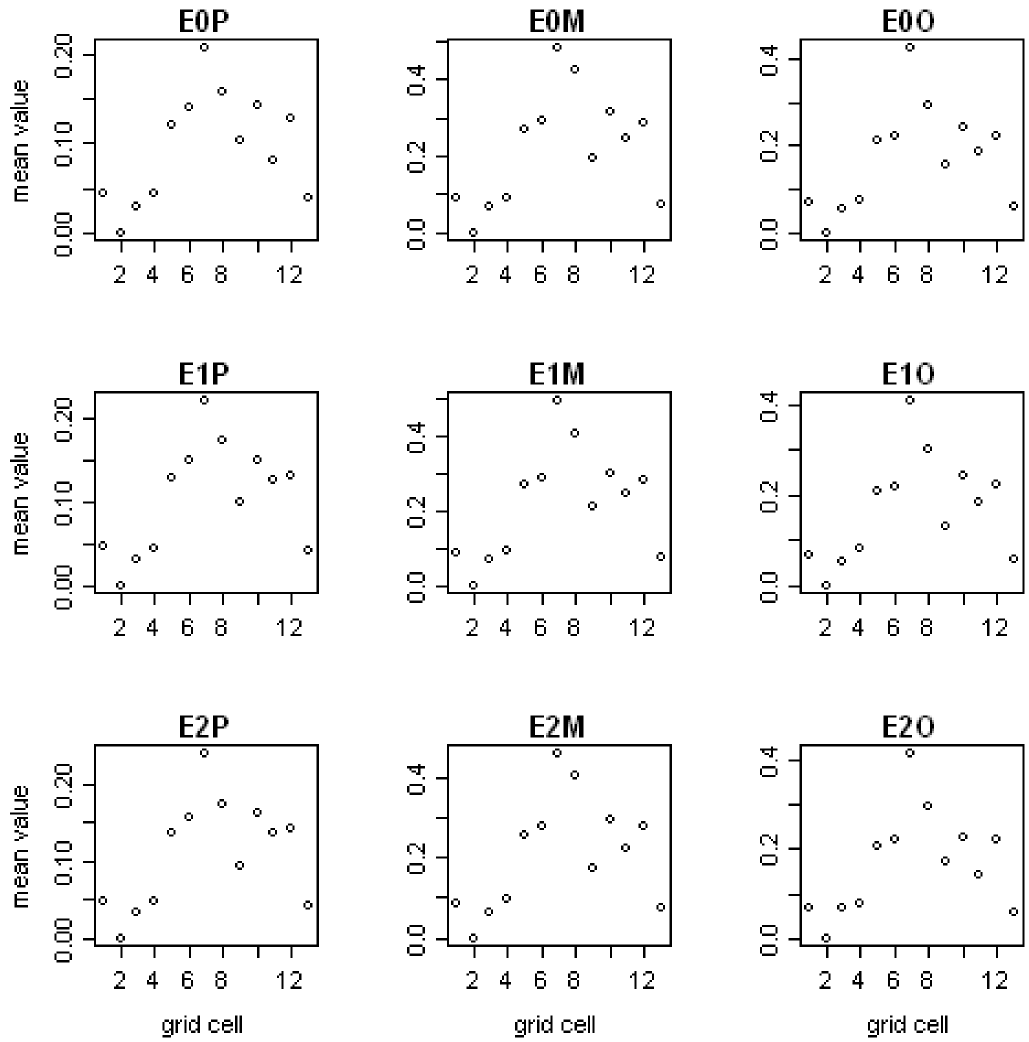


Figure A.50: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for small lutjanids under enhanced management for each combination of development scenario and model specification.

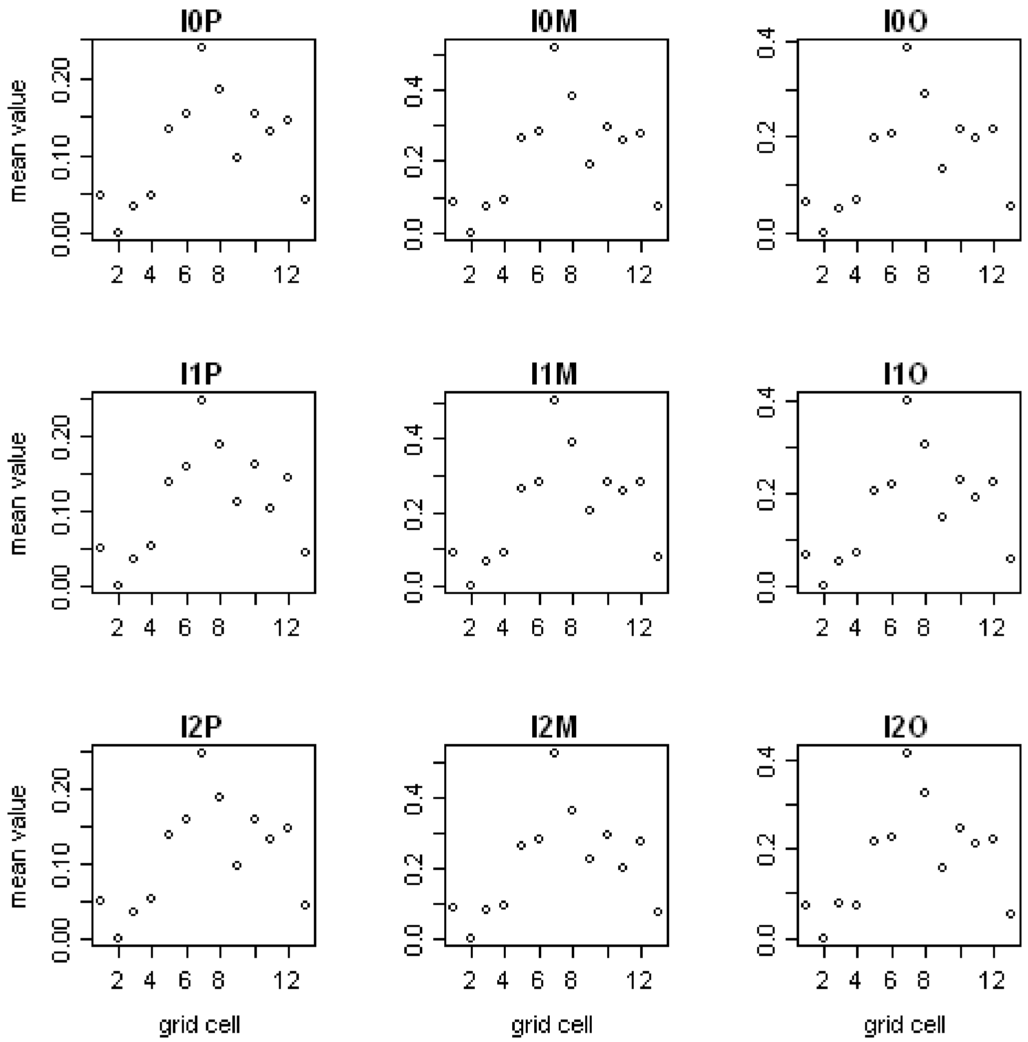


Figure A.51: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for small lutjanids under integrated management for each combination of development scenario and model specification.

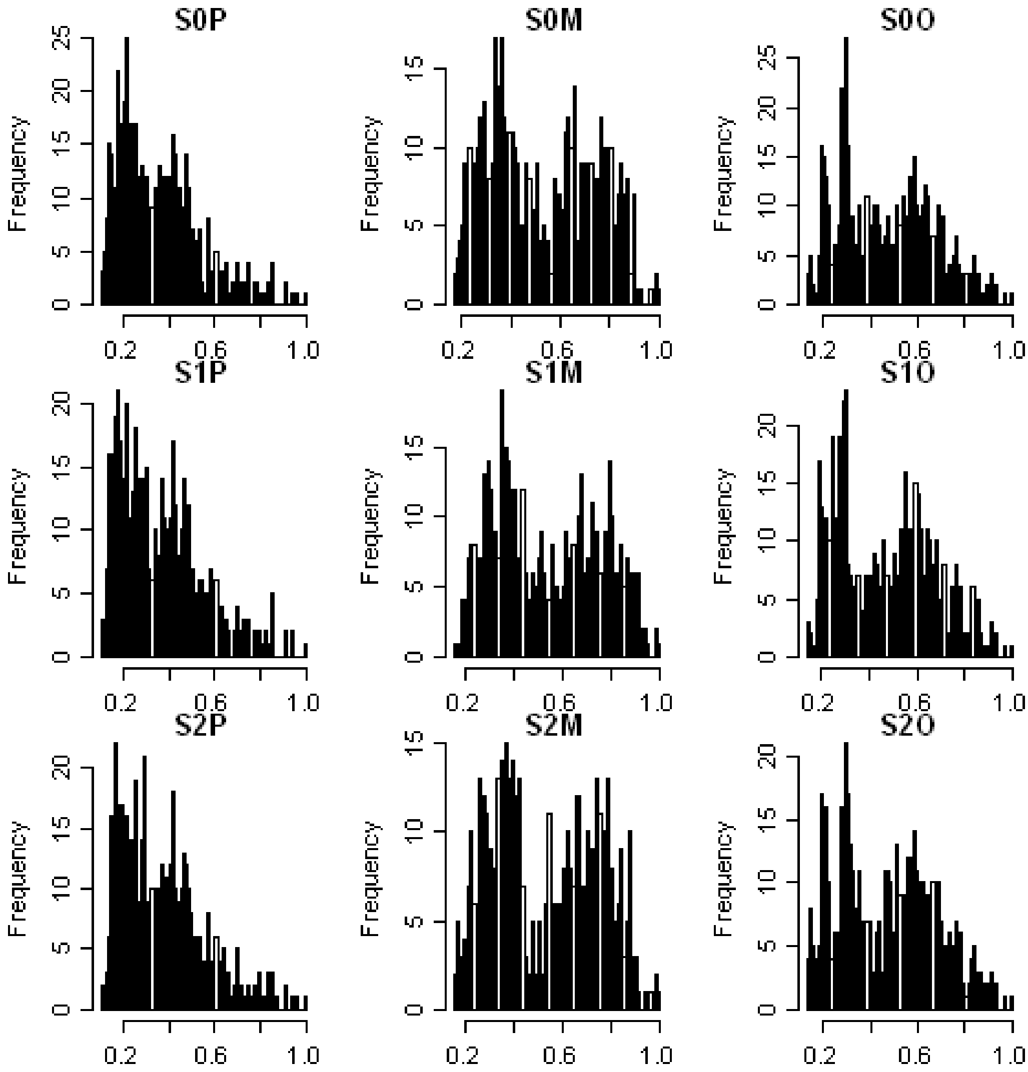


Figure A.52: Frequency histogram of coarse scale relative biomass (over time) for small lutjanids under status quo management for each combination of development scenario and model specification.

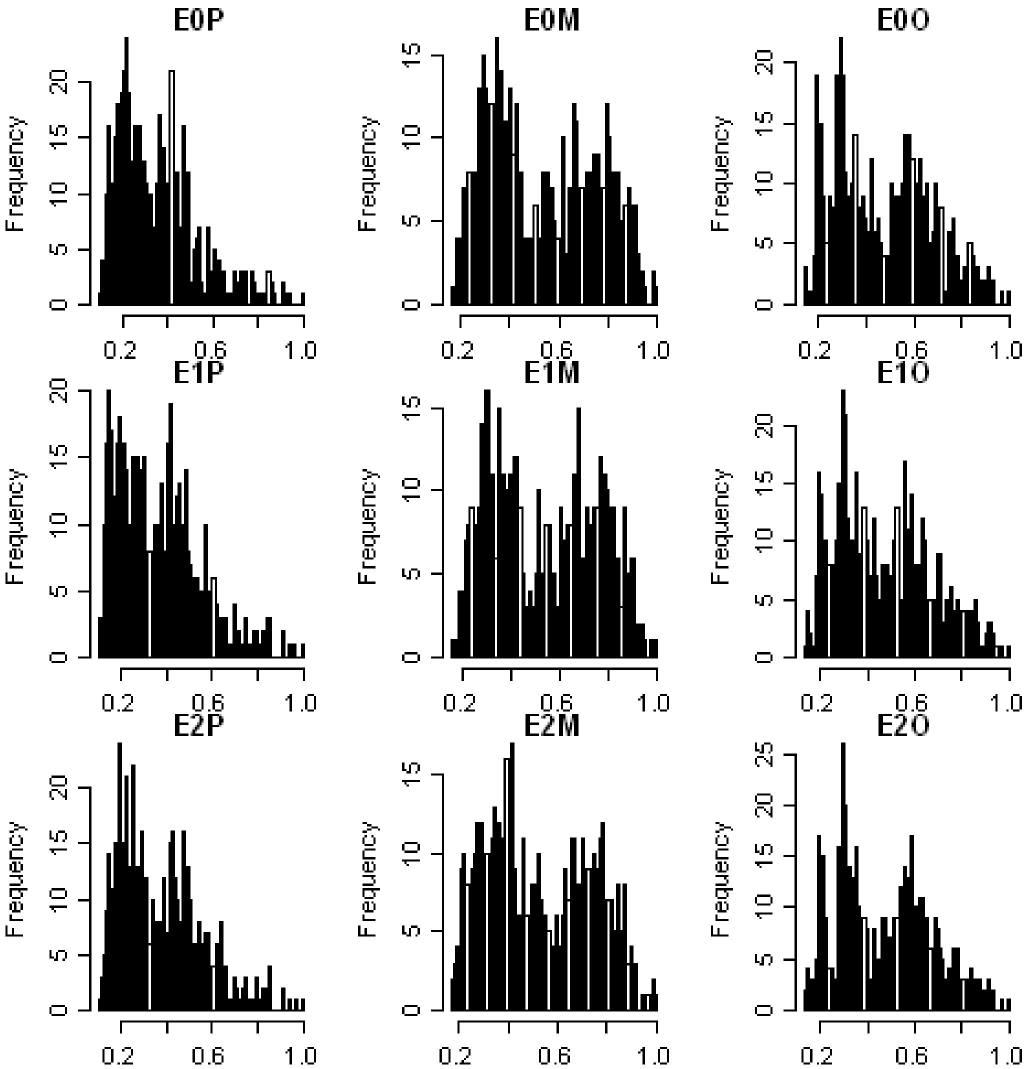


Figure A.53: Frequency histogram of coarse scale relative biomass (over time) for small lutjanids under enhanced management for each combination of development scenario and model specification.

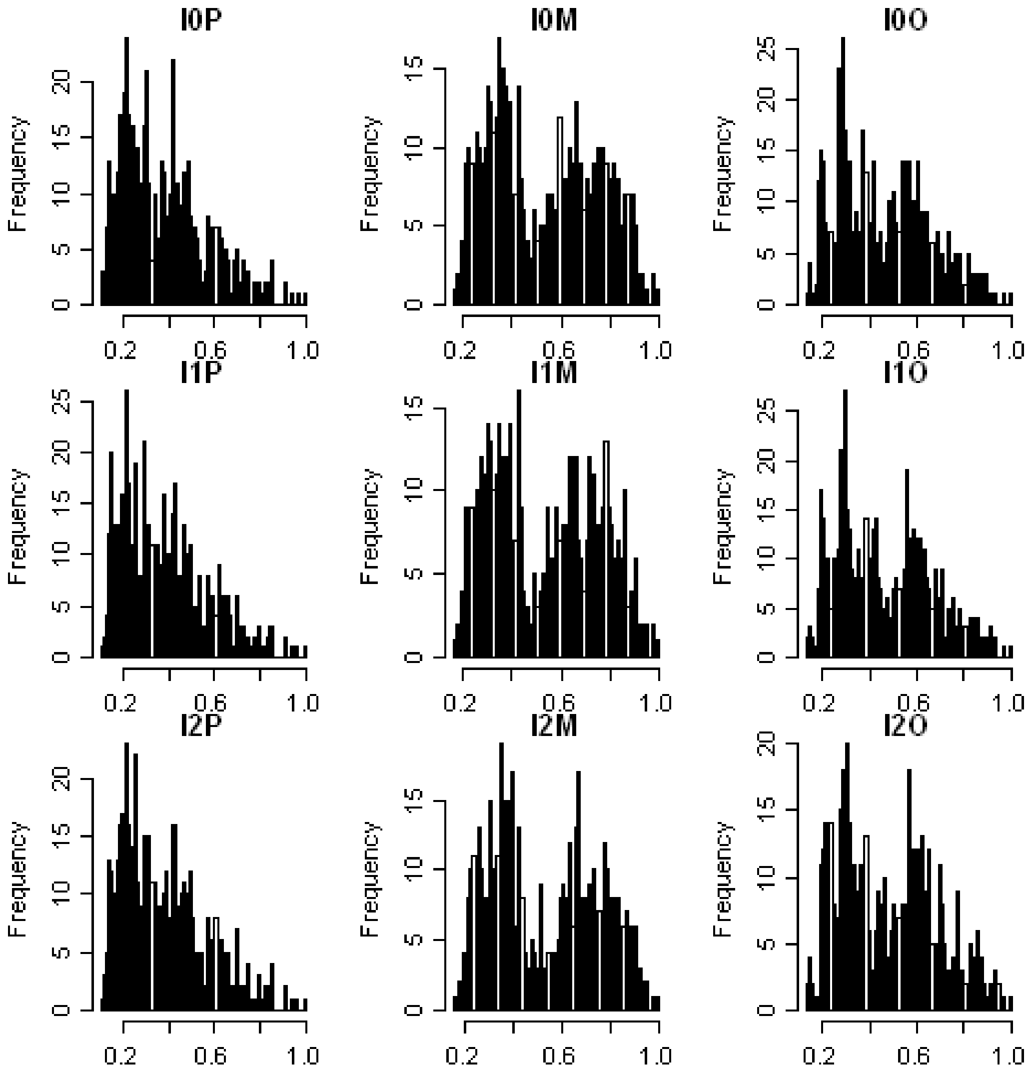


Figure A.54: Frequency histogram of coarse scale relative biomass (over time) for small lutjanids under integrated management for each combination of development scenario and model specification.

A.7 *Lutjanus sebae*

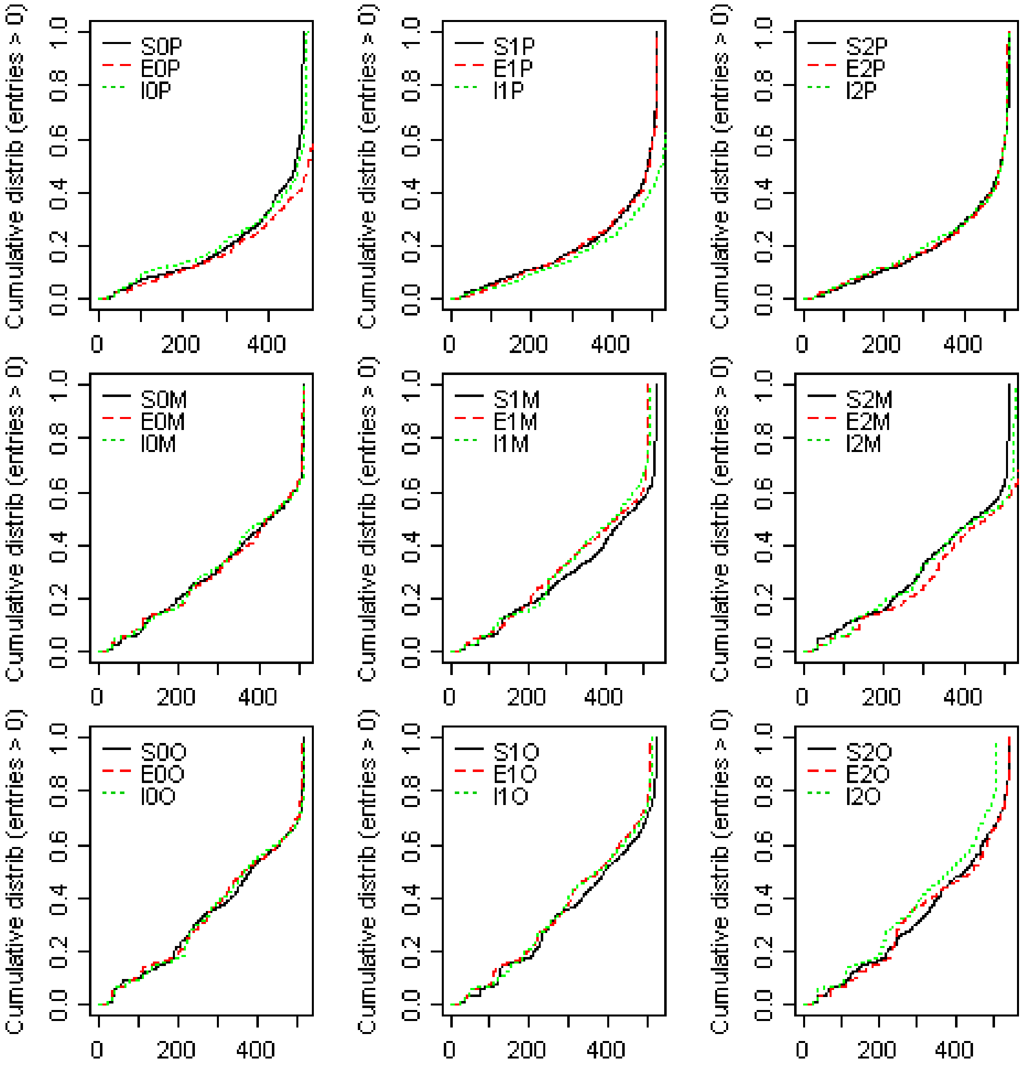


Figure A.55: Cumulative distribution plot for coarse scale spatial analysis of *Lutjanus sebae* average grid-cell relative biomass, comparing management strategies (each box contains the cumulative distributions for status quo [black], enhanced [red] and integrated [green] management for a given combination of model specification and development scenario).

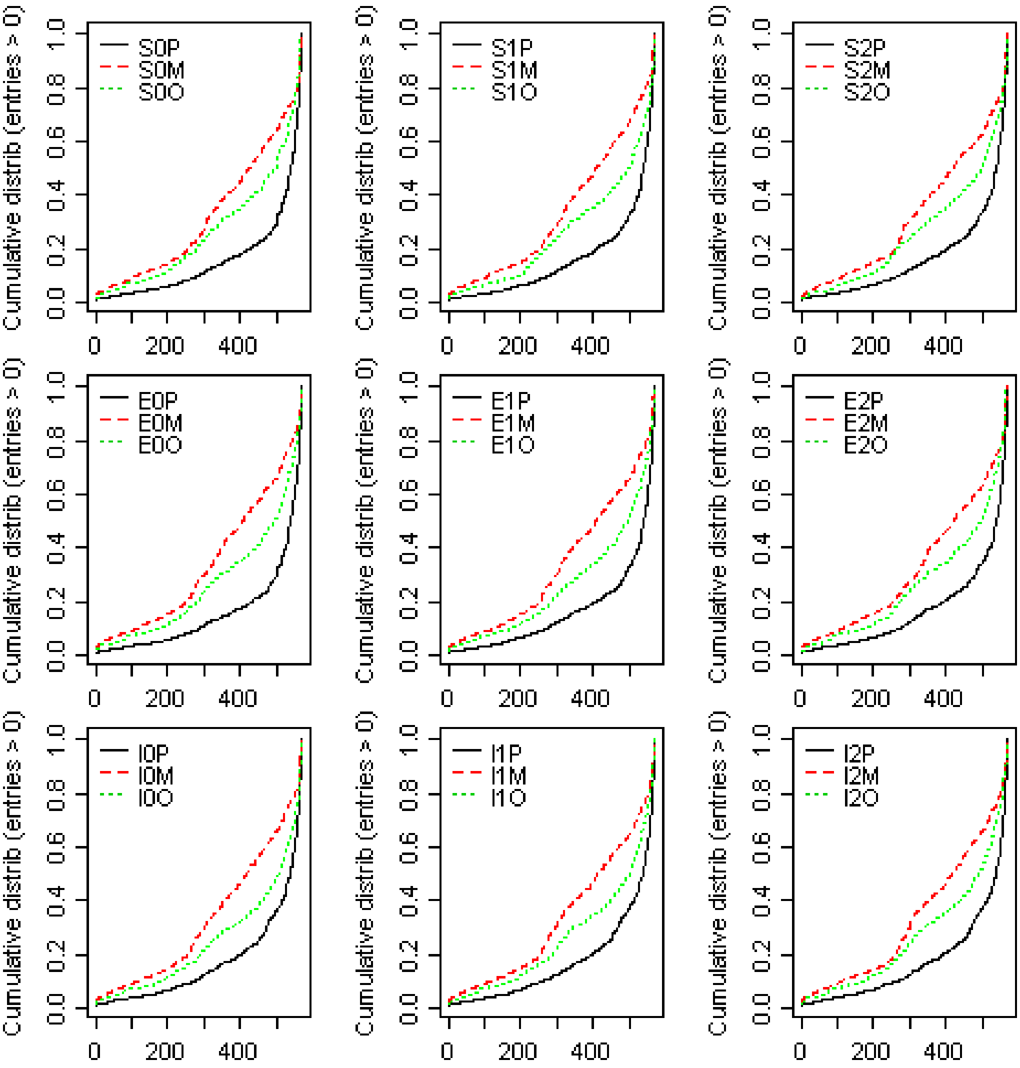


Figure A.56: Cumulative distribution plot for coarse scale spatial analysis of *Lutjanus sebae* average grid-cell relative biomass, comparing model specifications (each box contains the cumulative distributions for pessimistic [black], base case [red] and optimistic [green] specifications for a given combination of management strategy and development scenario).

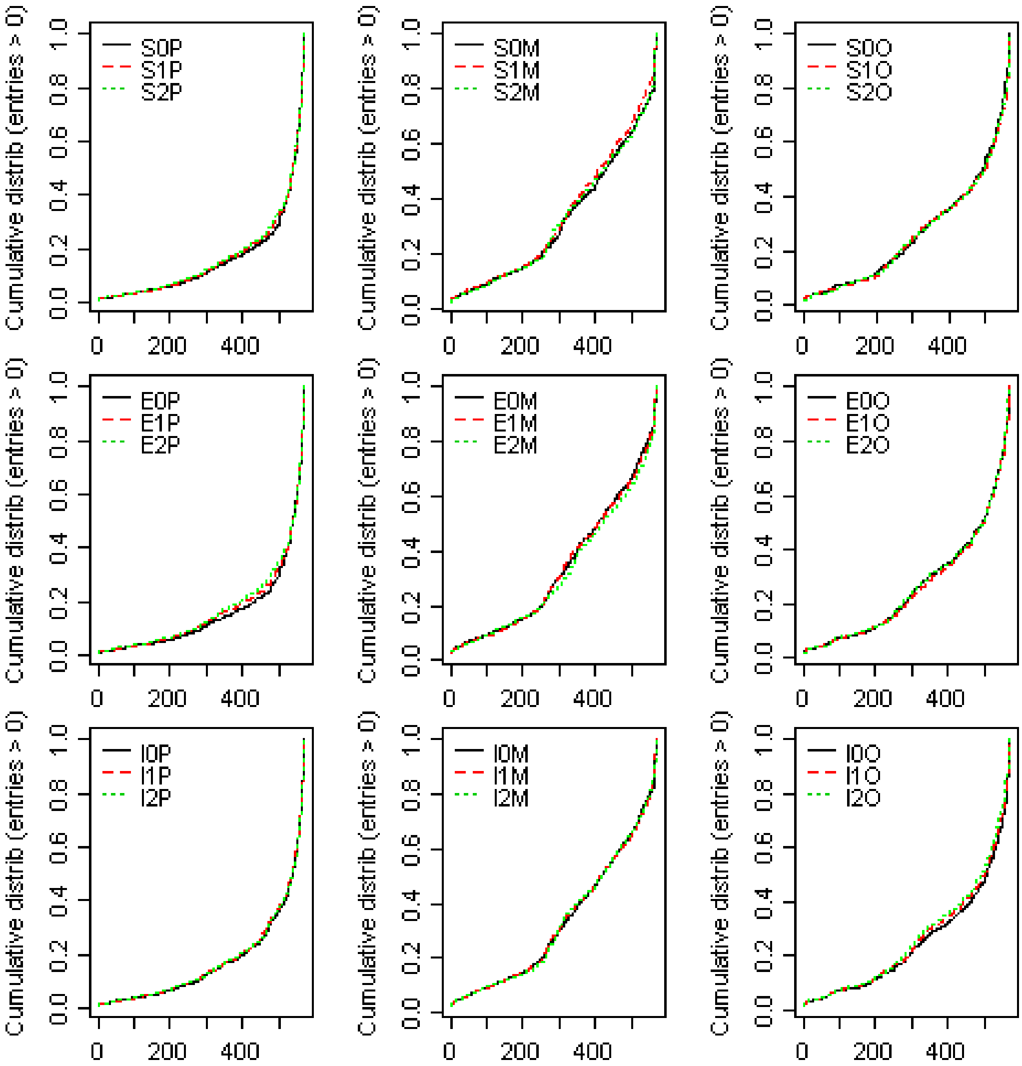


Figure A.57: Cumulative distribution plot for coarse scale spatial analysis of *Lutjanus sebae* average grid-cell relative biomass, comparing development scenarios (each box contains the cumulative distributions for 0-pulse [black], 1-pulse [red] and 2-pulse [green] development scenarios for a given combination of management strategy and model specification).

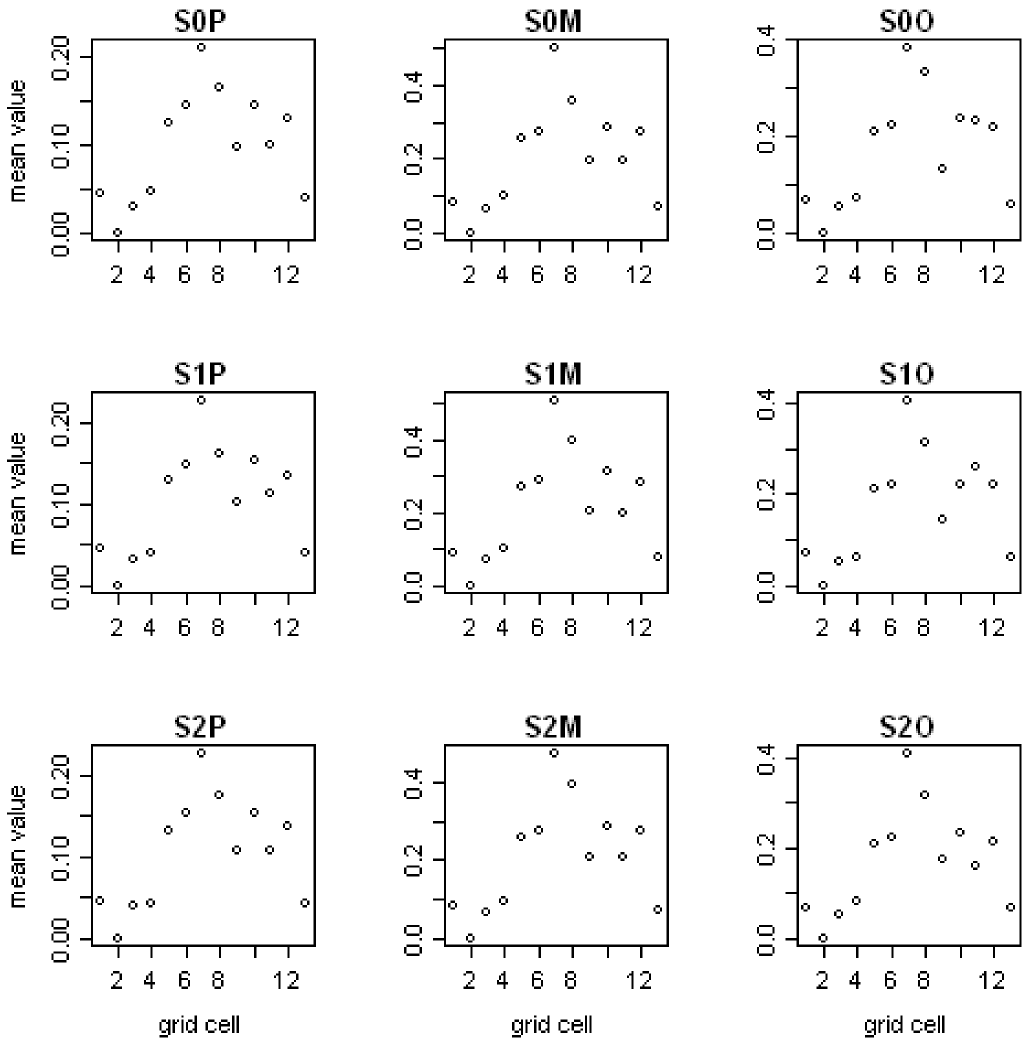


Figure A.58: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for *Lutjanus sebae* under status quo management for each combination of development scenario and model specification.

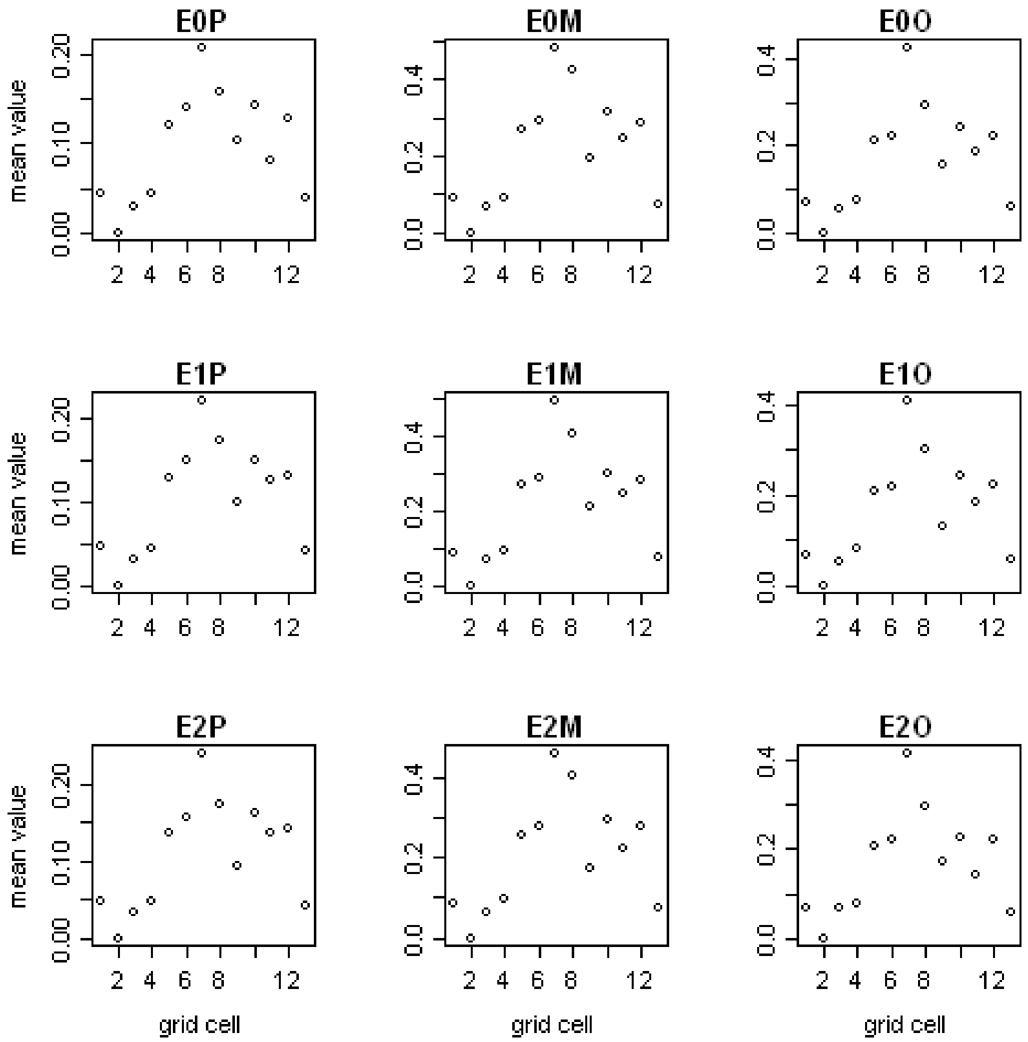


Figure A.59: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for *Lutjanus sebae* under enhanced management for each combination of development scenario and model specification.

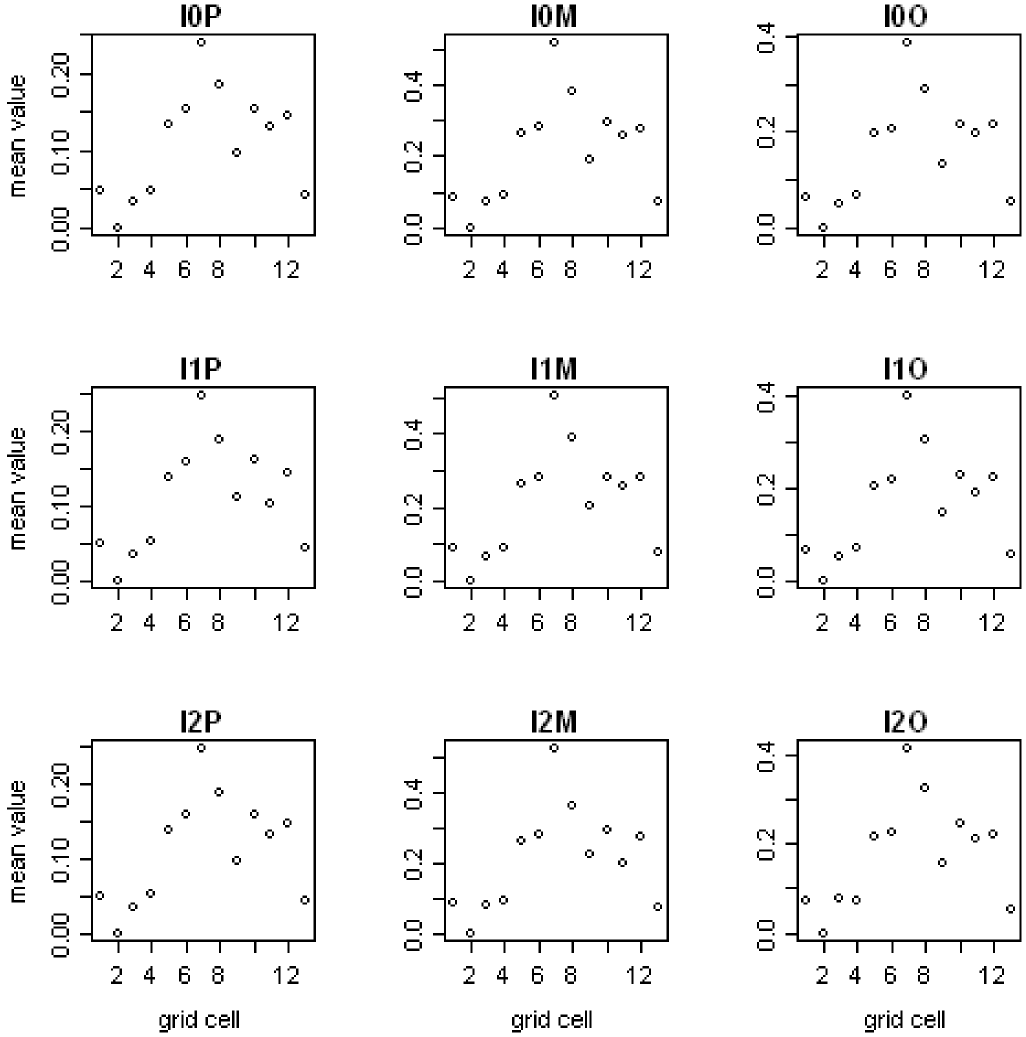


Figure A.60: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for *Lutjanus sebae* under integrated management for each combination of development scenario and model specification.

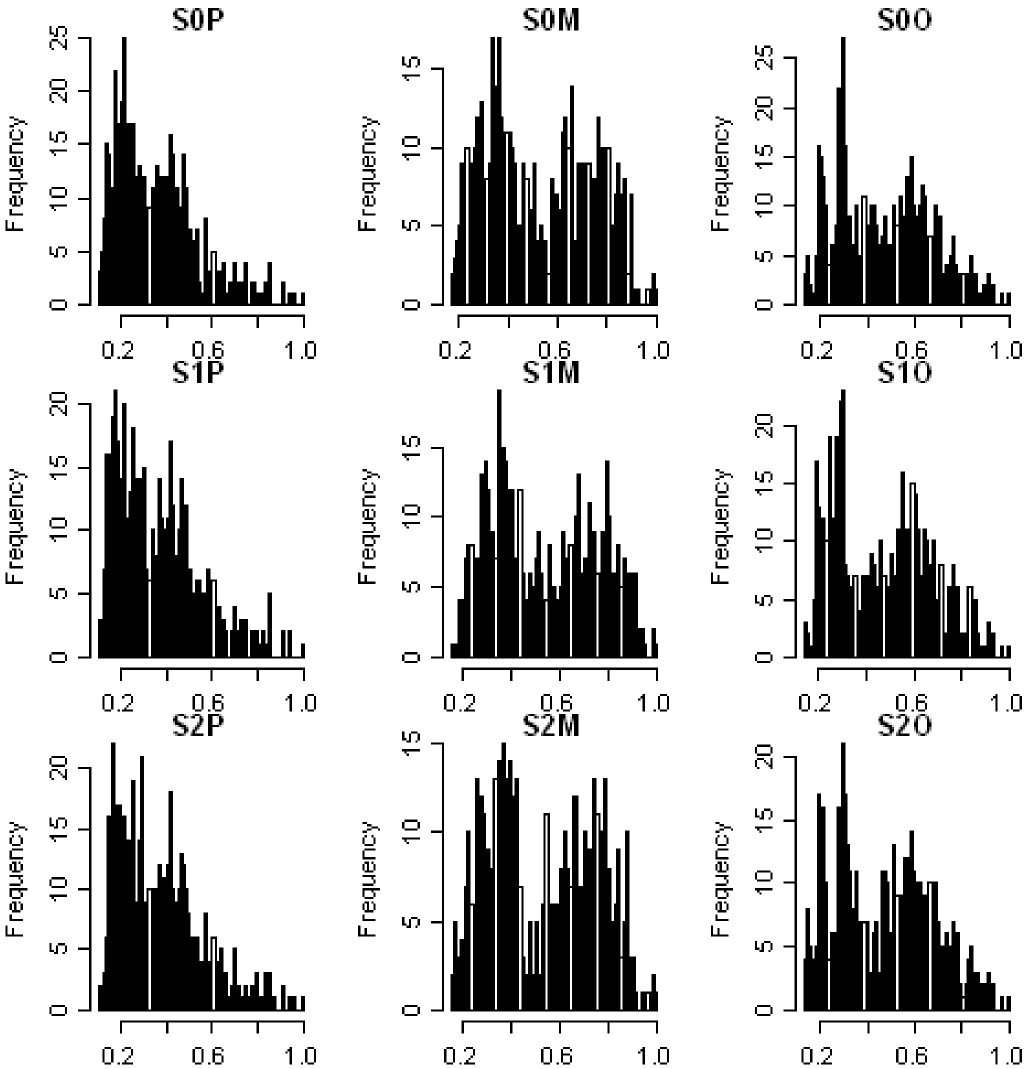


Figure A.61: Frequency histogram of coarse scale relative biomass (over time) for *Lutjanus sebae* under status quo management for each combination of development scenario and model specification.

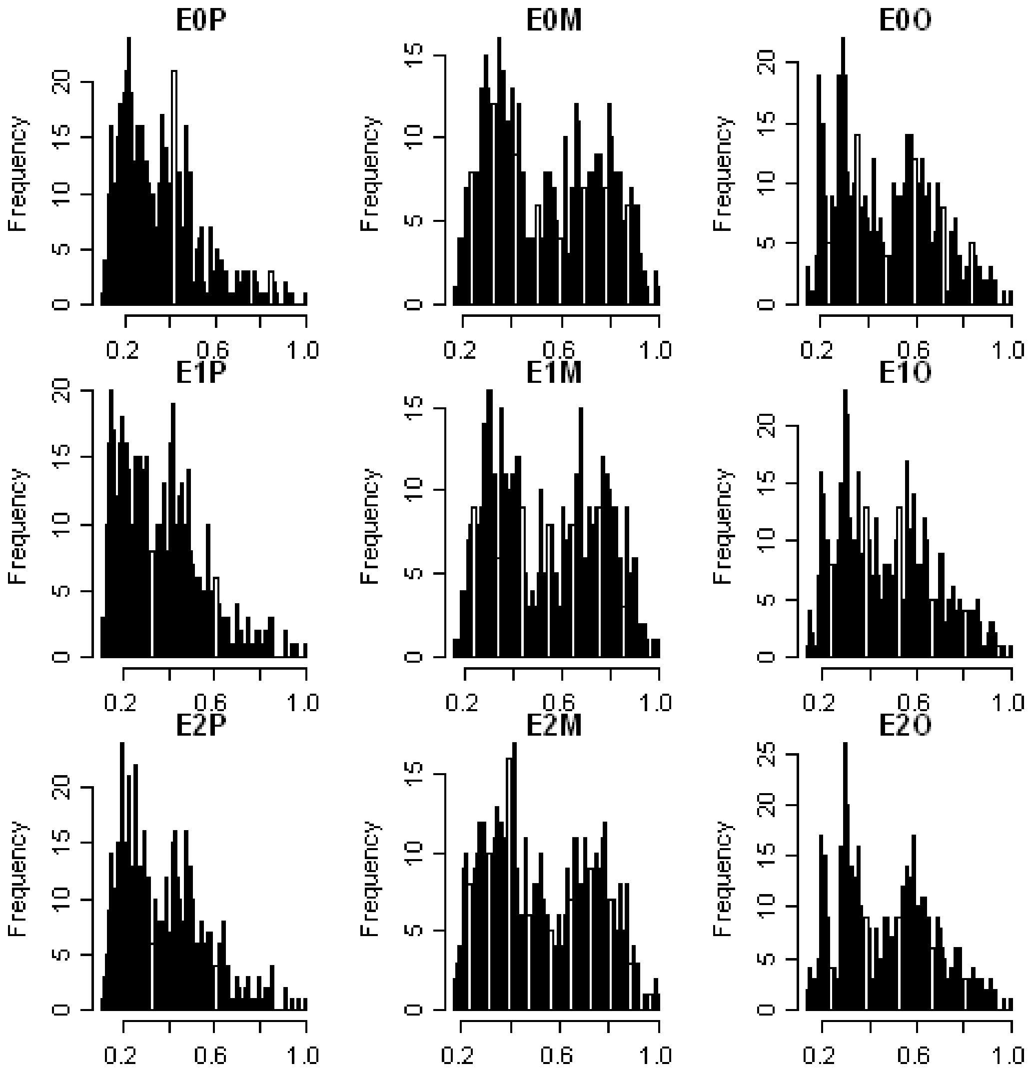


Figure A.62: Frequency histogram of coarse scale relative biomass (over time) for *Lutjanus sebae* under enhanced management for each combination of development scenario and model specification.

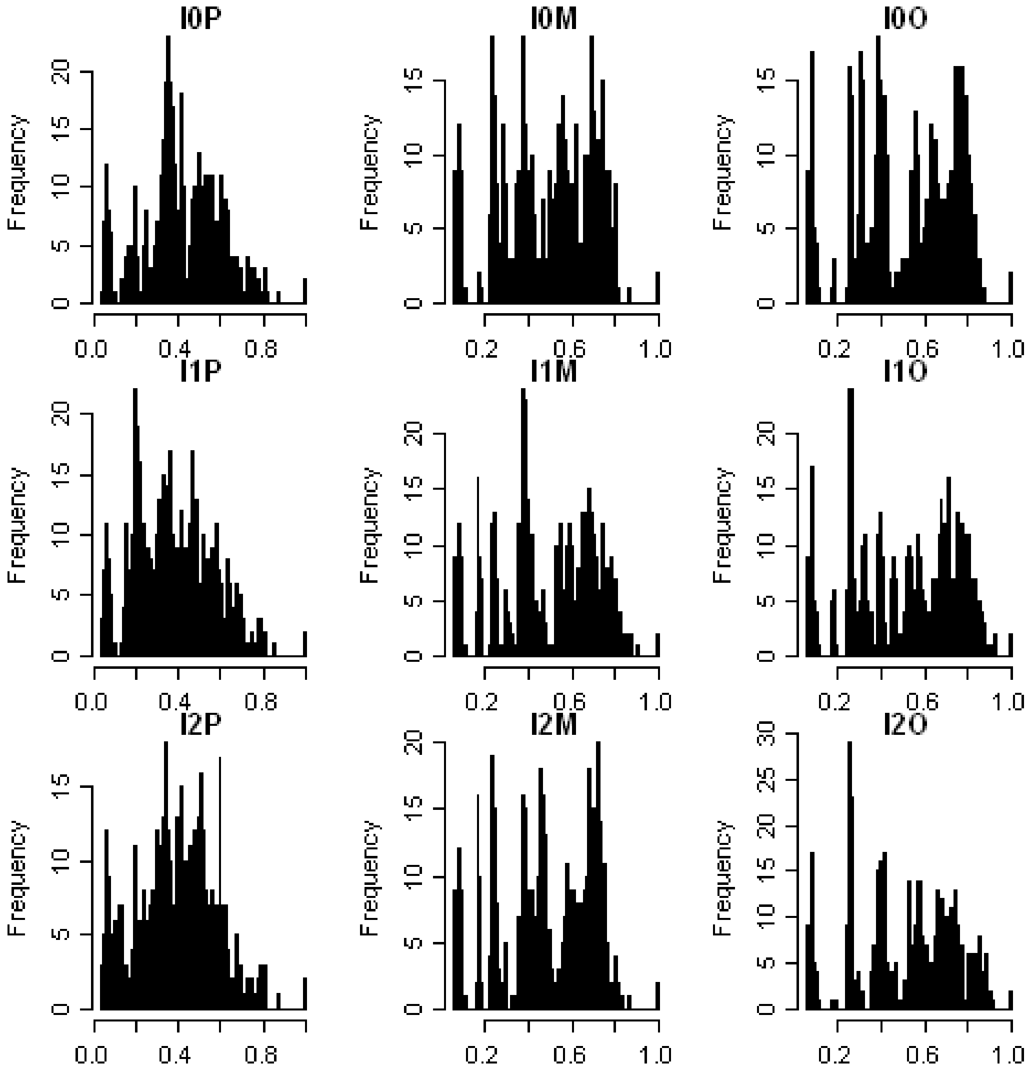


Figure A.63: Frequency histogram of coarse scale relative biomass (over time) for *Lutjanus sebae* under integrated management for each combination of development scenario and model specification.

A.8 Lethrinids

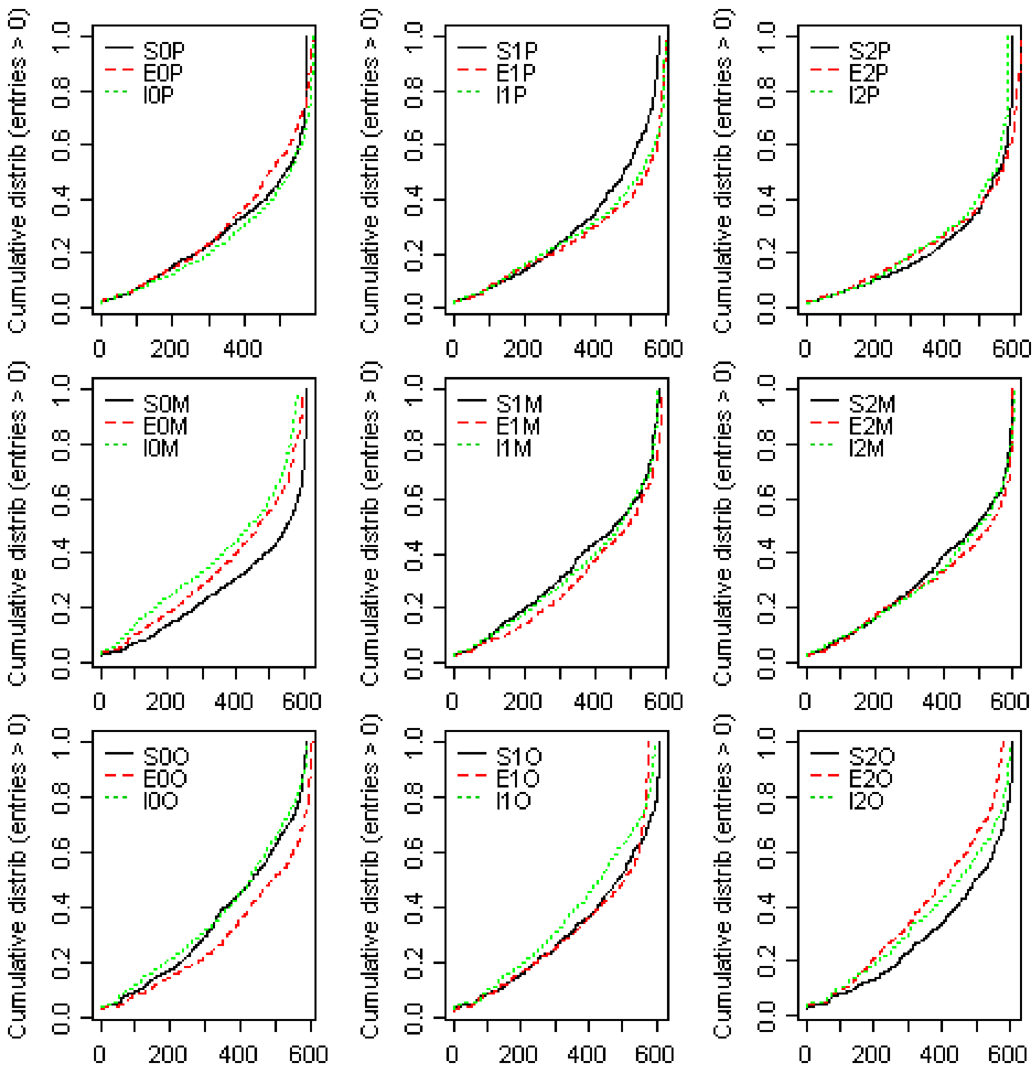


Figure A.64: Cumulative distribution plot for coarse scale spatial analysis of lethrinid average grid-cell relative biomass, comparing management strategies (each box contains the cumulative distributions for status quo [black], enhanced [red] and integrated [green] management for a given combination of model specification and development scenario).

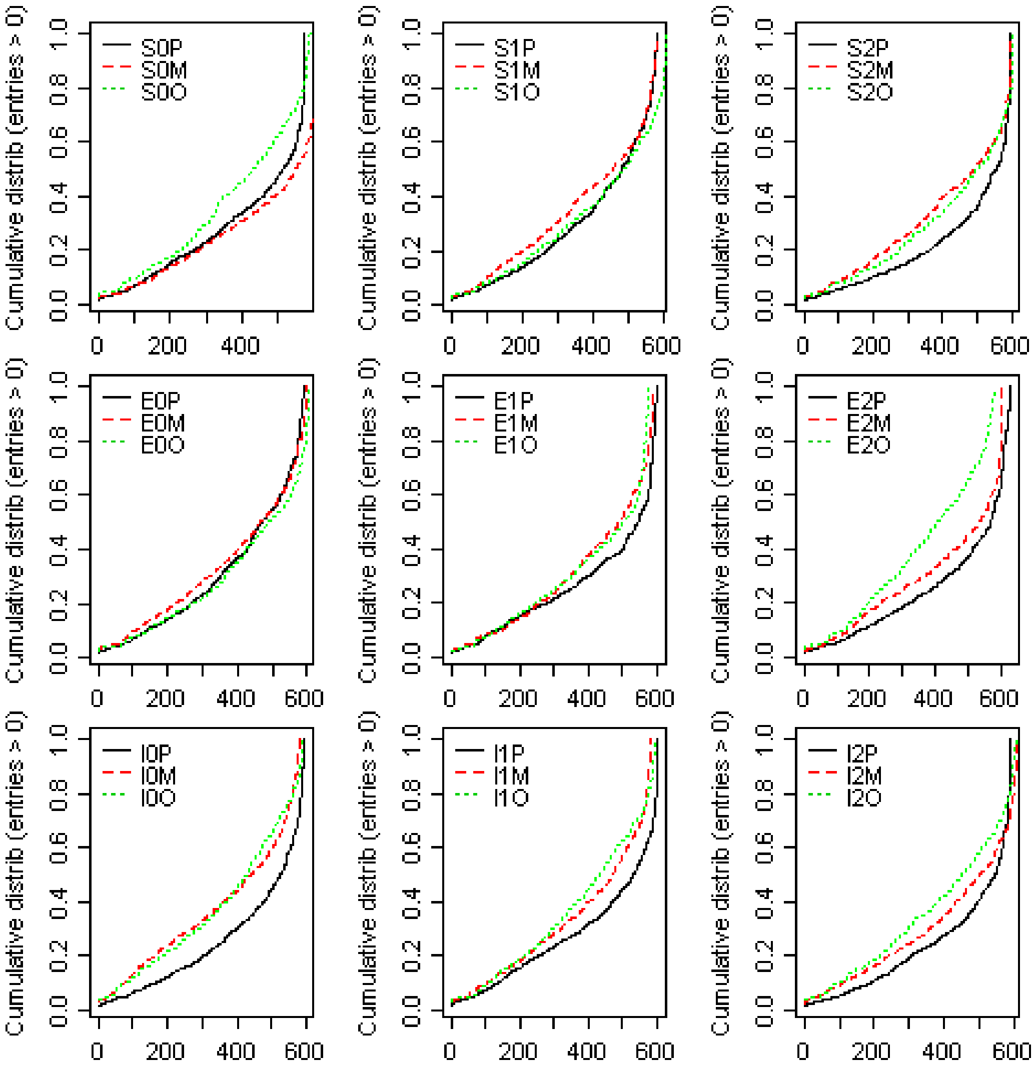


Figure A.65: Cumulative distribution plot for coarse scale spatial analysis of lethrinid average grid-cell relative biomass, comparing model specifications (each box contains the cumulative distributions for pessimistic [black], base case [red] and optimistic [green] specifications for a given combination of management strategy and development scenario).

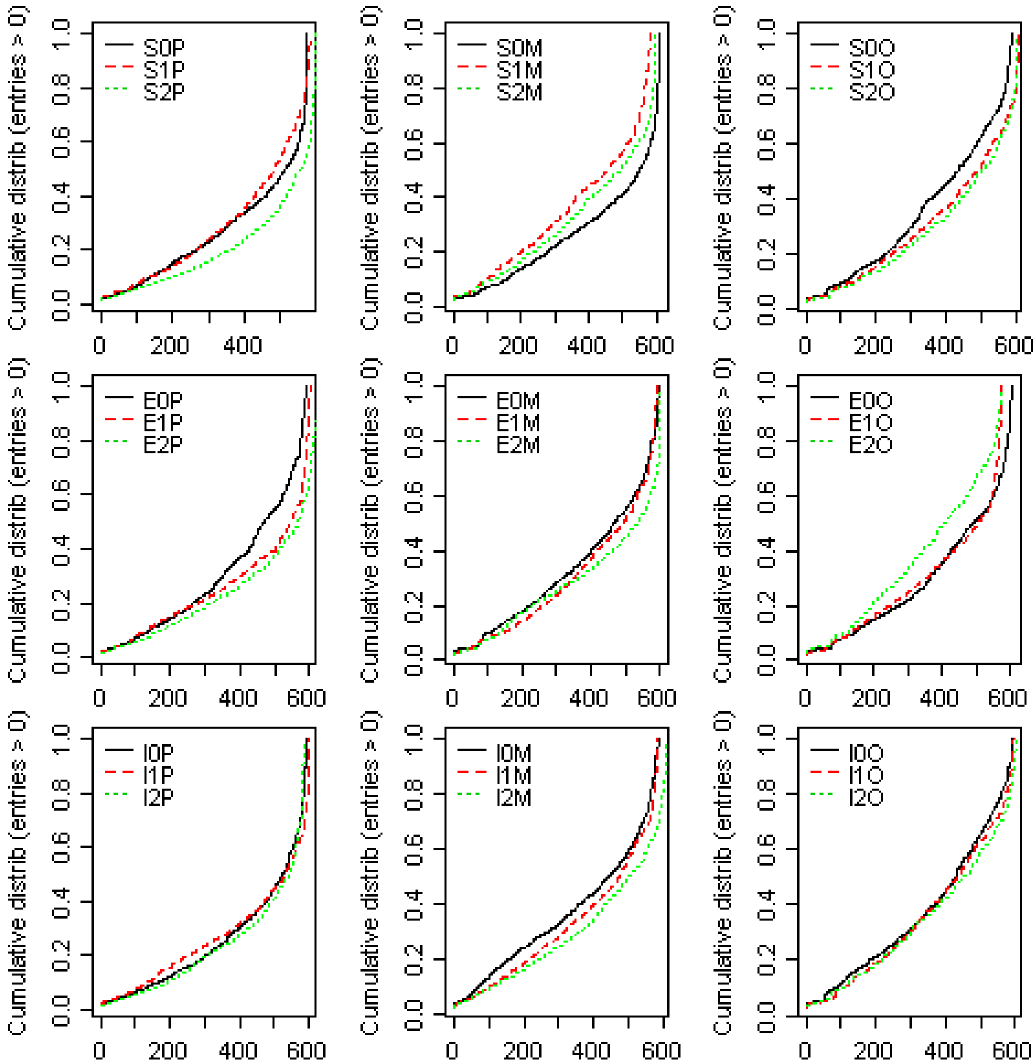


Figure A.66: Cumulative distribution plot for coarse scale spatial analysis of lethrinid average grid-cell relative biomass, comparing development scenarios (each box contains the cumulative distributions for 0-pulse [black], 1-pulse [red] and 2-pulse [green] development scenarios for a given combination of management strategy and model specification).

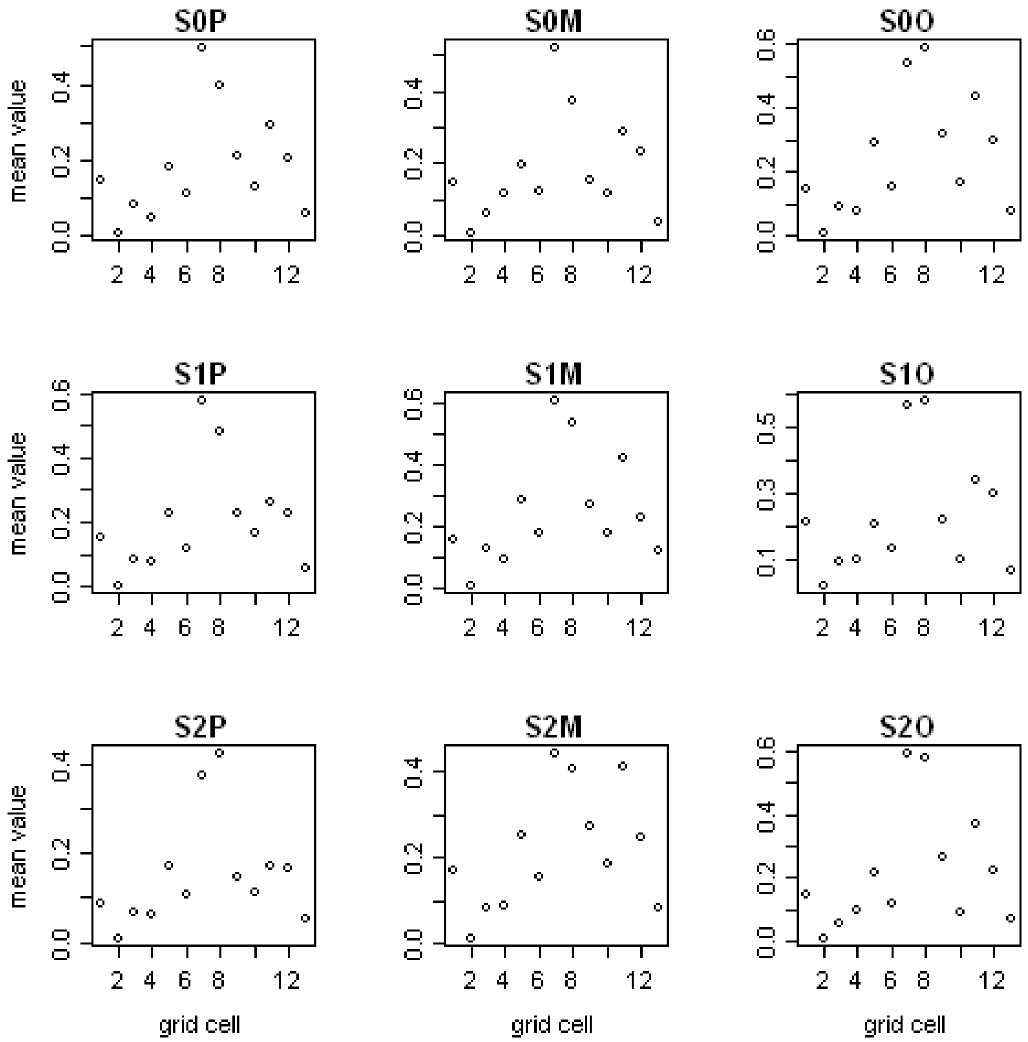


Figure A.67: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for lethrinids under status quo management for each combination of development scenario and model specification.

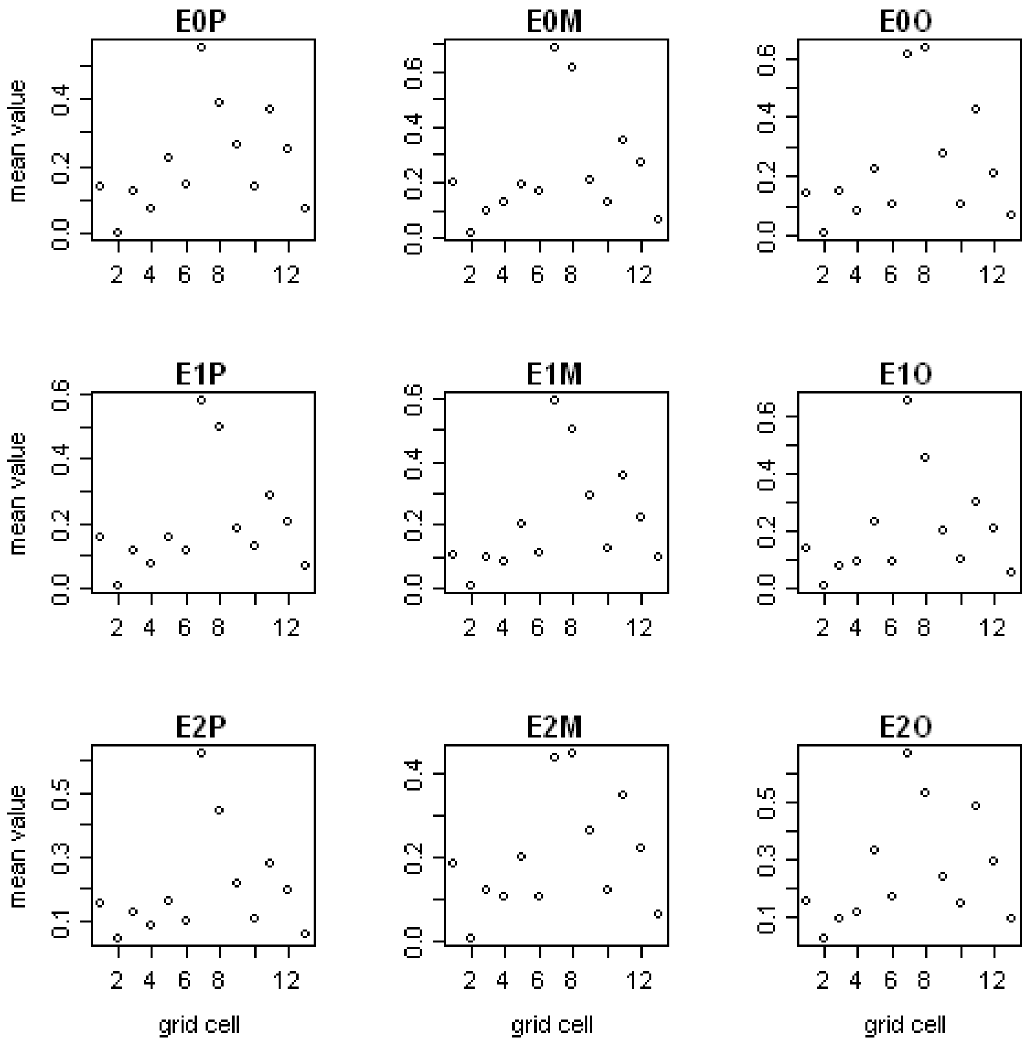


Figure A.68: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for lethrinids under enhanced management for each combination of development scenario and model specification.

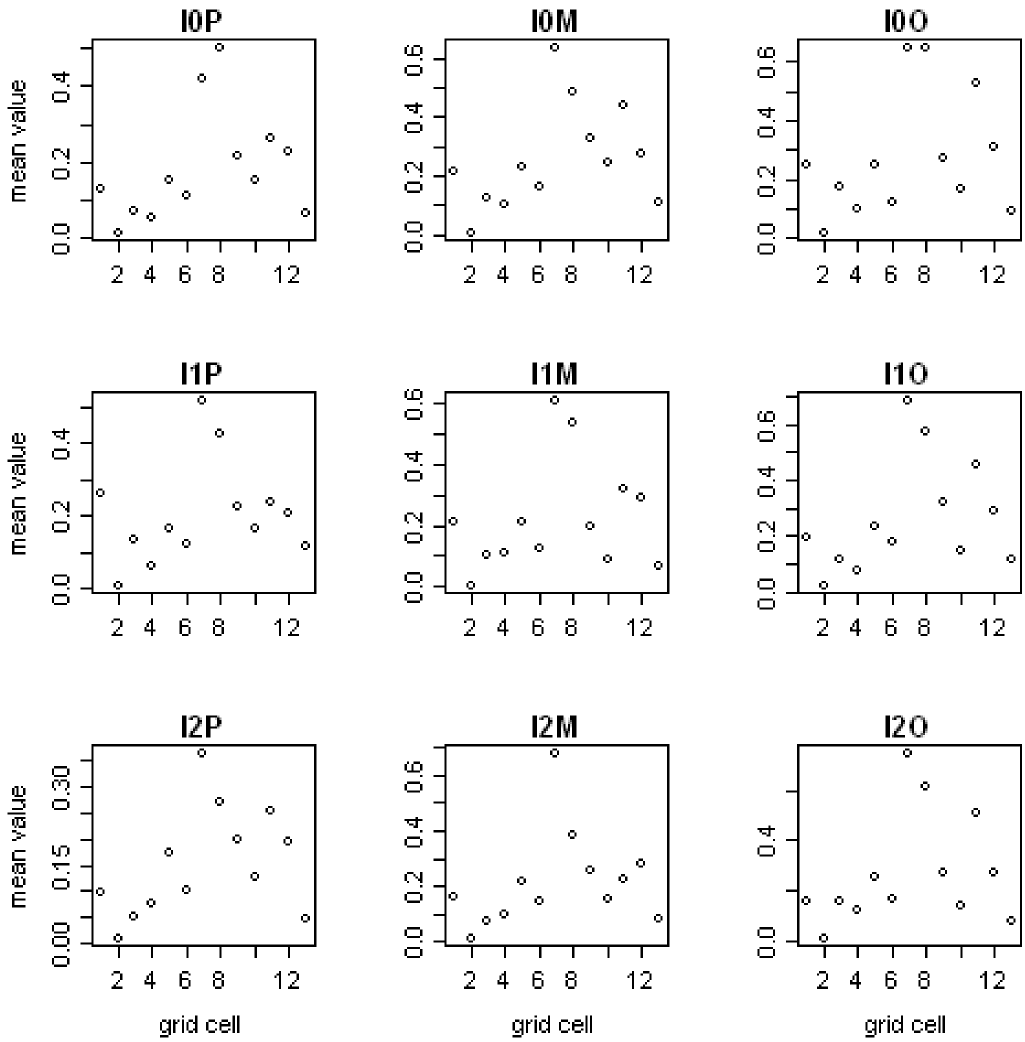


Figure A.69: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for lethrinids under integrated management for each combination of development scenario and model specification.

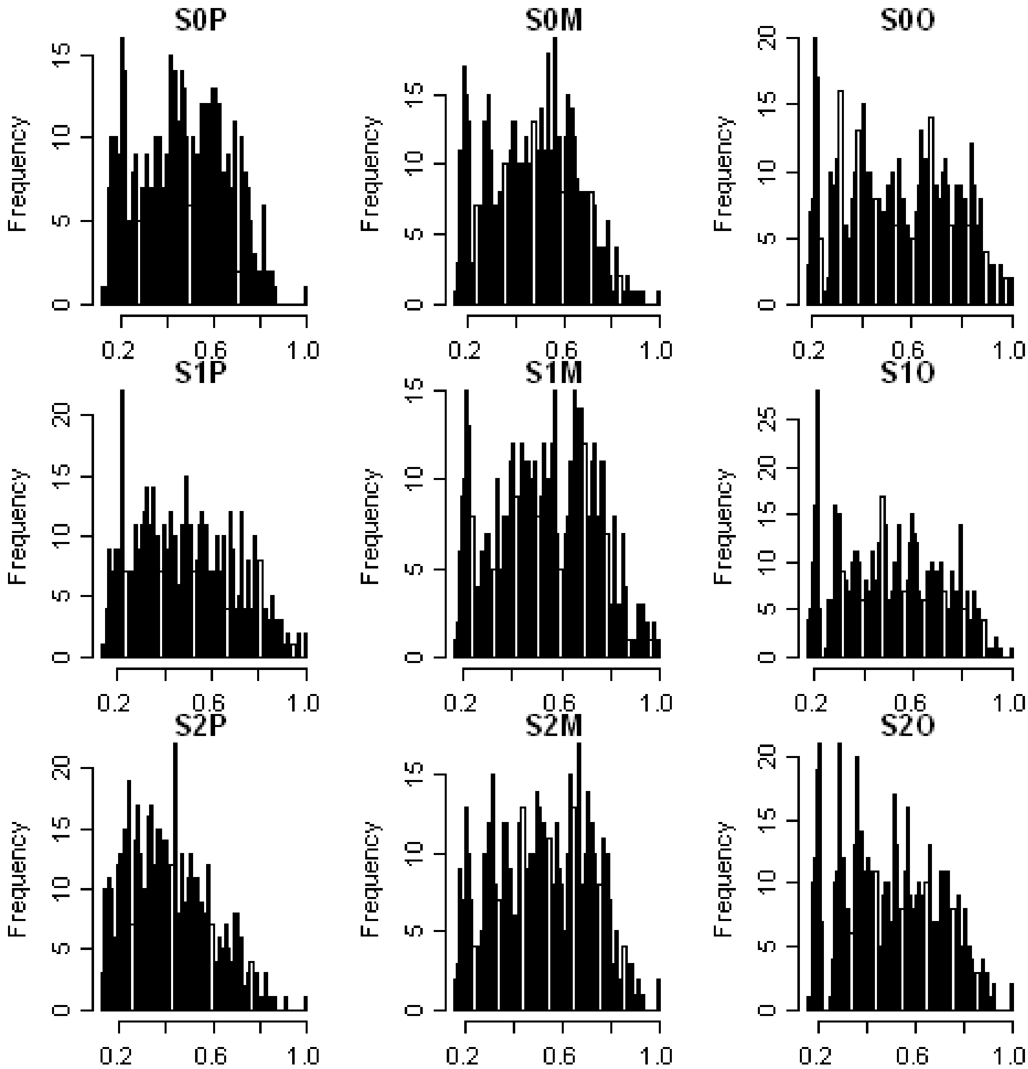


Figure A.70: Frequency histogram of coarse scale relative biomass (over time) for lethrinids under status quo management for each combination of development scenario and model specification.

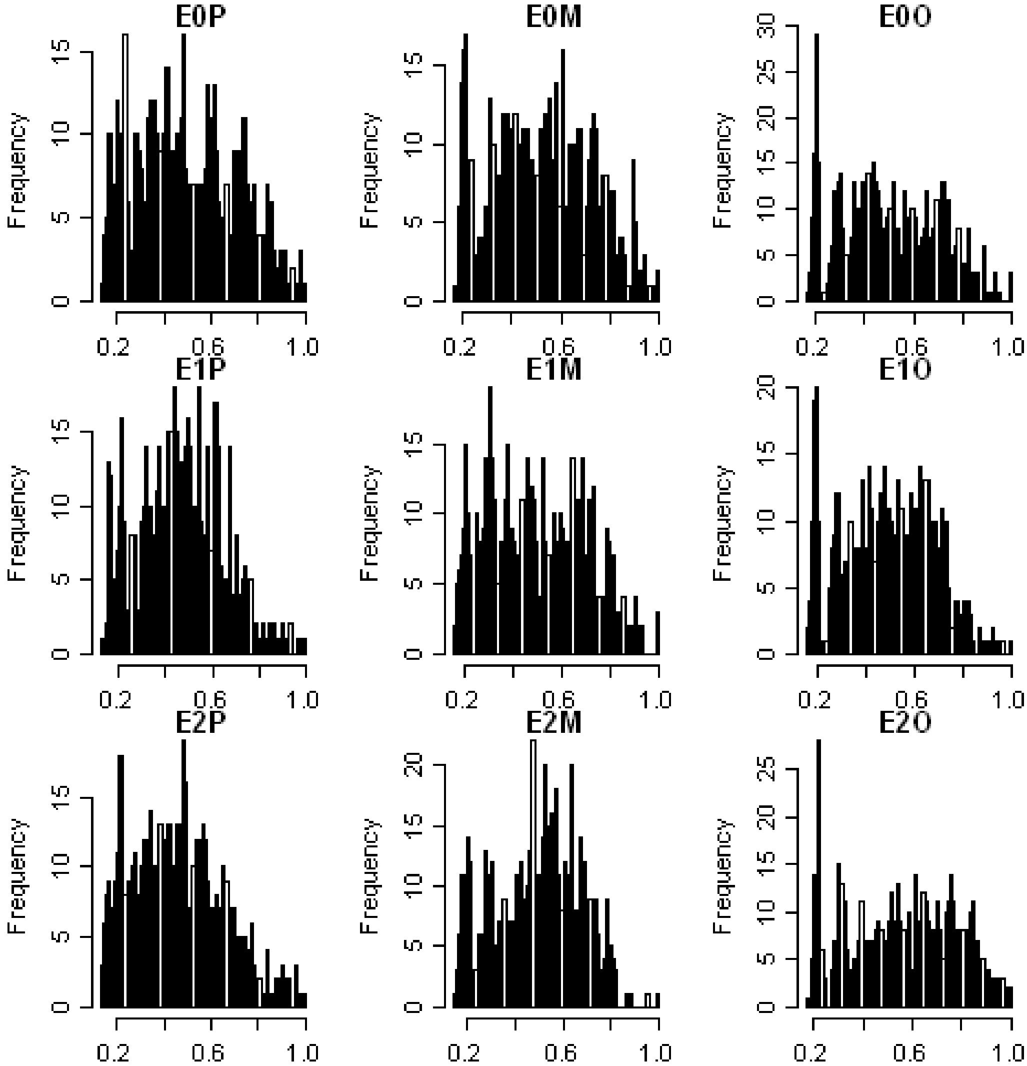


Figure A.71: Frequency histogram of coarse scale relative biomass (over time) for lethrinids under enhanced management for each combination of development scenario and model specification.

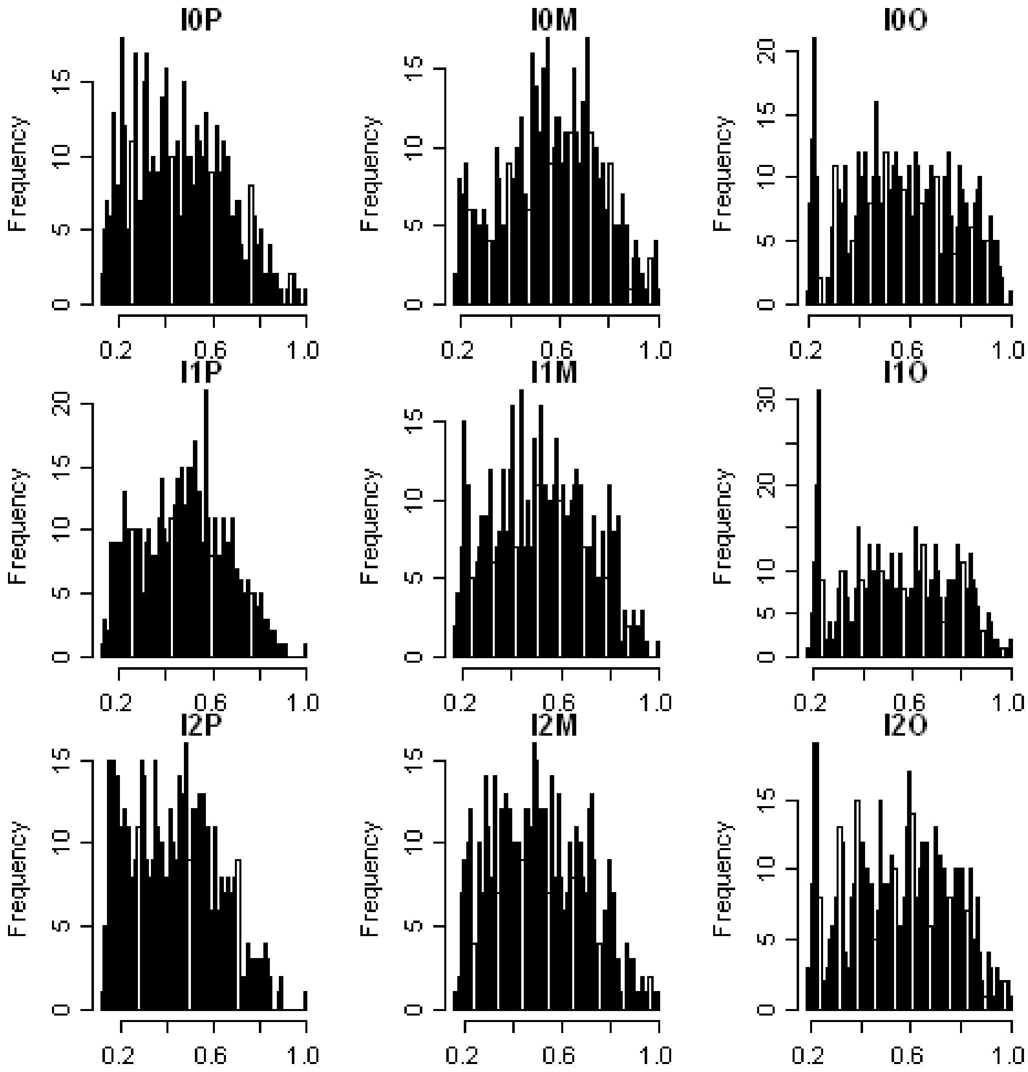


Figure A.72: Frequency histogram of coarse scale relative biomass (over time) for lethrinids under integrated management for each combination of development scenario and model specification.

A.9 Nemipterids

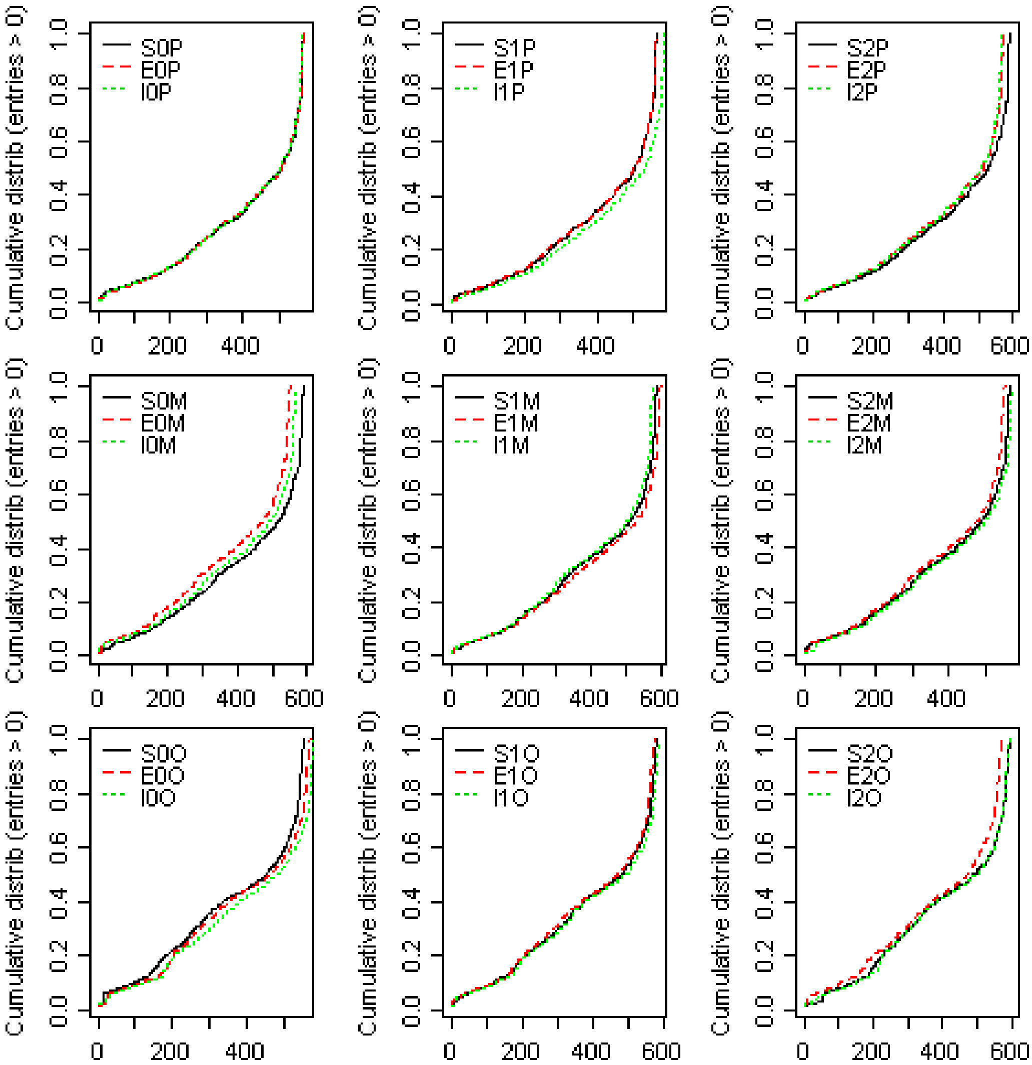


Figure A.73: Cumulative distribution plot for coarse scale spatial analysis of nemipterid average grid-cell relative biomass, comparing management strategies (each box contains the cumulative distributions for status quo [black], enhanced [red] and integrated [green] management for a given combination of model specification and development scenario).

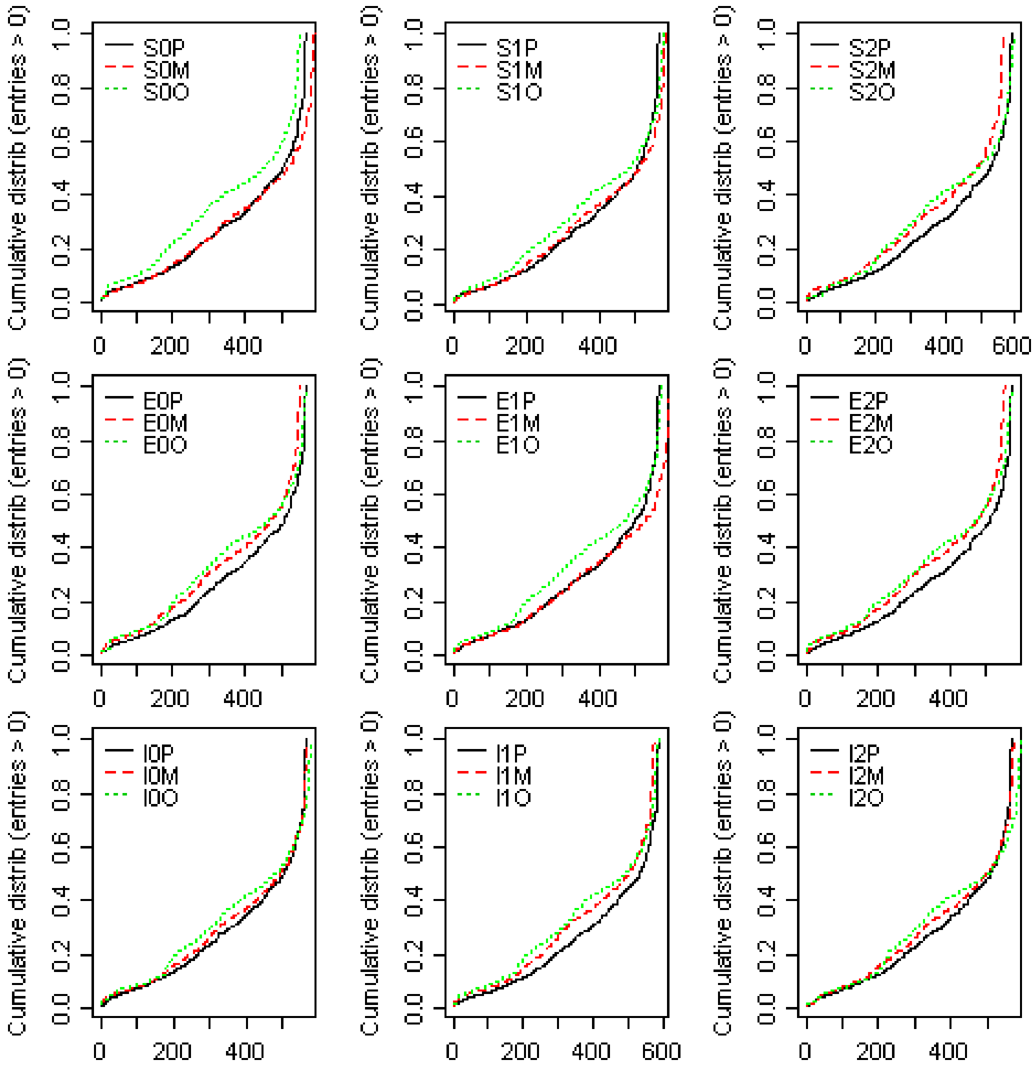


Figure A.74: Cumulative distribution plot for coarse scale spatial analysis of nemipterid average grid-cell relative biomass, comparing model specifications (each box contains the cumulative distributions for pessimistic [black], base case [red] and optimistic [green] specifications for a given combination of management strategy and development scenario).

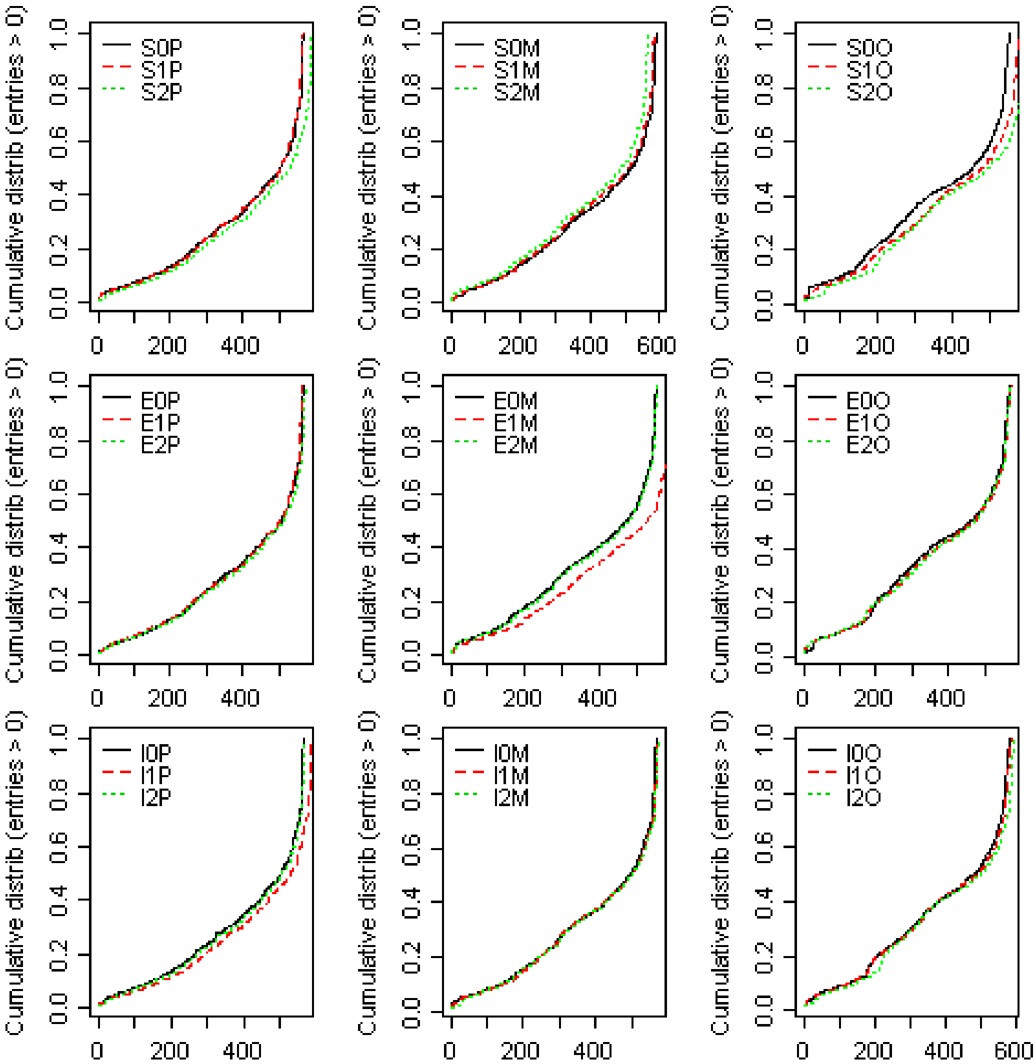


Figure A.75: Cumulative distribution plot for coarse scale spatial analysis of nemipterid average grid-cell relative biomass, comparing development scenarios (each box contains the cumulative distributions for 0-pulse [black], 1-pulse [red] and 2-pulse [green] development scenarios for a given combination of management strategy and model specification).

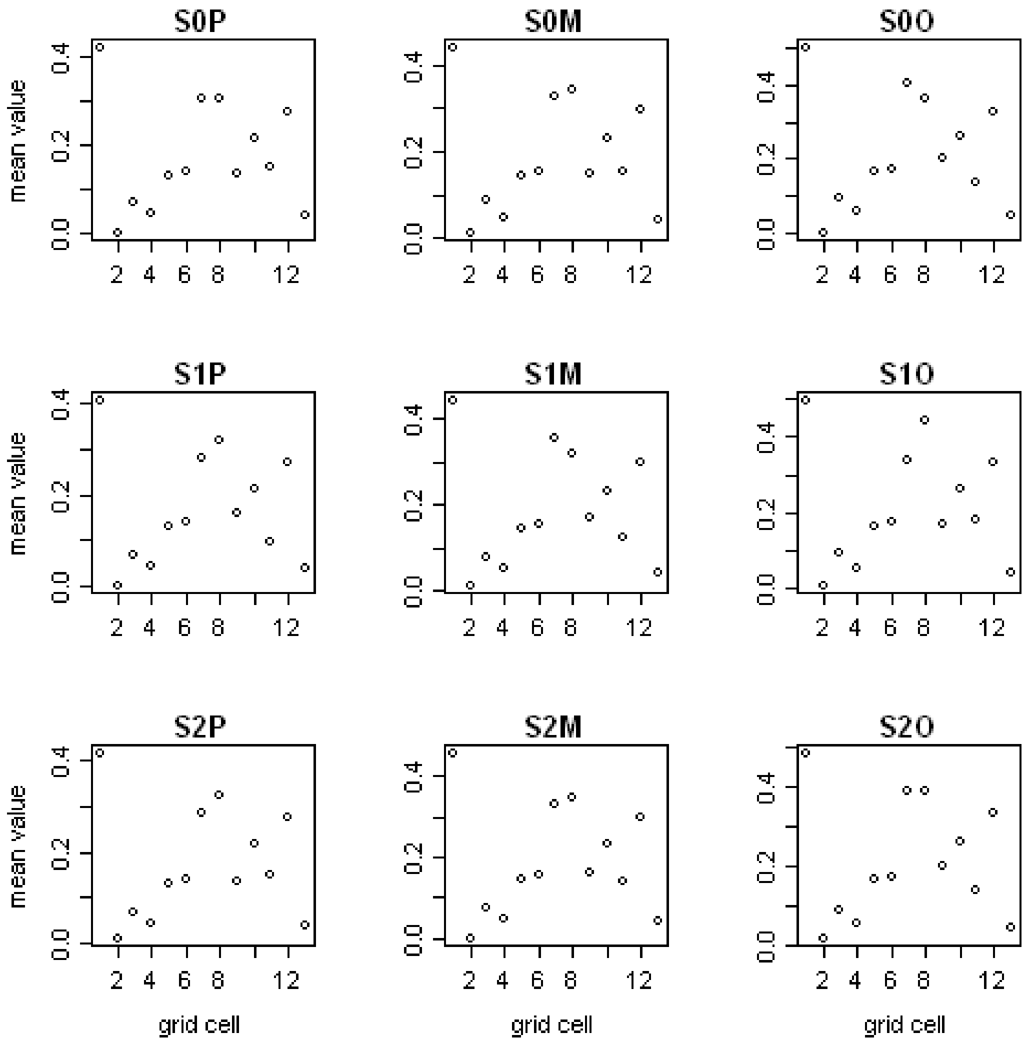


Figure A.76: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for nemipterids under status quo management for each combination of development scenario and model specification.

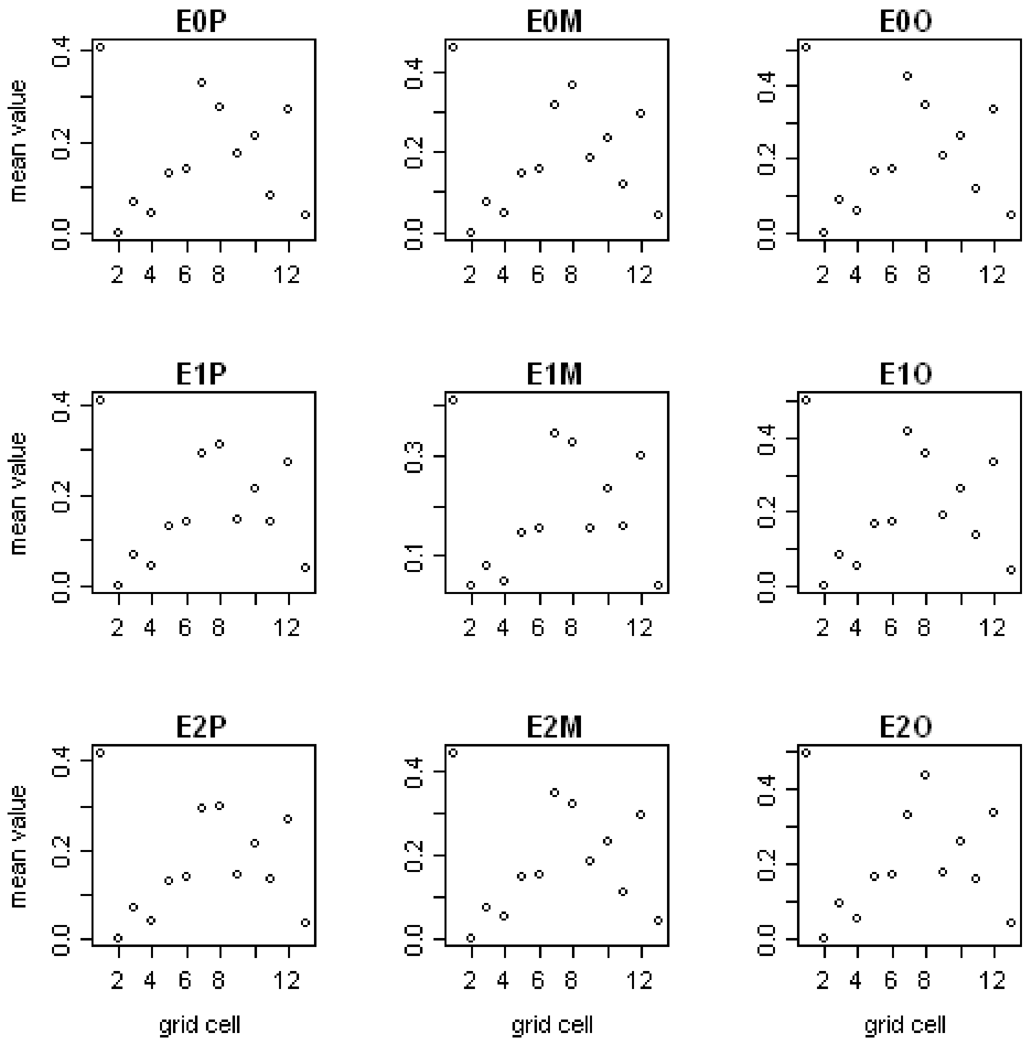


Figure A.77: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for nemipterids under enhanced management for each combination of development scenario and model specification.

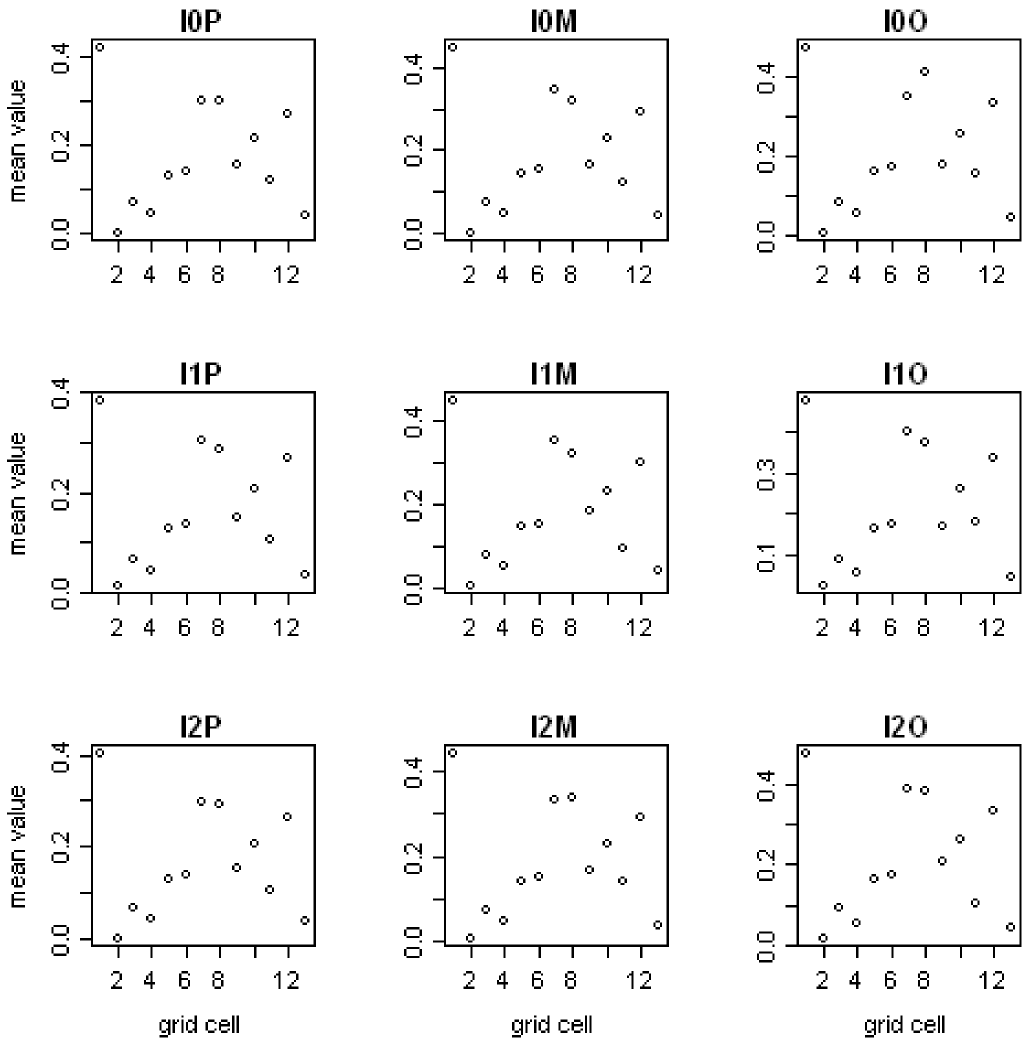


Figure A.78: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for nemipterids under integrated management for each combination of development scenario and model specification.

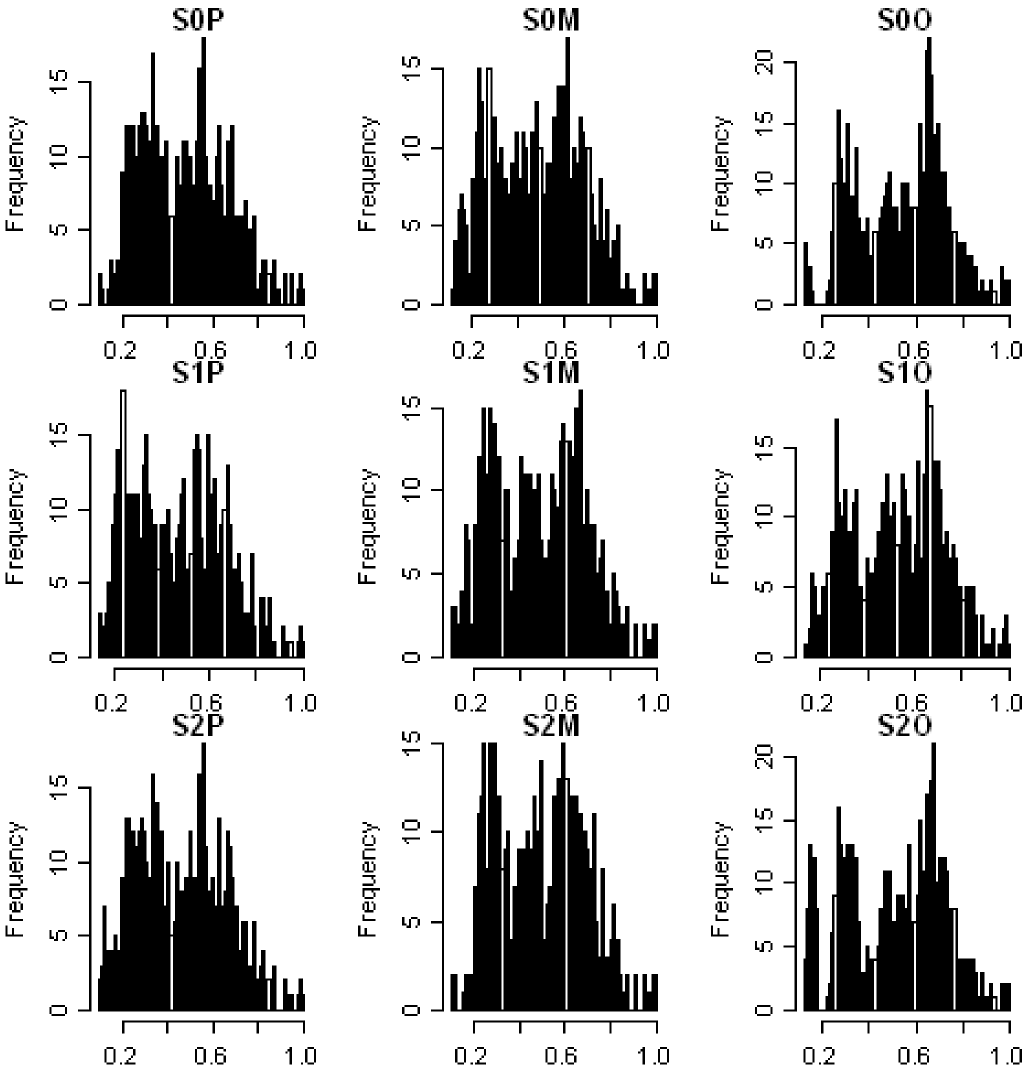


Figure A.79: Frequency histogram of coarse scale relative biomass (over time) for nemipterids under status quo management for each combination of development scenario and model specification.

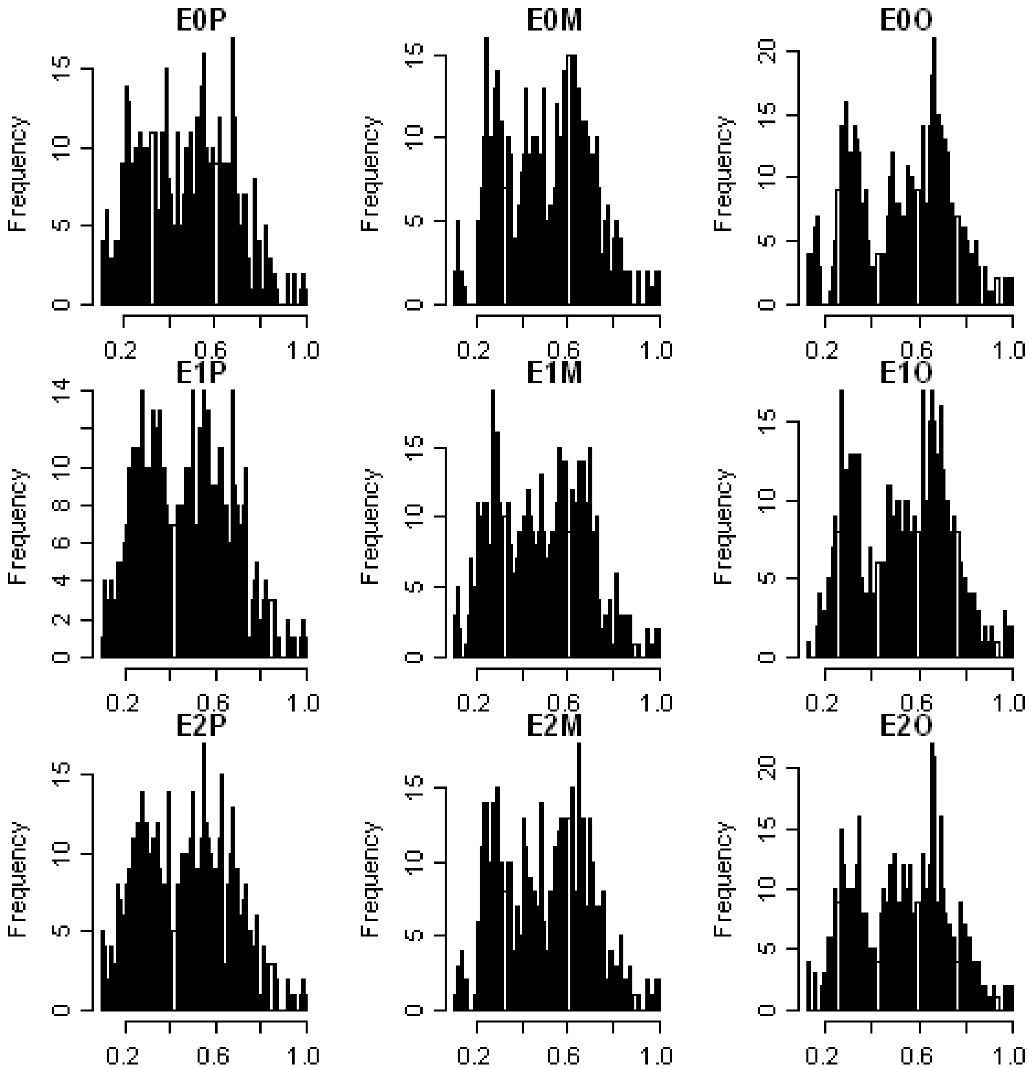


Figure A.80: Frequency histogram of coarse scale relative biomass (over time) for nemipterids under enhanced management for each combination of development scenario and model specification.

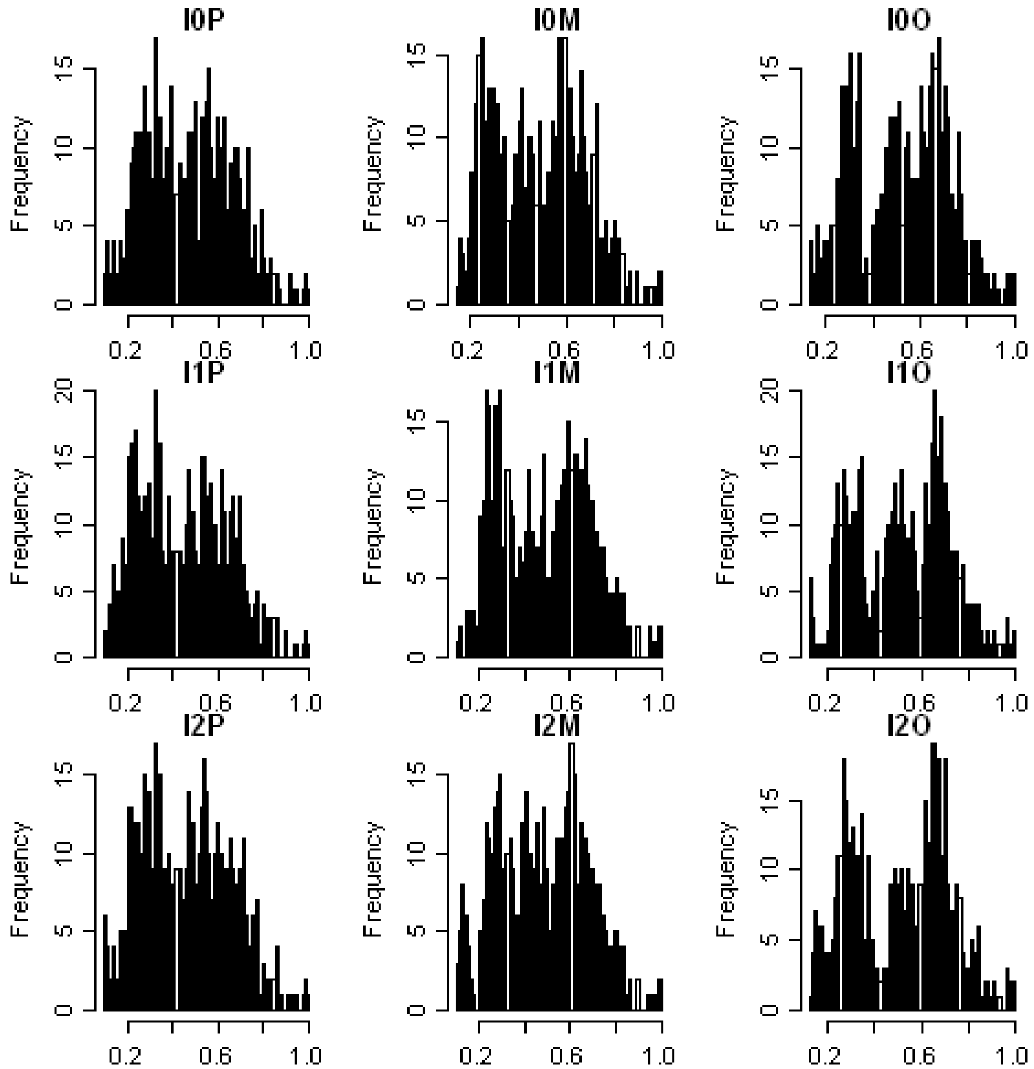


Figure A.81: Frequency histogram of coarse scale relative biomass (over time) for nemipterids under integrated management for each combination of development scenario and model specification.

A.10 Saurids

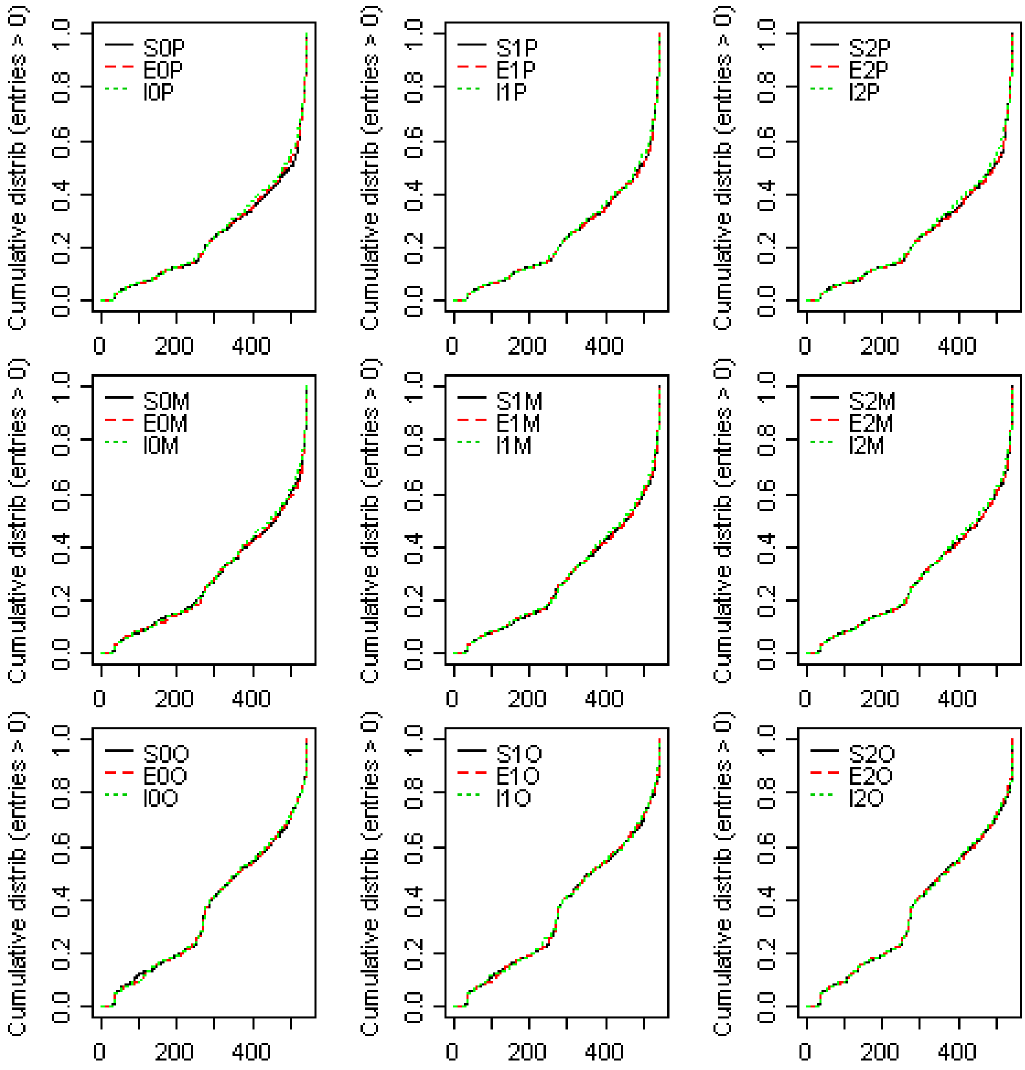


Figure A.82: Cumulative distribution plot for coarse scale spatial analysis of saurid average grid-cell relative biomass, comparing management strategies (each box contains the cumulative distributions for status quo [black], enhanced [red] and integrated [green] management for a given combination of model specification and development scenario).

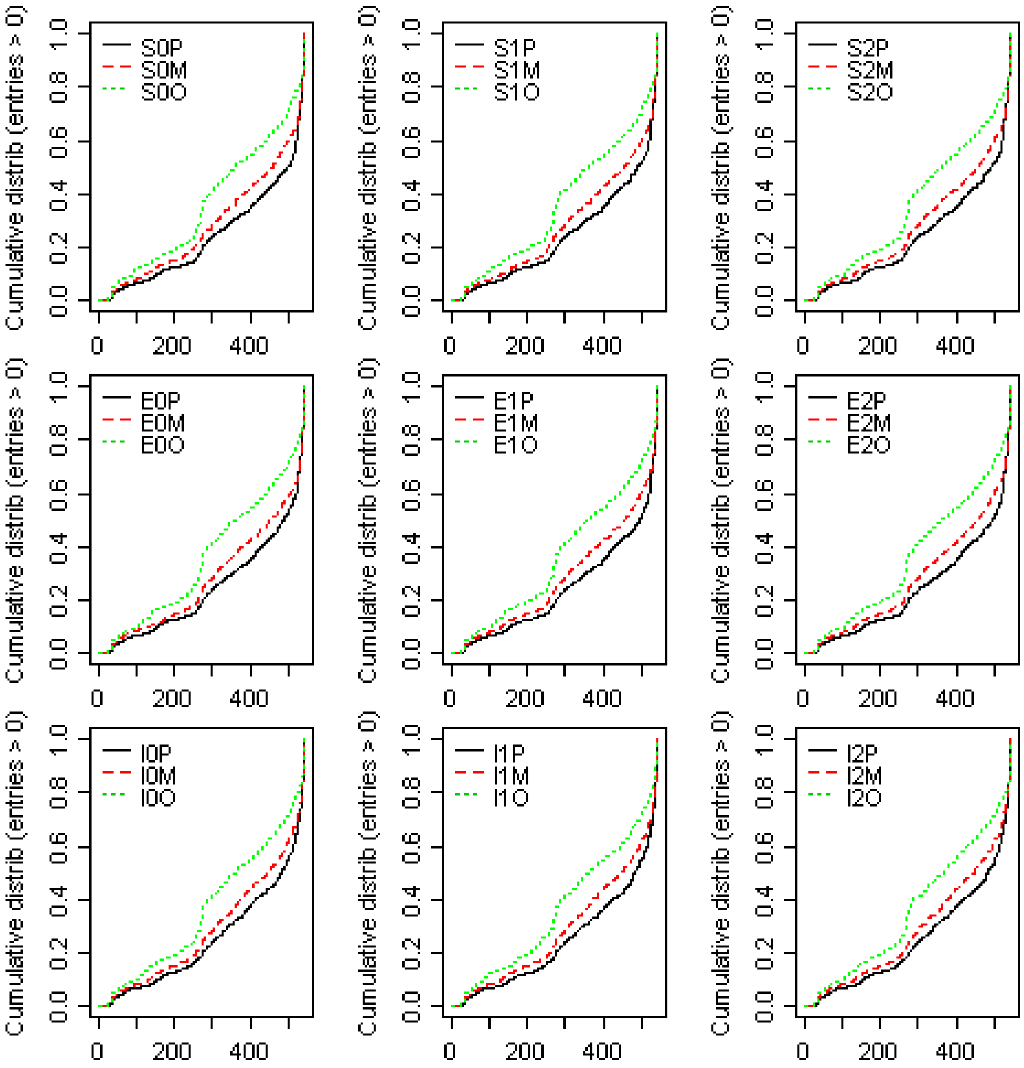


Figure A.83: Cumulative distribution plot for coarse scale spatial analysis of saurid average grid-cell relative biomass, comparing model specifications (each box contains the cumulative distributions for pessimistic [black], base case [red] and optimistic [green] specifications for a given combination of management strategy and development scenario).

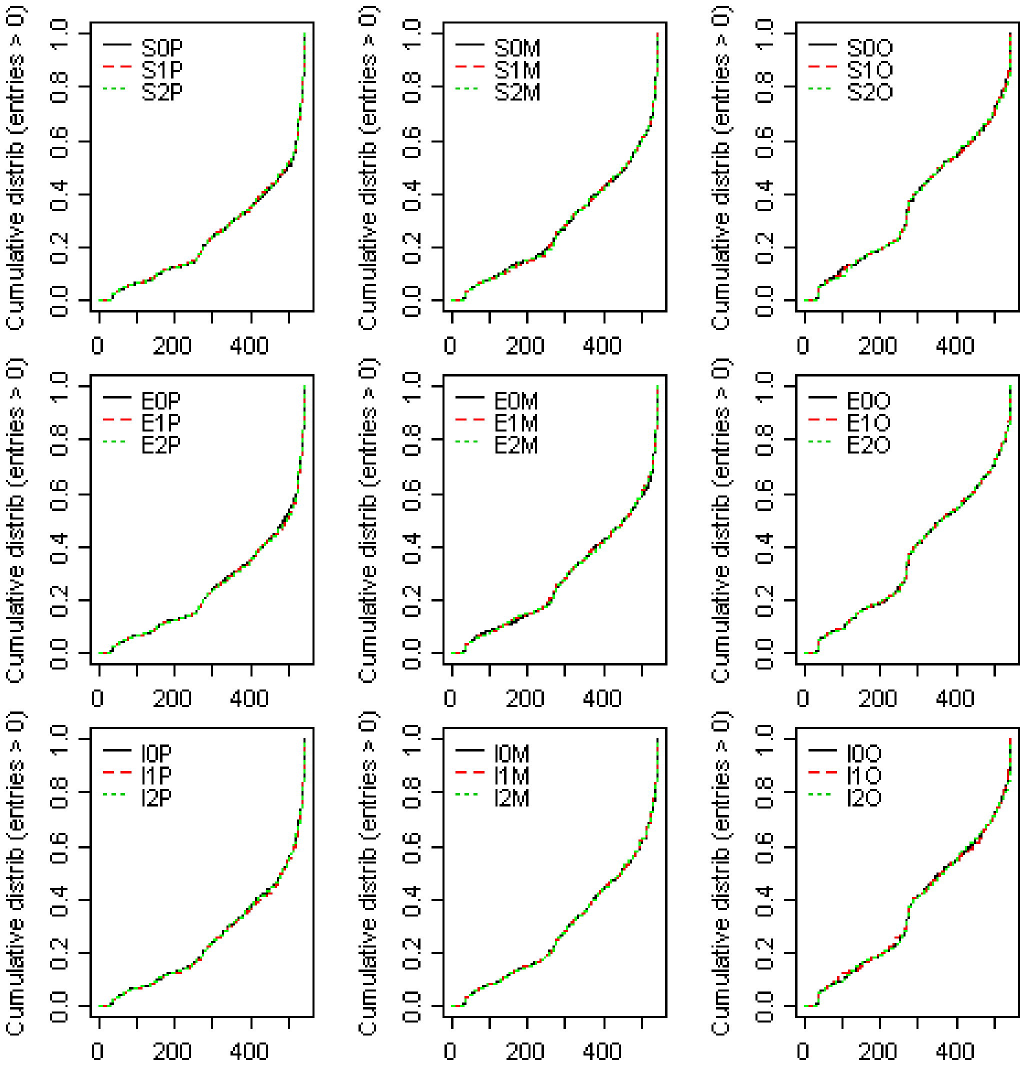


Figure A.84: Cumulative distribution plot for coarse scale spatial analysis of saurid average grid-cell relative biomass, comparing development scenarios (each box contains the cumulative distributions for 0-pulse [black], 1-pulse [red] and 2-pulse [green] development scenarios for a given combination of management strategy and model specification).

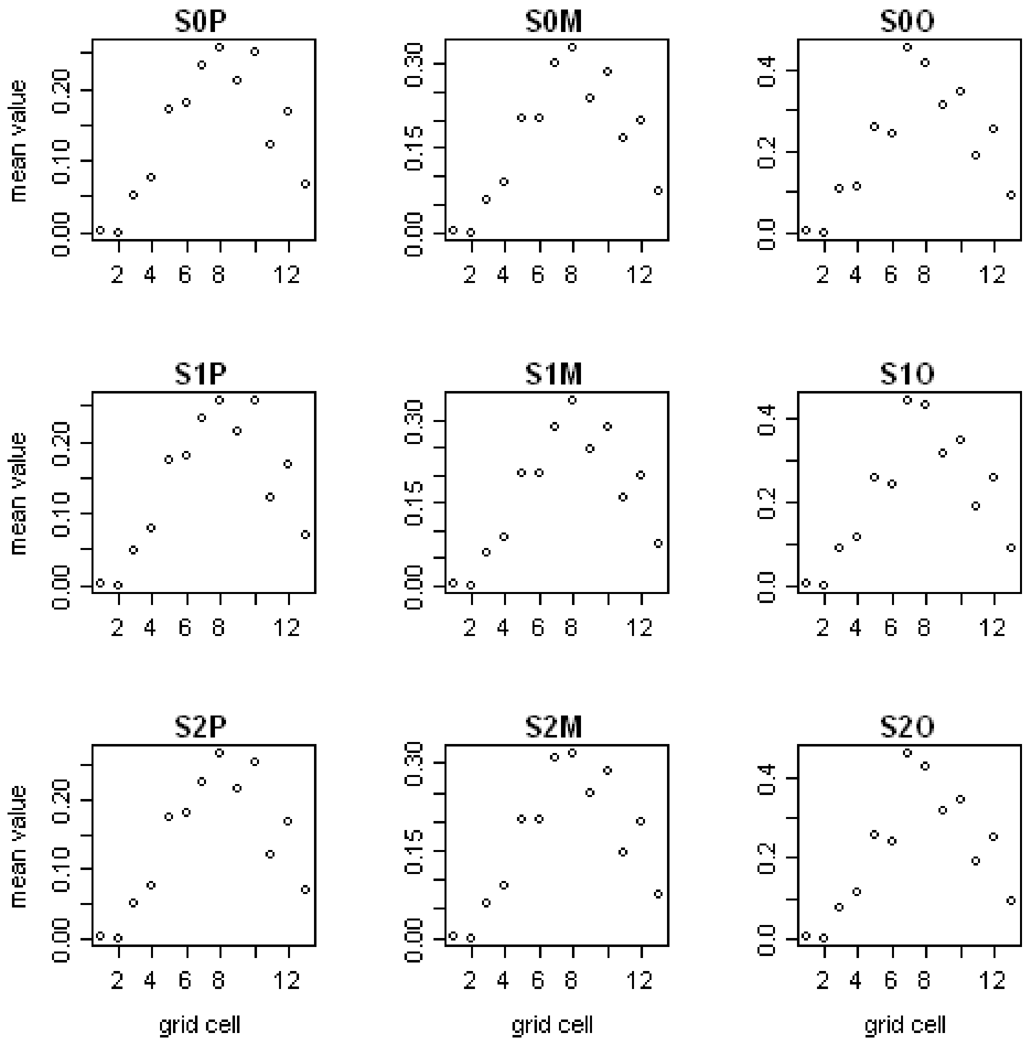


Figure A.85: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for saurids under status quo management for each combination of development scenario and model specification.

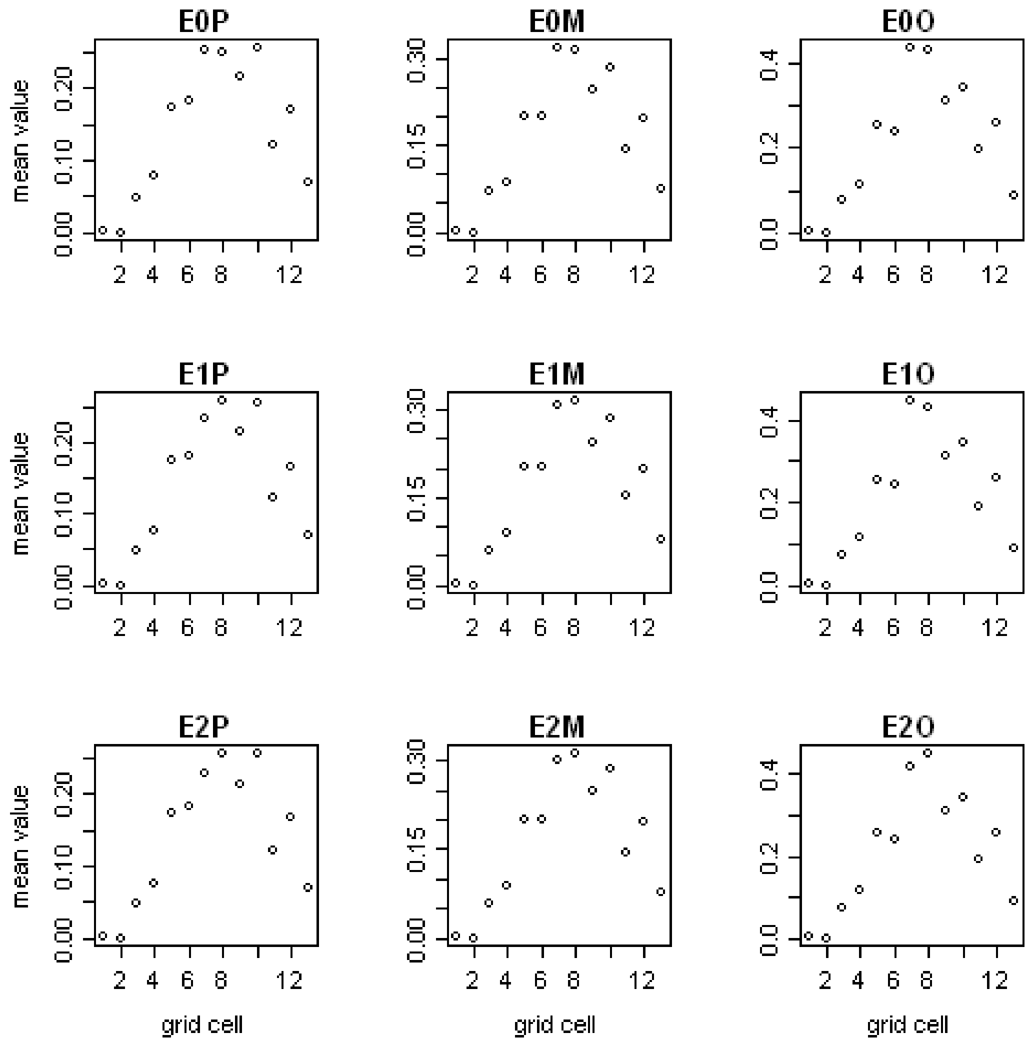


Figure A.86: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for saurids under enhanced management for each combination of development scenario and model specification.

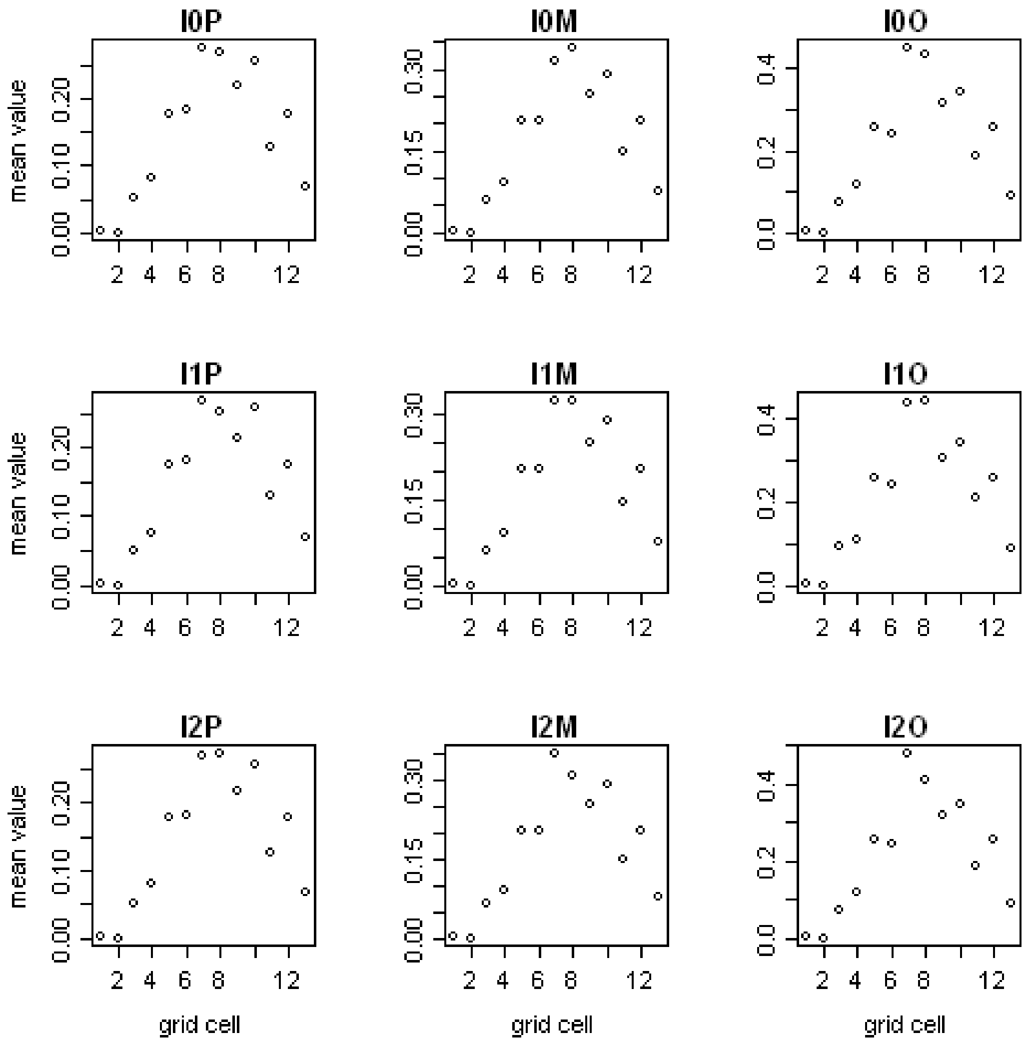


Figure A.87: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for saurids under integrated management for each combination of development scenario and model specification.

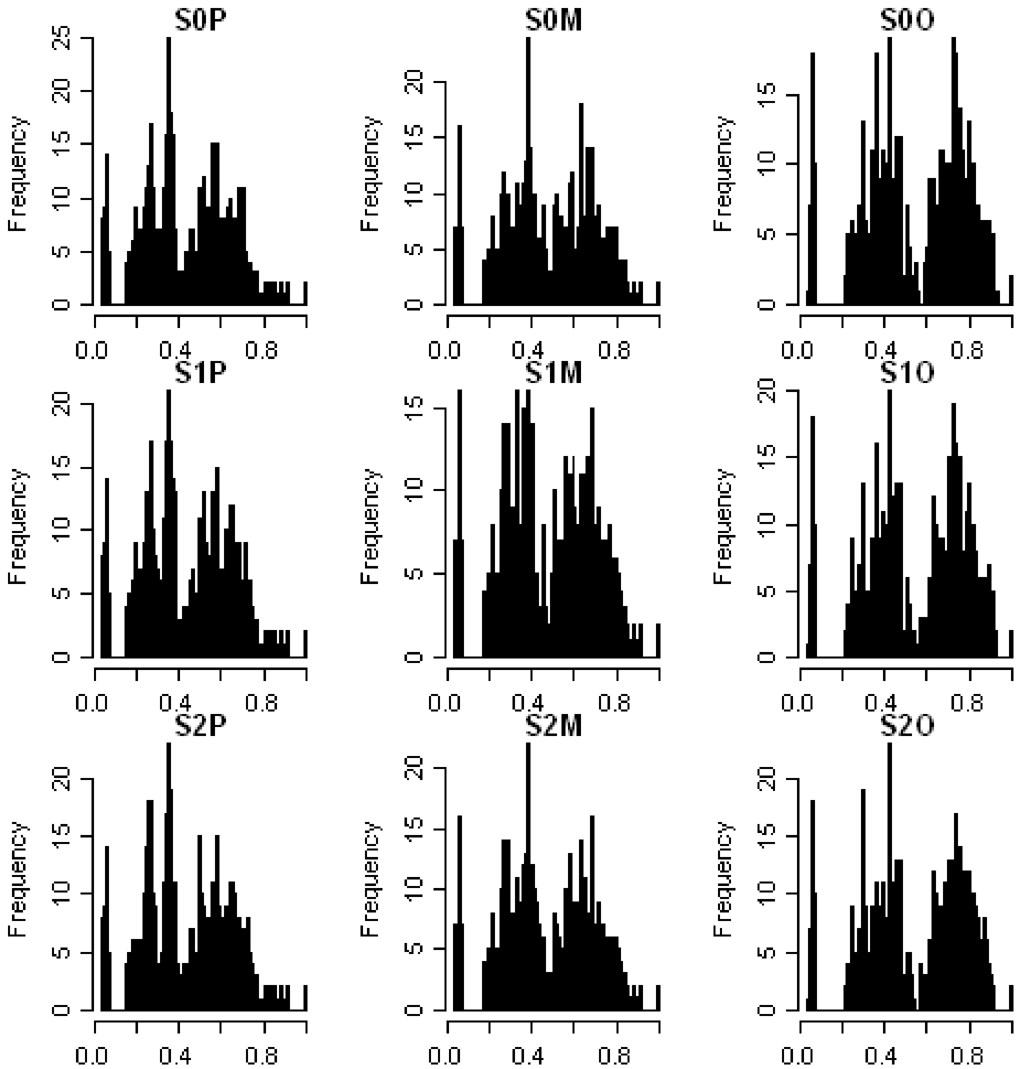


Figure A.88: Frequency histogram of coarse scale relative biomass (over time) for saurids under status quo management for each combination of development scenario and model specification.

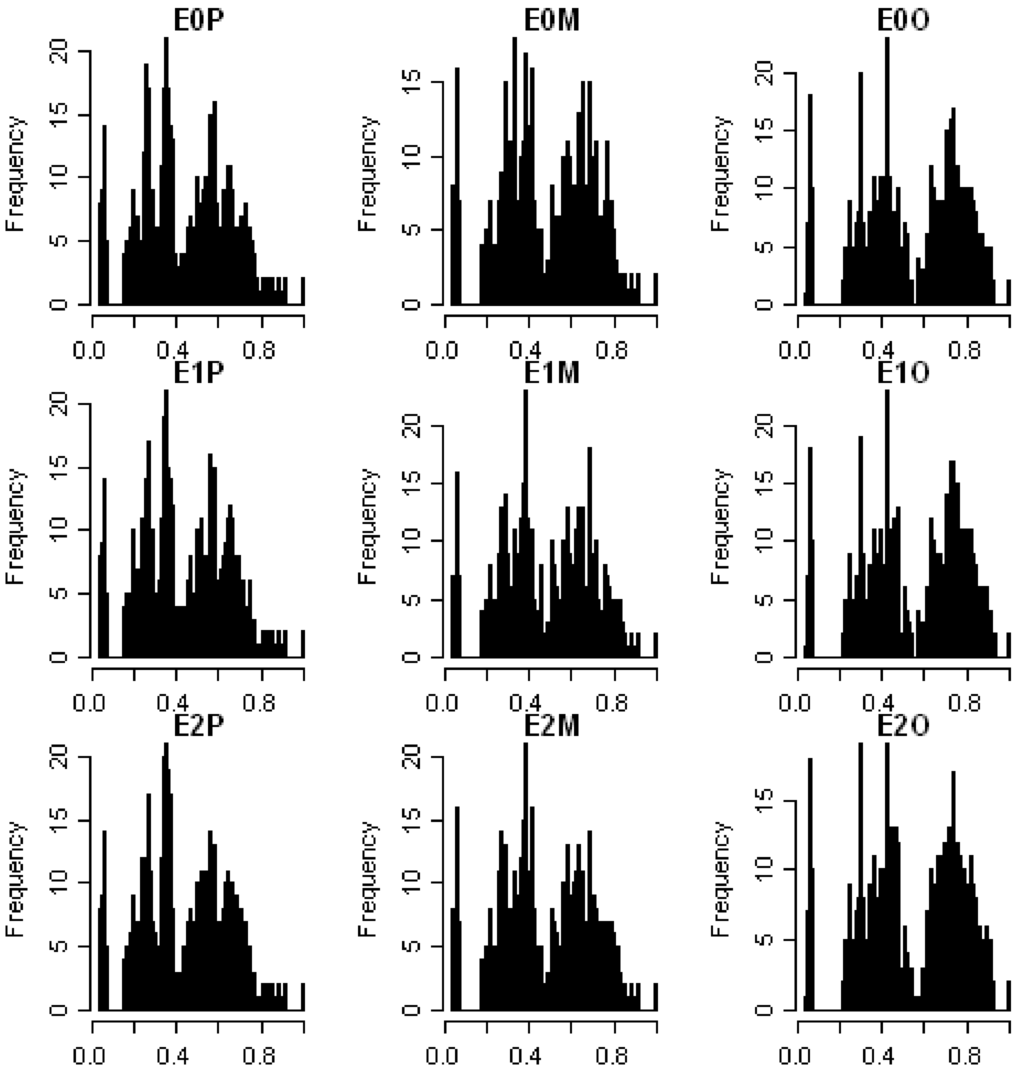


Figure A.89: Frequency histogram of coarse scale relative biomass (over time) for saurids under enhanced management for each combination of development scenario and model specification.

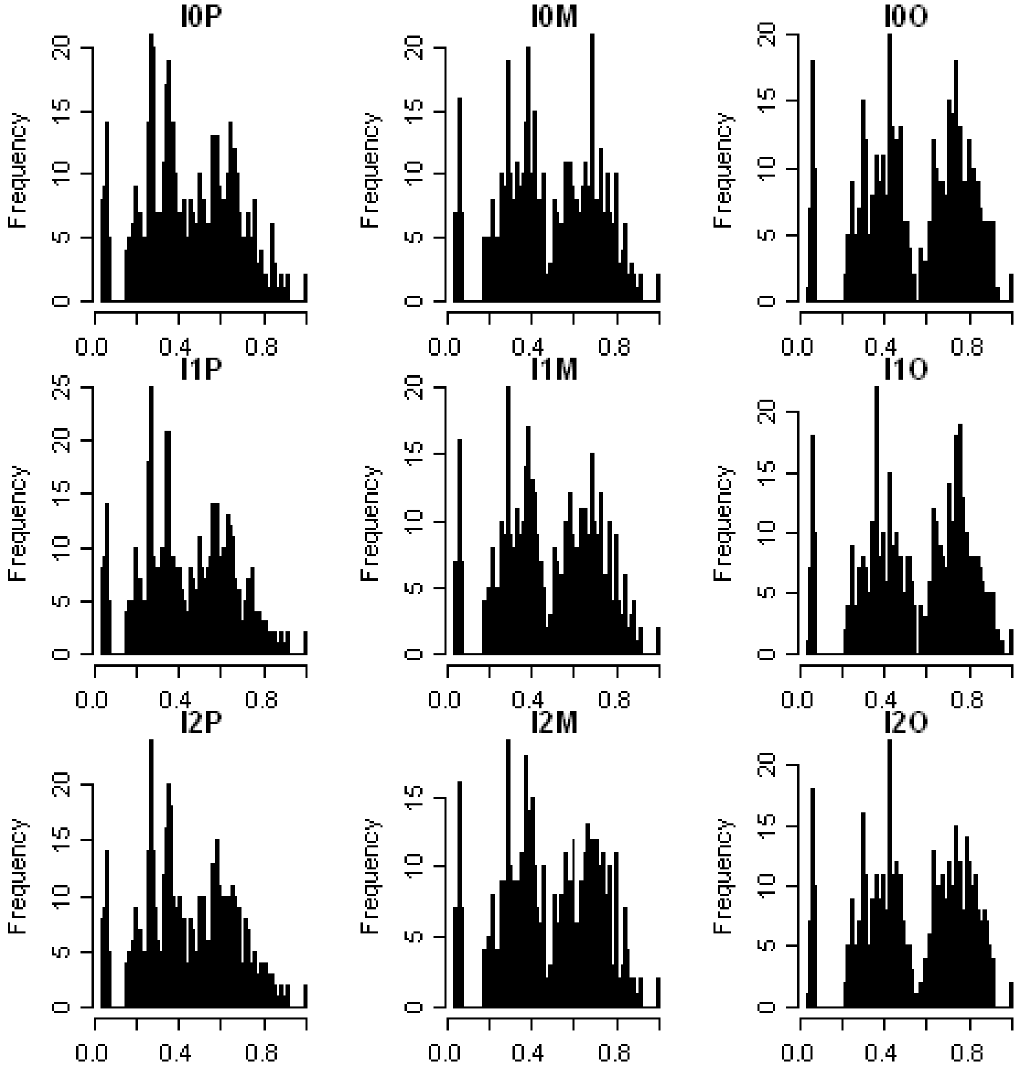


Figure A.90: Frequency histogram of coarse scale relative biomass (over time) for saurids under integrated management for each combination of development scenario and model specification.

A.11 Seagrass

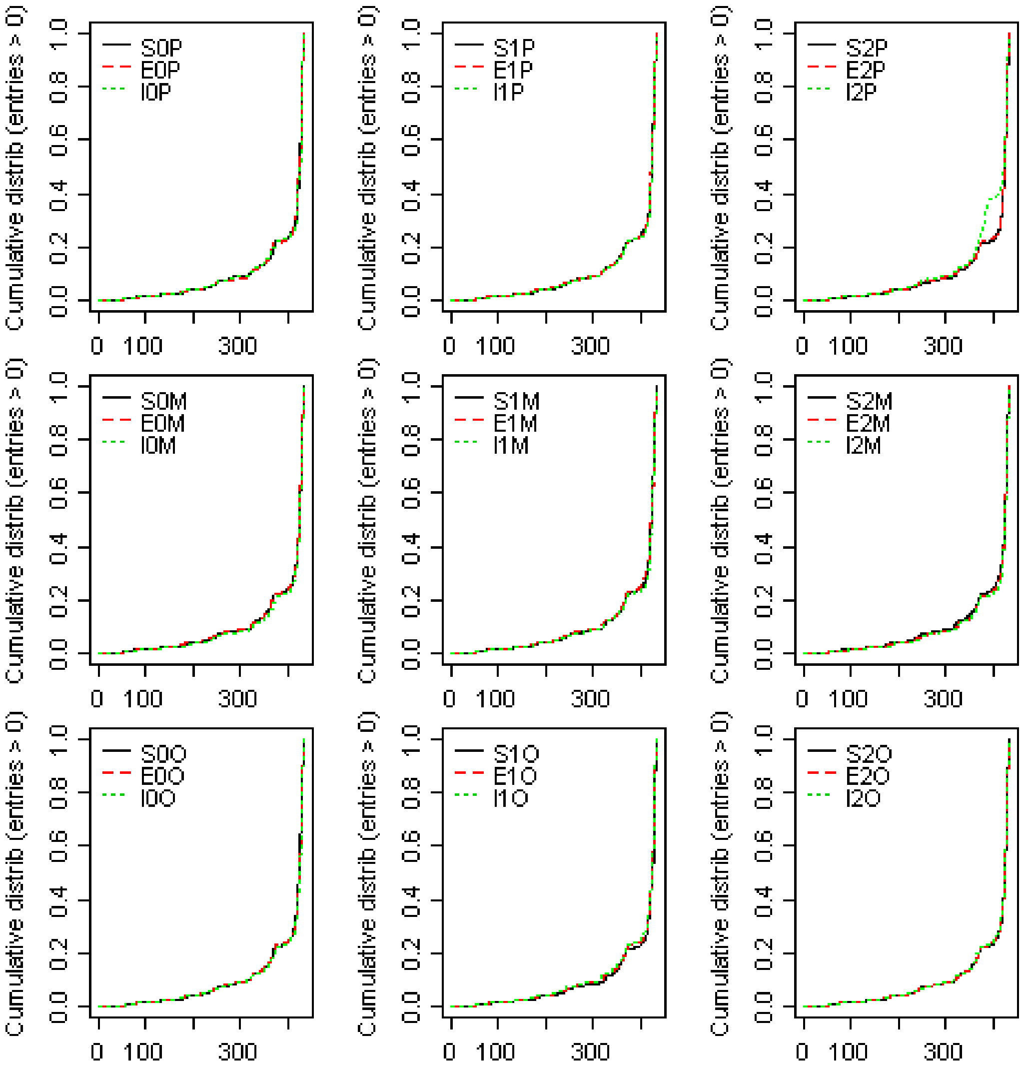


Figure A.91: Cumulative distribution plot for coarse scale spatial analysis of seagrass average grid-cell relative biomass, comparing management strategies (each box contains the cumulative distributions for status quo [black], enhanced [red] and integrated [green] management for a given combination of model specification and development scenario).

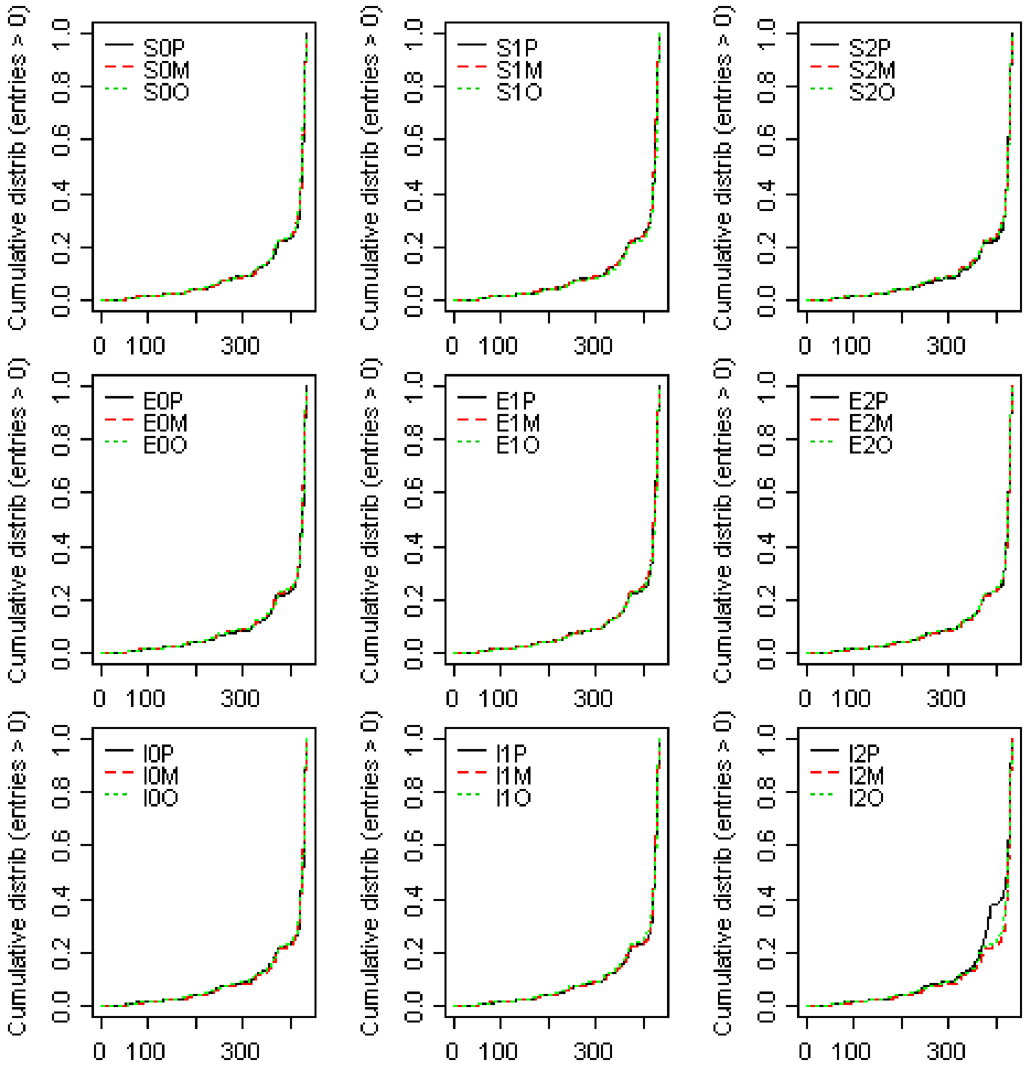


Figure A.92: Cumulative distribution plot for coarse scale spatial analysis of seagrass average grid-cell relative biomass, comparing model specifications (each box contains the cumulative distributions for pessimistic [black], base case [red] and optimistic [green] specifications for a given combination of management strategy and development scenario).

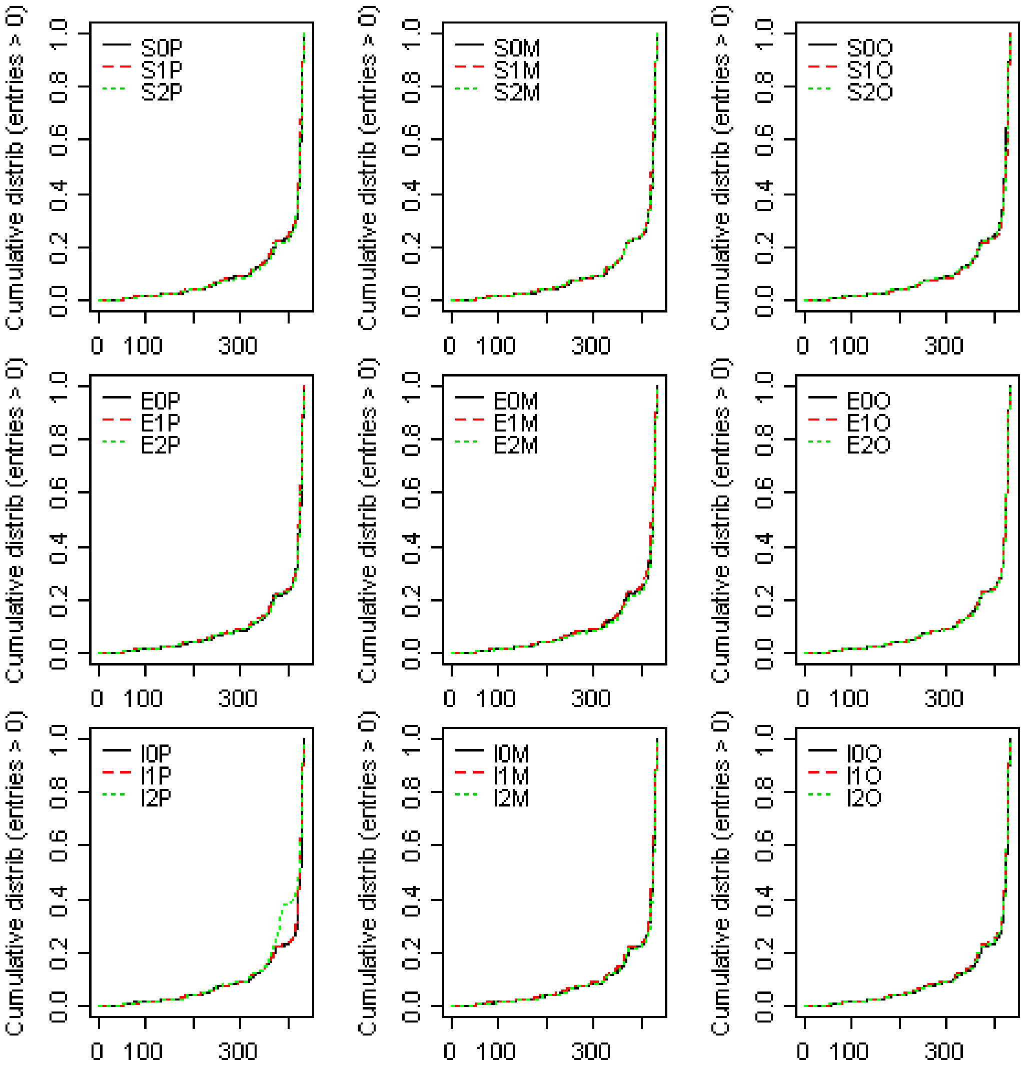


Figure A.93: Cumulative distribution plot for coarse scale spatial analysis of seagrass average grid-cell relative biomass, comparing development scenarios (each box contains the cumulative distributions for 0-pulse [black], 1-pulse [red] and 2-pulse [green] development scenarios for a given combination of management strategy and model specification).

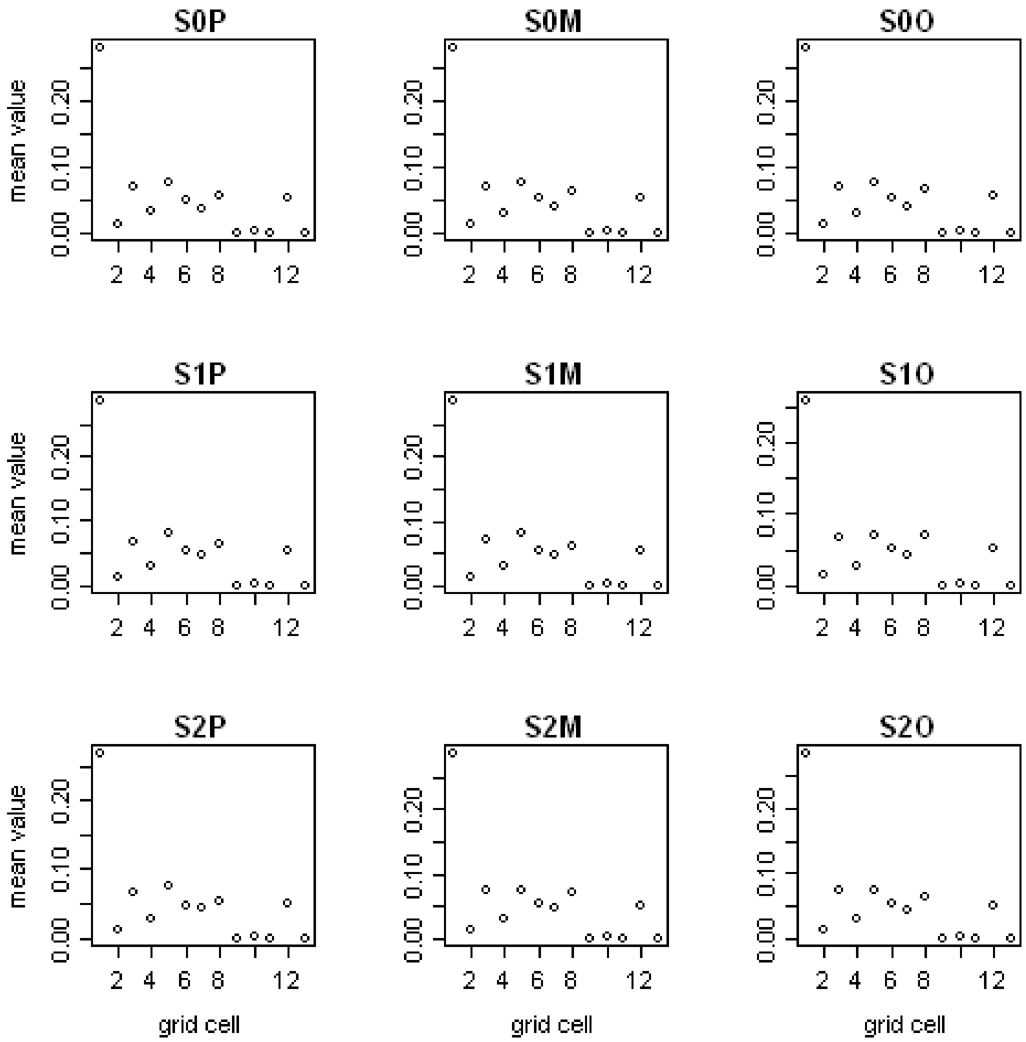


Figure A.94: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for seagrass under status quo management for each combination of development scenario and model specification.

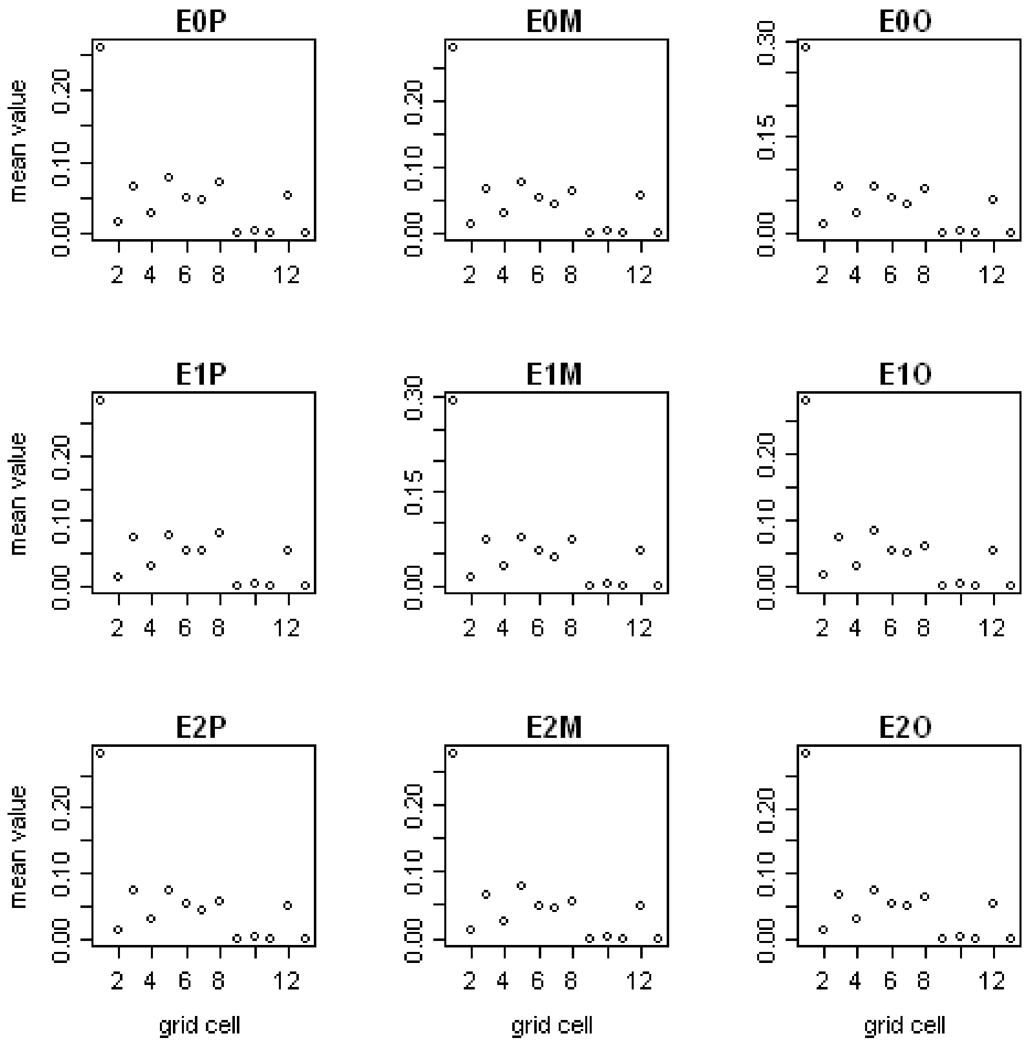


Figure A.95: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for seagrass under enhanced management for each combination of development scenario and model specification.

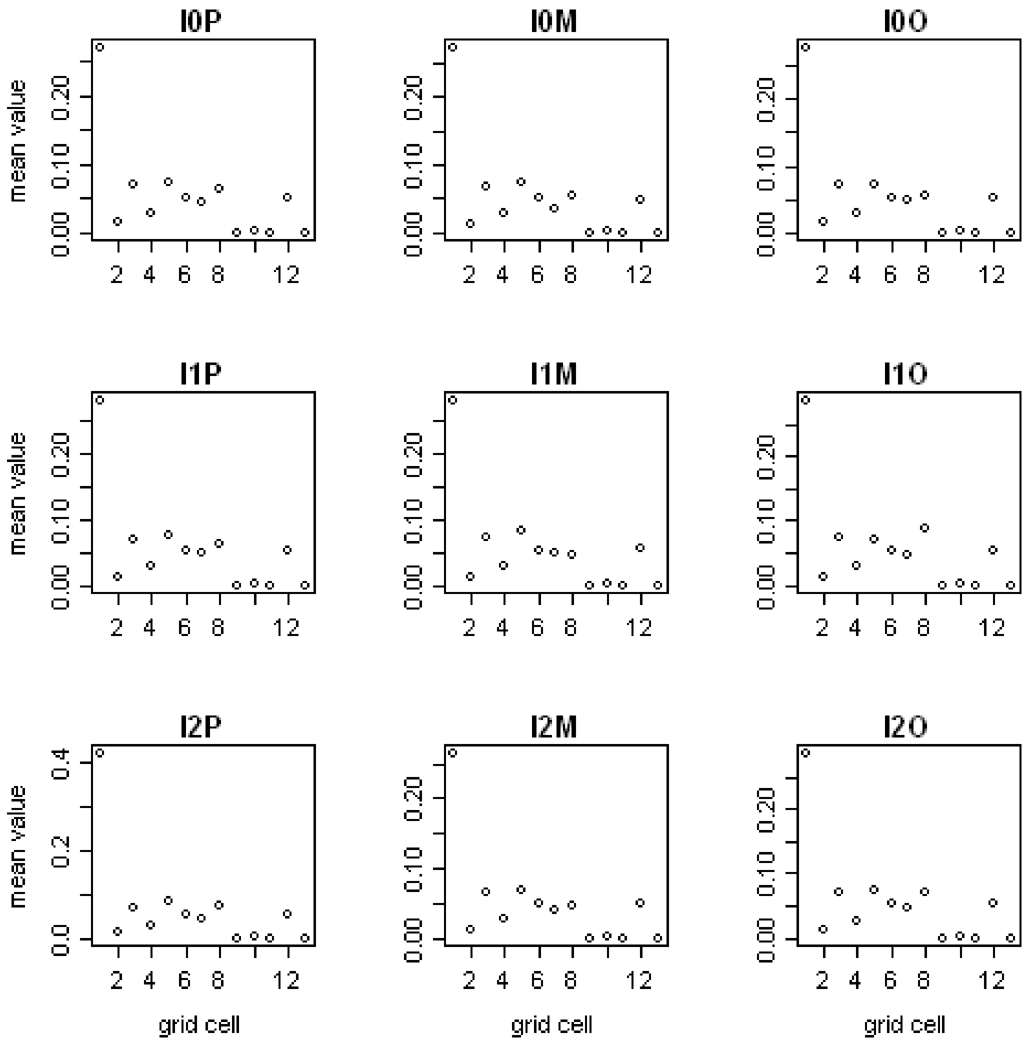


Figure A.96: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for seagrass under integrated management for each combination of development scenario and model specification.

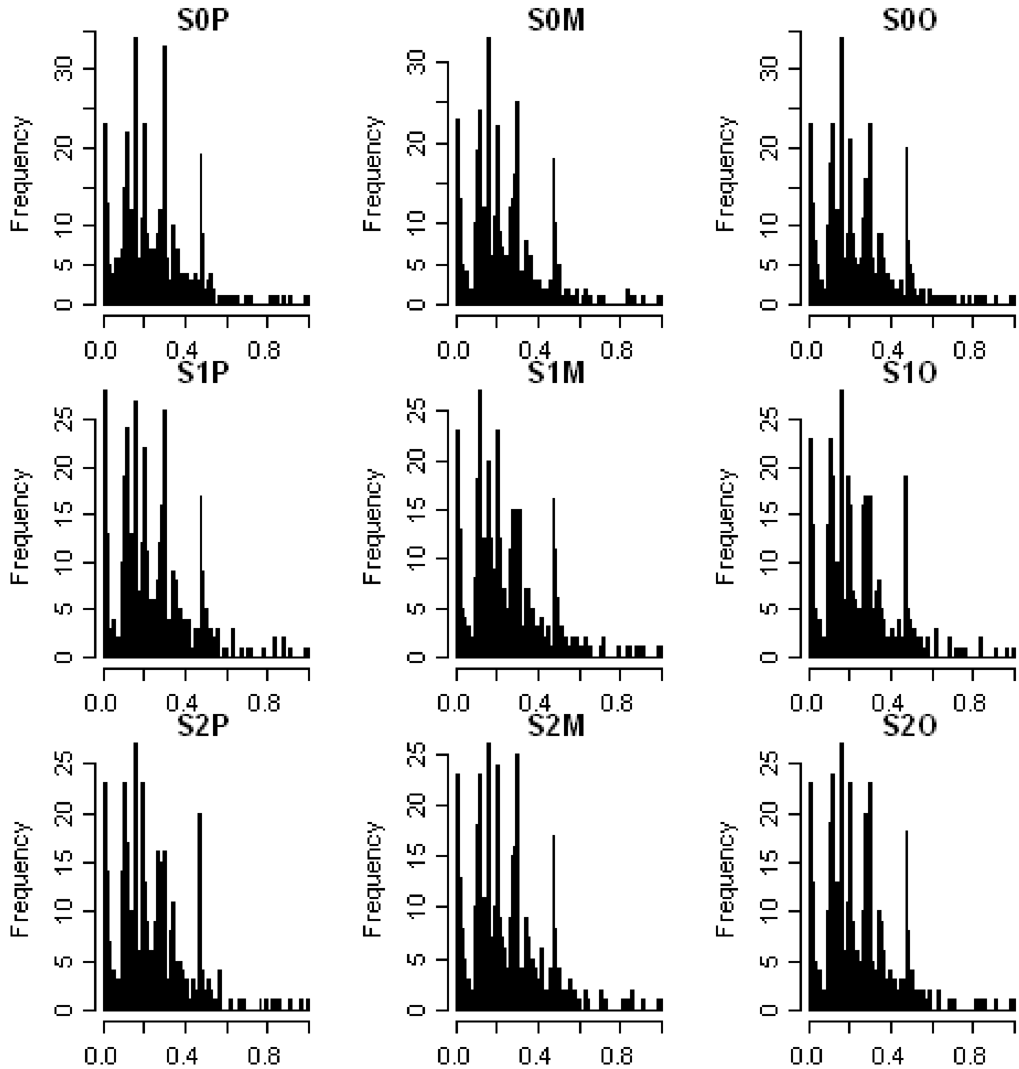


Figure A.97: Frequency histogram of coarse scale relative biomass (over time) for seagrass under status quo management for each combination of development scenario and model specification.

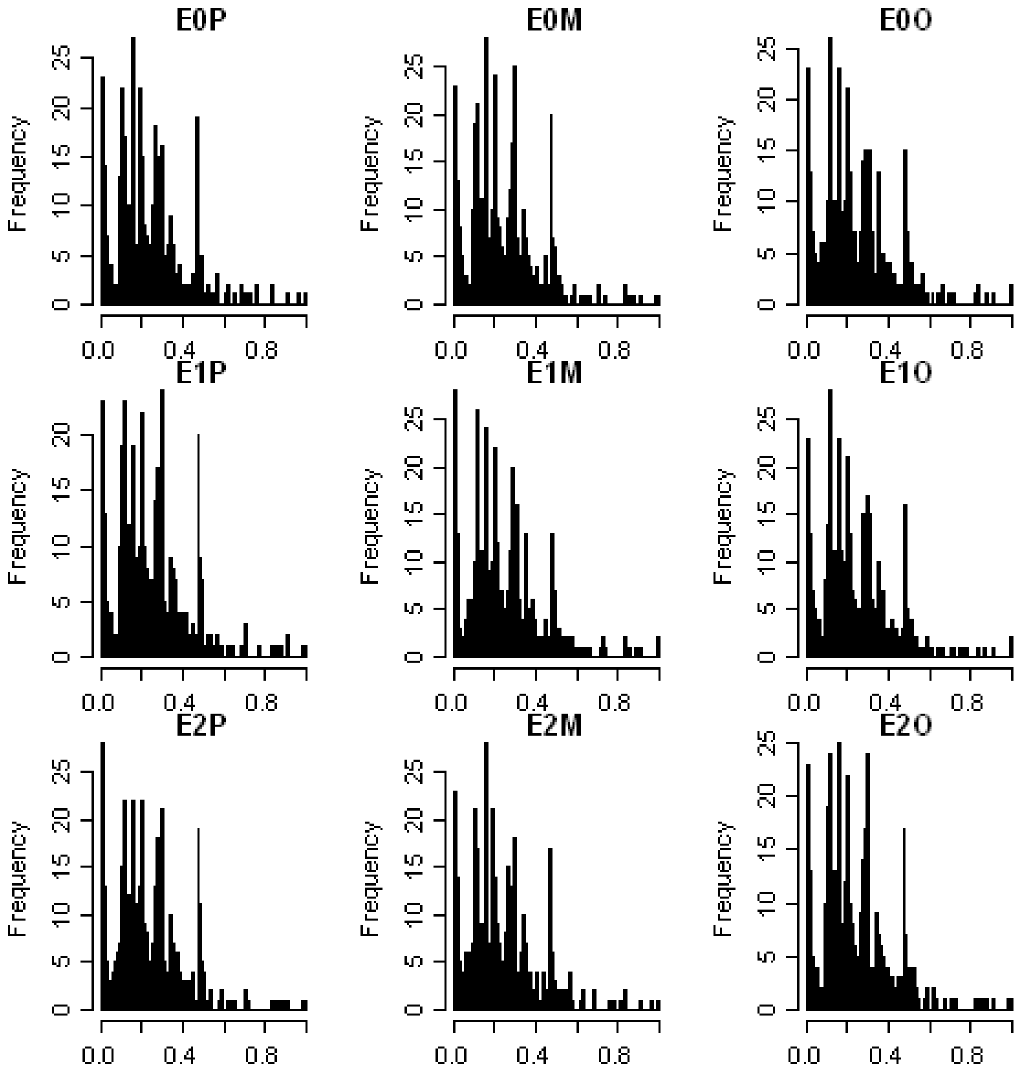


Figure A.98: Frequency histogram of coarse scale relative biomass (over time) for seagrass under enhanced management for each combination of development scenario and model specification.

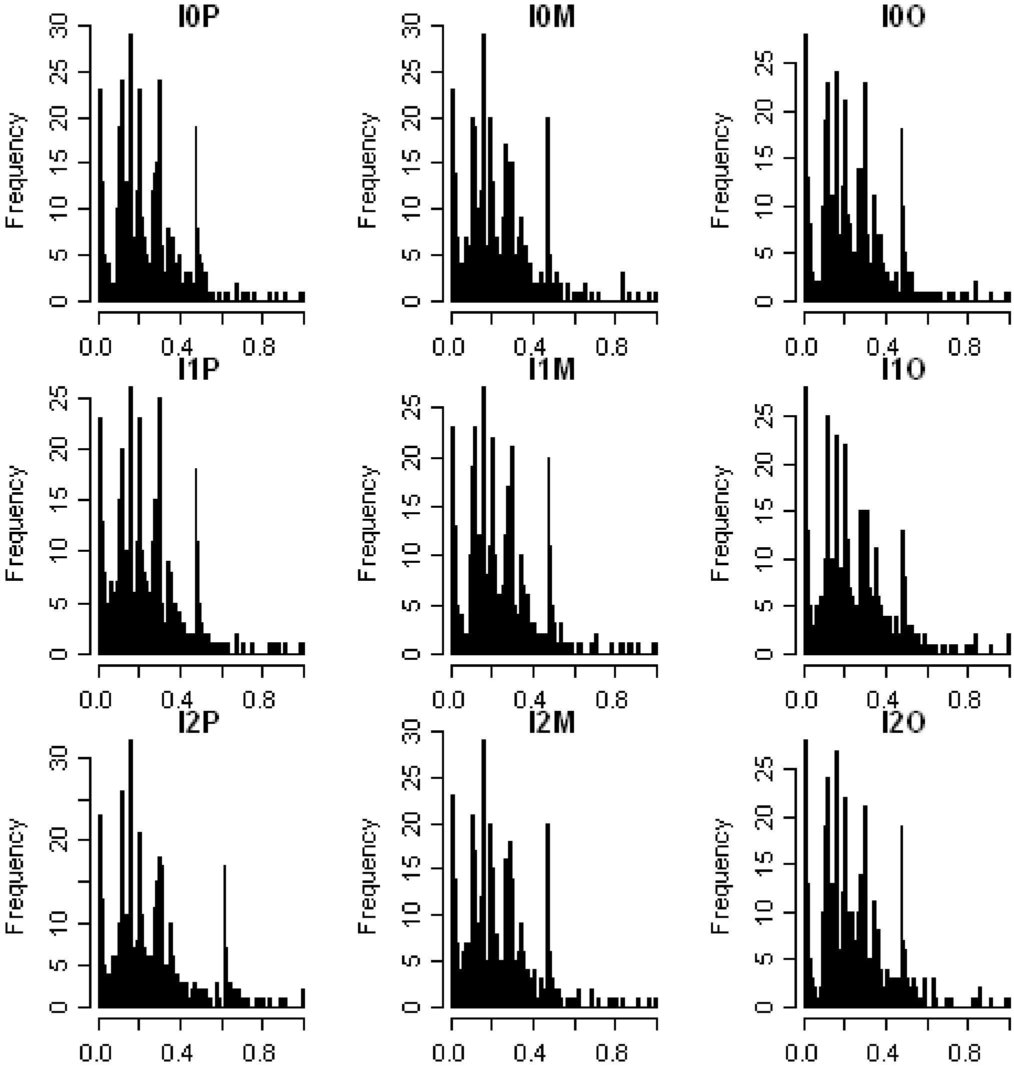


Figure A.99: Frequency histogram of coarse scale relative biomass (over time) for seagrass under integrated management for each combination of development scenario and model specification.

A.12 Sponge and reefs

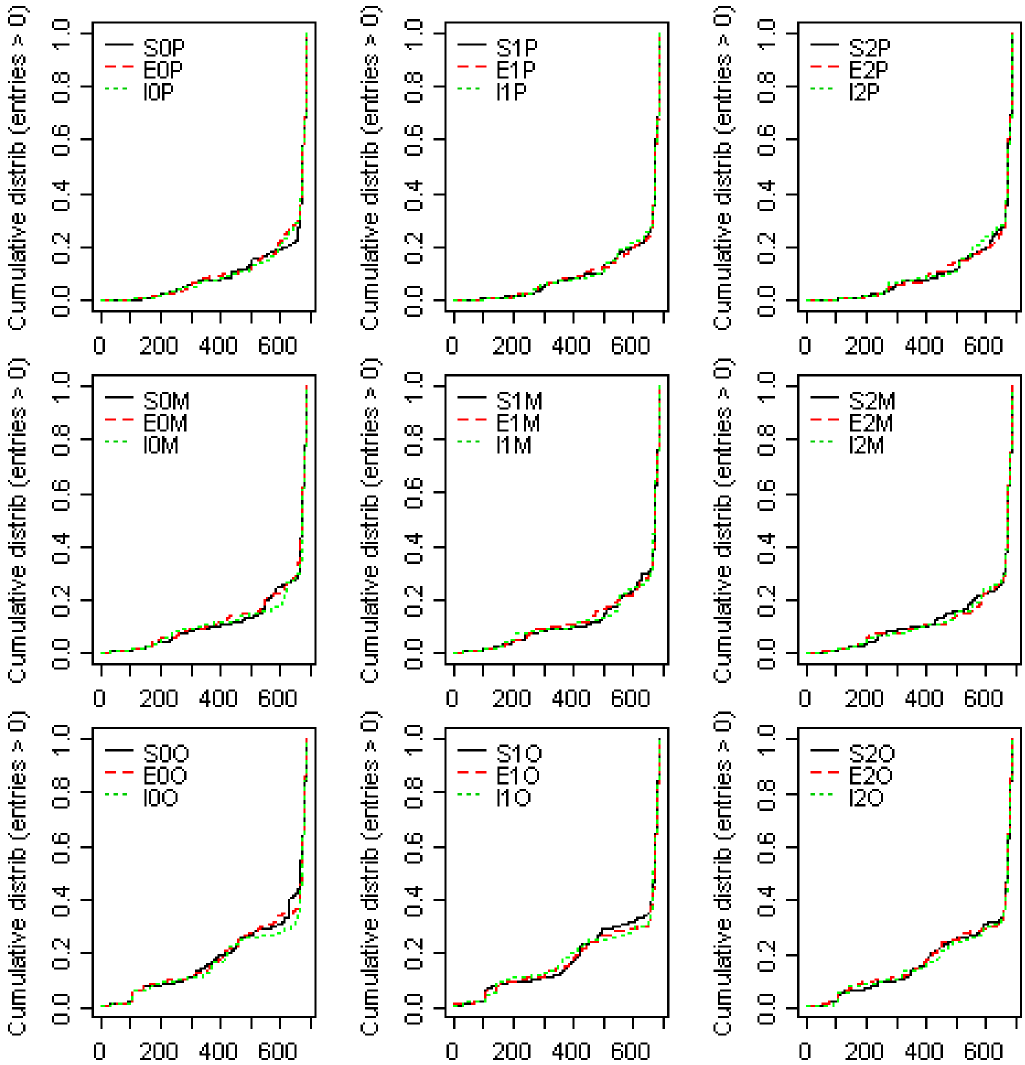


Figure A.100: Cumulative distribution plot for coarse scale spatial analysis of sponge and reef habitat average grid-cell relative biomass, comparing management strategies (each box contains the cumulative distributions for status quo [black], enhanced [red] and integrated [green] management for a given combination of model specification and development scenario).

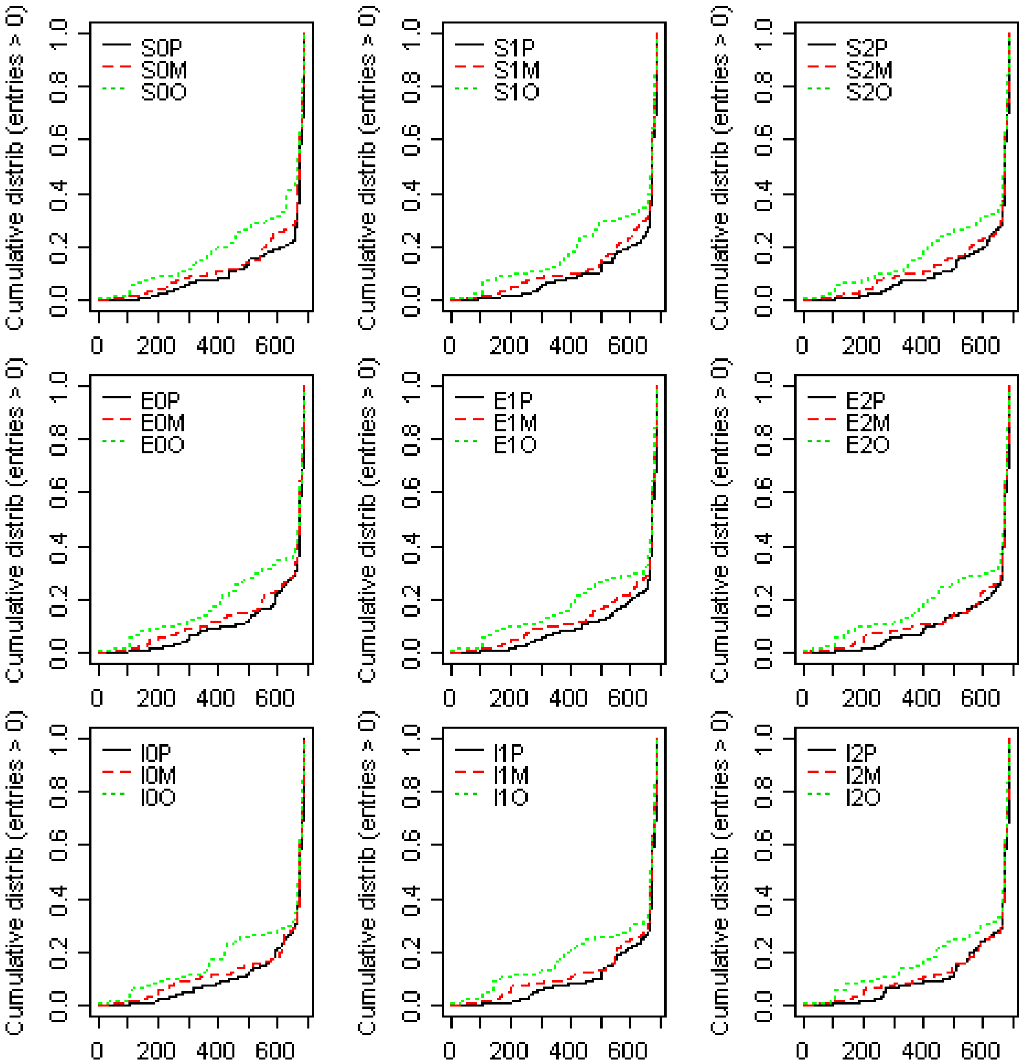


Figure A.101: Cumulative distribution plot for coarse scale spatial analysis of sponge and reef habitat average grid-cell relative biomass, comparing model specifications (each box contains the cumulative distributions for pessimistic [black], base case [red] and optimistic [green] specifications for a given combination of management strategy and development scenario).

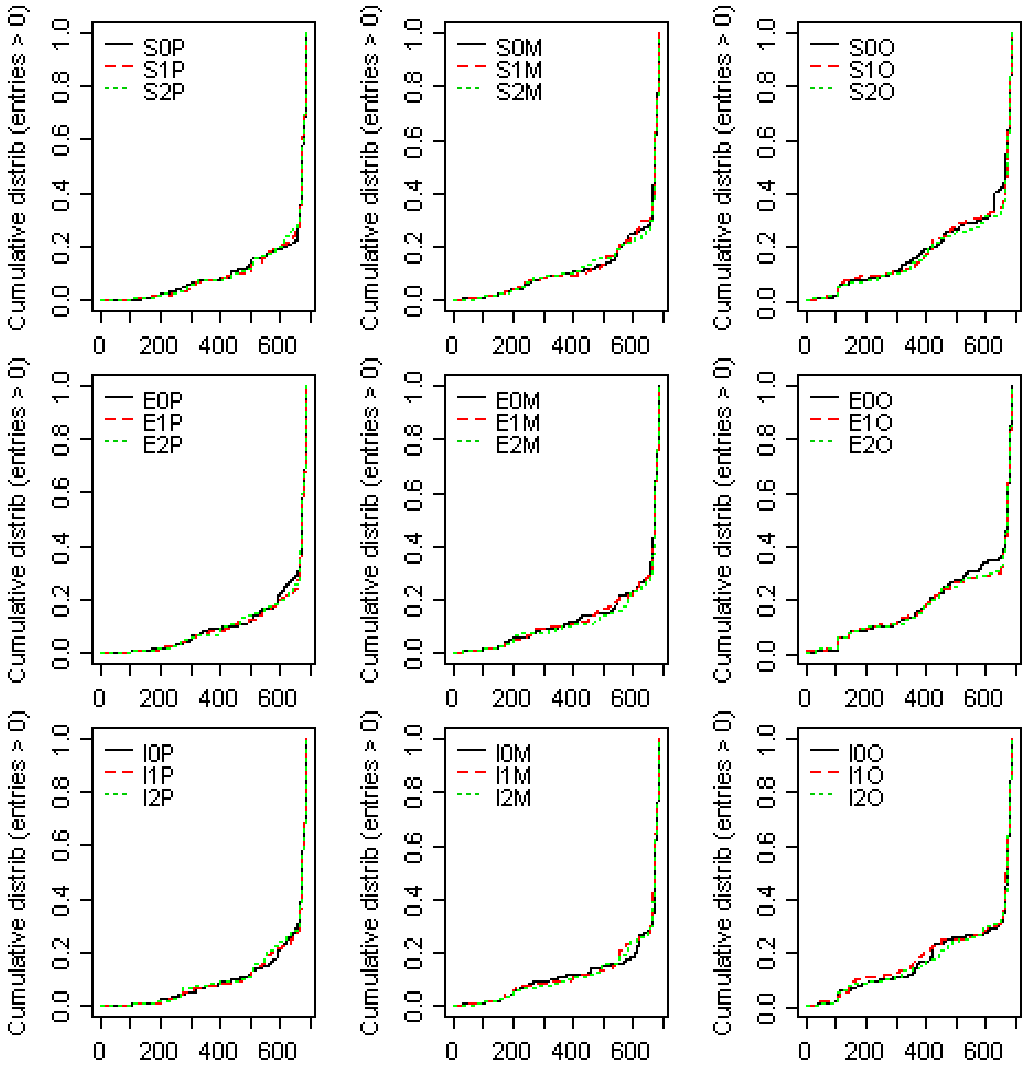


Figure A.102: Cumulative distribution plot for coarse scale spatial analysis of sponge and reef habitat average grid-cell relative biomass, comparing development scenarios (each box contains the cumulative distributions for 0-pulse [black], 1-pulse [red] and 2-pulse [green] development scenarios for a given combination of management strategy and model specification).

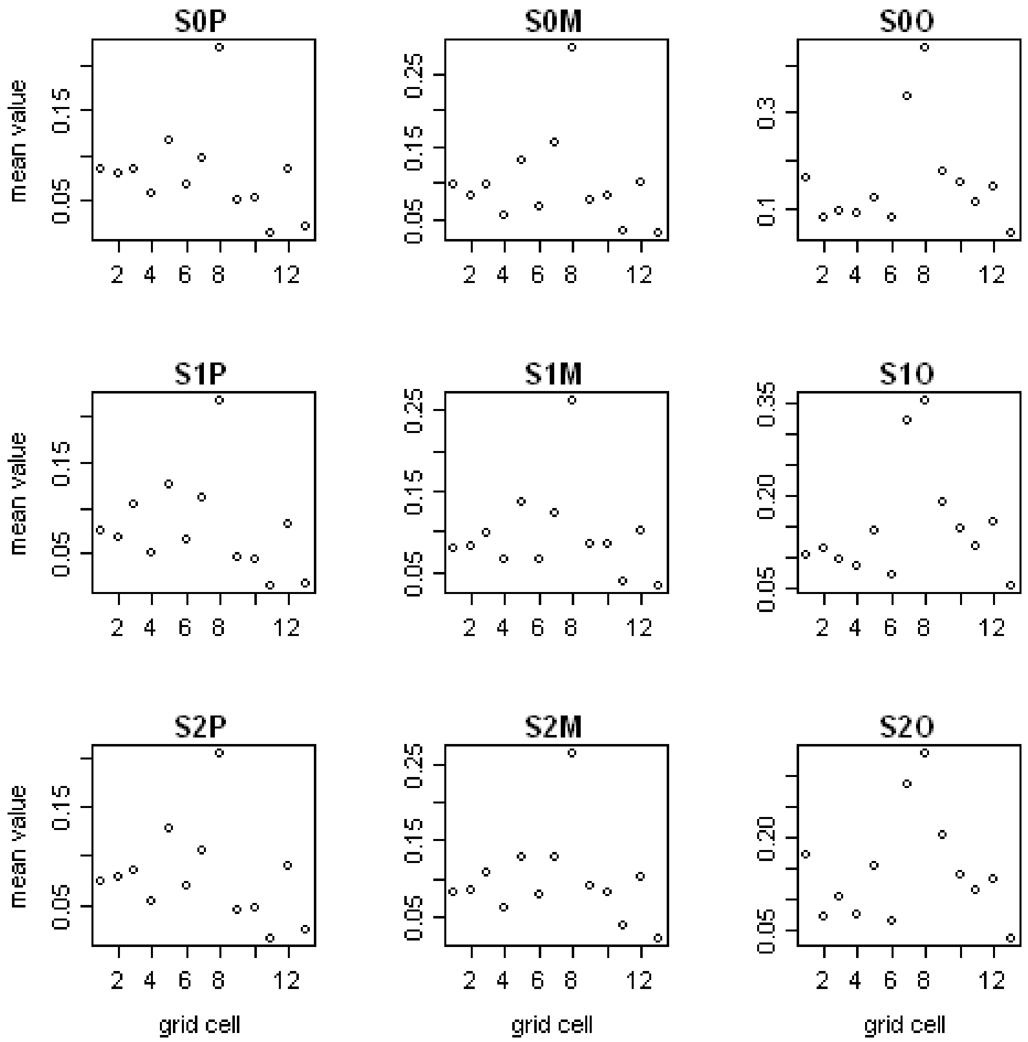


Figure A.103: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for sponge and reef habitats under status quo management for each combination of development scenario and model specification.

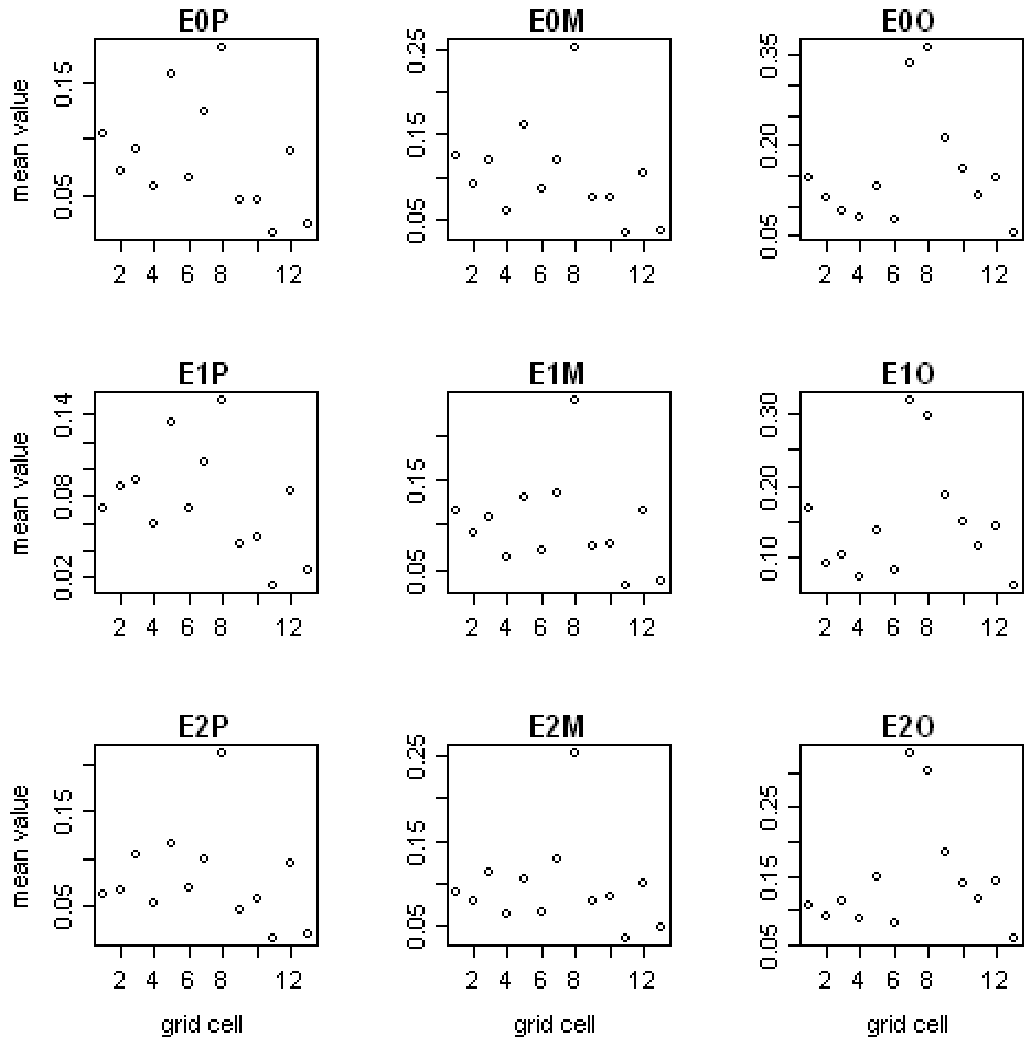


Figure A.104: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for sponge and reef habitats under enhanced management for each combination of development scenario and model specification.

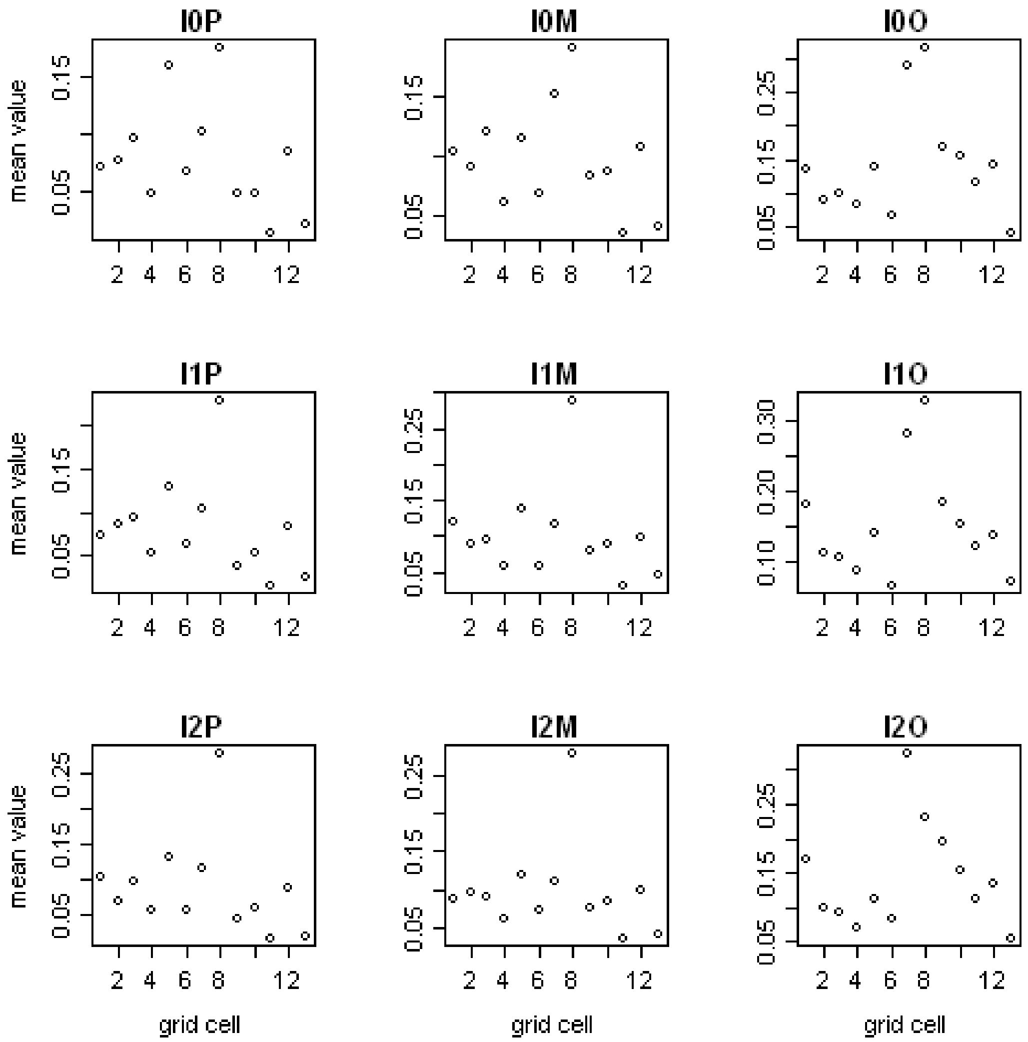


Figure A.105: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for sponge and reef habitats under integrated management for each combination of development scenario and model specification.

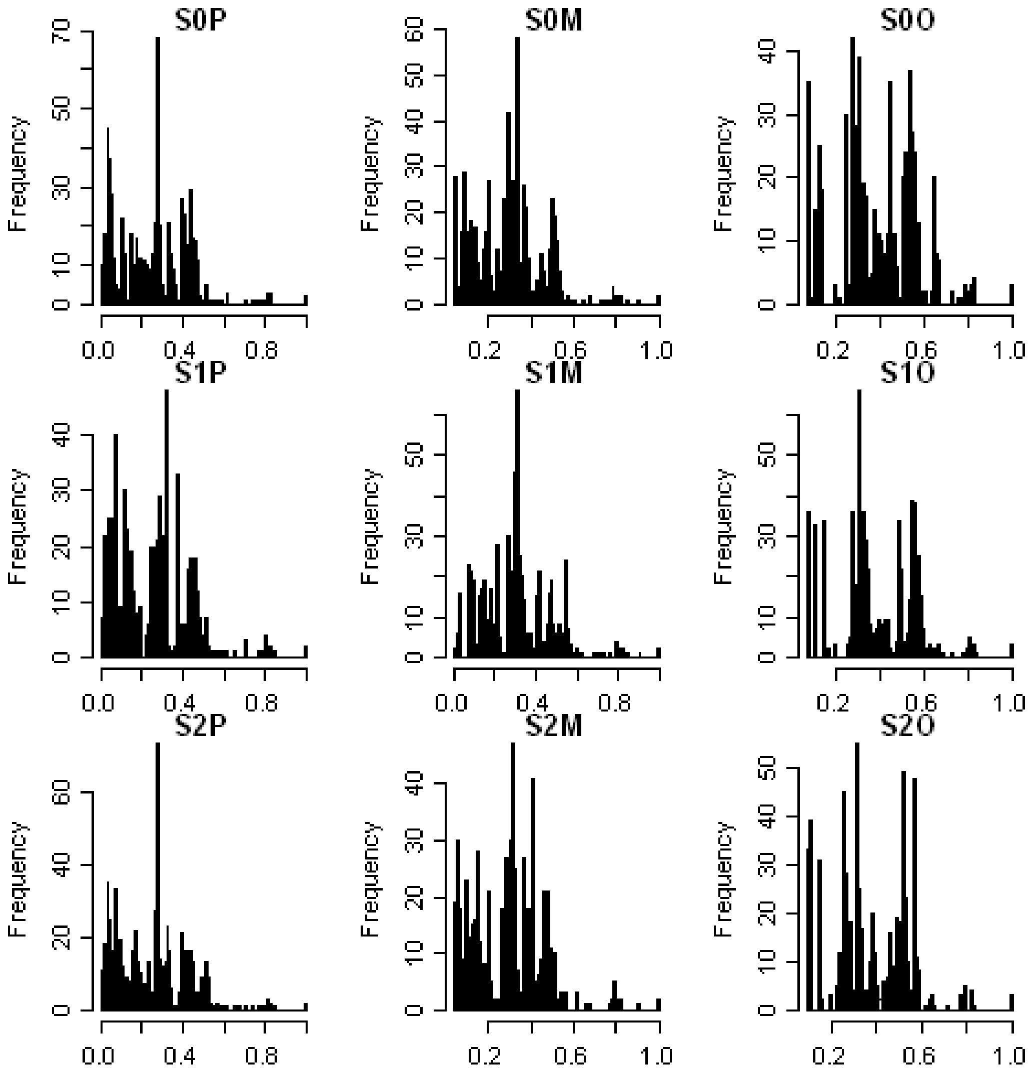


Figure A.106: Frequency histogram of coarse scale relative biomass (over time) for sponge and reef habitats under status quo management for each combination of development scenario and model specification.

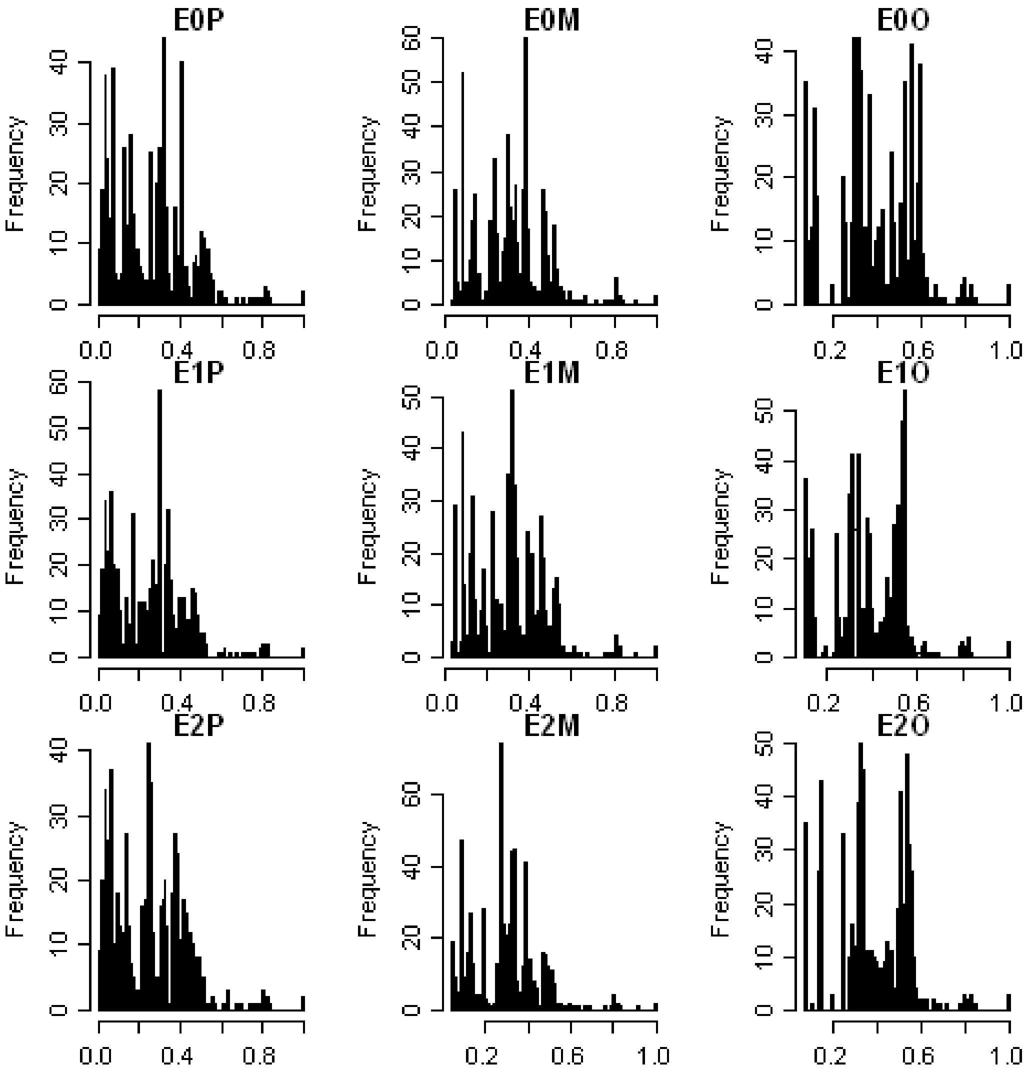


Figure A.107: Frequency histogram of coarse scale relative biomass (over time) for sponge and reef habitats under enhanced management for each combination of development scenario and model specification.

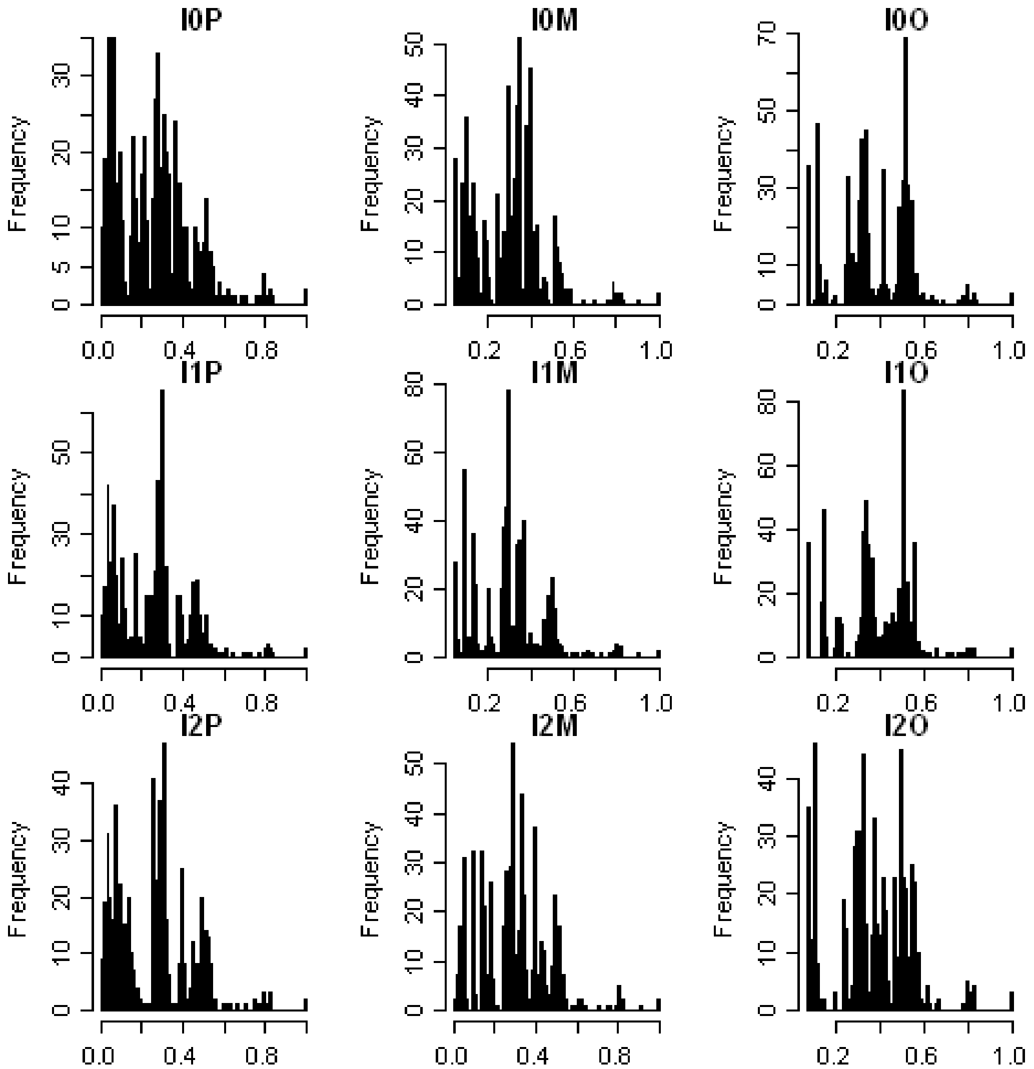


Figure A.108: Frequency histogram of coarse scale relative biomass (over time) for sponge and reef habitats under integrated management for each combination of development scenario and model specification.

A.13 Mangroves

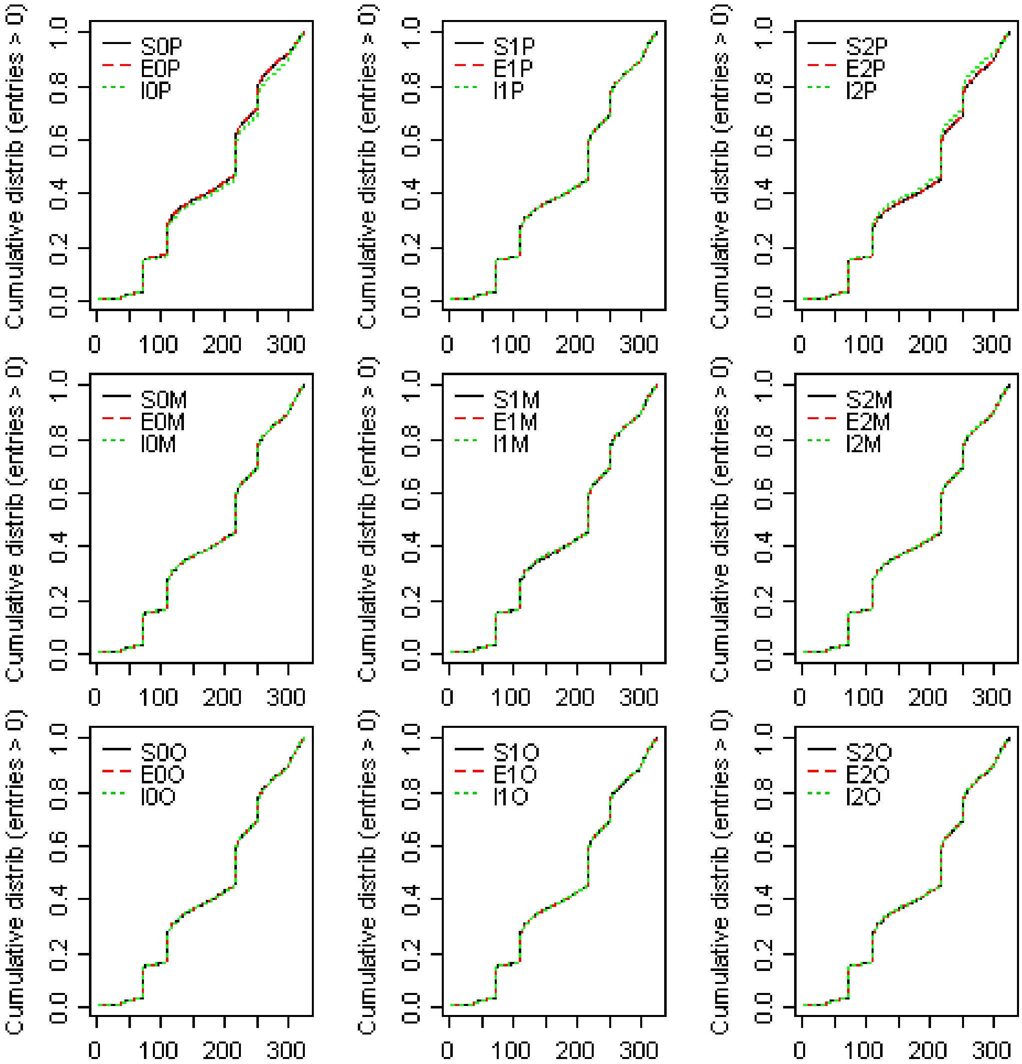


Figure A.109: Cumulative distribution plot for coarse scale spatial analysis of mangrove average grid-cell relative biomass, comparing management strategies (each box contains the cumulative distributions for status quo [black], enhanced [red] and integrated [green] management for a given combination of model specification and development scenario).

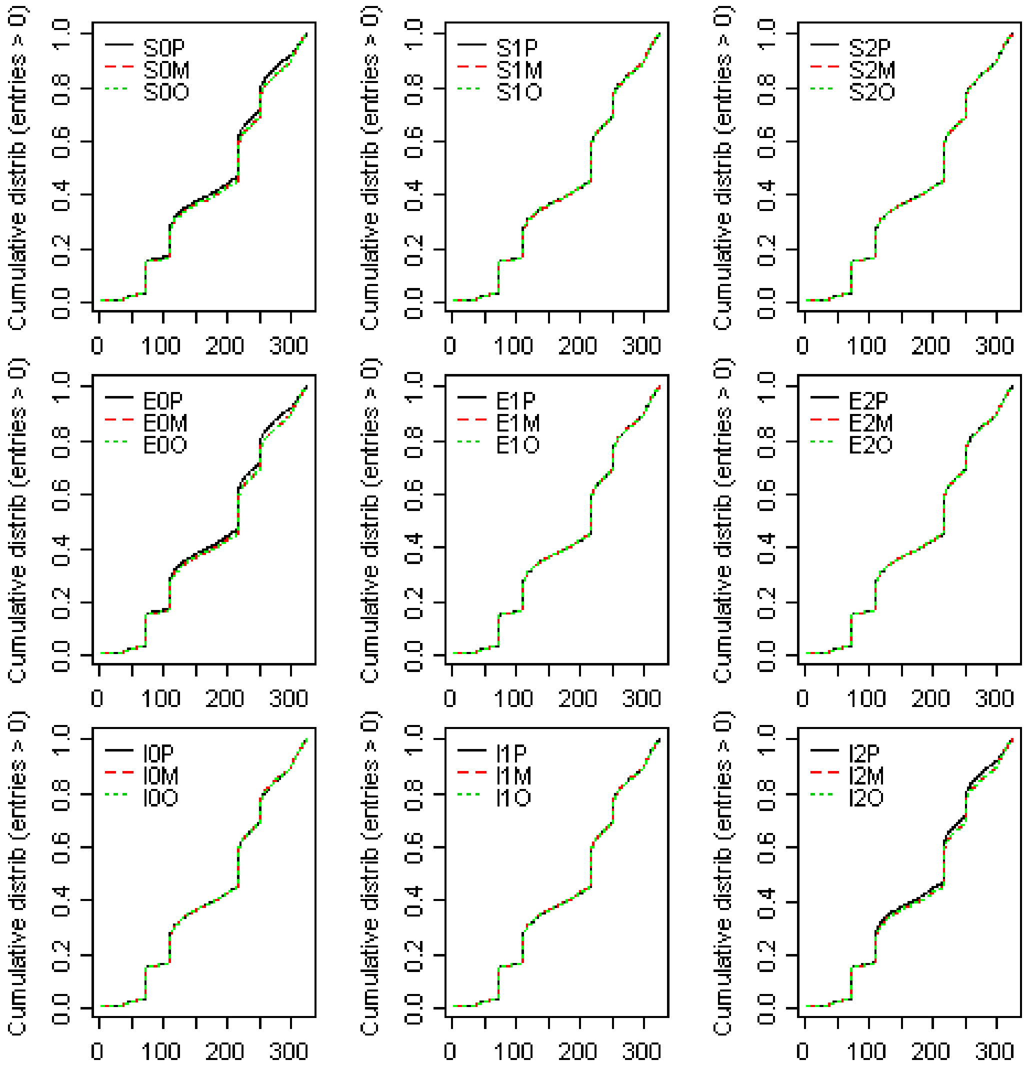


Figure A.110: Cumulative distribution plot for coarse scale spatial analysis of mangrove average grid-cell relative biomass, comparing model specifications (each box contains the cumulative distributions for pessimistic [black], base case [red] and optimistic [green] specifications for a given combination of management strategy and development scenario).

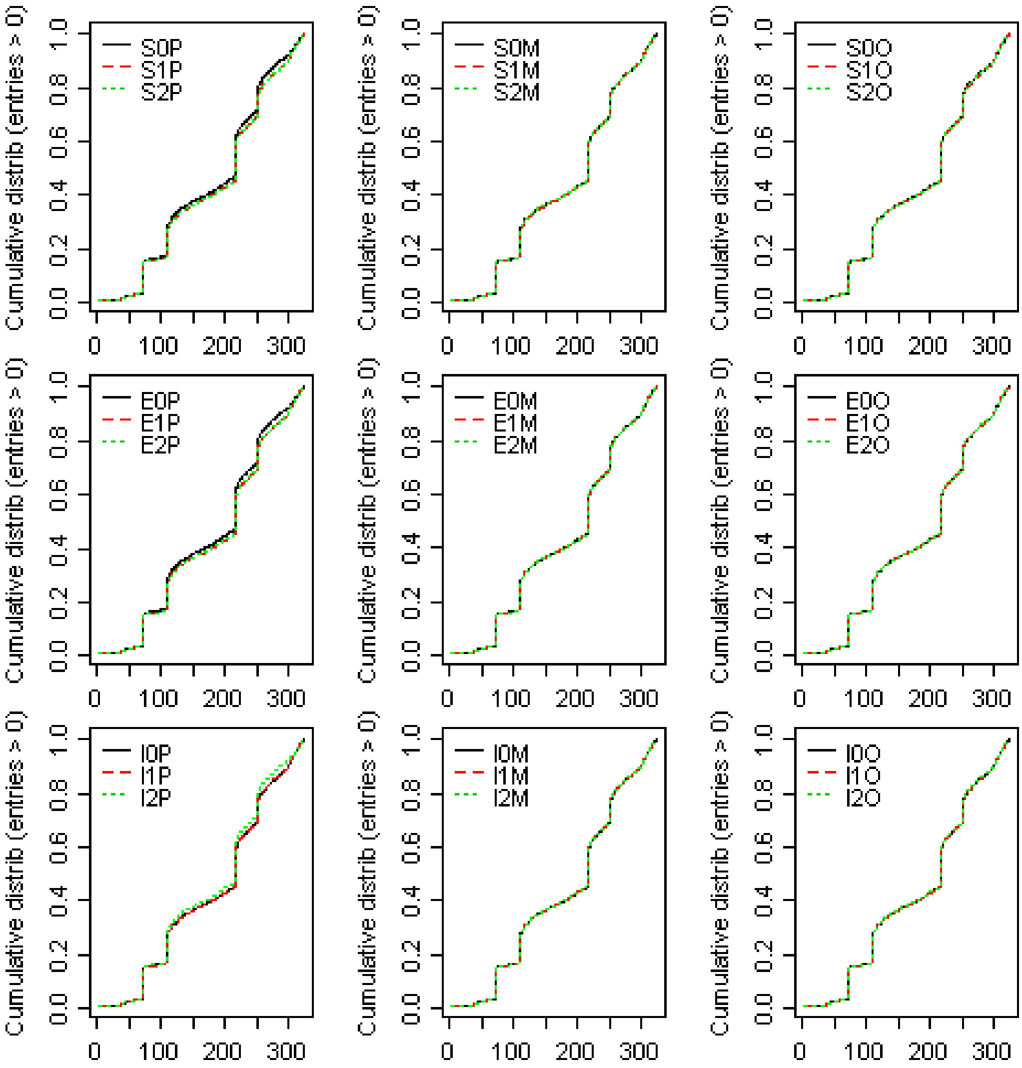


Figure A.111: Cumulative distribution plot for coarse scale spatial analysis of mangrove average grid-cell relative biomass, comparing development scenarios (each box contains the cumulative distributions for 0-pulse [black], 1-pulse [red] and 2-pulse [green] development scenarios for a given combination of management strategy and model specification).

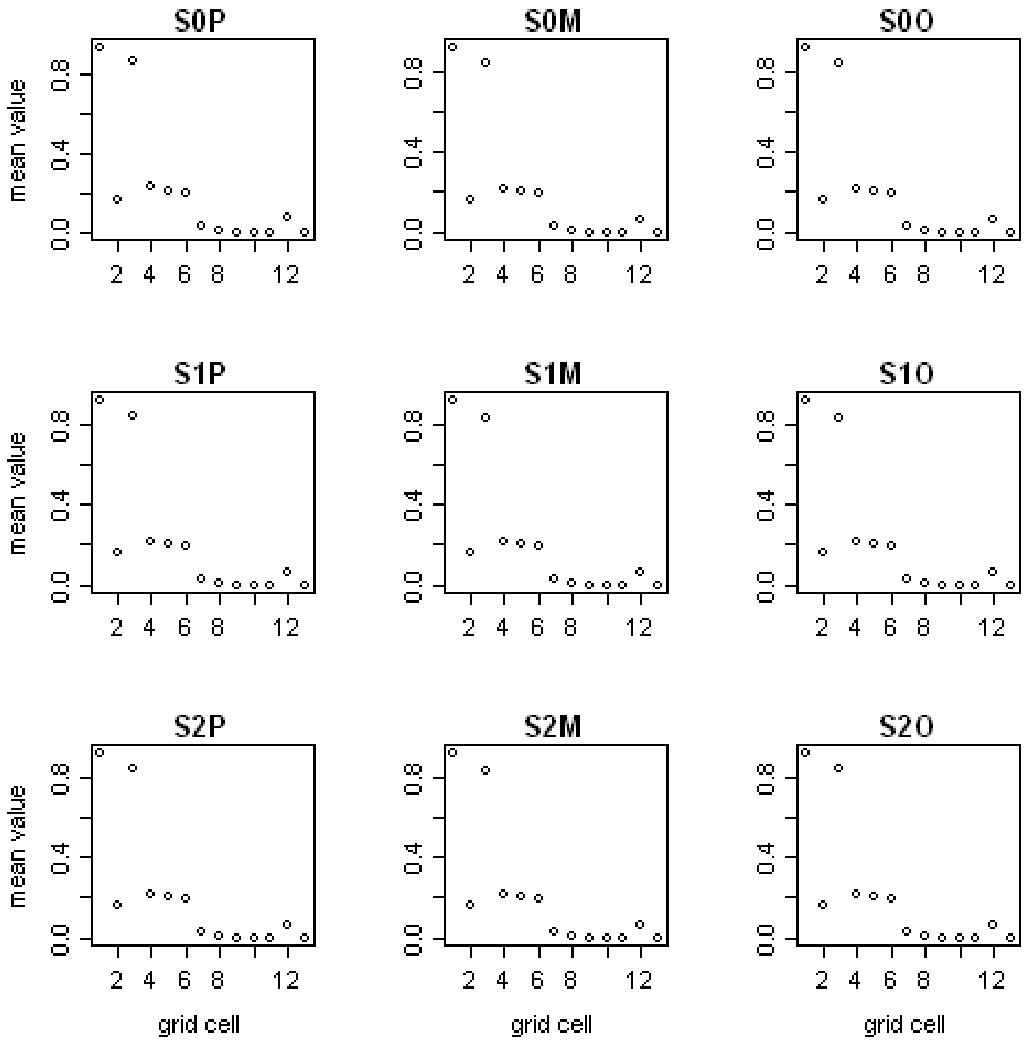


Figure A.112: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for mangroves under status quo management for each combination of development scenario and model specification.

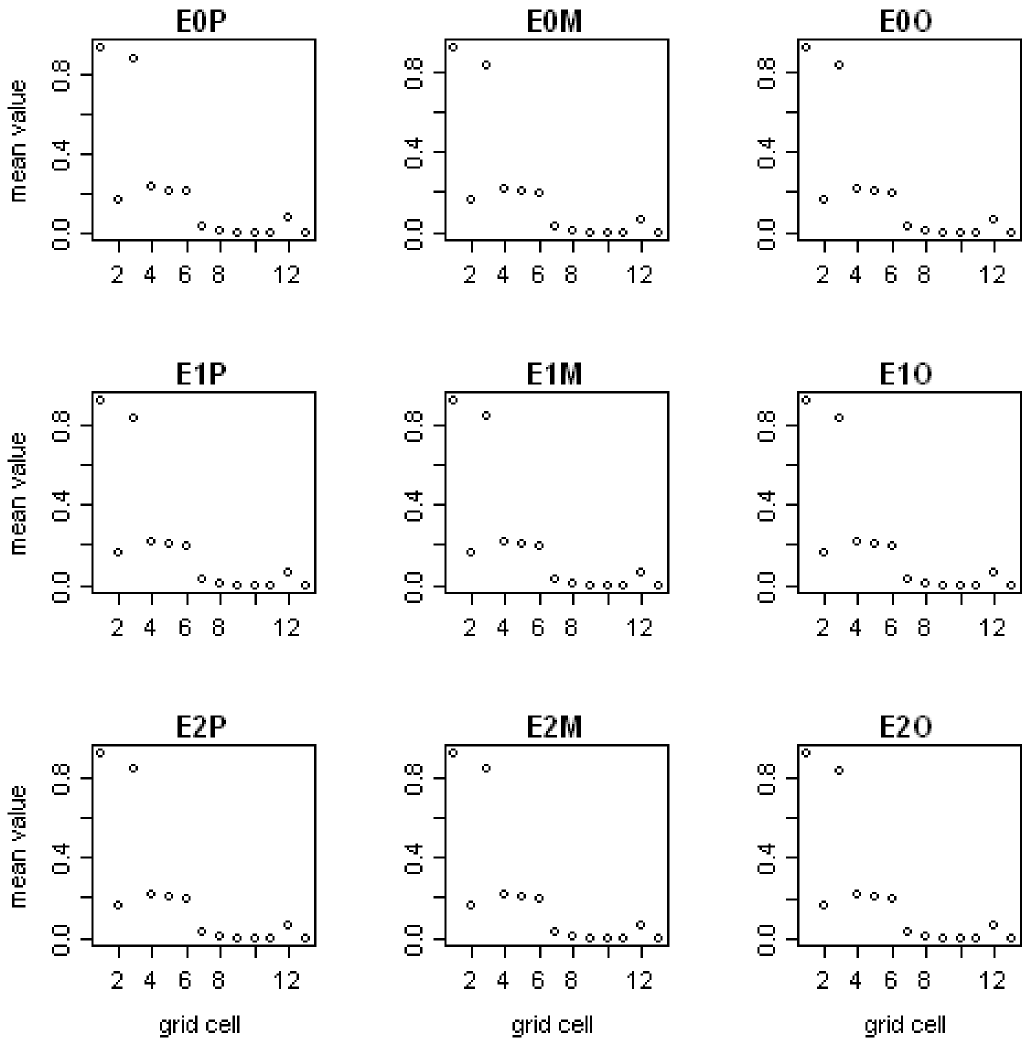


Figure A.113: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for mangroves under enhanced management for each combination of development scenario and model specification.

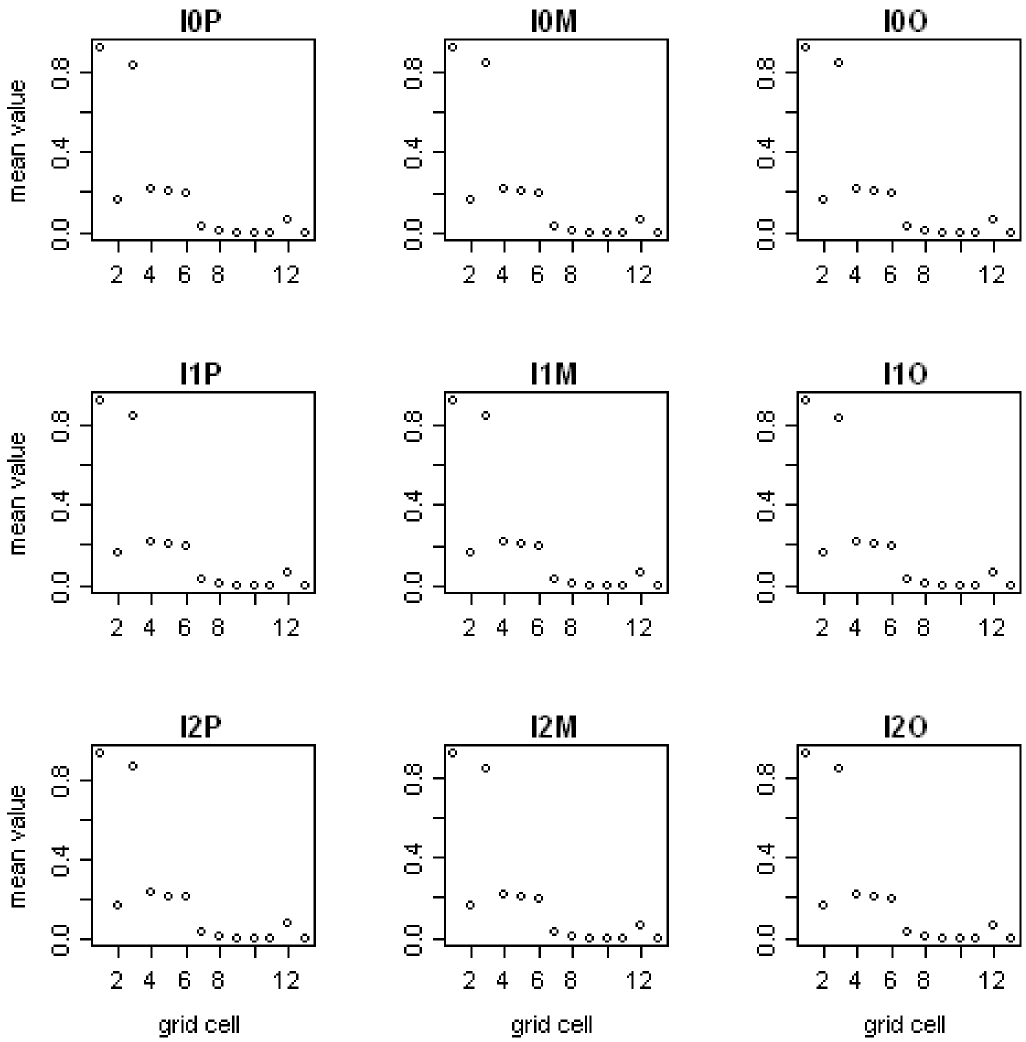


Figure A.114: Average coarse scale relative biomass per cell (ordered inshore to offshore, west to east) for mangroves under integrated management for each combination of development scenario and model specification.

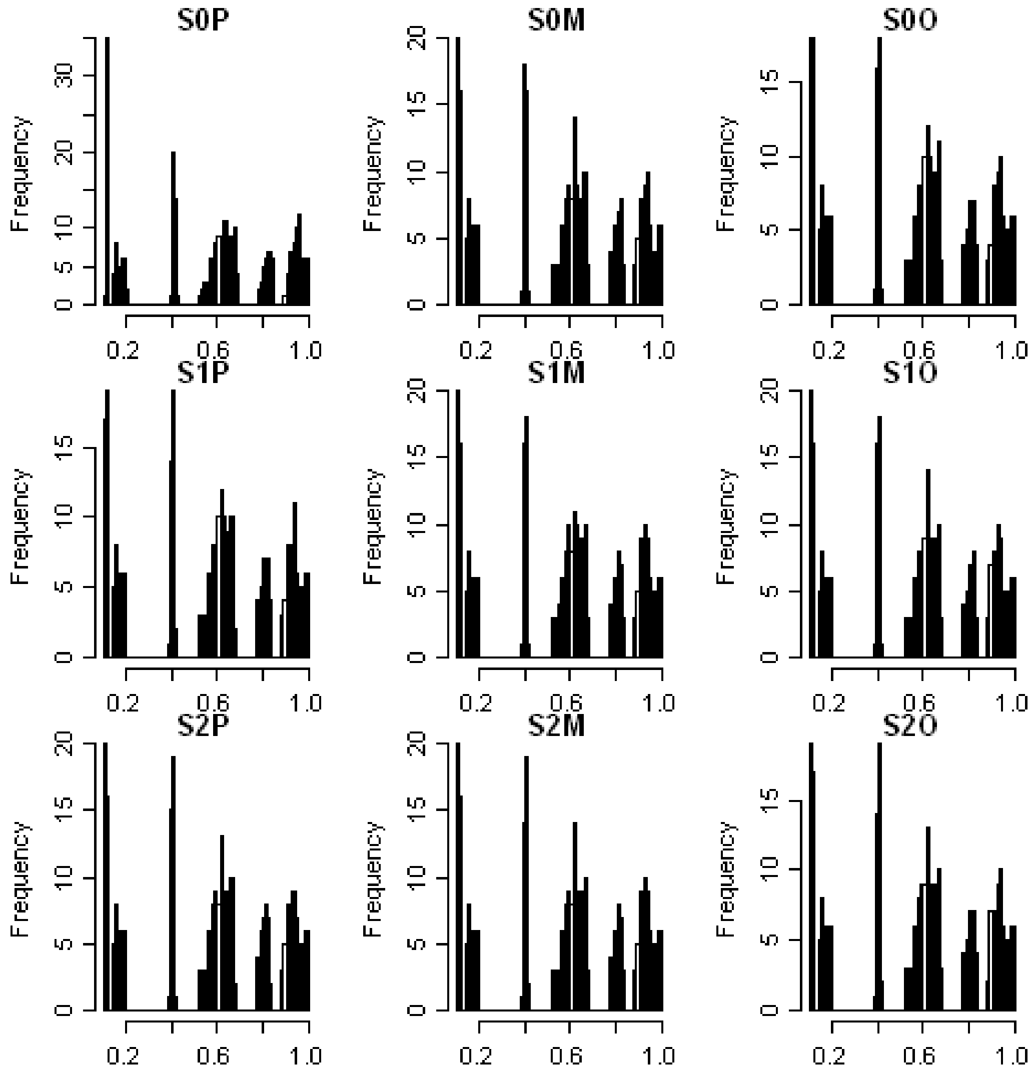


Figure A.115: Frequency histogram of coarse scale relative biomass (over time) for mangroves under status quo management for each combination of development scenario and model specification.

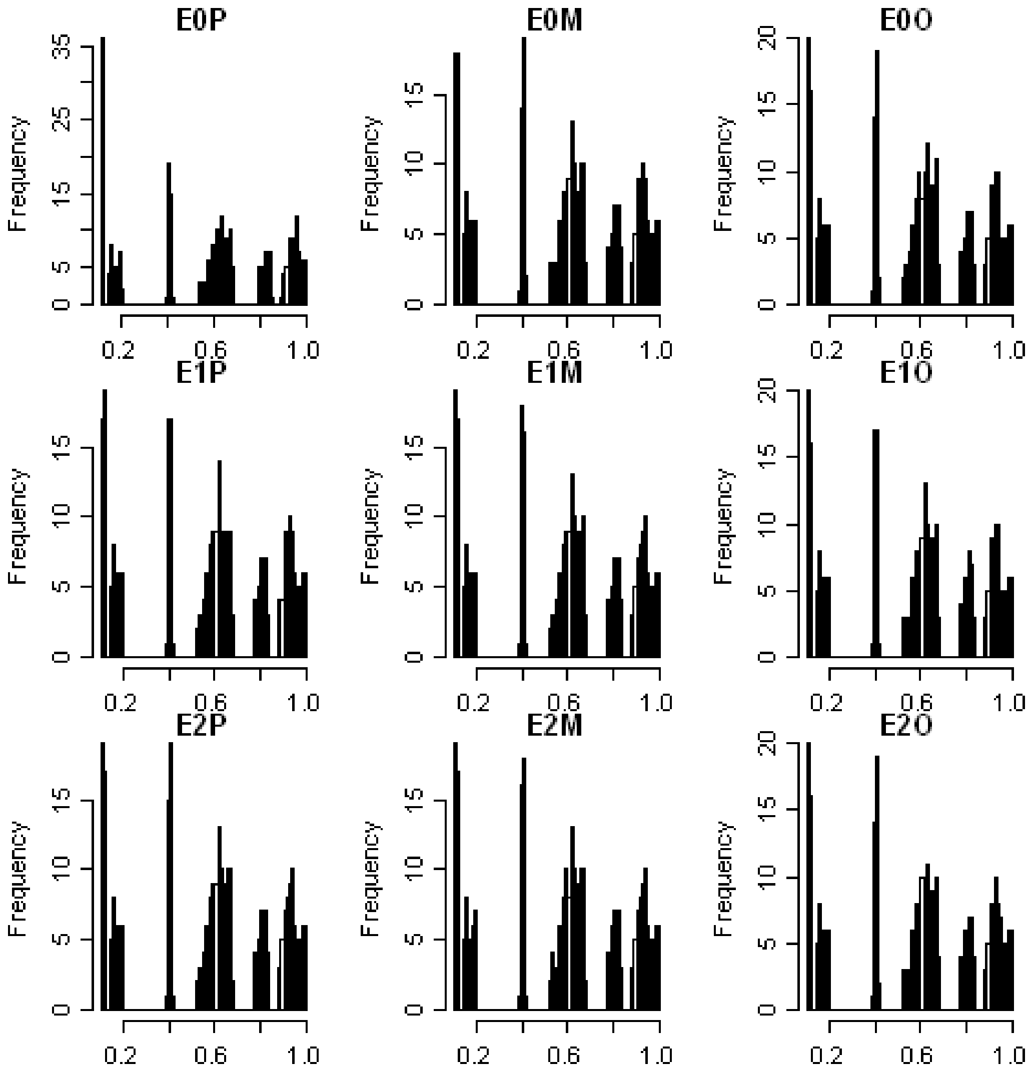


Figure A.116: Frequency histogram of coarse scale relative biomass (over time) for mangroves under enhanced management for each combination of development scenario and model specification.

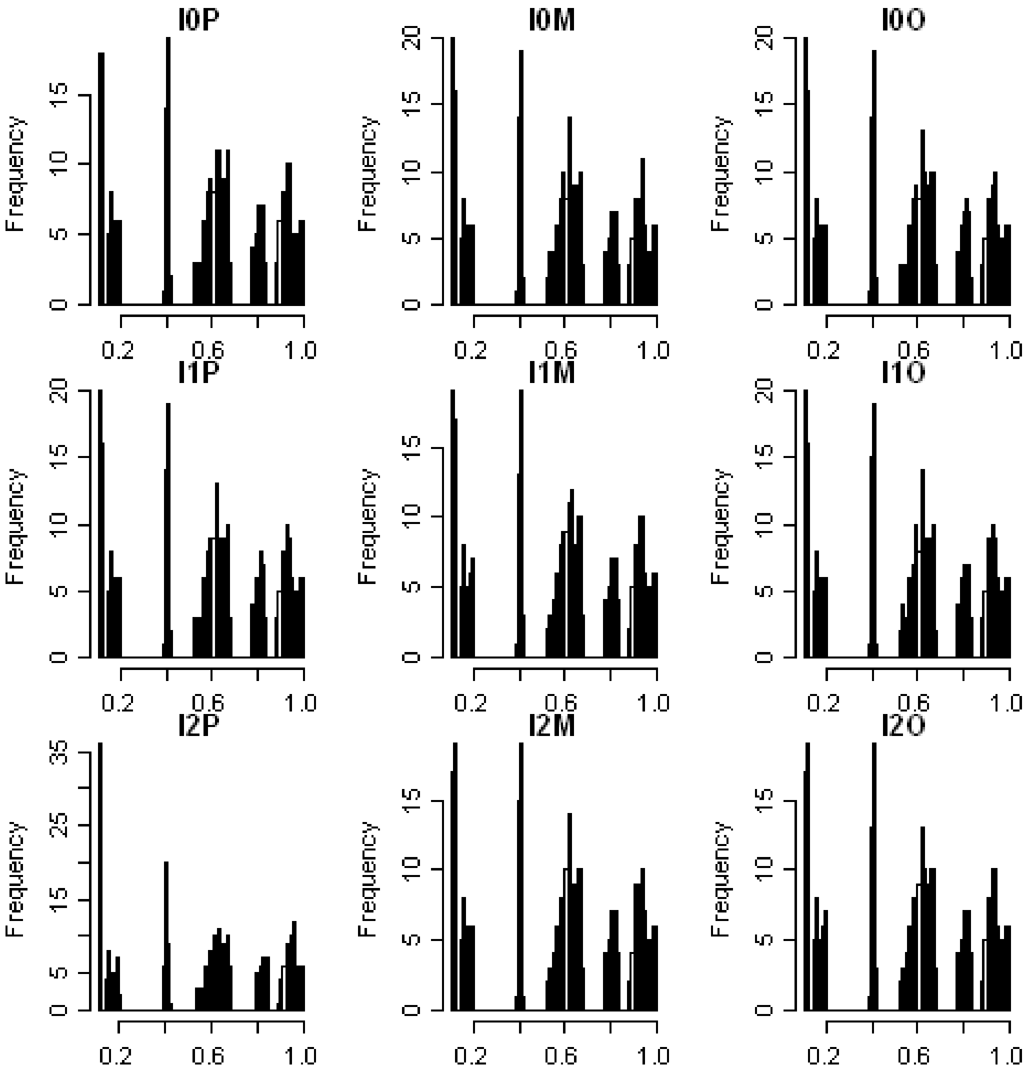


Figure A.117: Frequency histogram of coarse scale relative biomass (over time) for mangroves under integrated management for each combination of development scenario and model specification.

APPENDIX B: FINE SCALE SPATIAL ANALYSIS FREQUENCY HISTOGRAMS AND CUMULATIVE DISTRIBUTION PLOTS

B.1 Banana prawns

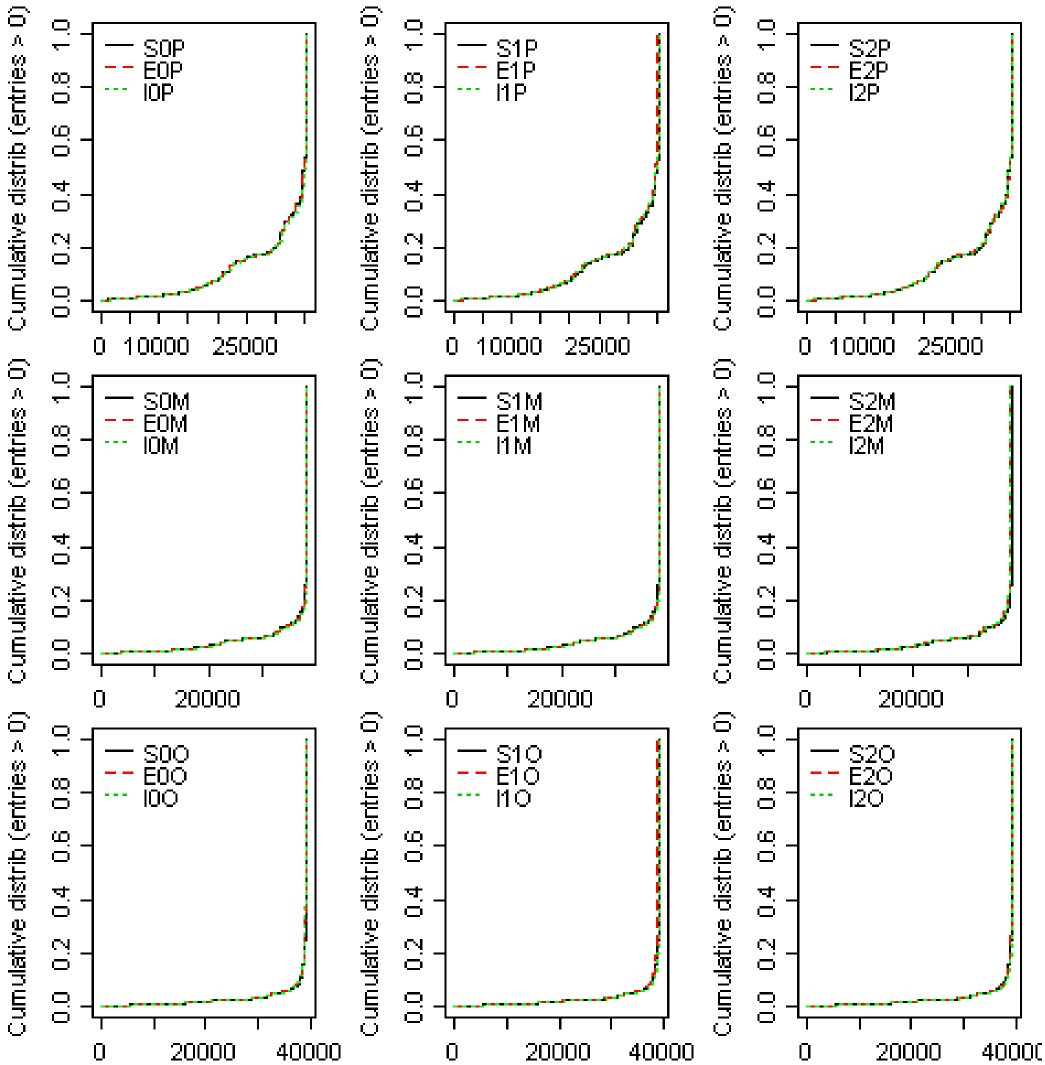


Figure B.1: Cumulative distribution plot for fine scale spatial analysis of banana prawn average grid-cell relative biomass, comparing management strategies (each box contains the cumulative distributions for status quo [black], enhanced [red] and integrated [green] management for a given combination of model specification and development scenario).

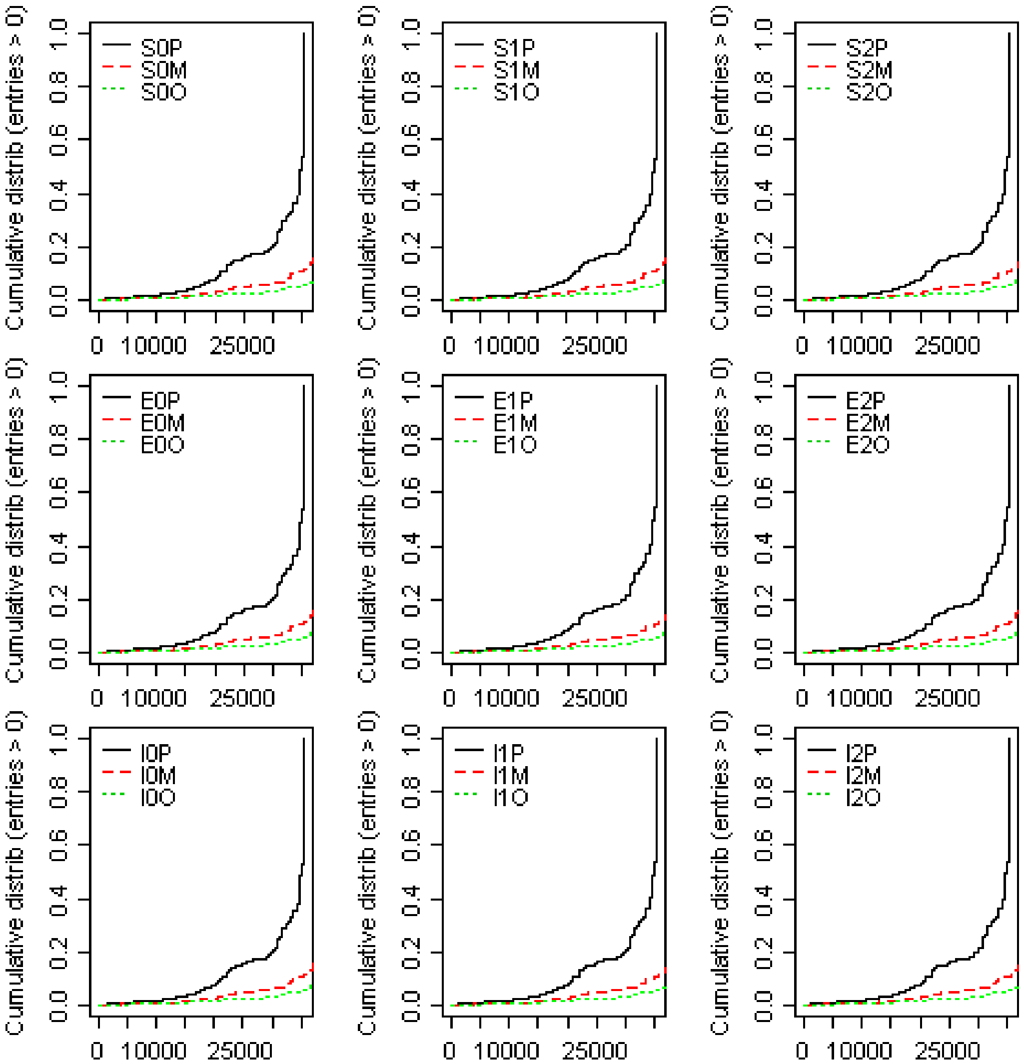


Figure B.2: Cumulative distribution plot for fine scale spatial analysis of banana prawn average grid-cell relative biomass, comparing model specifications (each box contains the cumulative distributions for pessimistic [black], base case [red] and optimistic [green] specifications for a given combination of management strategy and development scenario).

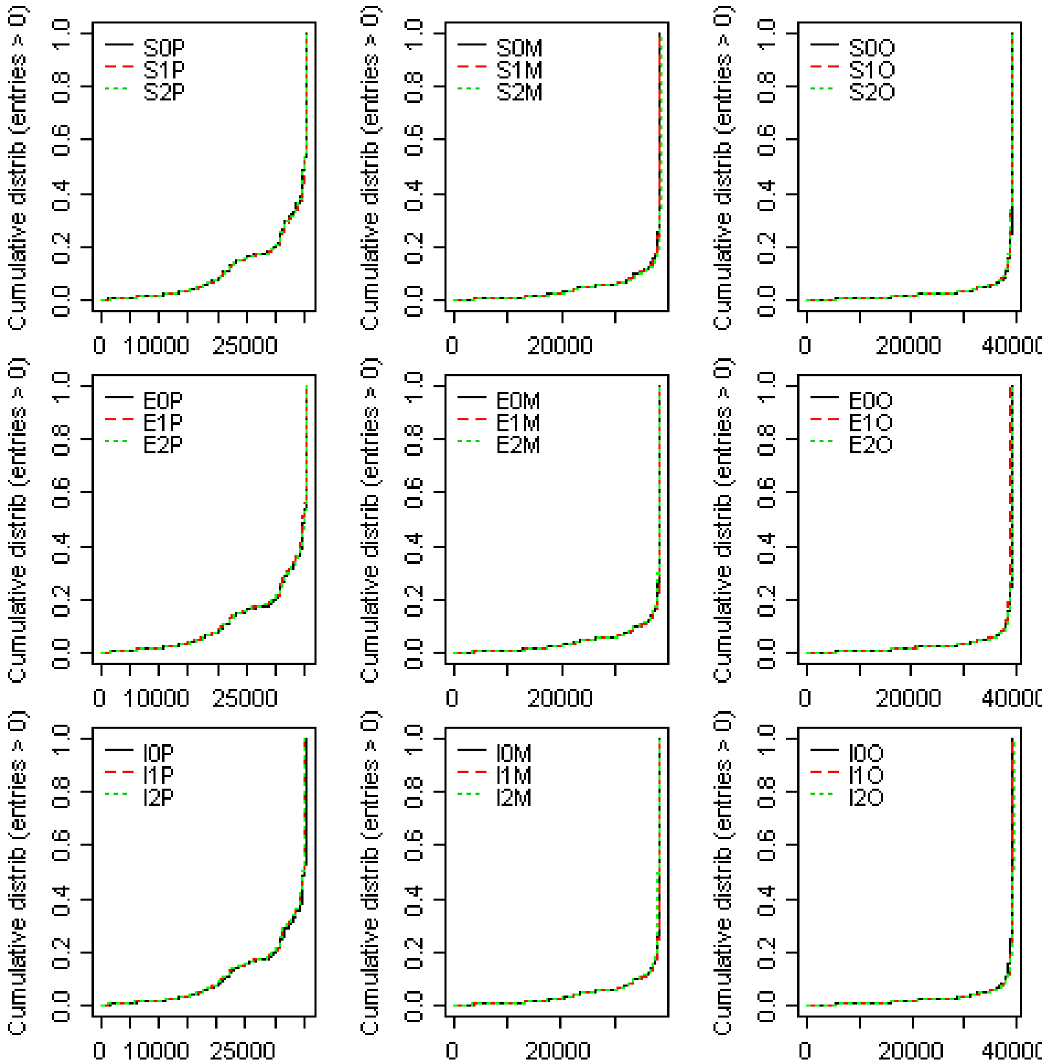


Figure B.3: Cumulative distribution plot for fine scale spatial analysis of banana prawn average grid-cell relative biomass, comparing development scenarios (each box contains the cumulative distributions for 0-pulse [black], 1-pulse [red] and 2-pulse [green] development scenarios for a given combination of management strategy and model specification).

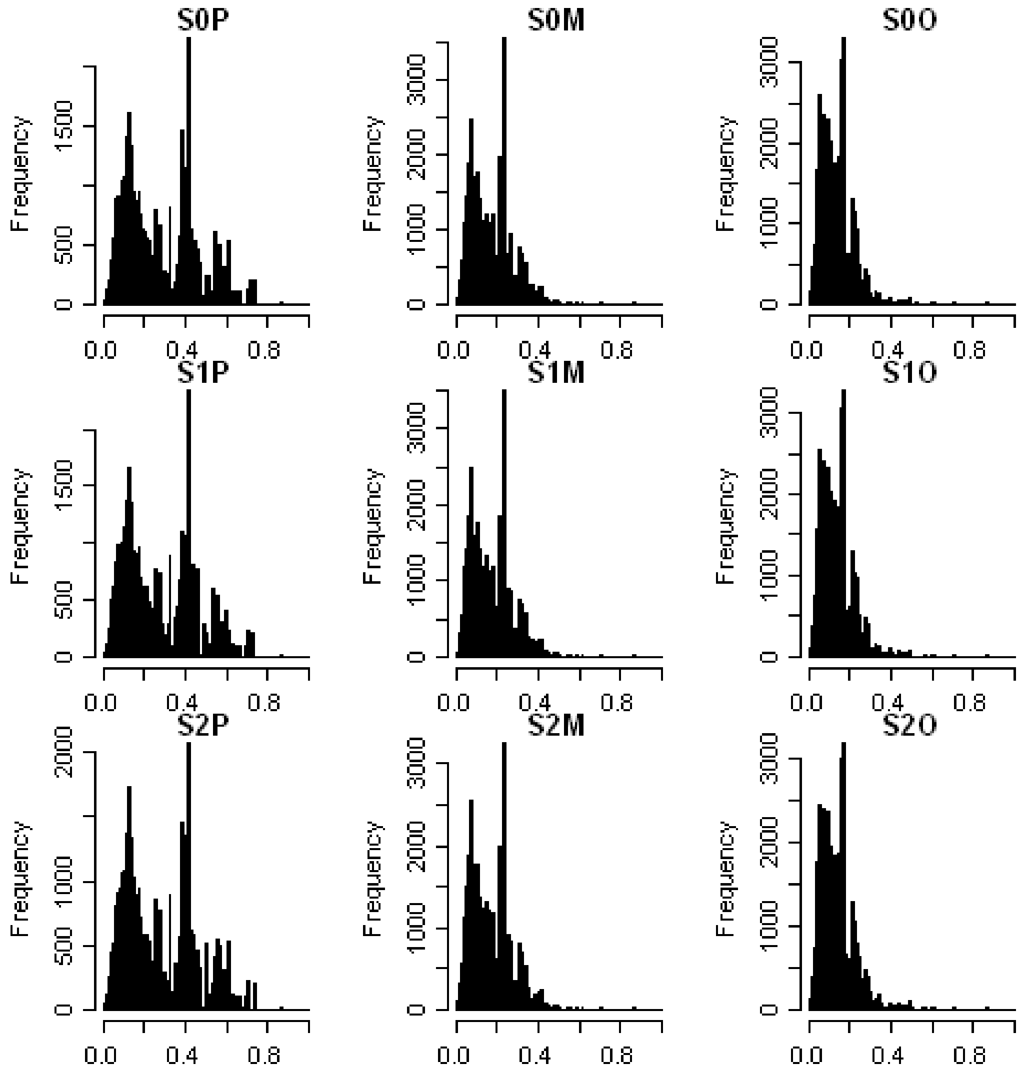


Figure B.4: Frequency histogram of fine scale relative biomass (over time) for banana prawns under status quo management for each combination of development scenario and model specification.

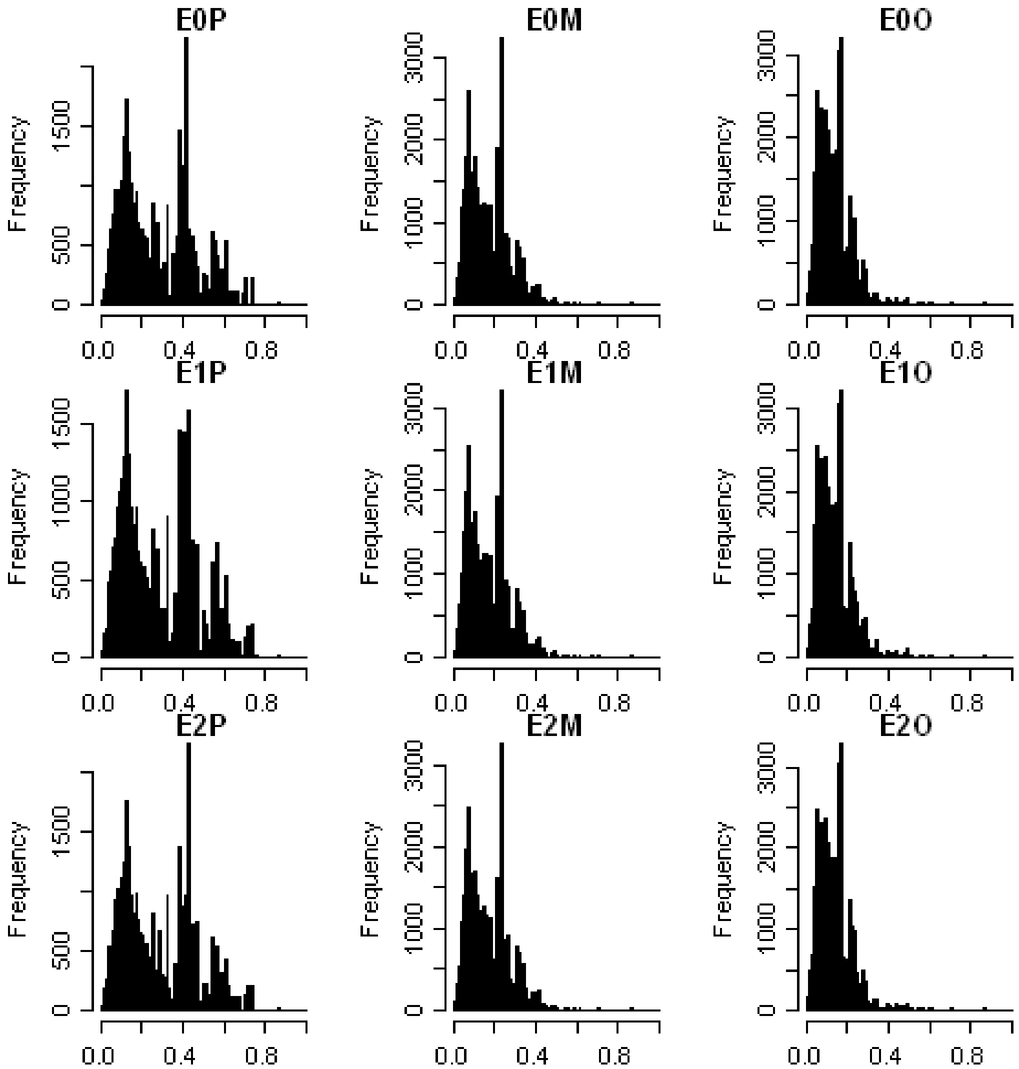


Figure B.5: Frequency histogram of fine scale relative biomass (over time) for banana prawns under enhanced management for each combination of development scenario and model specification.

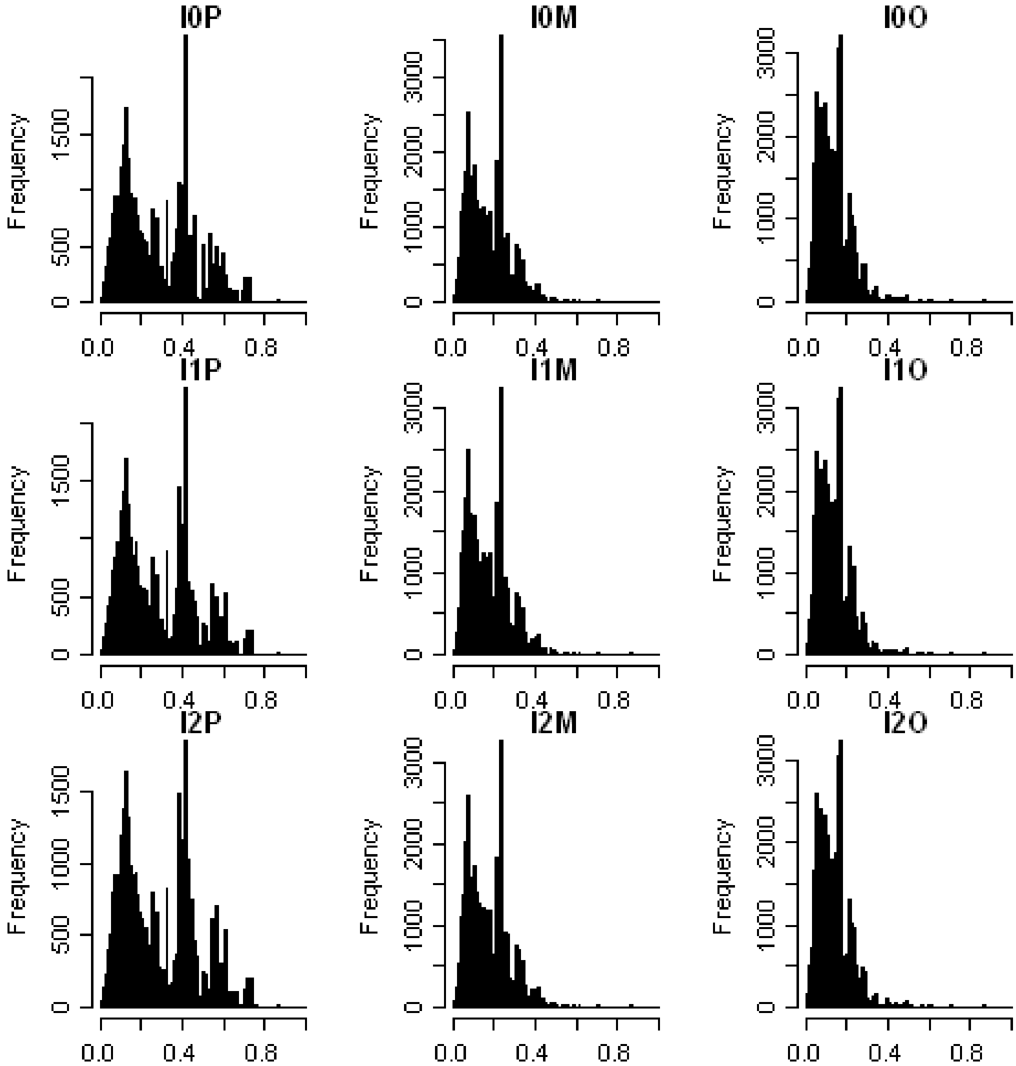


Figure B.6: Frequency histogram of fine scale relative biomass (over time) for banana prawns under integrated management for each combination of development scenario and model specification.

B.2 King prawns

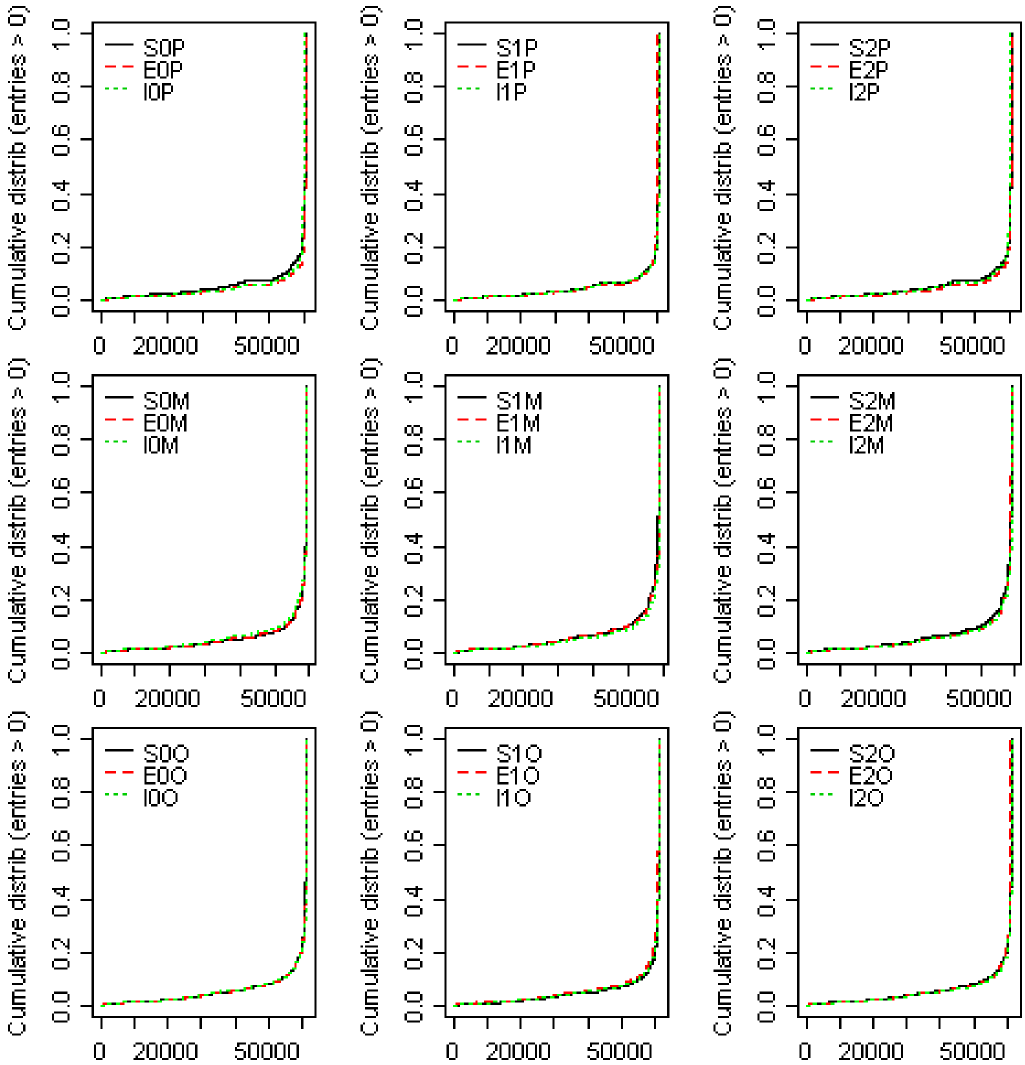


Figure B.7: Cumulative distribution plot for fine scale spatial analysis of king prawn average grid-cell relative biomass, comparing management strategies (each box contains the cumulative distributions for status quo [black], enhanced [red] and integrated [green] management for a given combination of model specification and development scenario).

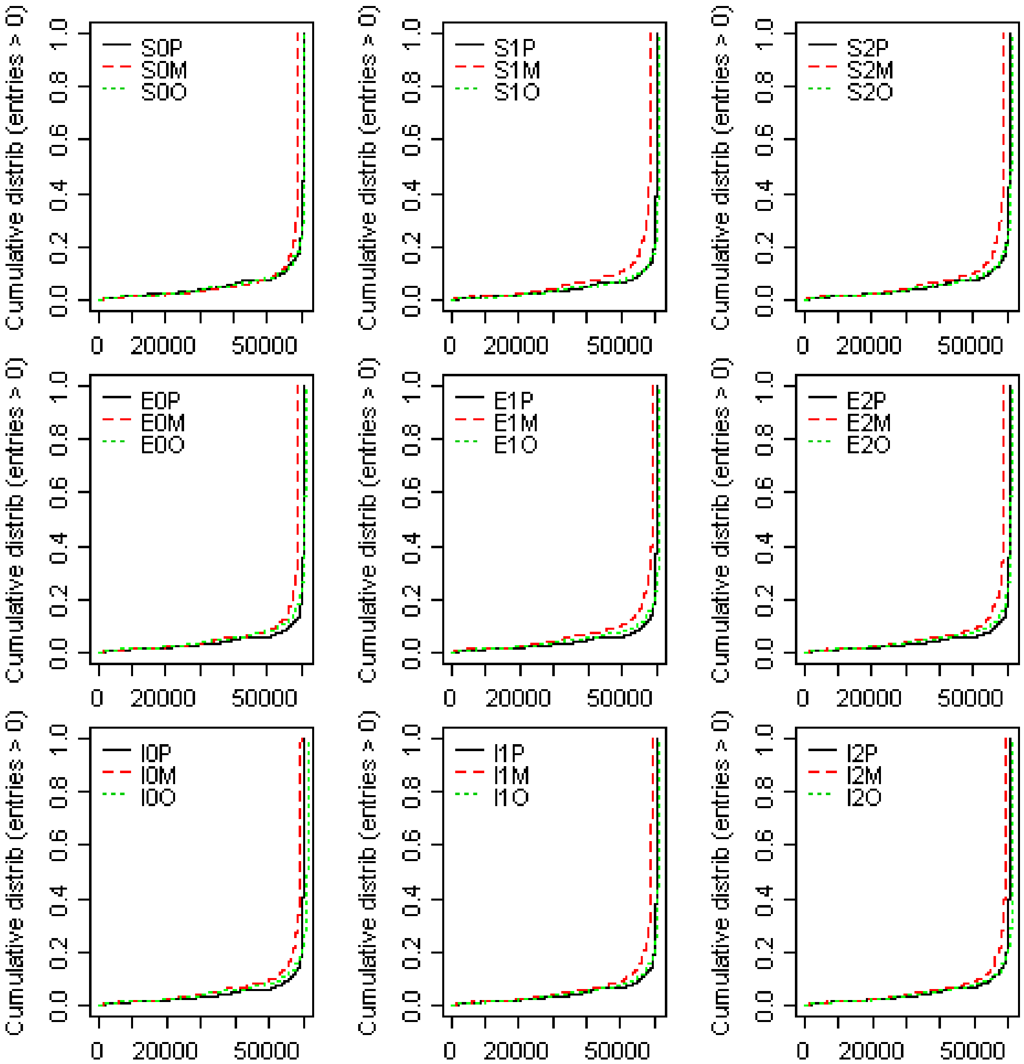


Figure B.8: Cumulative distribution plot for fine scale spatial analysis of king prawn average grid-cell relative biomass, comparing model specifications (each box contains the cumulative distributions for pessimistic [black], base case [red] and optimistic [green] specifications for a given combination of management strategy and development scenario).

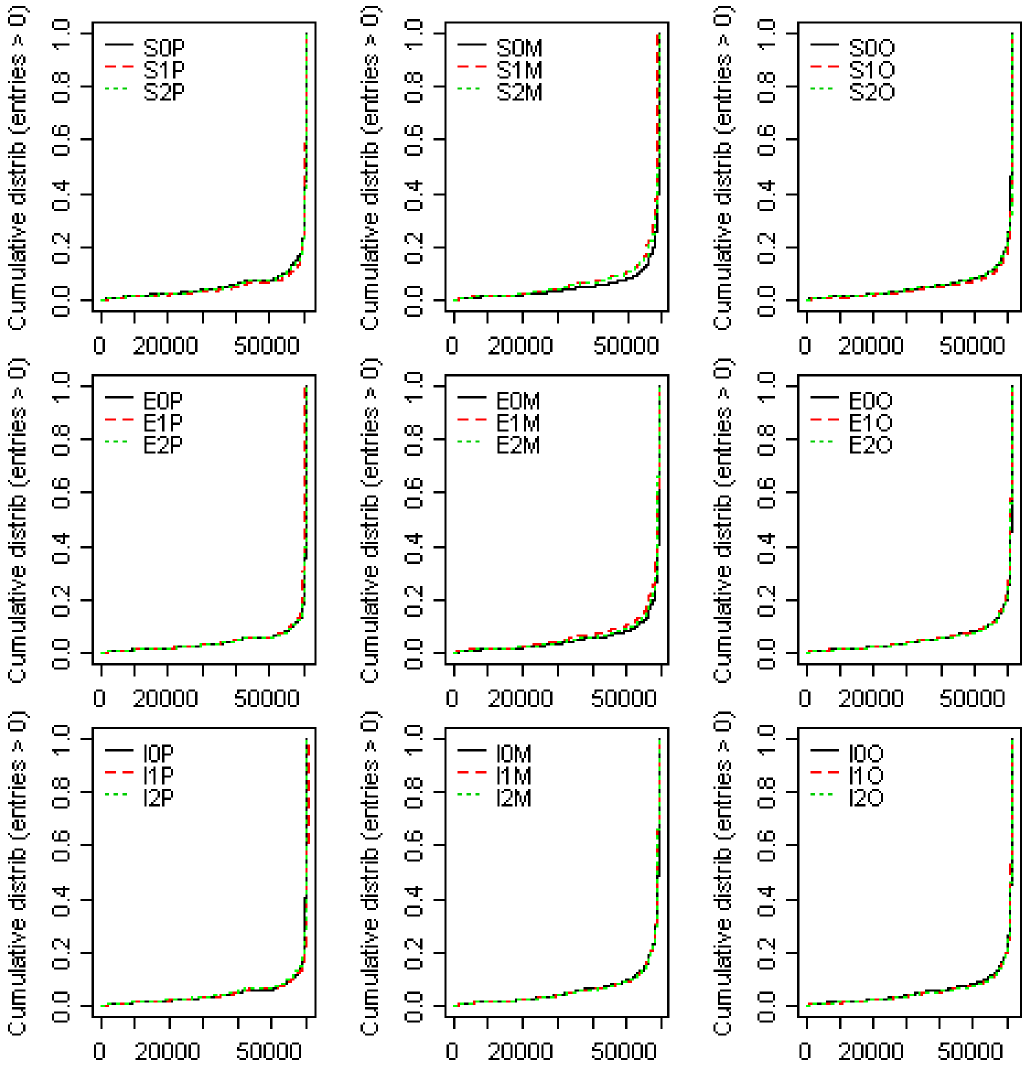


Figure B.9: Cumulative distribution plot for fine scale spatial analysis of king prawn average grid-cell relative biomass, comparing development scenarios (each box contains the cumulative distributions for 0-pulse [black], 1-pulse [red] and 2-pulse [green] development scenarios for a given combination of management strategy and model specification).

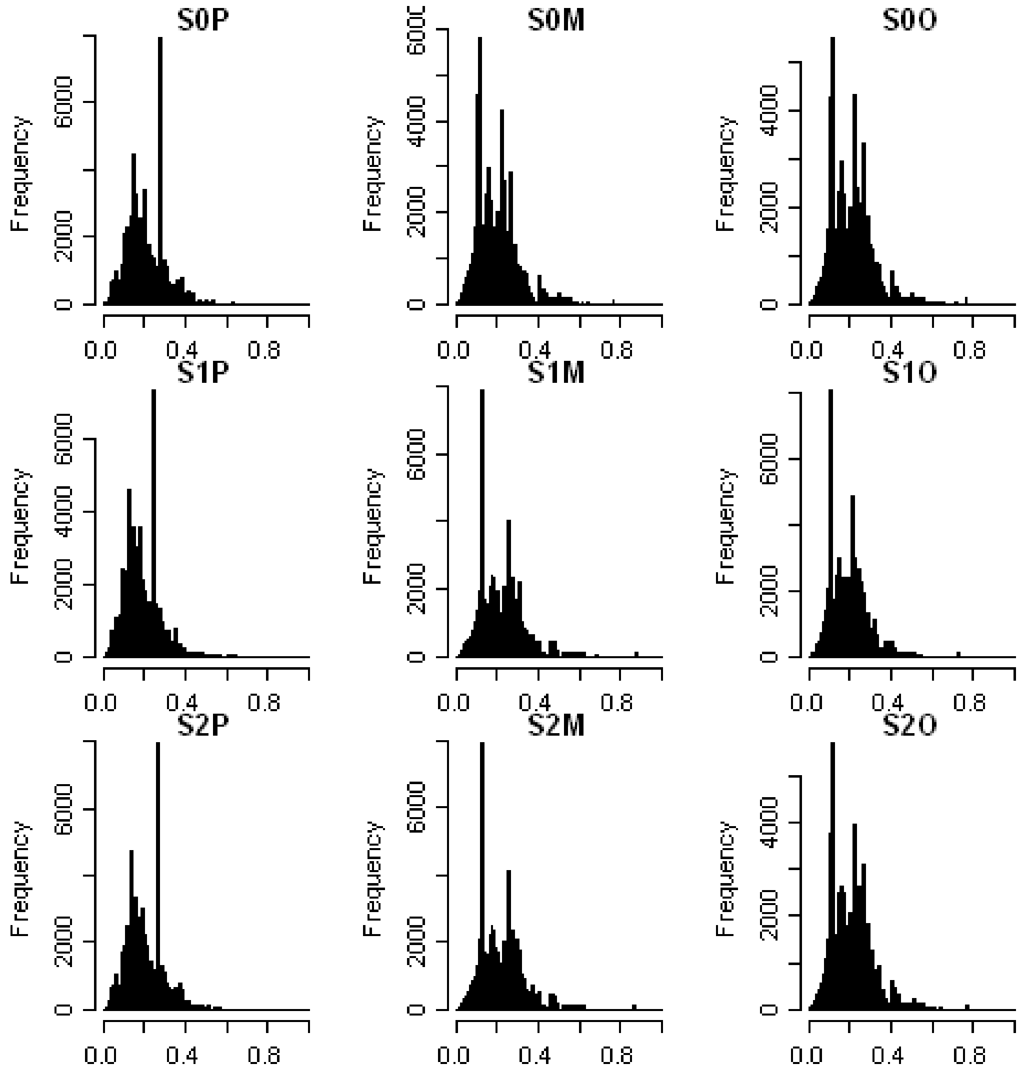


Figure B.10: Frequency histogram of fine scale relative biomass (over time) for king prawns under status quo management for each combination of development scenario and model specification.

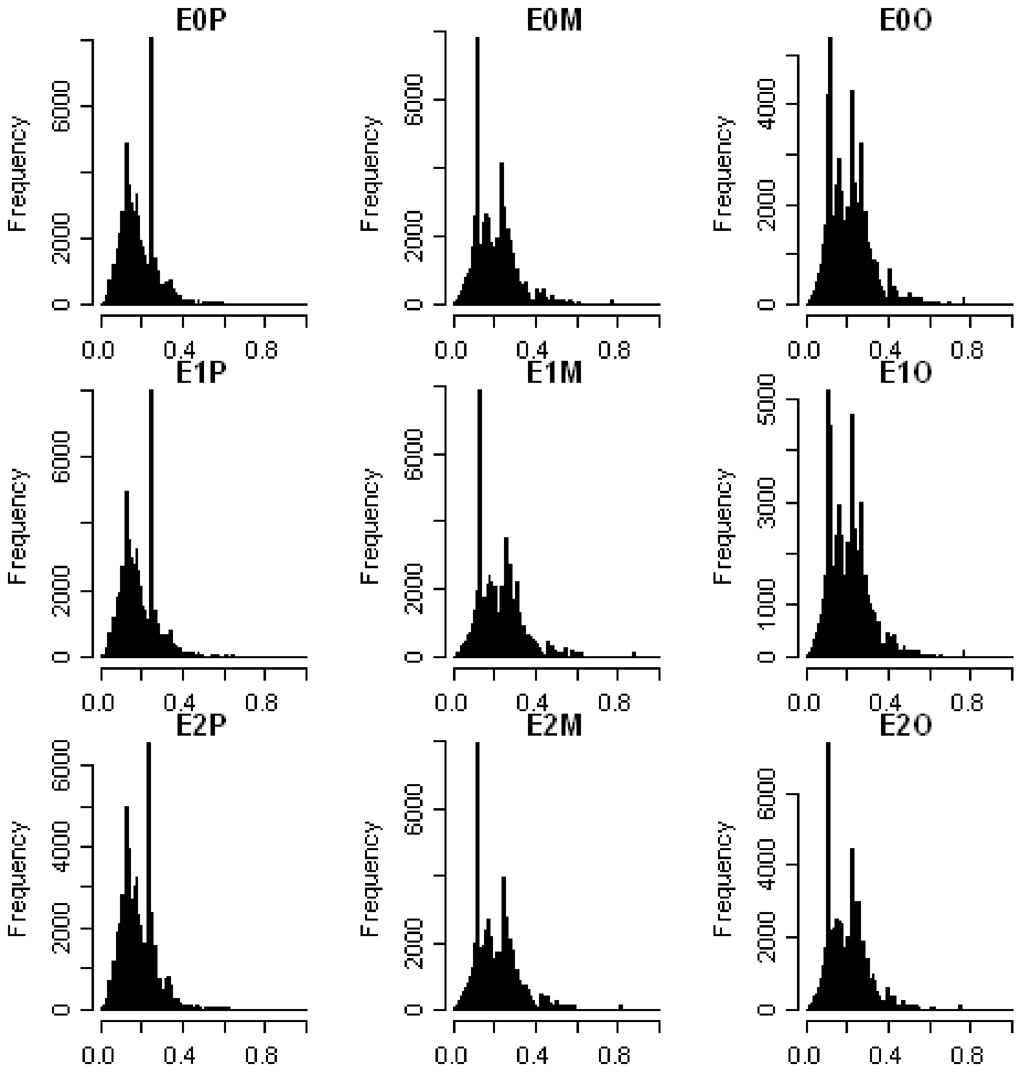


Figure B.11: Frequency histogram of fine scale relative biomass (over time) for king prawns under enhanced management for each combination of development scenario and model specification.

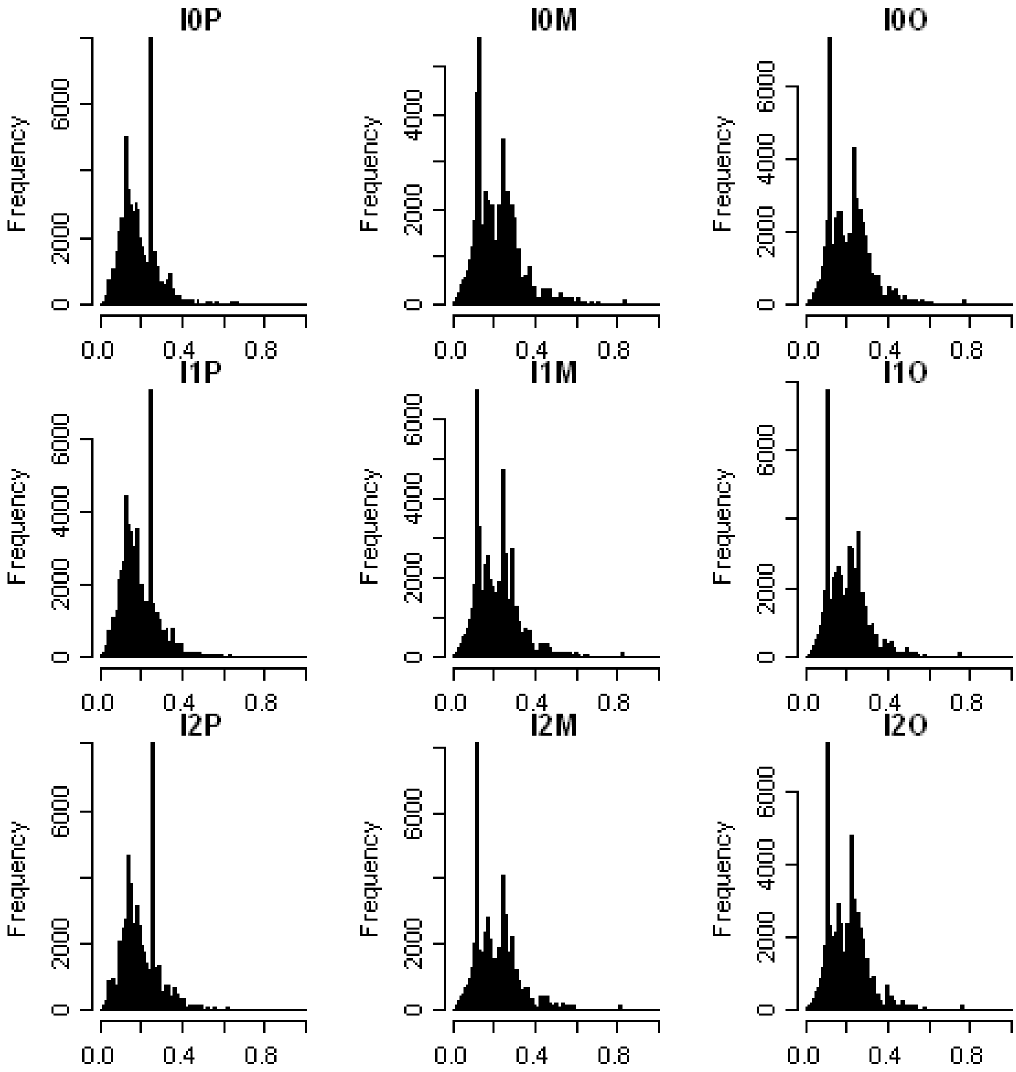


Figure B.12: Frequency histogram of fine scale relative biomass (over time) for king prawns under integrated management for each combination of development scenario and model specification.

B.3 Turtles

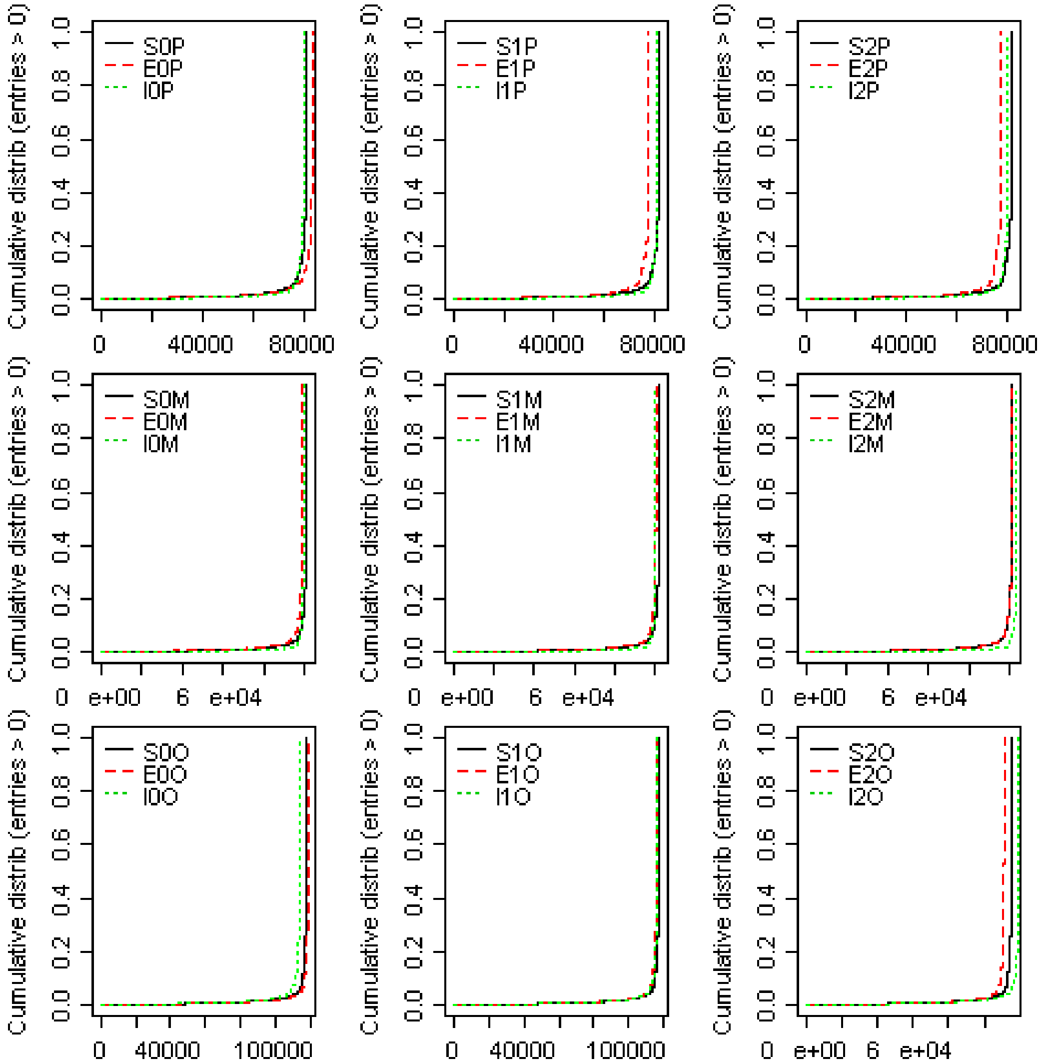


Figure B.13: Cumulative distribution plot for fine scale spatial analysis of turtles average grid-cell relative biomass, comparing management strategies (each box contains the cumulative distributions for status quo [black], enhanced [red] and integrated [green] management for a given combination of model specification and development scenario).

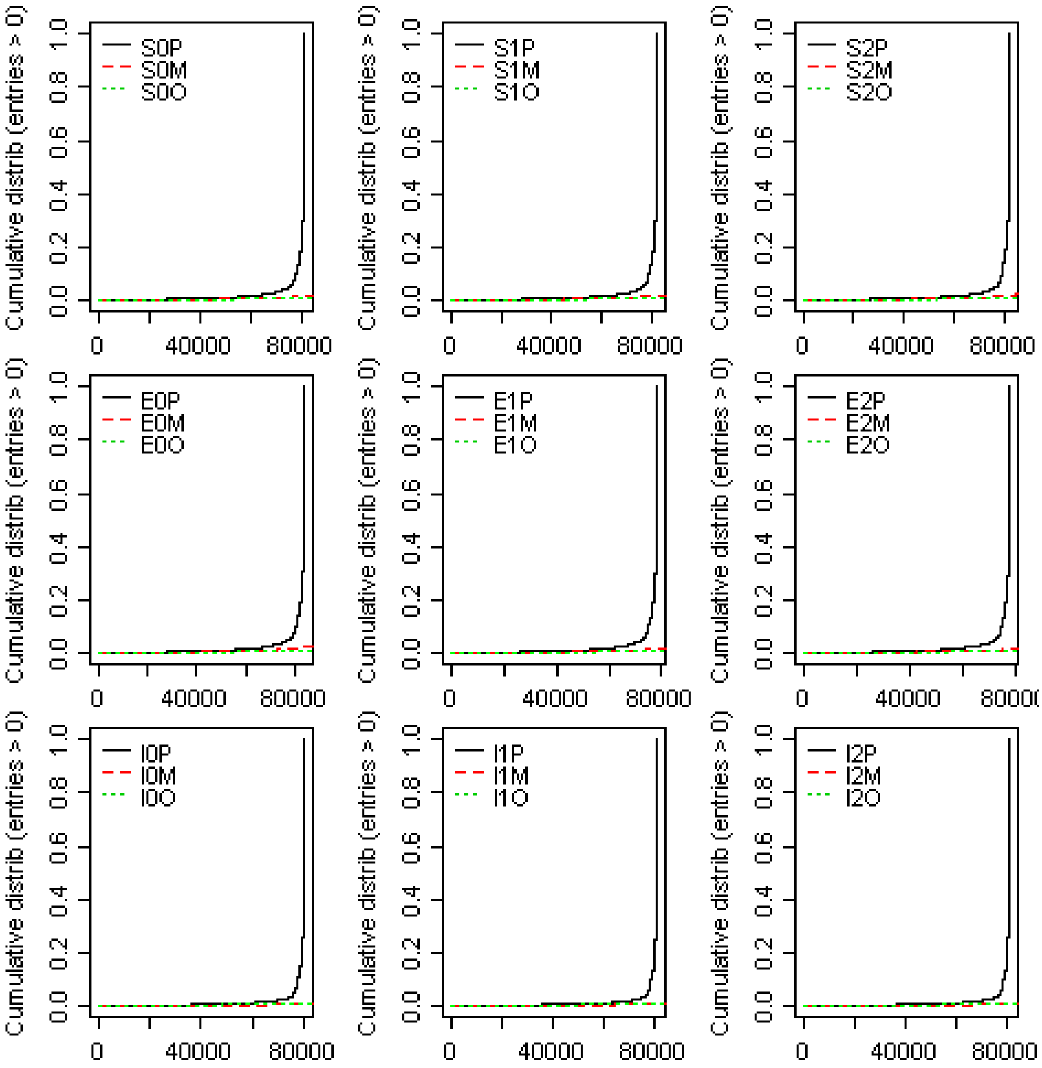


Figure B.14: Cumulative distribution plot for fine scale spatial analysis of turtles average grid-cell relative biomass, comparing model specifications (each box contains the cumulative distributions for pessimistic [black], base case [red] and optimistic [green] specifications for a given combination of management strategy and development scenario).

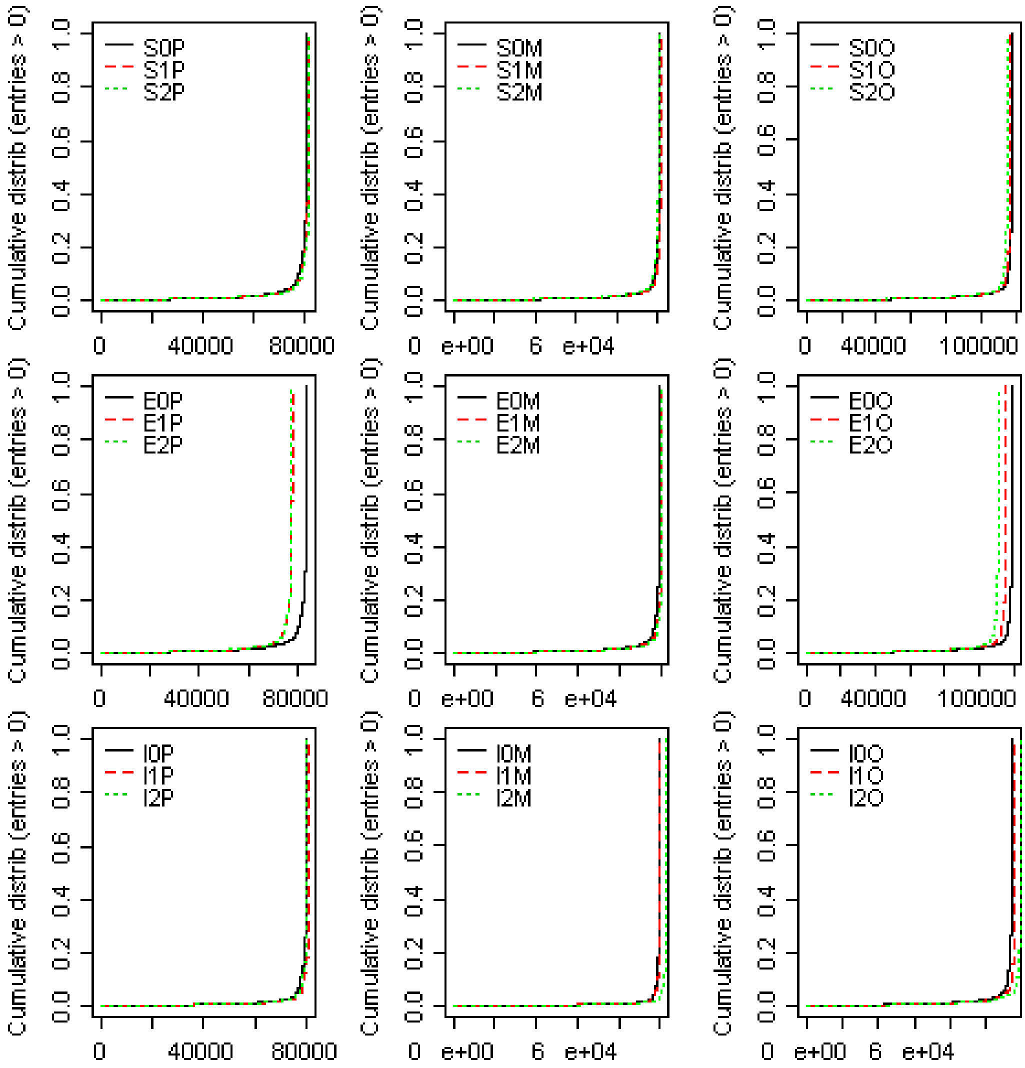


Figure B.15: Cumulative distribution plot for fine scale spatial analysis of turtles average grid-cell relative biomass, comparing development scenarios (each box contains the cumulative distributions for 0-pulse [black], 1-pulse [red] and 2-pulse [green] development scenarios for a given combination of management strategy and model specification).

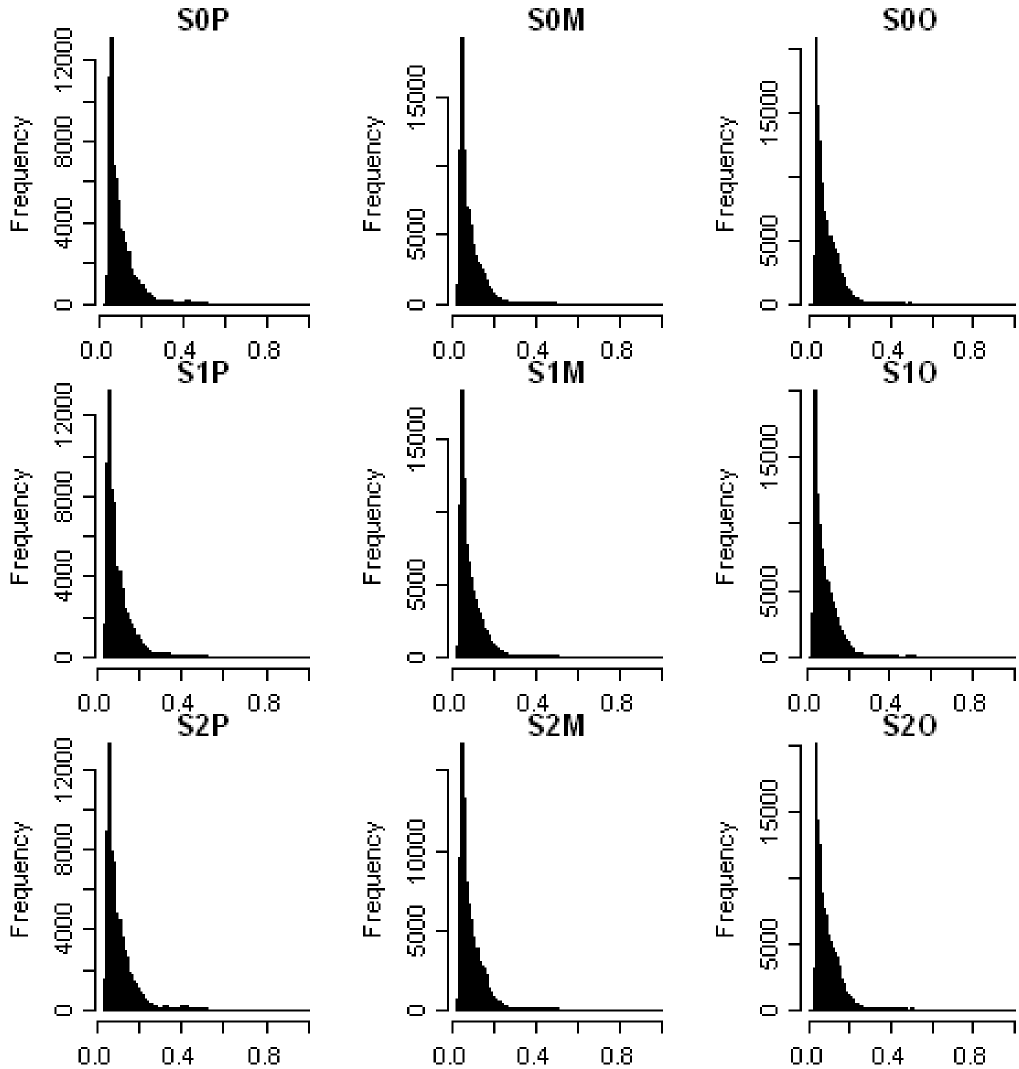


Figure B.16: Frequency histogram of fine scale relative biomass (over time) for turtles under status quo management for each combination of development scenario and model specification.

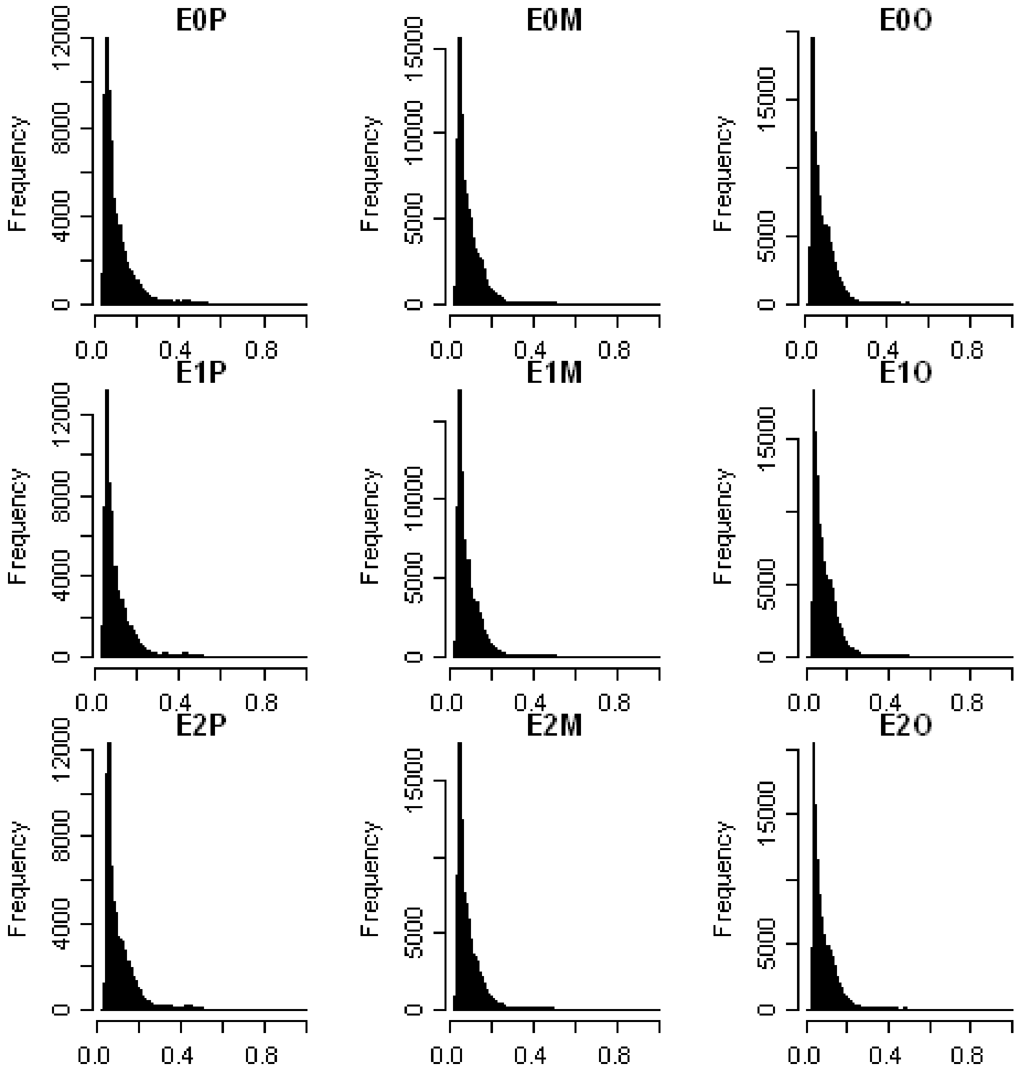


Figure B.17: Frequency histogram of fine scale relative biomass (over time) for turtles under enhanced management for each combination of development scenario and model specification.

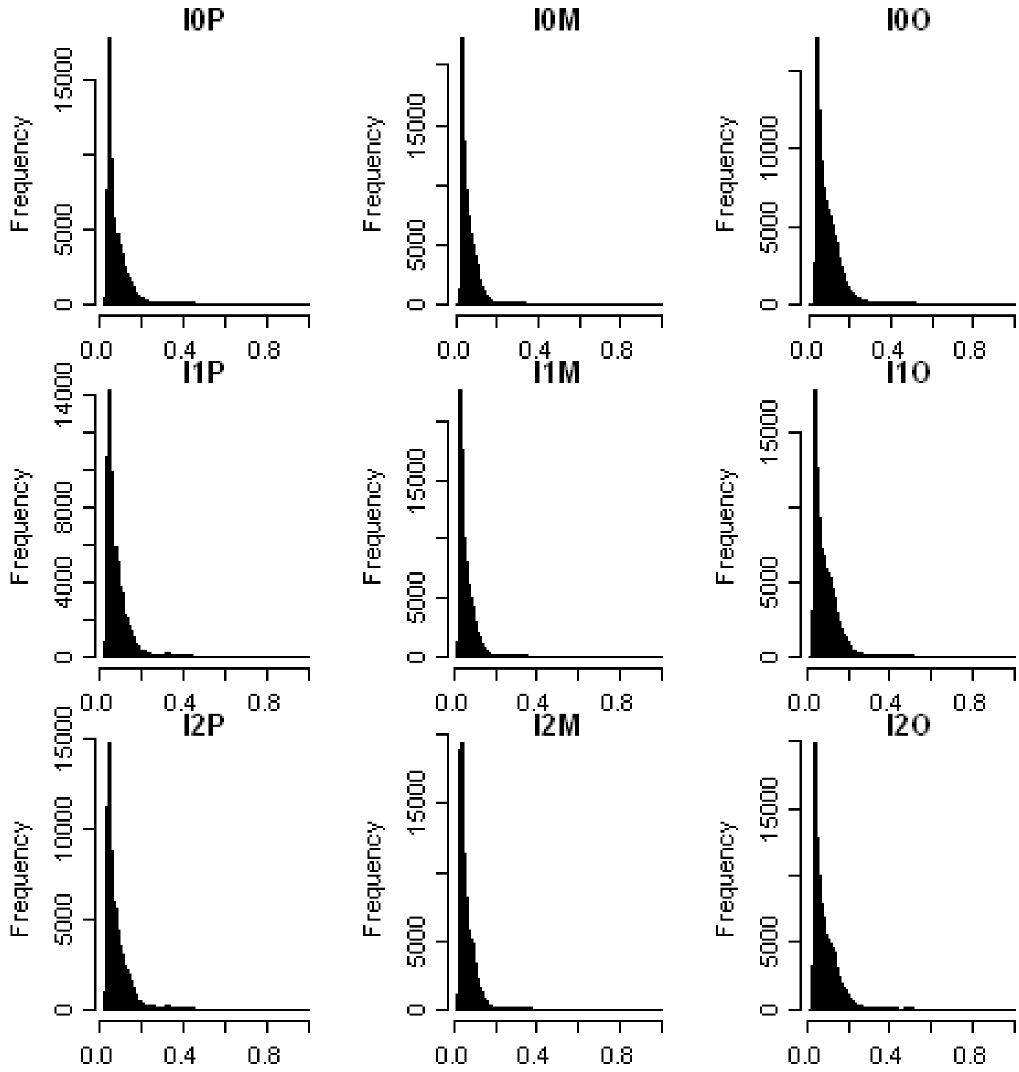


Figure B.18: Frequency histogram of fine scale relative biomass (over time) for turtles under integrated management for each combination of development scenario and model specification.

B.4 Sharks

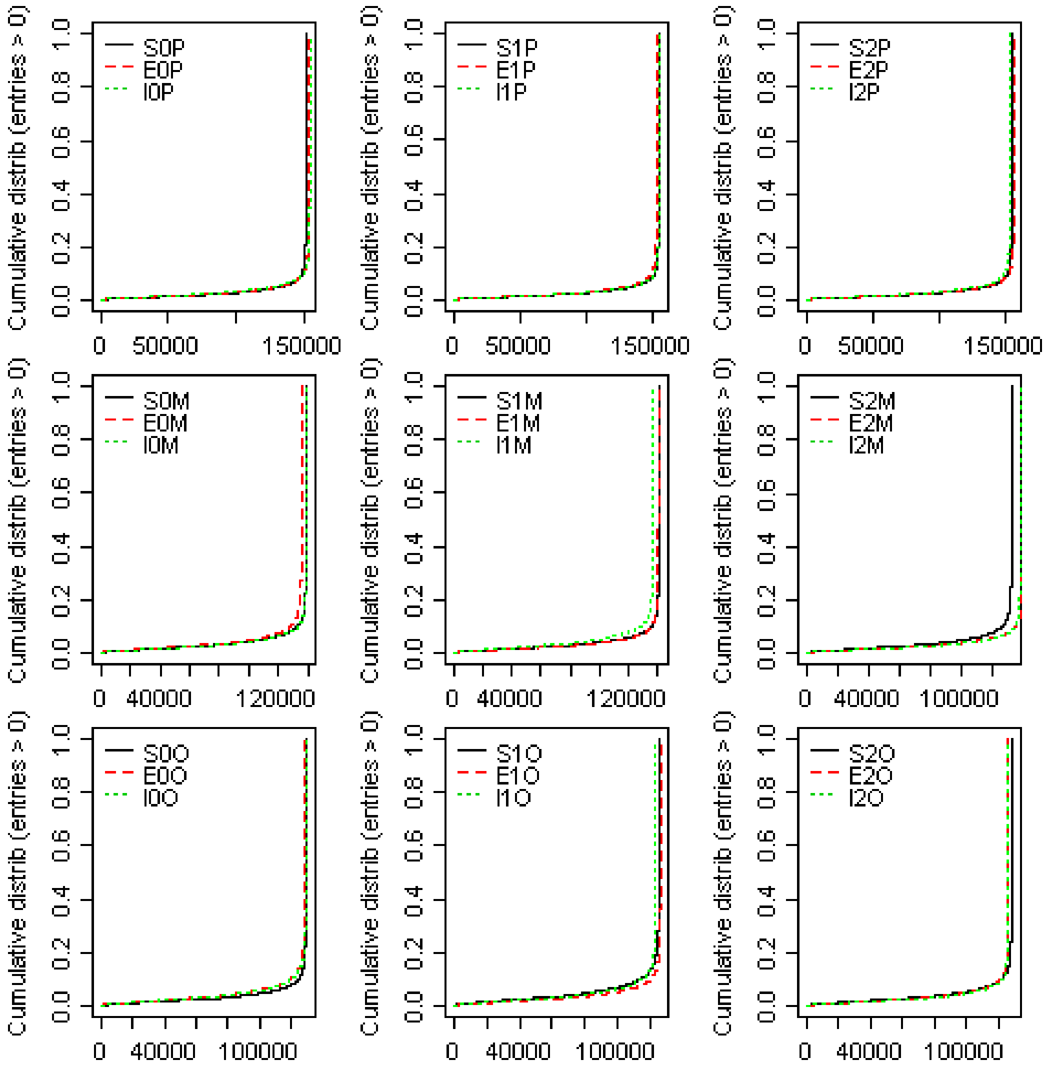


Figure B.19: Cumulative distribution plot for fine scale spatial analysis of sharks average grid-cell relative biomass, comparing management strategies (each box contains the cumulative distributions for status quo [black], enhanced [red] and integrated [green] management for a given combination of model specification and development scenario).

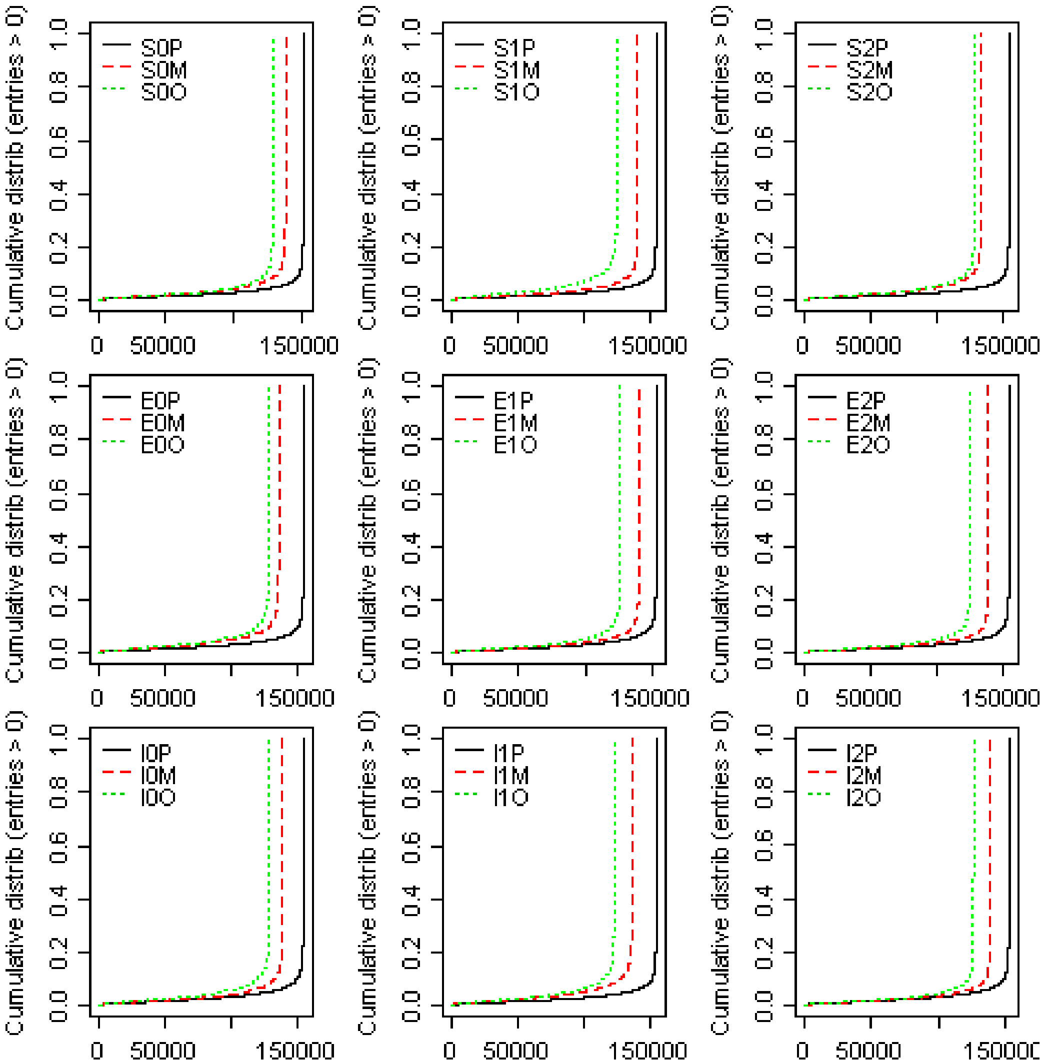


Figure B.20: Cumulative distribution plot for fine scale spatial analysis of sharks average grid-cell relative biomass, comparing model specifications (each box contains the cumulative distributions for pessimistic [black], base case [red] and optimistic [green] specifications for a given combination of management strategy and development scenario).

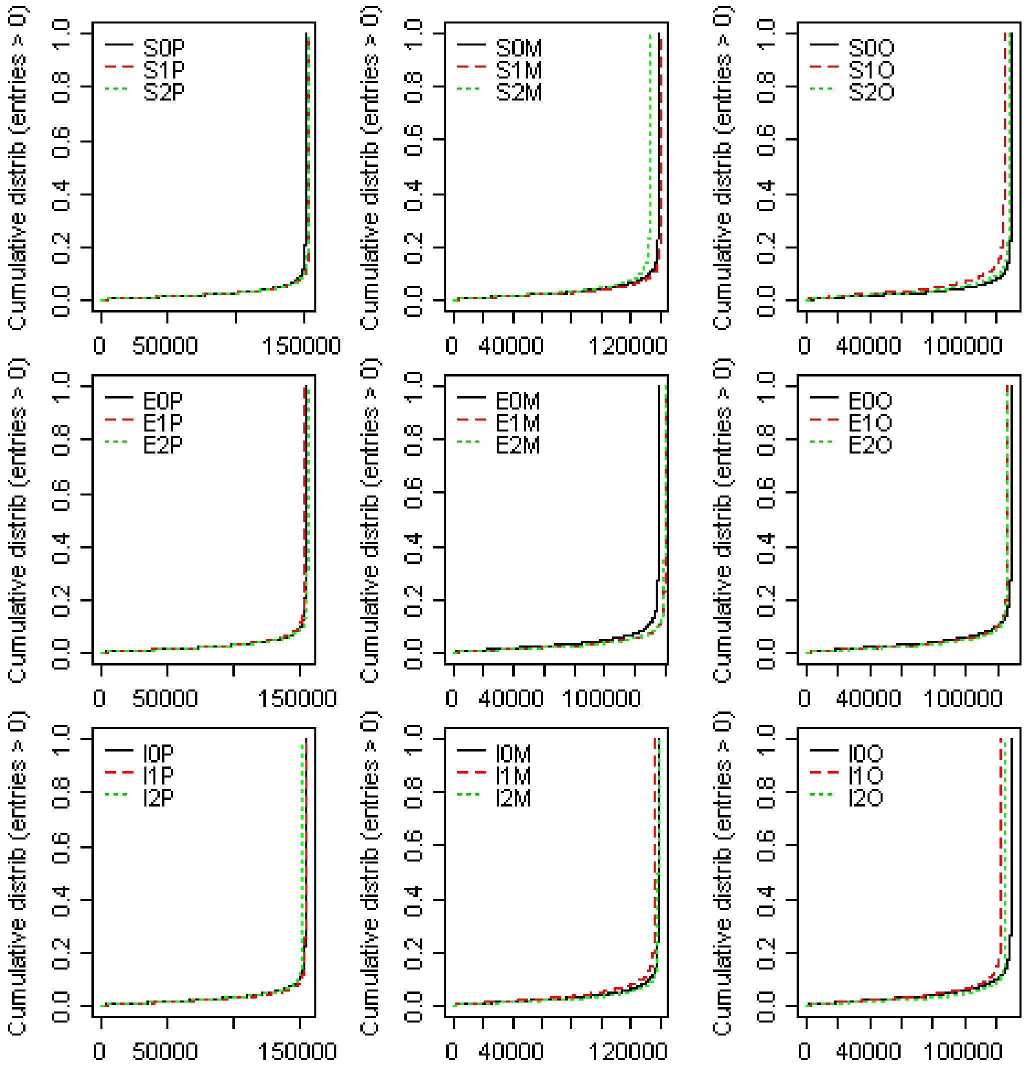


Figure B.21: Cumulative distribution plot for fine scale spatial analysis of sharks average grid-cell relative biomass, comparing development scenarios (each box contains the cumulative distributions for 0-pulse [black], 1-pulse [red] and 2-pulse [green] development scenarios for a given combination of management strategy and model specification).

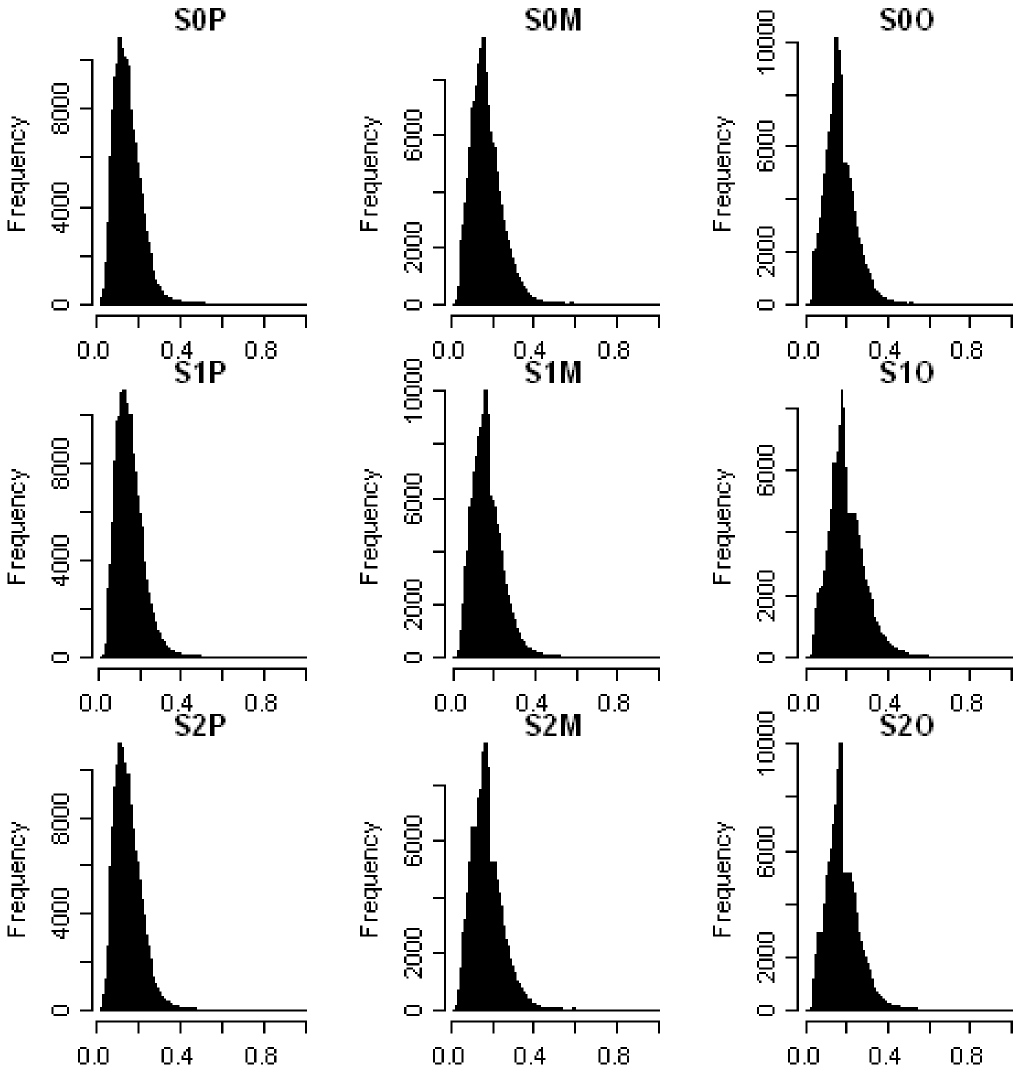


Figure B.22: Frequency histogram of fine scale relative biomass (over time) for sharks under status quo management for each combination of development scenario and model specification.

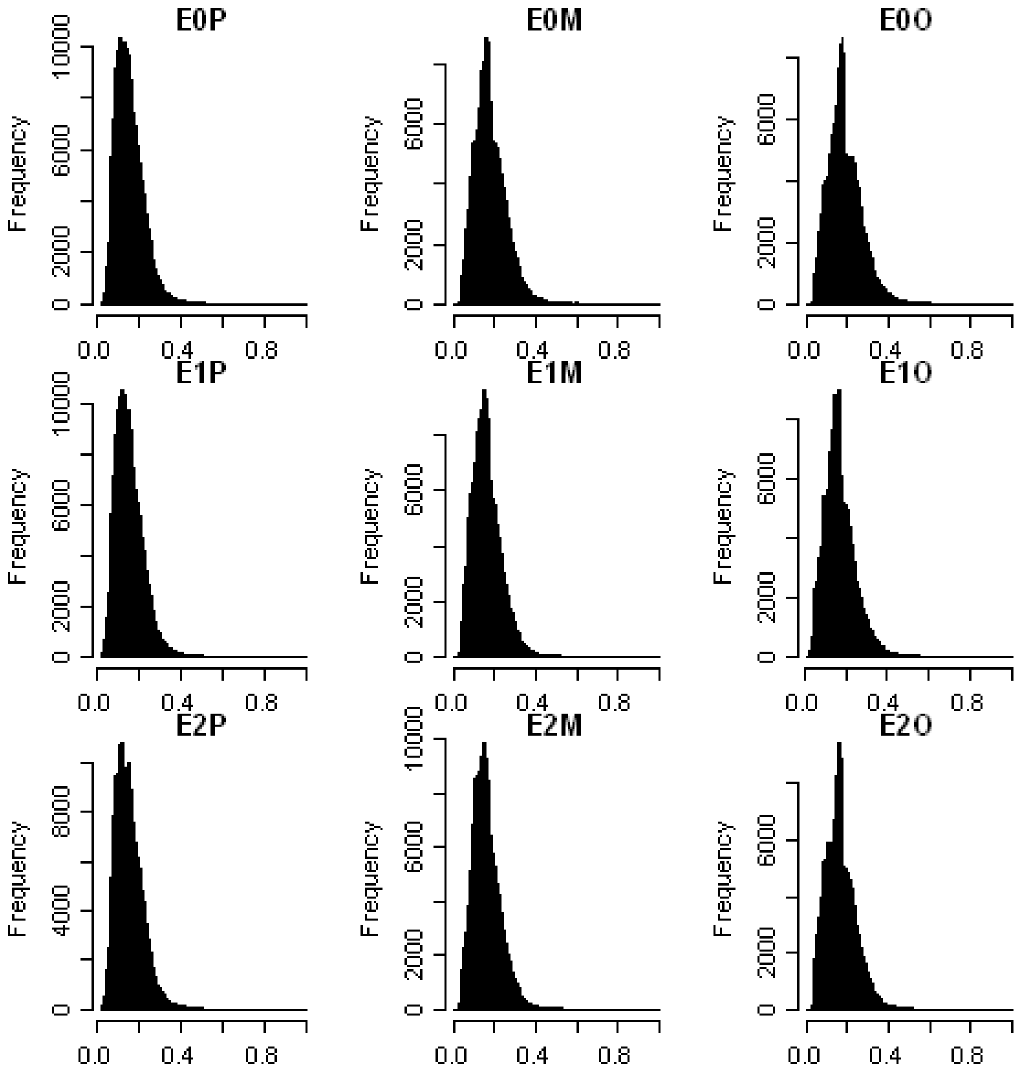


Figure B.23: Frequency histogram of fine scale relative biomass (over time) for sharks under enhanced management for each combination of development scenario and model specification.

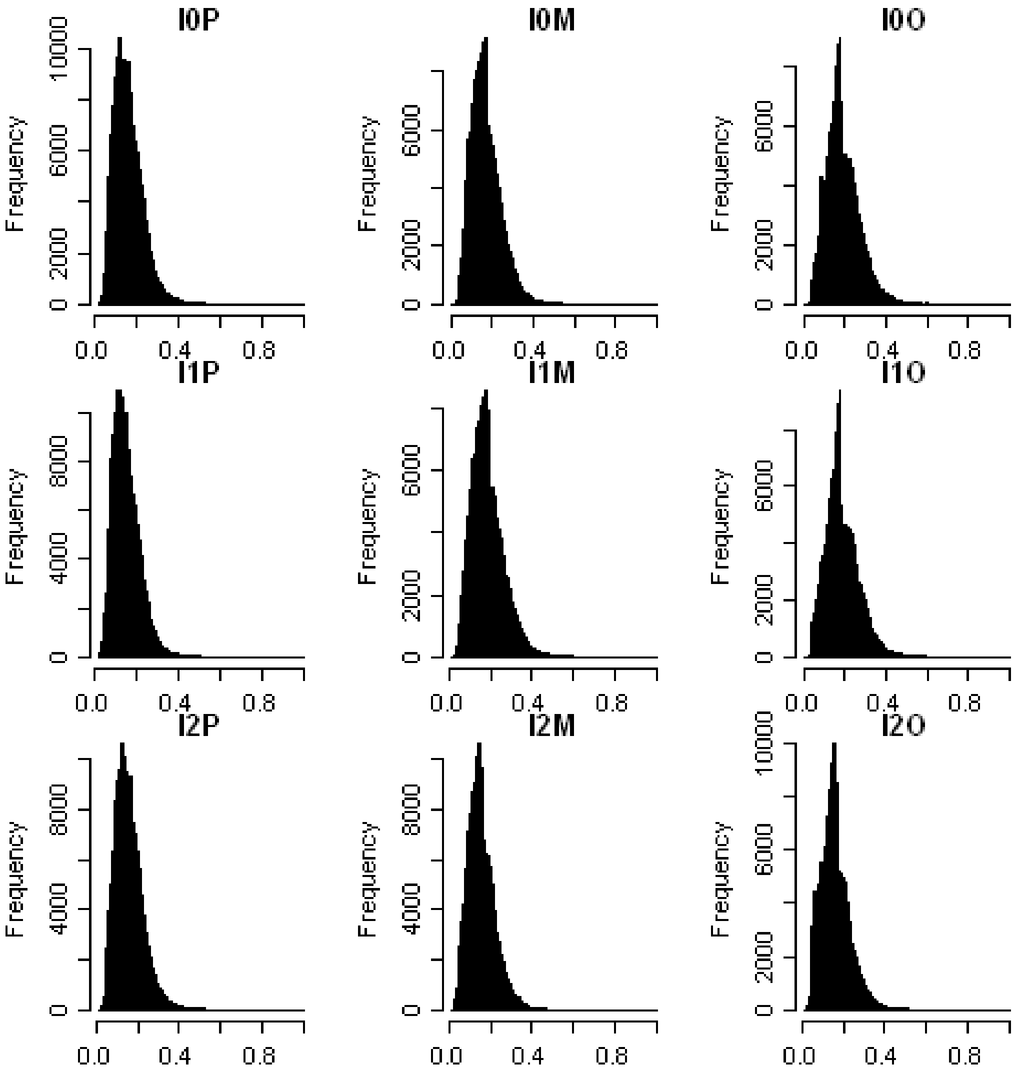


Figure B.24: Frequency histogram of fine scale relative biomass (over time) for sharks under integrated management for each combination of development scenario and model specification.

B.5 Large Lutjanids

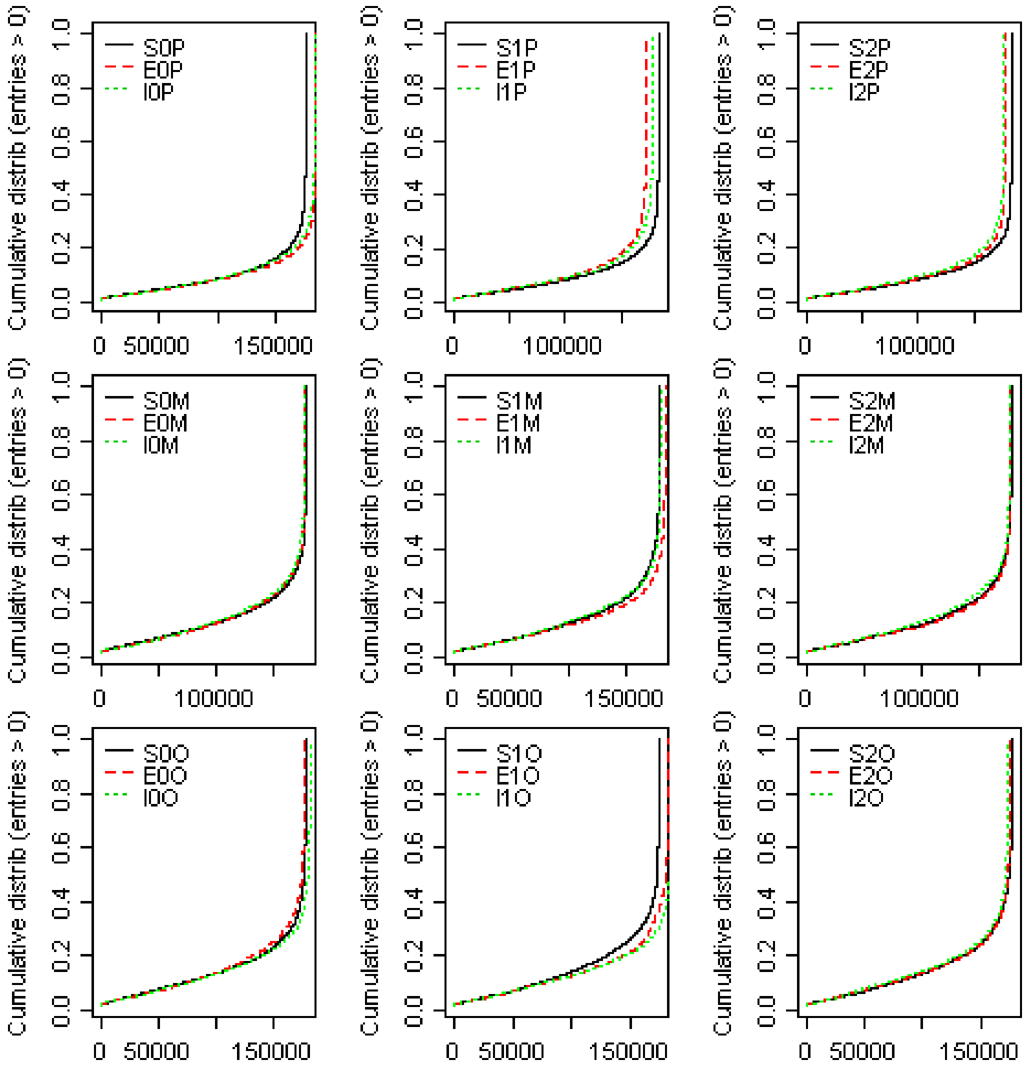


Figure B.25: Cumulative distribution plot for fine scale spatial analysis of large lutjanids average grid-cell relative biomass, comparing management strategies (each box contains the cumulative distributions for status quo [black], enhanced [red] and integrated [green] management for a given combination of model specification and development scenario).

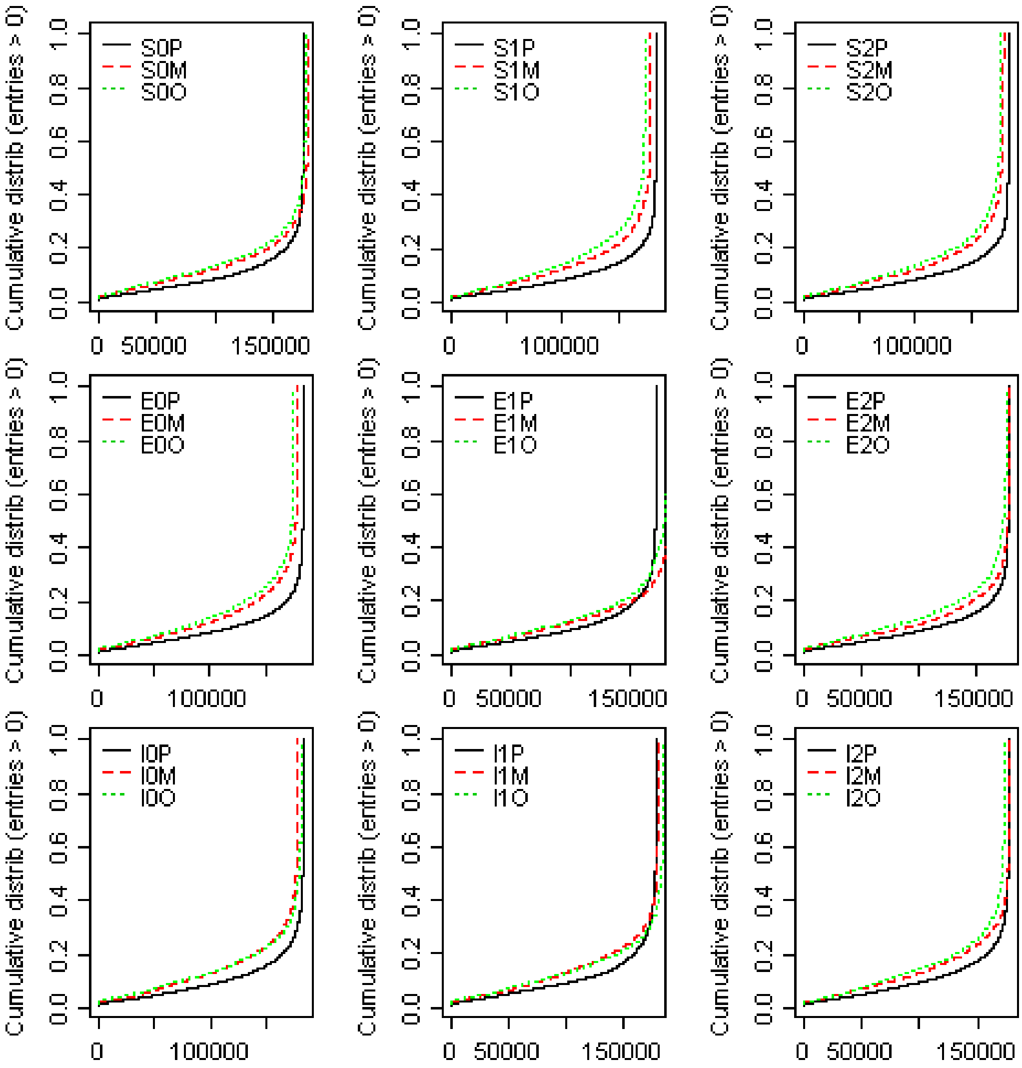


Figure B.26: Cumulative distribution plot for large fine scale spatial analysis of lutjanids average grid-cell relative biomass, comparing model specifications (each box contains the cumulative distributions for pessimistic [black], base case [red] and optimistic [green] specifications for a given combination of management strategy and development scenario).

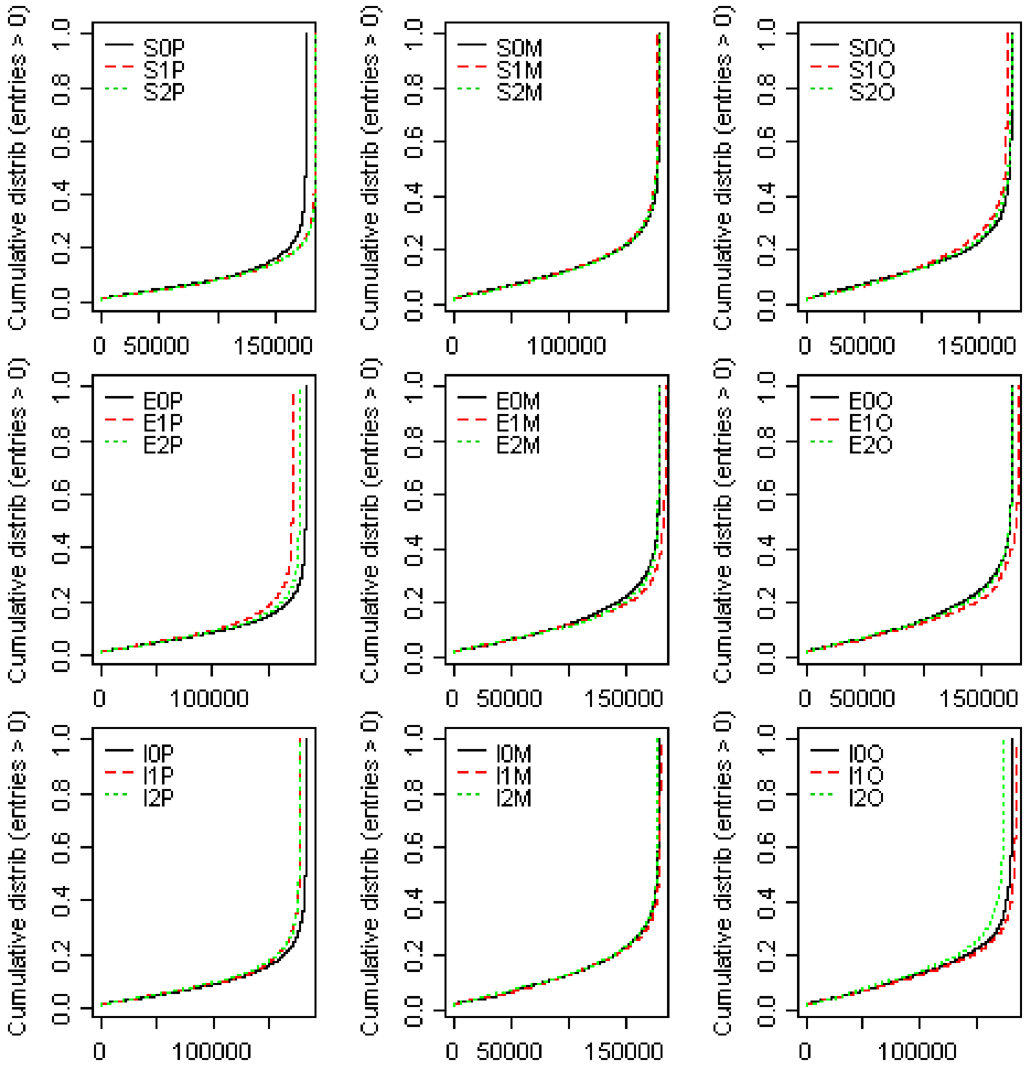


Figure B.27: Cumulative distribution plot for fine scale spatial analysis of large lutjanids average grid-cell relative biomass, comparing development scenarios (each box contains the cumulative distributions for 0-pulse [black], 1-pulse [red] and 2-pulse [green] development scenarios for a given combination of management strategy and model specification).

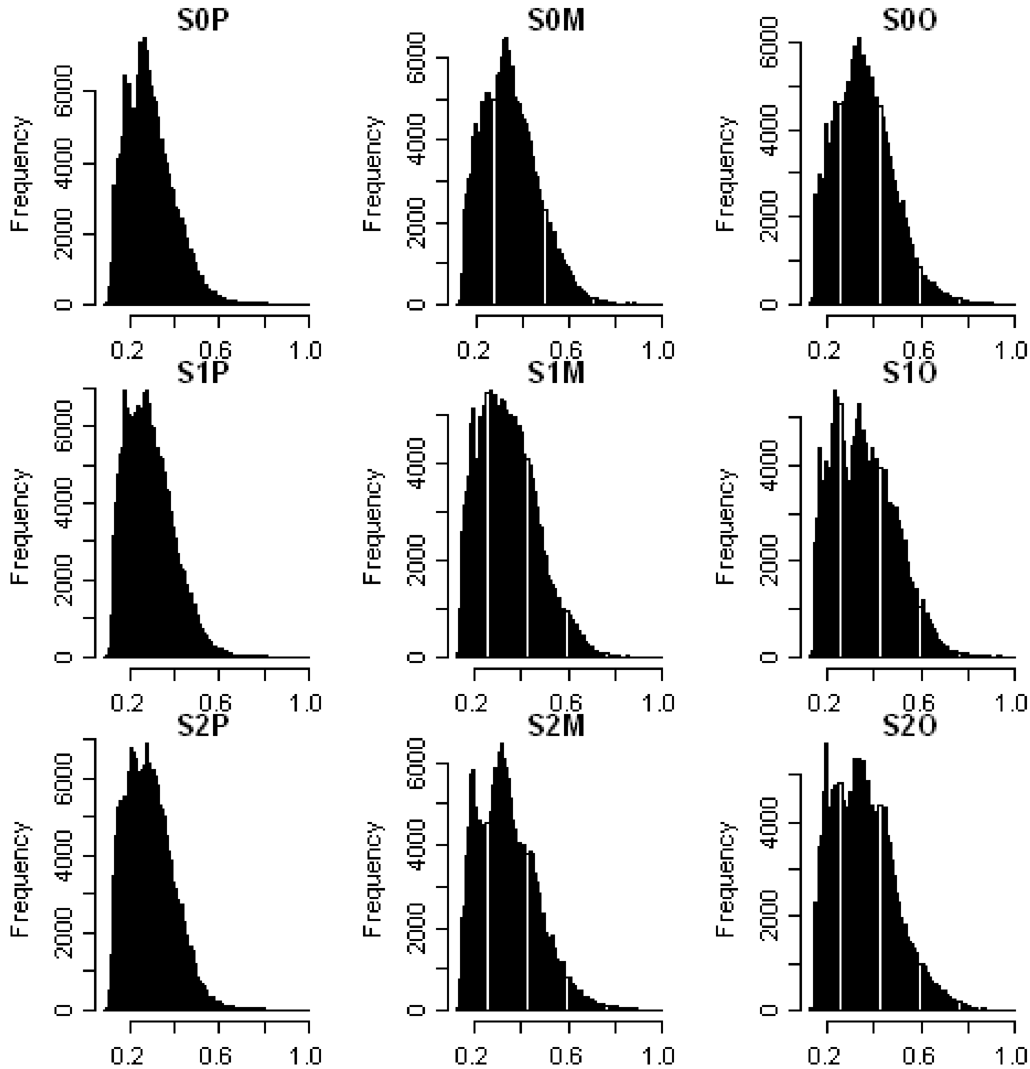


Figure B.28: Frequency histogram of fine scale relative biomass (over time) for large lutjanids under status quo management for each combination of development scenario and model specification.

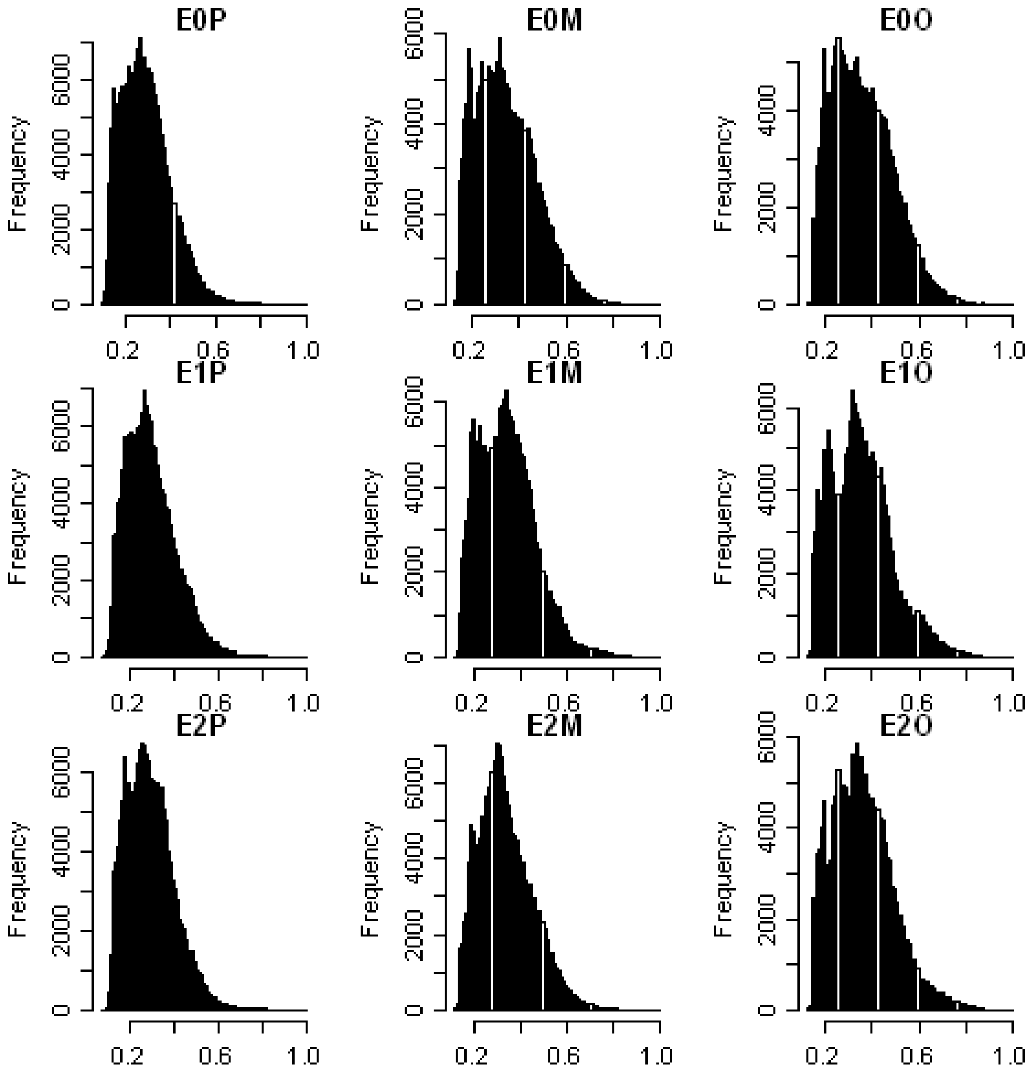


Figure B.29: Frequency histogram of fine scale relative biomass (over time) for large lutjanids under enhanced management for each combination of development scenario and model specification.

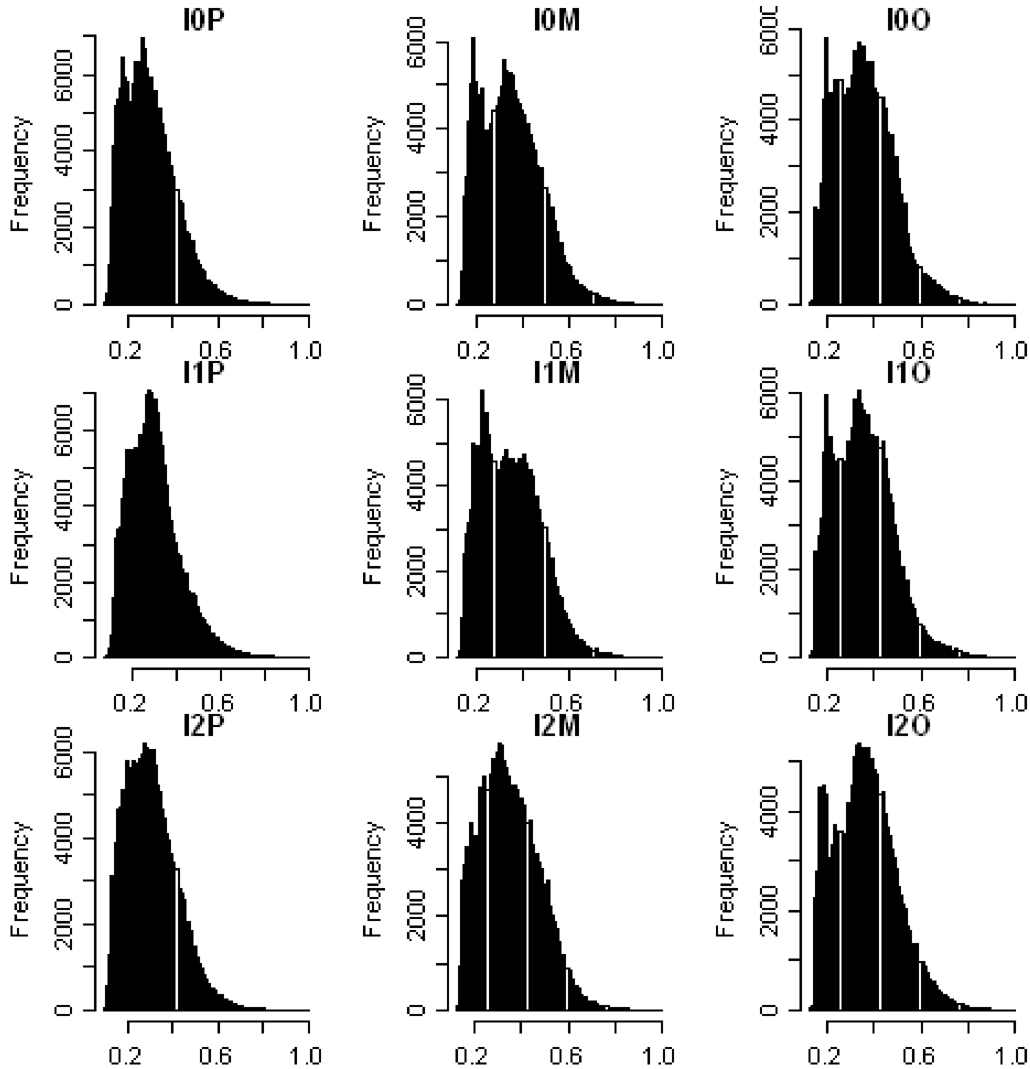


Figure B.30: Frequency histogram of fine scale relative biomass (over time) for large lutjanids under integrated management for each combination of development scenario and model specification.

B.6 Small Lutjanids

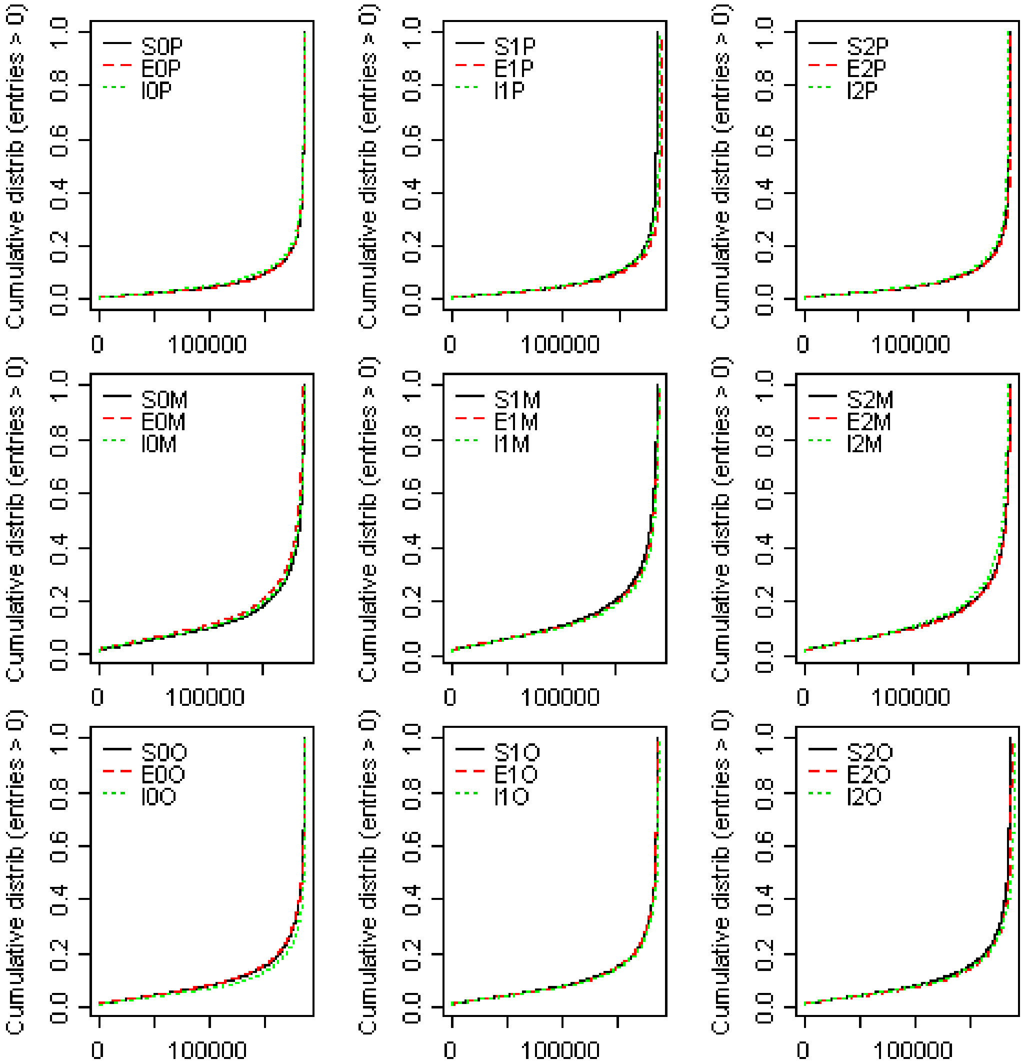


Figure B.31: Cumulative distribution plot for fine scale spatial analysis of small lutjanids average grid-cell relative biomass, comparing management strategies (each box contains the cumulative distributions for status quo [black], enhanced [red] and integrated [green] management for a given combination of model specification and development scenario).

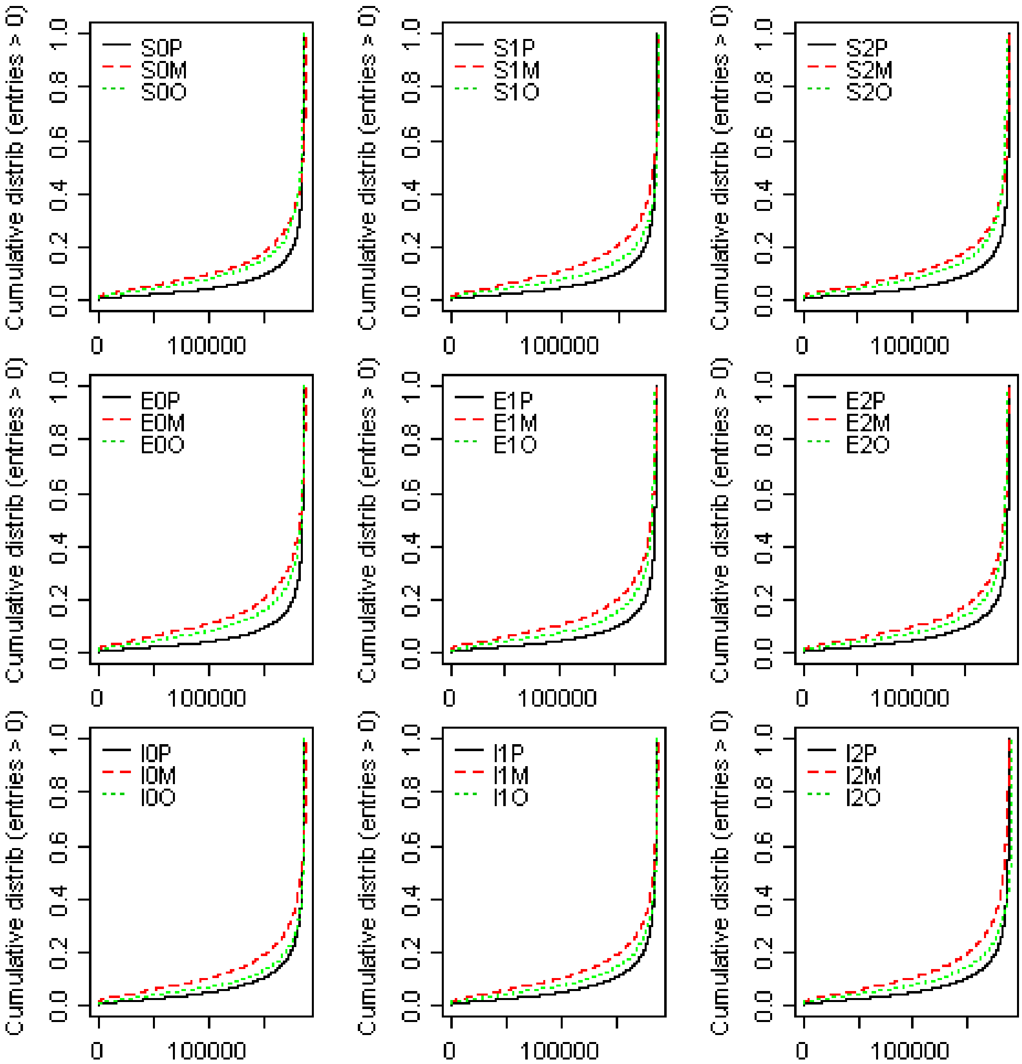


Figure B.32: Cumulative distribution plot for fine scale spatial analysis of small lutjanids average grid-cell relative biomass, comparing model specifications (each box contains the cumulative distributions for pessimistic [black], base case [red] and optimistic [green] specifications for a given combination of management strategy and development scenario).

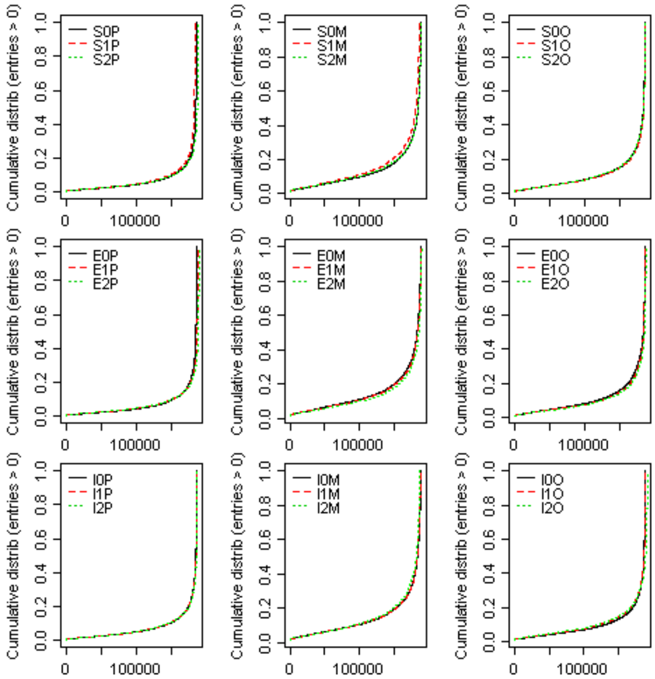


Figure B.33: Cumulative distribution plot for fine scale spatial analysis of small lutjanids average grid-cell relative biomass, comparing development scenarios (each box contains the cumulative distributions for 0-pulse [black], 1-pulse [red] and 2-pulse [green] development scenarios for a given combination of management strategy and model specification).

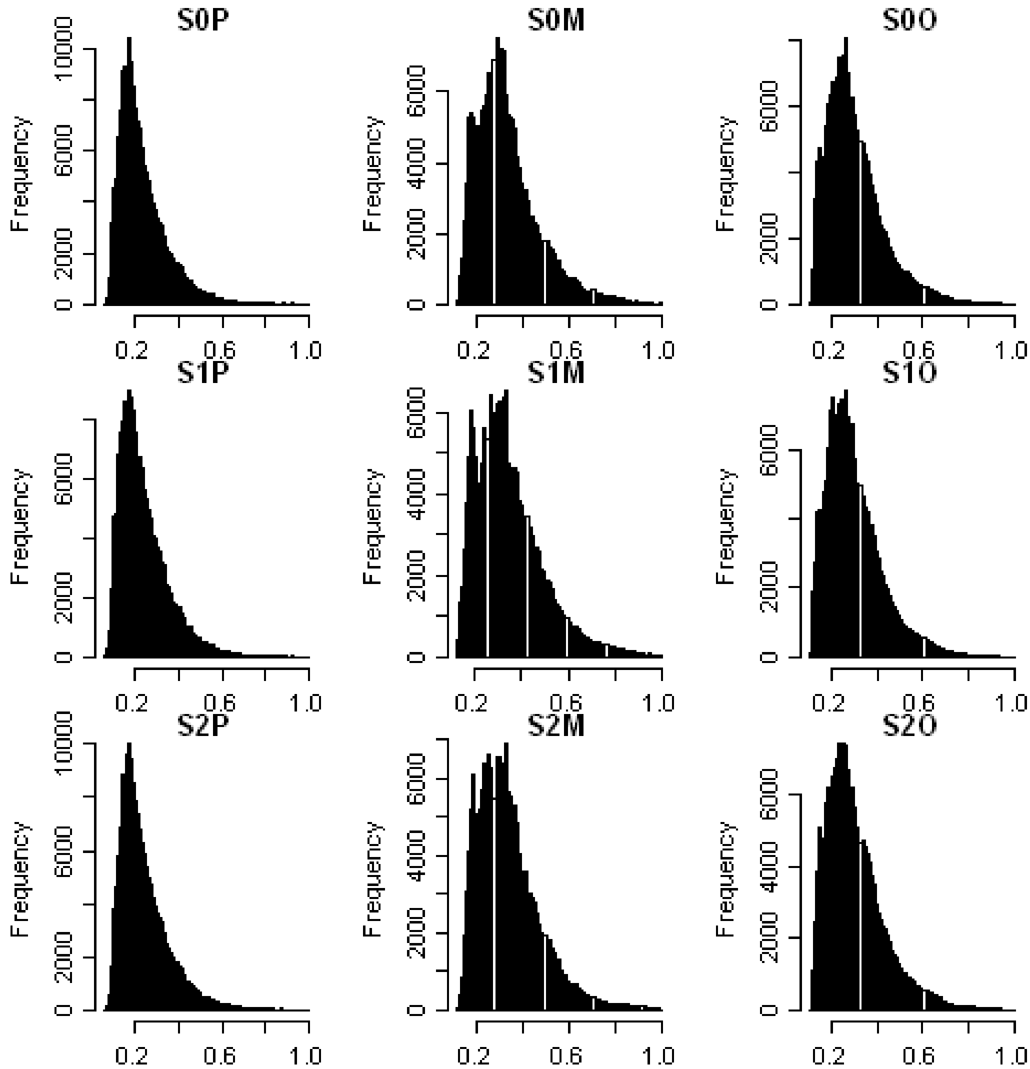


Figure B.34: Frequency histogram of fine scale relative biomass (over time) for small lutjanids under status quo management for each combination of development scenario and model specification.

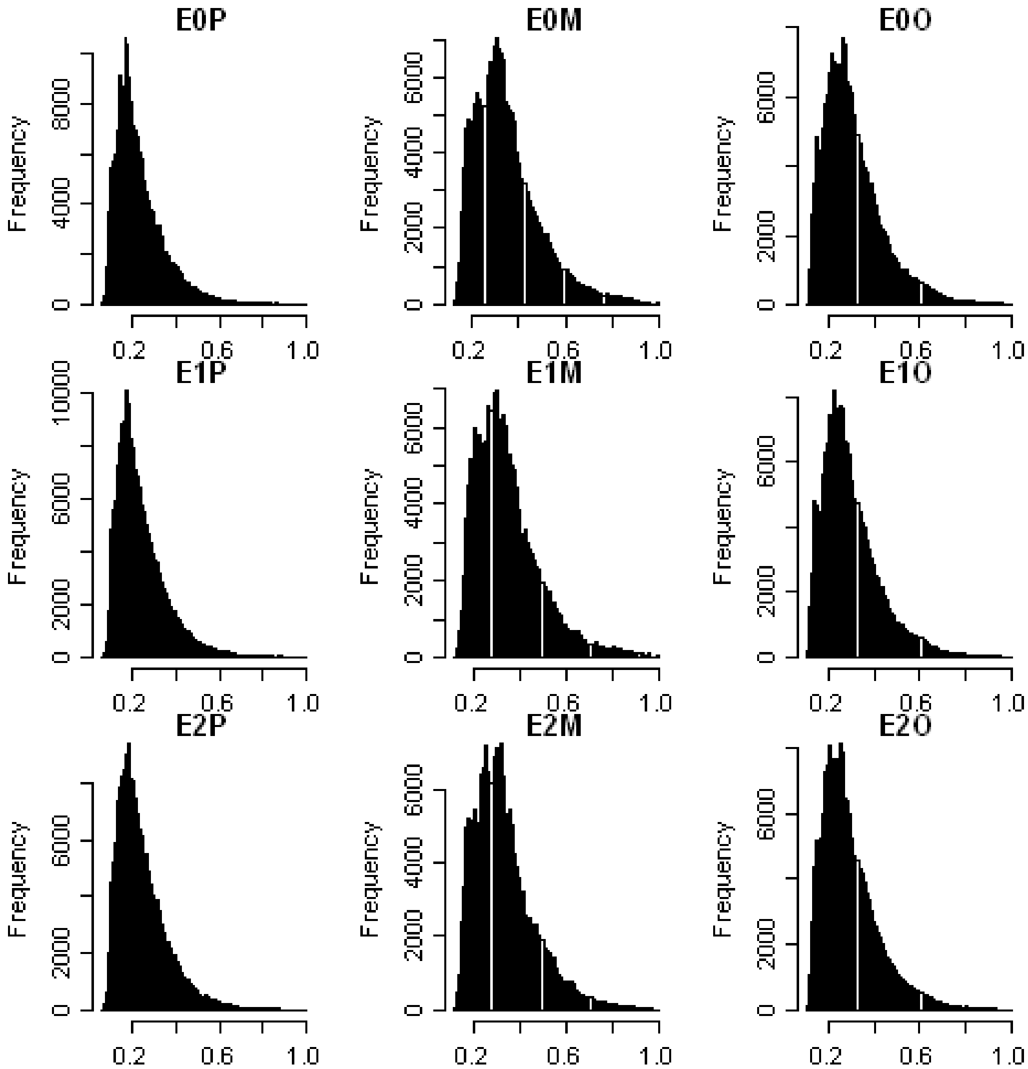


Figure B.35: Frequency histogram of fine scale relative biomass (over time) for small lutjanids under enhanced management for each combination of development scenario and model specification.

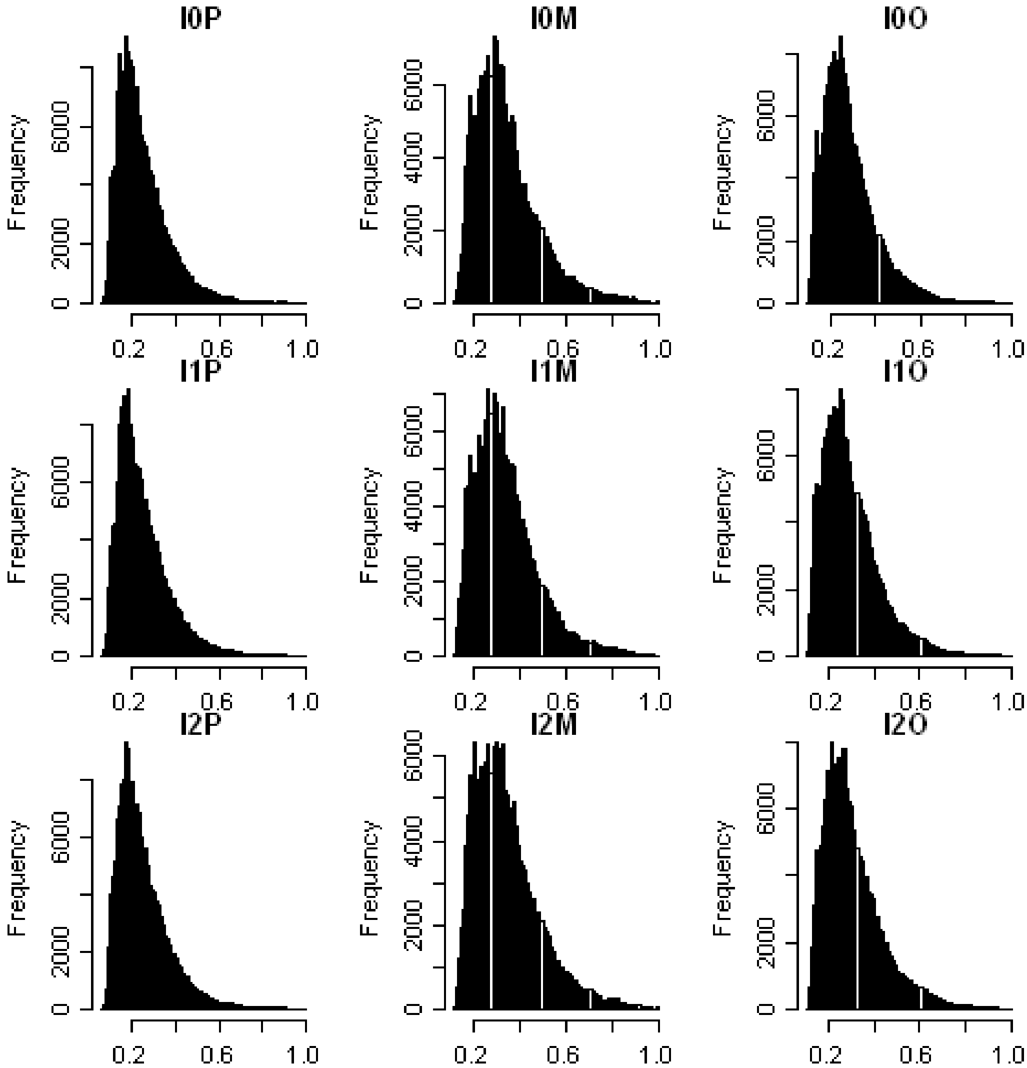


Figure B.36: Frequency histogram of fine scale relative biomass (over time) for small lutjanids under integrated management for each combination of development scenario and model specification.

B.7 *Lutjanus sebae*

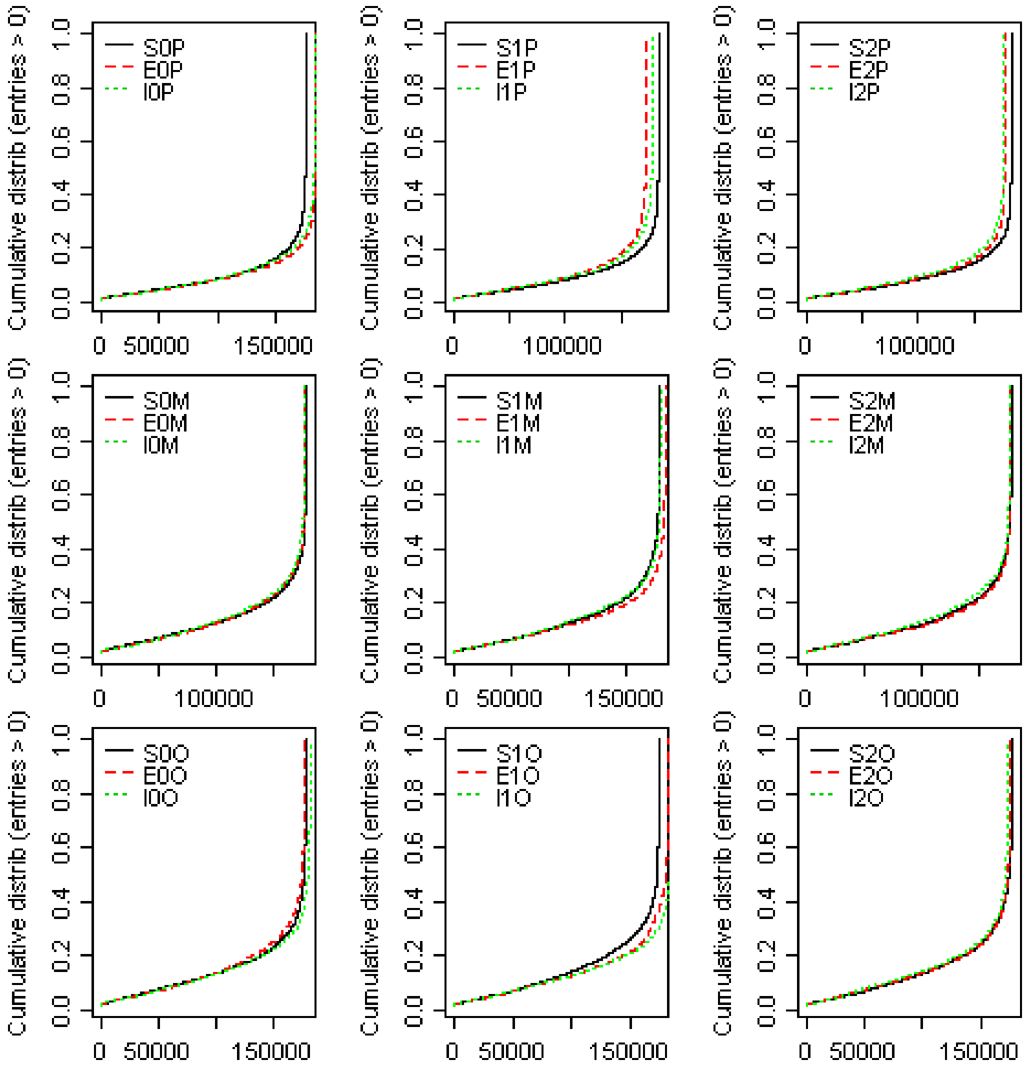


Figure B.37: Cumulative distribution plot for fine scale spatial analysis of *Lutjanus sebae* average grid-cell relative biomass, comparing management strategies (each box contains the cumulative distributions for status quo [black], enhanced [red] and integrated [green] management for a given combination of model specification and development scenario).

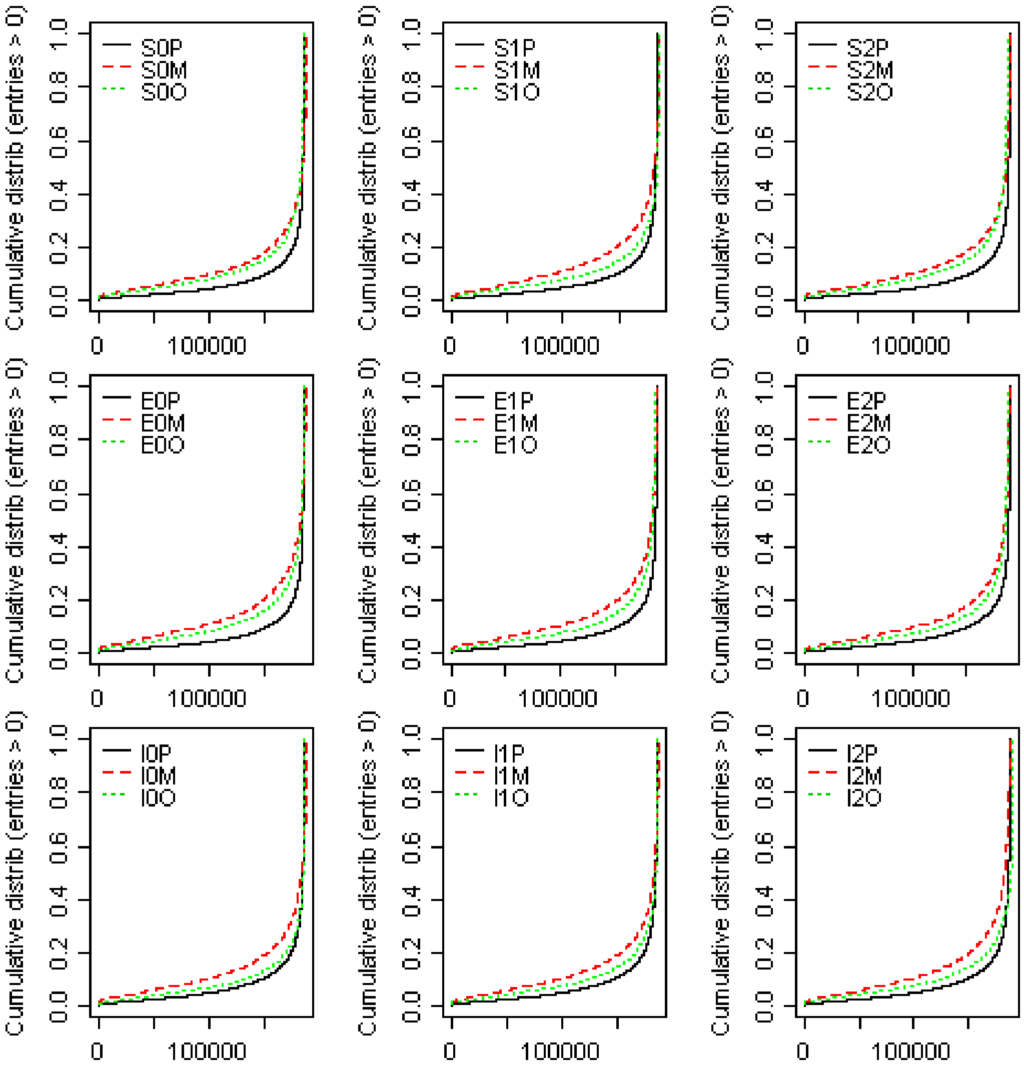


Figure B.38: Cumulative distribution plot for fine scale spatial analysis of *Lutjanus sebae* average grid-cell relative biomass, comparing model specifications (each box contains the cumulative distributions for pessimistic [black], base case [red] and optimistic [green] specifications for a given combination of management strategy and development scenario).

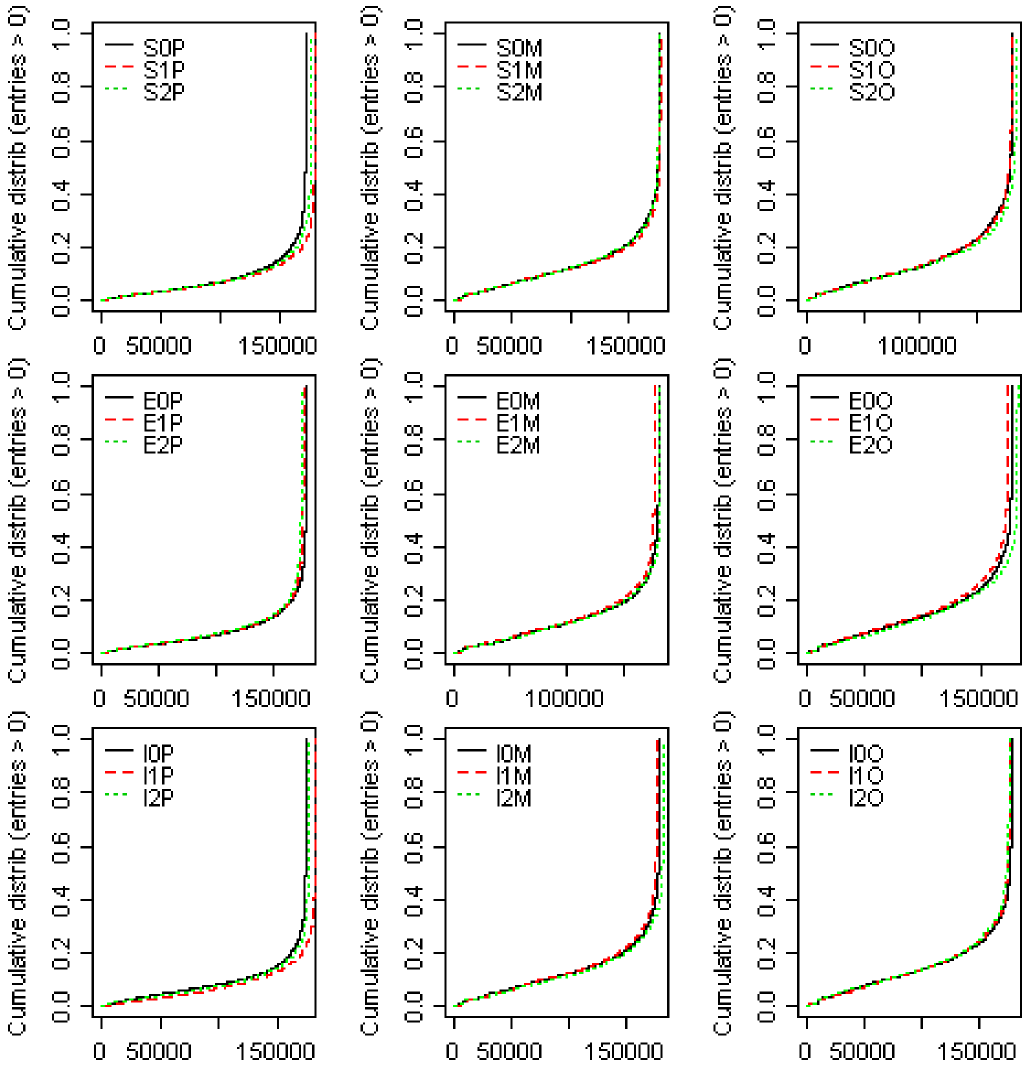


Figure B.39: Cumulative distribution plot for fine scale spatial analysis of *Lutjanus sebae* average grid-cell relative biomass, comparing development scenarios (each box contains the cumulative distributions for 0-pulse [black], 1-pulse [red] and 2-pulse [green] development scenarios for a given combination of management strategy and model specification).

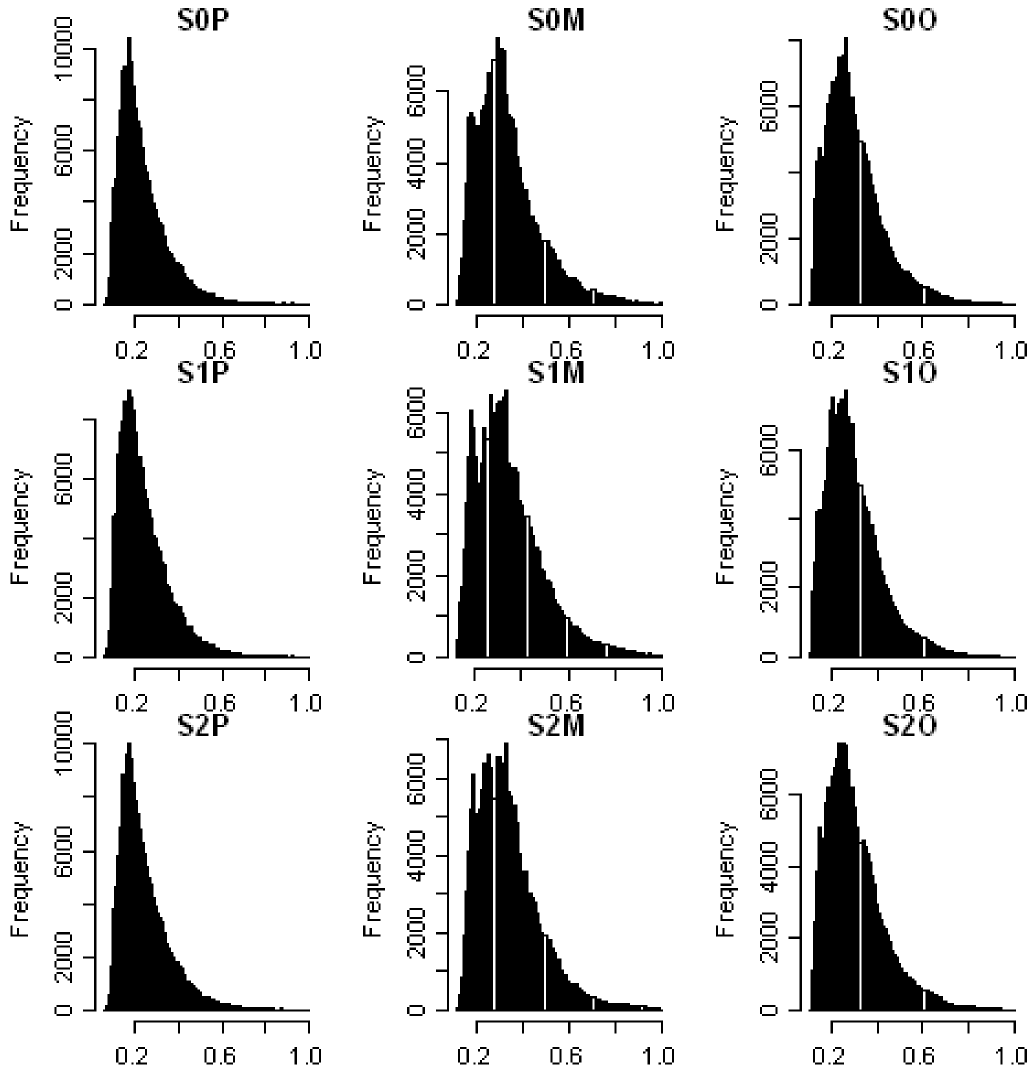


Figure B.40: Frequency histogram of fine scale relative biomass (over time) for *Lutjanus sebae* under status quo management for each combination of development scenario and model specification.

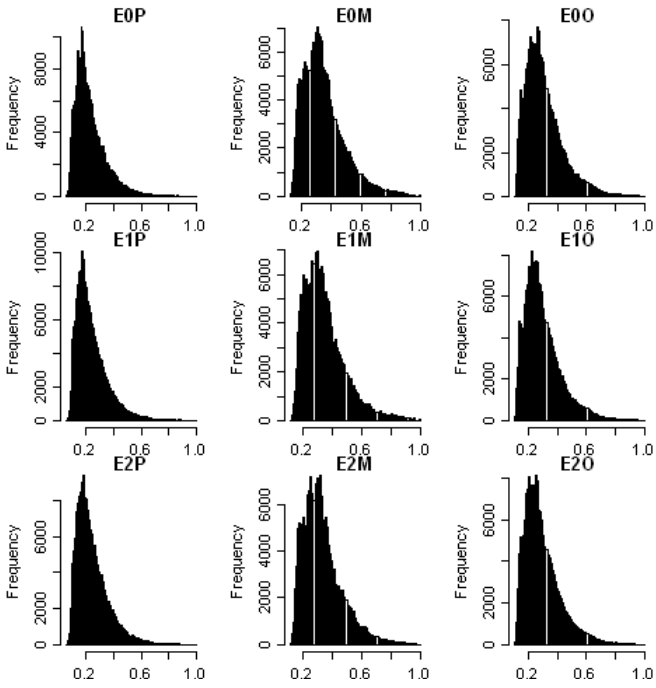


Figure B.41: Frequency histogram of fine scale relative biomass (over time) for *Lutjanus sebae* under enhanced management for each combination of development scenario and model specification.

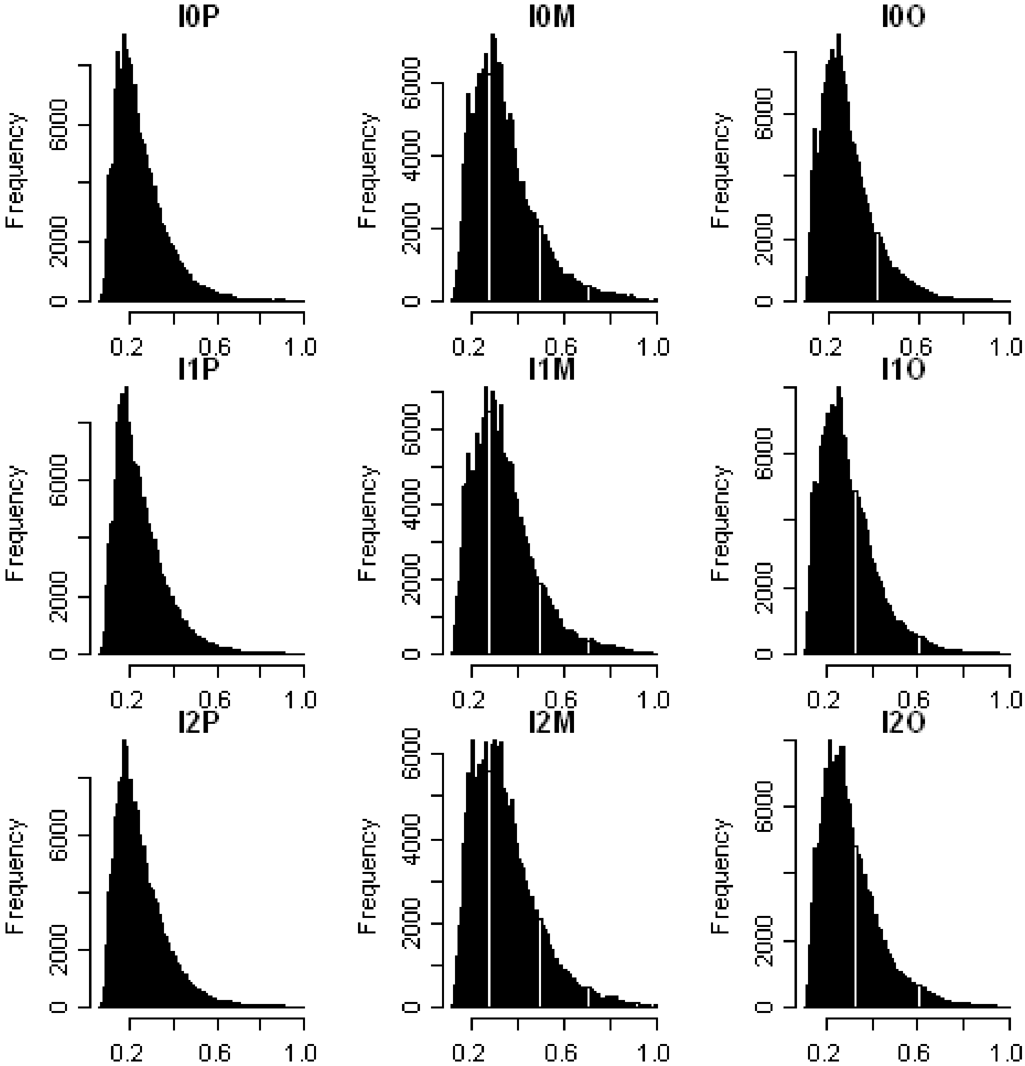


Figure B.42: Frequency histogram of fine scale relative biomass (over time) for *Lutjanus sebae* under integrated management for each combination of development scenario and model specification.

B.8 Lethrinids

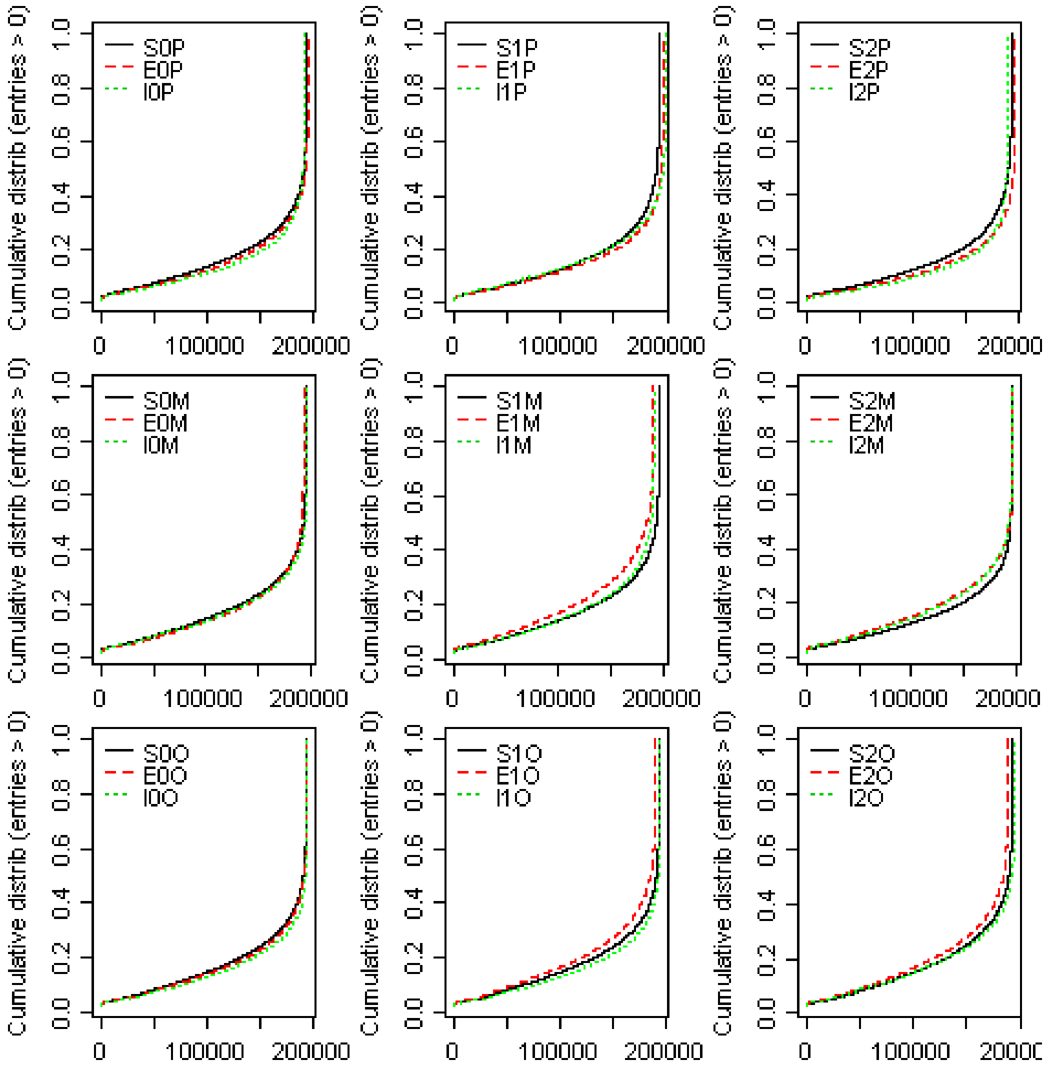


Figure B.43: Cumulative distribution plot for fine scale spatial analysis of lethrinids average grid-cell relative biomass, comparing management strategies (each box contains the cumulative distributions for status quo [black], enhanced [red] and integrated [green] management for a given combination of model specification and development scenario).

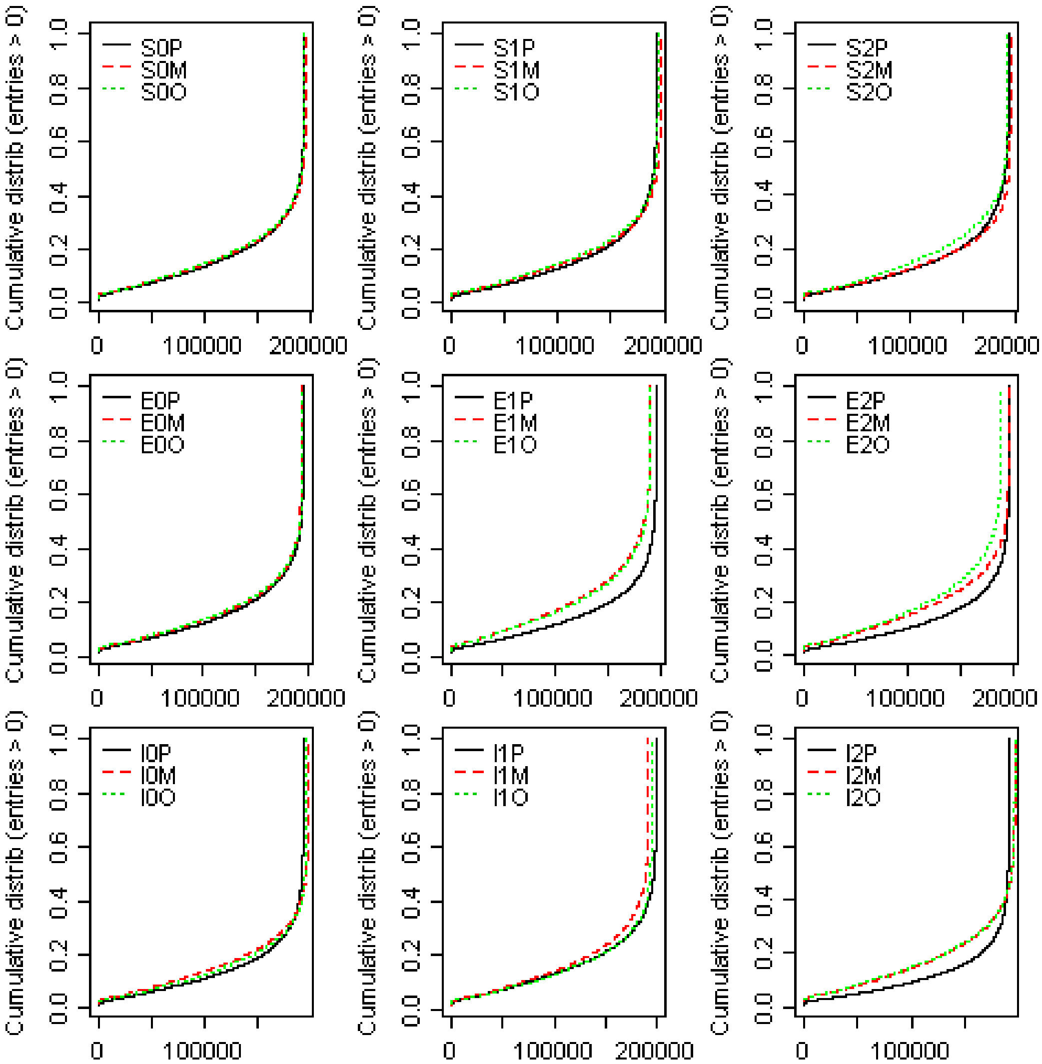


Figure B.44: Cumulative distribution plot for fine scale spatial analysis of lethrinids average grid-cell relative biomass, comparing model specifications (each box contains the cumulative distributions for pessimistic [black], base case [red] and optimistic [green] specifications for a given combination of management strategy and development scenario).

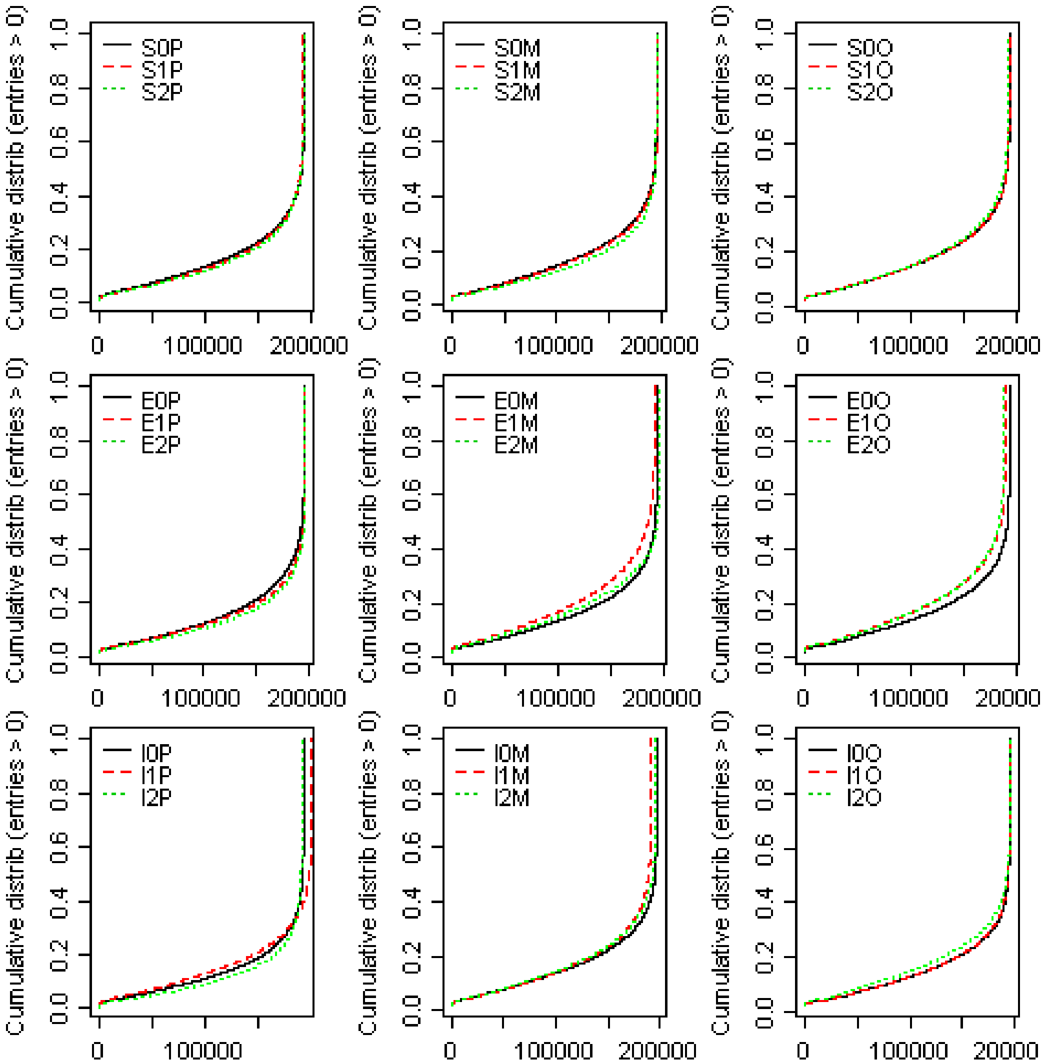


Figure B.45: Cumulative distribution plot for fine scale spatial analysis of lethrinids average grid-cell relative biomass, comparing development scenarios (each box contains the cumulative distributions for 0-pulse [black], 1-pulse [red] and 2-pulse [green] development scenarios for a given combination of management strategy and model specification).

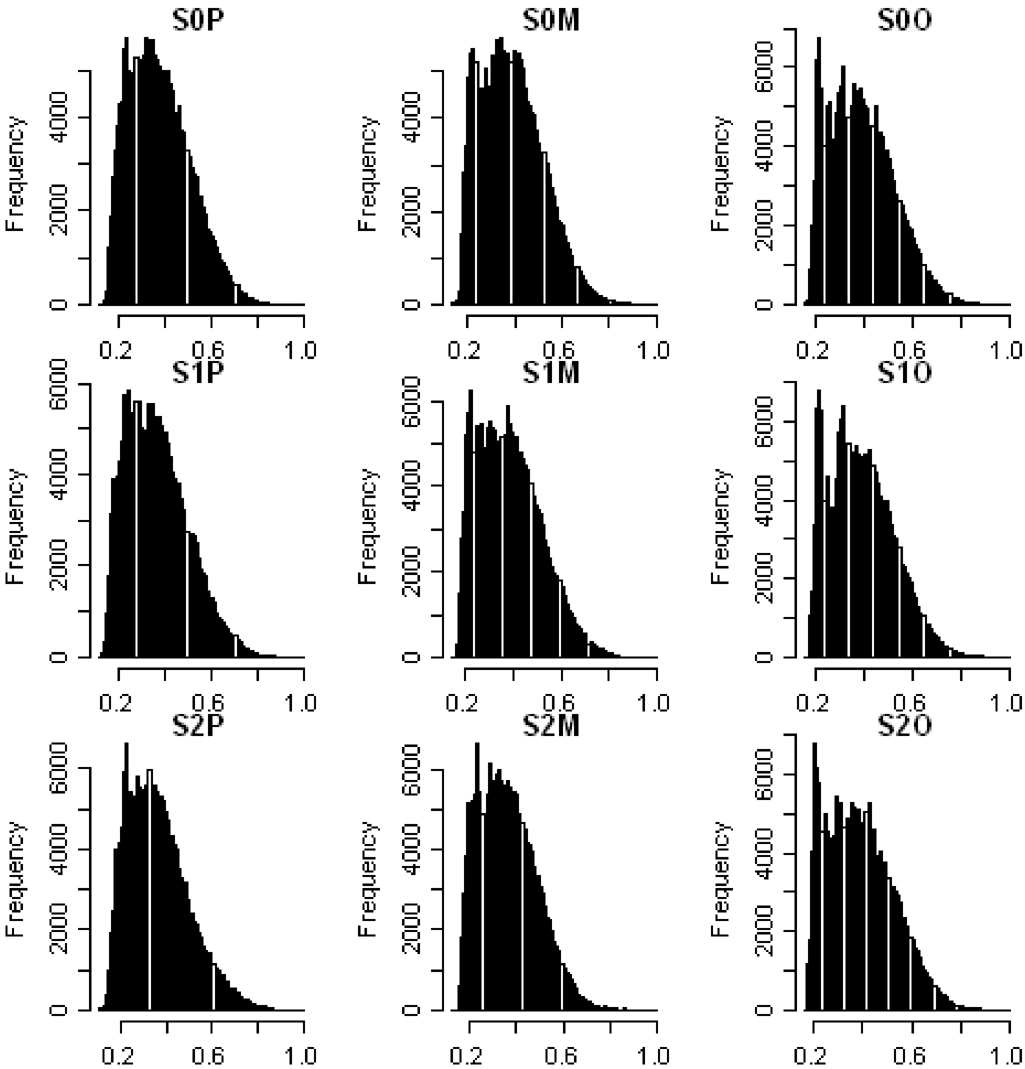


Figure B.46: Frequency histogram of fine scale relative biomass (over time) for lethrinids under status quo management for each combination of development scenario and model specification.

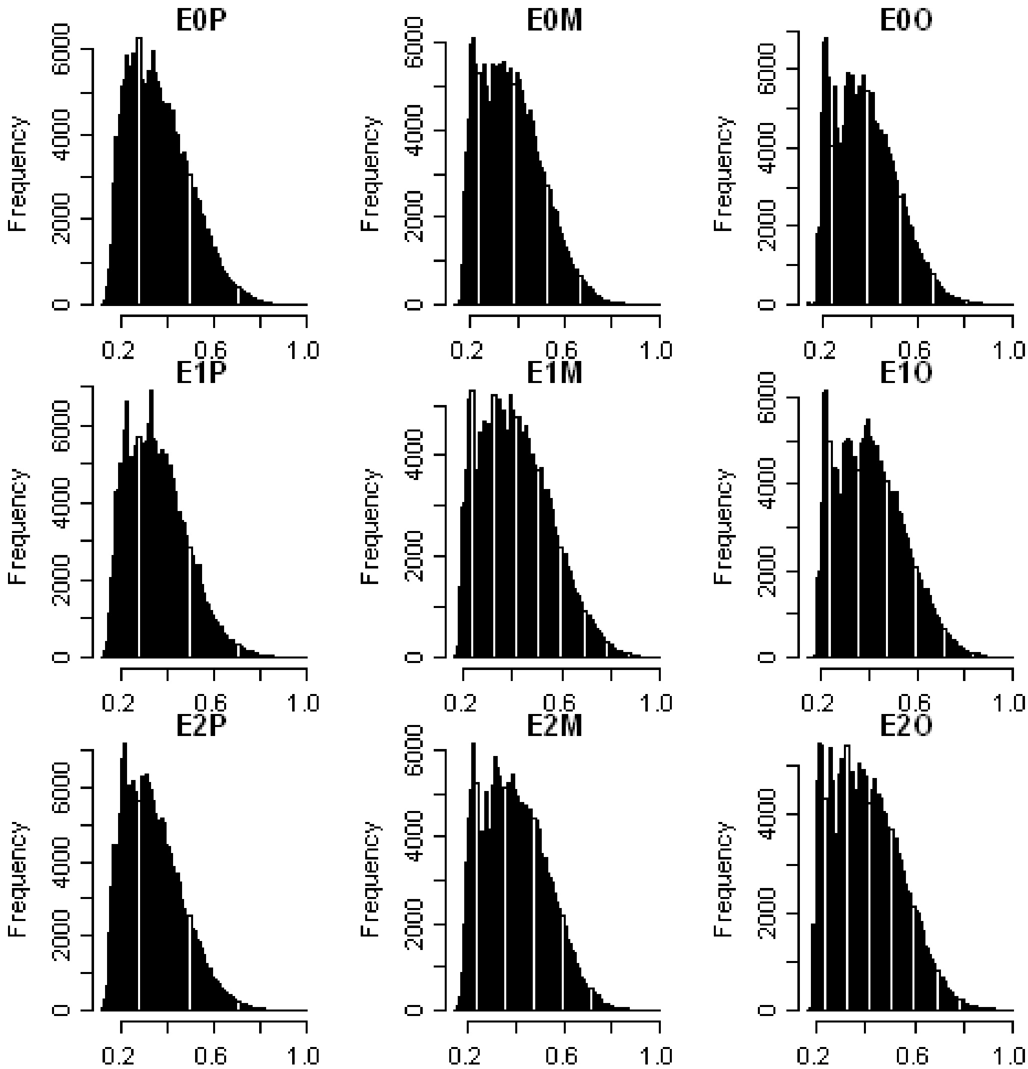


Figure B.47: Frequency histogram of fine scale relative biomass (over time) for lethrinids under enhanced management for each combination of development scenario and model specification.

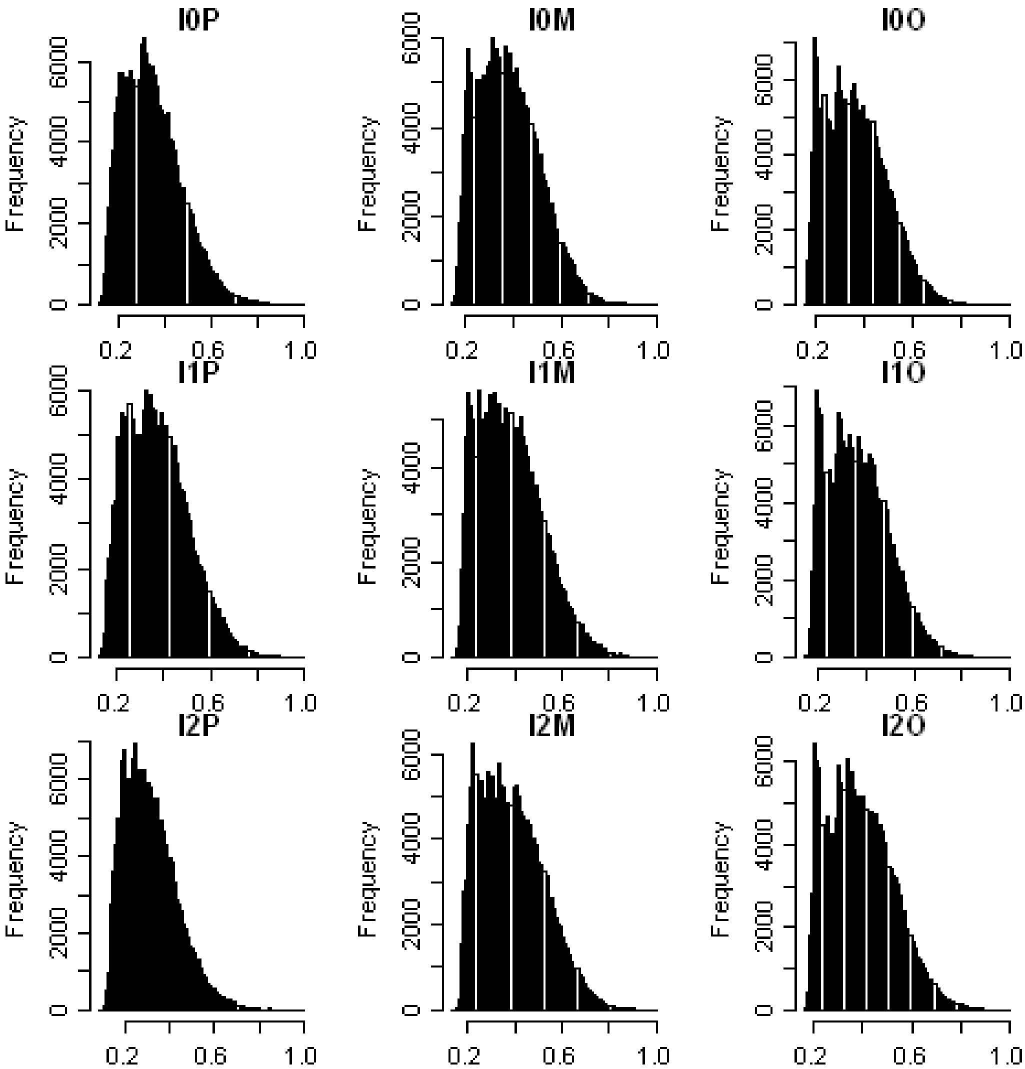


Figure B.48: Frequency histogram of fine scale relative biomass (over time) for lethrinids under integrated management for each combination of development scenario and model specification.

B.9 Nemipterids

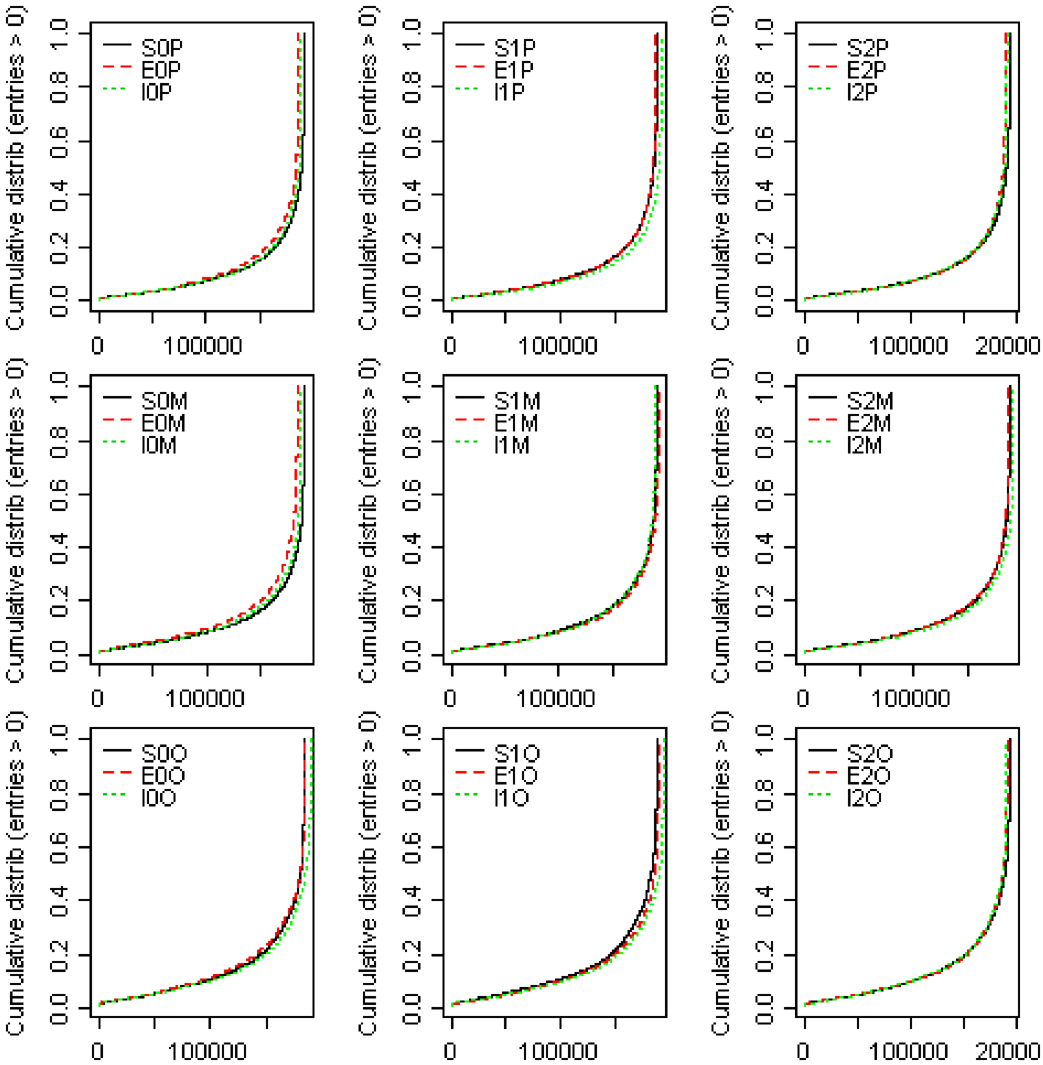


Figure B.49: Cumulative distribution plot for fine scale spatial analysis of nemipterids average grid-cell relative biomass, comparing management strategies (each box contains the cumulative distributions for status quo [black], enhanced [red] and integrated [green] management for a given combination of model specification and development scenario).

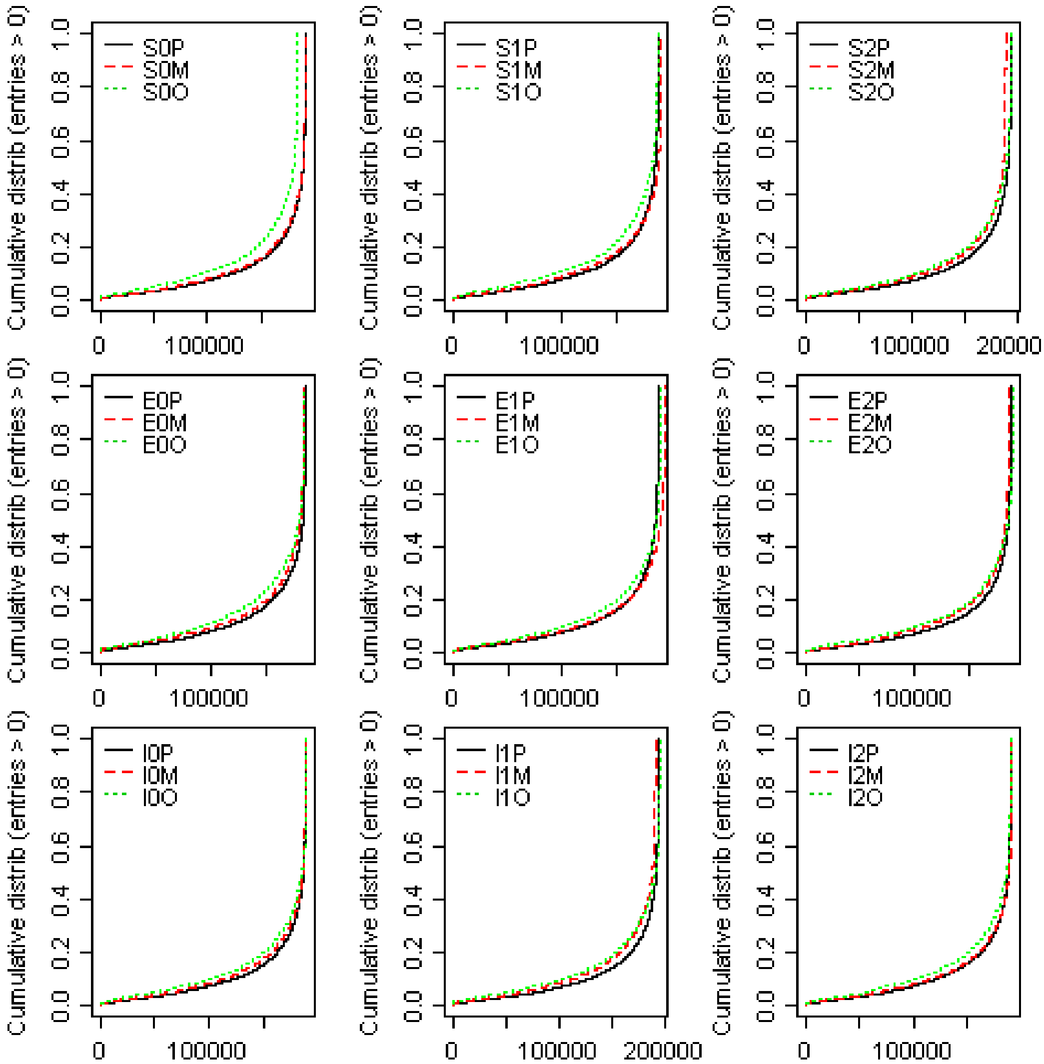


Figure B.50: Cumulative distribution plot for fine scale spatial analysis of nemipterids average grid-cell relative biomass, comparing model specifications (each box contains the cumulative distributions for pessimistic [black], base case [red] and optimistic [green] specifications for a given combination of management strategy and development scenario).

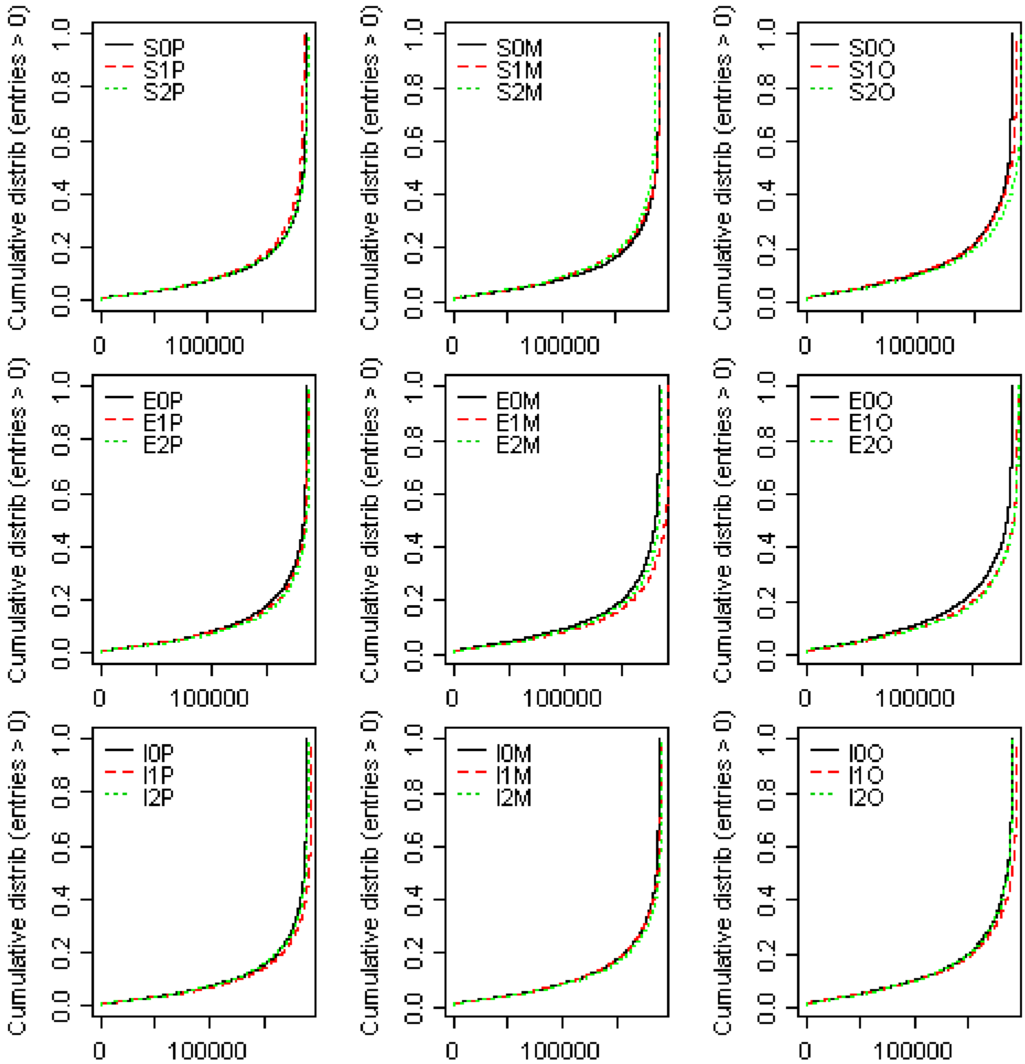


Figure B.51: Cumulative distribution plot for fine scale spatial analysis of nemipterids average grid-cell relative biomass, comparing development scenarios (each box contains the cumulative distributions for 0-pulse [black], 1-pulse [red] and 2-pulse [green] development scenarios for a given combination of management strategy and model specification).

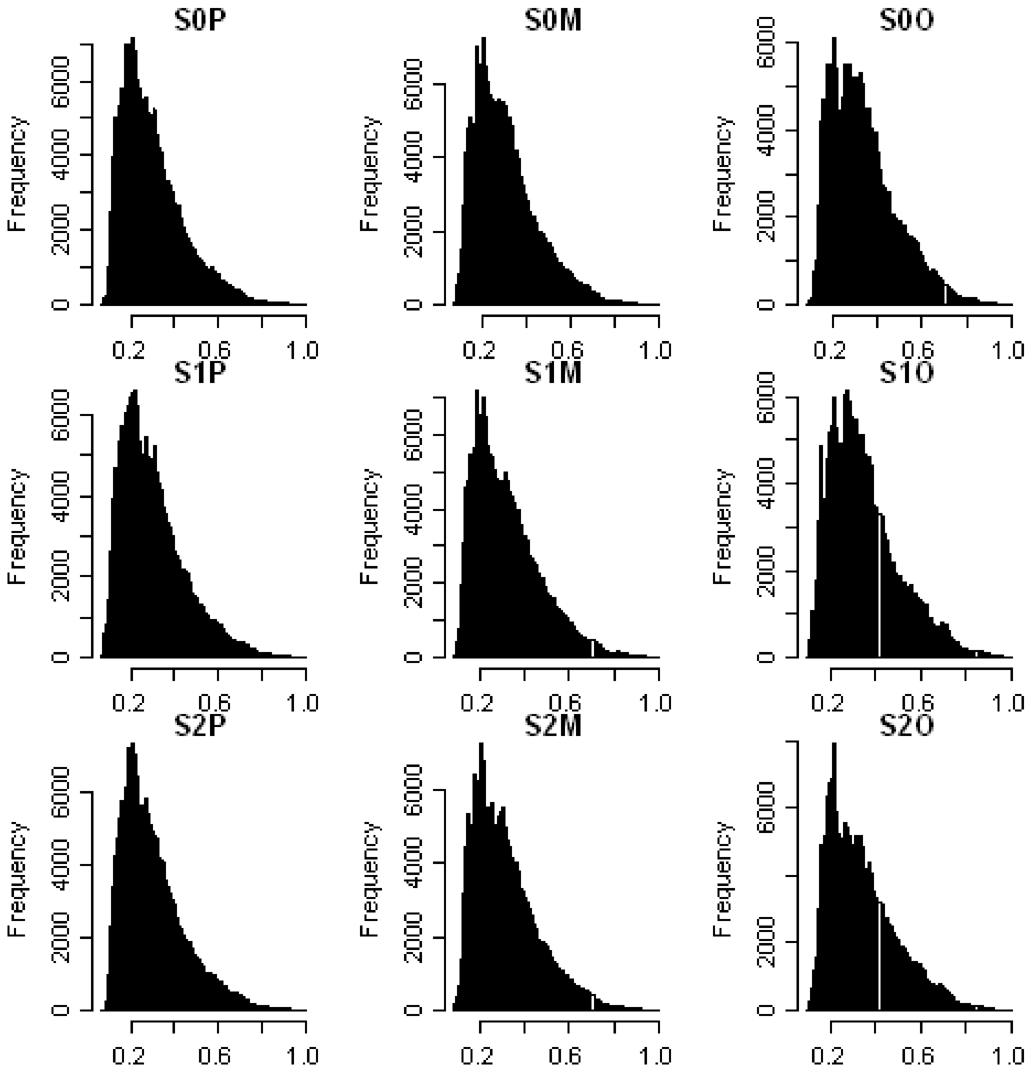


Figure B.52: Frequency histogram of fine scale relative biomass (over time) for nemipterids under status quo management for each combination of development scenario and model specification.

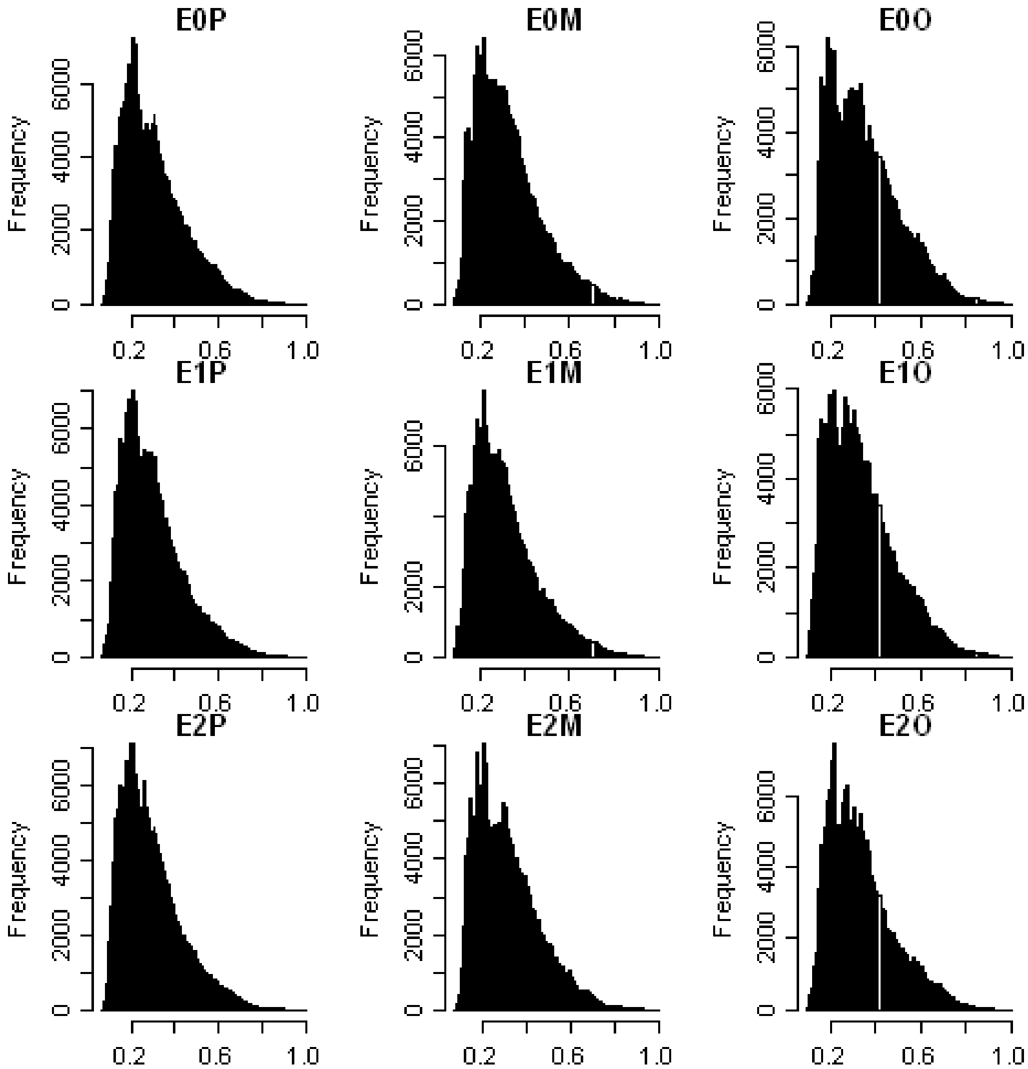


Figure B.53: Frequency histogram of fine scale relative biomass (over time) for nemipterids under enhanced management for each combination of development scenario and model specification.

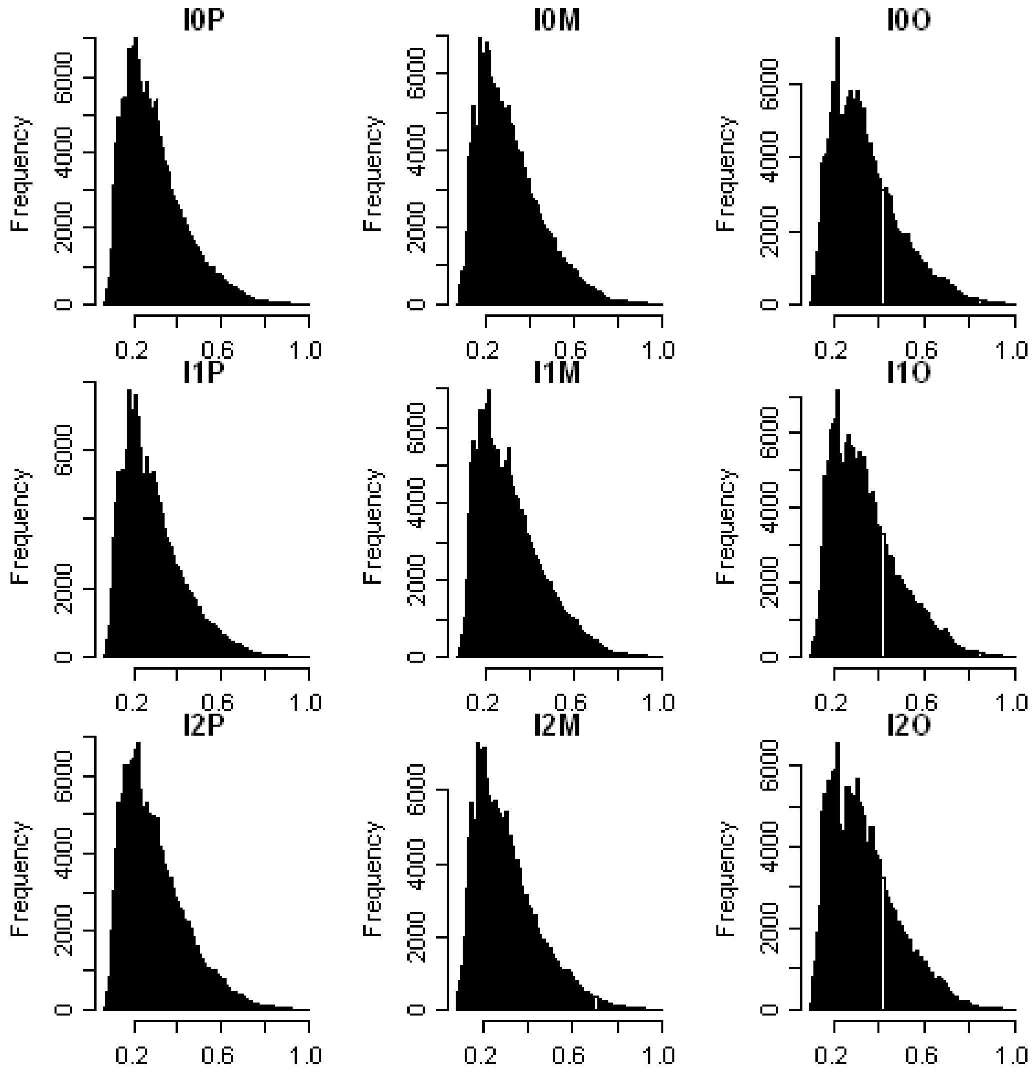


Figure B.54: Frequency histogram of fine scale relative biomass (over time) for nemipterids under integrated management for each combination of development scenario and model specification.

B.10 Saurids

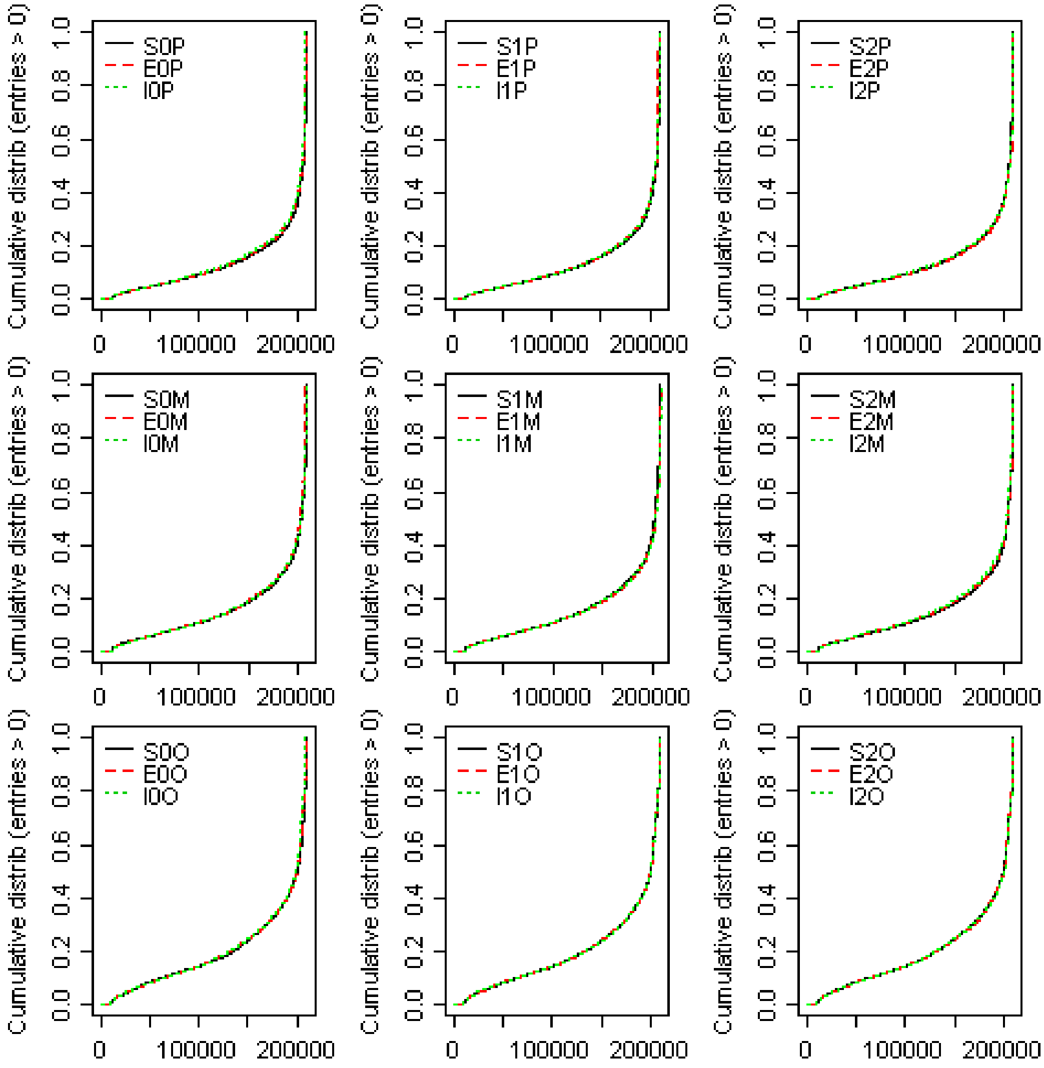


Figure B.55: Cumulative distribution plot for fine scale spatial analysis of saurids average grid-cell relative biomass, comparing management strategies (each box contains the cumulative distributions for status quo [black], enhanced [red] and integrated [green] management for a given combination of model specification and development scenario).

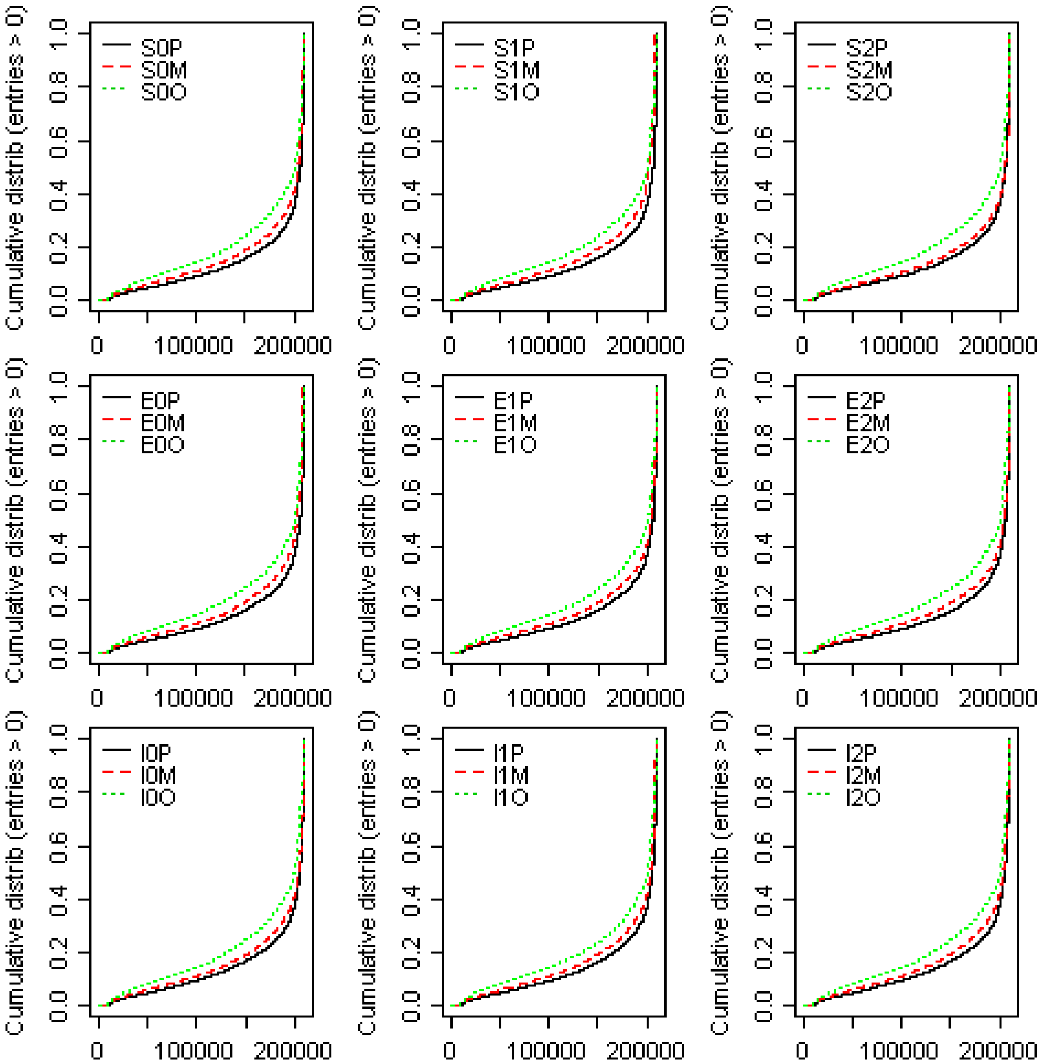


Figure B.56: Cumulative distribution plot for fine scale spatial analysis of saurids average grid-cell relative biomass, comparing model specifications (each box contains the cumulative distributions for pessimistic [black], base case [red] and optimistic [green] specifications for a given combination of management strategy and development scenario).

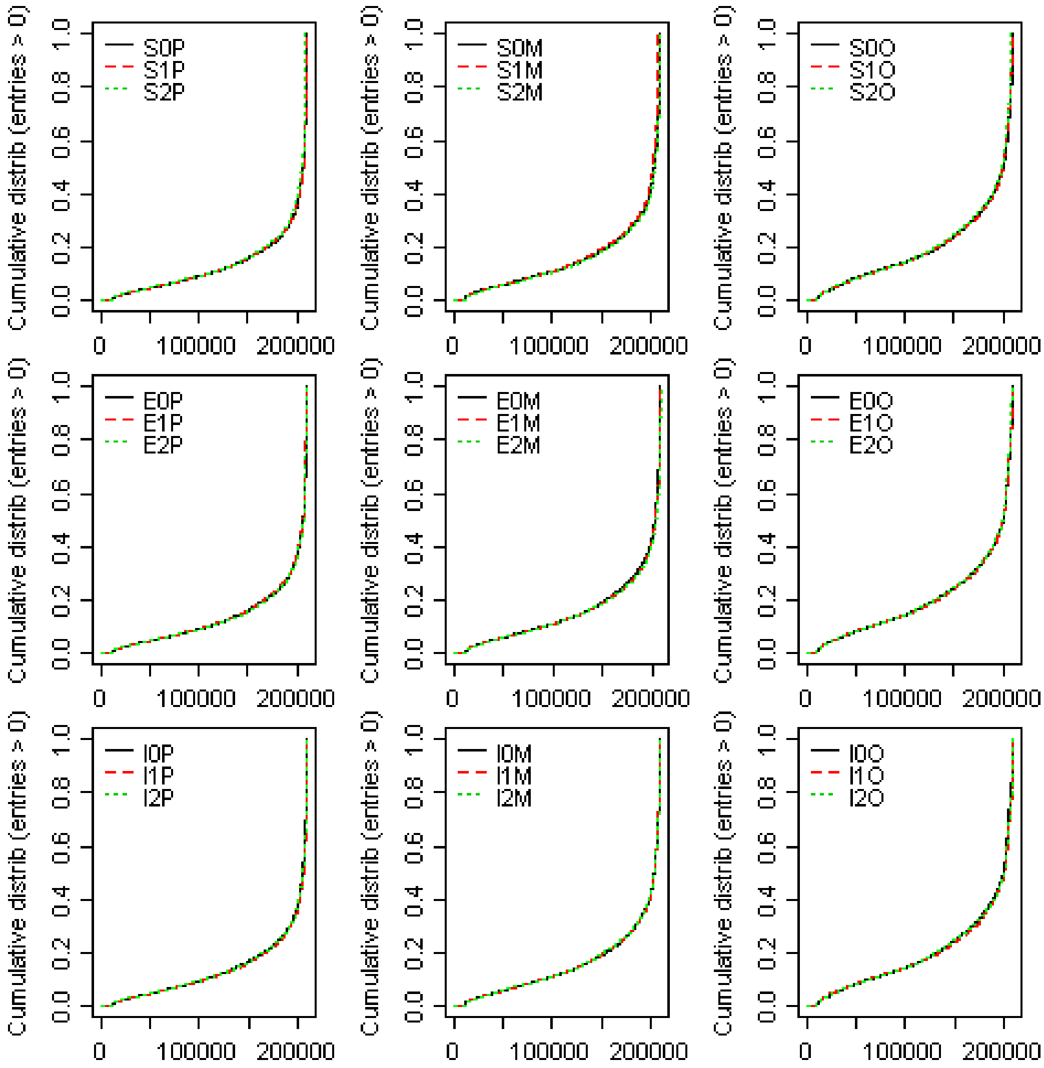


Figure B.57: Cumulative distribution plot for fine scale spatial analysis of saurids average grid-cell relative biomass, comparing development scenarios (each box contains the cumulative distributions for 0-pulse [black], 1-pulse [red] and 2-pulse [green] development scenarios for a given combination of management strategy and model specification).

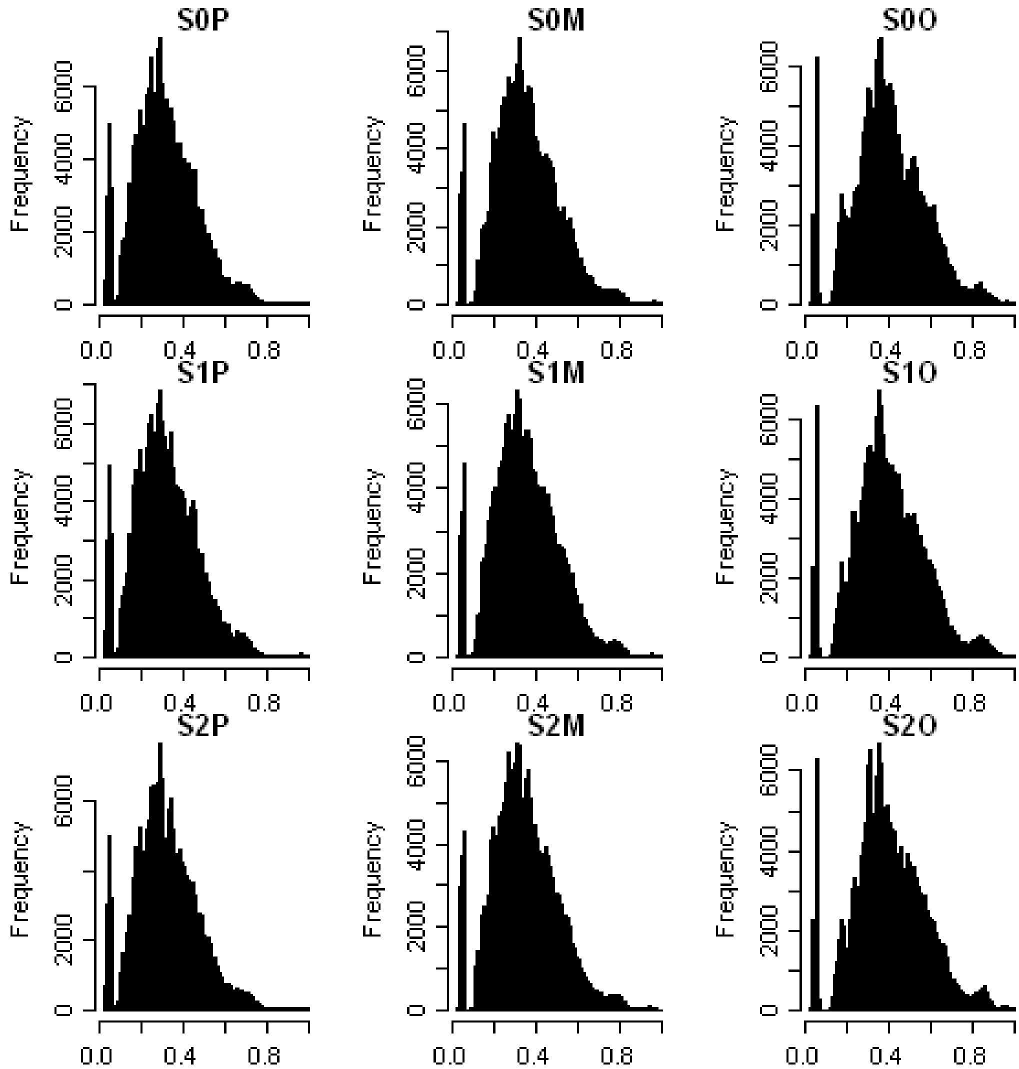


Figure B.58: Frequency histogram of fine scale relative biomass (over time) for saurids under status quo management for each combination of development scenario and model specification.

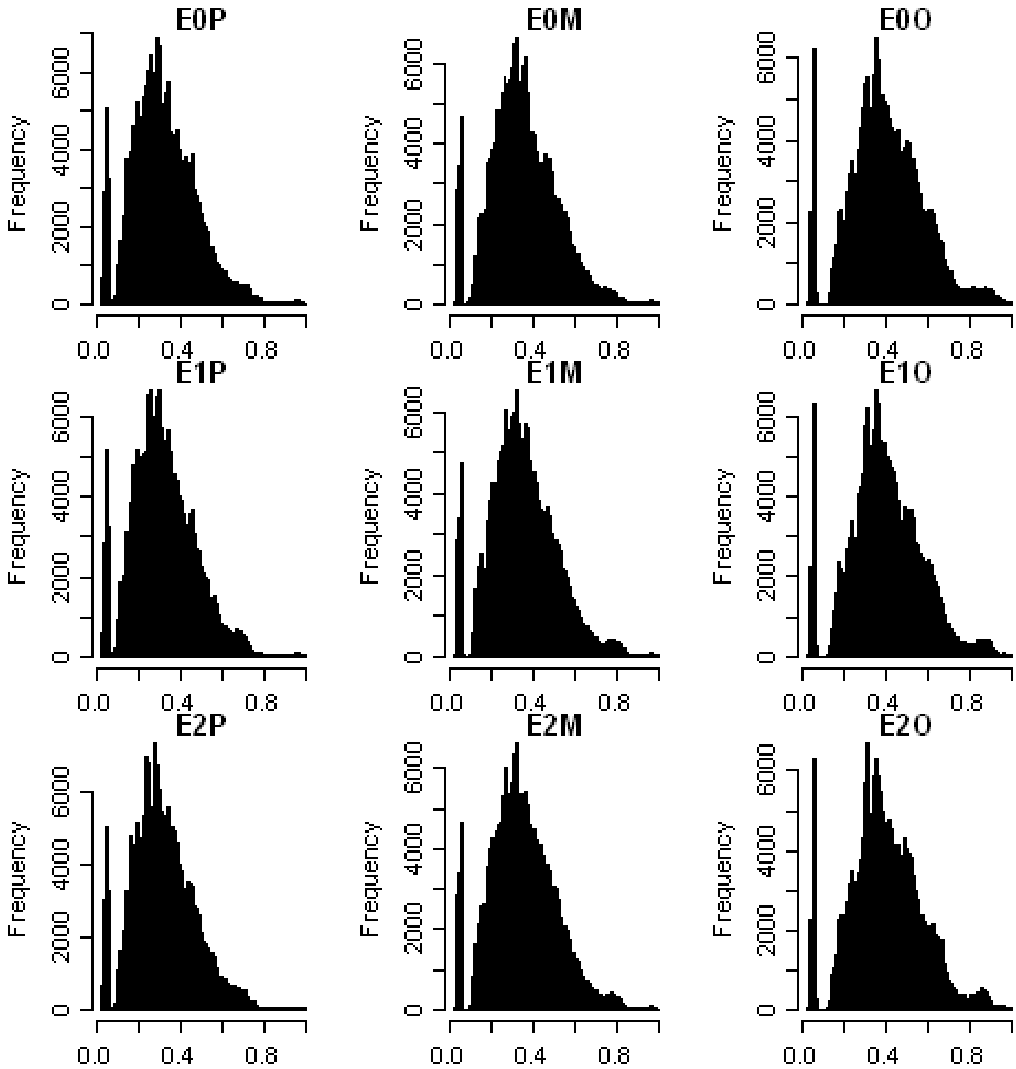


Figure B.59: Frequency histogram of fine scale relative biomass (over time) for saurids under enhanced management for each combination of development scenario and model specification.

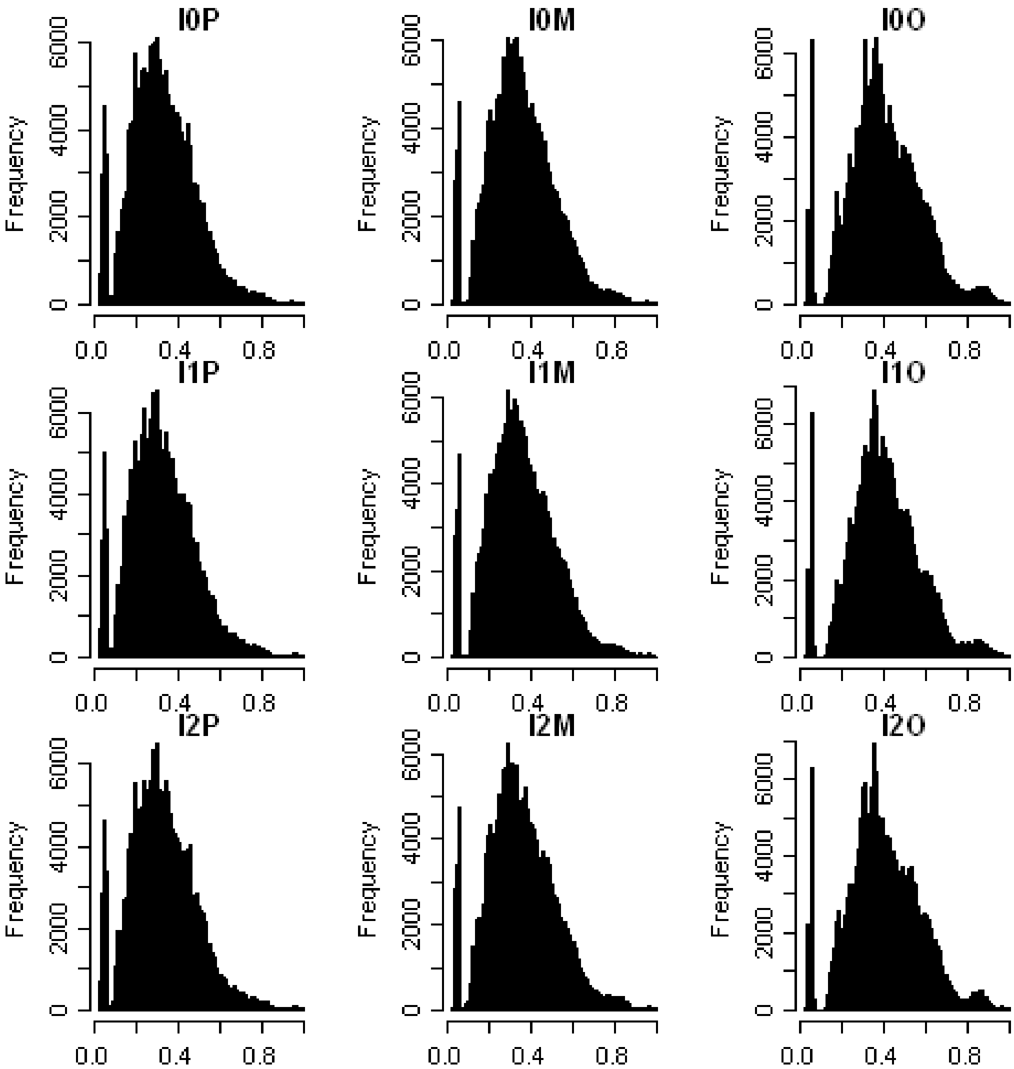


Figure B.60: Frequency histogram of fine scale relative biomass (over time) for saurids under integrated management for each combination of development scenario and model specification.

B.11 Seagrass

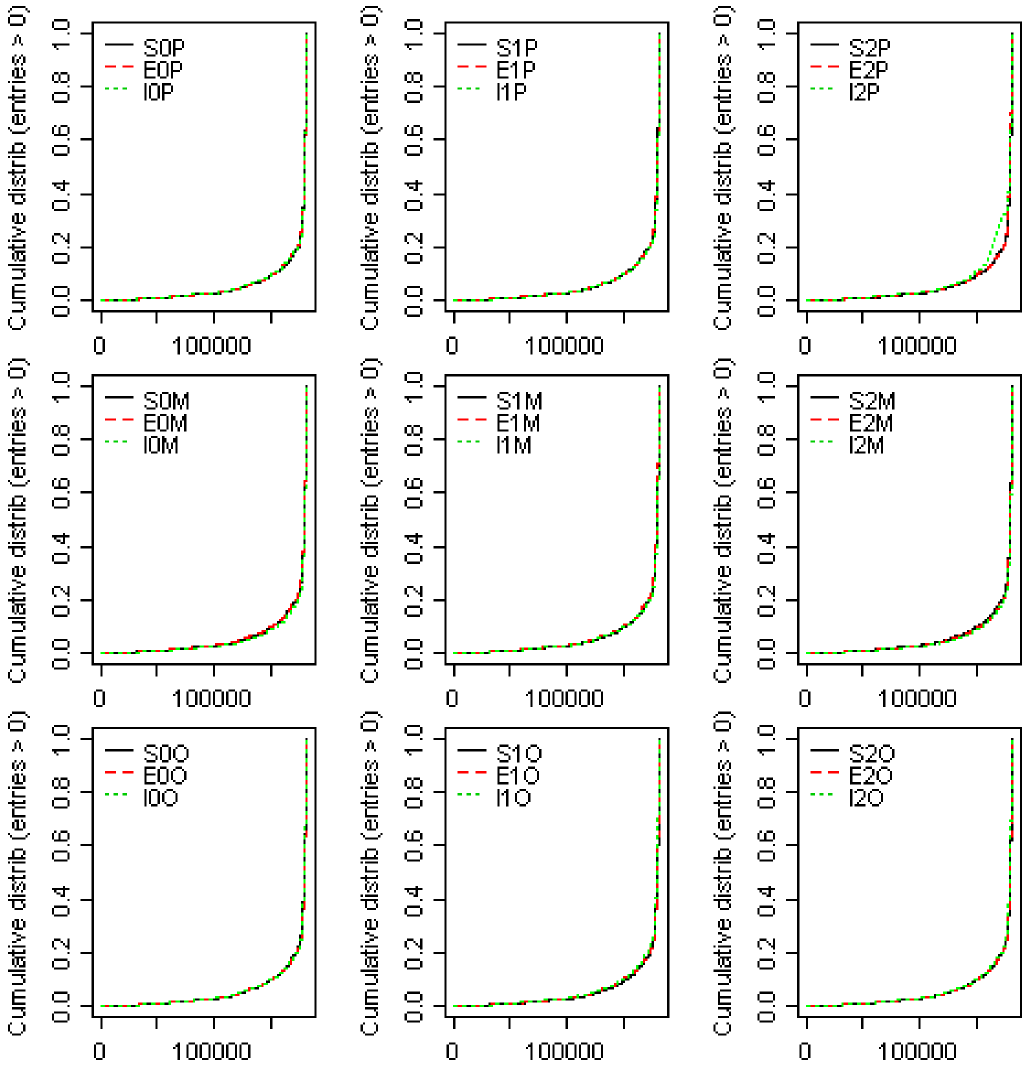


Figure B.61: Cumulative distribution plot for fine scale spatial analysis of seagrass average grid-cell relative biomass, comparing management strategies (each box contains the cumulative distributions for status quo [black], enhanced [red] and integrated [green] management for a given combination of model specification and development scenario).

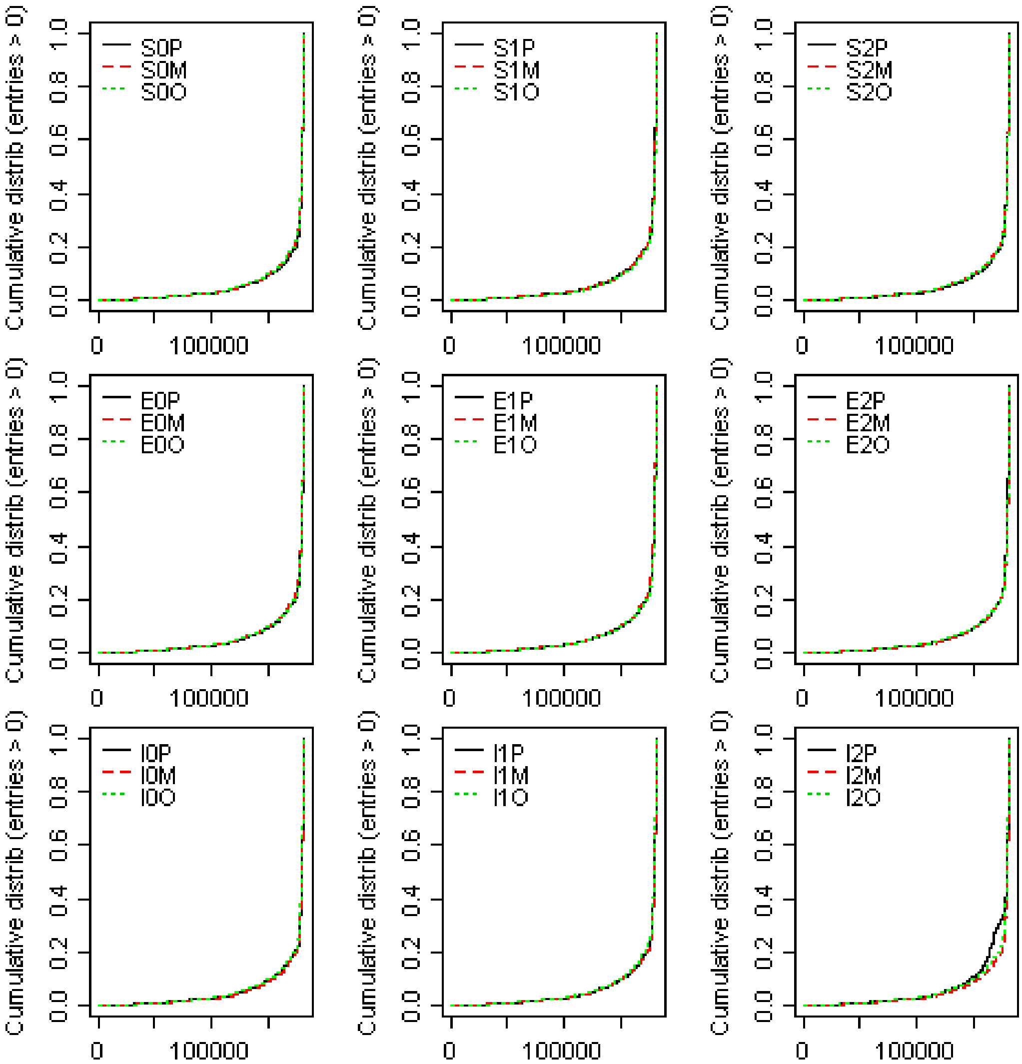


Figure B.62: Cumulative distribution plot for fine scale spatial analysis of seagrass average grid-cell relative biomass, comparing model specifications (each box contains the cumulative distributions for pessimistic [black], base case [red] and optimistic [green] specifications for a given combination of management strategy and development scenario).

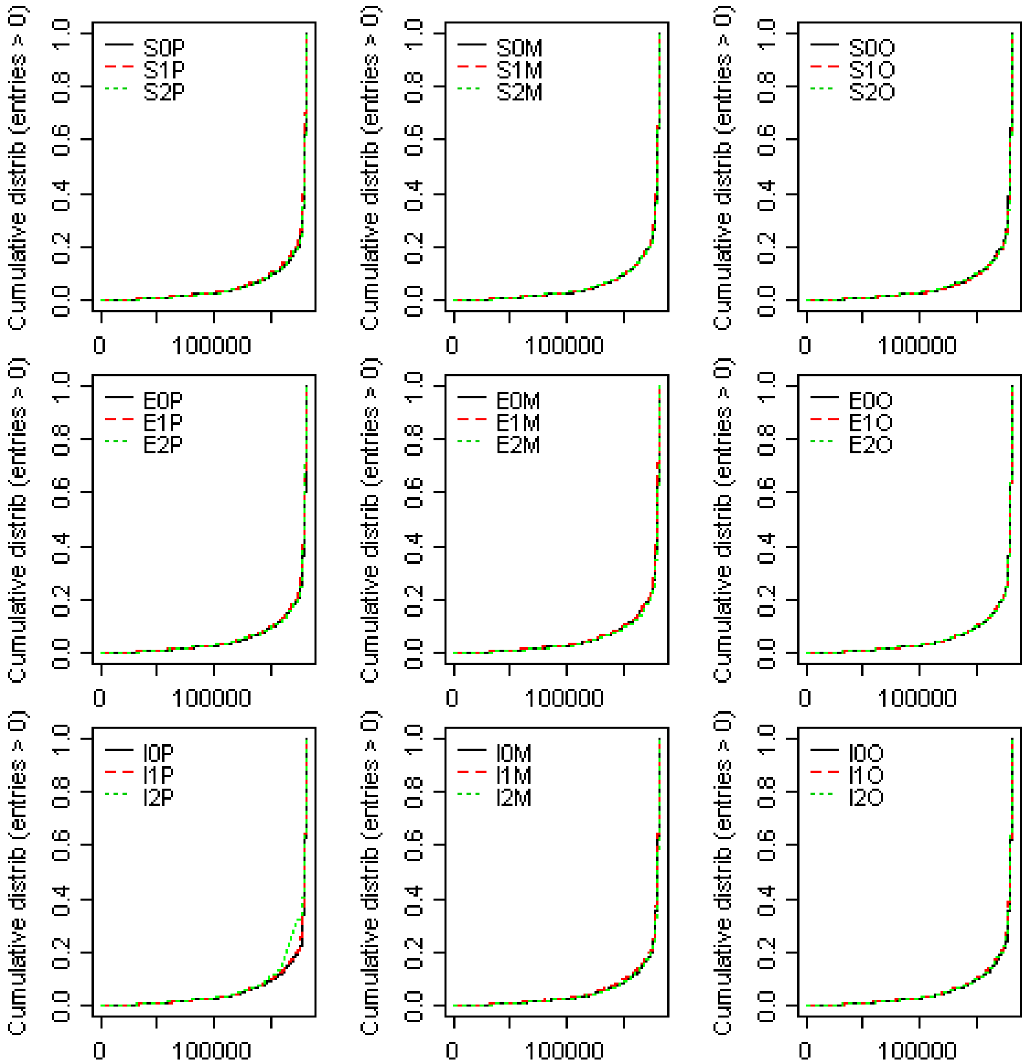


Figure B.63: Cumulative distribution plot for fine scale spatial analysis of seagrass average grid-cell relative biomass, comparing development scenarios (each box contains the cumulative distributions for 0-pulse [black], 1-pulse [red] and 2-pulse [green] development scenarios for a given combination of management strategy and model specification).

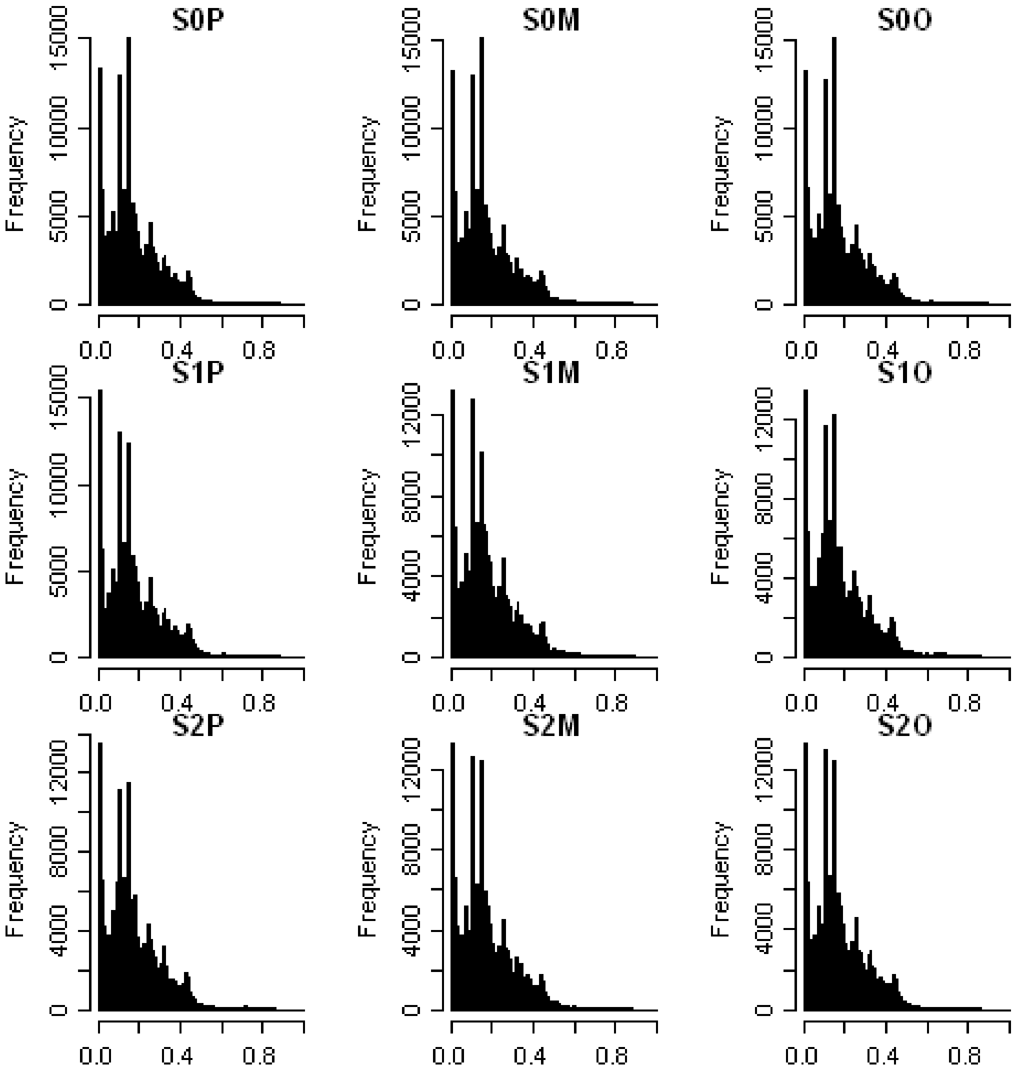


Figure B.64: Frequency histogram of fine scale relative biomass (over time) for seagrass under status quo management for each combination of development scenario and model specification.

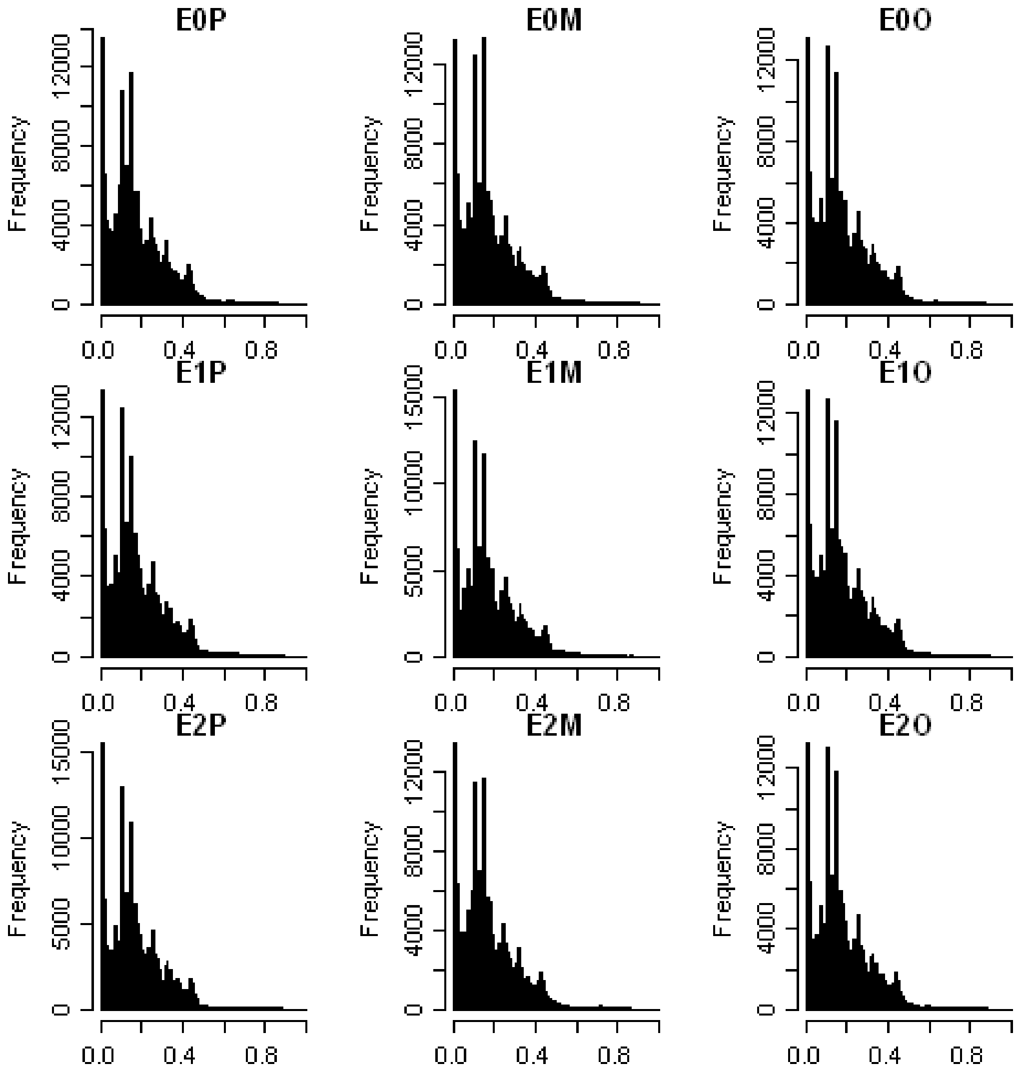


Figure B.65: Frequency histogram of fine scale relative biomass (over time) for seagrass under enhanced management for each combination of development scenario and model specification.

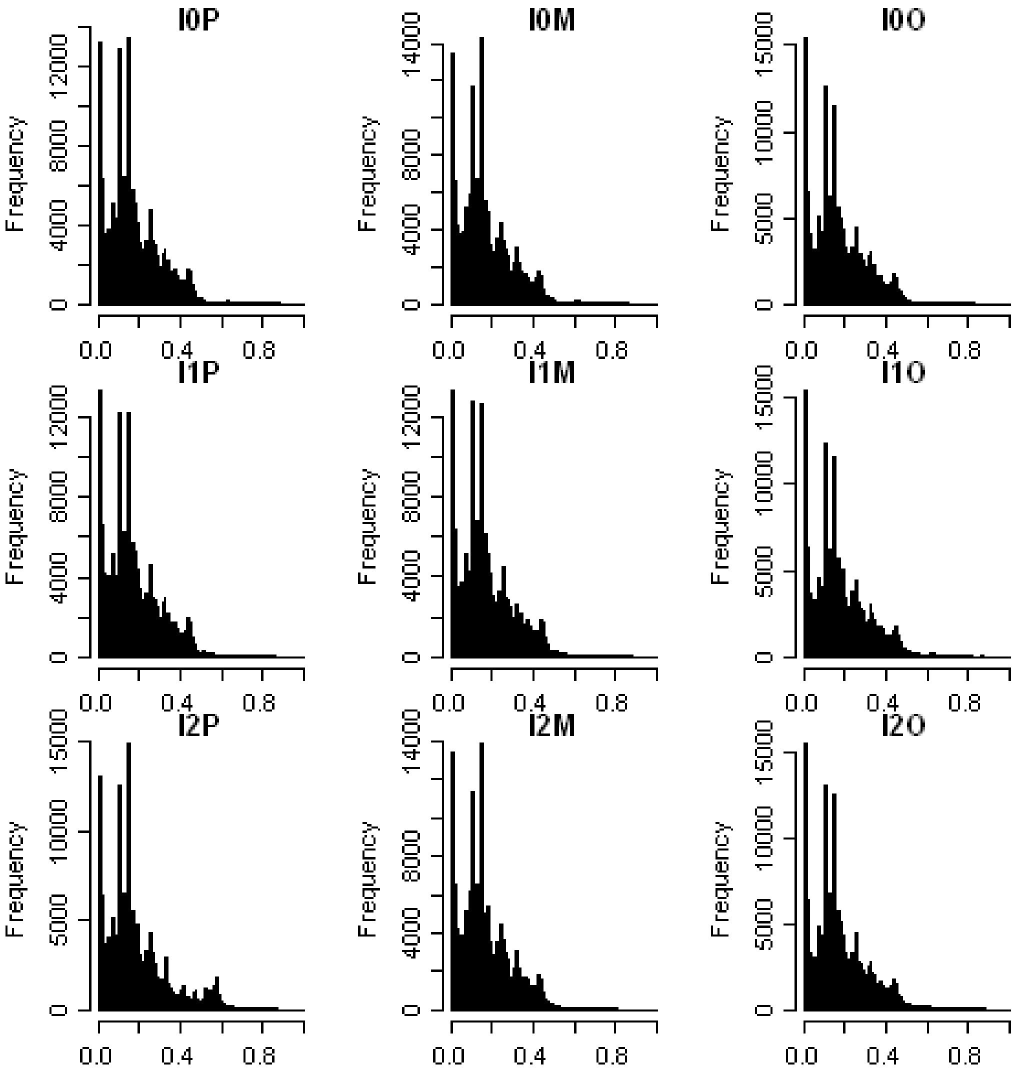


Figure B.66: Frequency histogram of fine scale relative biomass (over time) for seagrass under integrated management for each combination of development scenario and model specification.

B.12 Sponge and reefs

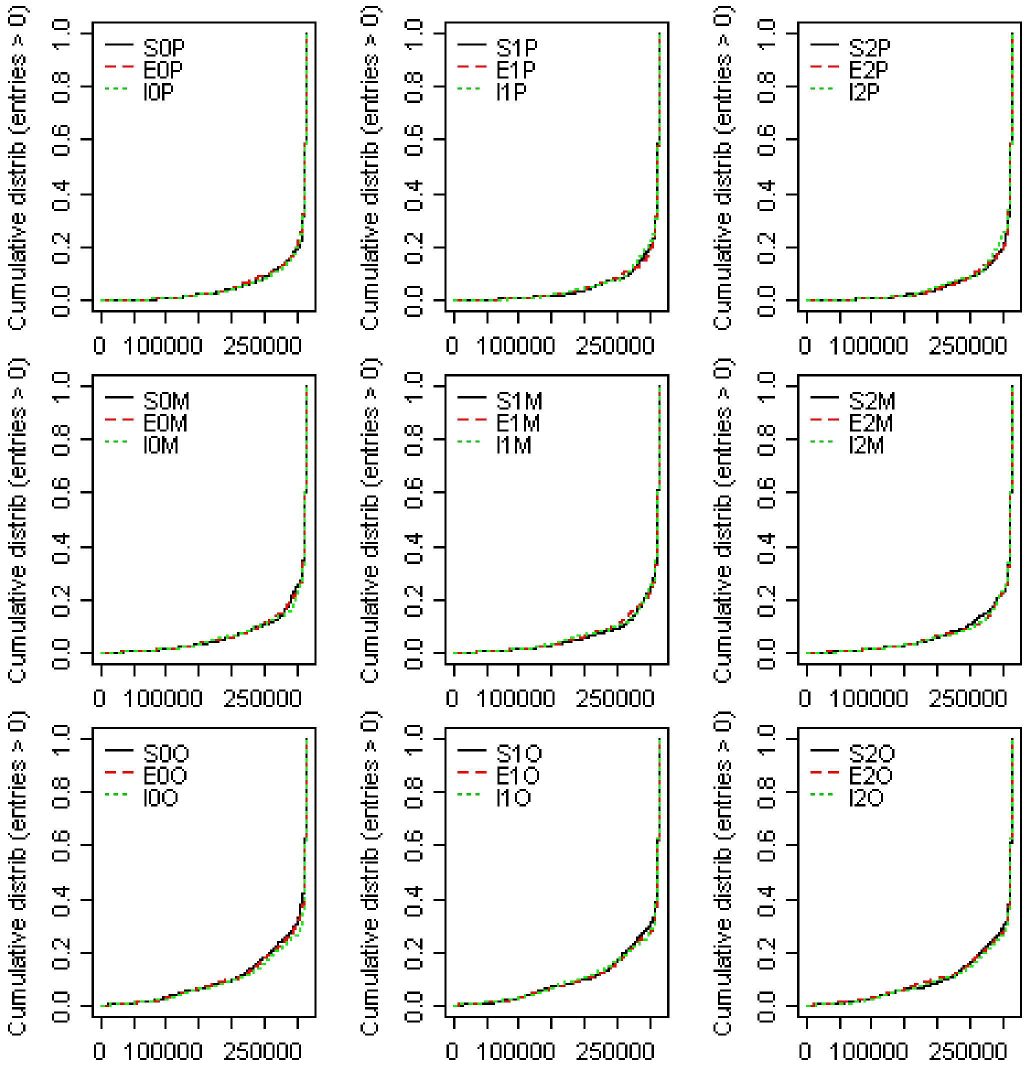


Figure B.67: Cumulative distribution plot for fine scale spatial analysis of sponge and reef habitat average grid-cell relative biomass, comparing management strategies (each box contains the cumulative distributions for status quo [black], enhanced [red] and integrated [green] management for a given combination of model specification and development scenario).

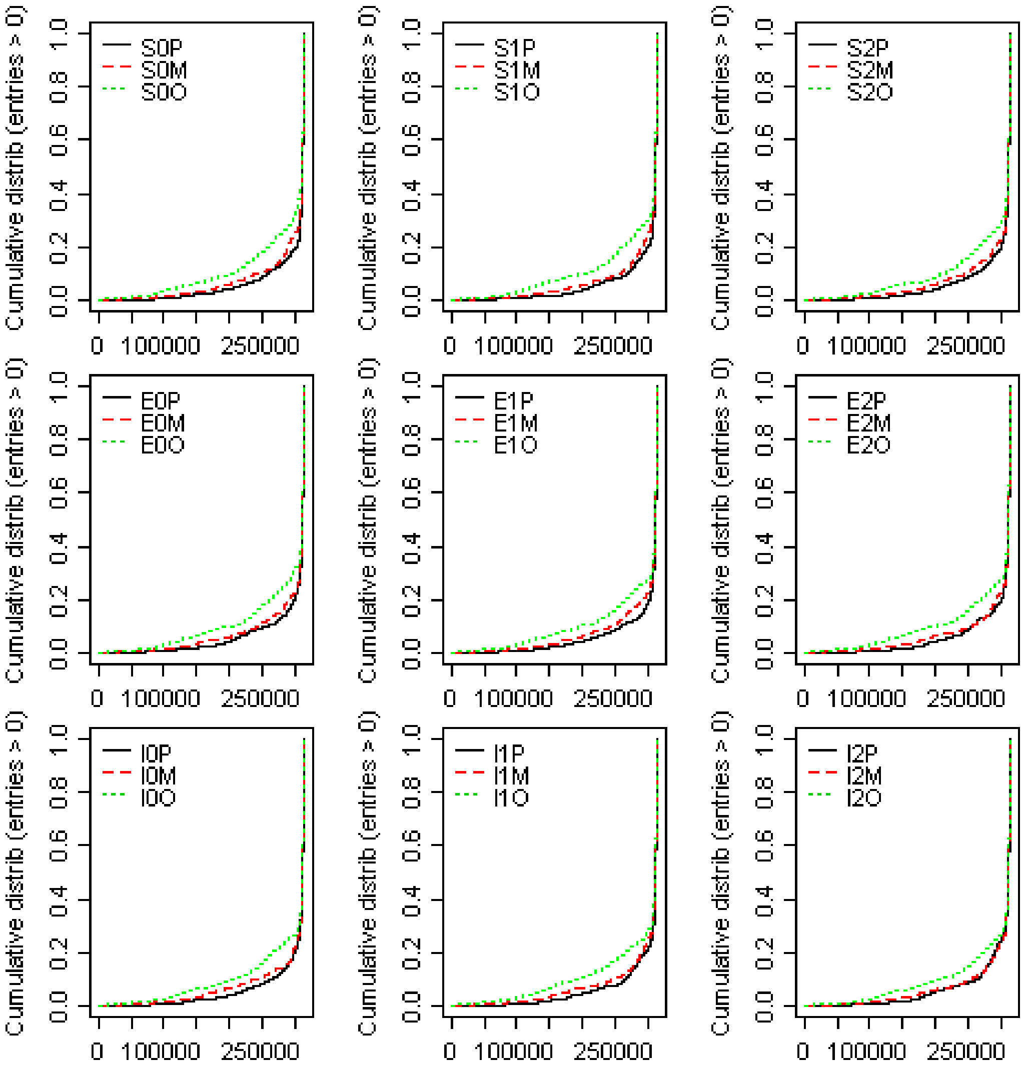


Figure B.68: Cumulative distribution plot for fine scale spatial analysis of sponge and reef habitat average grid-cell relative biomass, comparing model specifications (each box contains the cumulative distributions for pessimistic [black], base case [red] and optimistic [green] specifications for a given combination of management strategy and development scenario).

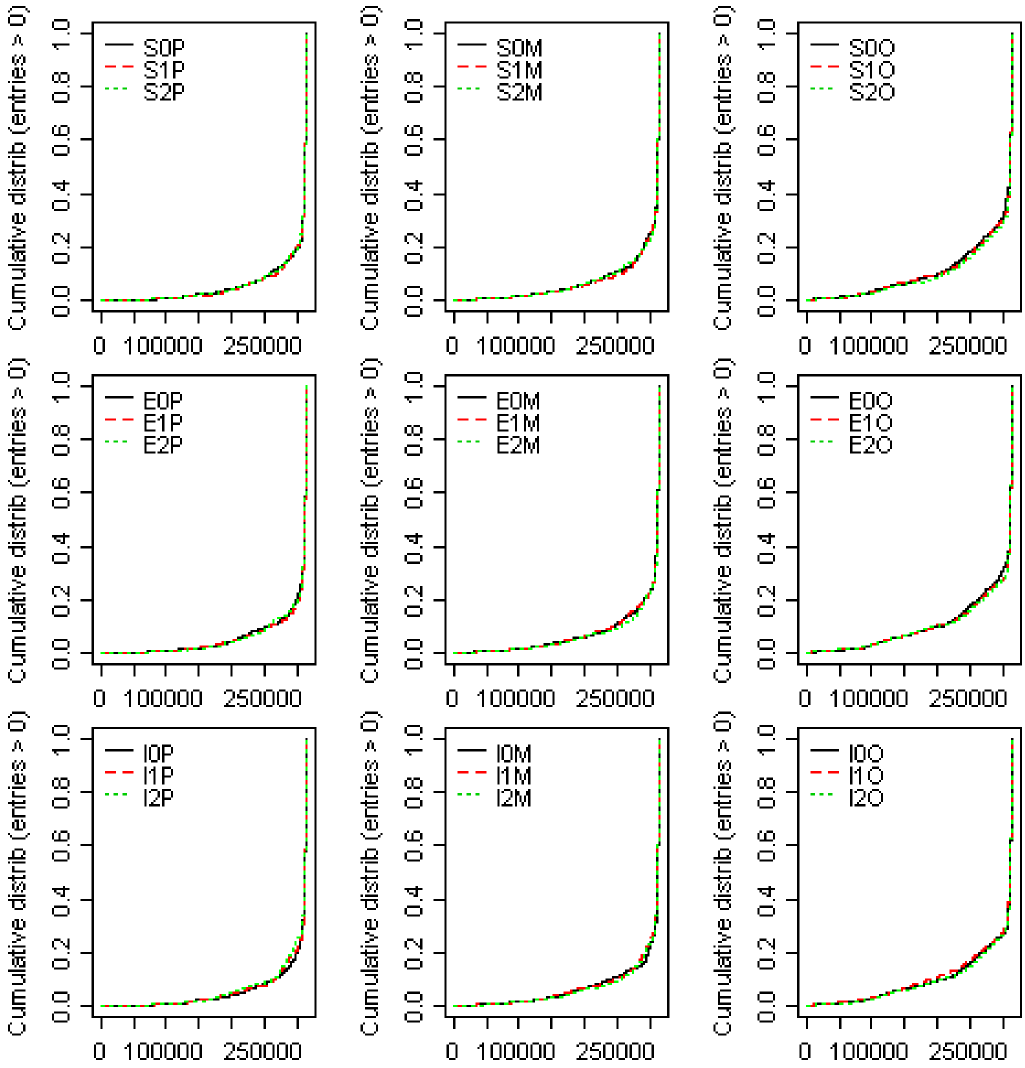


Figure B.69: Cumulative distribution plot for fine scale spatial analysis of sponge and reef habitat average grid-cell relative biomass, comparing development scenarios (each box contains the cumulative distributions for 0-pulse [black], 1-pulse [red] and 2-pulse [green] development scenarios for a given combination of management strategy and model specification).

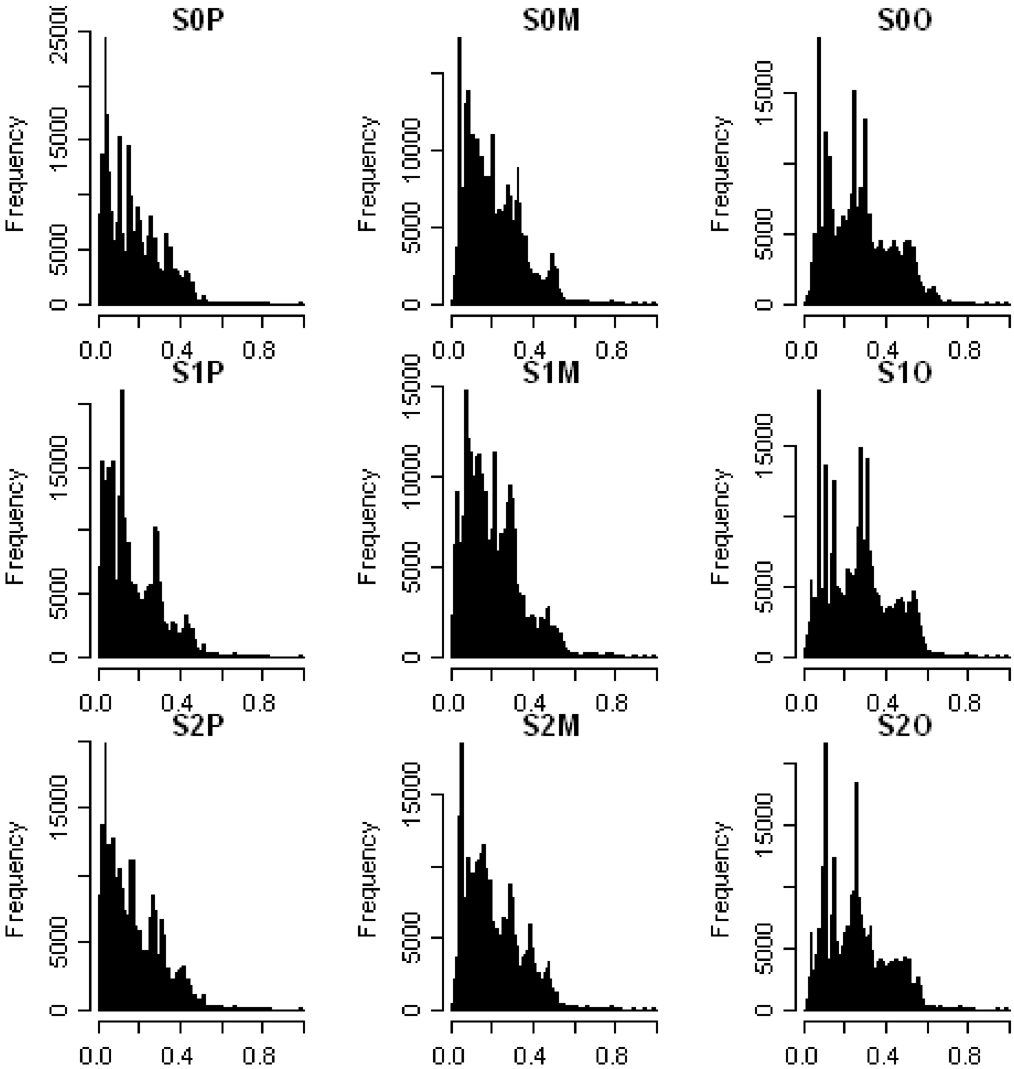


Figure B.70: Frequency histogram of fine scale relative biomass (over time) for sponge and reef habitats under status quo management for each combination of development scenario and model specification.

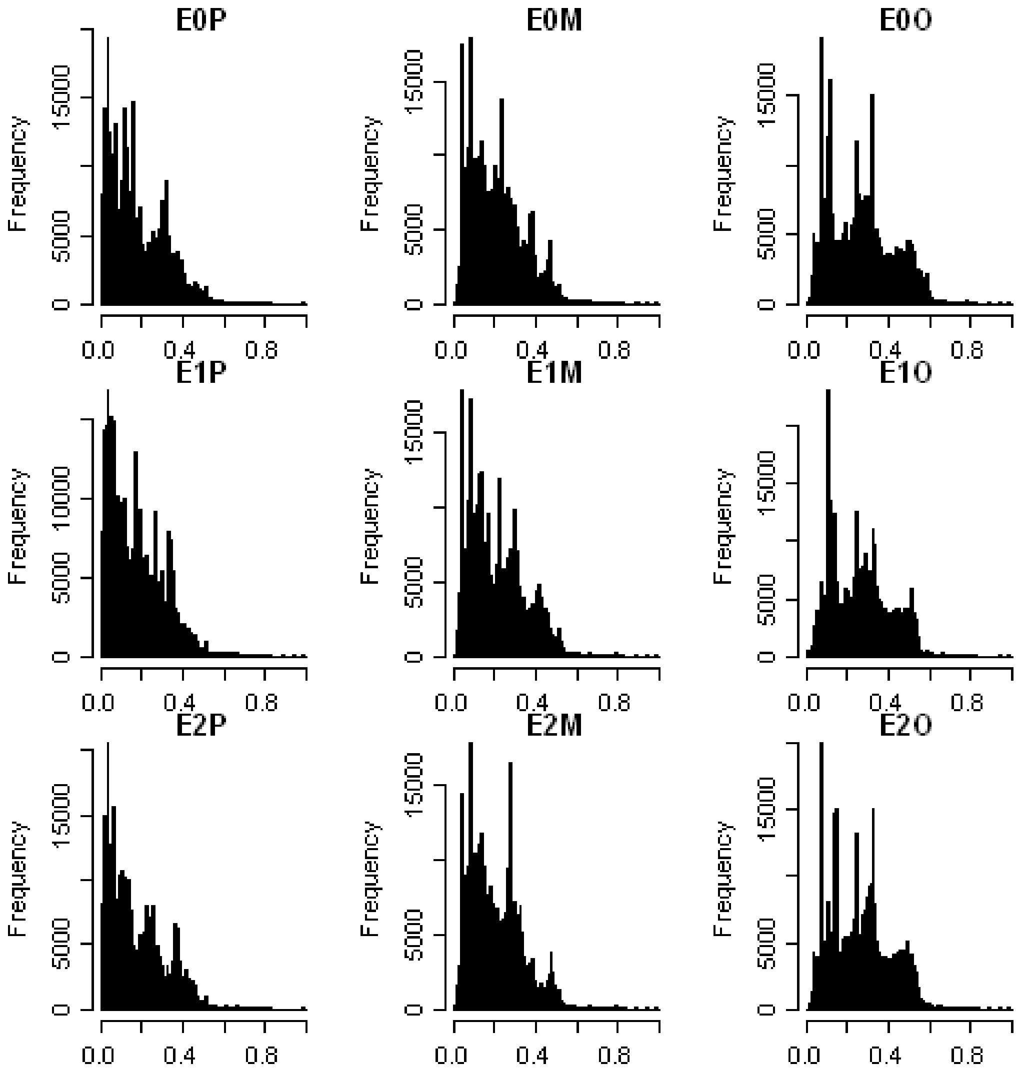


Figure B.71: Frequency histogram of fine scale relative biomass (over time) for sponge and reef habitats under enhanced management for each combination of development scenario and model specification.

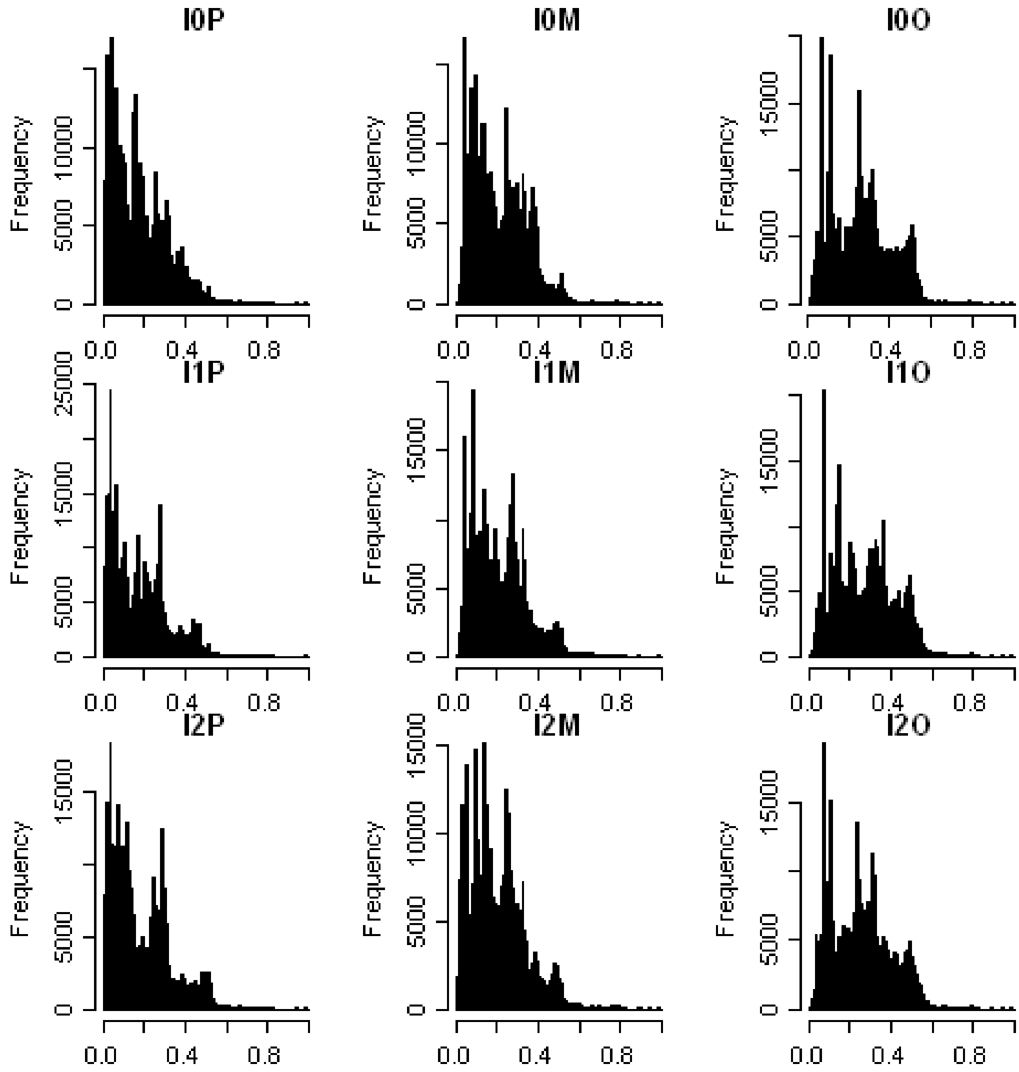


Figure B.72: Frequency histogram of fine scale relative biomass (over time) for sponge and reef habitats under integrated management for each combination of development scenario and model specification.

B.13 Mangroves

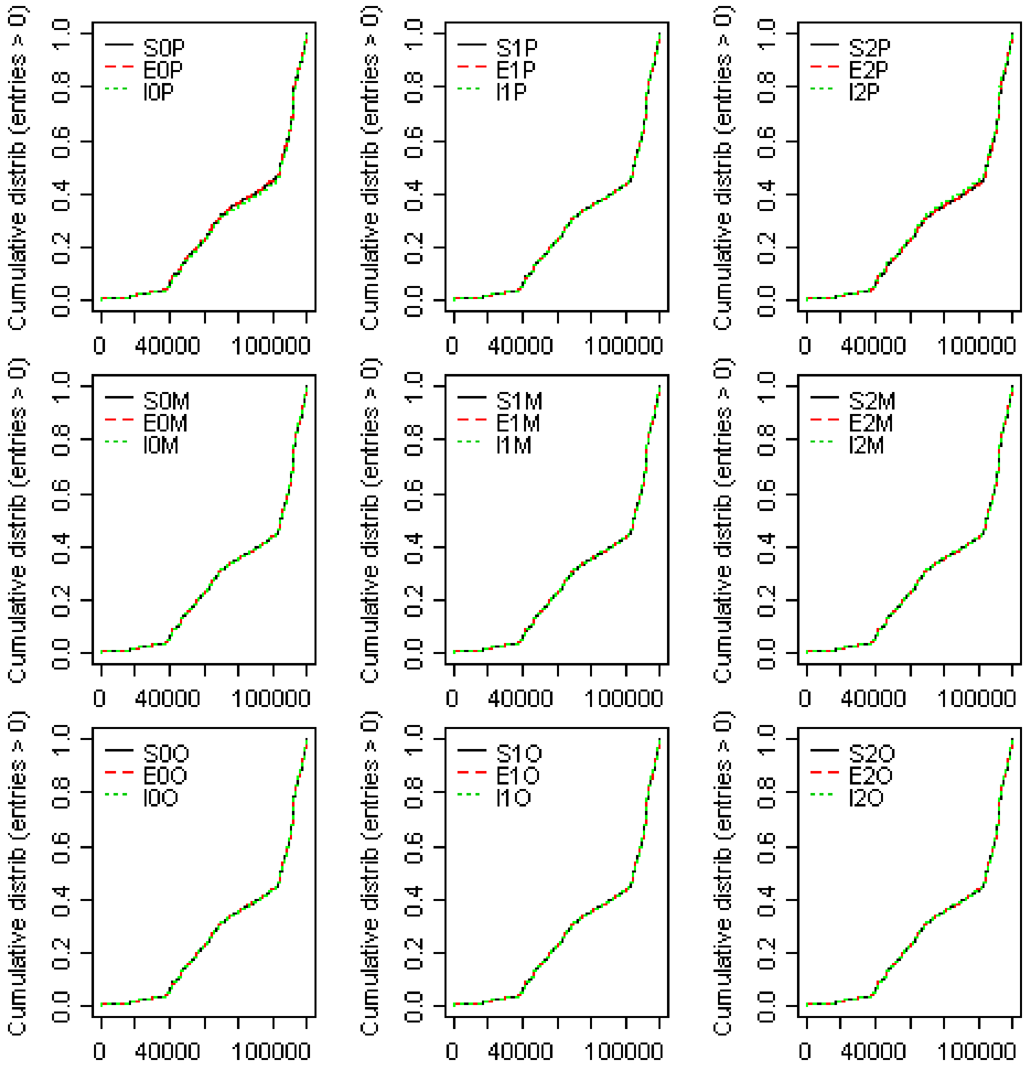


Figure B.73: Cumulative distribution plot for fine scale spatial analysis of mangroves average grid-cell relative biomass, comparing management strategies (each box contains the cumulative distributions for status quo [black], enhanced [red] and integrated [green] management for a given combination of model specification and development scenario).

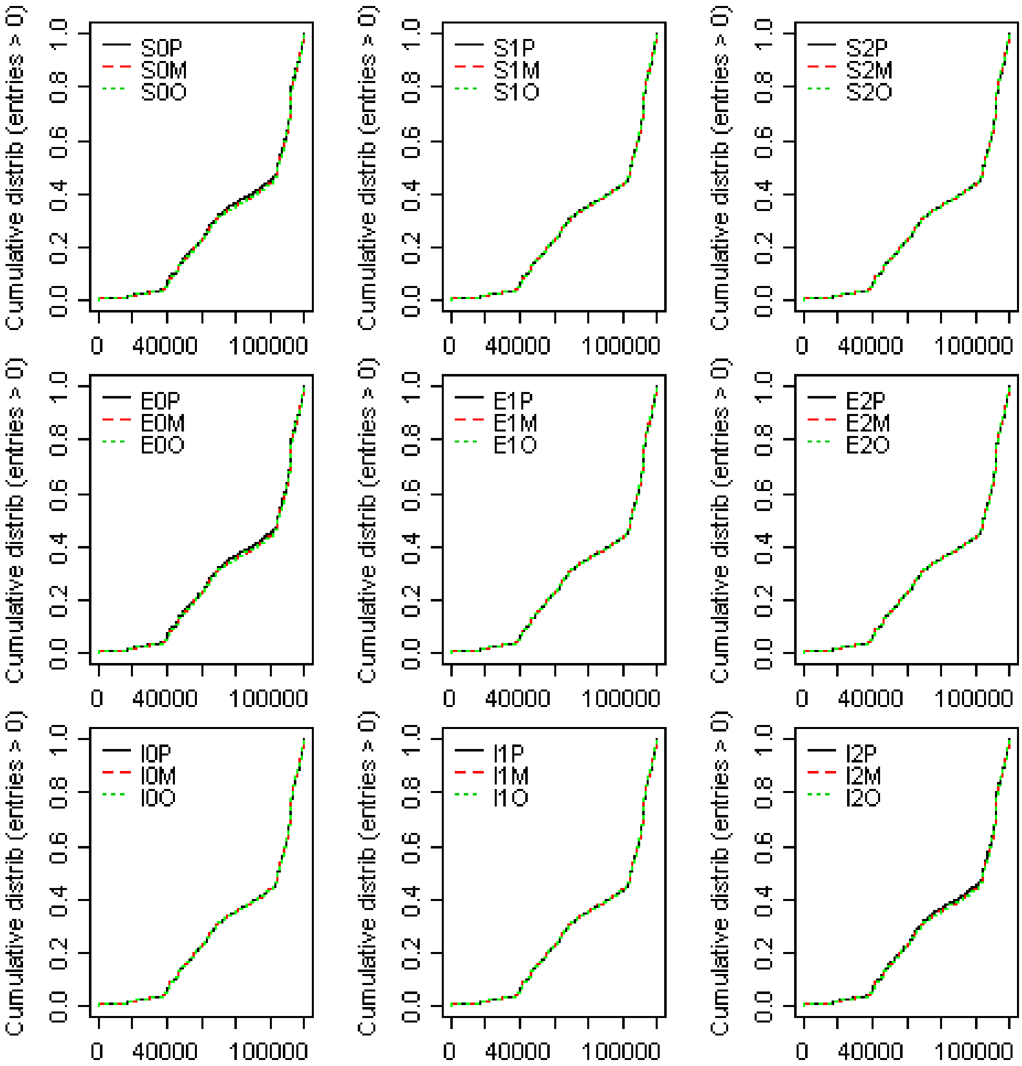


Figure B.74: Cumulative distribution plot for fine scale spatial analysis of mangroves average grid-cell relative biomass, comparing model specifications (each box contains the cumulative distributions for pessimistic [black], base case [red] and optimistic [green] specifications for a given combination of management strategy and development scenario).

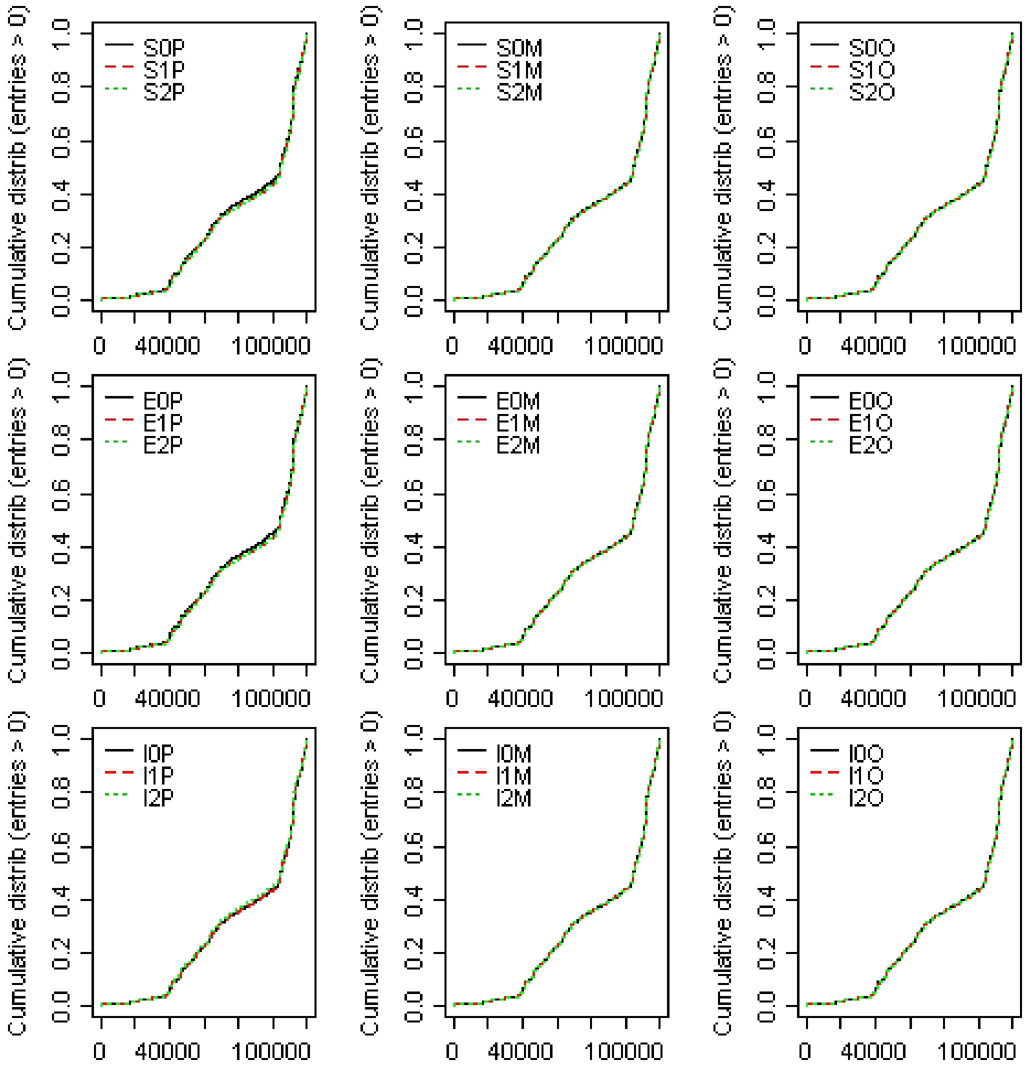


Figure B.75: Cumulative distribution plot for fine scale spatial analysis of mangroves average grid-cell relative biomass, comparing development scenarios (each box contains the cumulative distributions for 0-pulse [black], 1-pulse [red] and 2-pulse [green] development scenarios for a given combination of management strategy and model specification).

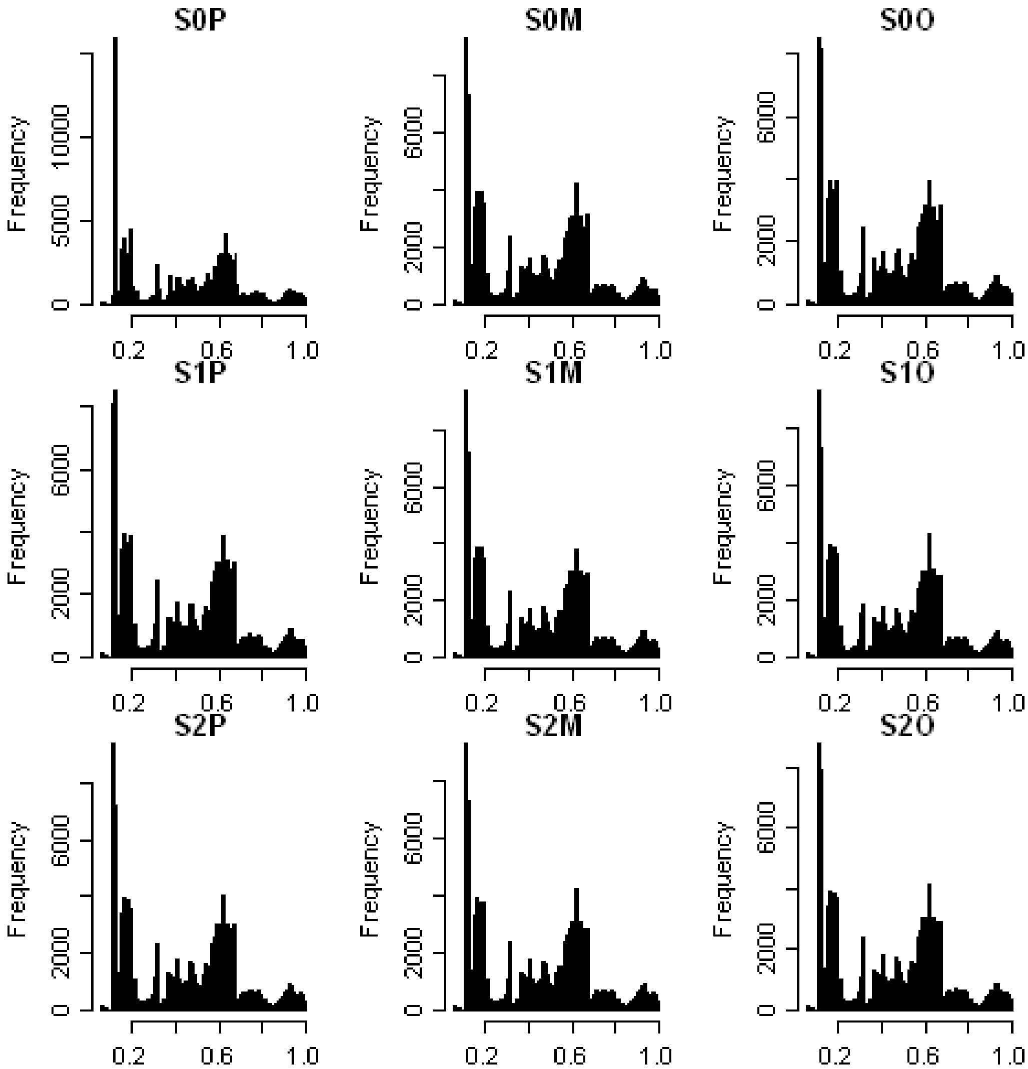


Figure B.76: Frequency histogram of fine scale relative biomass (over time) for mangroves under status quo management for each combination of development scenario and model specification.

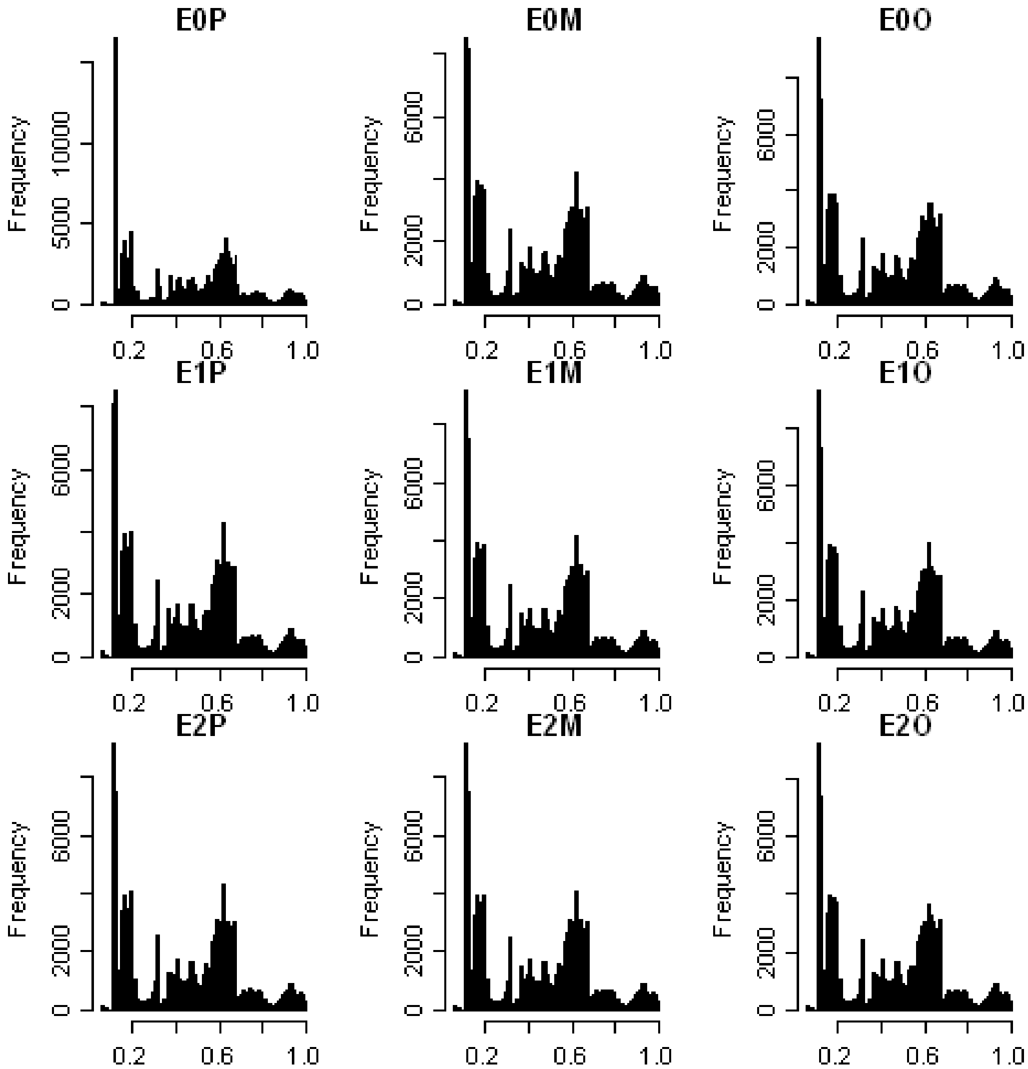


Figure B.77: Frequency histogram of fine scale relative biomass (over time) for mangroves under enhanced management for each combination of development scenario and model specification.

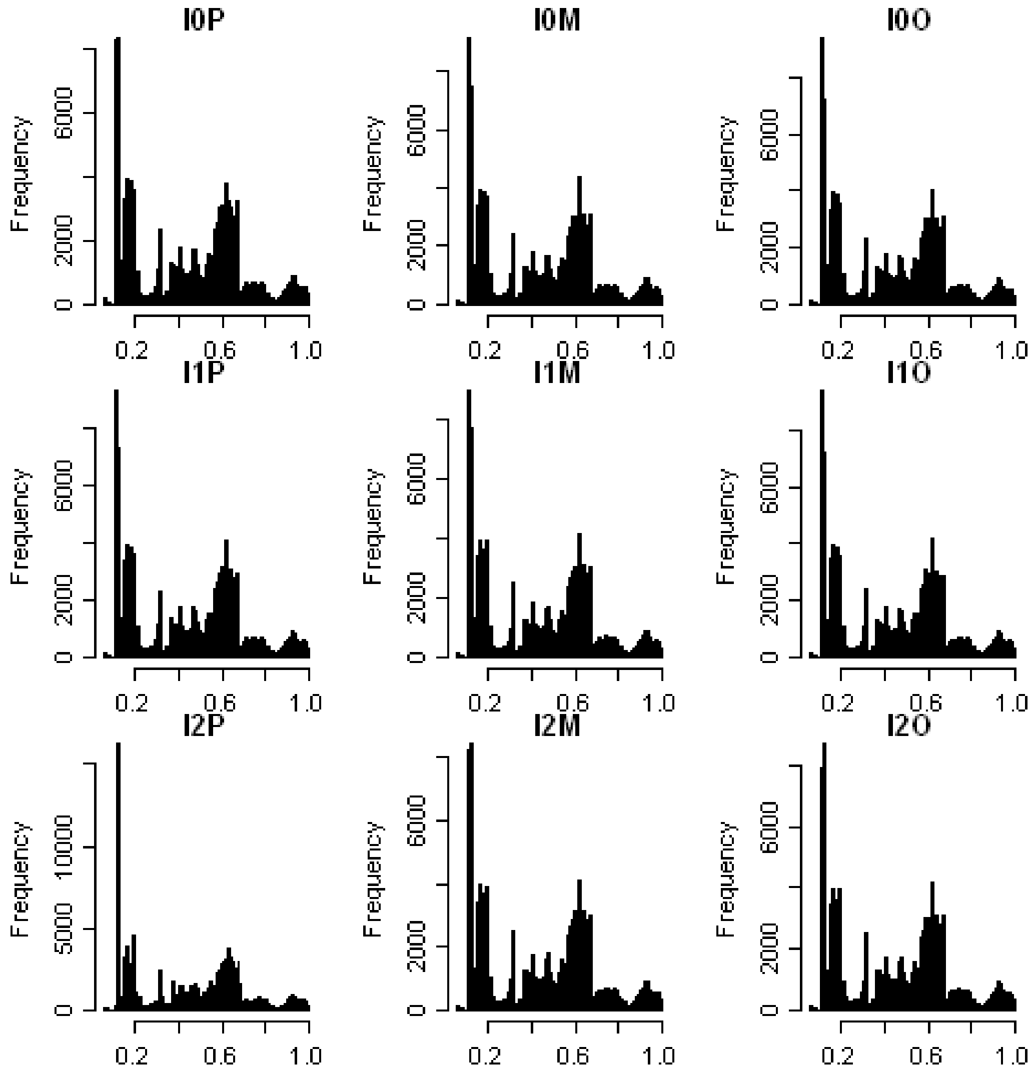


Figure B.78: Frequency histogram of fine scale relative biomass (over time) for mangroves under integrated management for each combination of development scenario and model specification.

APPENDIX C: CLUSTER ANALYSIS DENDROGRAMS

C.1 Pessimistic system state trees

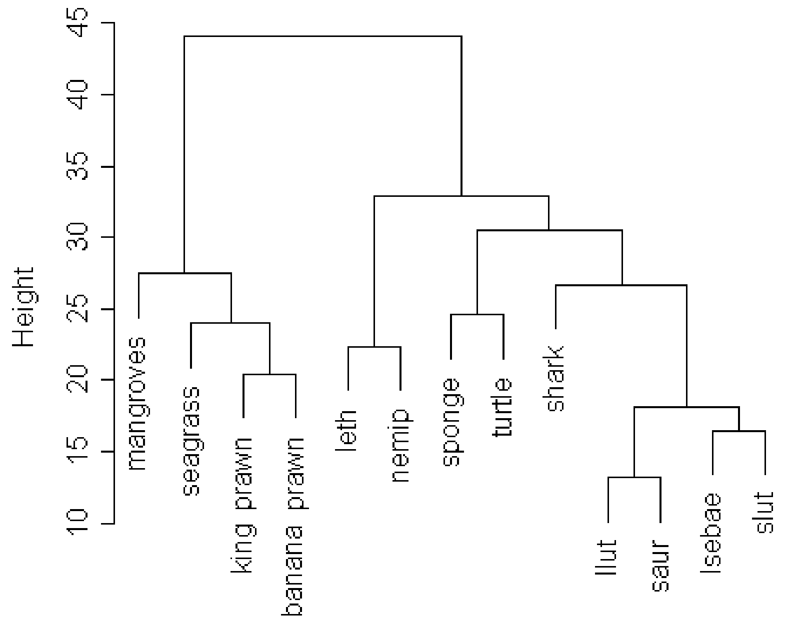


Figure C.1: Dendrogram for the cluster analysis of the relative spatial biomasses in the status quo management, 0-pulse development, pessimistic model specification case.

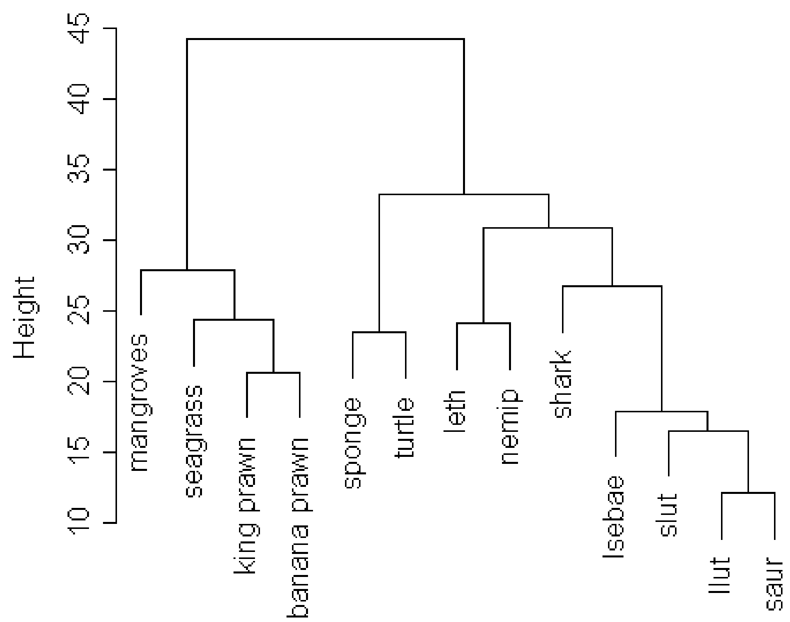


Figure C.2: Dendrogram for the cluster analysis of the relative spatial biomasses in the status quo management, 2-pulse development, pessimistic model specification case.

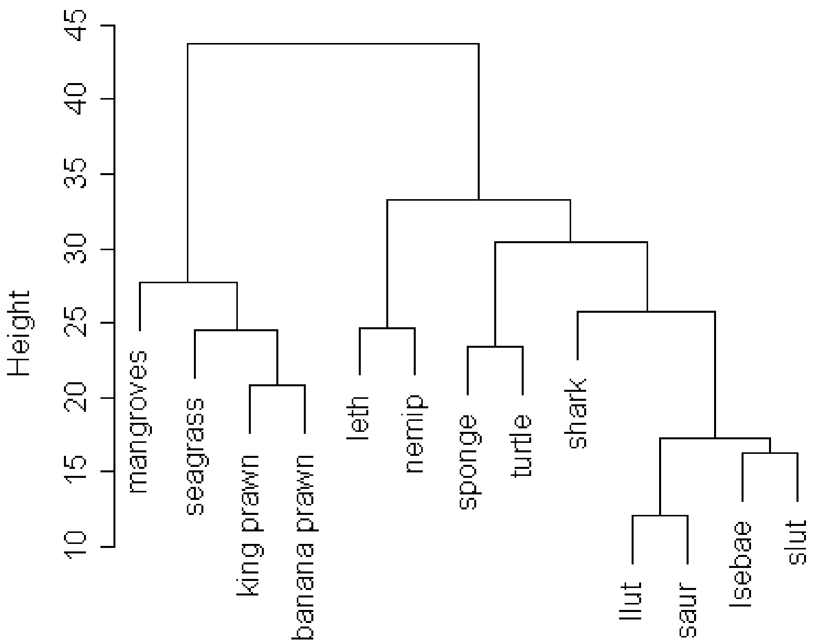


Figure C.3: Dendrogram for the cluster analysis of the relative spatial biomasses in the enhanced management, 2-pulse development, pessimistic model specification case.

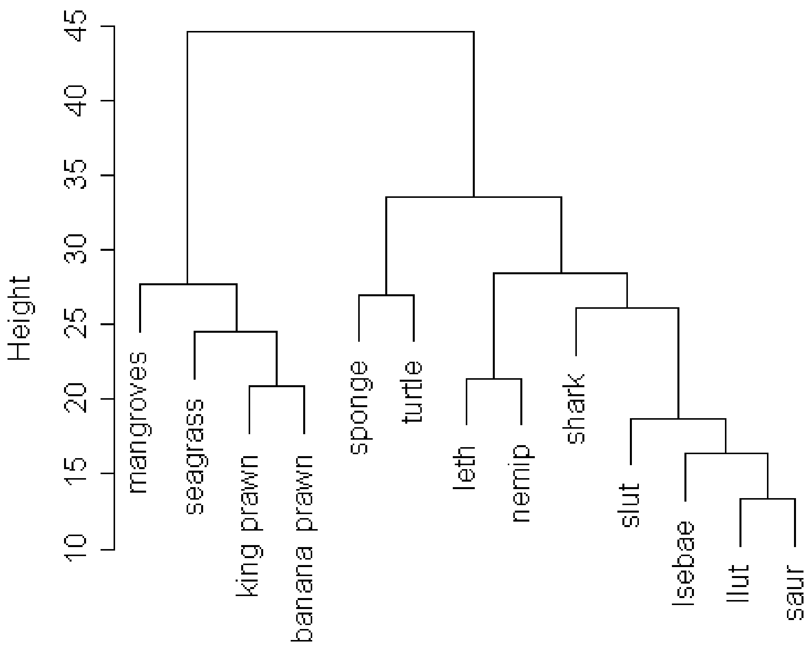


Figure C.4: Dendrogram for the cluster analysis of the relative spatial biomasses in the integrated management, 0-pulse development, pessimistic model specification case.

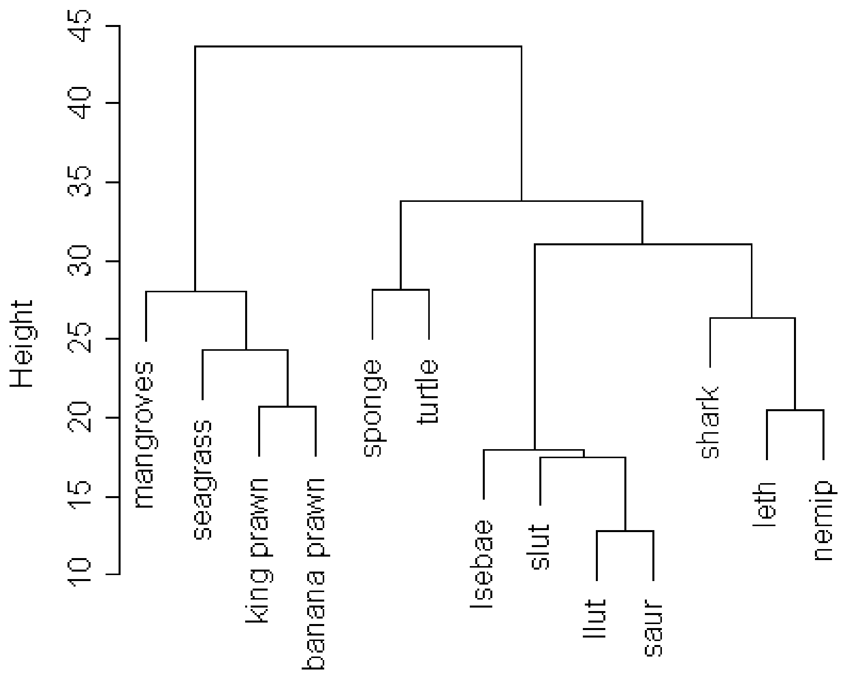


Figure C.5: Dendrogram for the cluster analysis of the relative spatial biomasses in the integrated management, 1-pulse development, pessimistic model specification case

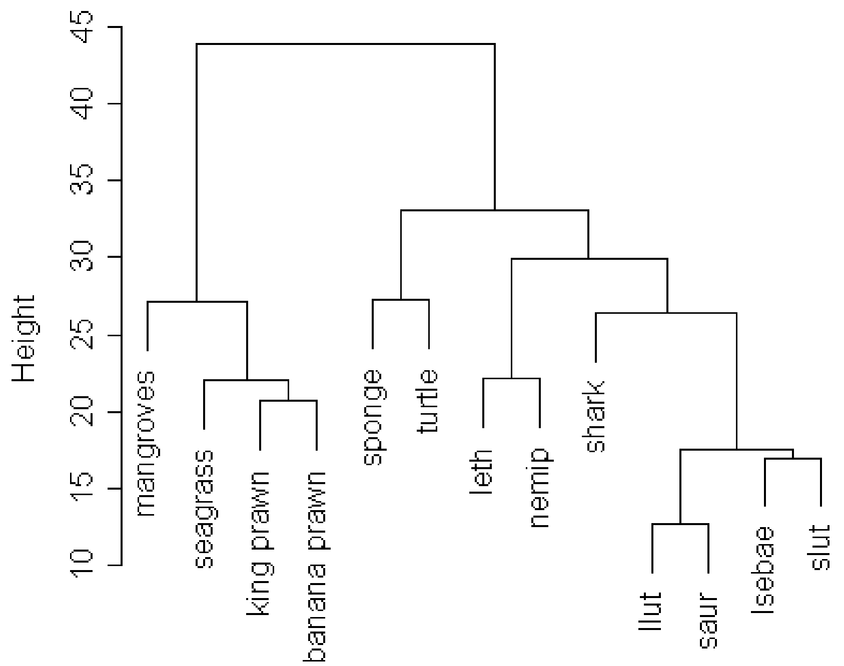


Figure C.6: Dendrogram for the cluster analysis of the relative spatial biomasses in the integrated management, 2-pulse development, pessimistic model specification case.

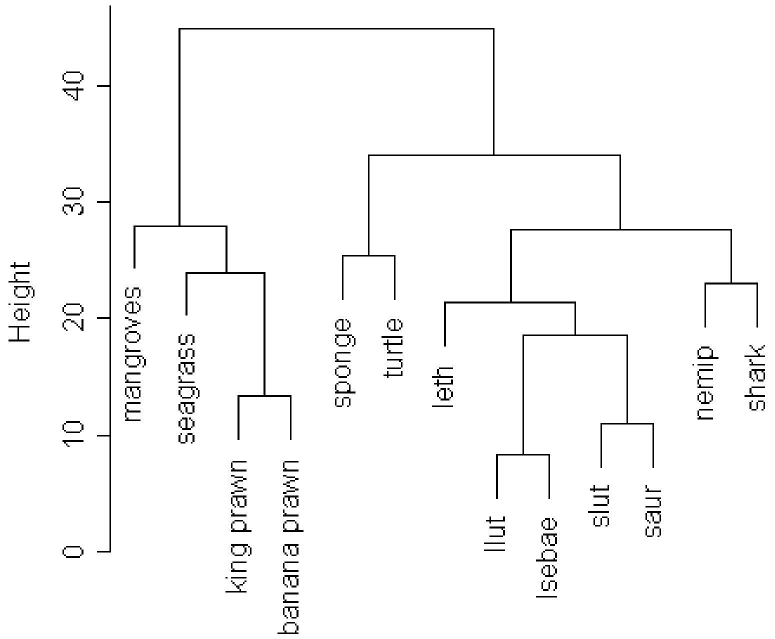


Figure C.7: Dendrogram for the cluster analysis of the relative spatial biomasses in the enhanced management, 1-pulse development, base case model specification case

C.2 Optimistic system state

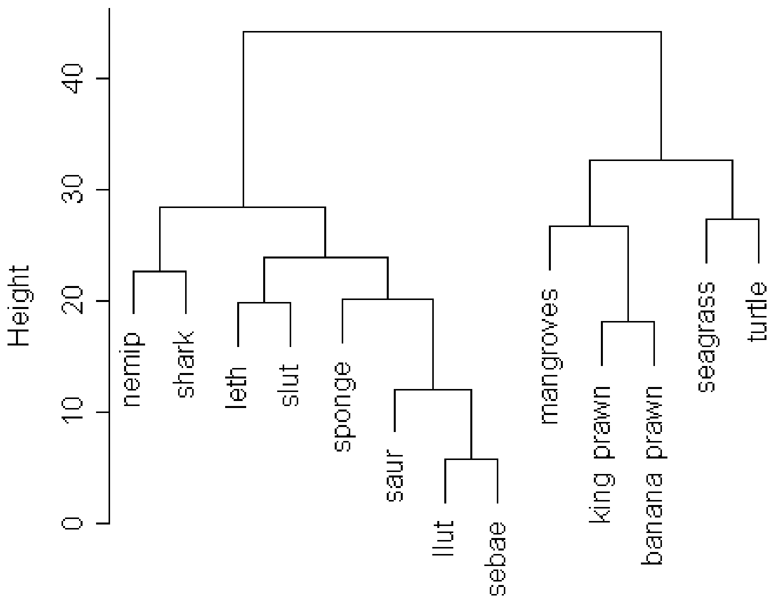


Figure C.8: Dendrogram for the cluster analysis of the relative spatial biomasses in the status quo management, 0-pulse development, optimistic model specification case.

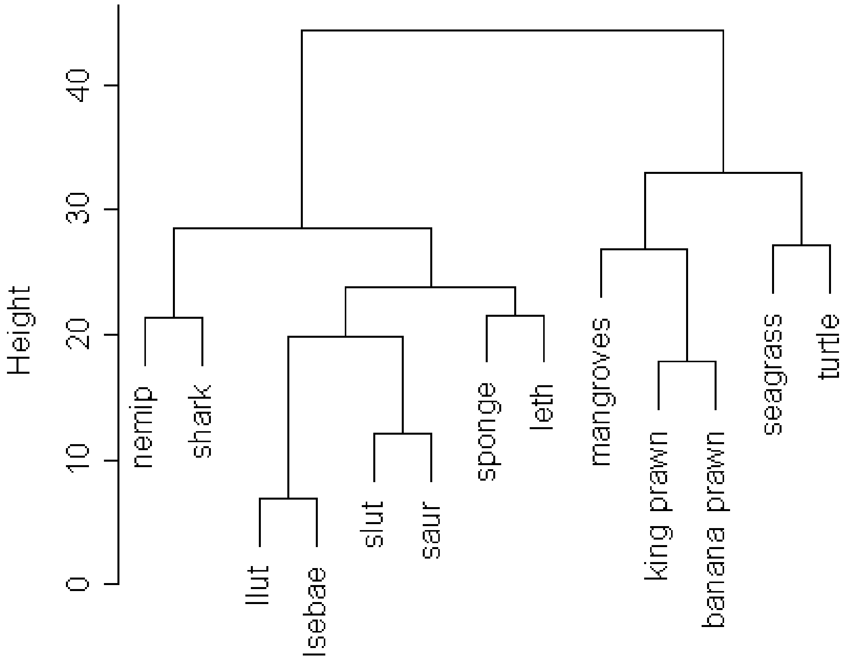


Figure C.9: Dendrogram for the cluster analysis of the relative spatial biomasses in the enhanced management, 0-pulse development, optimistic model specification case.

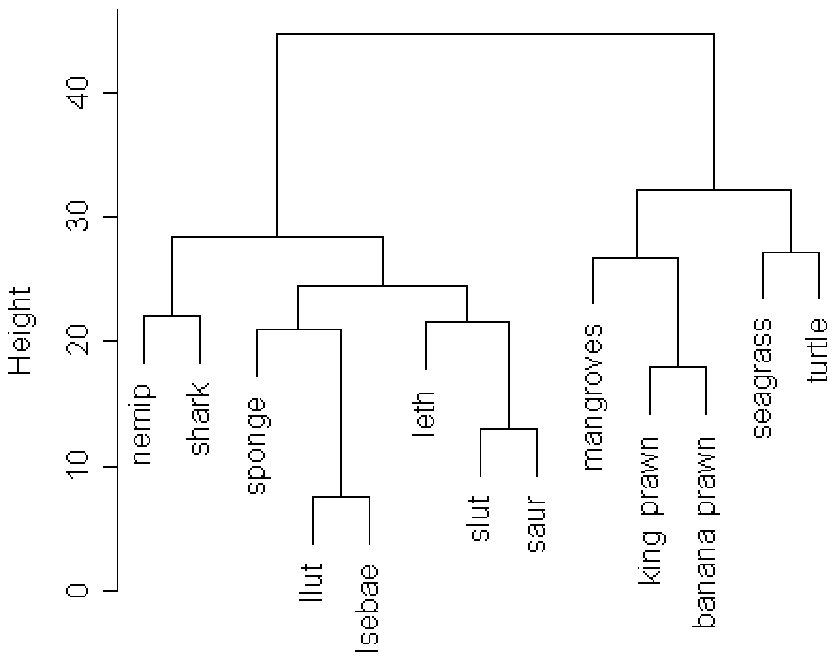


Figure C.10: Dendrogram for the cluster analysis of the relative spatial biomasses in the integrated management, 0-pulse development, optimistic model specification case.

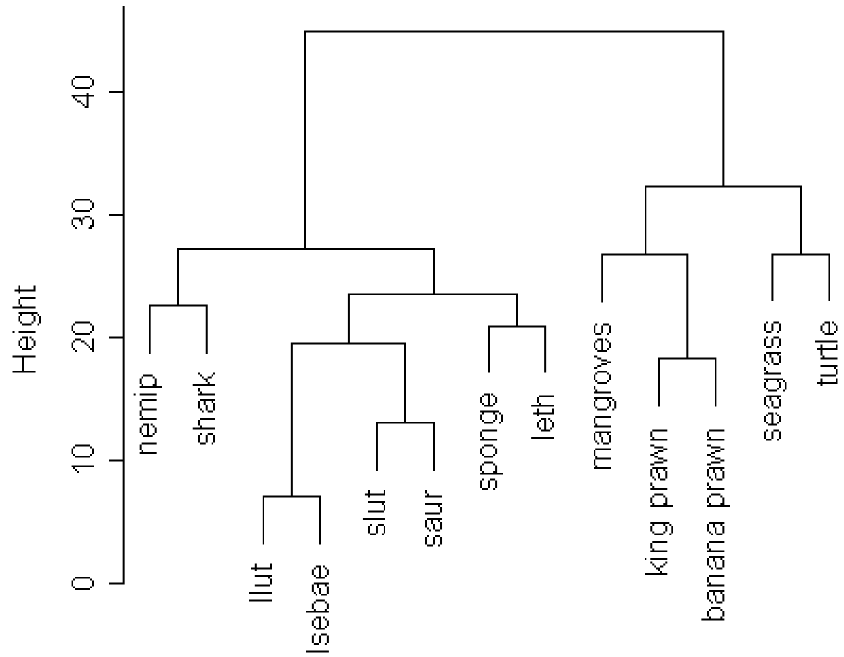


Figure C.11: Dendrogram for the cluster analysis of the relative spatial biomasses in the status quo management, 1- pulse development, optimistic model specification case.

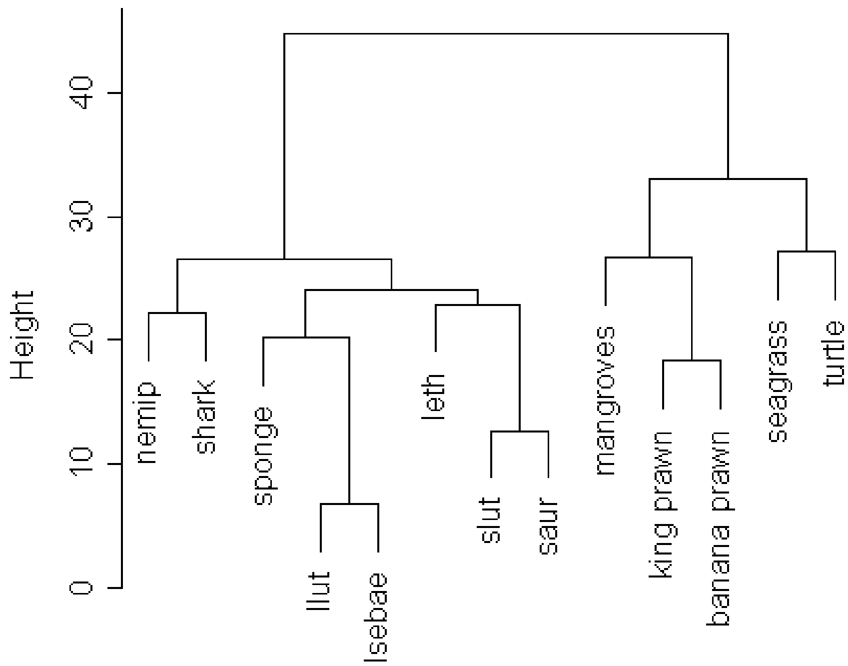


Figure C.12: Dendrogram for the cluster analysis of the relative spatial biomasses in the enhanced management, 1-pulse development, optimistic model specification case.

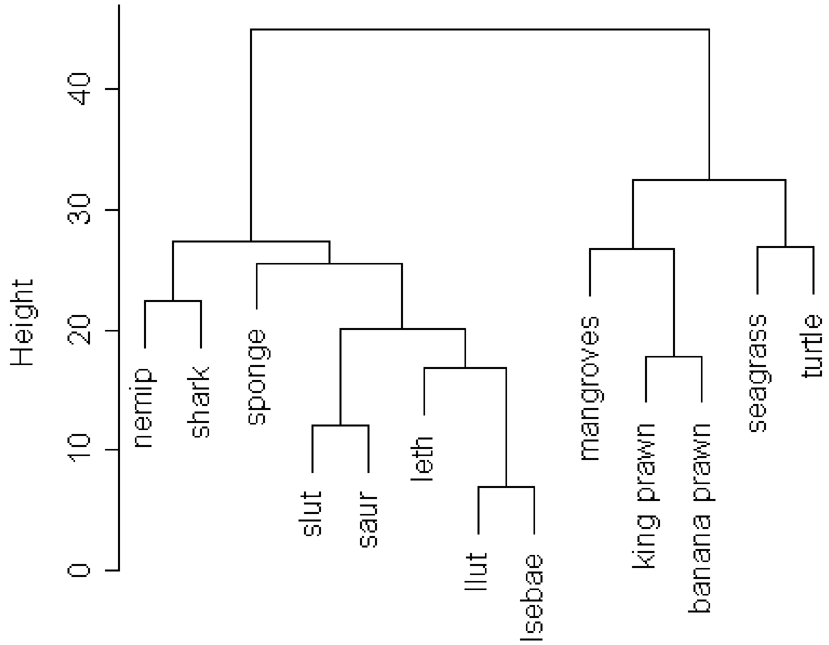


Figure C.13: Dendrogram for the cluster analysis of the relative spatial biomasses in the integrated management, 1-pulse development, optimistic model specification case.

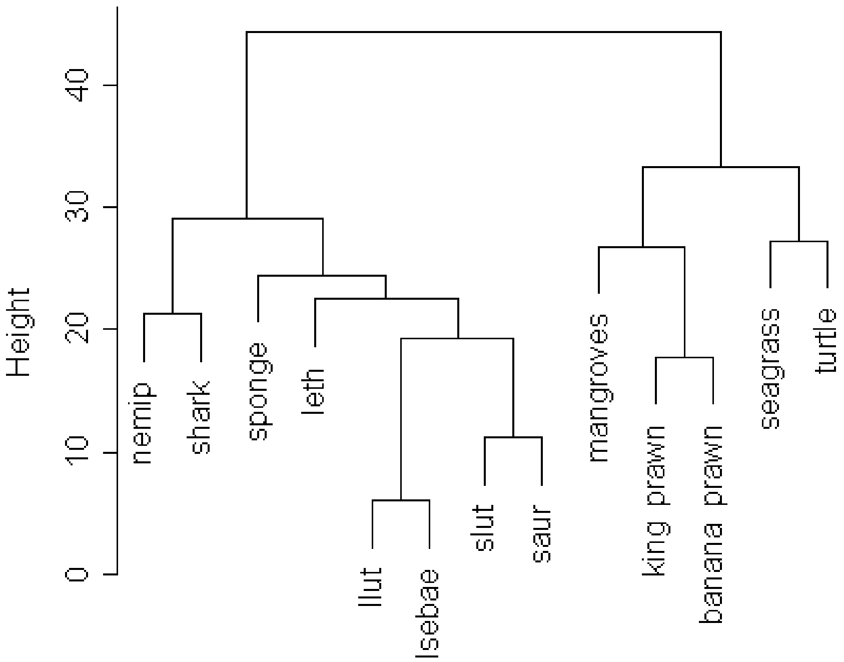


Figure C.14: Dendrogram for the cluster analysis of the relative spatial biomasses in the status quo management, 2-pulse development, optimistic model specification case.

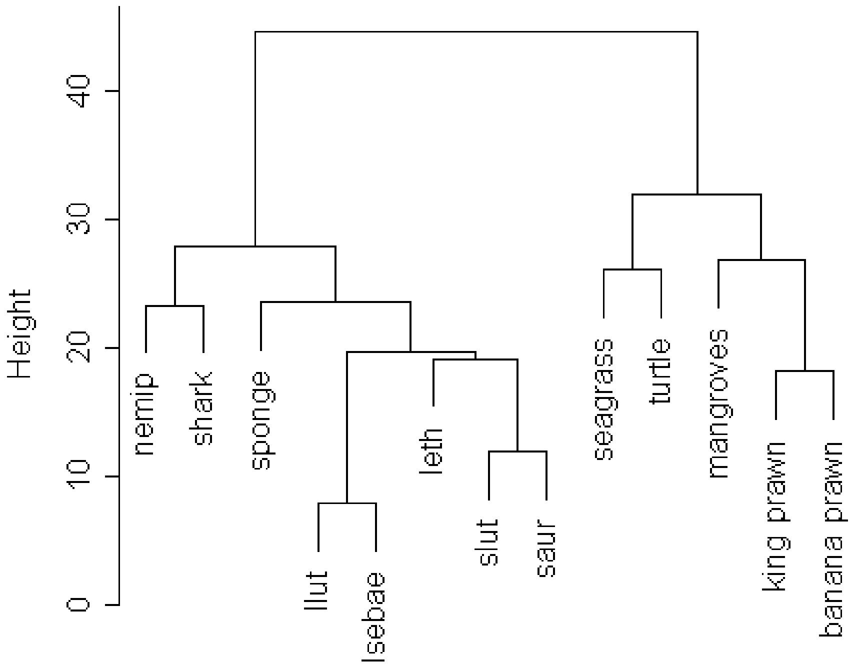


Figure C.15: Dendrogram for the cluster analysis of the relative spatial biomasses in the enhanced management, 2-pulse, optimistic model specification case.

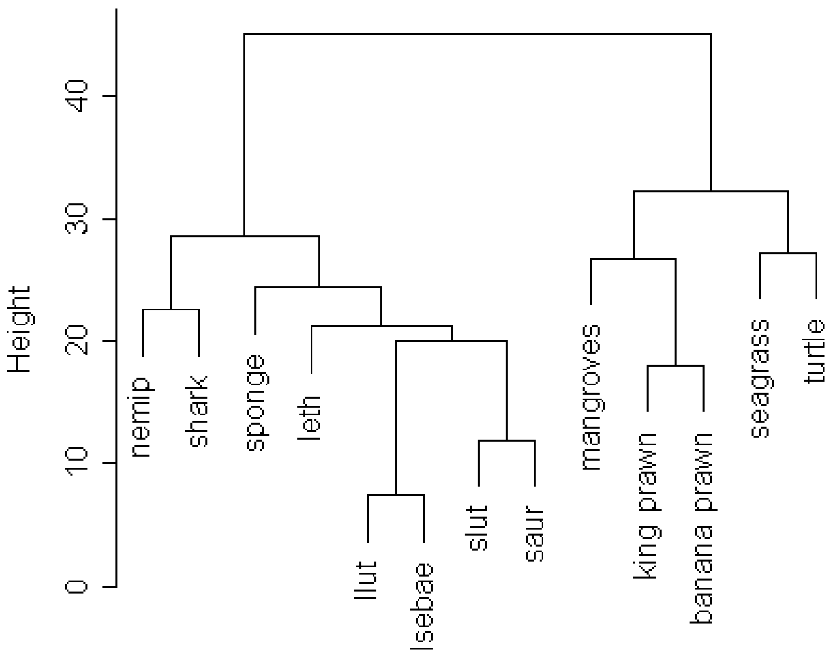


Figure C.16: Dendrogram for the cluster analysis of the relative spatial biomasses in the integrated management, 2-pulse, optimistic model specification case.

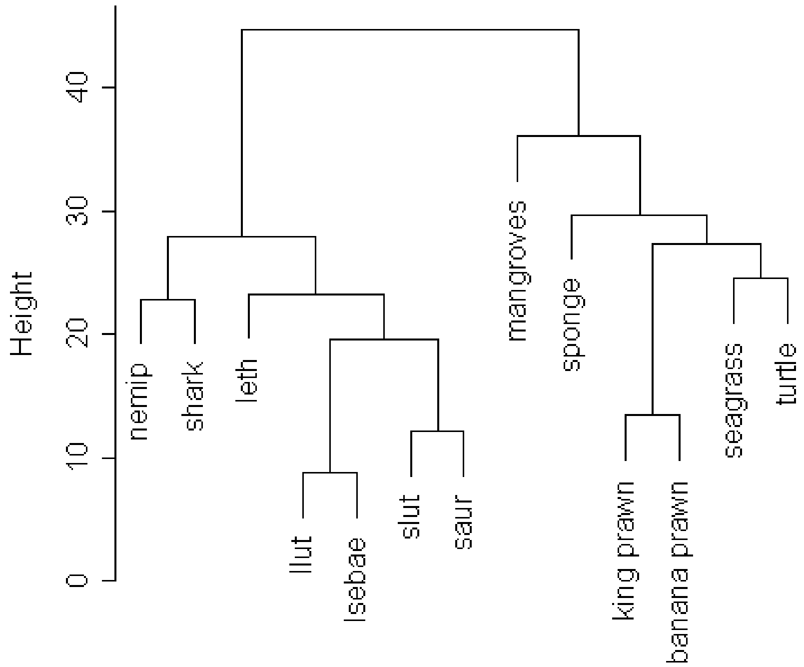


Figure C.17: Dendrogram for the cluster analysis of the relative spatial biomasses in the enhanced management, 2-pulse development base case model specification case.

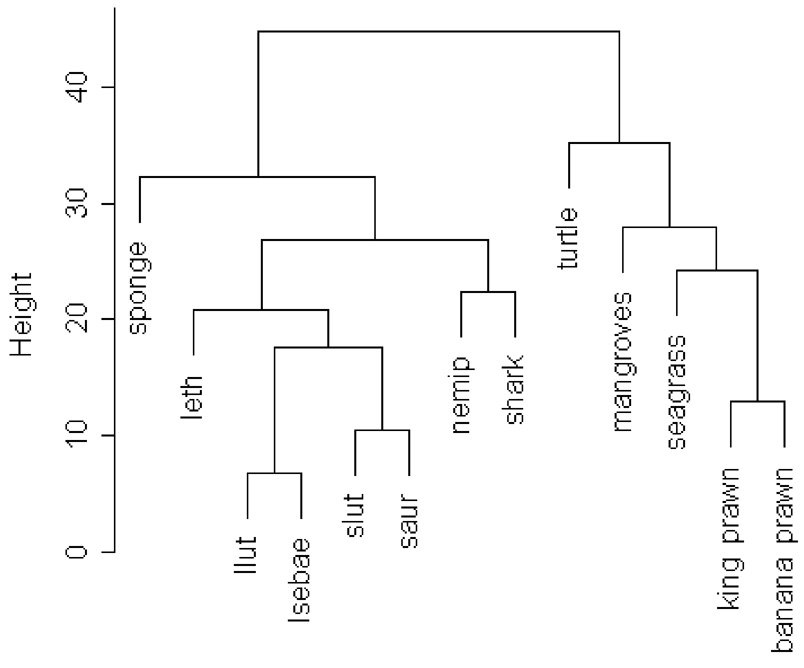


Figure C.18: Dendrogram for the cluster analysis of the relative spatial biomasses in the integrated management, 2-pulse development, base case model specification case.

C.3 Mixed system state

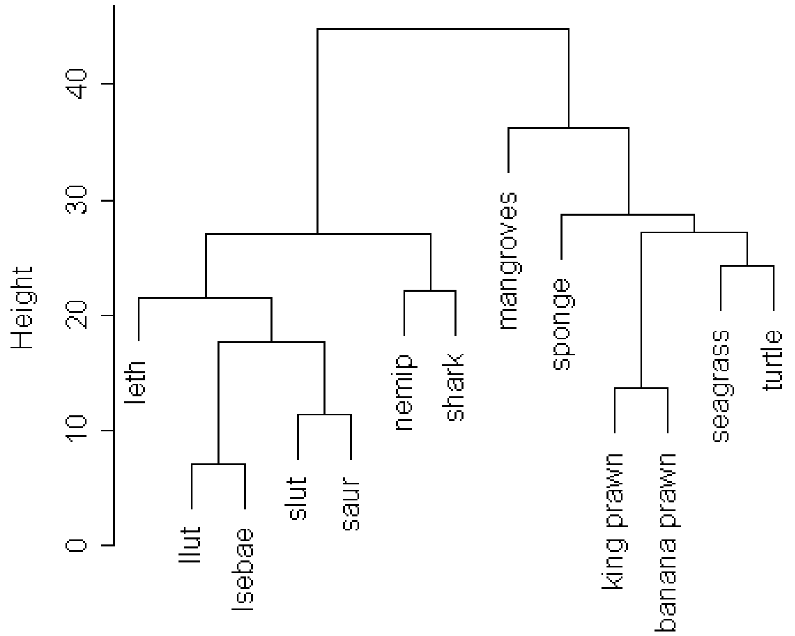


Figure C.19: Dendrogram for the cluster analysis of the relative spatial biomasses in the status quo management, 0-pulse development, base case model specification case.

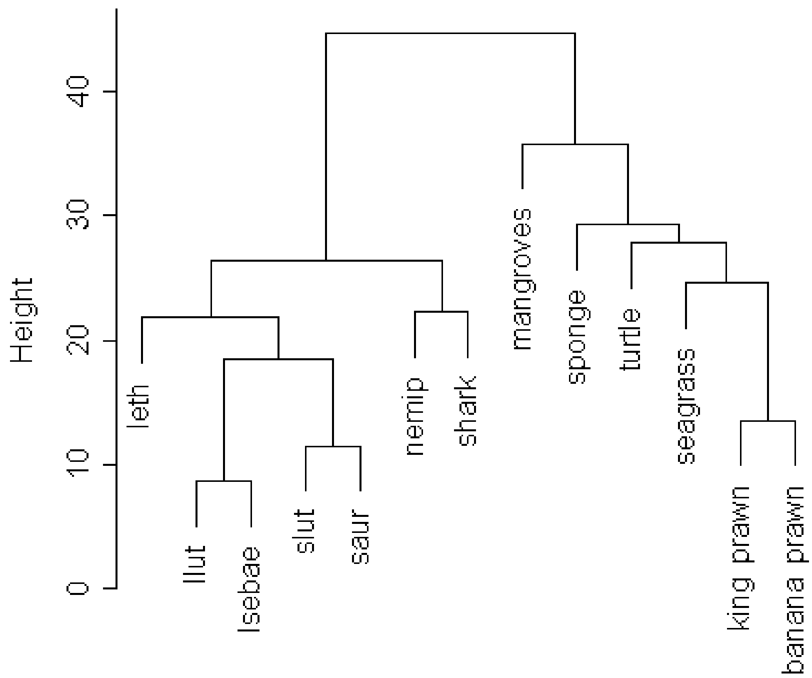


Figure C.20: Dendrogram for the cluster analysis of the relative spatial biomasses in the status quo management, 1-pulse development, base case model specification case.

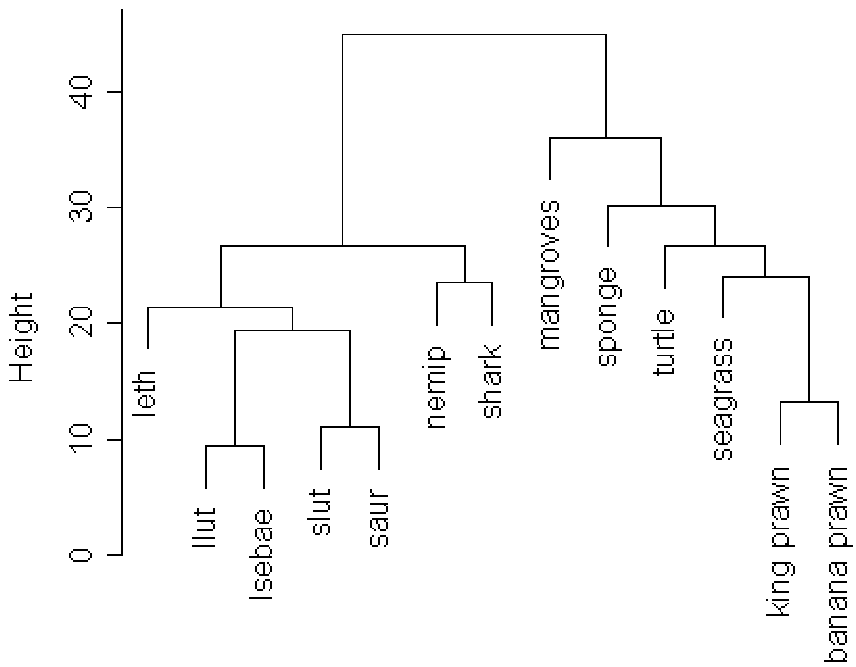


Figure C.21: Dendrogram for the cluster analysis of the relative spatial biomasses in the status quo management, 2-pulse development, base case model specification case.

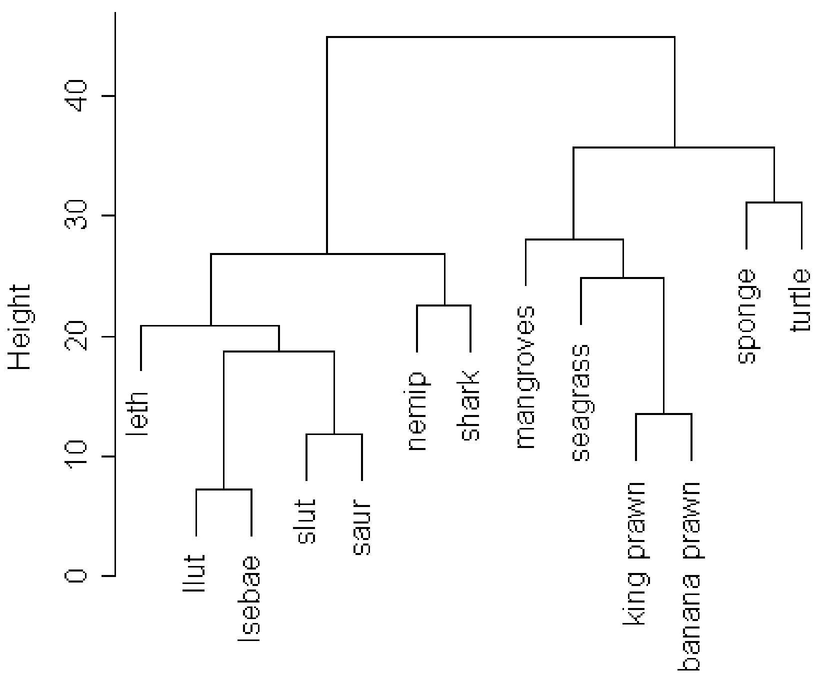


Figure C.22: Dendrogram for the cluster analysis of the relative spatial biomasses in the integrated management, 0- pulse development, base case model specification case.

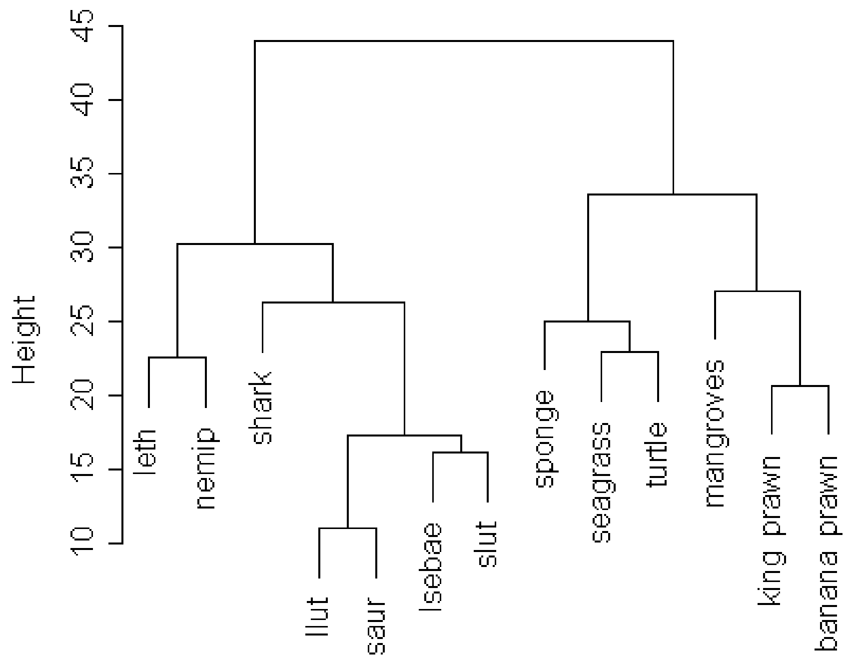


Figure C.23: Dendrogram for the cluster analysis of the relative spatial biomasses in the enhanced management, 0-pulse development, pessimistic model specification case.

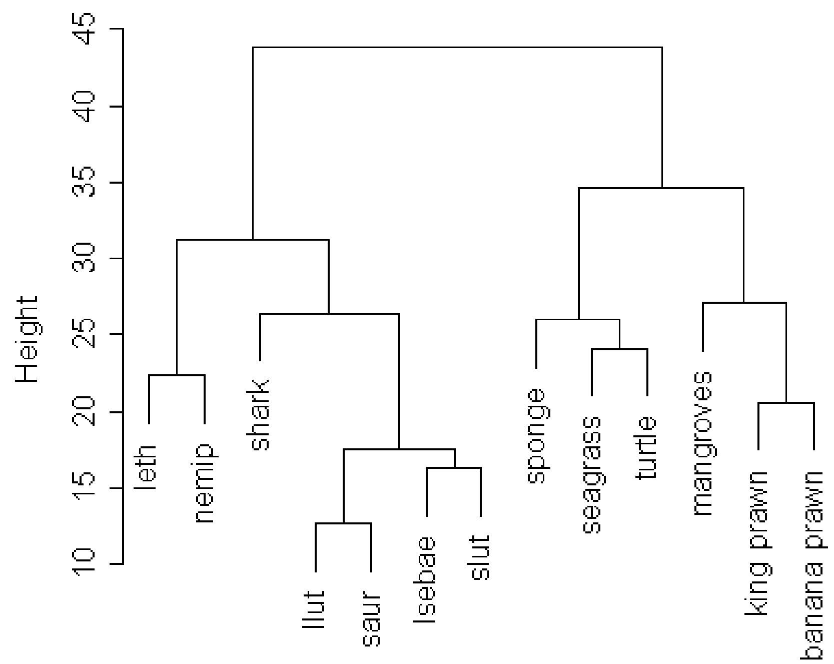


Figure C.24: Dendrogram for the cluster analysis of the relative spatial biomasses in the status quo management, 1-pulse development, pessimistic model specification case.

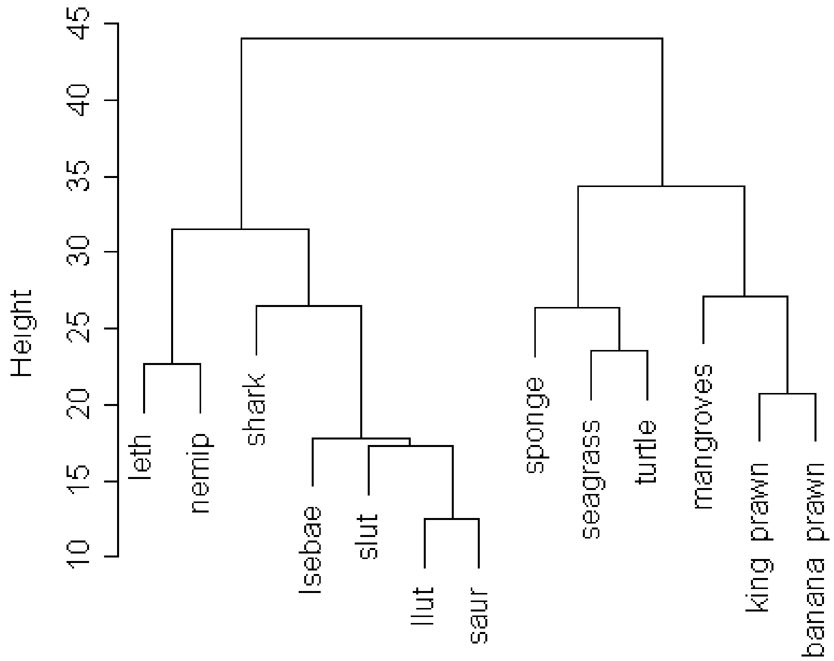


Figure C.25: Dendrogram for the cluster analysis of the relative spatial biomasses in the enhanced management, 1-pulse development, pessimistic model specification case.

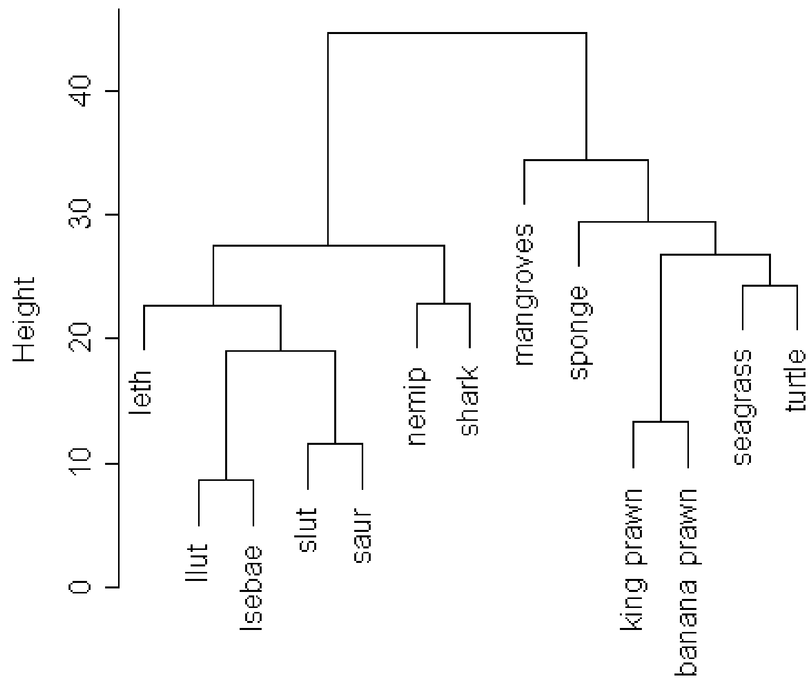


Figure C.26: Dendrogram for the cluster analysis of the relative spatial biomasses in the enhanced management, 0-pulse development, base case model specification case.

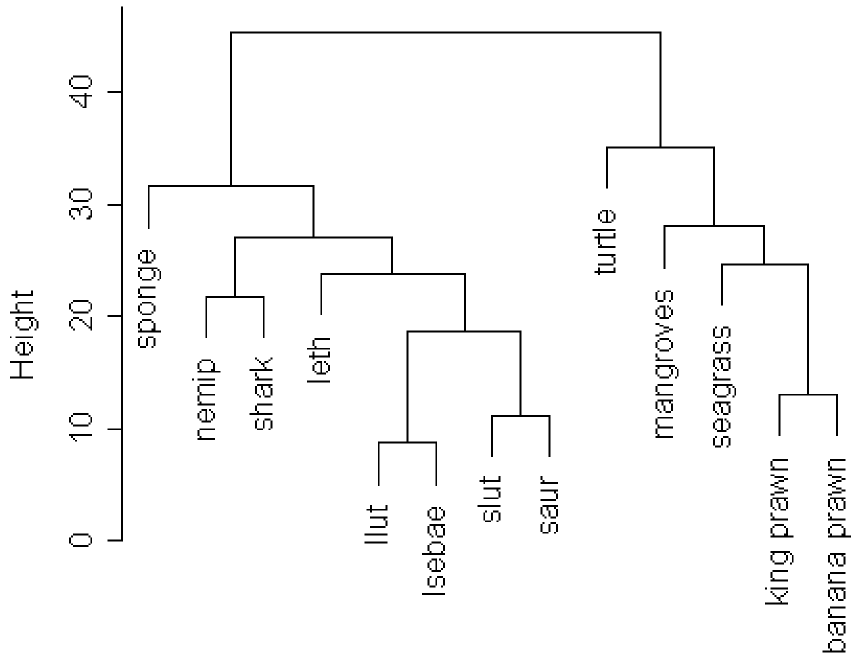


Figure C.27: Dendrogram for the cluster analysis of the relative spatial biomasses in the integrated management, 1-pulse development, base case model specification case.

APPENDIX D: COMPARISONS OF MODEL SPECIFICATIONS, MANAGEMENT STRATEGIES AND DEVELOPMENT SCENARIOS

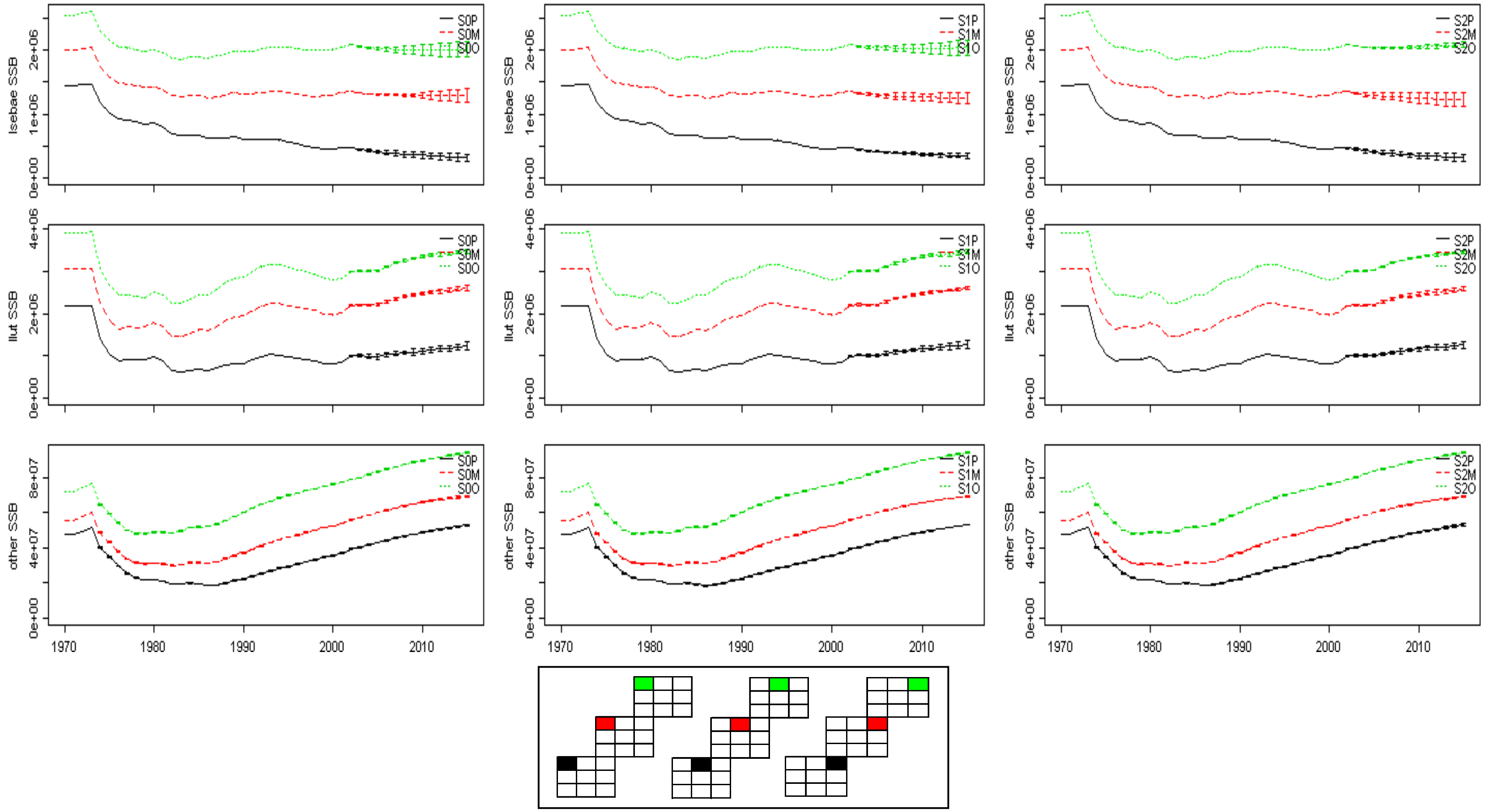


Figure D.1: Comparison of model specifications for spawning stock biomass (kg) of *Lutjanus sebae*, large Lutjanids (*L. erythropterus*, *L. malabaricus*) and all other finfish combined under the status quo management strategy across zero-pulse, 1-pulse and 2-pulse (left to right) development scenarios.

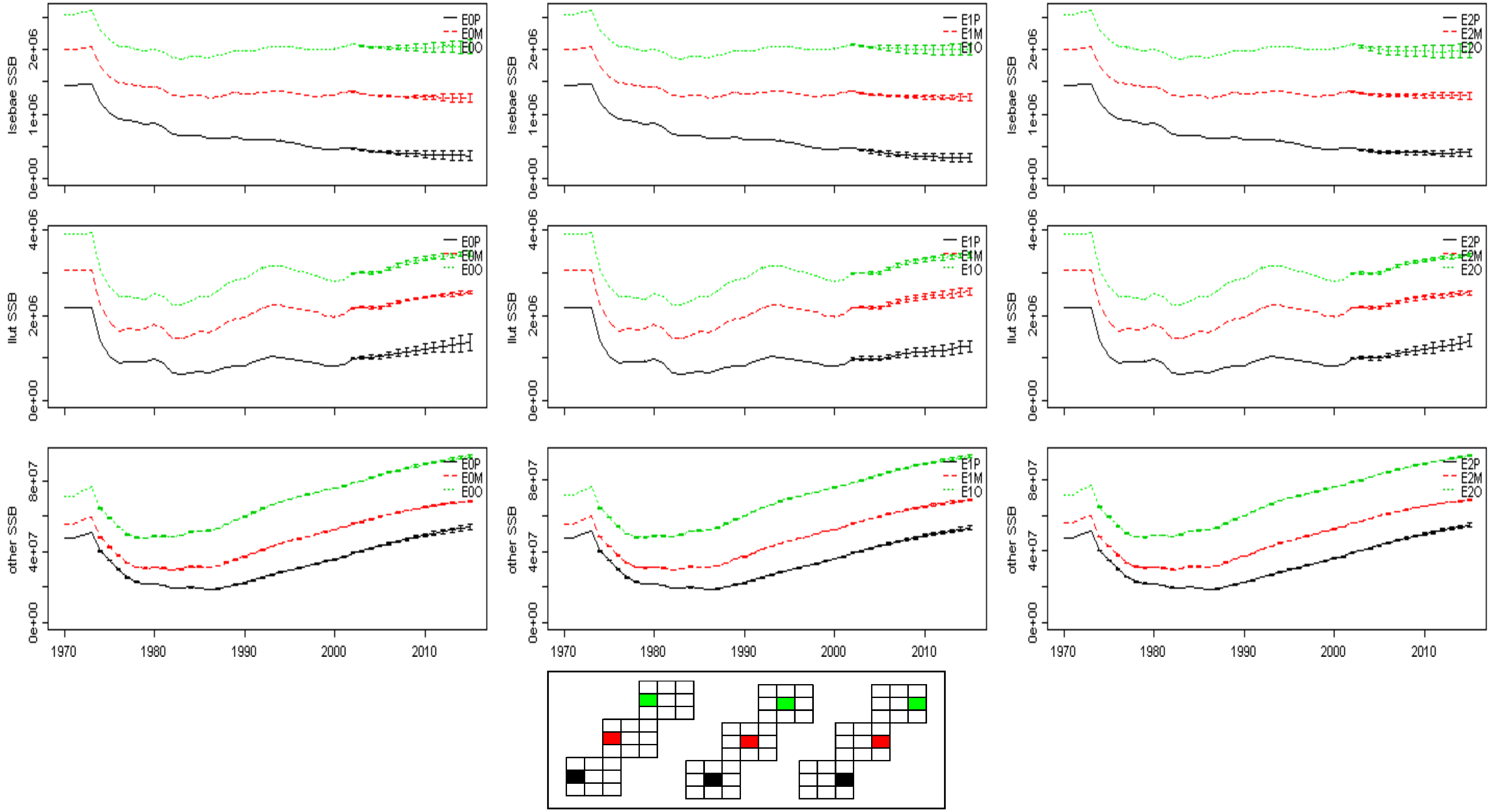


Figure D.2: Comparison of model specifications for spawning stock biomass (kg) of *Lutjanus sebae*, large Lutjanids (*L. erythropterus*, *L. malabaricus*) and all other finfish groups combined under the enhanced management strategy across 0-pulse, 1-pulse and 2-pulse (left to right) development scenarios.

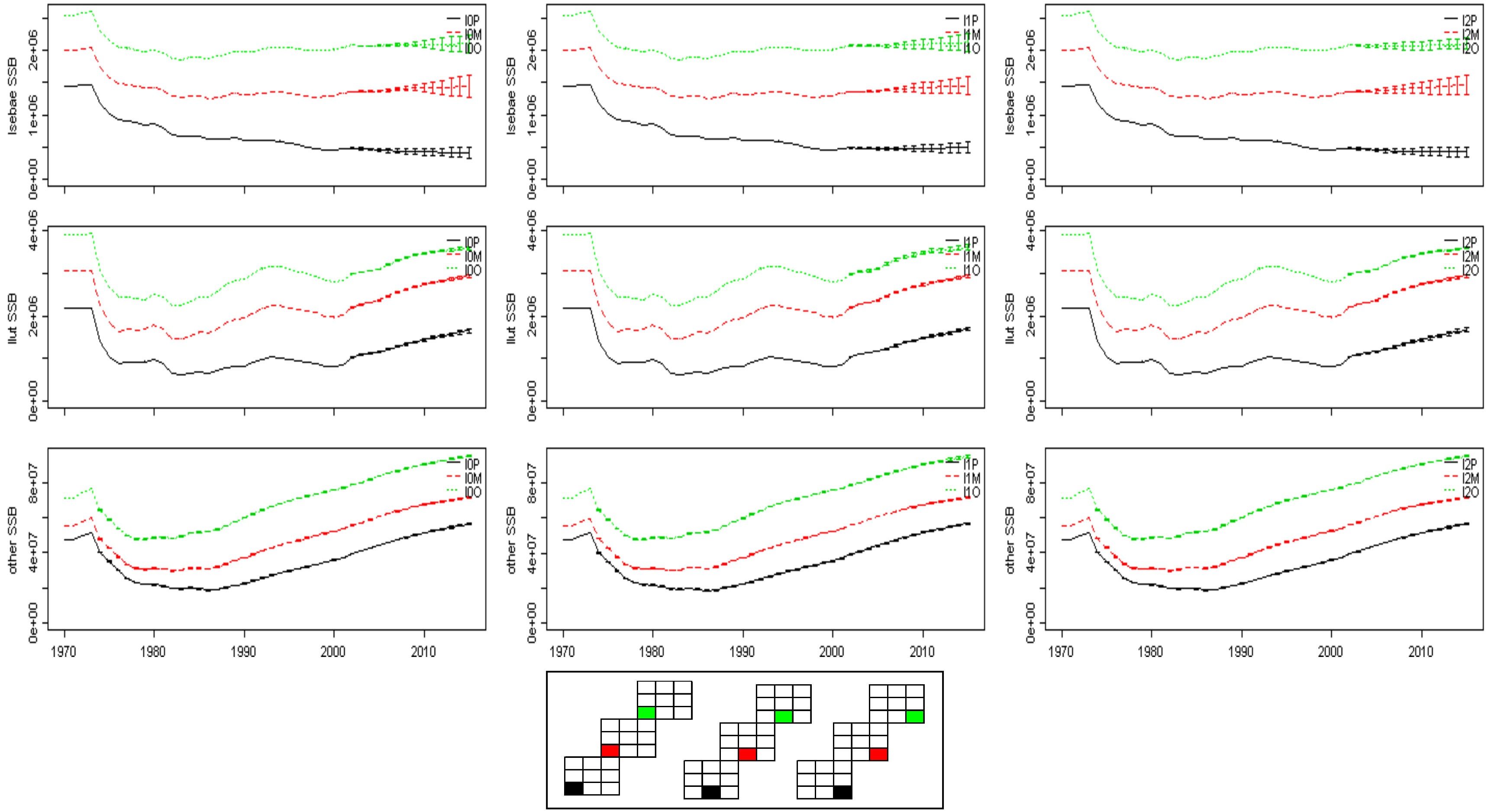


Figure D.3: Comparison of model specifications for spawning stock biomass (kg) of *Lutjanus sebae*, large Lutjanids (*L. erythropterus, L. malabaricus*) and all other finfish groups combined under the integrated management strategy across 0-pulse, 1-pulse and 2-pulse (left to right) development scenarios.

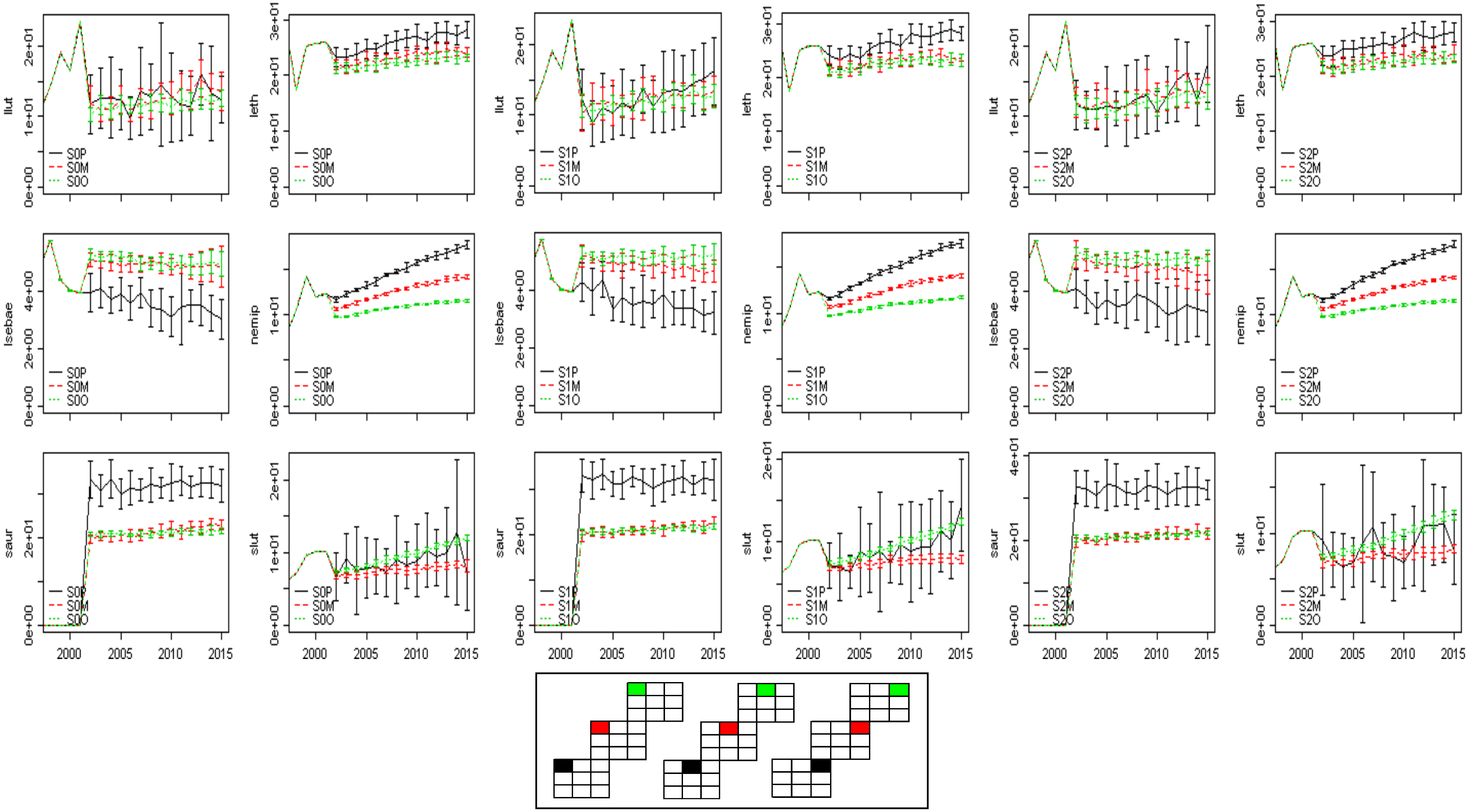


Figure D.4: Comparison of model specifications for trawl CPUE (kg per trawl hour) of different species groups under the status quo management strategy (leth = lethrinids, llut = large lutjanids, lsebae = *Lutjanus sebae*, slut = small lutjanids, nemip = nemipterids and saur = saurids) across 0-pulse, 1-pulse and 2-pulse (left to right) development scenarios.

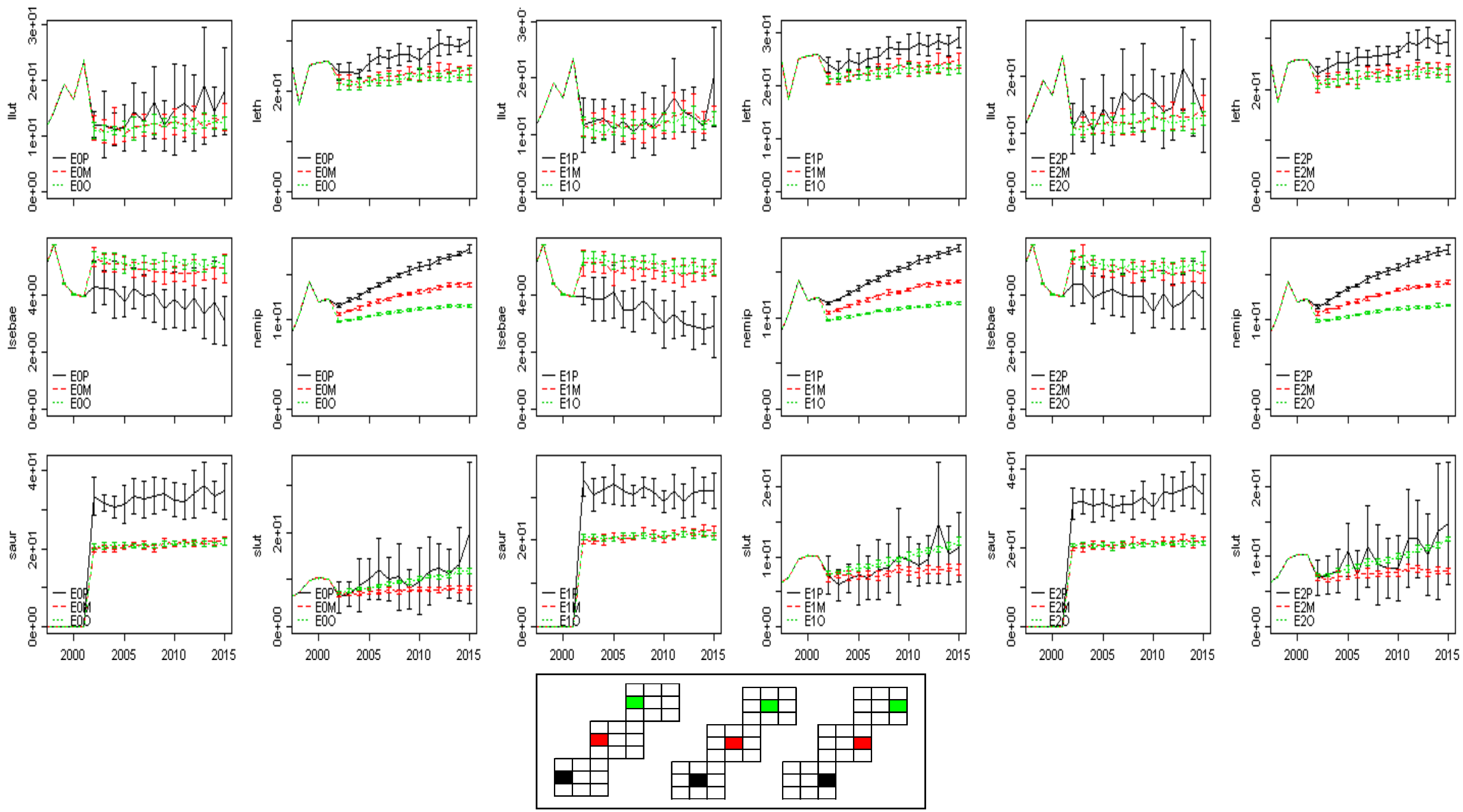


Figure D.5: Comparison of model specifications for trawl CPUE (kg per trawl hour) of different species groups under the enhanced management strategy (leth = lethrinids, llut = large lutjanids, lsebae = *Lutjanus sebae*, slut = small lutjanids, nemip = nemipterids and saur = saurids) across 0-pulse, 1-pulse and 2-pulse (left to right) development scenarios.

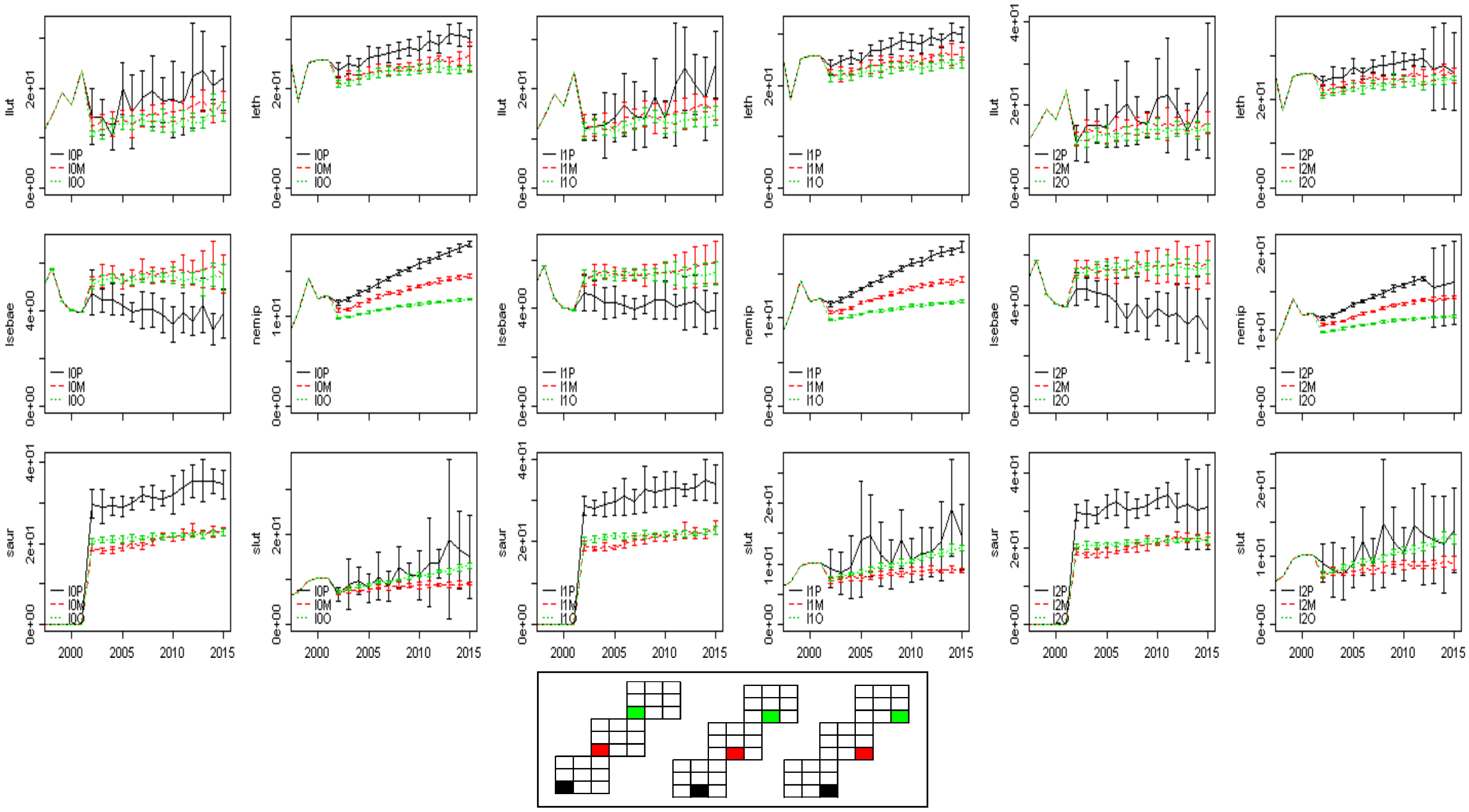


Figure D.6: Comparison of model specifications for trawl CPUE (tonnes per fishing day) of different species groups under the integrated management strategy (leth = lethrinids, llut = large lutjanids, lsebae = Lutjanus sebae, slut = small lutjanids, nemip = nemipterids and saur = saurids) across 0-pulse, 1-pulse and 2-pulse (left to right) development scenarios.

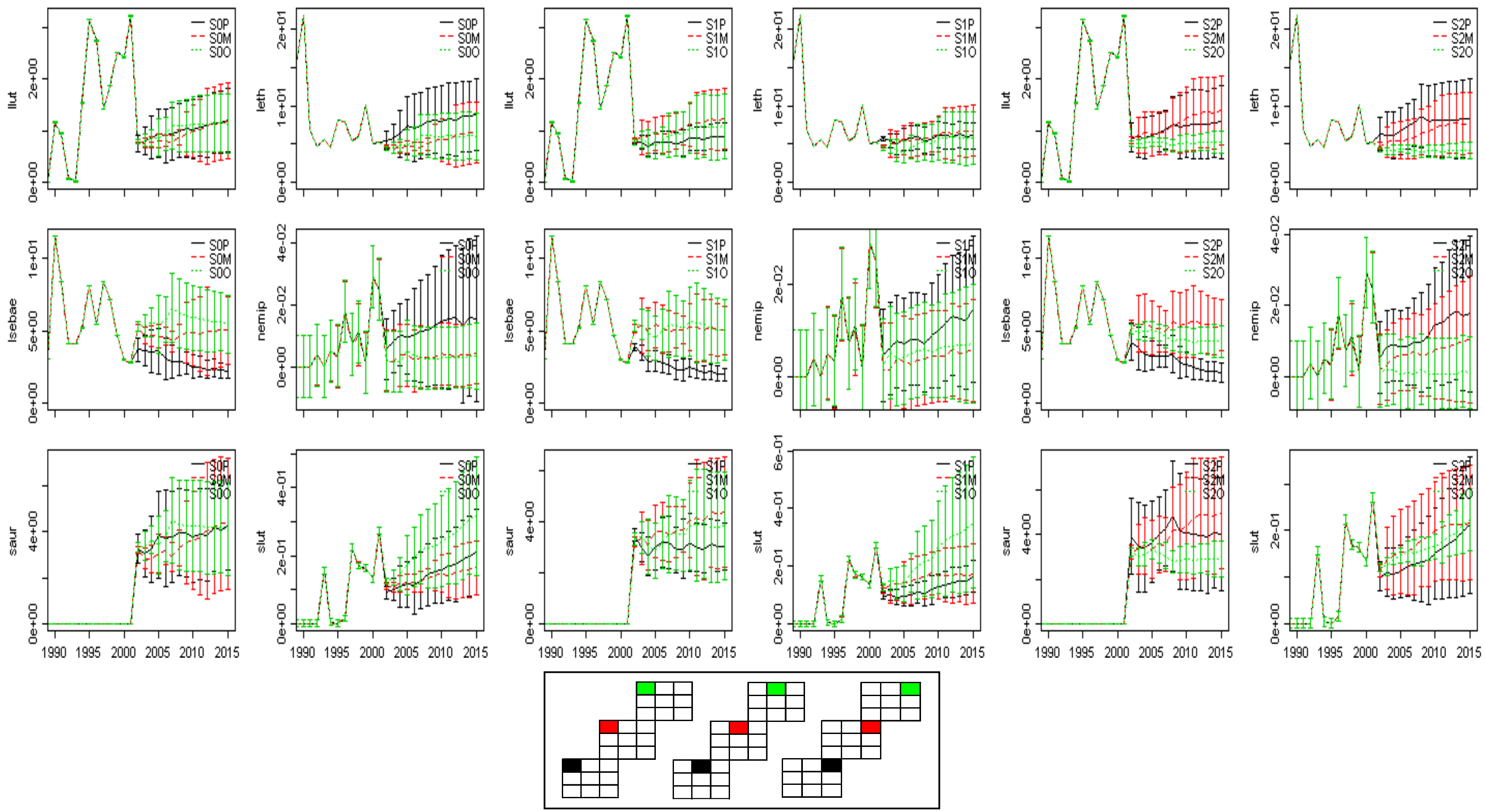


Figure D.7: Comparison of model specifications for trap CPUE (kg per trap soak hour) of different species groups under the status quo management strategy (leth = lethrinids, llut = large lutjanids, lsebae = *Lutjanus sebae*, slut = small lutjanids, nemip = nemipterids and saur = saurids) across 0-pulse, 1-pulse and 2-pulse (left to right) development scenarios.

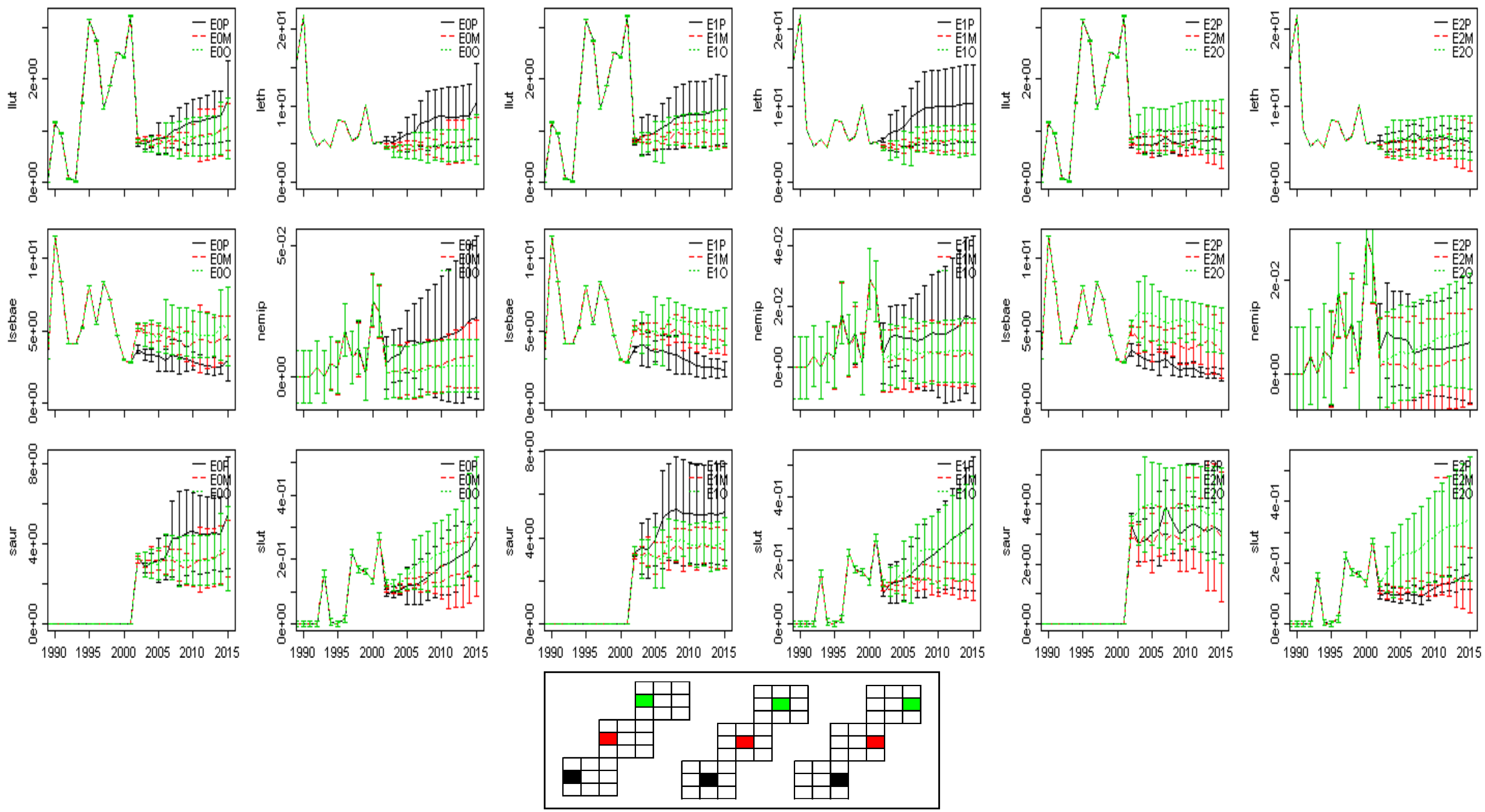


Figure D.8: Comparison of model specifications for trap CPUE (kg per trap soak hours) of different species groups under the enhanced management strategy (leth = lethrinids, llut = large lutjanids, lsebae = *Lutjanus sebae*, slut = small lutjanids, nemip = nemipterids and saur = saurids) across 0-pulse, 1-pulse and 2-pulse (left to right) development scenarios.

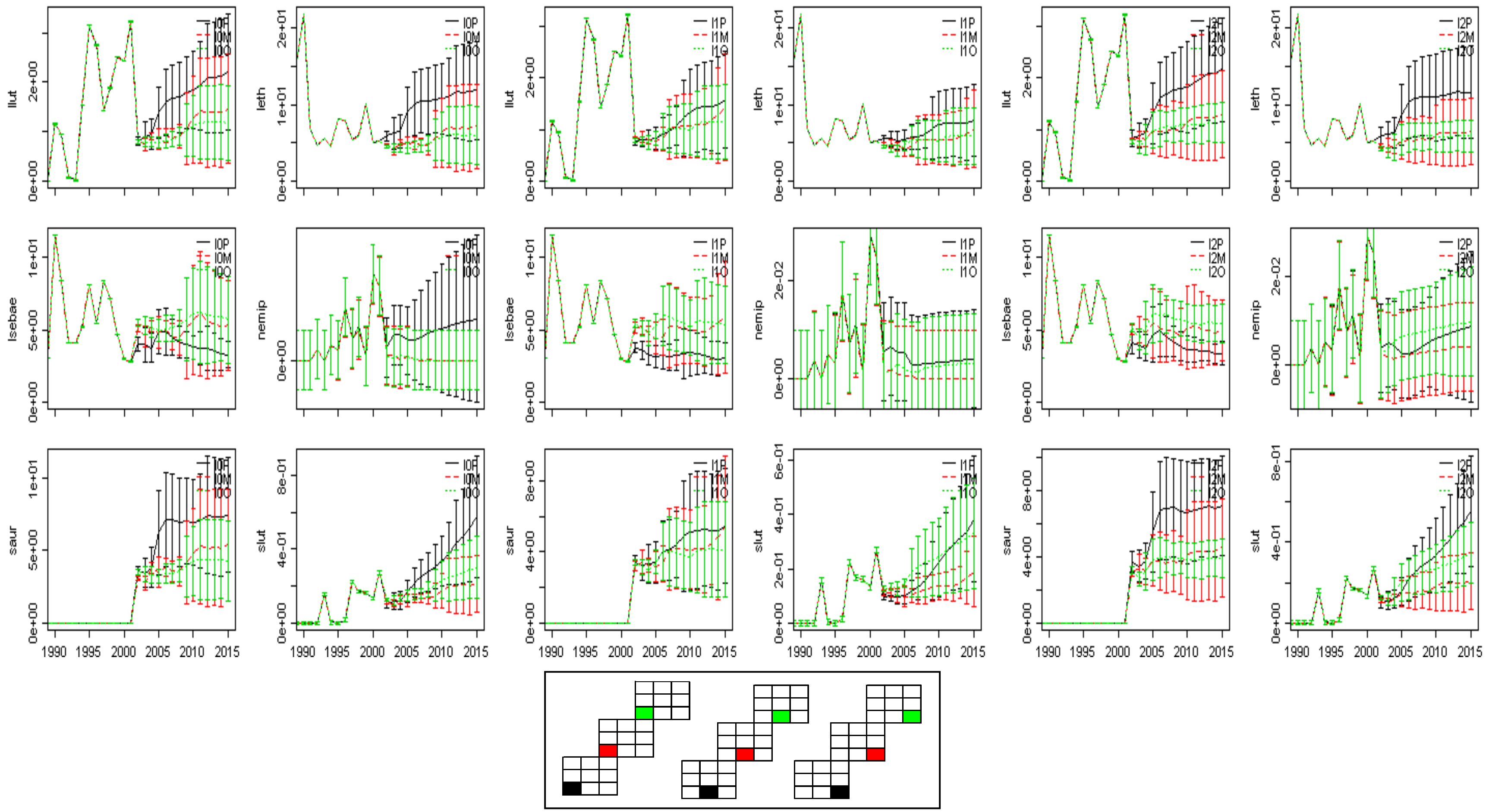


Figure D.9: Comparison of model specifications for trap CPUE (kg per trap soak hour) of different species groups under the integrated management strategy (leth = lethrinids, llut = large lutjanids, lsebae = *Lutjanus sebae*, slut = small lutjanids, nemip = nemipterids and saur = saurids) across 0-pulse, 1-pulse and 2-pulse (left to right) development scenarios.

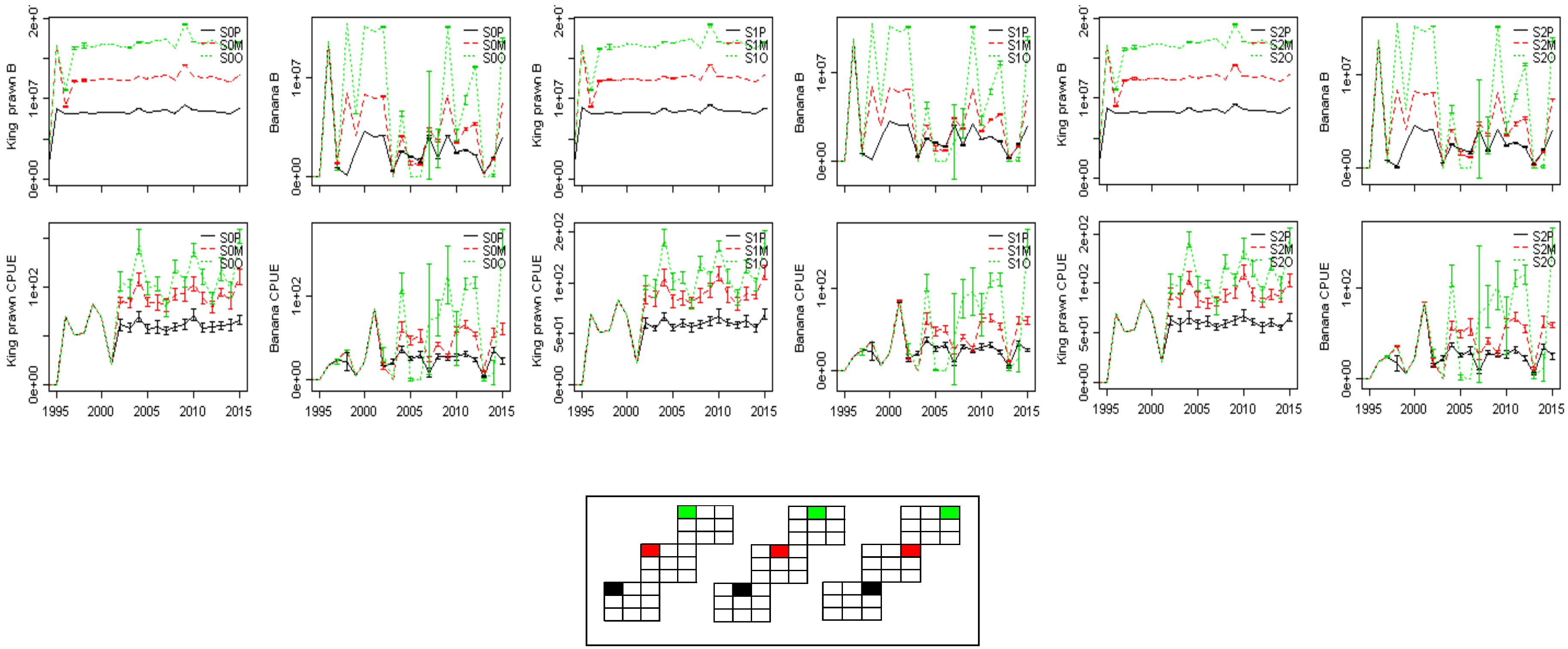


Figure D.10: Comparison of model specifications for total biomass (kg) and CPUE (kg per trawl hour) of the two prawn species under the status quo management strategy across 0-pulse, 1-pulse and 2-pulse (left to right) development scenarios.

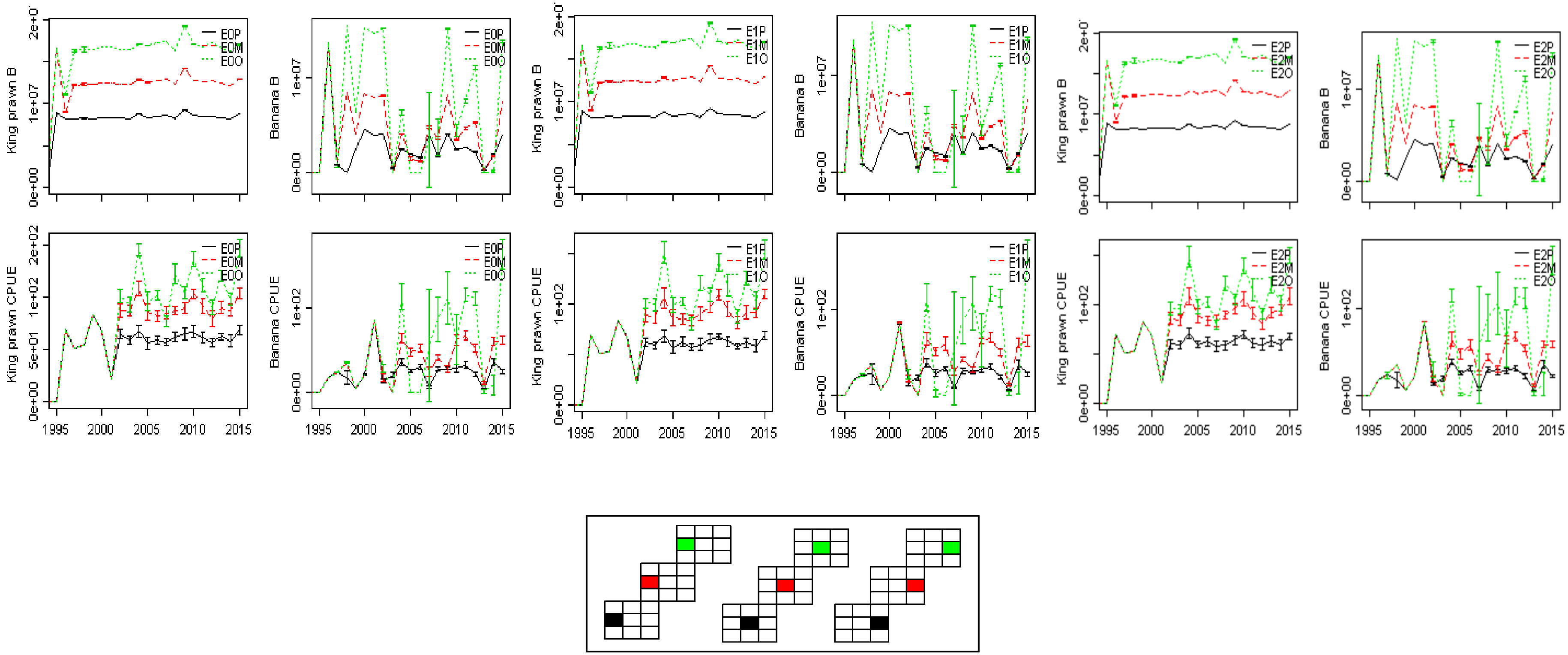
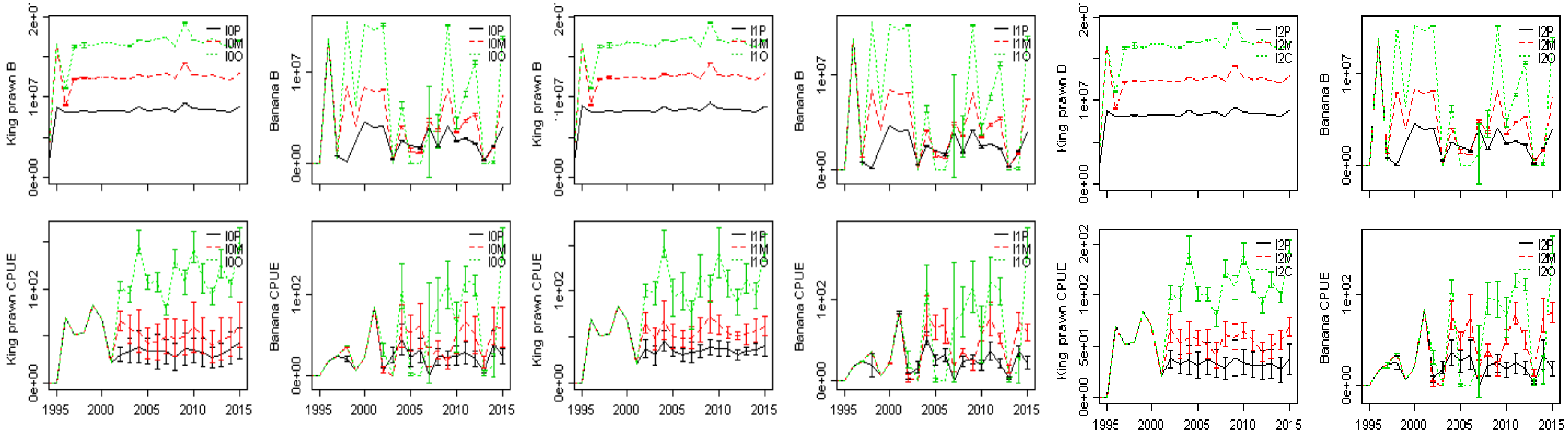


Figure D.11: Comparison of model specifications for total biomass (kg) and CPUE (kg per trawl hour) of the two prawn species under the enhanced management strategy across 0-pulse, 1-pulse and 2-pulse (left to right) development scenarios.



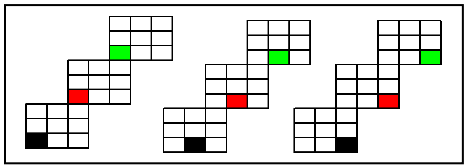
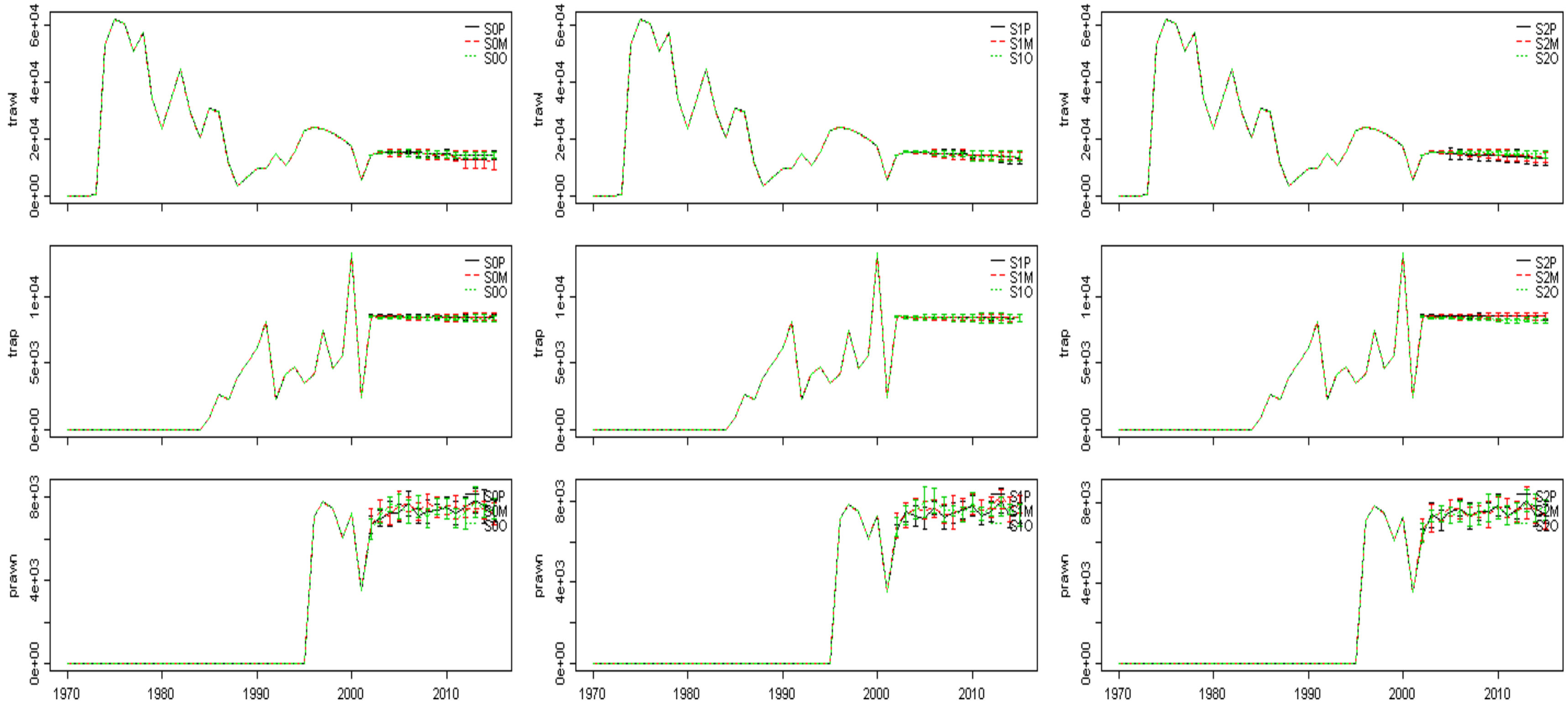


Figure D.12: Comparison of model specifications for total biomass (kg) and CPUE (kg per trawl hour) of the two prawn species under the integrated management strategy across 0-pulse, 1-pulse and 2-pulse (left to right) development scenarios.



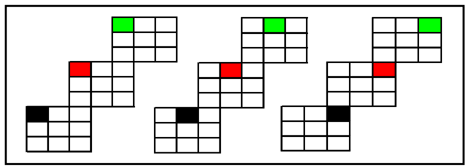


Figure D.13 (a): Comparison of model specifications for total effort (fishing hours) for the different fisheries under the status quo management strategy across 0-pulse, 1-pulse and 2-pulse (left to right) development scenarios over the entire period.

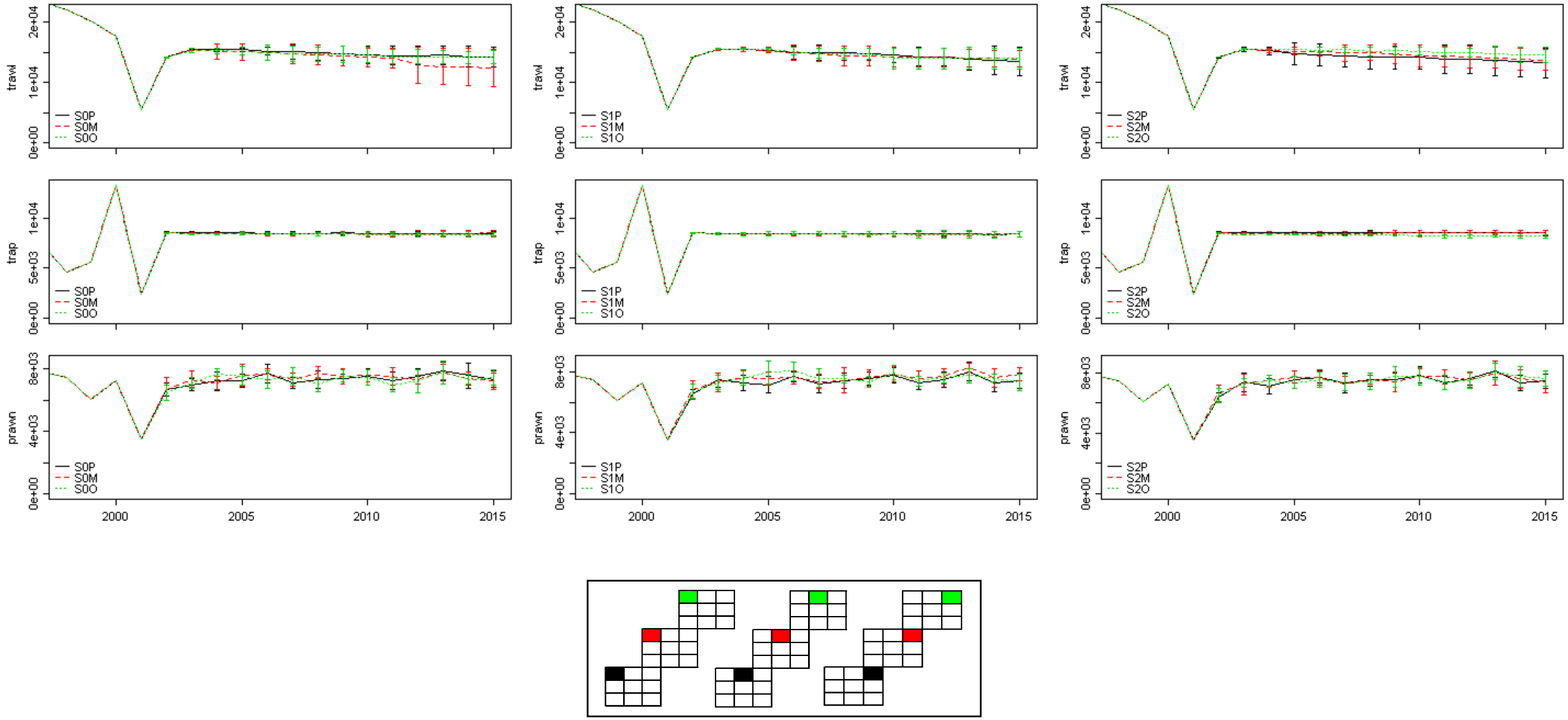


Figure D.13 (b): Comparison of model specifications for total effort (fishing hours) for the different fisheries under the status quo management strategy across 0-pulse, 1-pulse and 2-pulse (left to right) development scenarios for the projection period only.

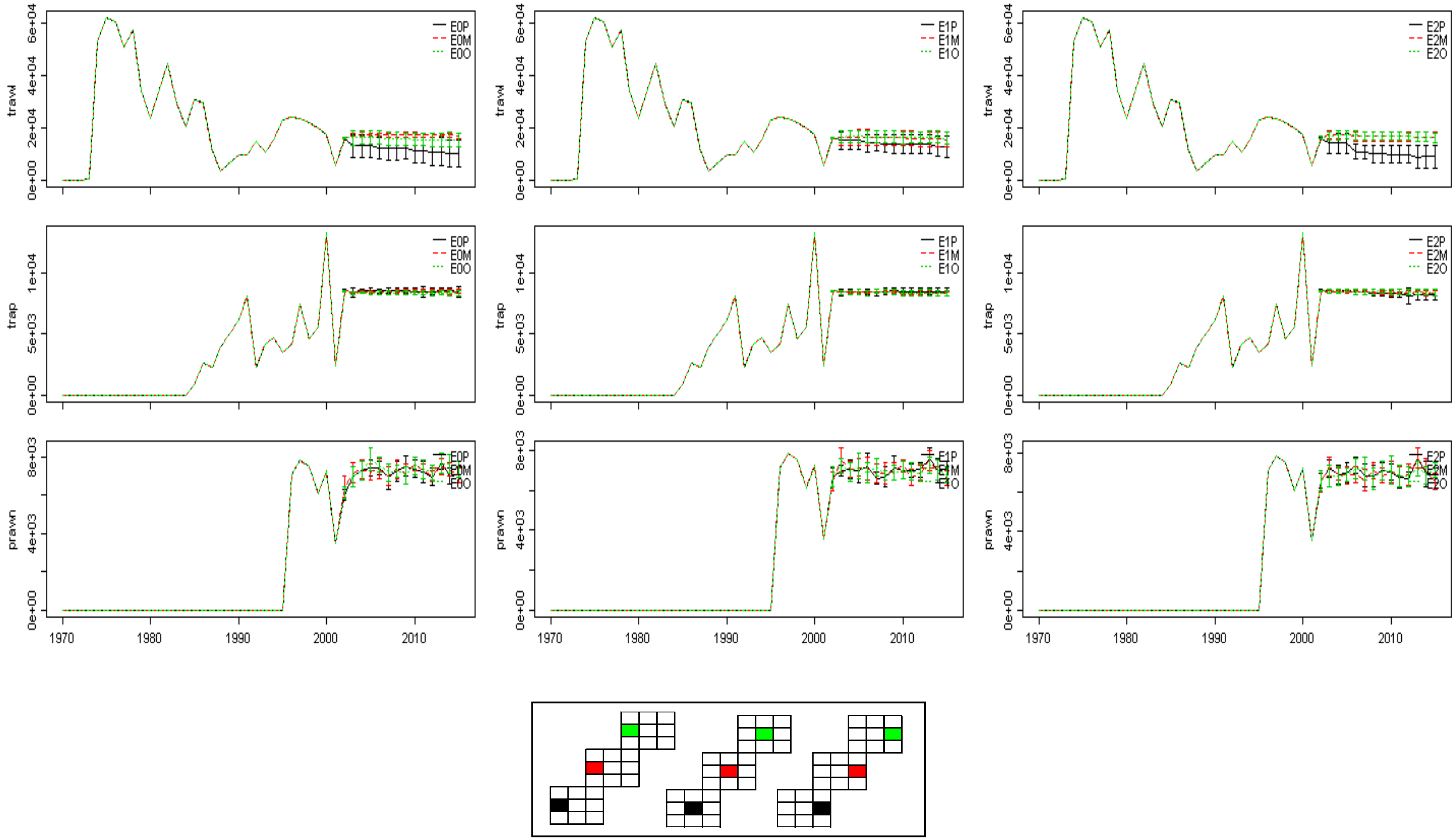


Figure D.14 (a): Comparison of model specifications for total effort (fishing hours) for the different fisheries under the enhanced management strategy across 0-pulse, 1-pulse and 2-pulse (left to right) development scenarios over the entire period.

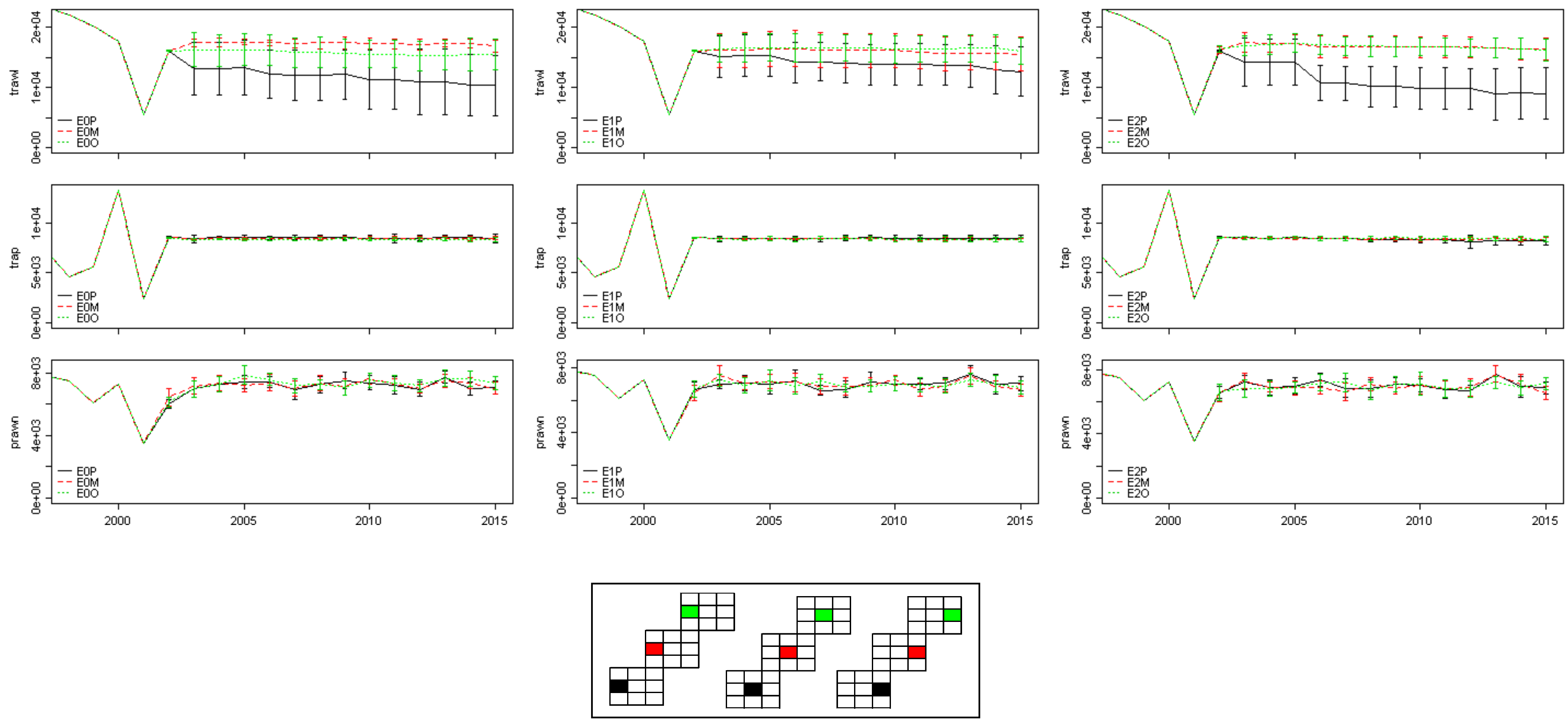
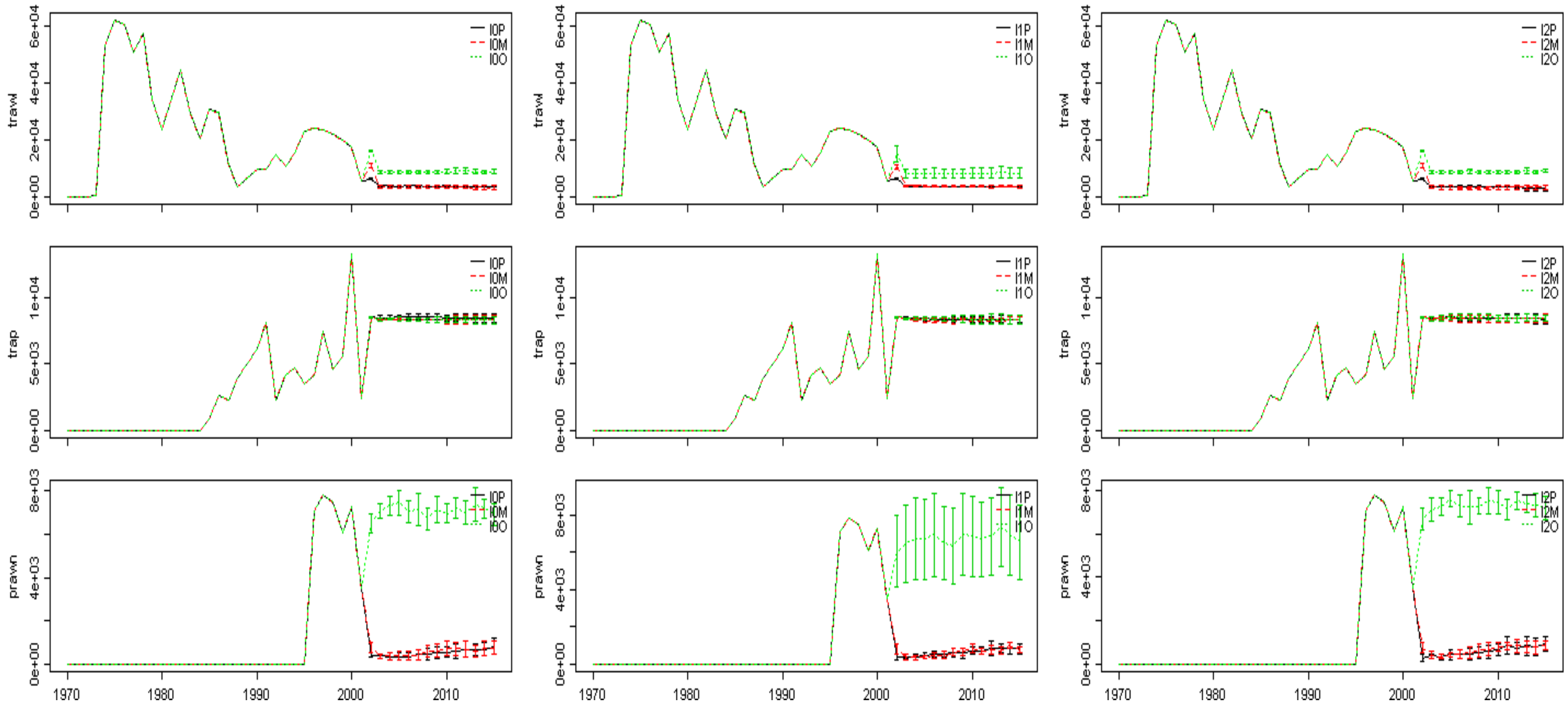


Figure D.14 (b): Comparison of model specifications for total effort (fishing hours) for the different fisheries under the enhanced management strategy across 0-pulse, 1-pulse and 2-pulse (left to right) development scenarios for the projection period only.



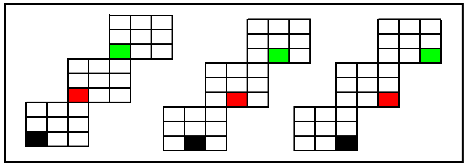


Figure D.15 (a): Comparison of model specifications for total effort (fishing hours) for the different fisheries under the integrated management strategy across 0-pulse, 1-pulse and 2-pulse (left to right) development scenarios over the entire period.

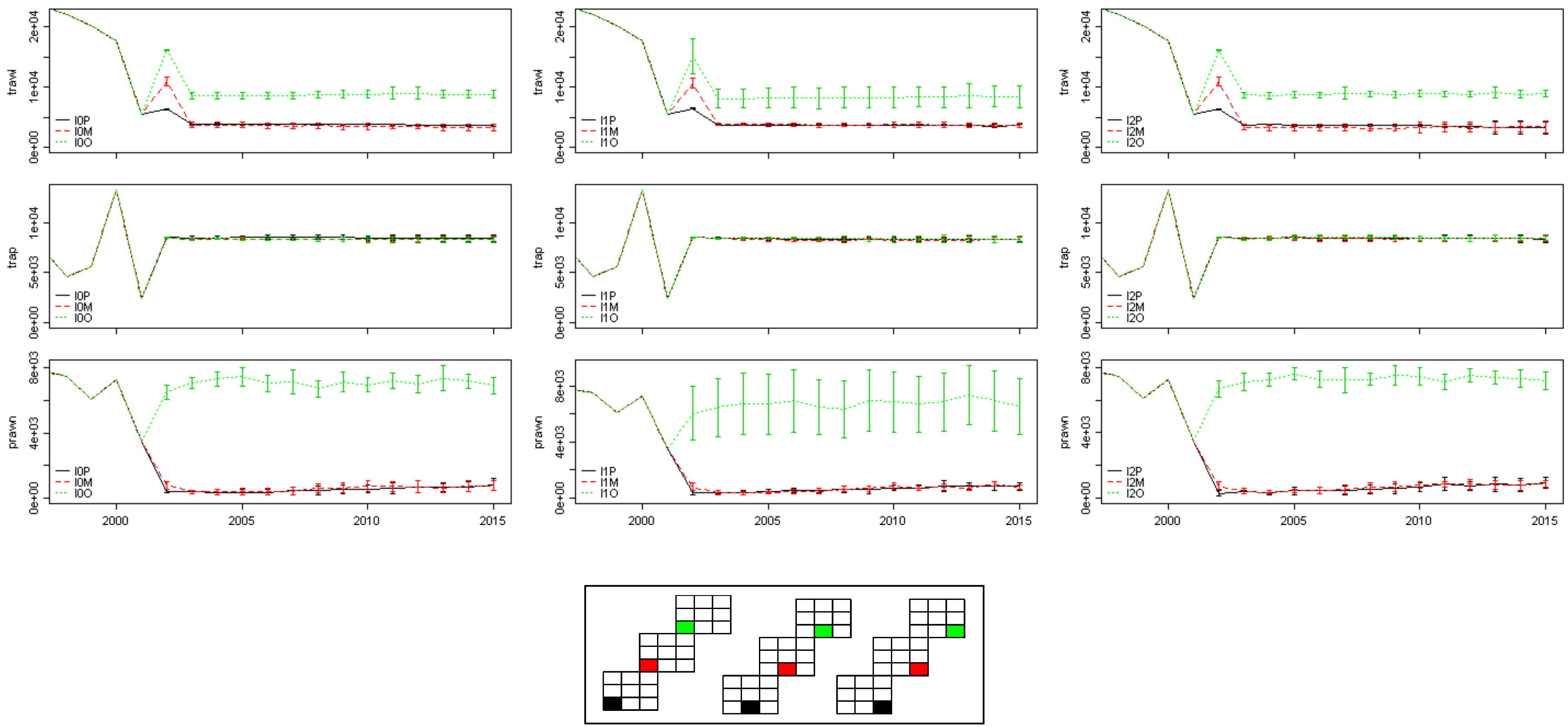


Figure D.15 (b): Comparison of model specifications for total effort (fishing hours) for the different fisheries under the integrated management strategy across 0-pulse, 1-pulse and 2-pulse (left to right) development scenarios for the projection period only.

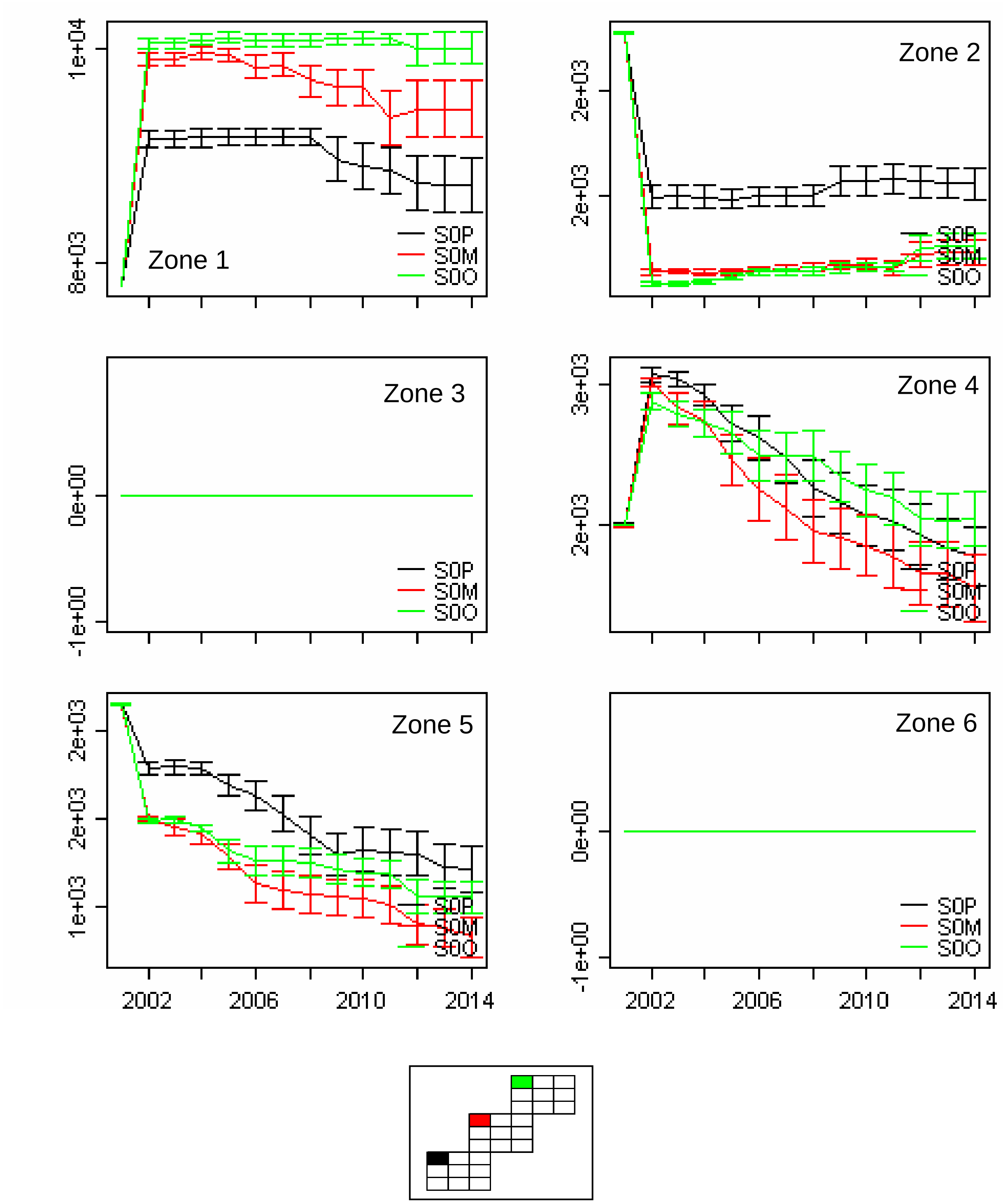
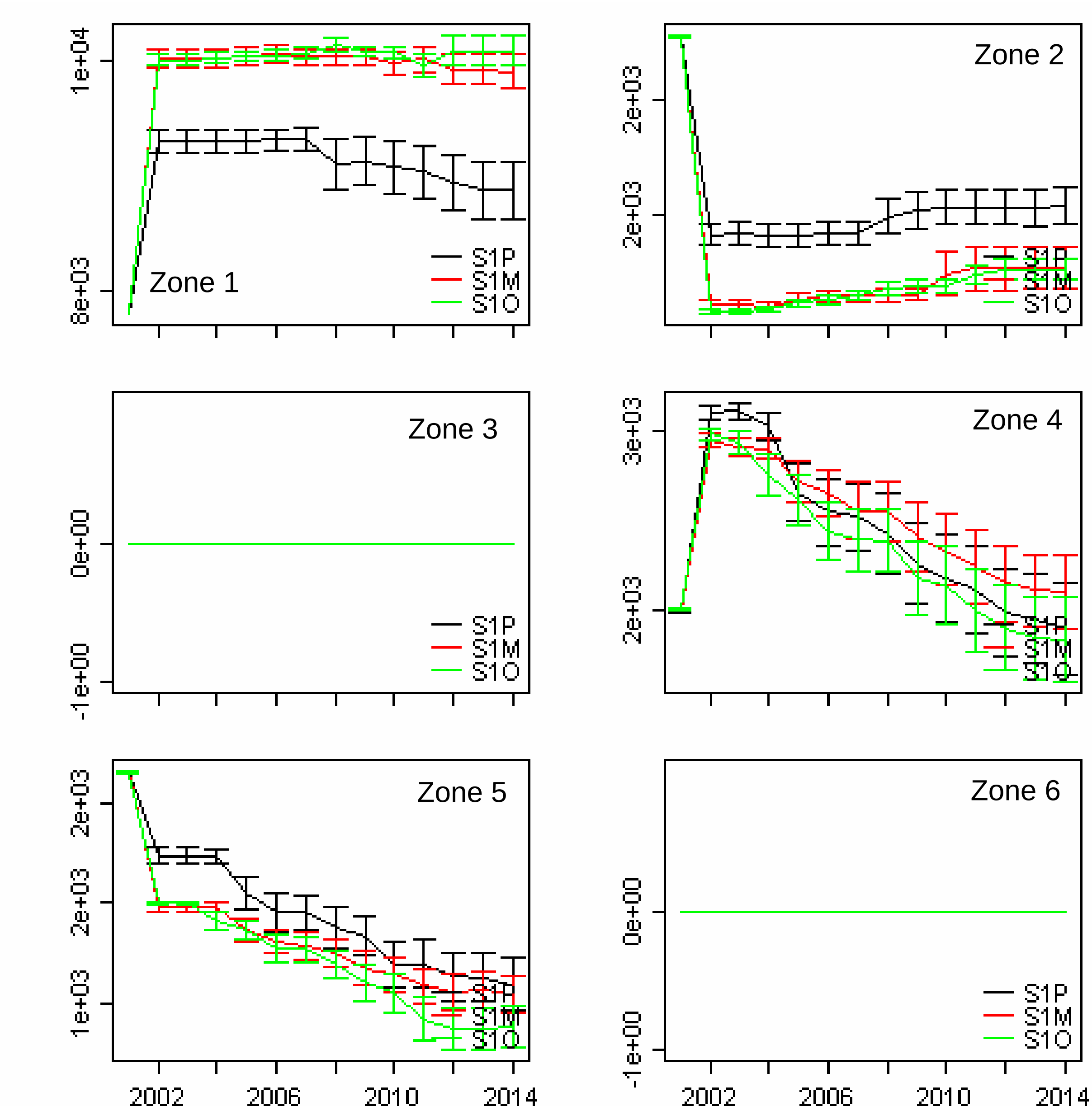


Figure D.16: Comparison of model specifications for finfish trawl effort (trawl hours) in the six trawl areas under the zero-pulse development scenario and status quo management.



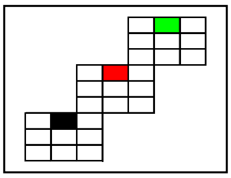
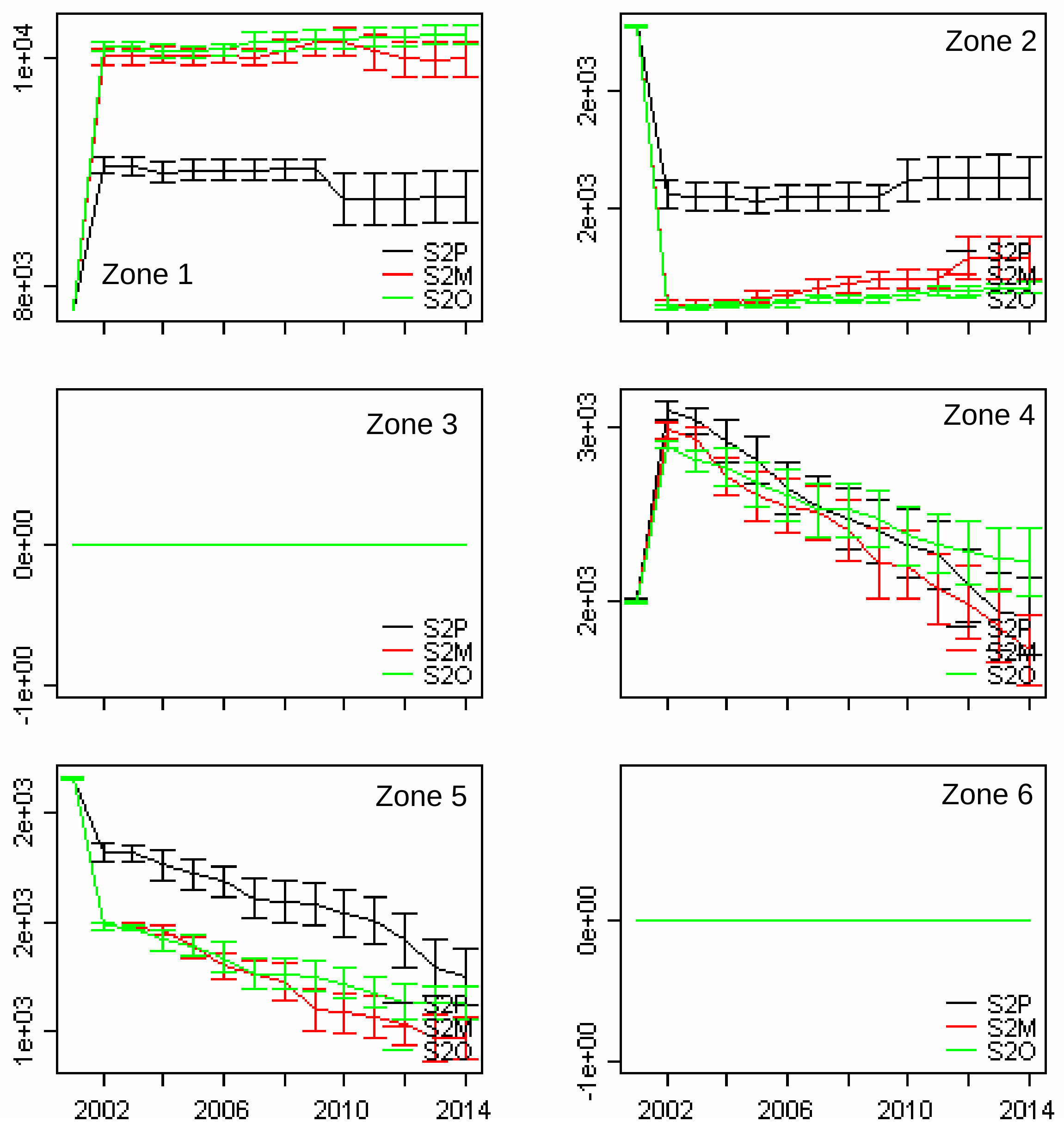


Figure D.17: Comparison of model specifications for finfish trawl effort (trawl hours) in the six trawl areas under the one-pulse development scenario and status quo management.



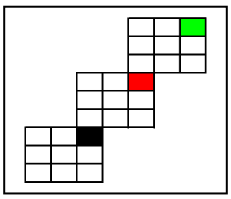


Figure D.18: Comparison of model specifications for finfish trawl effort (trawl hours) in the six trawl areas under the two-pulse development scenario and status quo management.

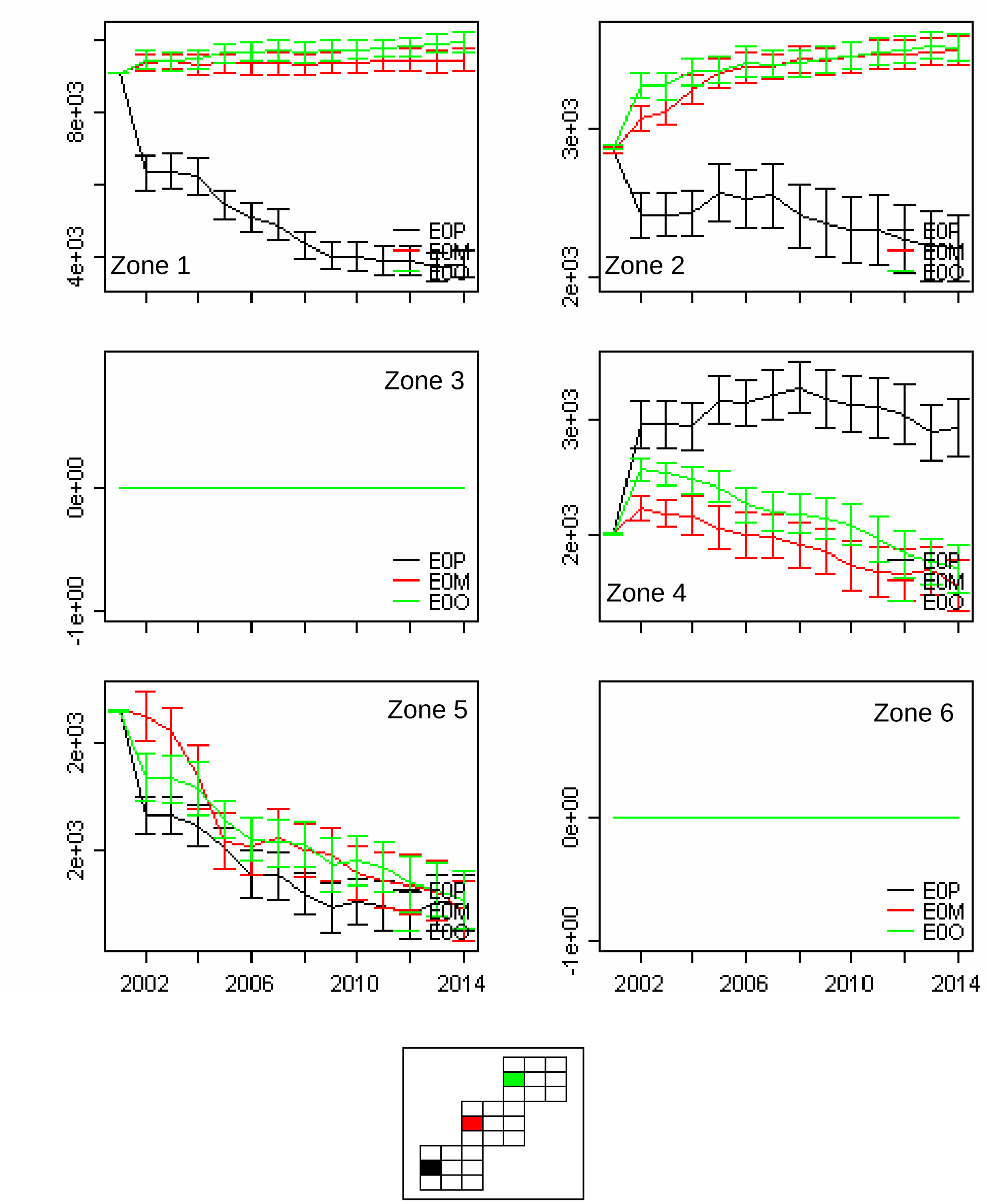
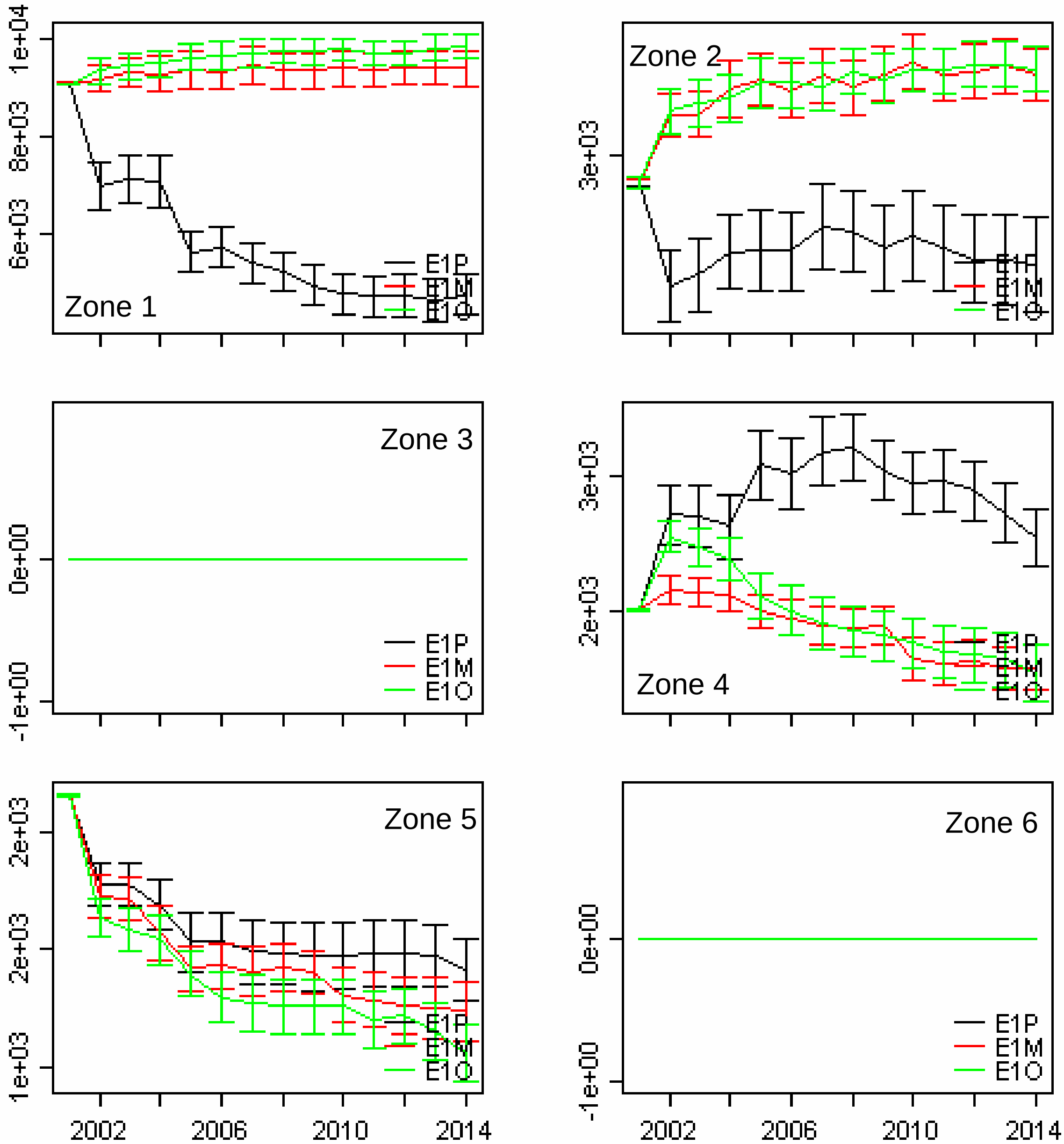


Figure D.19: Comparison of model specifications for finfish trawl effort (trawl hours) in the six trawl areas under the zero-pulse development scenario and enhanced management.



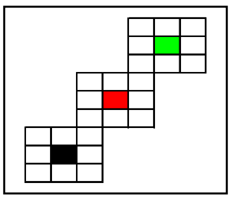


Figure D.20: Comparison of model specifications for finfish trawl effort (trawl hours) in the six trawl areas under the one-pulse development scenario and enhanced management.

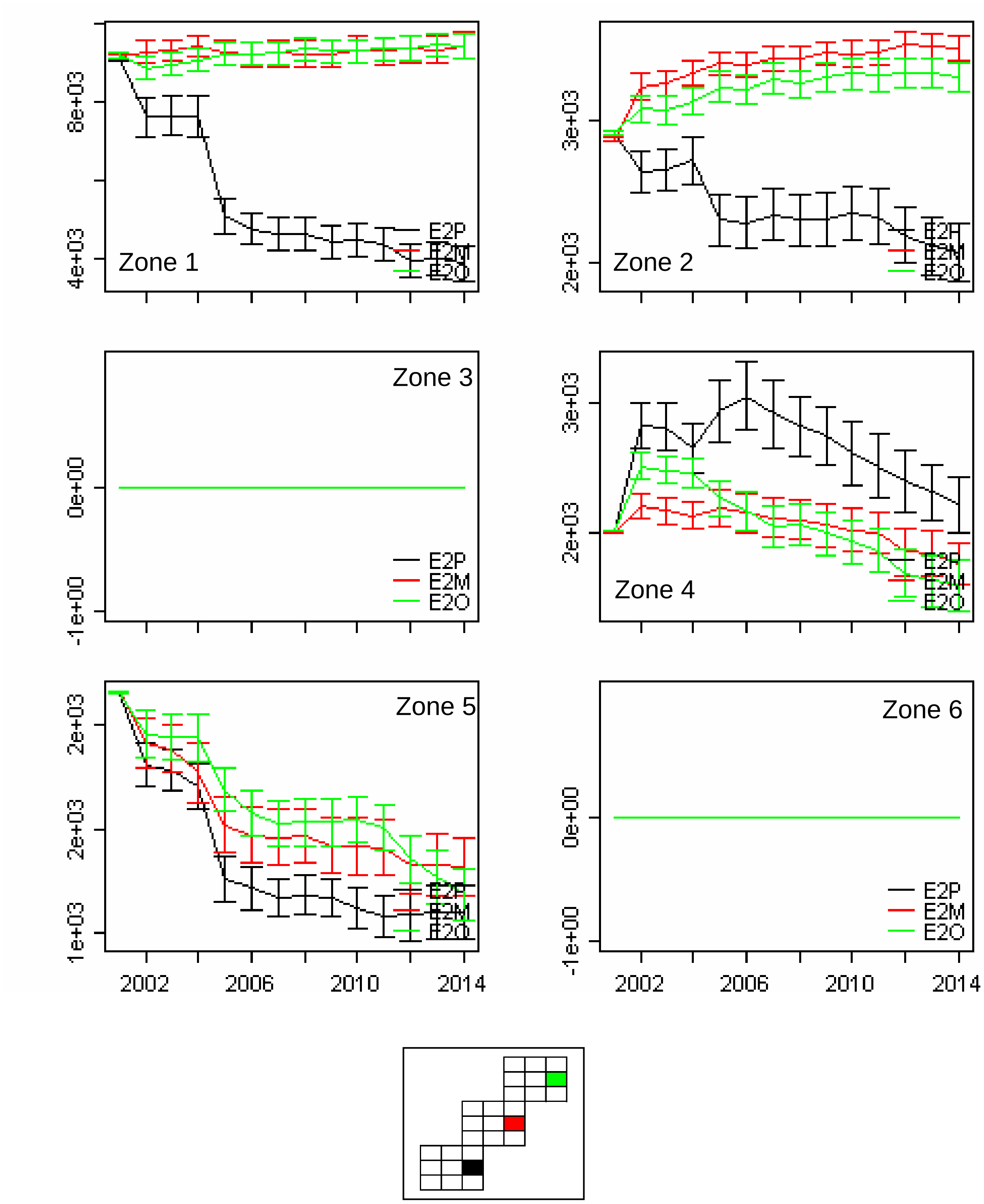
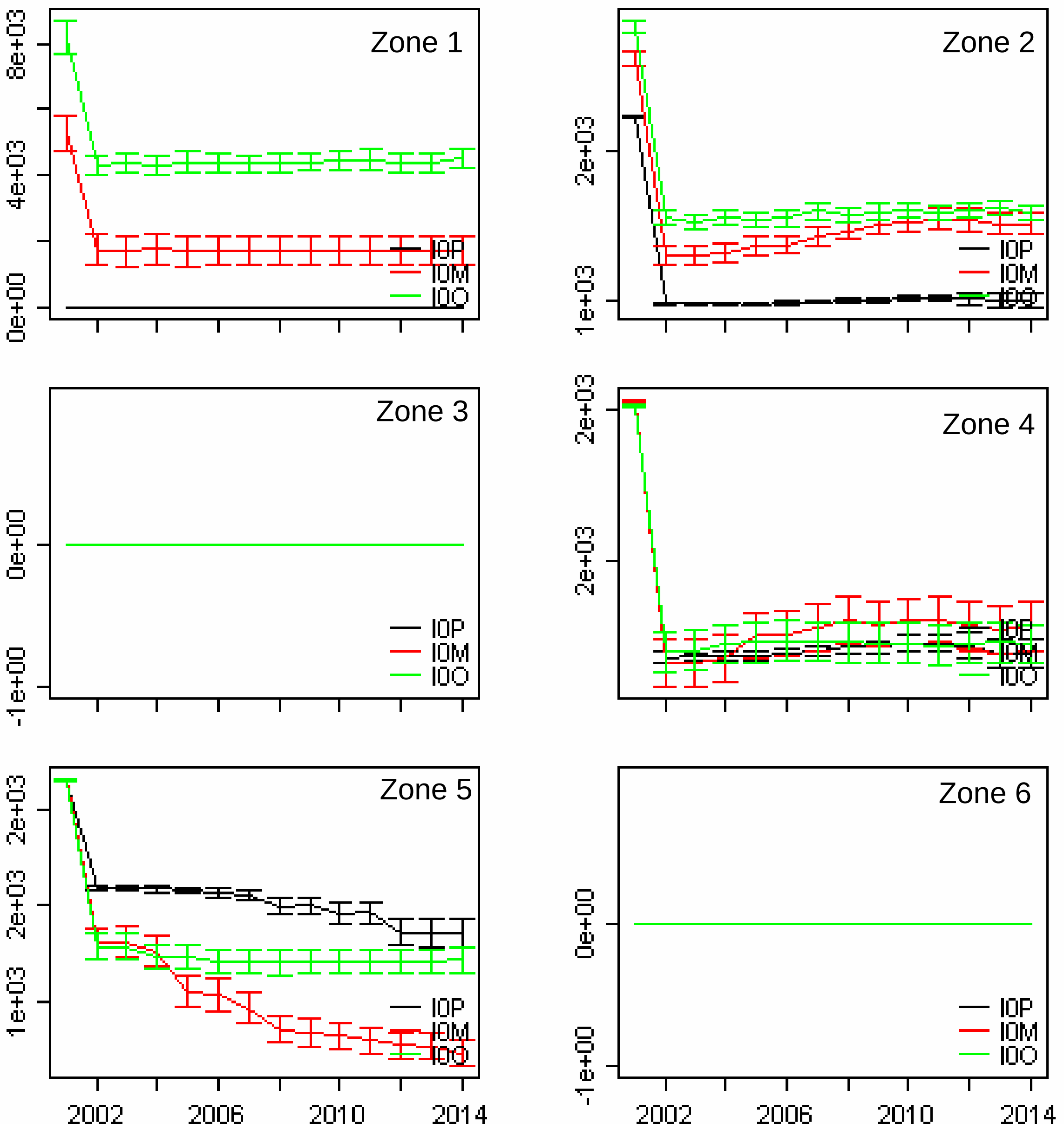


Figure D.21: Comparison of model specifications for finfish trawl effort (trawl hours) in the six trawl areas under the two-pulse development scenario and enhanced management.



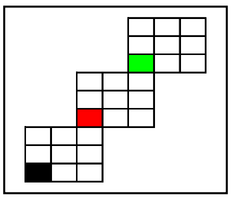


Figure D.22: Comparison of model specifications for finfish trawl effort (trawl hours) in the six trawl areas under the zero-pulse development scenario and integrated management.

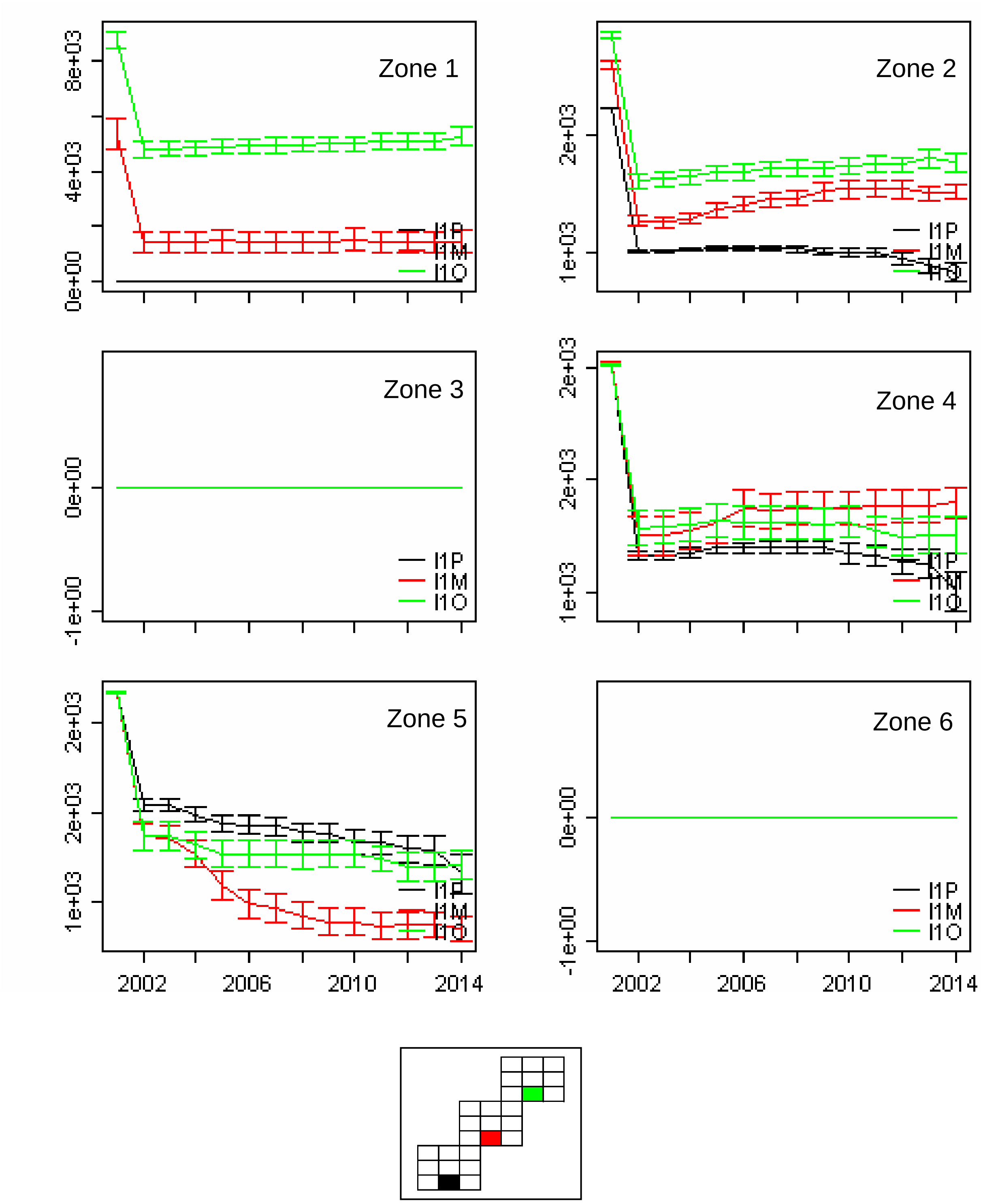
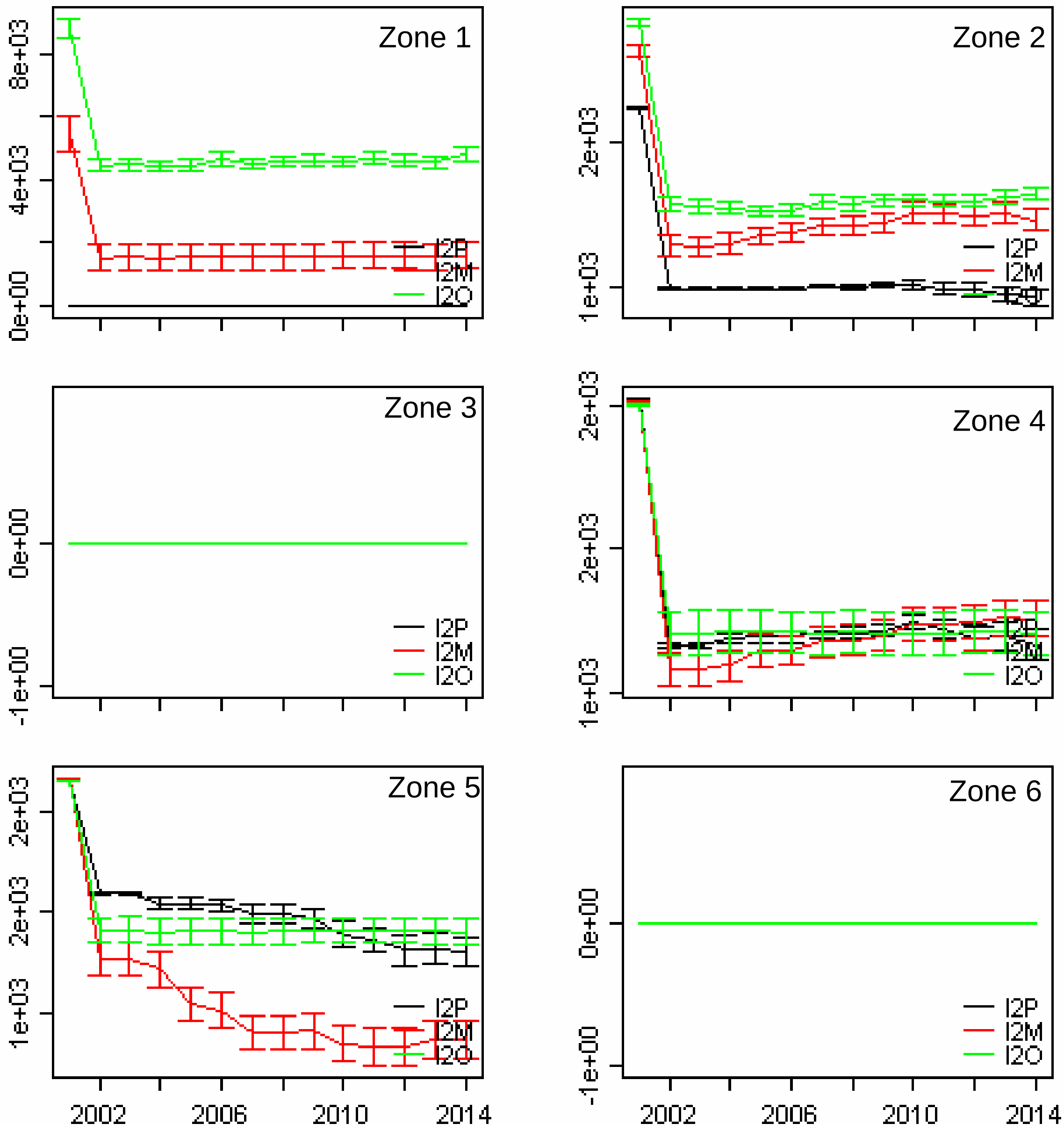


Figure D.23: Comparison of model specifications for finfish trawl effort (trawl hours) in the six trawl areas under the one-pulse development scenario and integrated management.



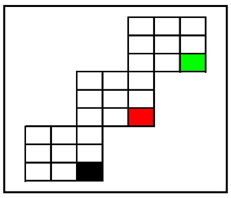


Figure D.24: Comparison of model specifications for finfish trawl effort (trawl hours) in the six trawl areas under the two-pulse development scenario and integrated management.

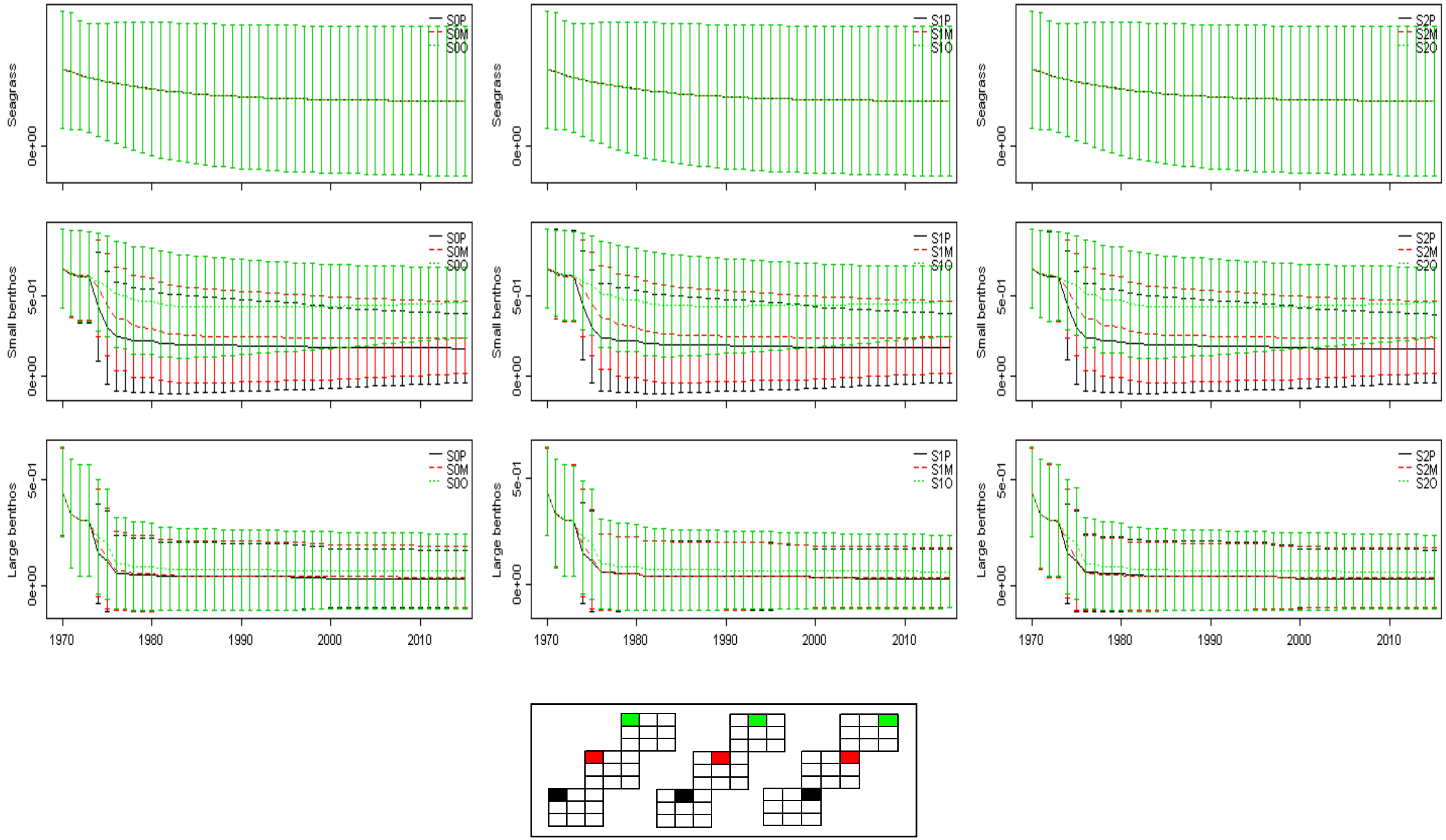


Figure D.25 (a): Comparison of model specifications for the spatial extent of three habitats under the status quo management strategy across 0-pulse, 1-pulse and 2-pulse (left to right) development scenarios for seagrass and large and small benthos.

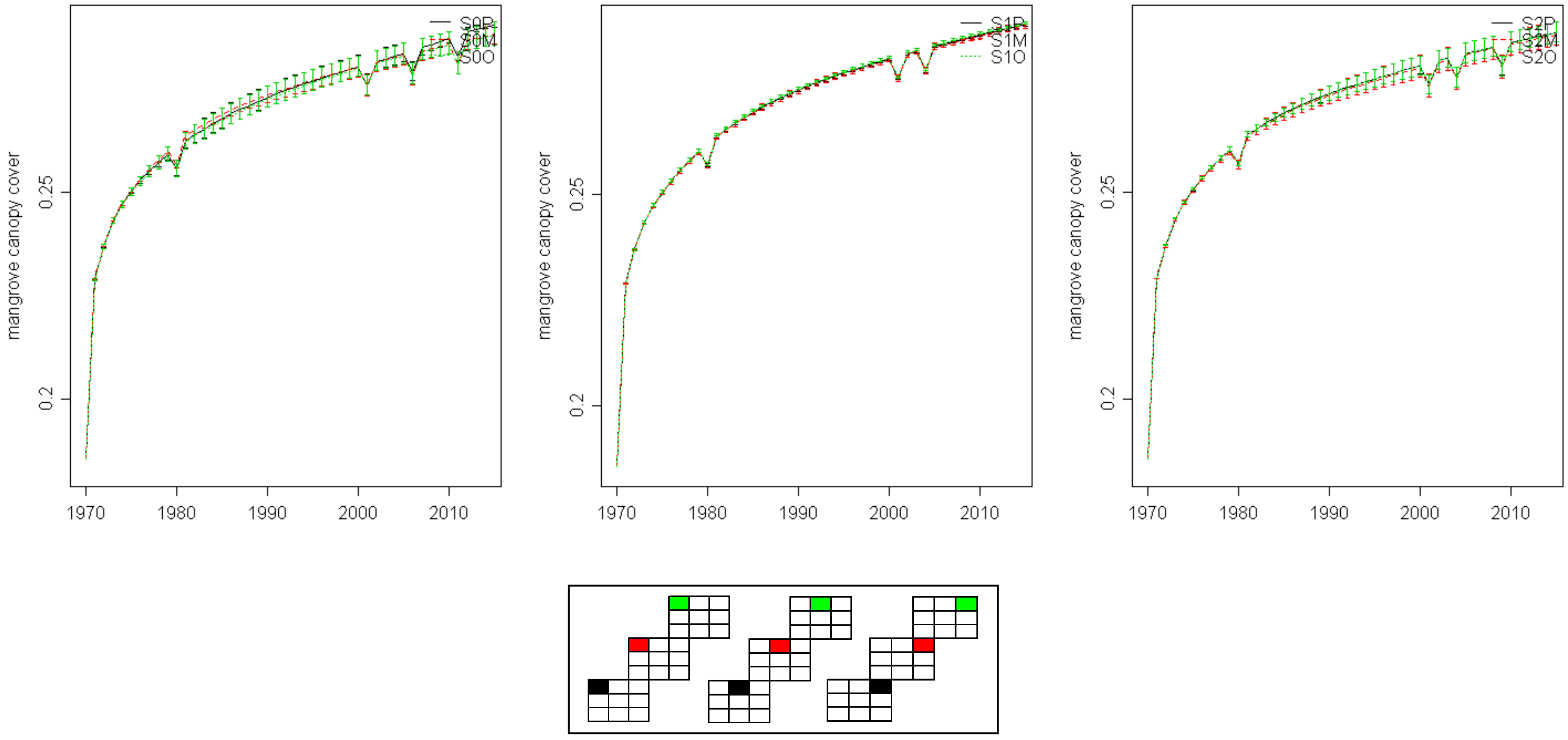


Figure D.25 (b): Comparison of model specifications for the spatial extent of three habitats under the status quo management strategy across 0-pulse, 1-pulse and 2-pulse (left to right) development scenarios for mangroves.

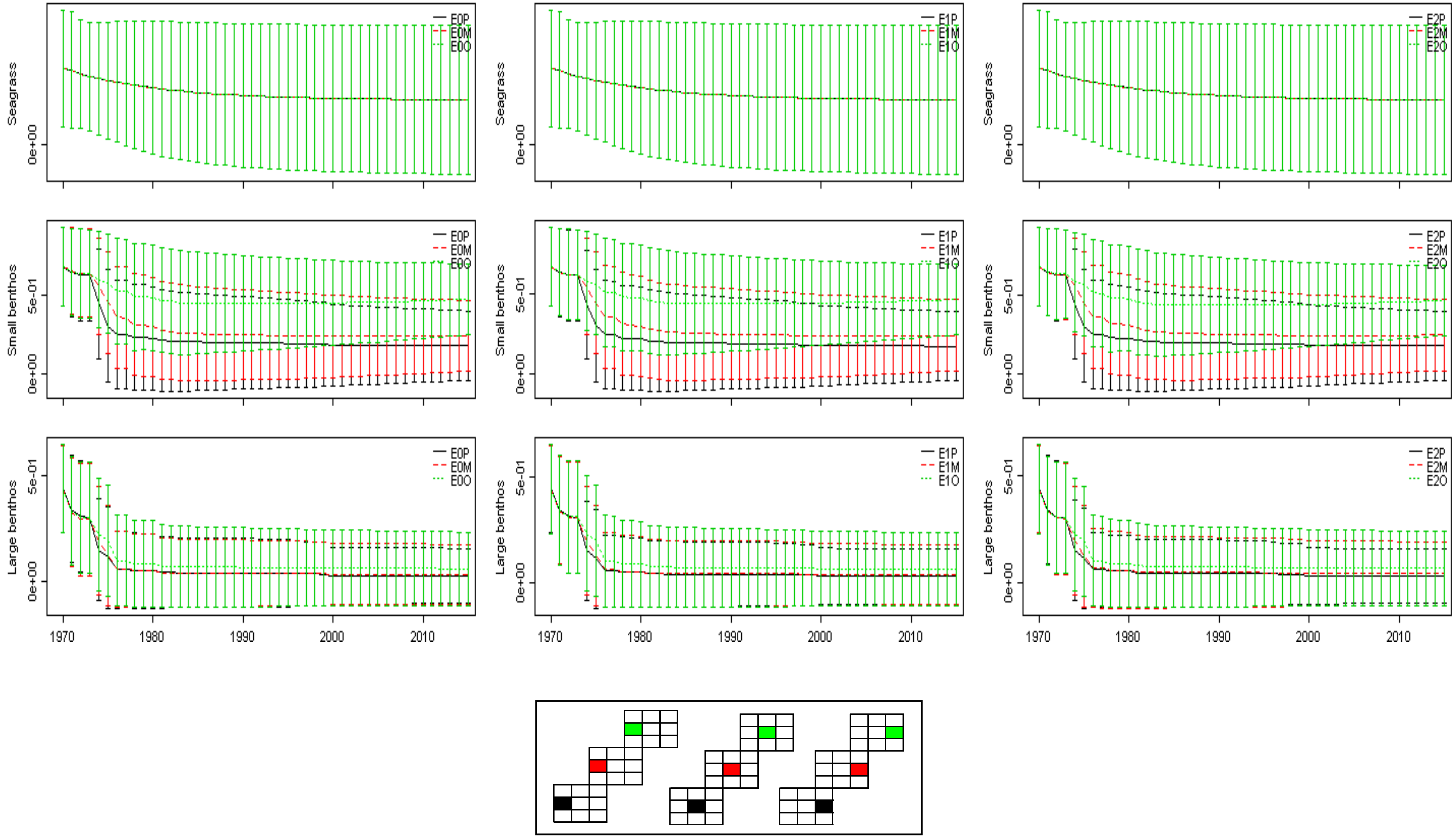


Figure D.26 (a): Comparison of model specifications for the spatial extent of three habitats under the enhanced management strategy across 0-pulse, 1-pulse and 2-pulse (left to right) development scenarios for seagrass and large and small benthos.

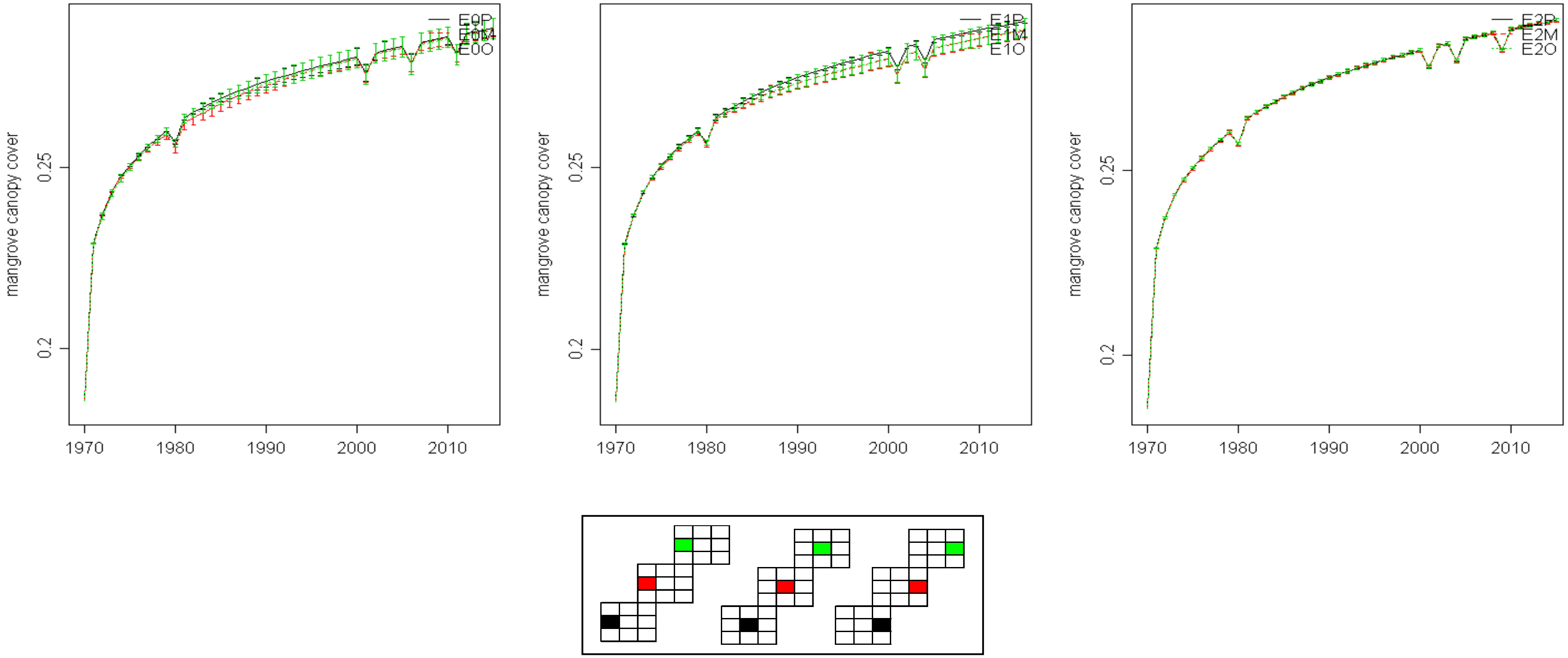


Figure D.26 (b): Comparison of model specifications for the spatial extent of three habitats under the enhanced management strategy across 0-pulse, 1-pulse and 2-pulse (left to right) development scenarios for mangroves.

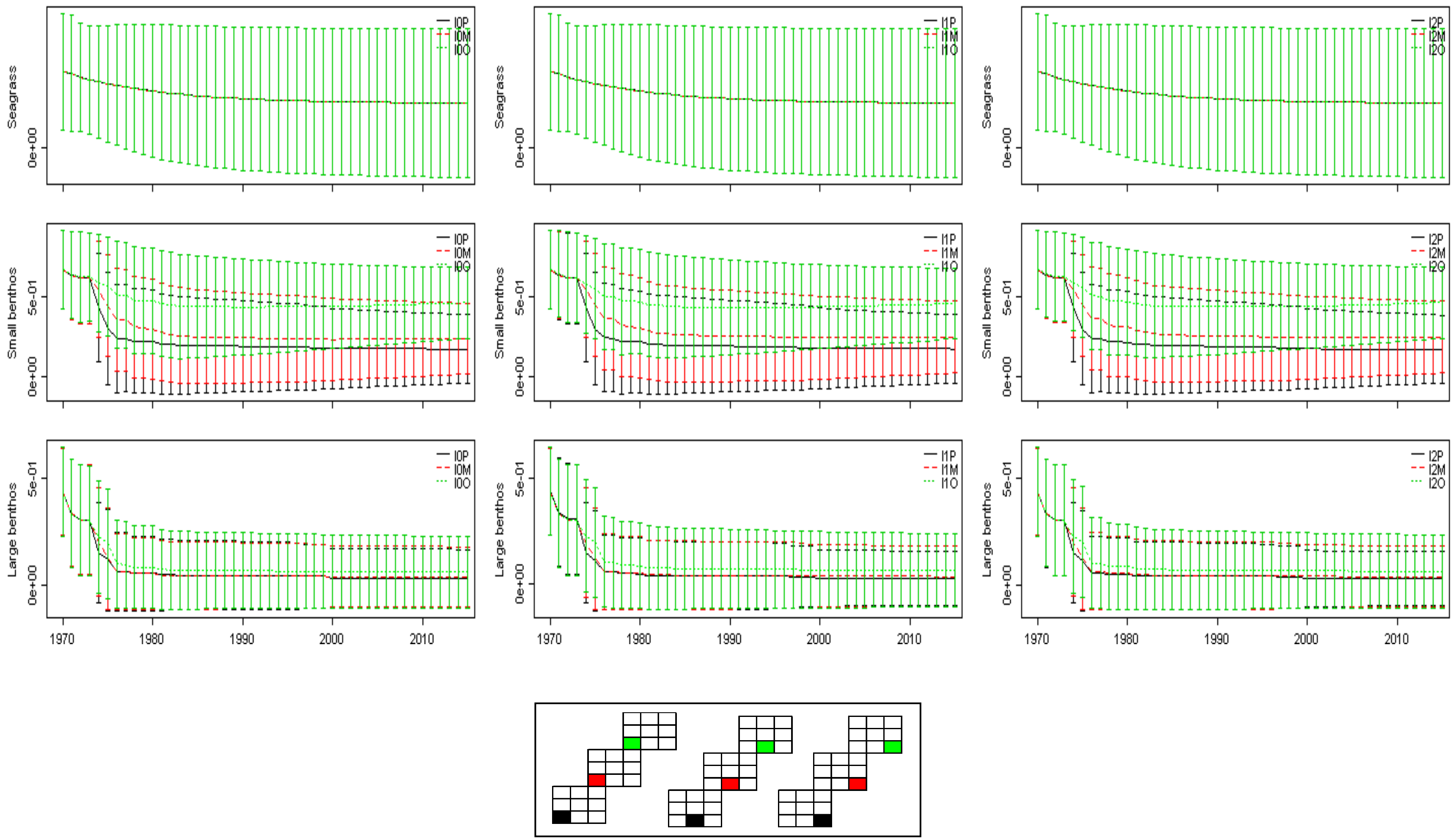


Figure D.27 (a): Comparison of model specifications for the spatial extent of three habitats under the integrated management strategy across 0-pulse, 1-pulse and 2-pulse (left to right) development scenarios for seagrass and large and small benthos.

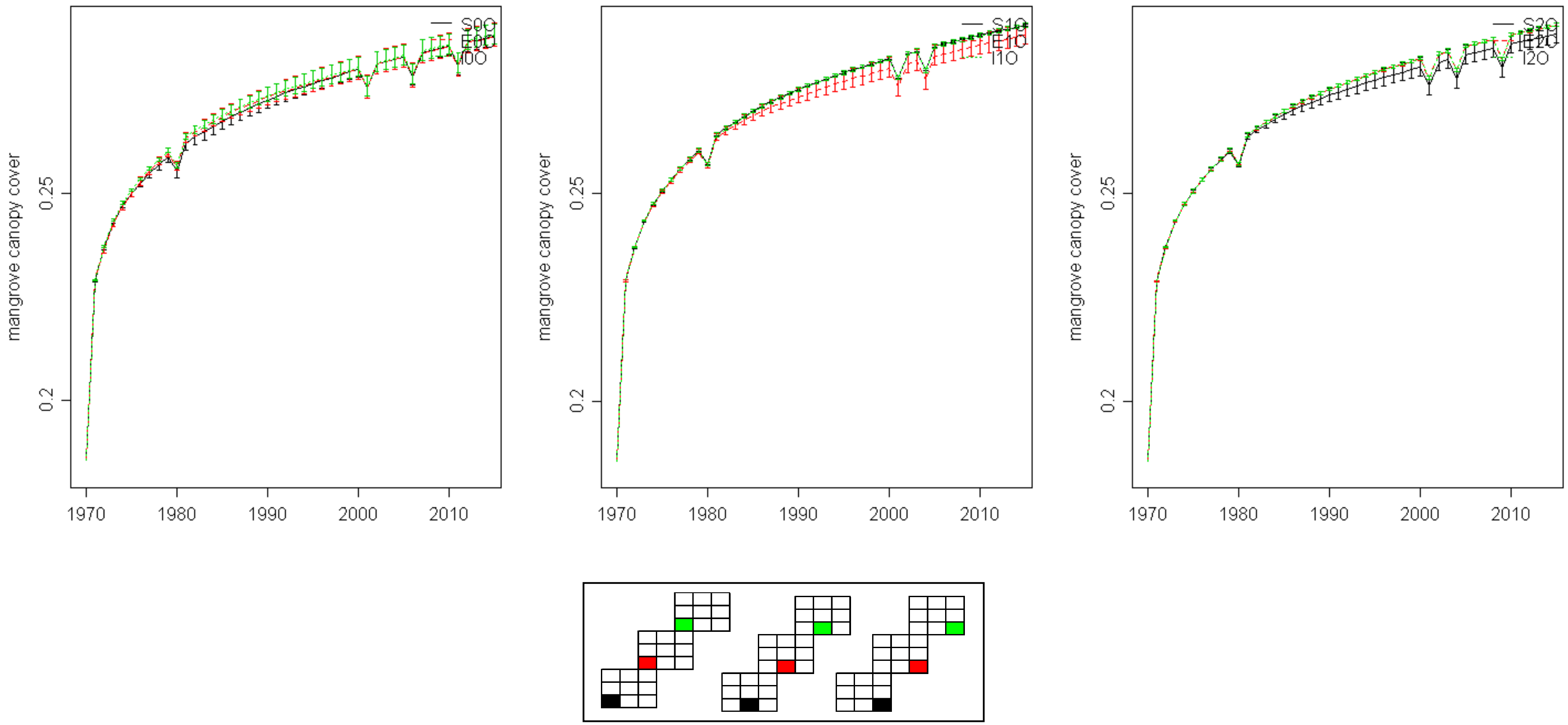


Figure D.27 (b): Comparison of model specifications for the spatial extent of three habitats under the integrated management strategy across 0-pulse, 1-pulse and 2-pulse (left to right) development scenarios for mangroves.

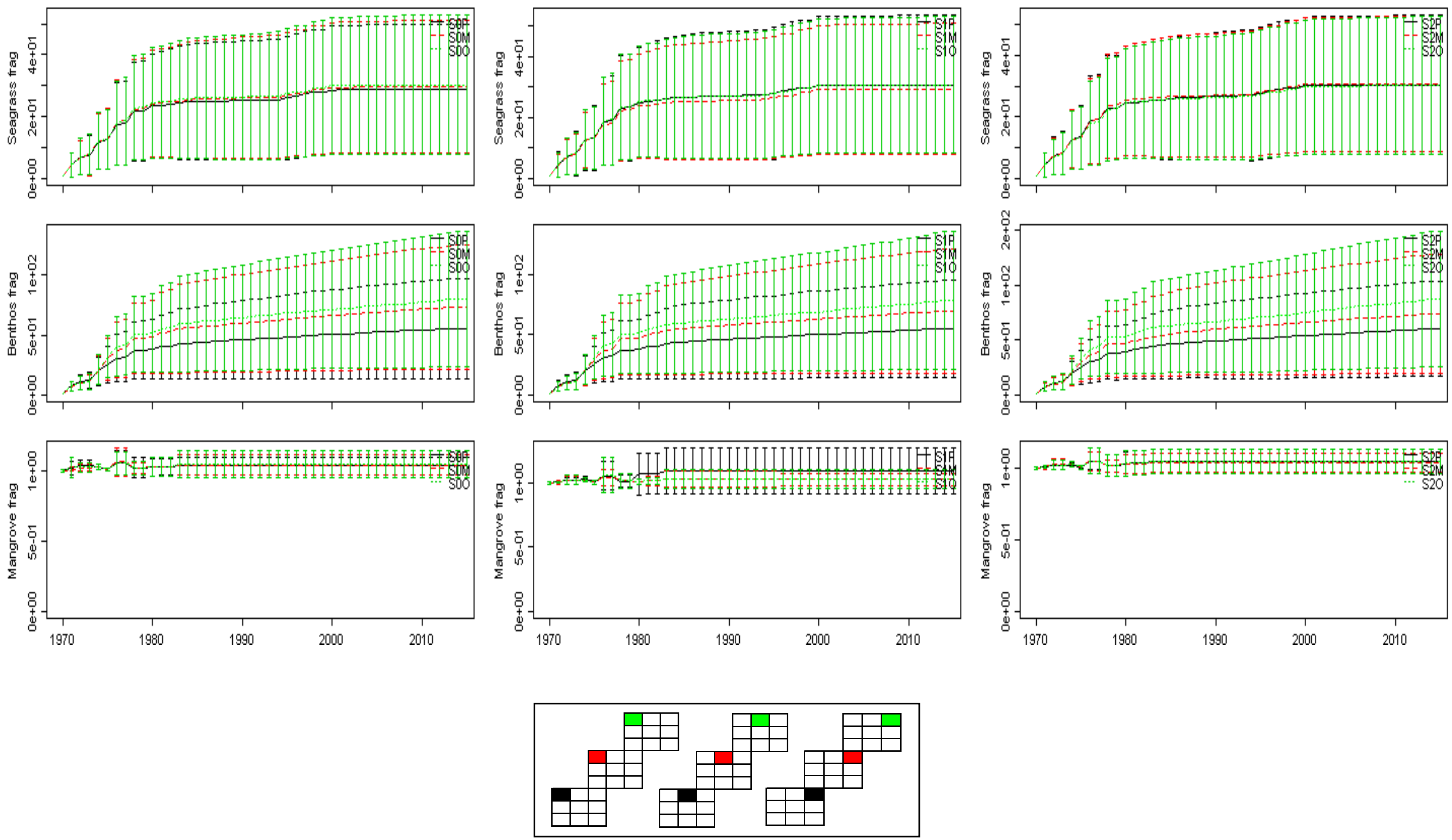


Figure D.28: Comparison of model specifications for the spatial fragmentation of three habitats under the status quo management strategy. Habitat fragmentation is measured by the number of patches per grid cell.

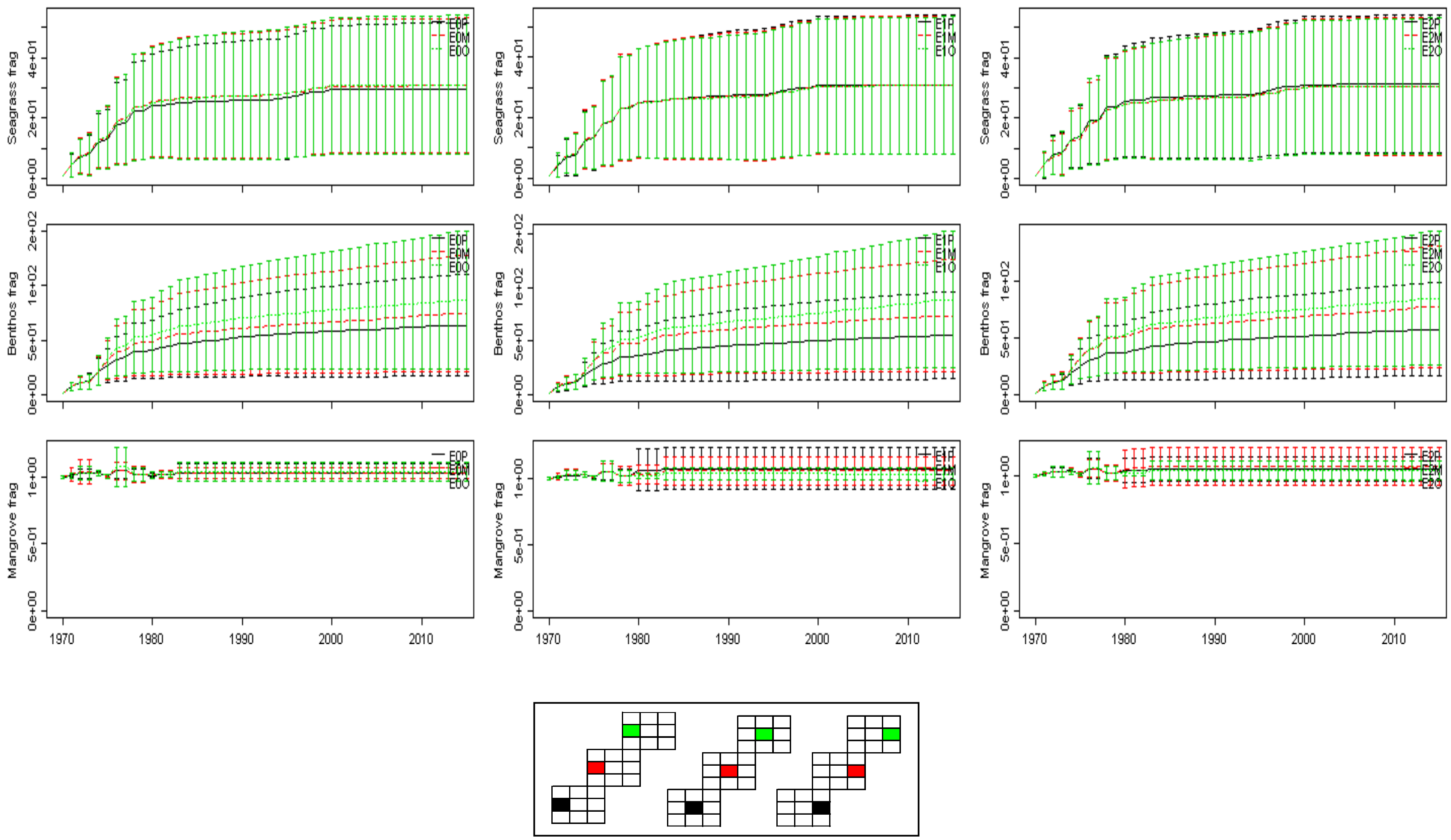


Figure D.29: Comparison of model specifications for the spatial fragmentation of three habitats under the enhanced management strategy. Habitat fragmentation is measured by the number of patches per grid cell.

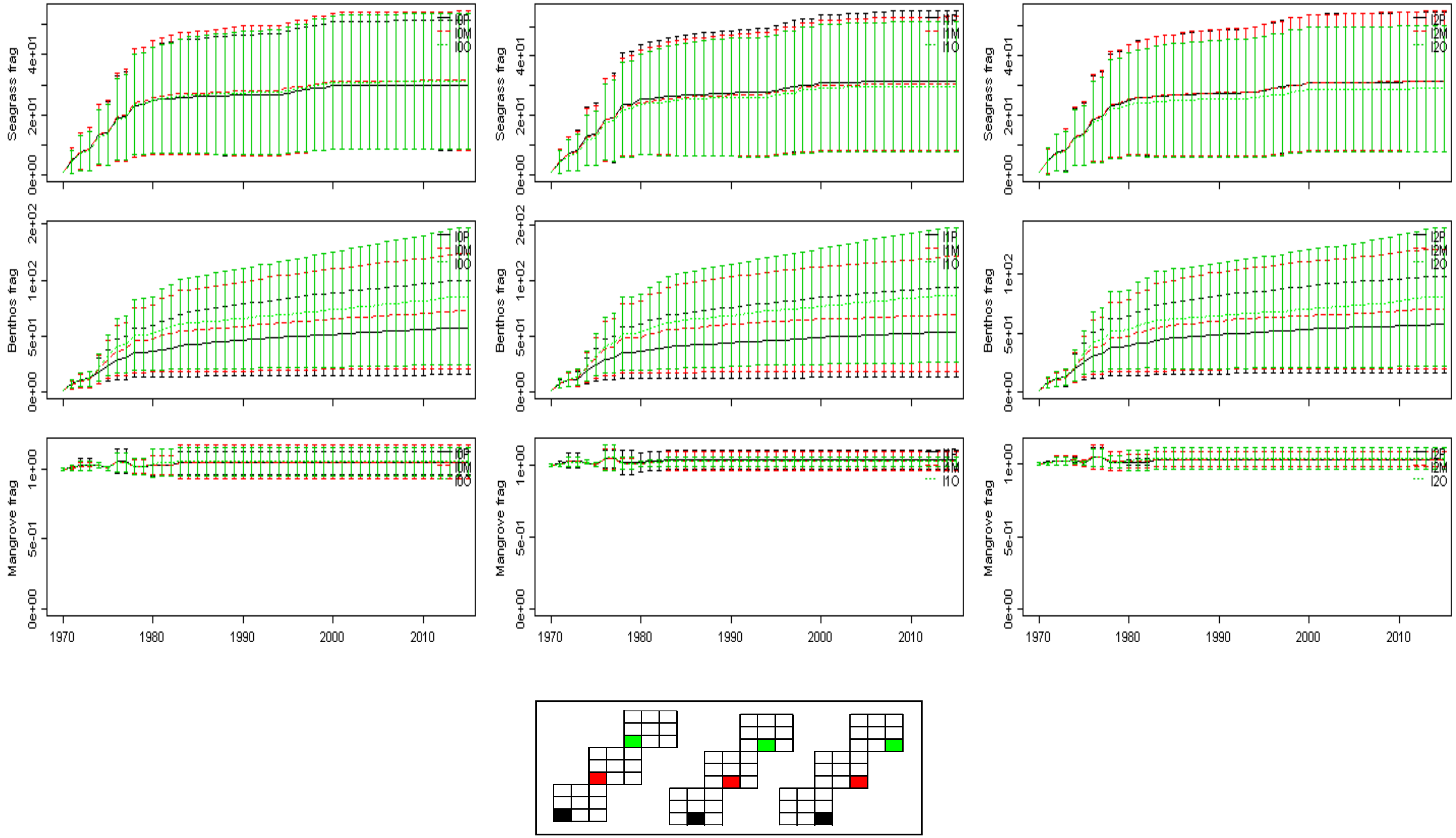
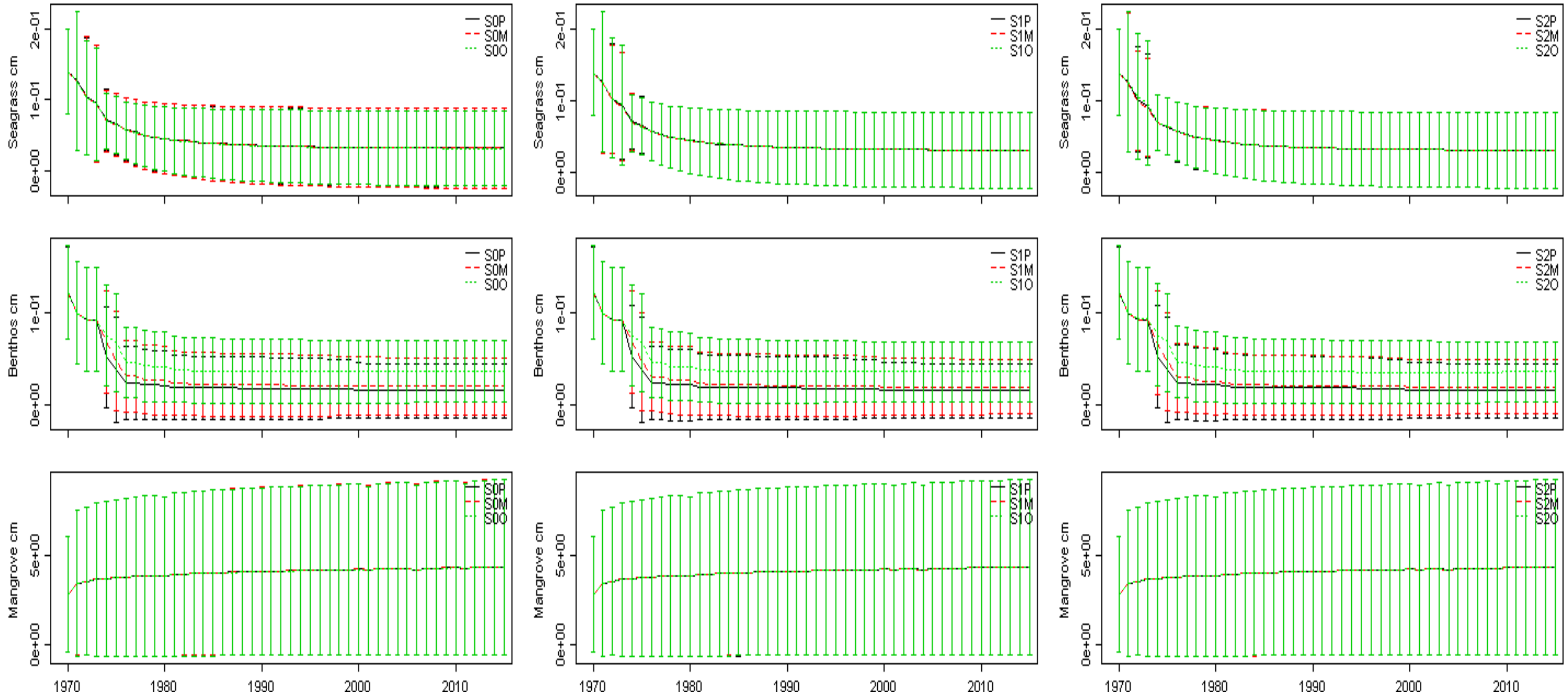


Figure D.30: Comparison of model specifications for the spatial fragmentation of three habitats under the integrated management strategy. Habitat fragmentation is measured by the number of patches per grid cell.



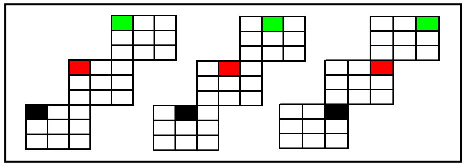


Figure D.31: Comparison of model specifications for the average vertical height of three habitats under the status quo management strategy.

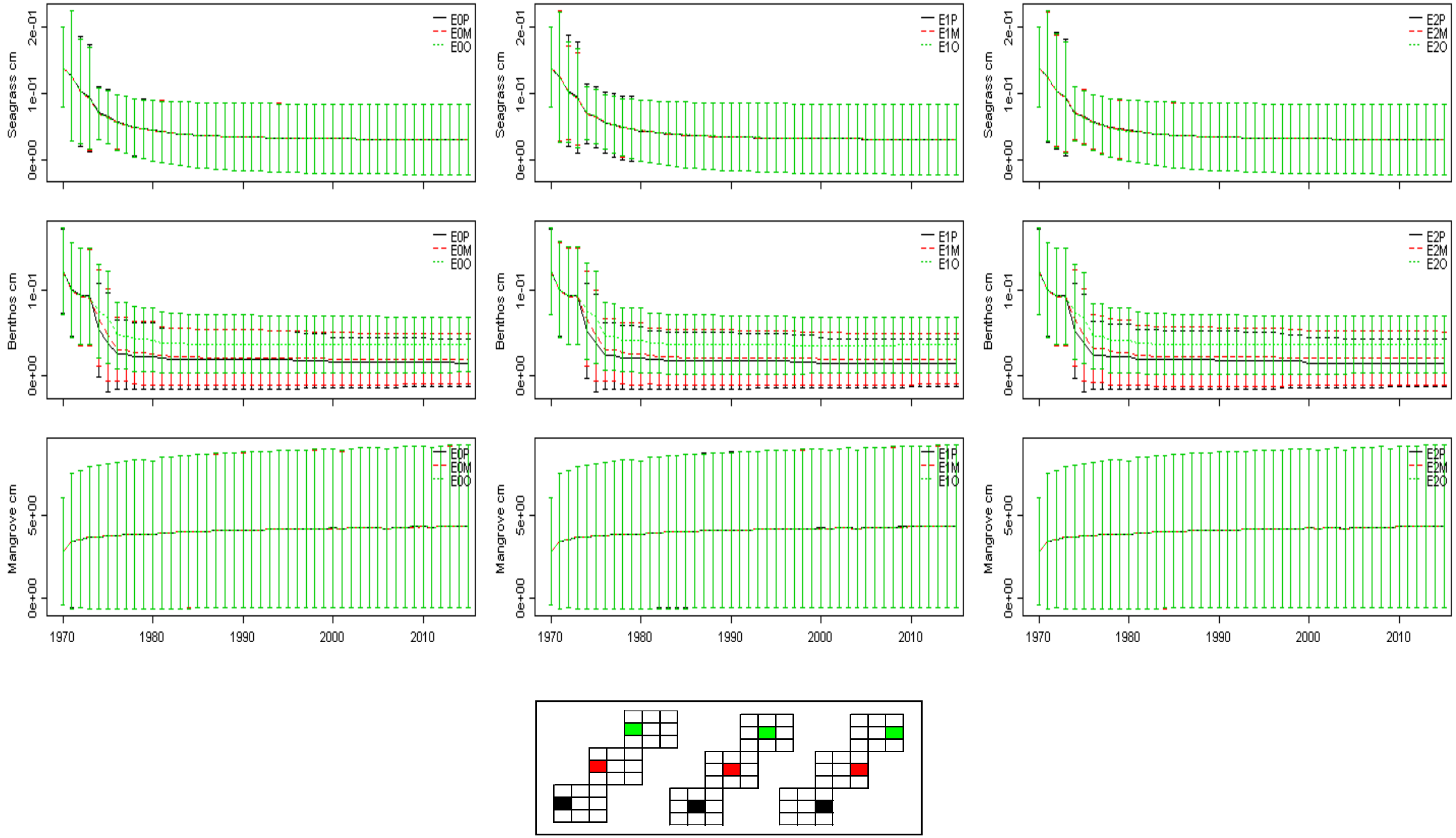


Figure D.32: Comparison of model specifications for the average vertical height of three habitats under the enhanced management strategy.

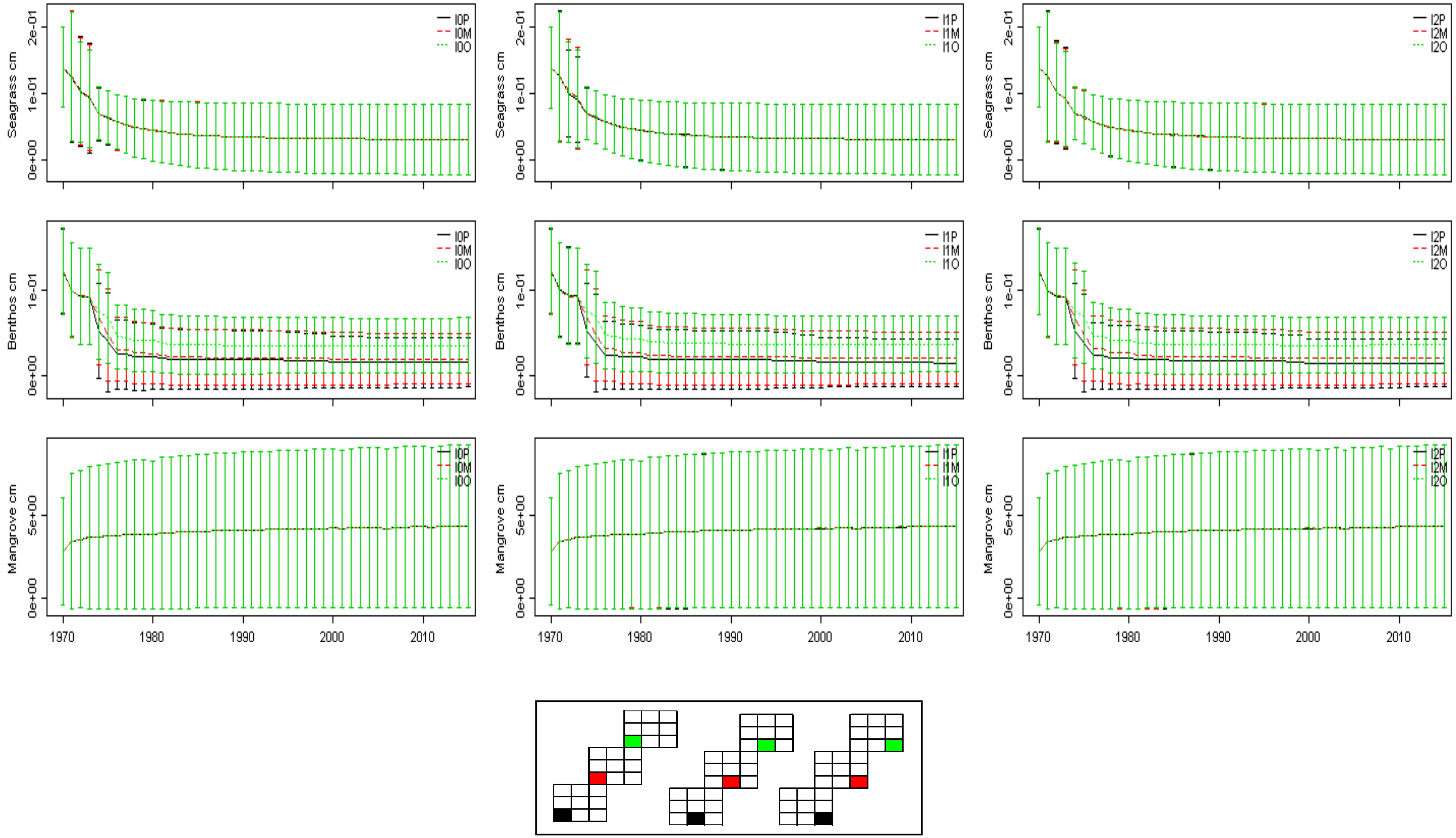


Figure D.33: Comparison of model specifications for the average vertical height (cm) of three habitats under the integrated management strategy.

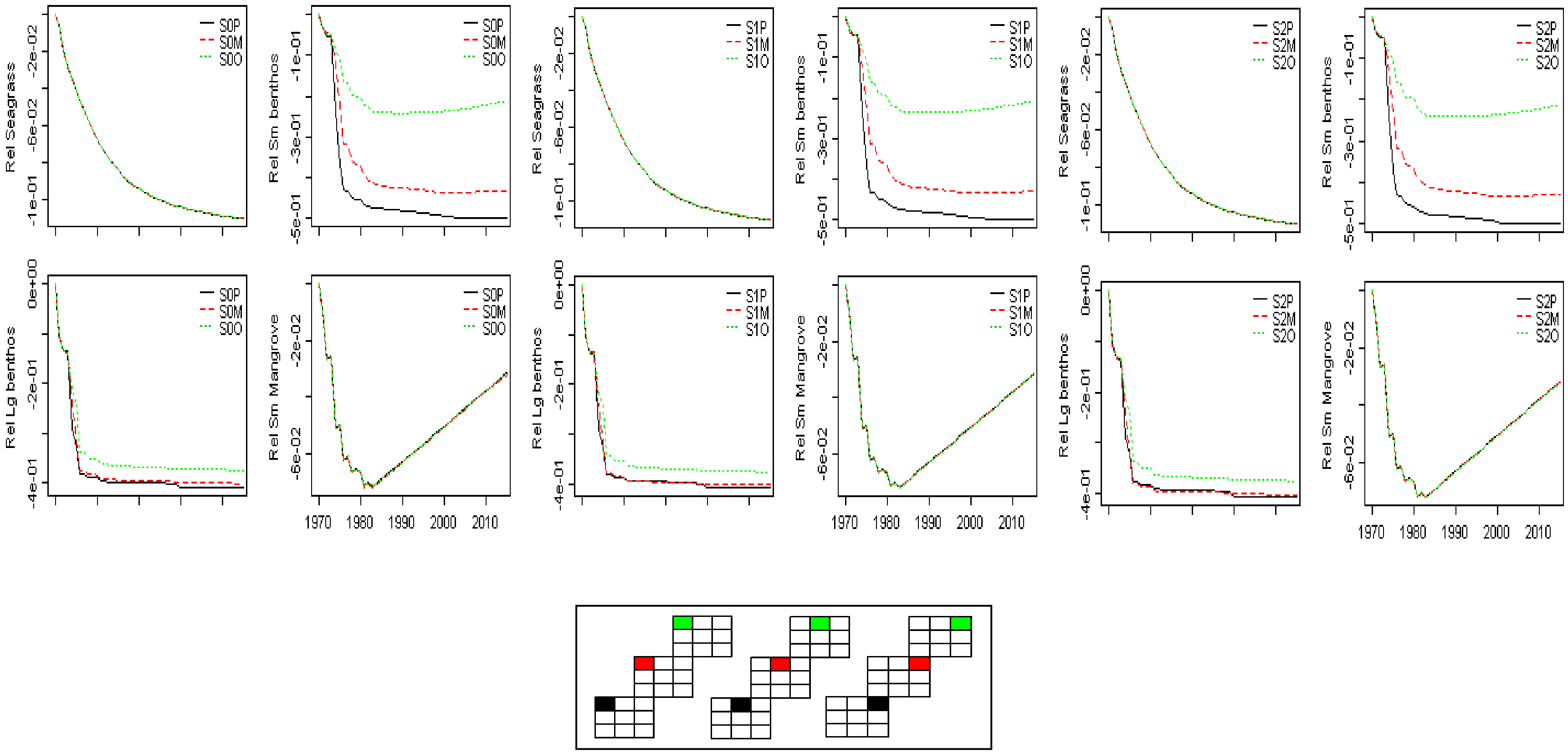


Figure D.34: Comparison of model specifications for habitat cover relative to initial amount in 1970 of seagrass, mangrove, large and small benthos under the status quo management strategy.

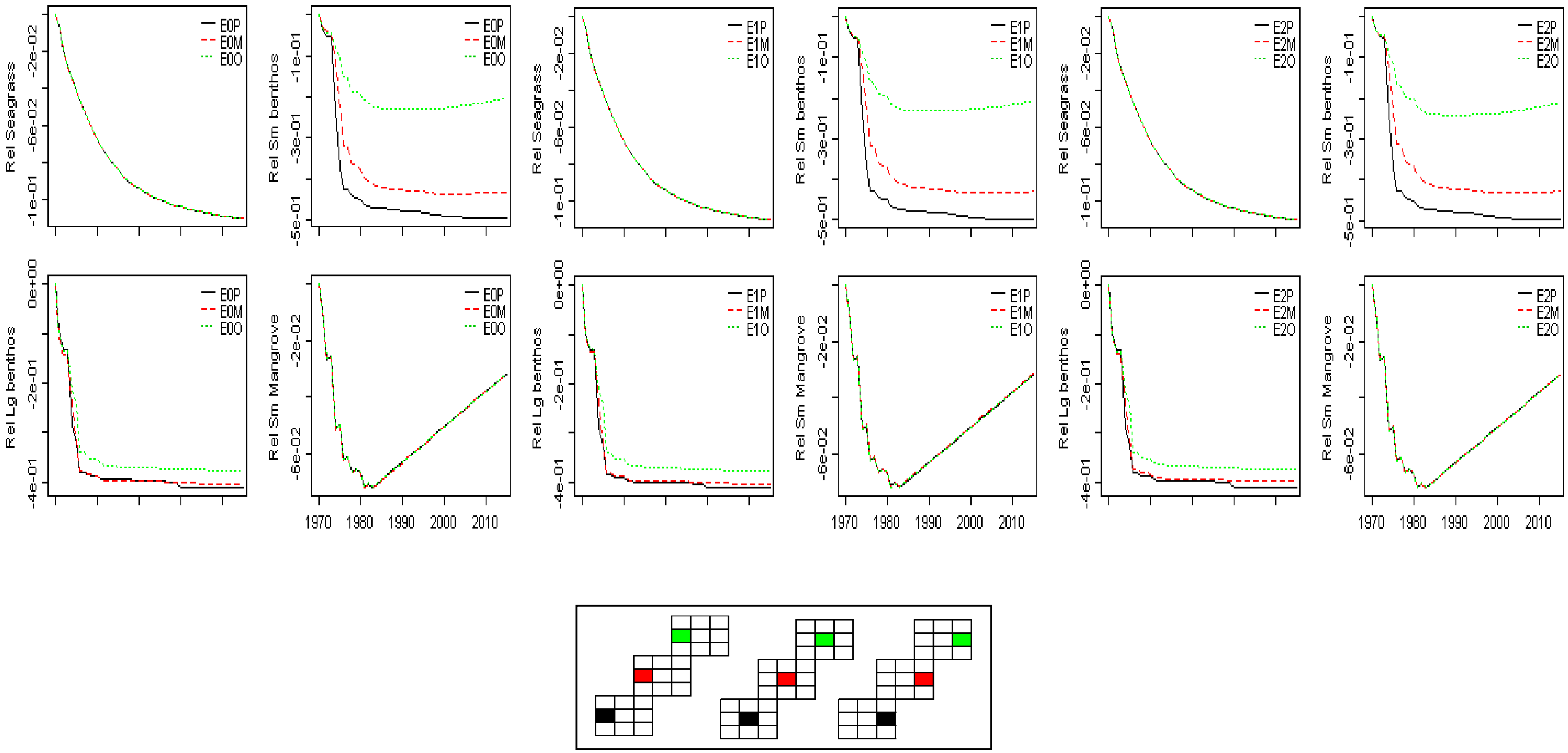


Figure D.35: Comparison of model specifications for habitat cover relative to initial amount in 1970 of seagrass, mangrove, large and small benthos under the enhanced management strategy.

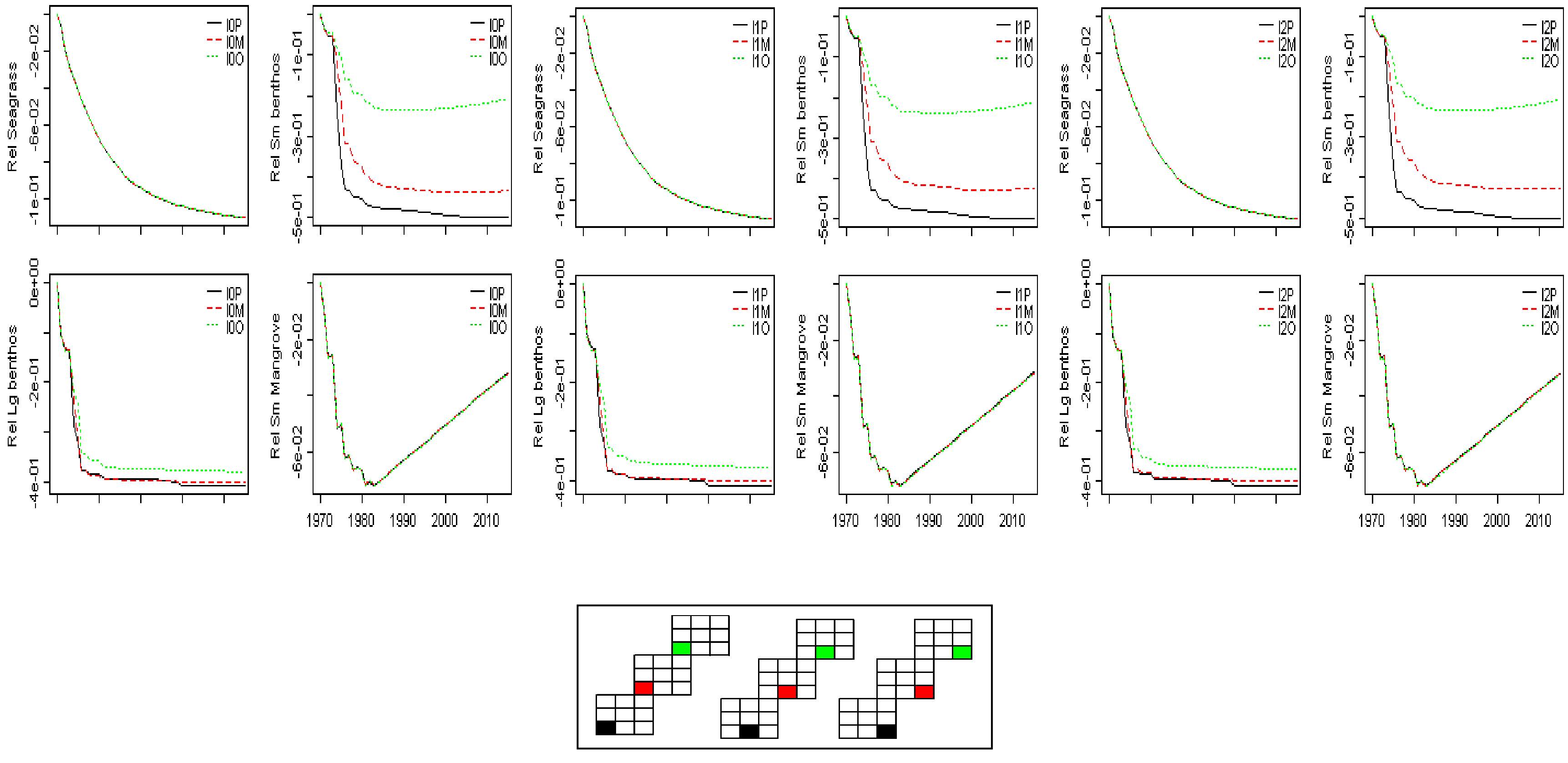


Figure D.36: Comparison of model specifications for habitat cover relative to initial amount in 1970 of seagrass, mangrove, large and small benthos under the integrated management strategy.

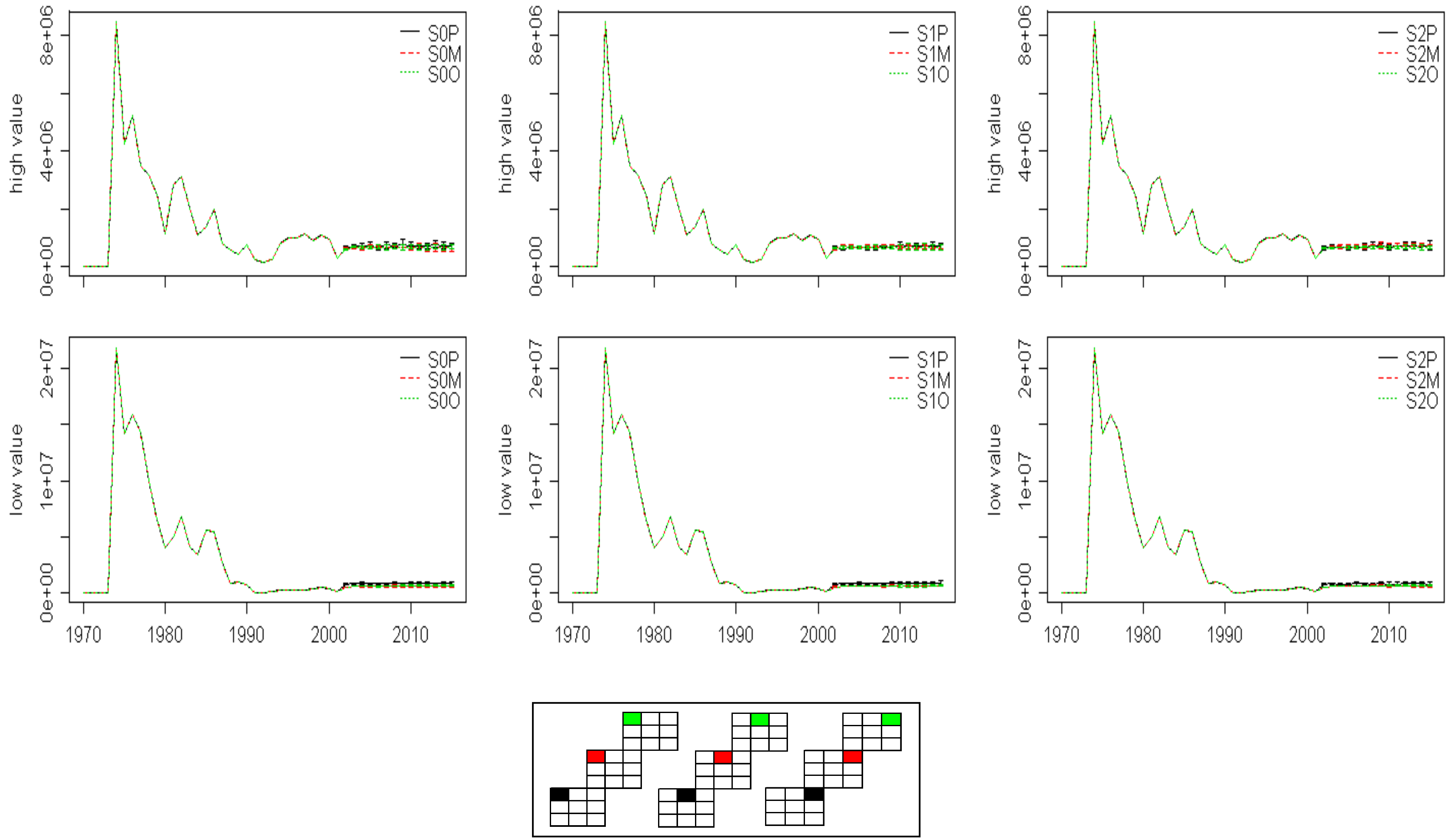


Figure D.37: Comparison of model specifications for total catches (kg) of high and low valued fish under the status quo management strategy.

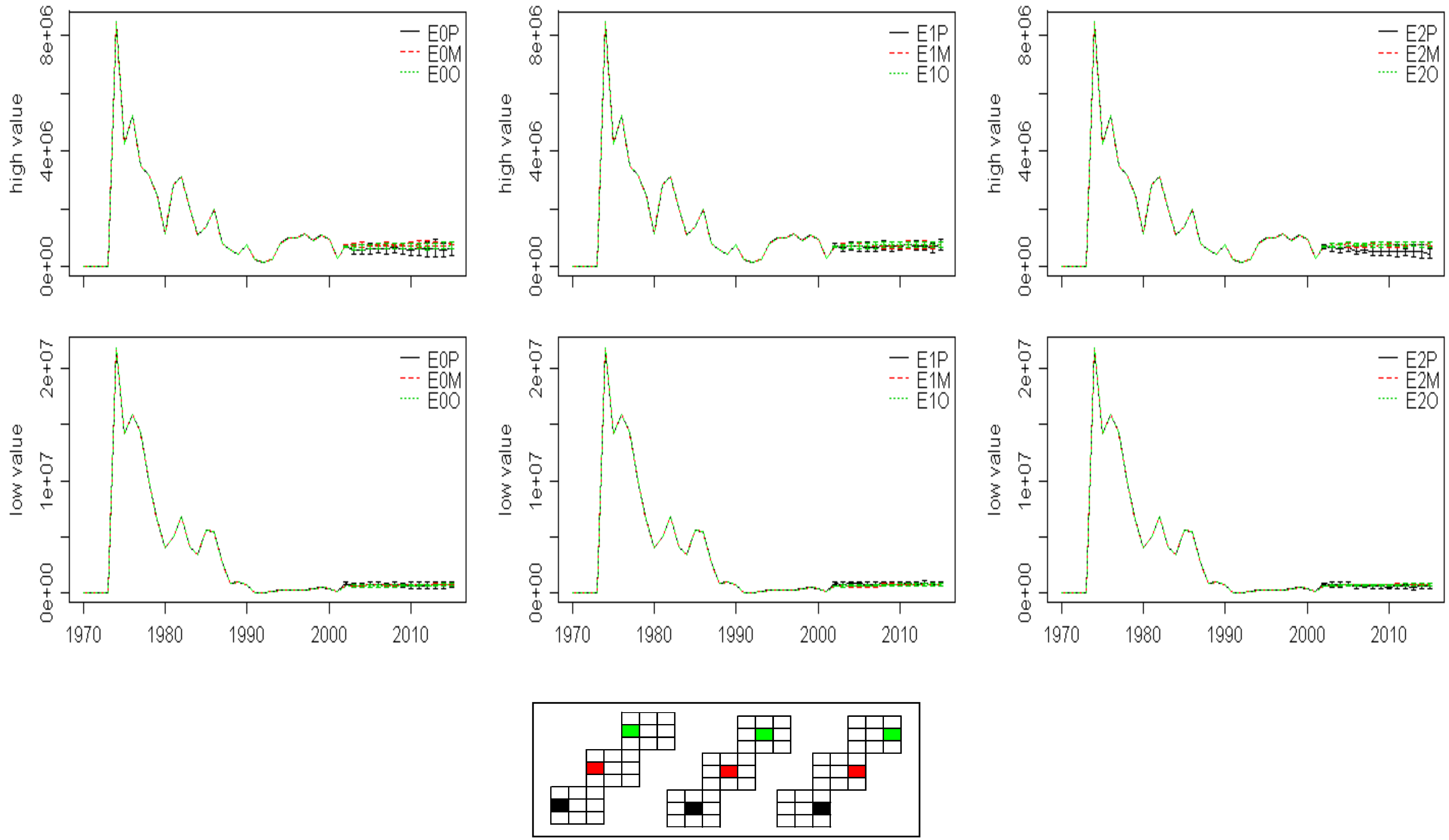


Figure D.38: Comparison of model specifications for total catches (kg) of high and low valued fish under the enhanced management strategy.

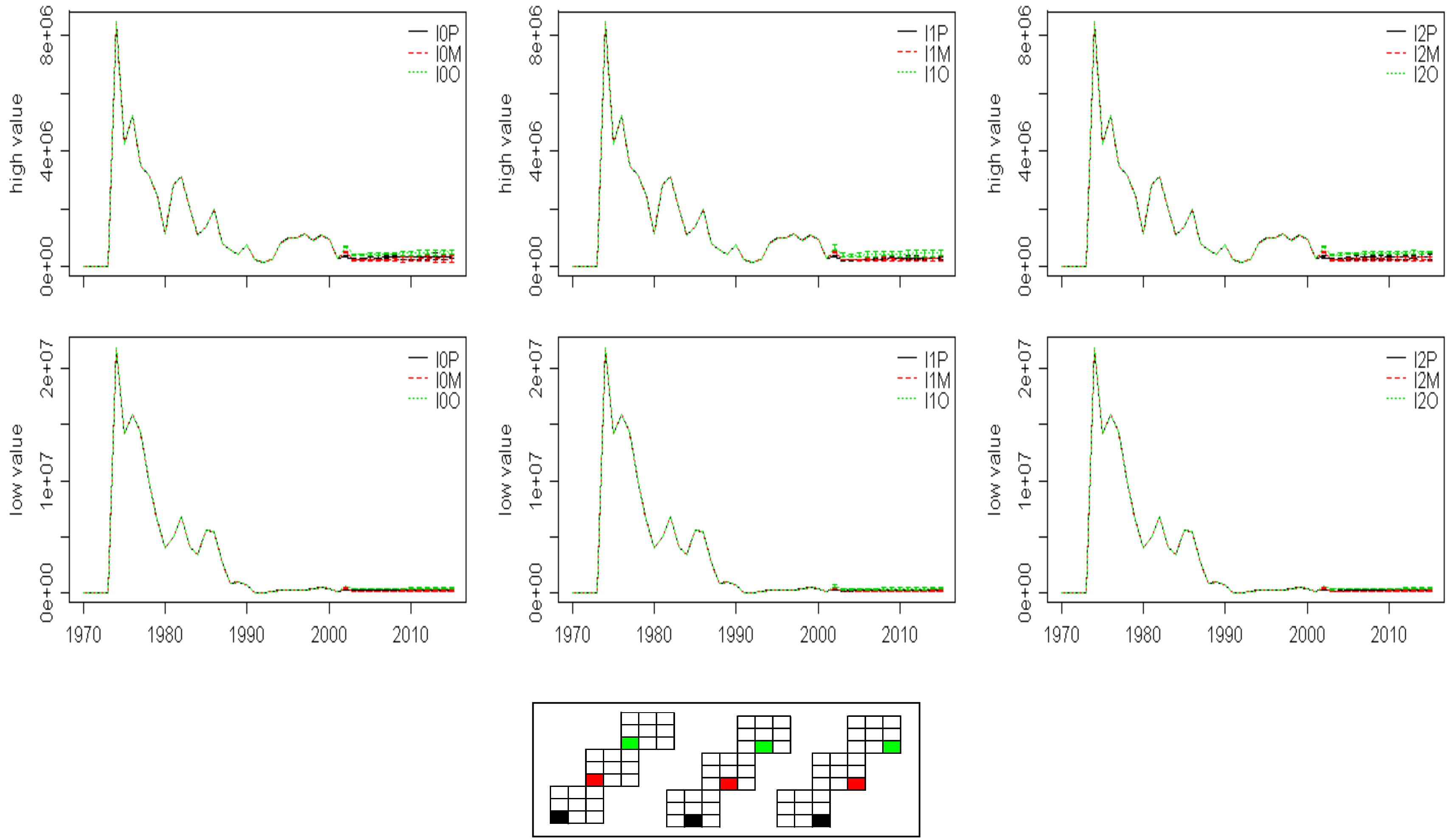


Figure D.39: Comparison of model specifications for total catches (kg) of high and low valued fish under the integrated management strategy.

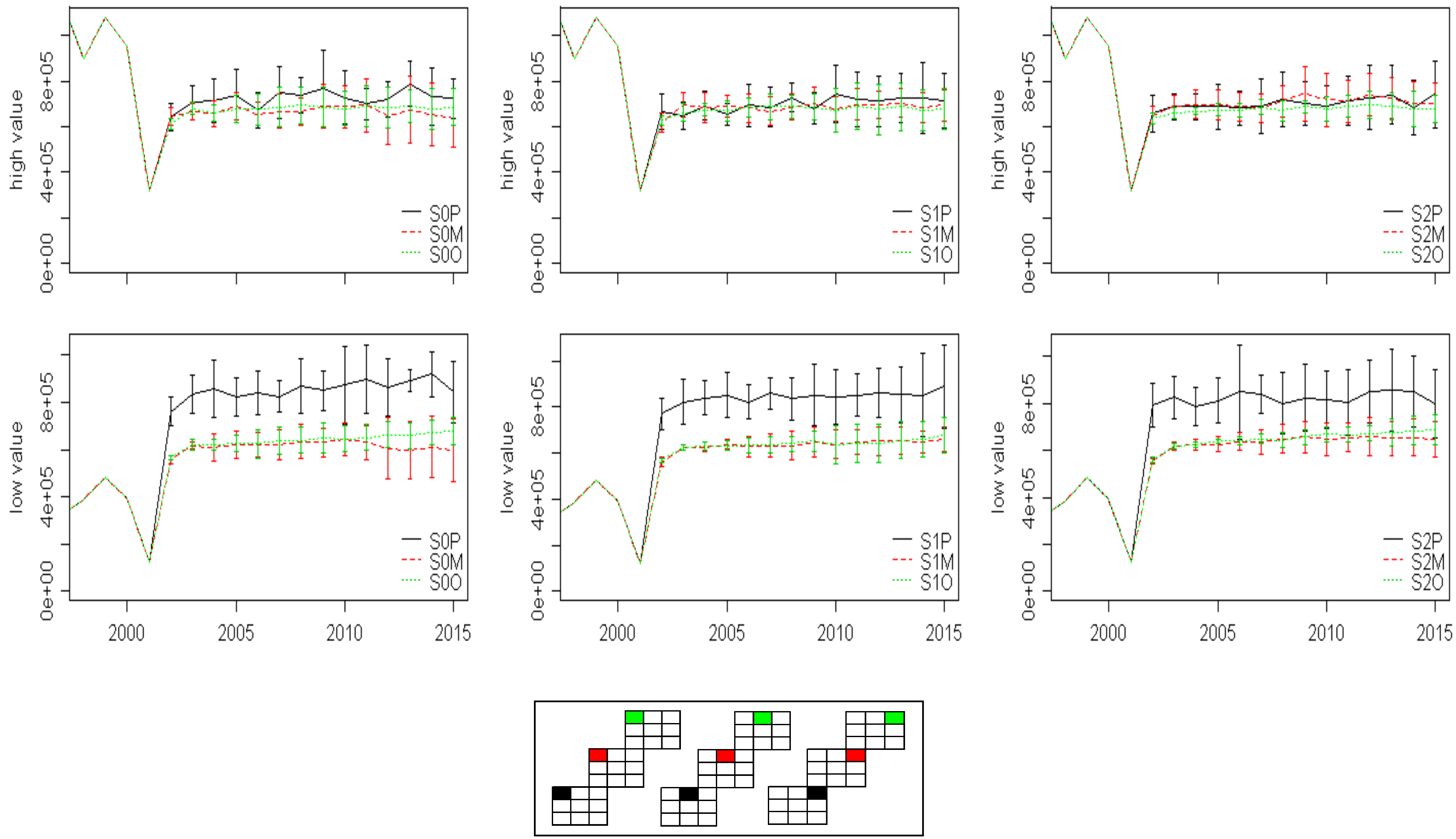


Figure D.40: Comparison of model specifications for total catch (kg) of high valued and low valued species under the status quo management strategy for the projection period only.

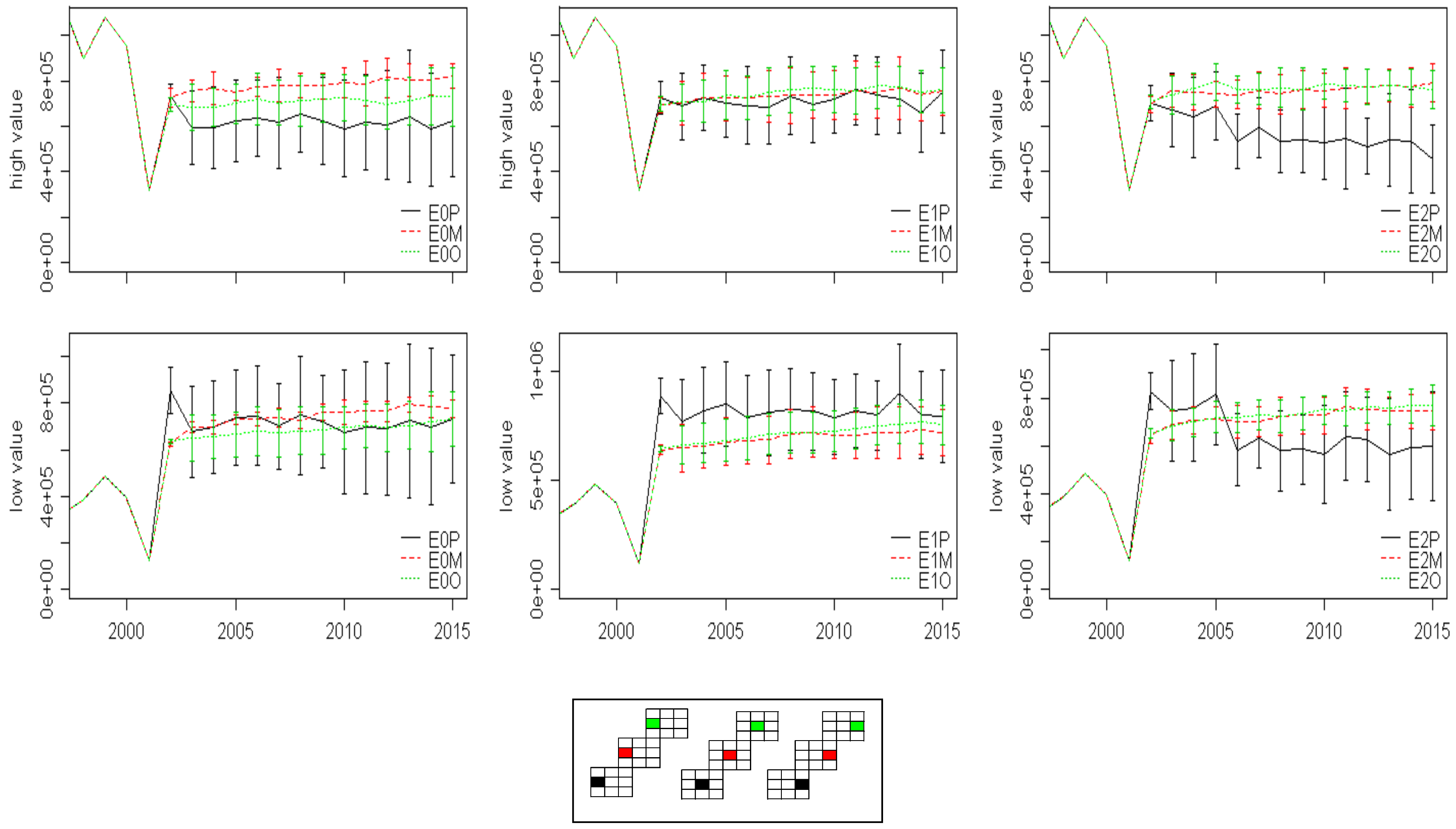


Figure D.41: Comparison of model specifications for total catch (kg) of high valued and low valued species under the enhanced management strategy for the projection period only.

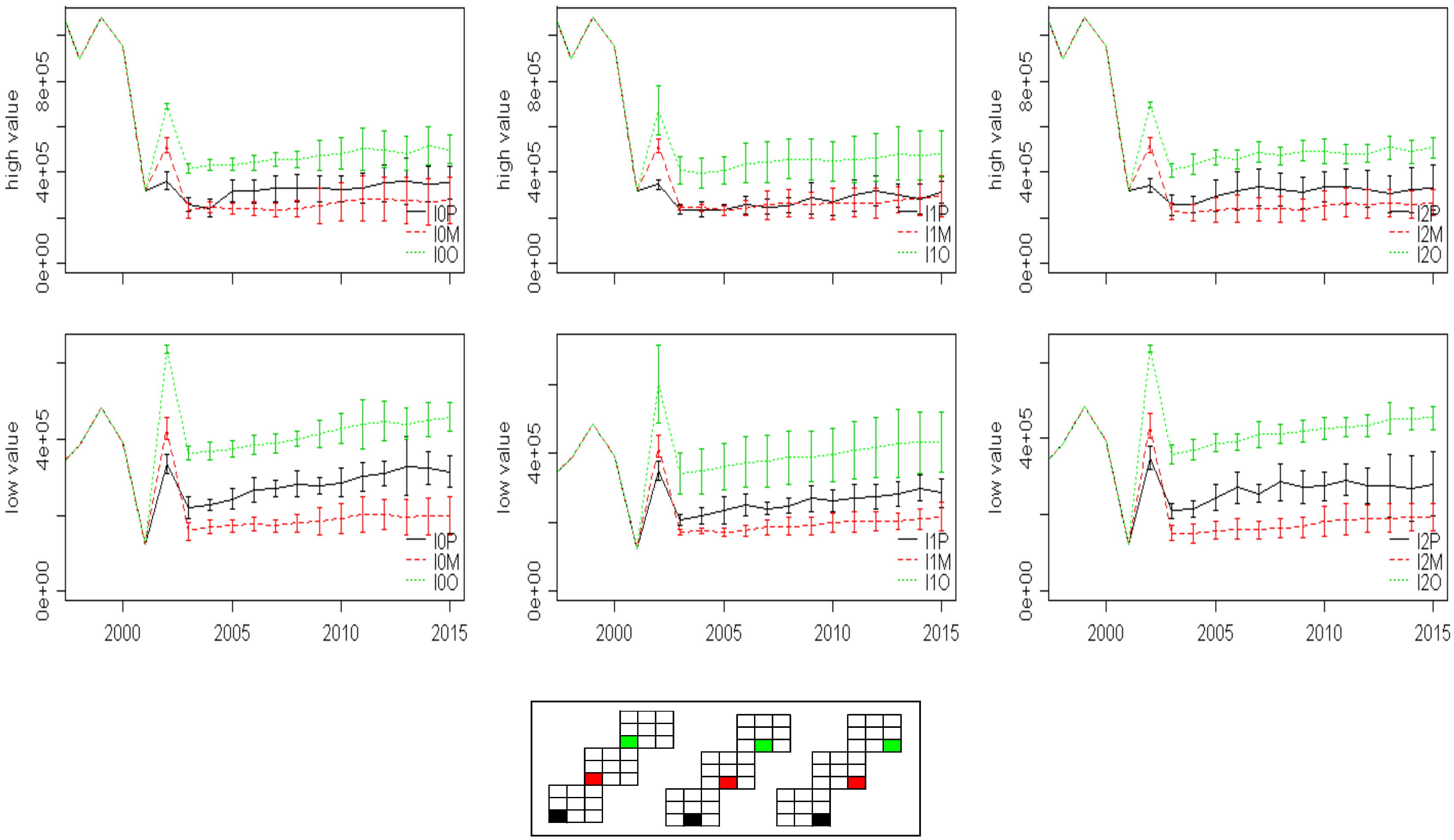


Figure D.42: Comparison of model specifications for total catch (kg) of high valued and low valued species under the integrated management strategy for the projection period only.

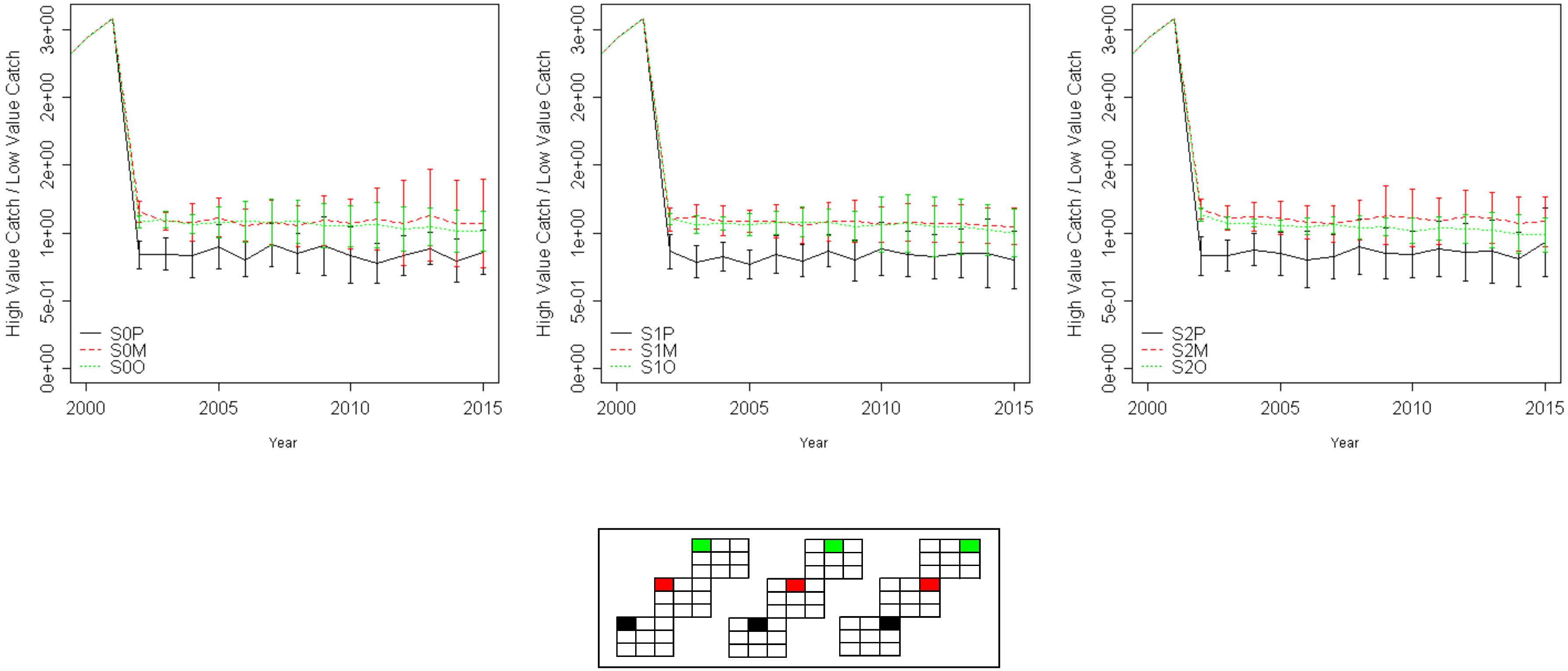


Figure D.43: Comparison of model specifications for the ratio of high-valued species catch to low-valued species catch under the status quo management strategy.

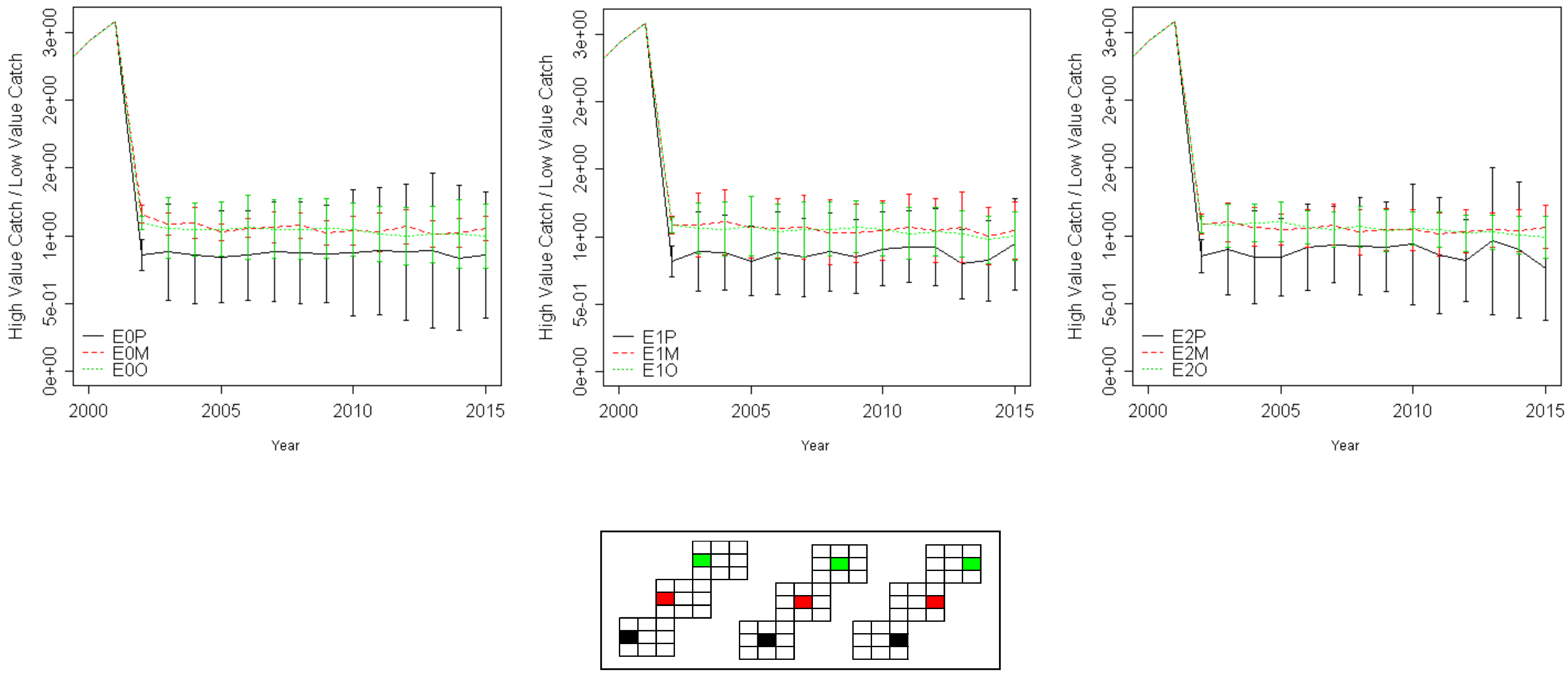
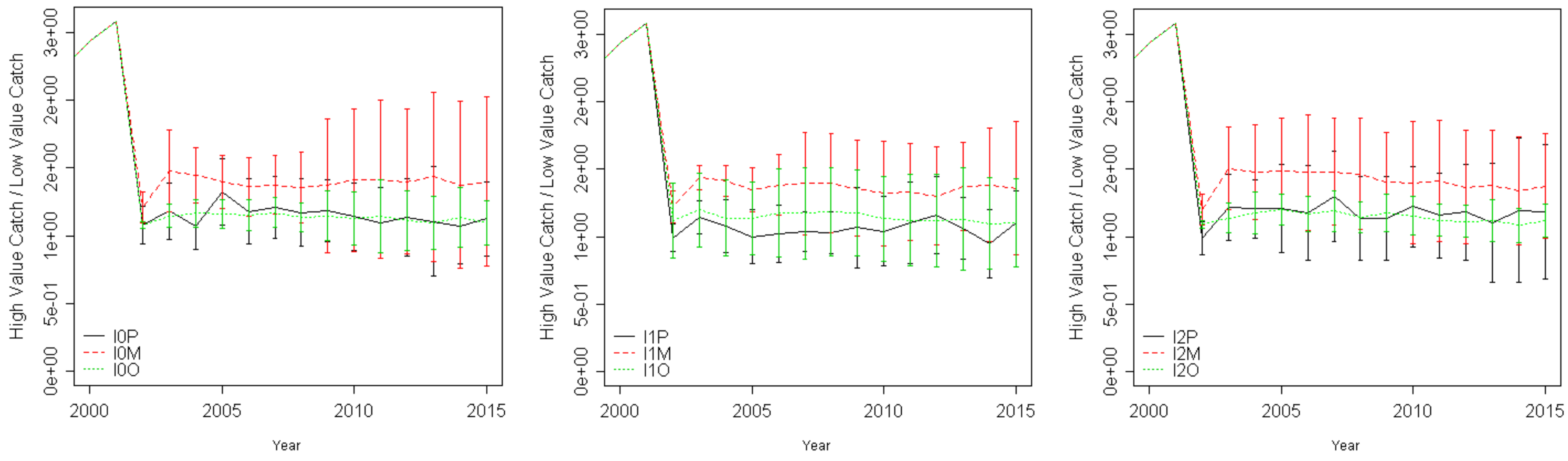


Figure D.44: Comparison of model specifications for the ratio of high-valued species catch to low-valued species catch under the enhanced management strategy.



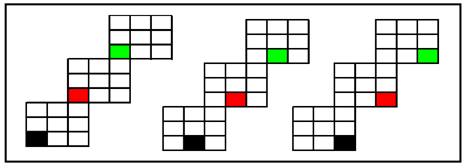


Figure D.45: Comparison of model specifications for the ratio of high-valued species catch to low-valued species catch under the integrated management strategy.

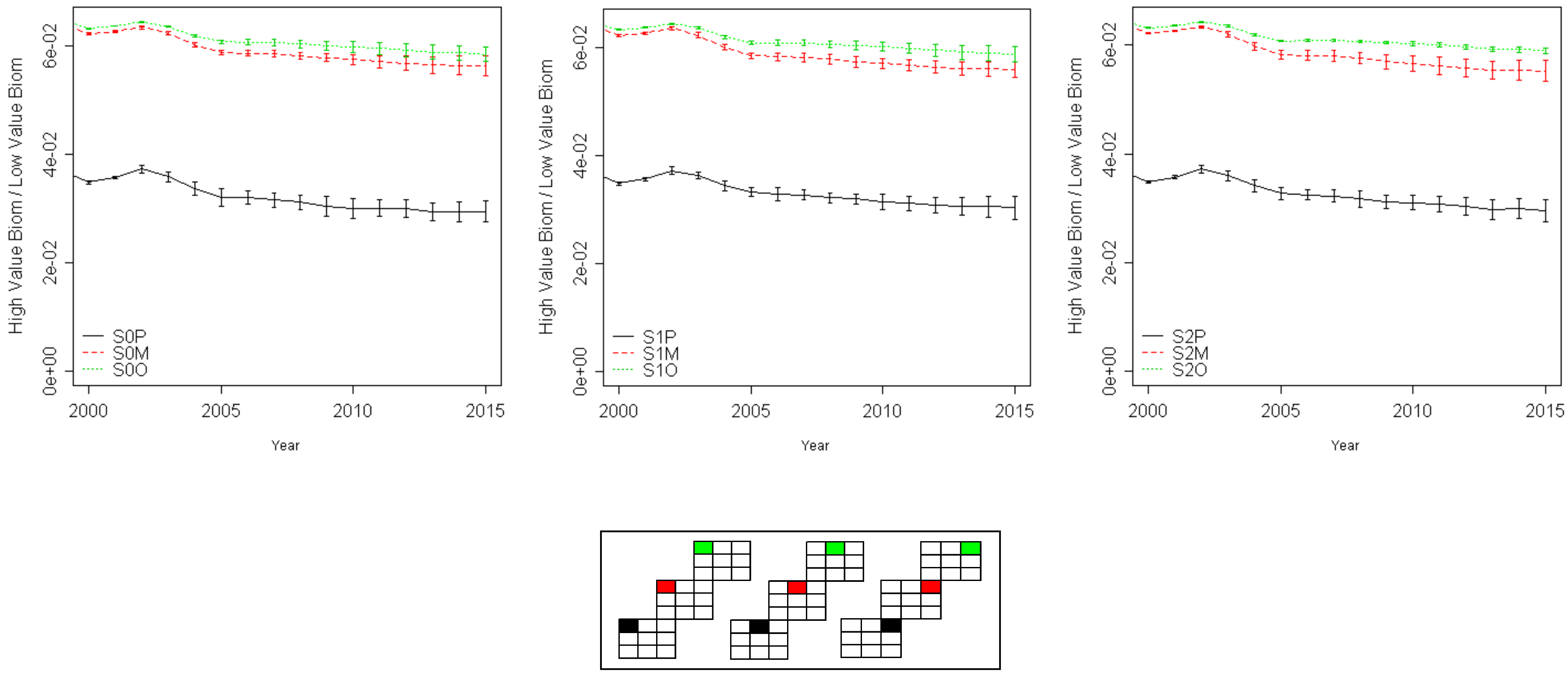


Figure D.46: Comparison of model specifications for the ratio of high-valued species biomass to low-valued species biomass under the status quo management strategy.

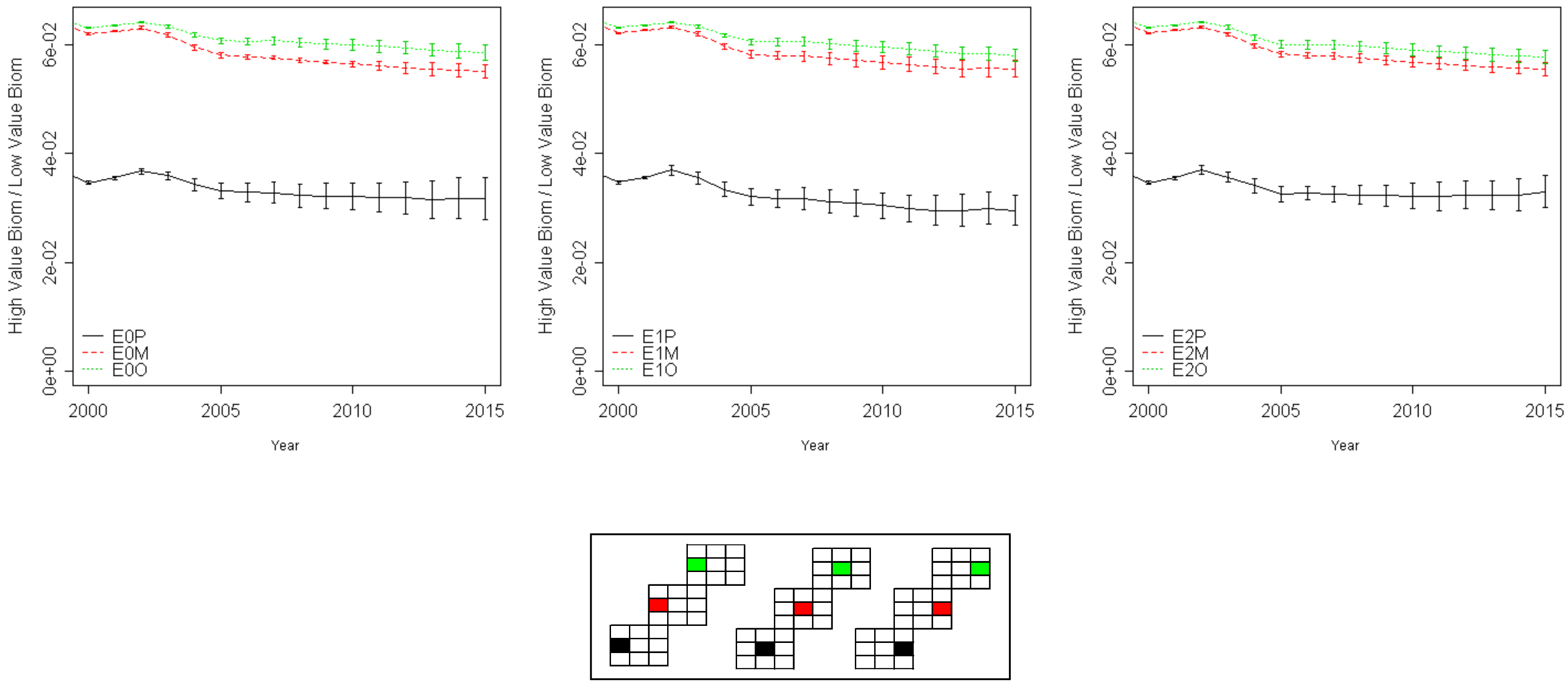


Figure D.47: Comparison of model specifications for the ratio of high-valued species biomass to low-valued species biomass under the enhanced management strategy.

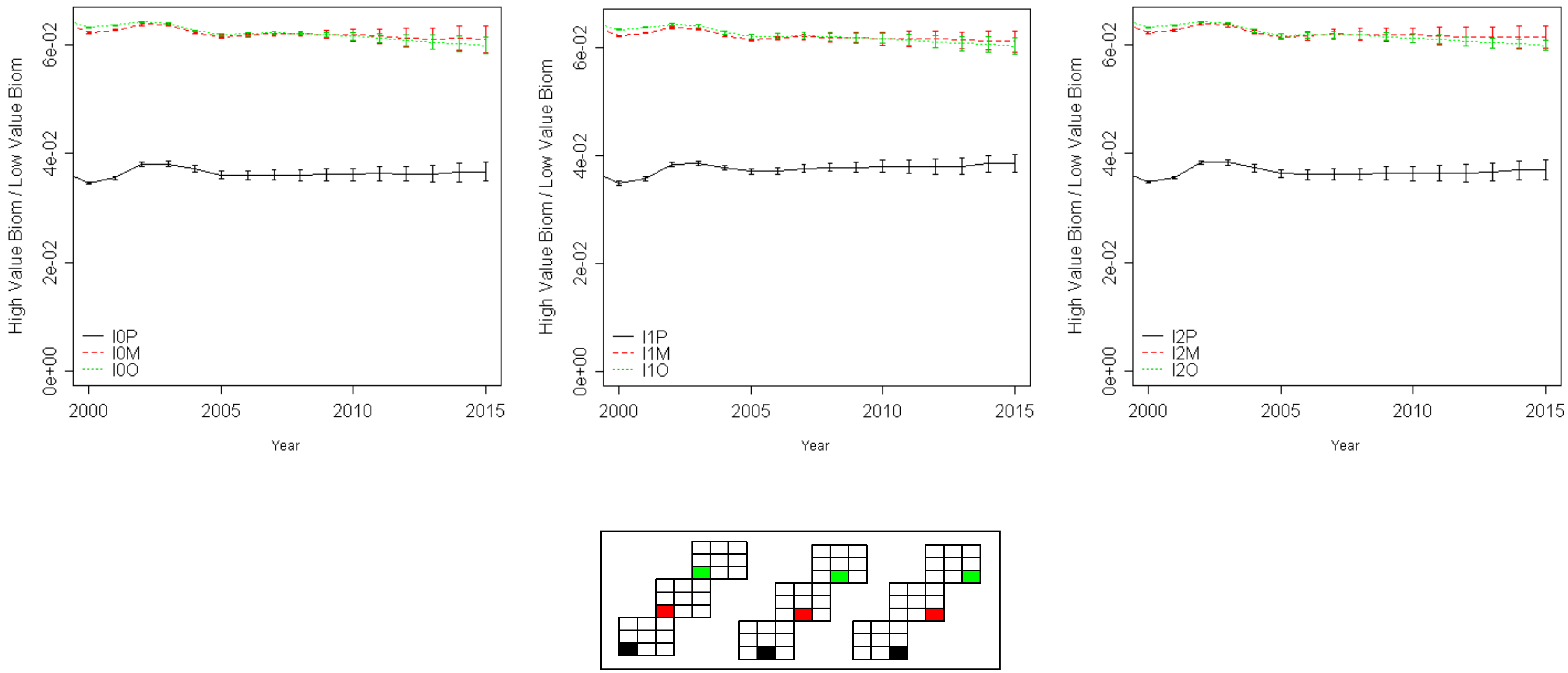


Figure D.48: Comparison of model specifications for the ratio of high-valued species biomass to low-valued species biomass under the integrated management strategy.

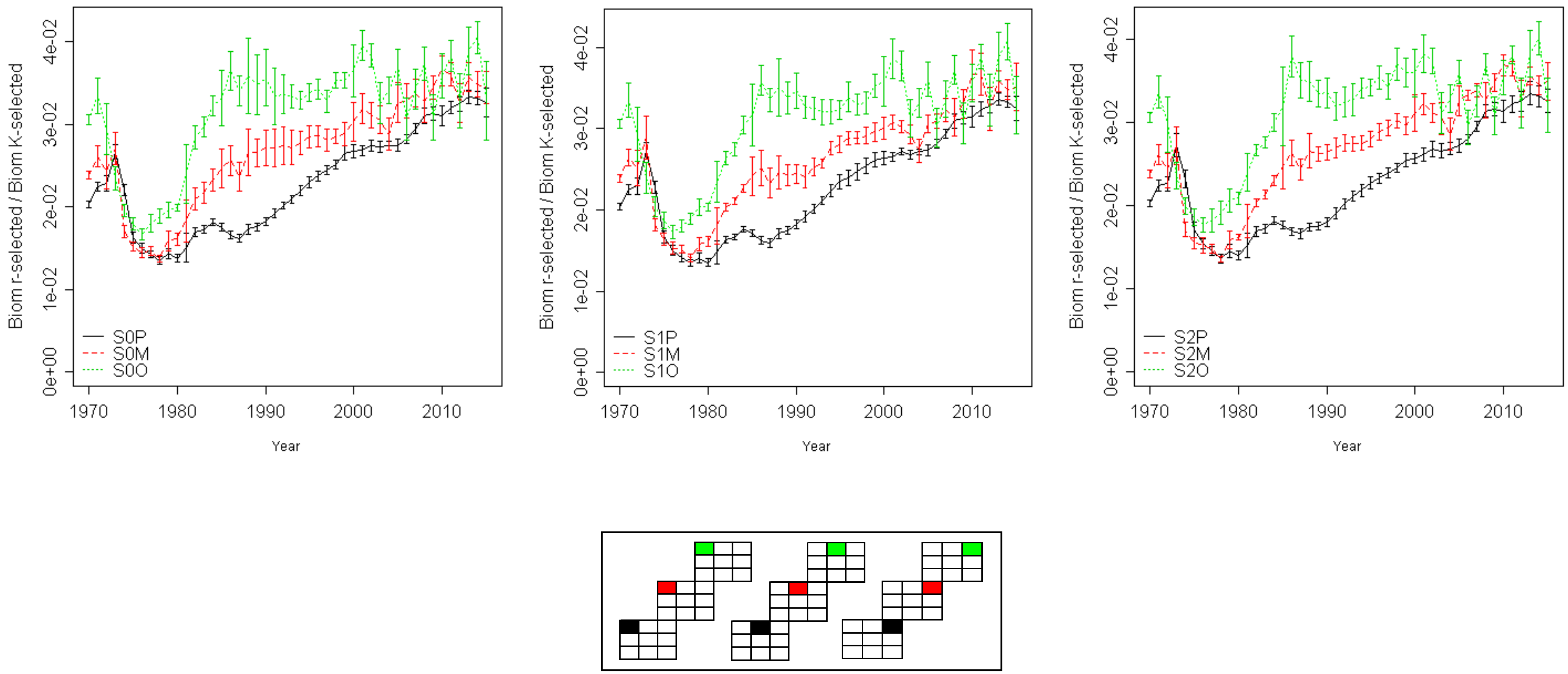


Figure D.49: Comparison of model specifications for the ratio of r-selected species biomass to K-selected species biomass under the status quo management strategy.

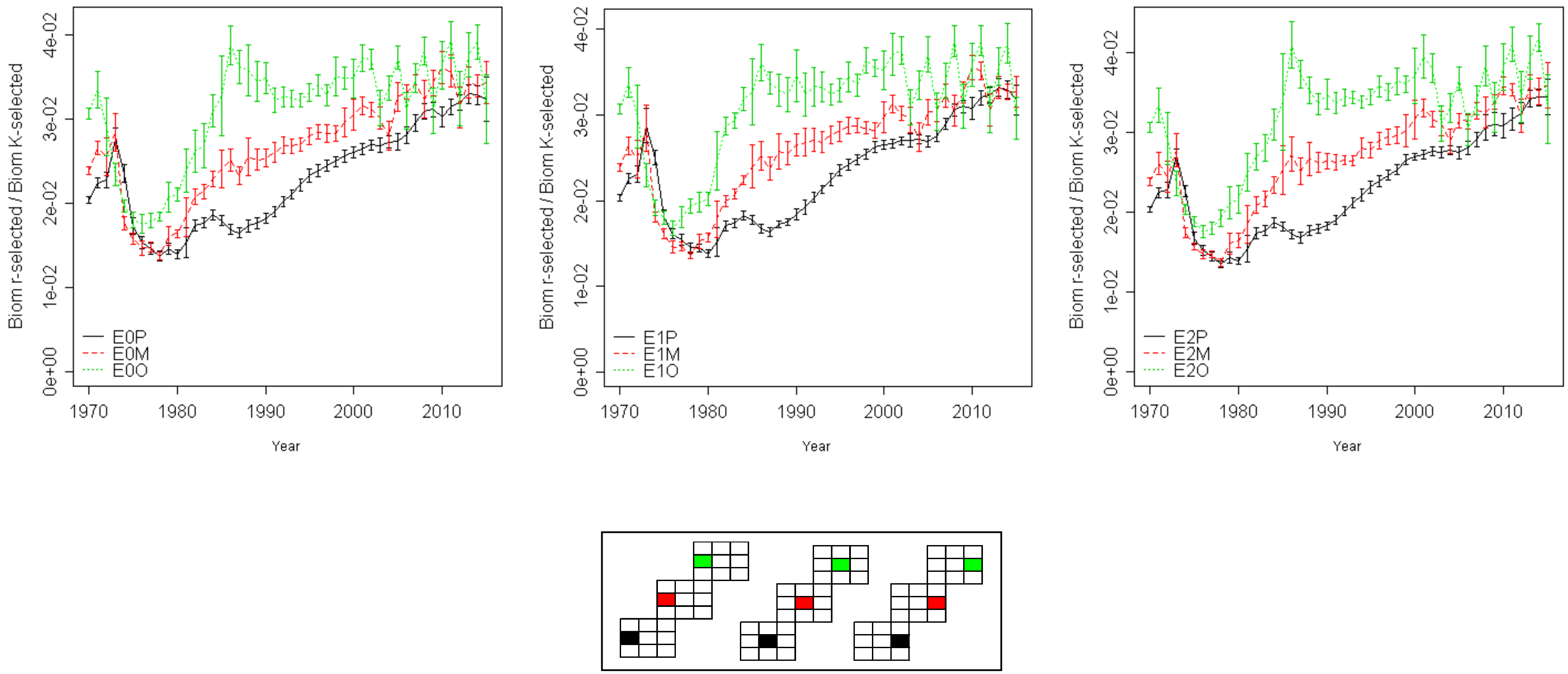


Figure D.50: Comparison of model specifications for the ratio of r-selected species biomass to K-selected species biomass under the enhanced management strategy.

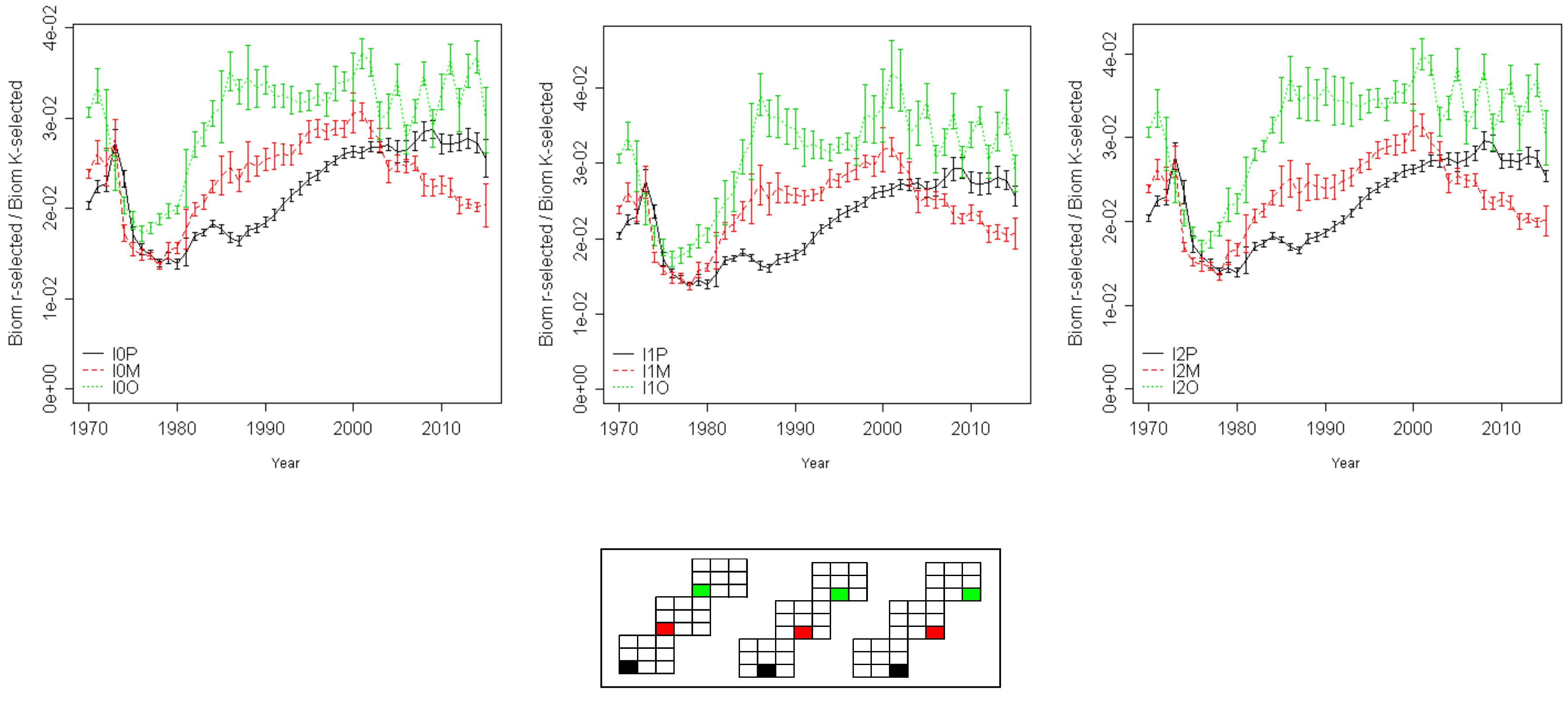


Figure D.51: Comparison of model specifications for the ratio of r-selected species biomass to K-selected species biomass under the integrated management strategy.

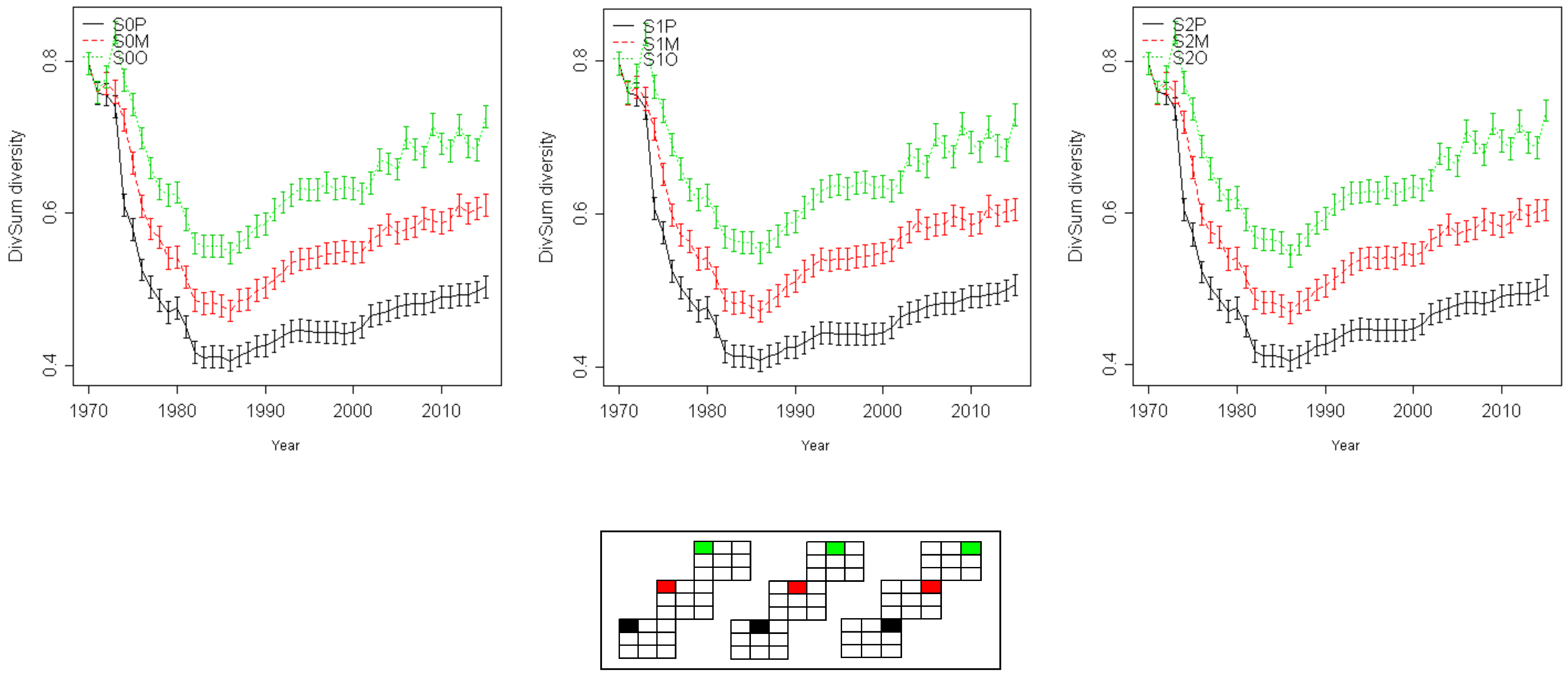


Figure D.52: Comparison of model specifications using the diversity proxy under the status quo management strategy.

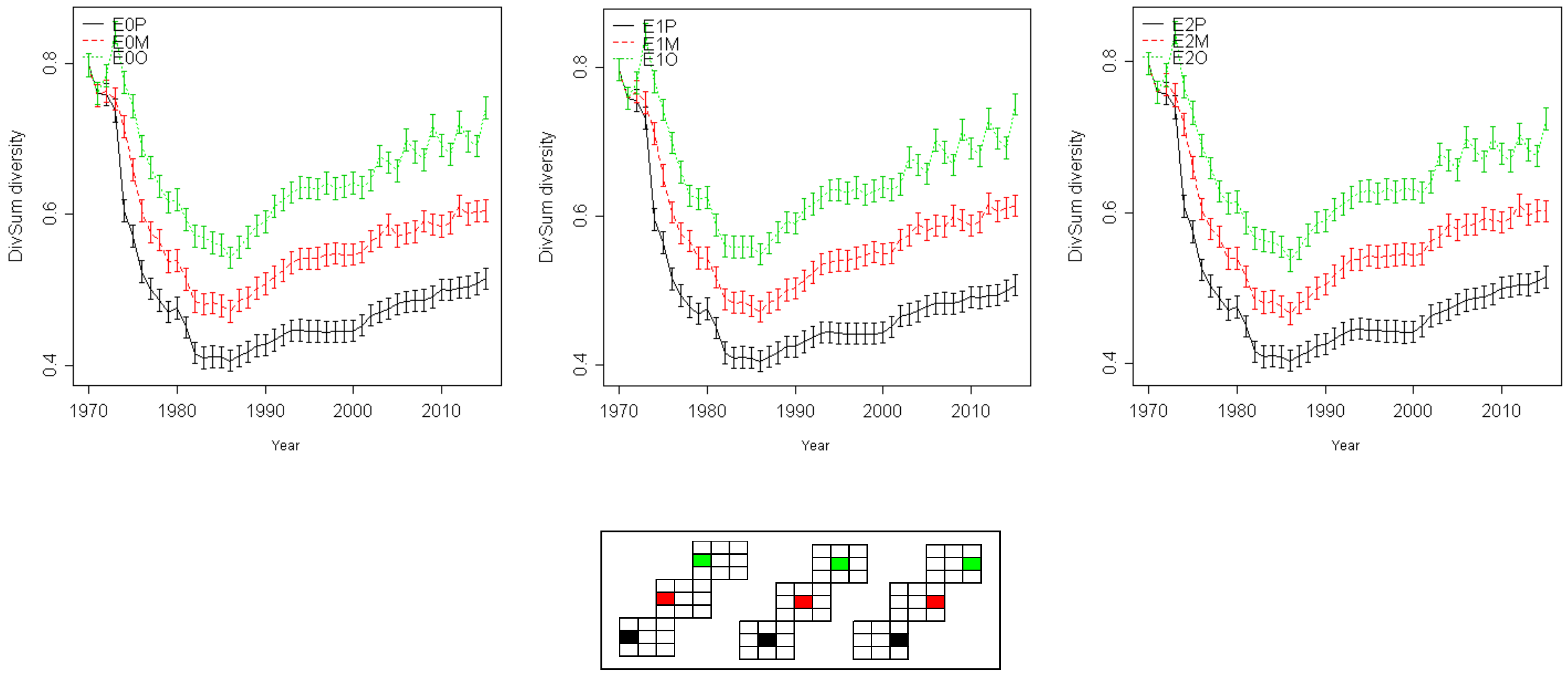


Figure D.53: Comparison of model specifications using the diversity proxy under the enhanced management strategy.

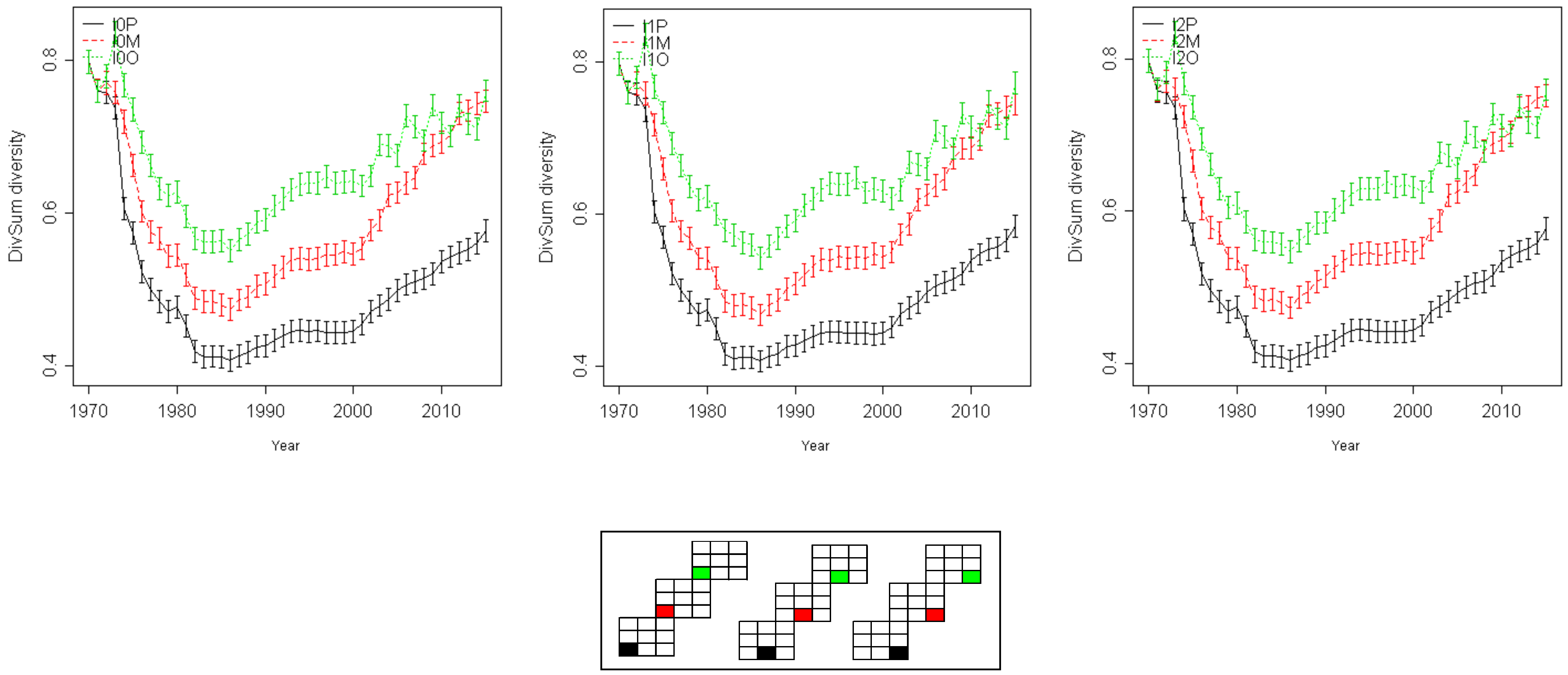
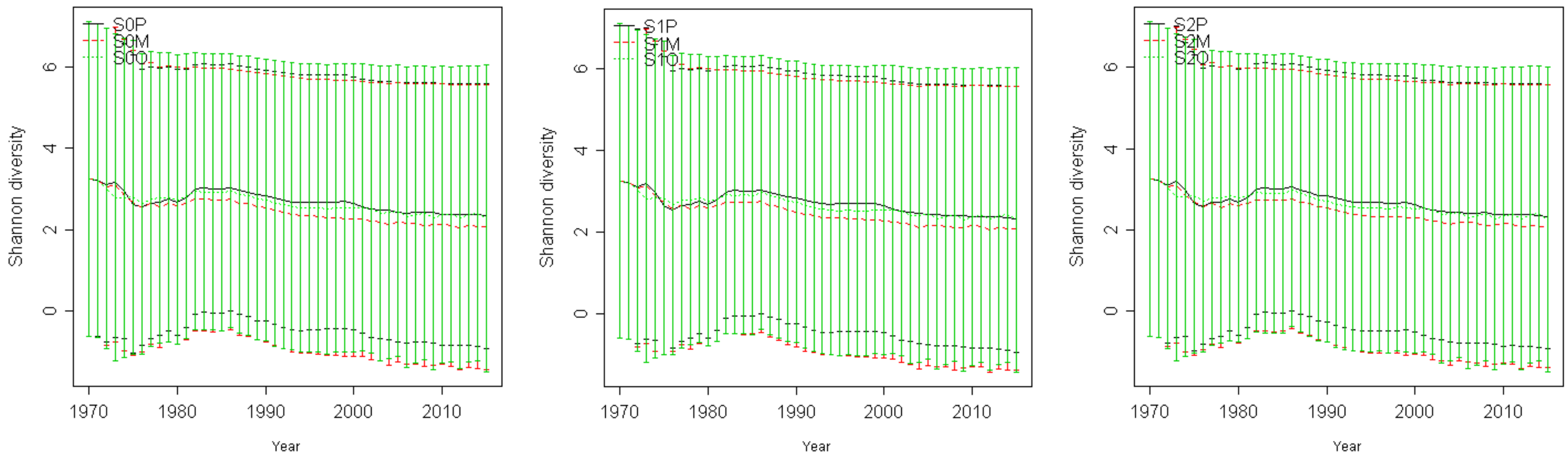


Figure D.54: Comparison of model specifications using the diversity proxy under the integrated management strategy.



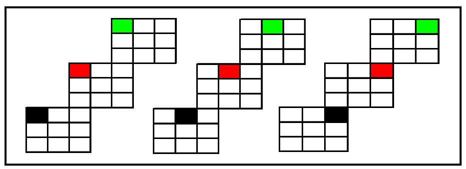


Figure D.55: Comparison of model specifications for the Shannon diversity index under the status quo management strategy.

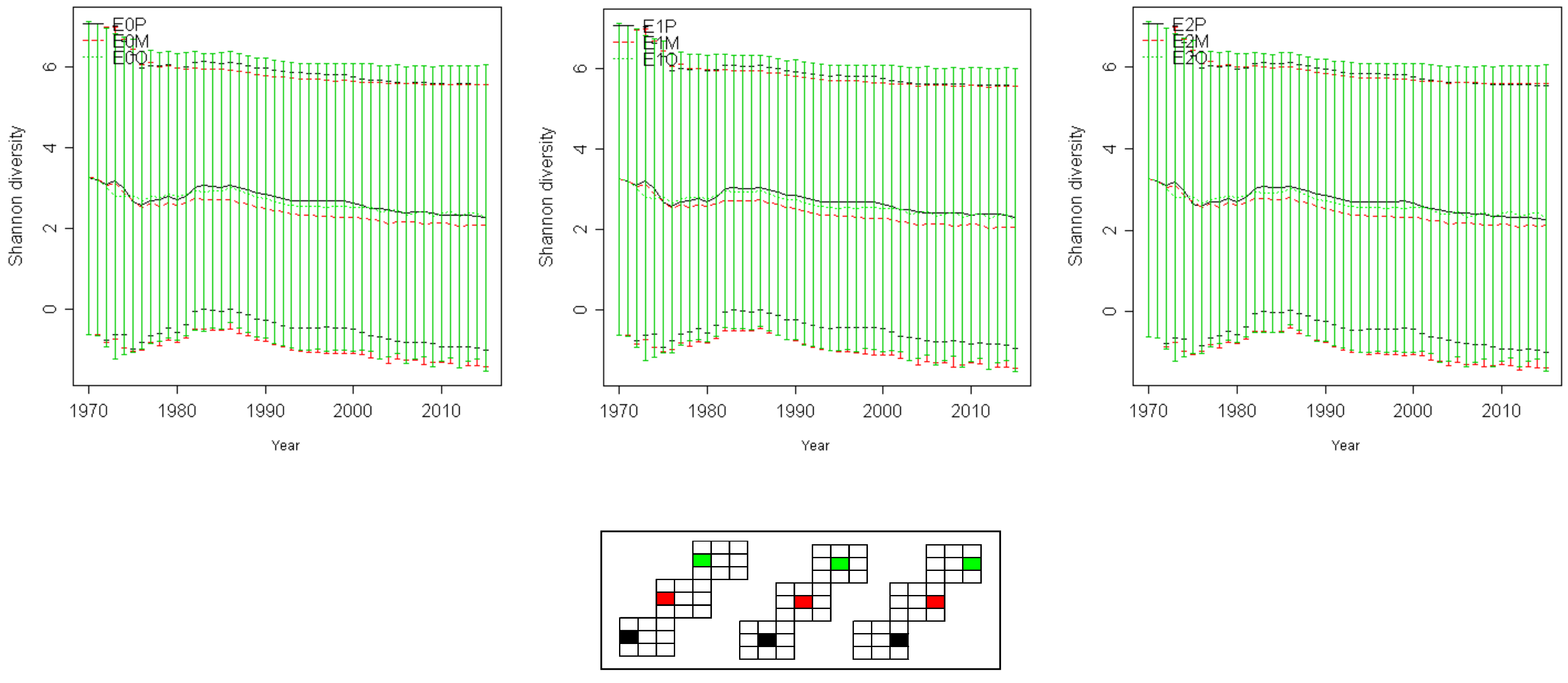


Figure D.56: Comparison of model specifications for the Shannon diversity index under the enhanced management strategy.

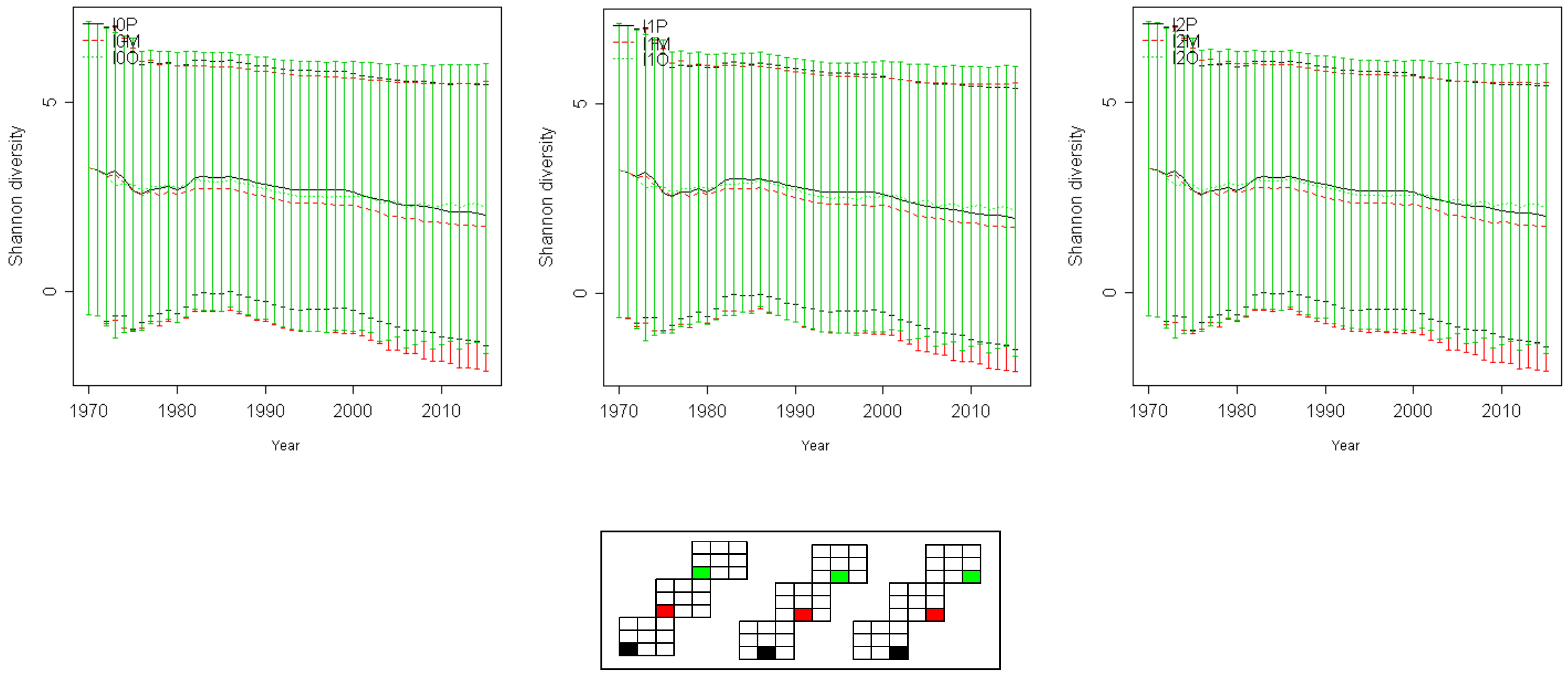


Figure D.57: Comparison of model specifications for the Shannon diversity index under the integrated management strategy.

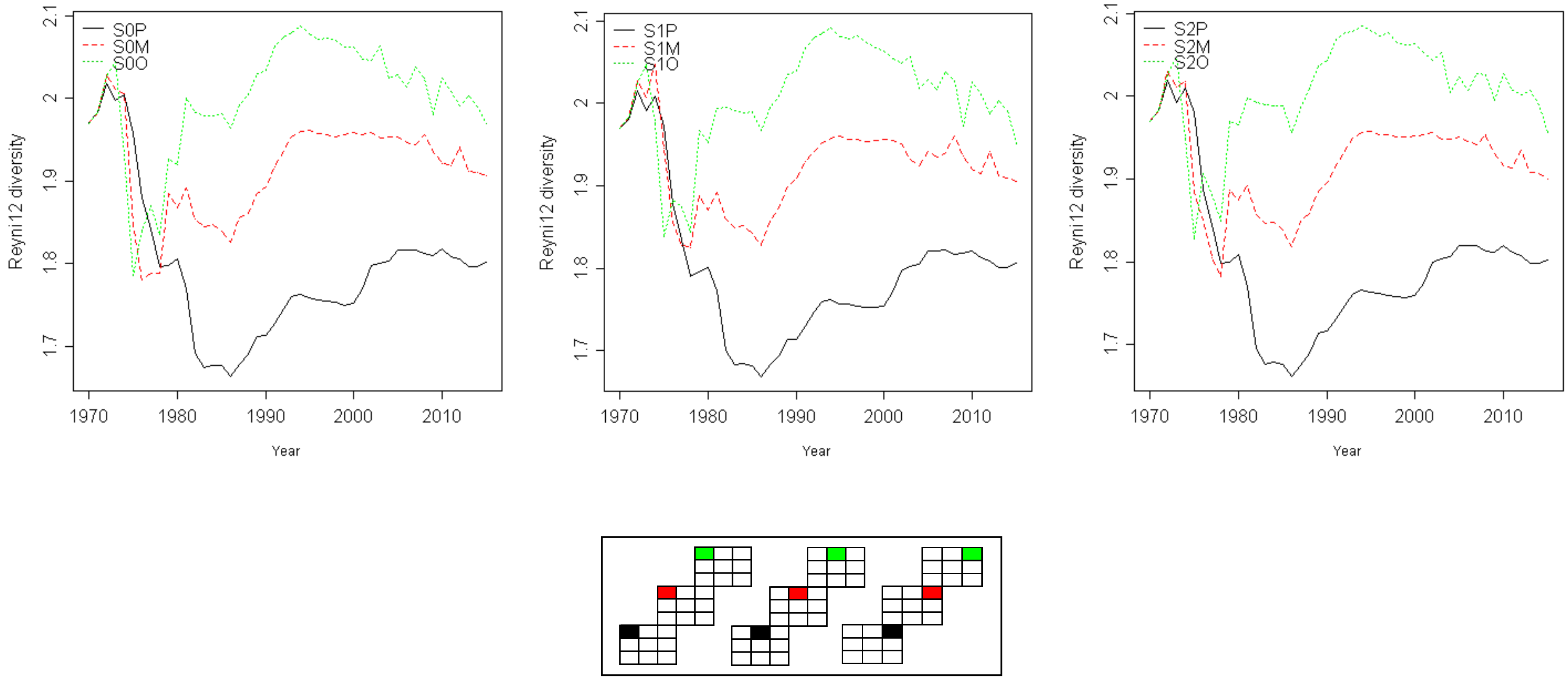


Figure D.58: Comparison of model specifications for Renyi generalised diversity of order 12 under the status quo management strategy.

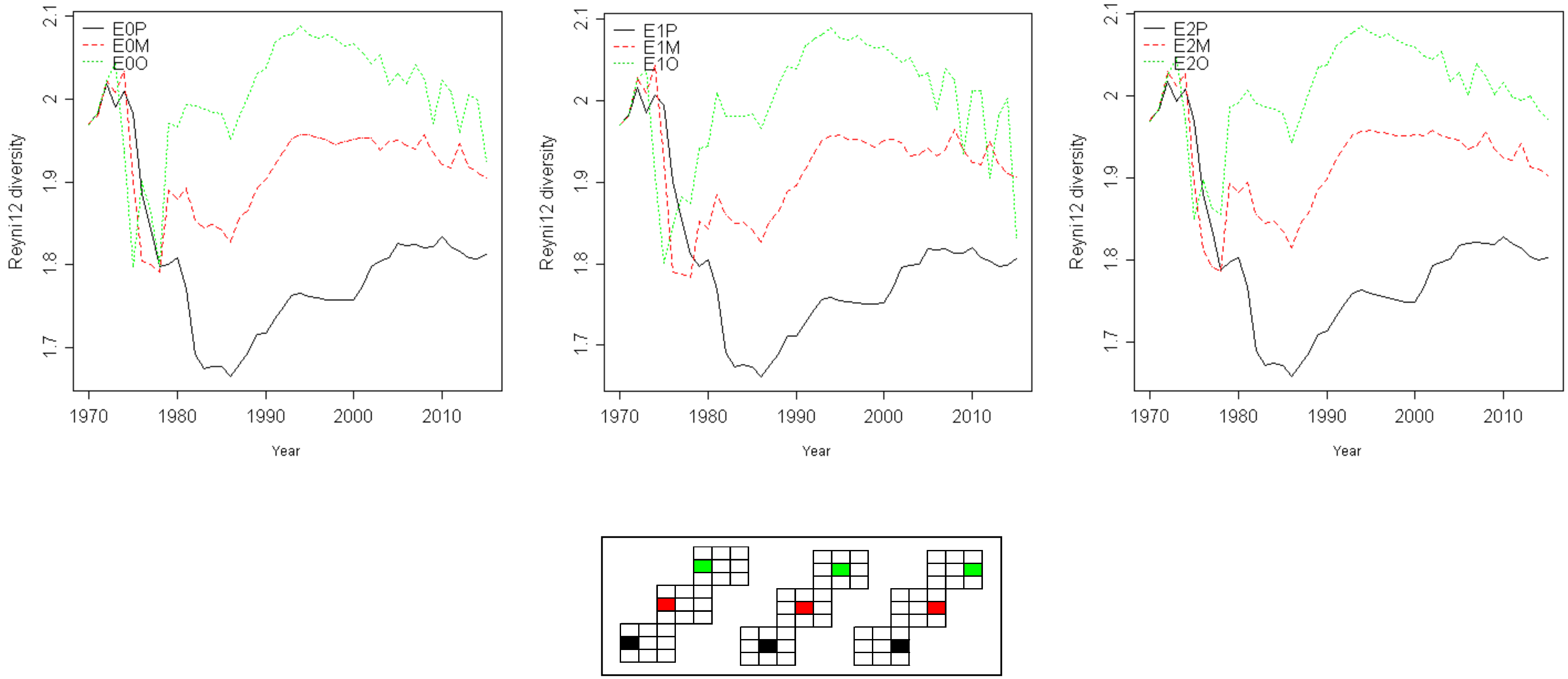


Figure D.59: Comparison of model specifications for Renyi generalised diversity of order 12 under the enhanced management strategy.

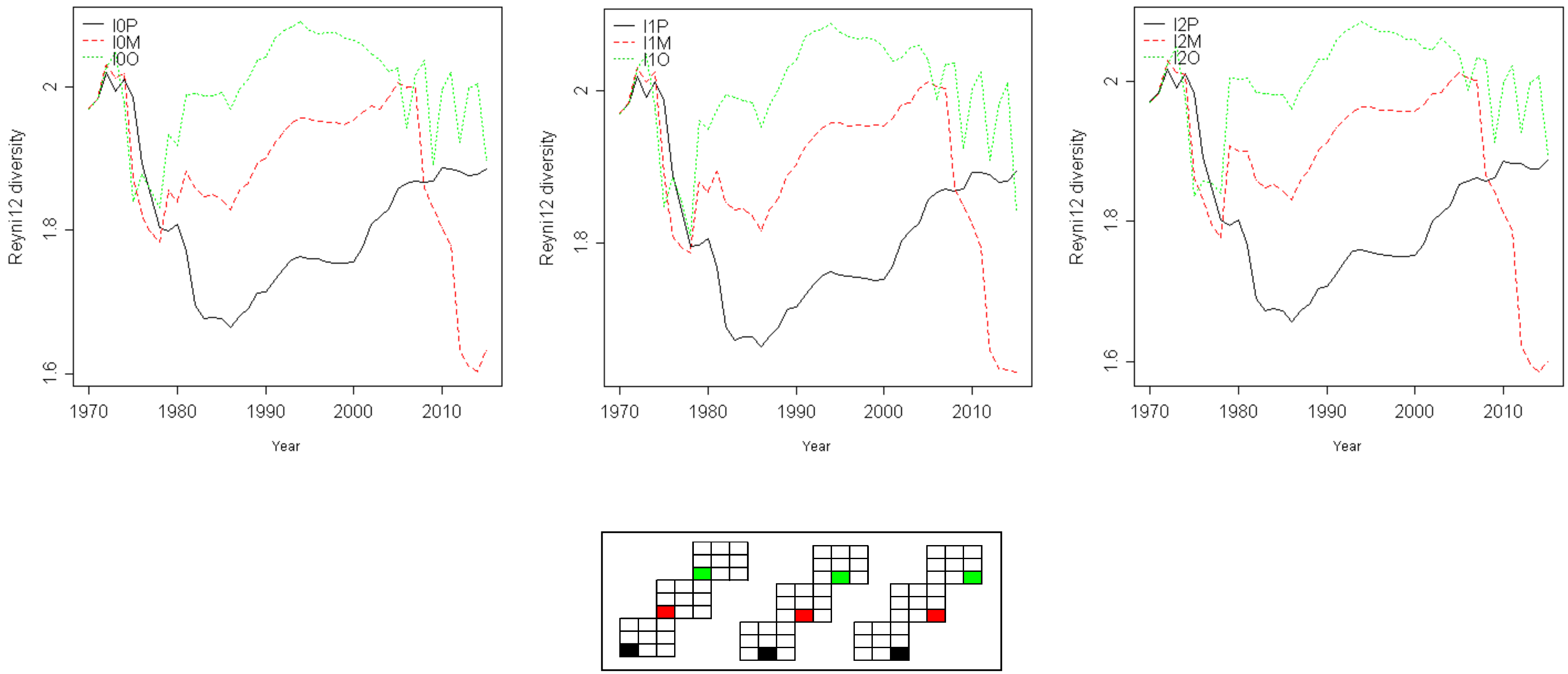


Figure D.60: Comparison of model specifications for Renyi generalised diversity of order 12 under the integrated management strategy.

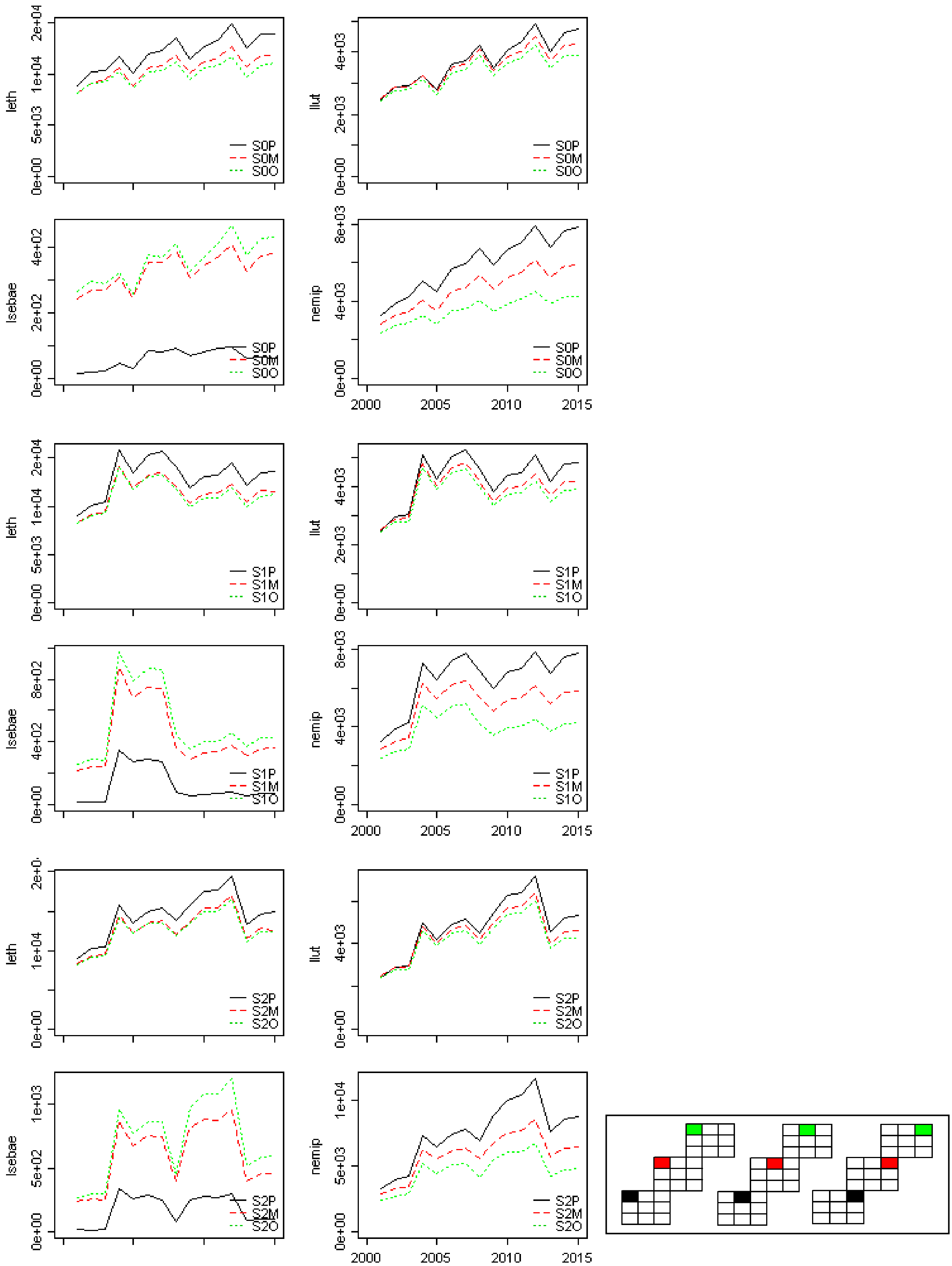


Figure D.61: Comparison of model specifications for total recreational catch under the status quo management strategy (leth = lethrinid, llut = large lutjanids, lsebae = *L. sebae*, nemip = nemipterids).

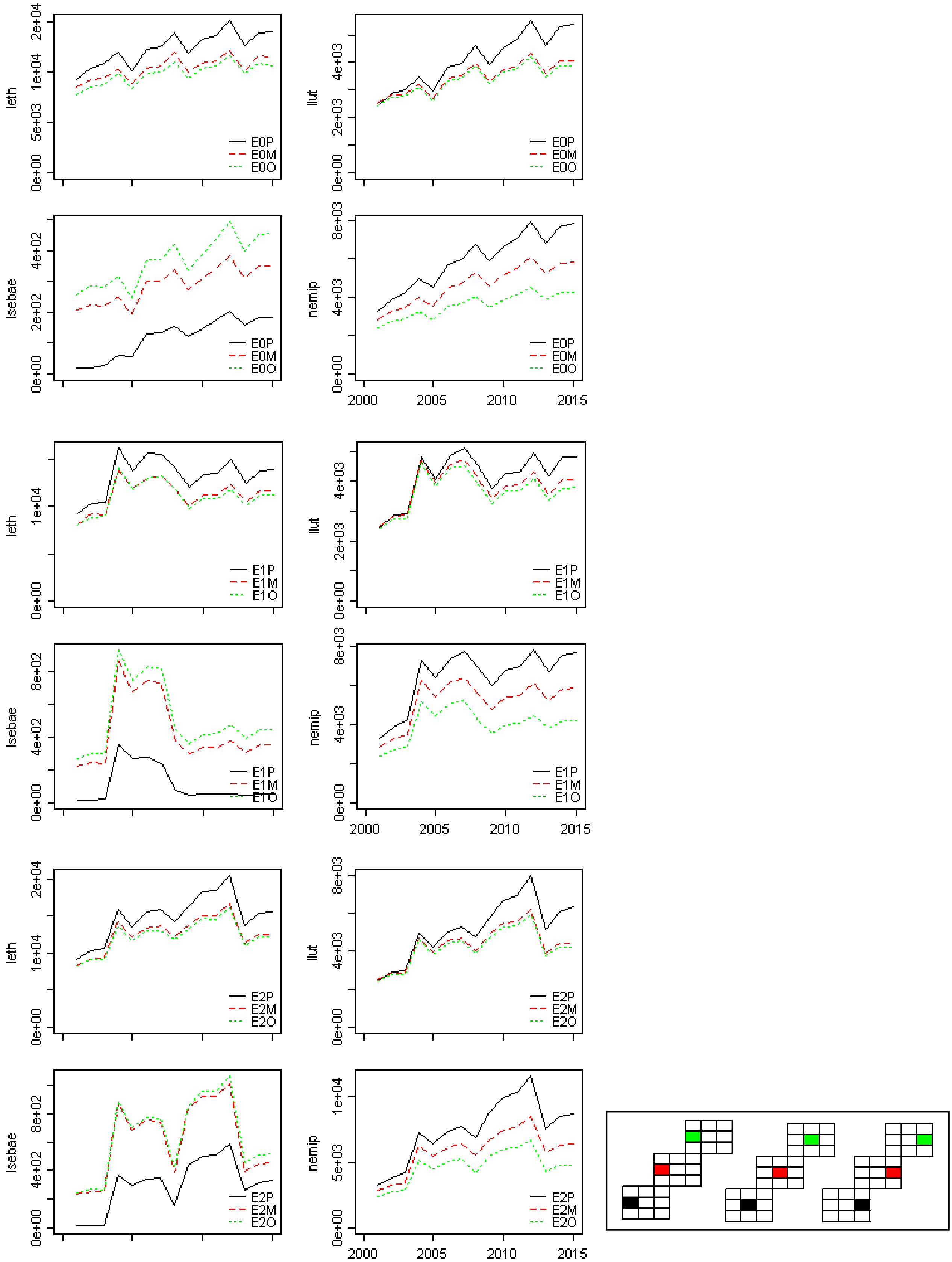


Figure D.62: Comparison of model specifications for total recreational catch under the enhanced management strategy (leth = lethrinid, llut = large lutjanids, lsebae = *L. sebae*, nemip = nemipterids).

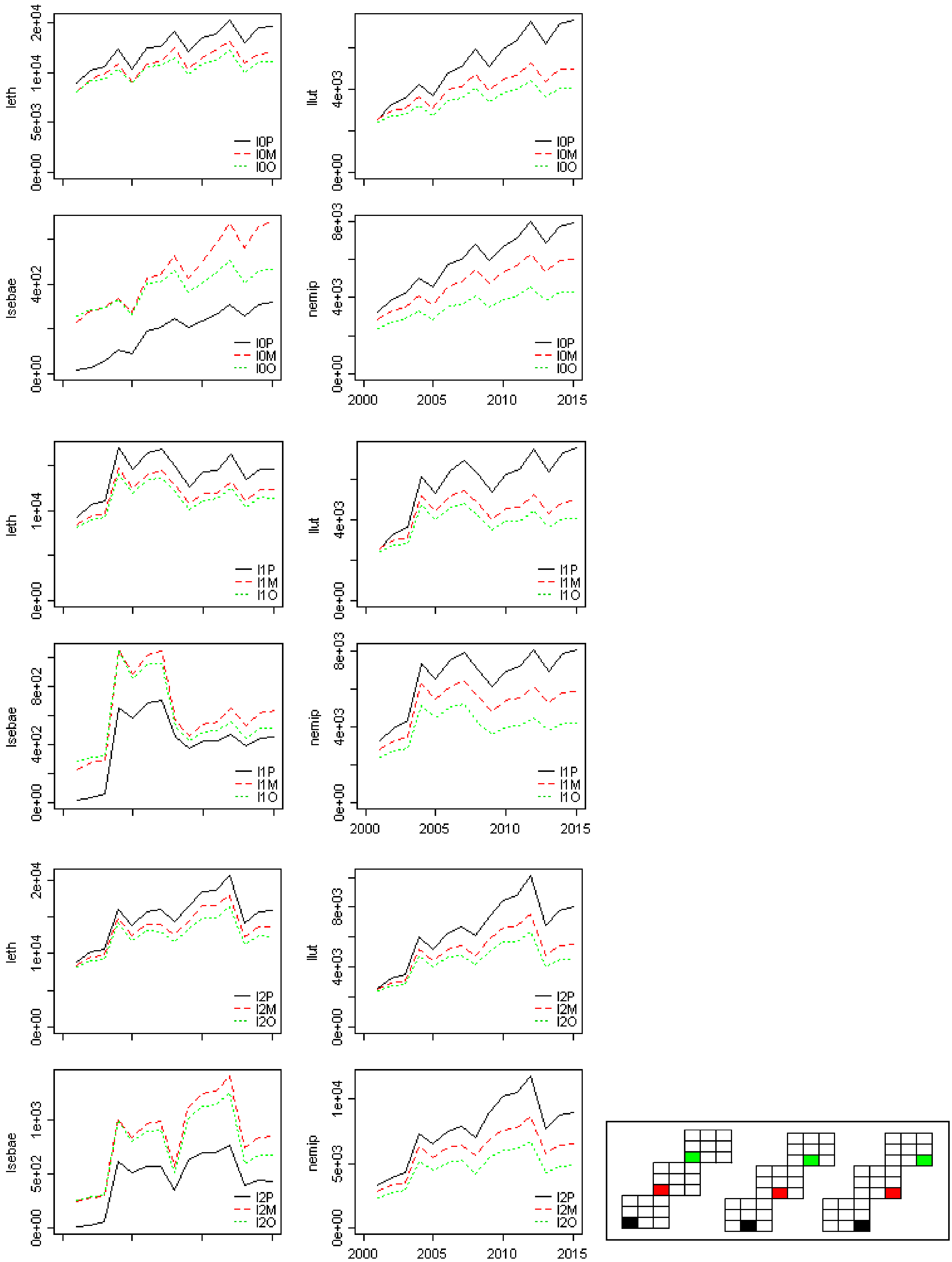


Figure D.63: Comparison of model specifications for total recreational catch under the integrated management strategy (leth = lethrinid, llut = large lutjanids, lsebae = *L. sebae*, nemip = nemipterids).

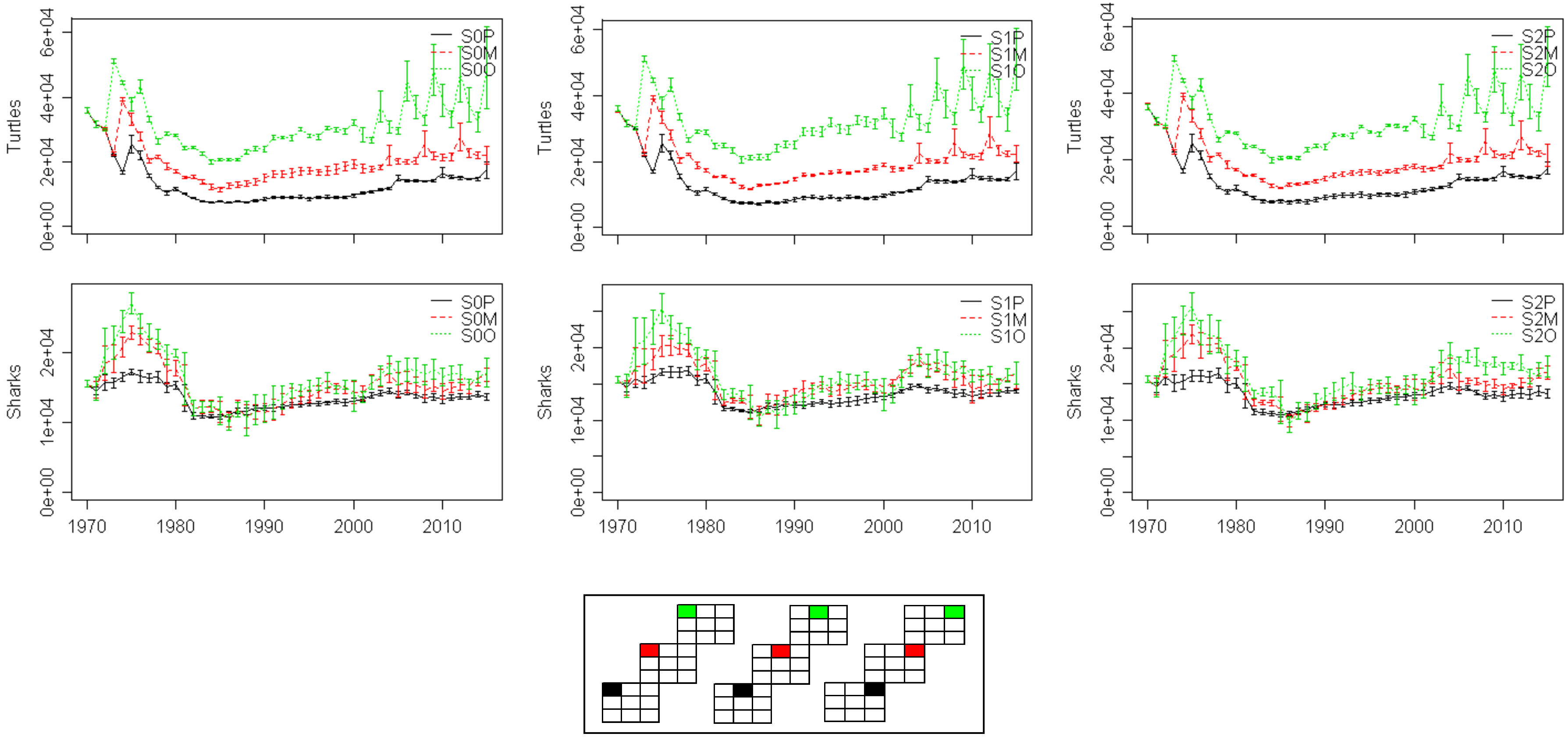


Figure D.64: Comparison of model specifications for total shark biomass and total turtle biomass under the status quo management strategy.

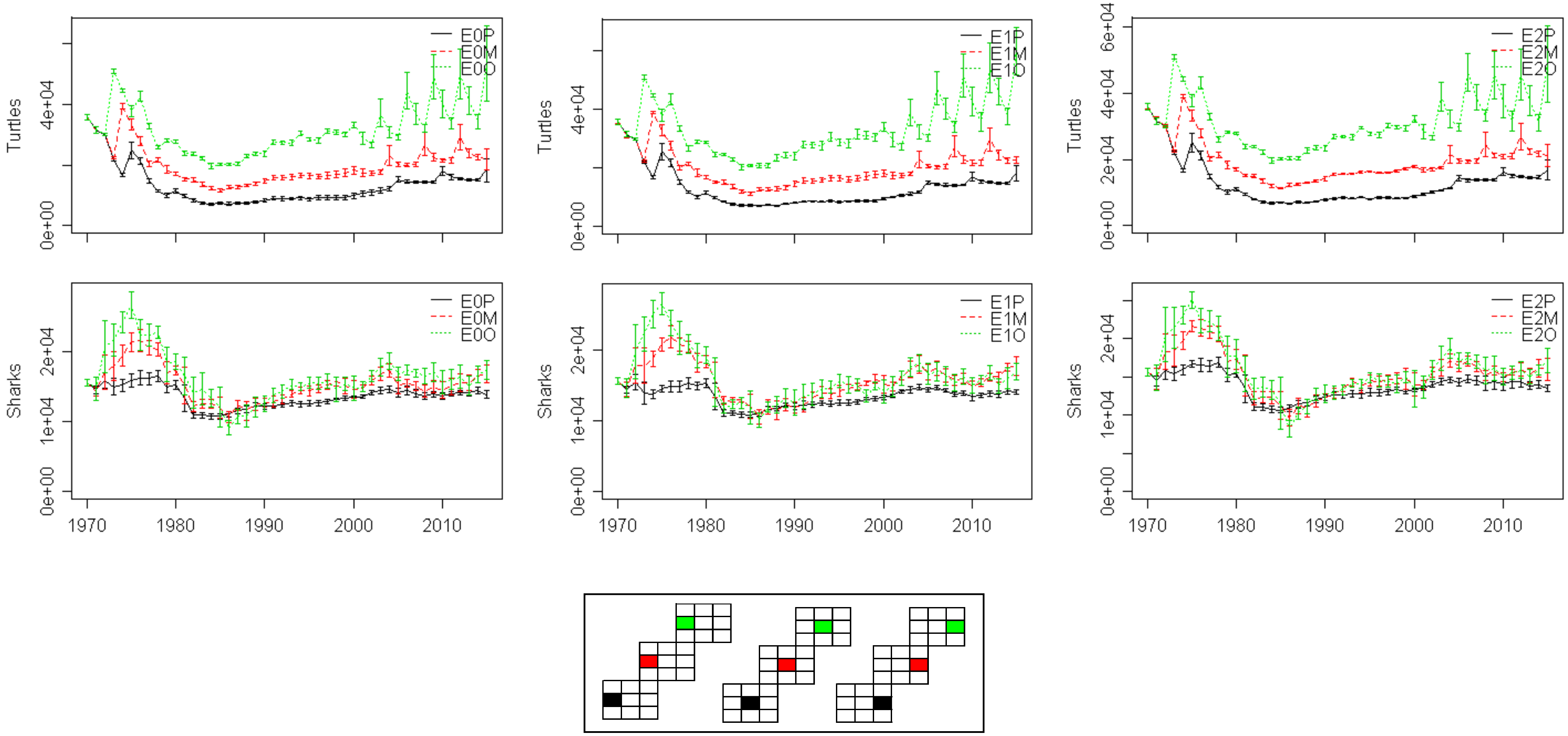


Figure D.65: Comparison of model specifications for total shark biomass and total turtle biomass under the enhanced management strategy.

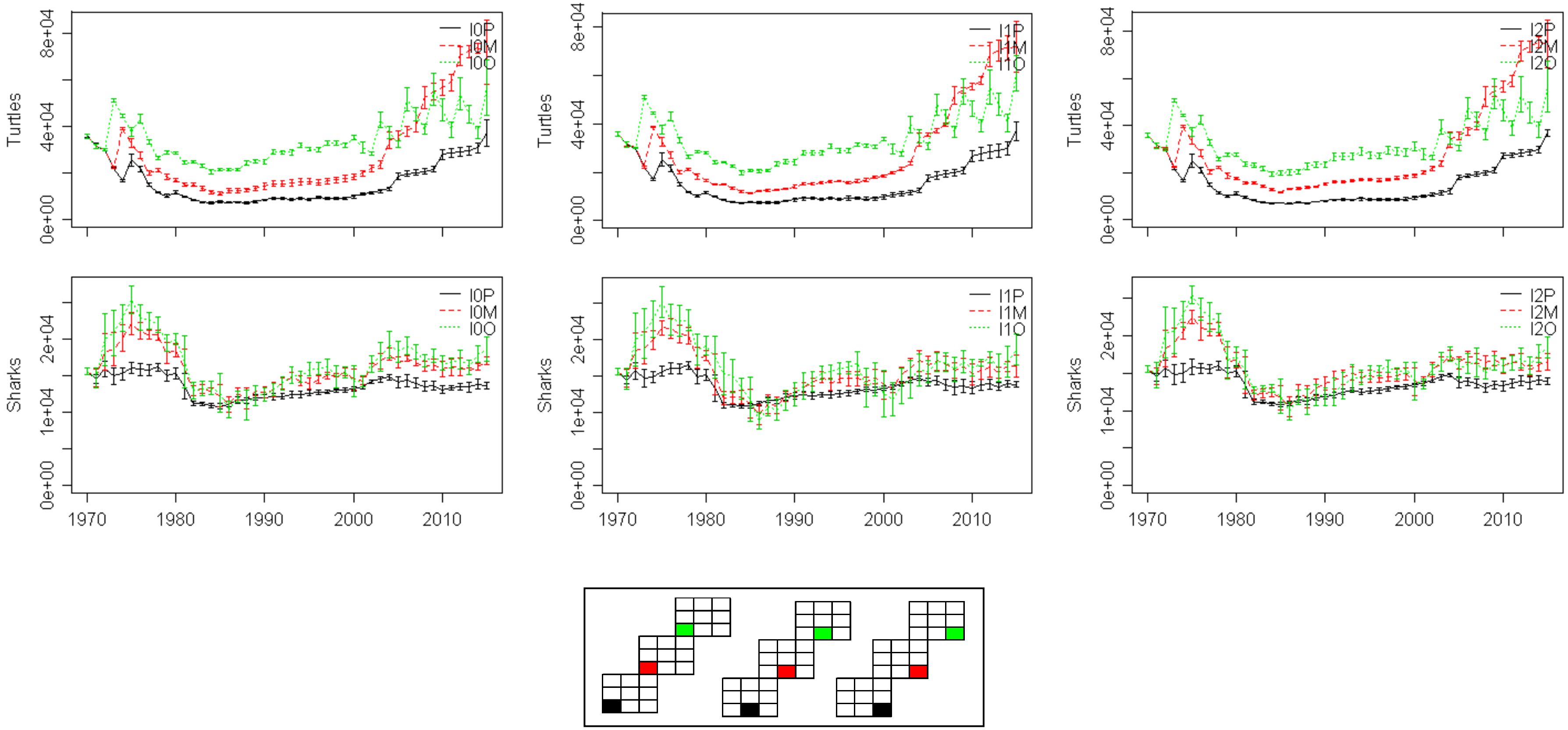


Figure D.66: Comparison of model specifications for total shark biomass and total turtle biomass under the integrated management strategy.

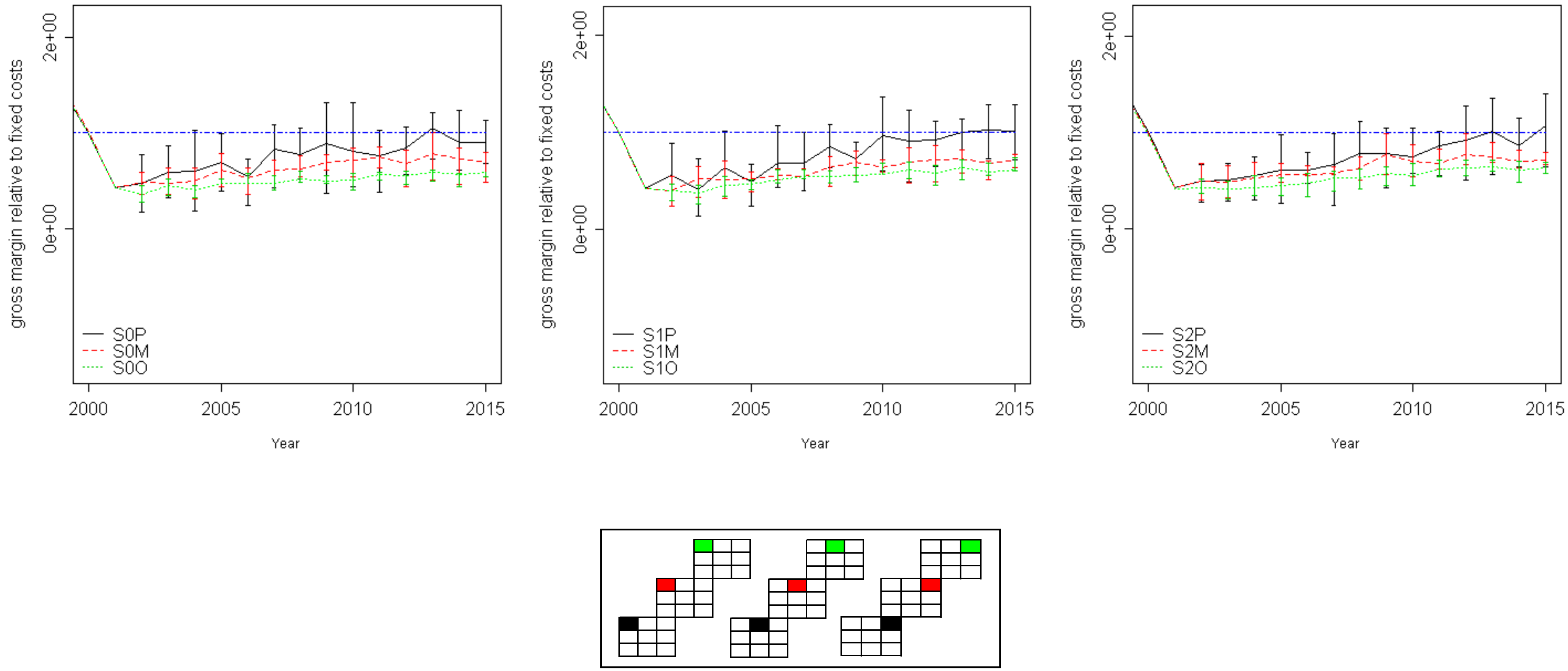


Figure D.67: Comparison of model specifications for the gross margin of the finfish trawl fishery under the status quo management strategy.

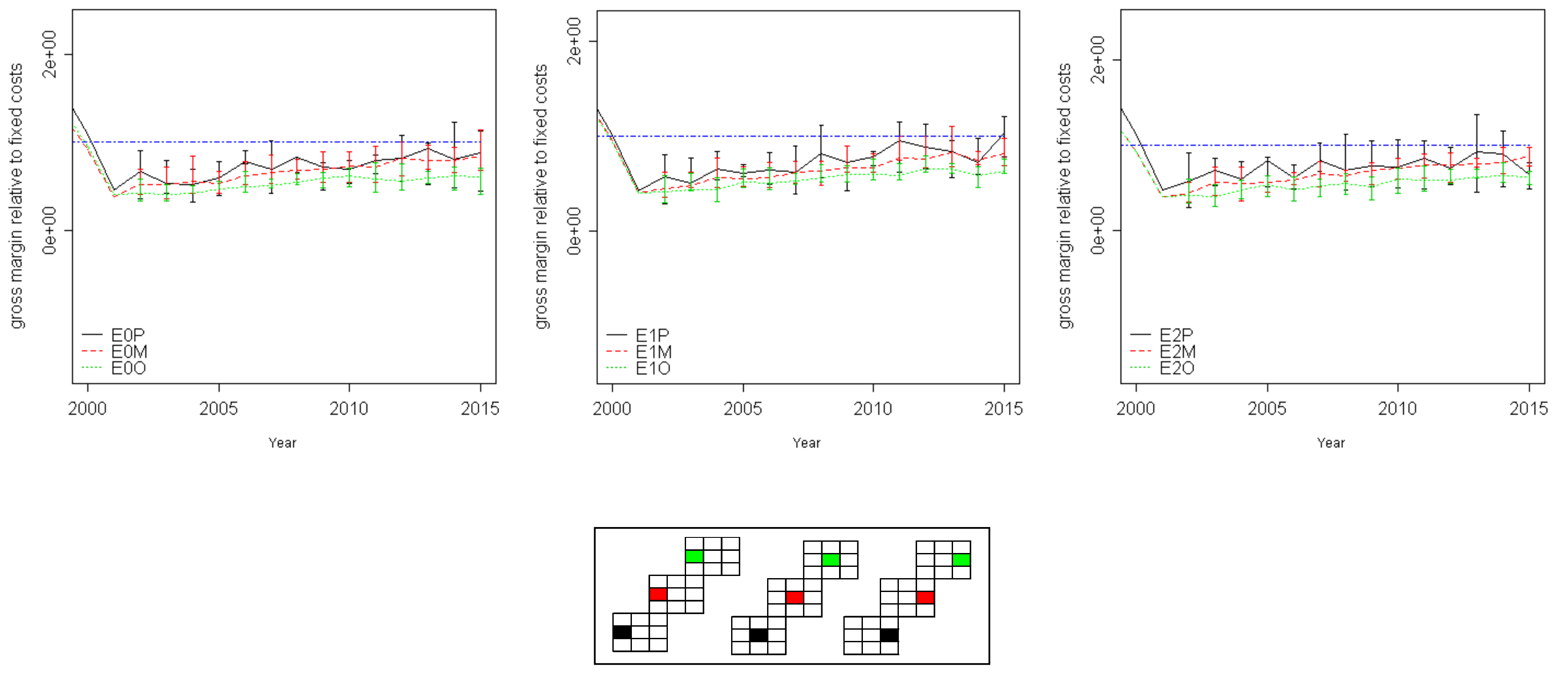


Figure D.68: Comparison of model specifications for the gross margin of the finfish trawl fishery under the enhanced management strategy.

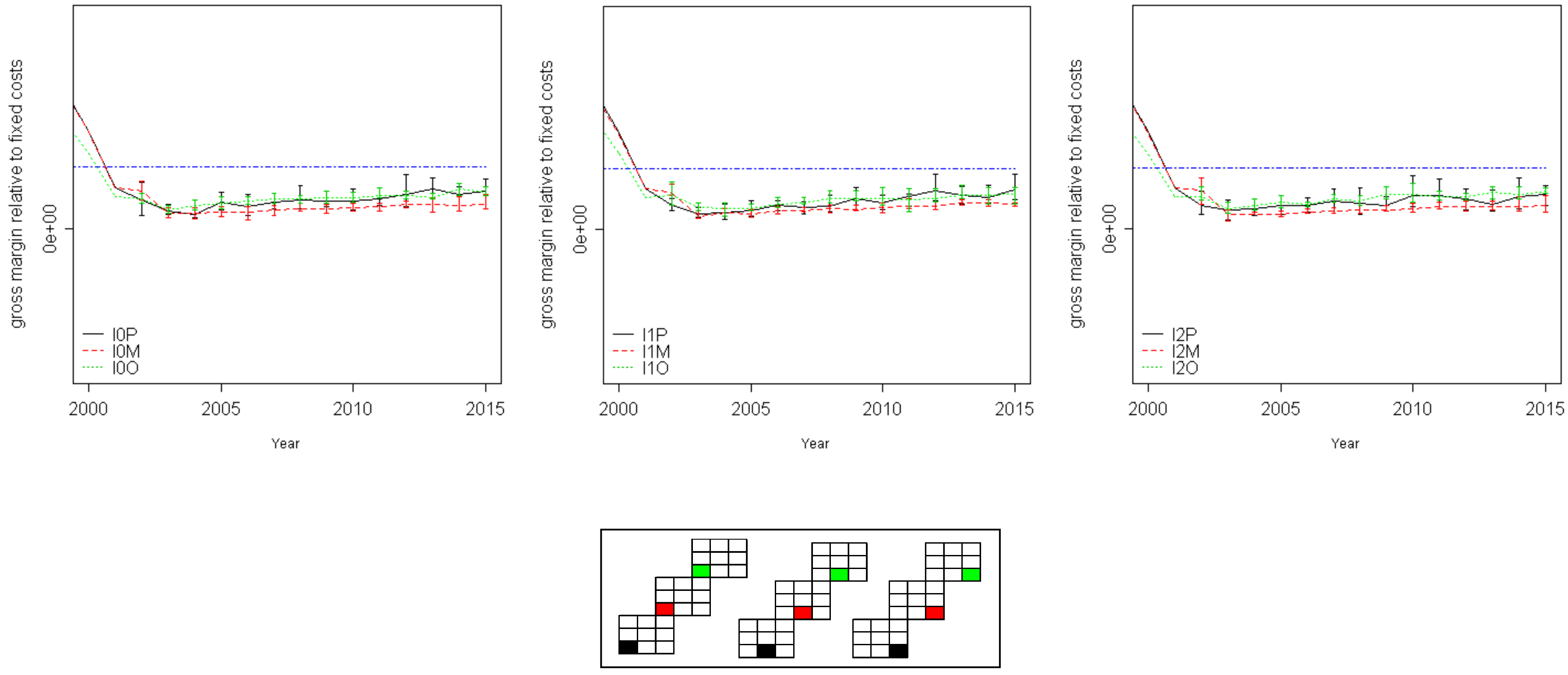


Figure D.69: Comparison of model specifications for the gross margin of the finfish trawl fishery under the integrated management strategy.

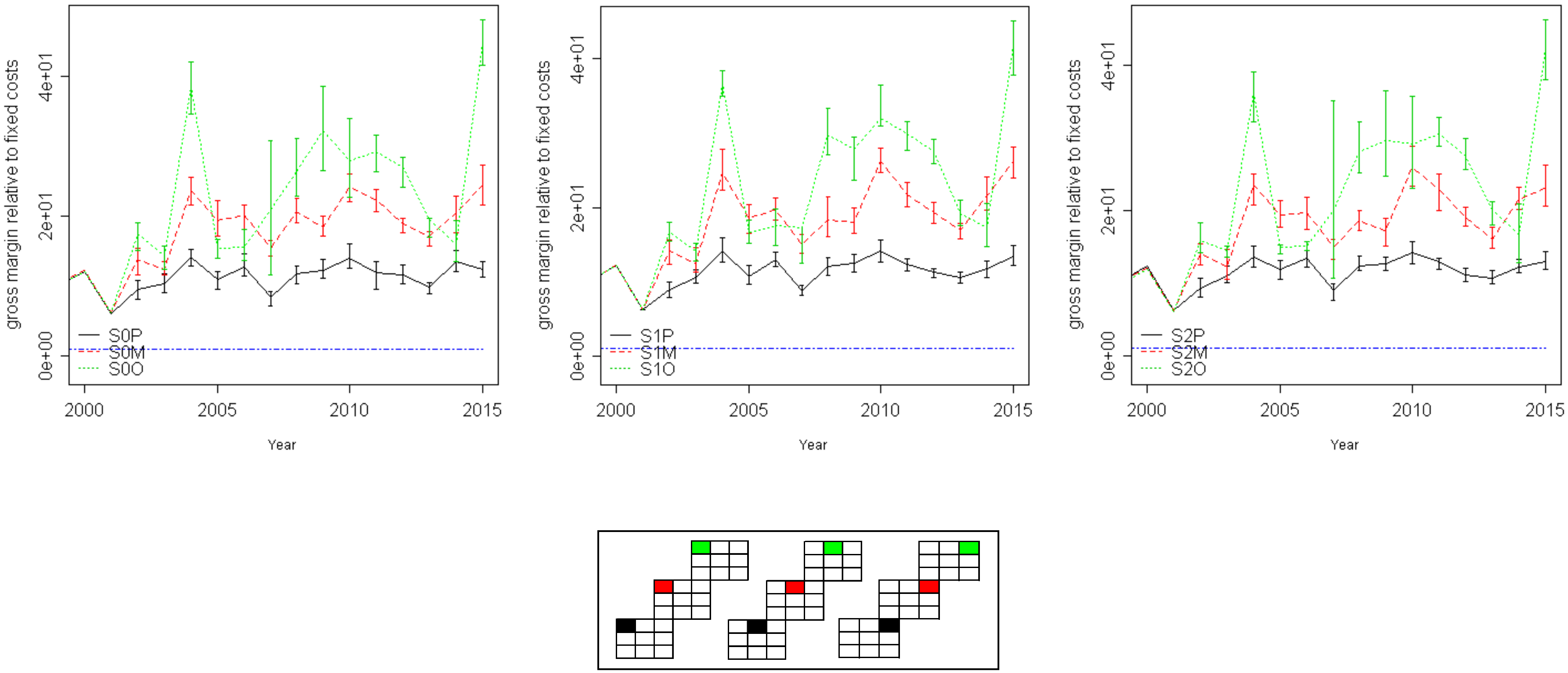
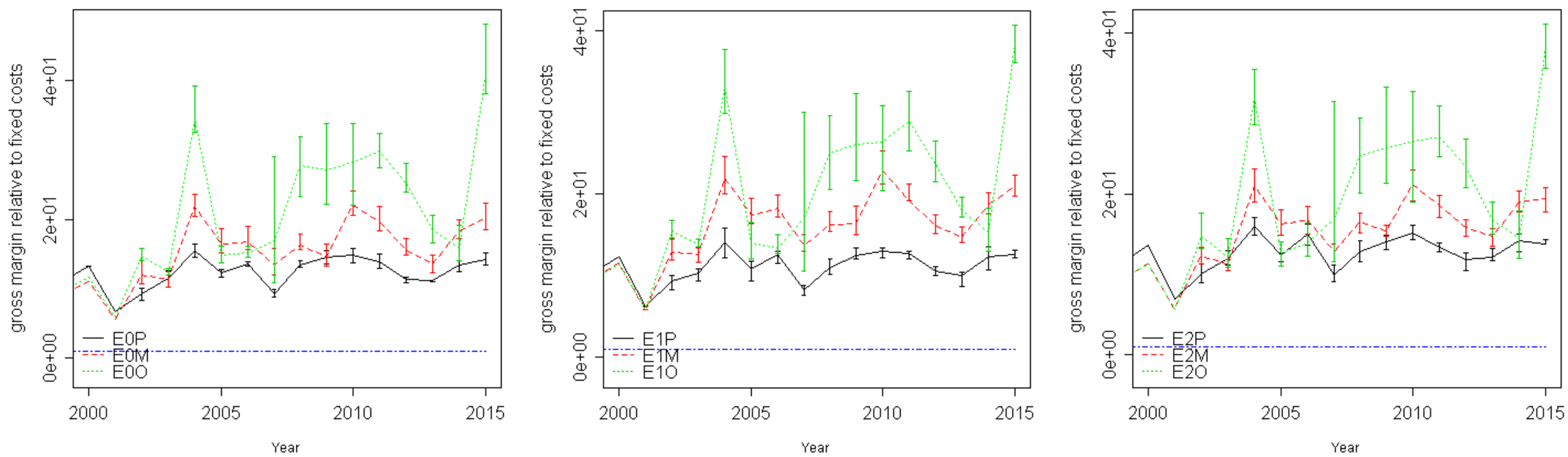


Figure D.70: Comparison of model specifications for the gross margin of the prawn trawl fishery under the status quo management strategy.



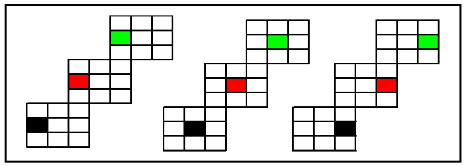
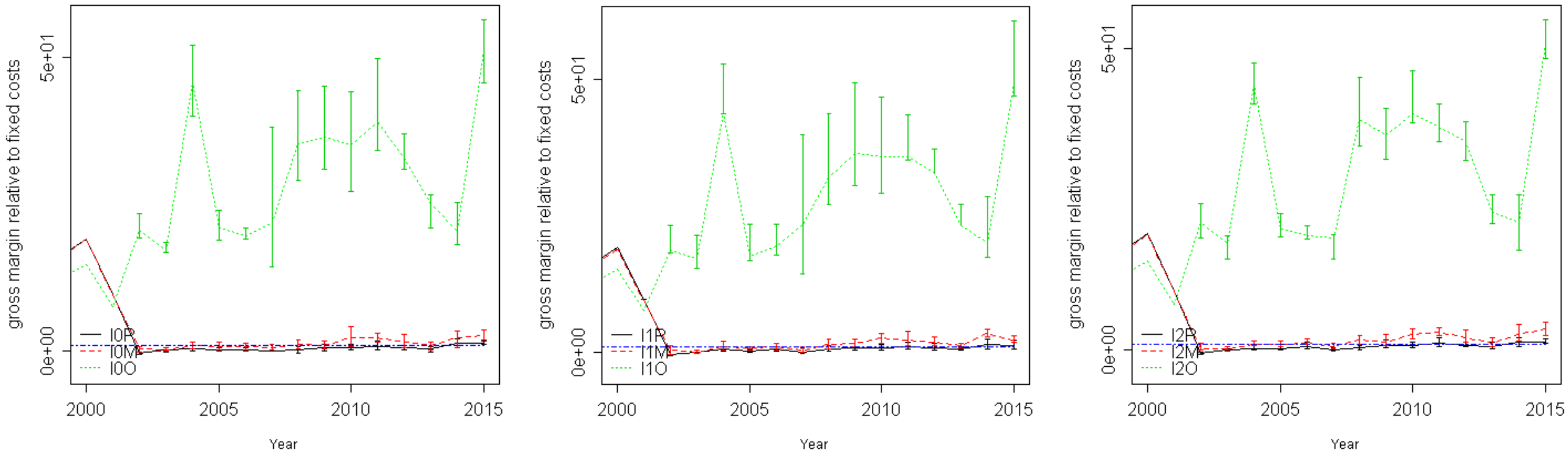


Figure D.71: Comparison of model specifications for the gross margin of the prawn trawl fishery under the enhanced management strategy.



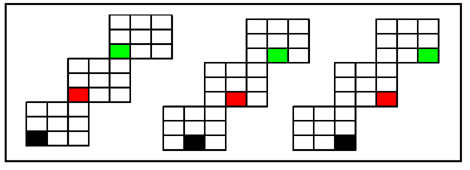


Figure D.72: Comparison of model specifications for the gross margin of the prawn trawl fishery under the integrated management strategy.

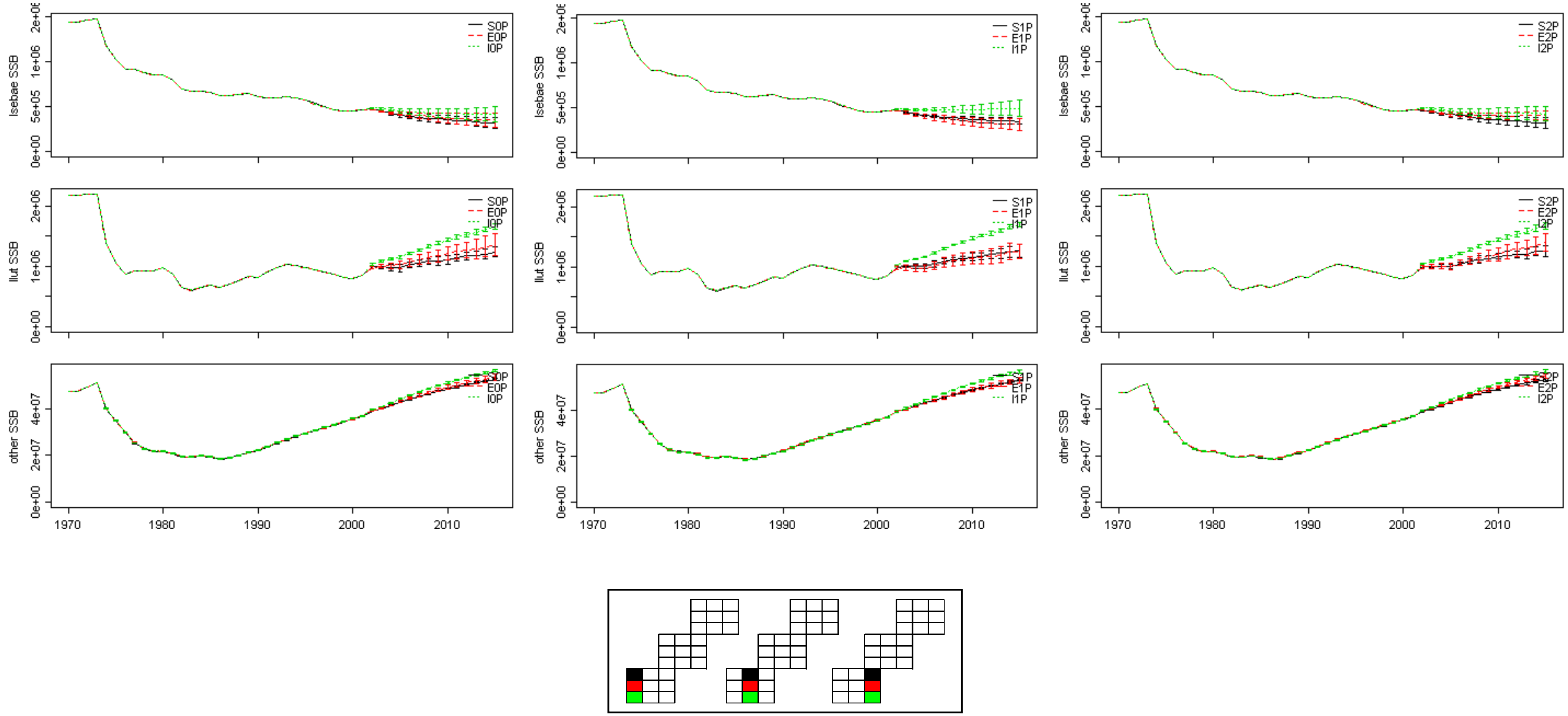


Figure D.73: Comparison of management strategies for spawning stock biomass of *Lutjanus sebae*, large Lutjanids (*L. erythropterus*, *L. malabaricus*) and all other finfish groups combined under the pessimistic model specification.

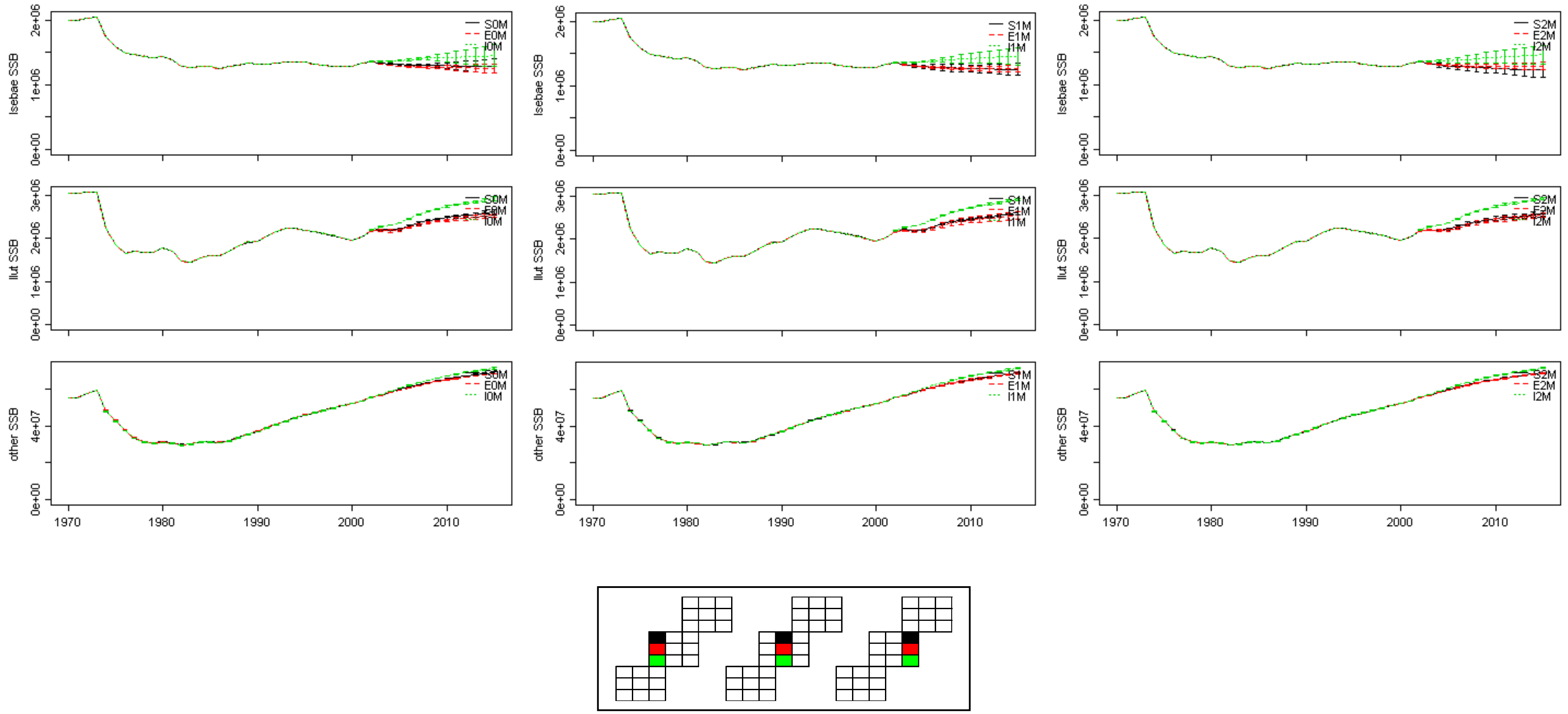


Figure D.74: Comparison of management strategies for spawning stock biomass of *Lutjanus sebae*, large Lutjanids (*L. erythropterus*, *L. malabaricus*) and all other finfish groups combined under base case model specification.

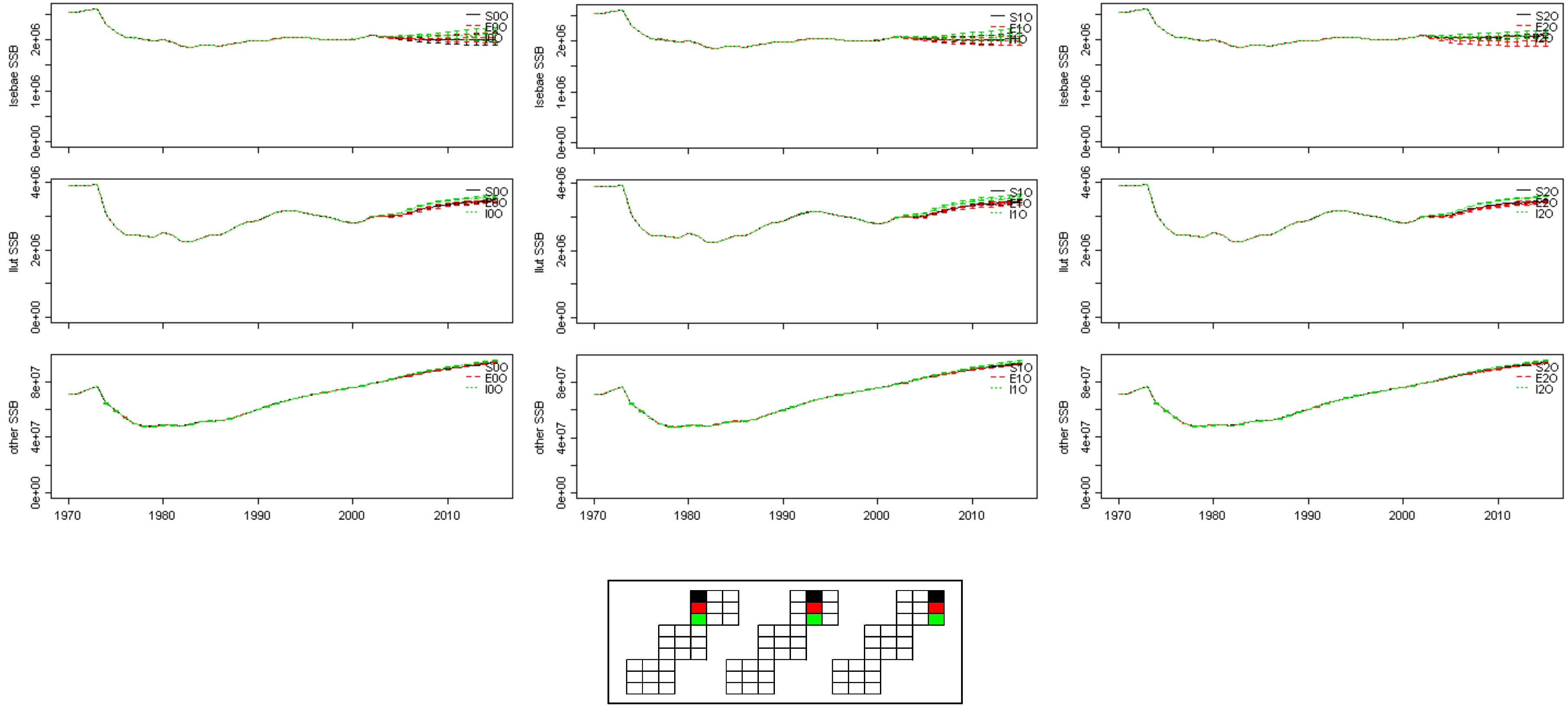
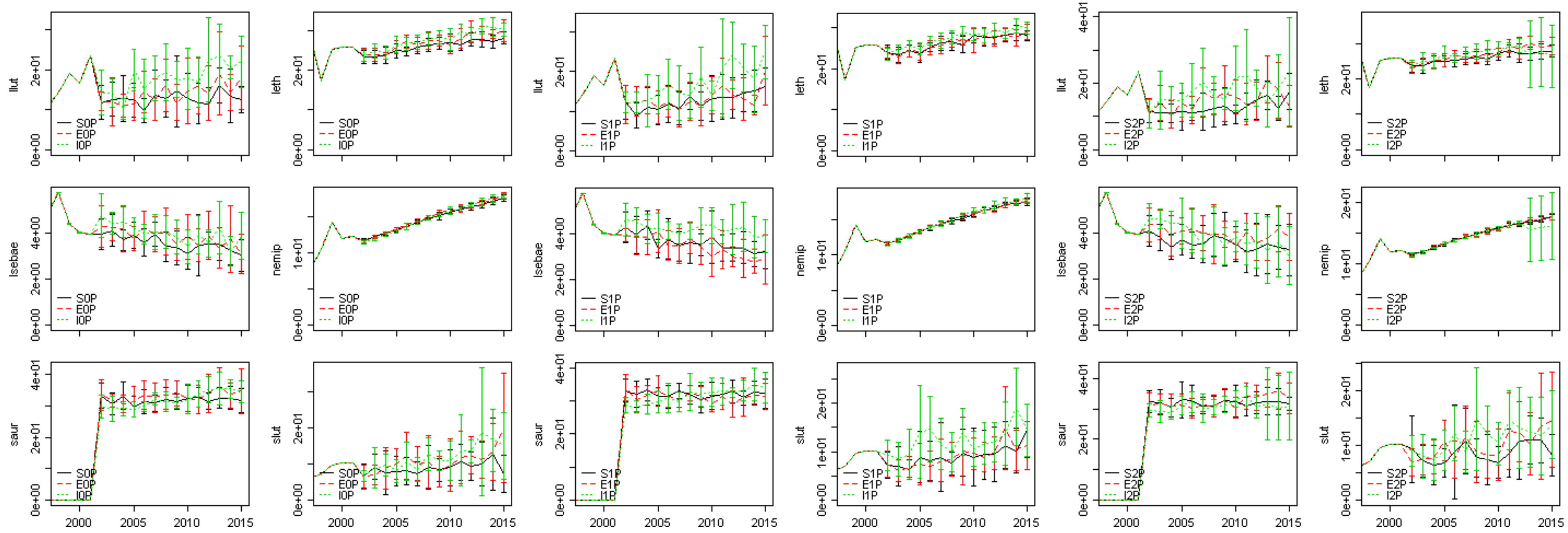


Figure D.75: Comparison of management strategies for spawning stock biomass (kg) of *Lutjanus sebae*, large Lutjanids (*L. erythropterus*, *L. malabaricus*) and all other finfish groups combined under the optimistic model specification.



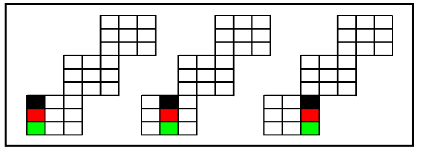


Figure D.76: Comparison of management strategies for trawl CPUE (kg per trawl hour) of different species groups under the pessimistic model specification (leth = lethrinid, llut = large lutjanids, lsebae = *L. sebae*, nemip = nemipterids, slut = small lutjanids, saur = saurids).

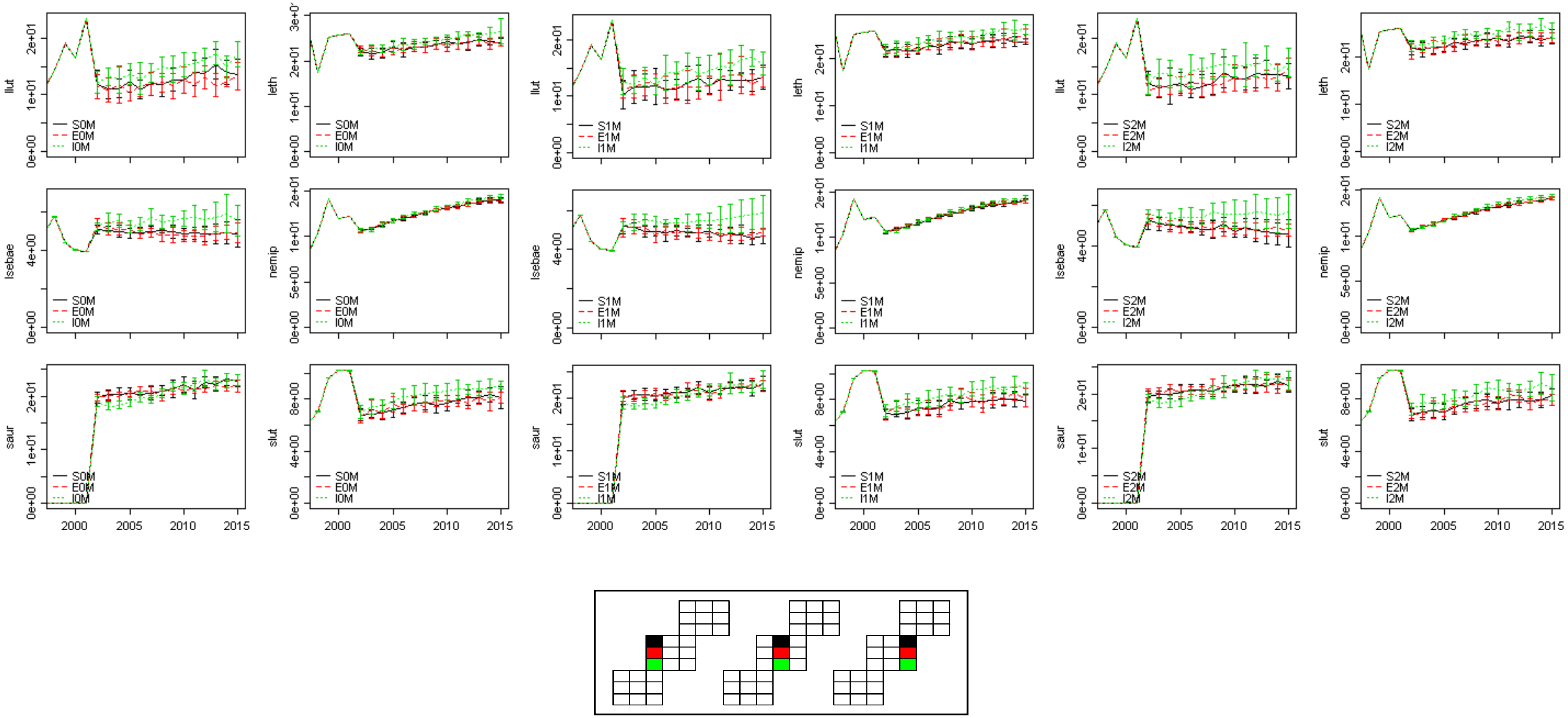


Figure D.77: Comparison of management strategies for trawl CPUE (kg per trawl hour) of different species groups under the base case model specification (leth = lethrinid, llut = large lutjanids, lsebae = *L. sebae*, nemip = nemipterids, slut = small lutjanids, saur = saurids).

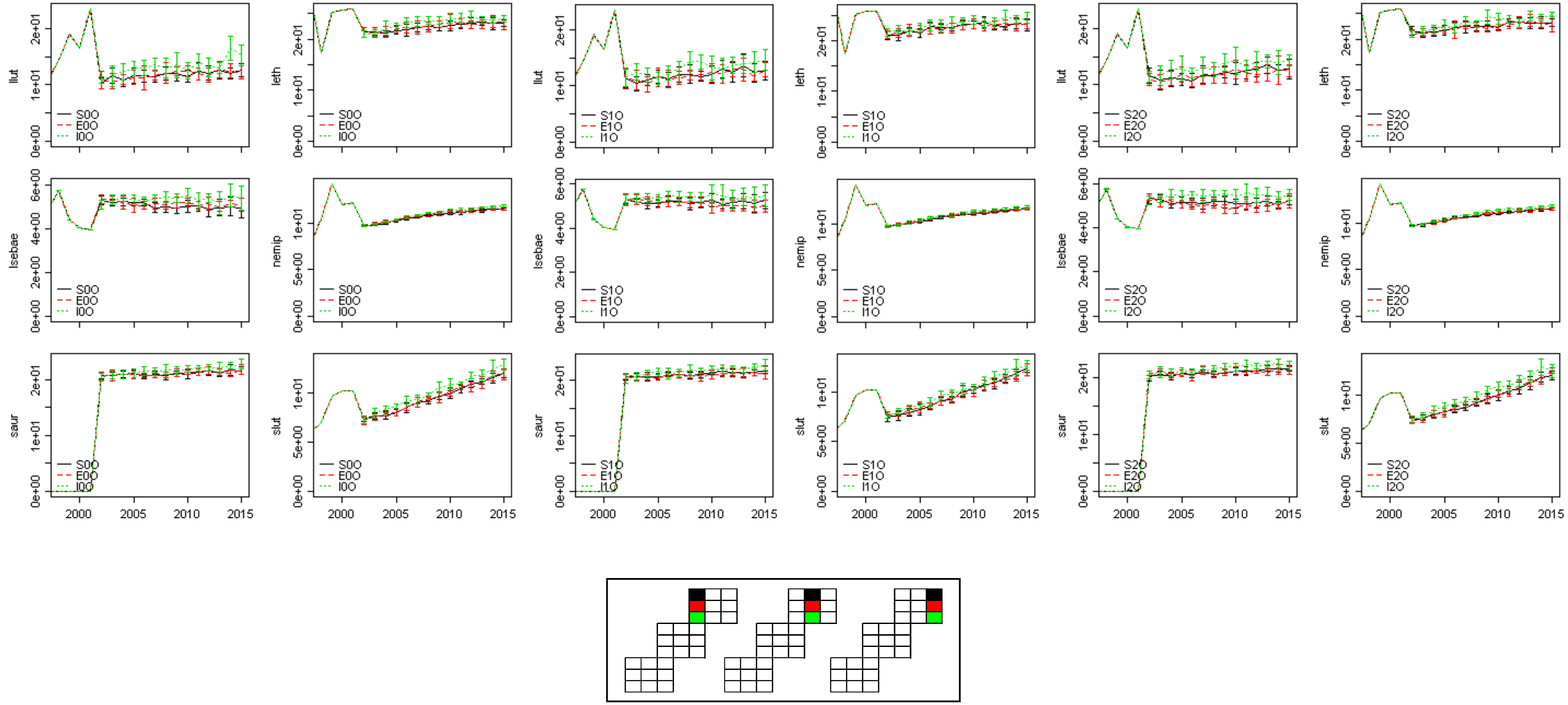
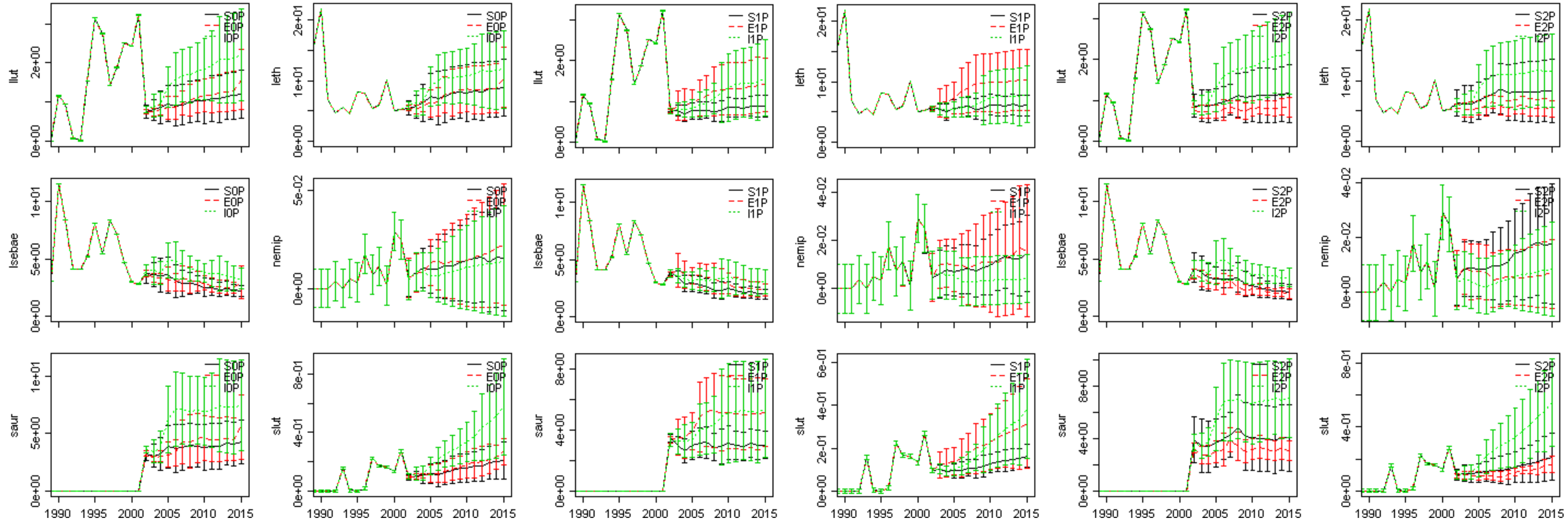


Figure D.78: Comparison of management strategies for trawl CPUE (kg per trawl hour) of different species groups under the optimistic model specification (leth = lethrinid, llut = large lutjanids, lsebae = *L. sebae*, nemip = nemipterids, slut = small lutjanids, saur = saurids).



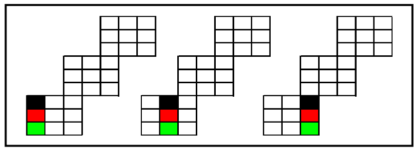


Figure D.79: Comparison of management strategies for trap CPUE (kg per trap soak hour) of different species groups under the pessimistic model specification (leth = lethrinid, llut = large lutjanids, lsebae = *L. sebae*, nemip = nemipterids, slut = small lutjanids, saur = saurids).

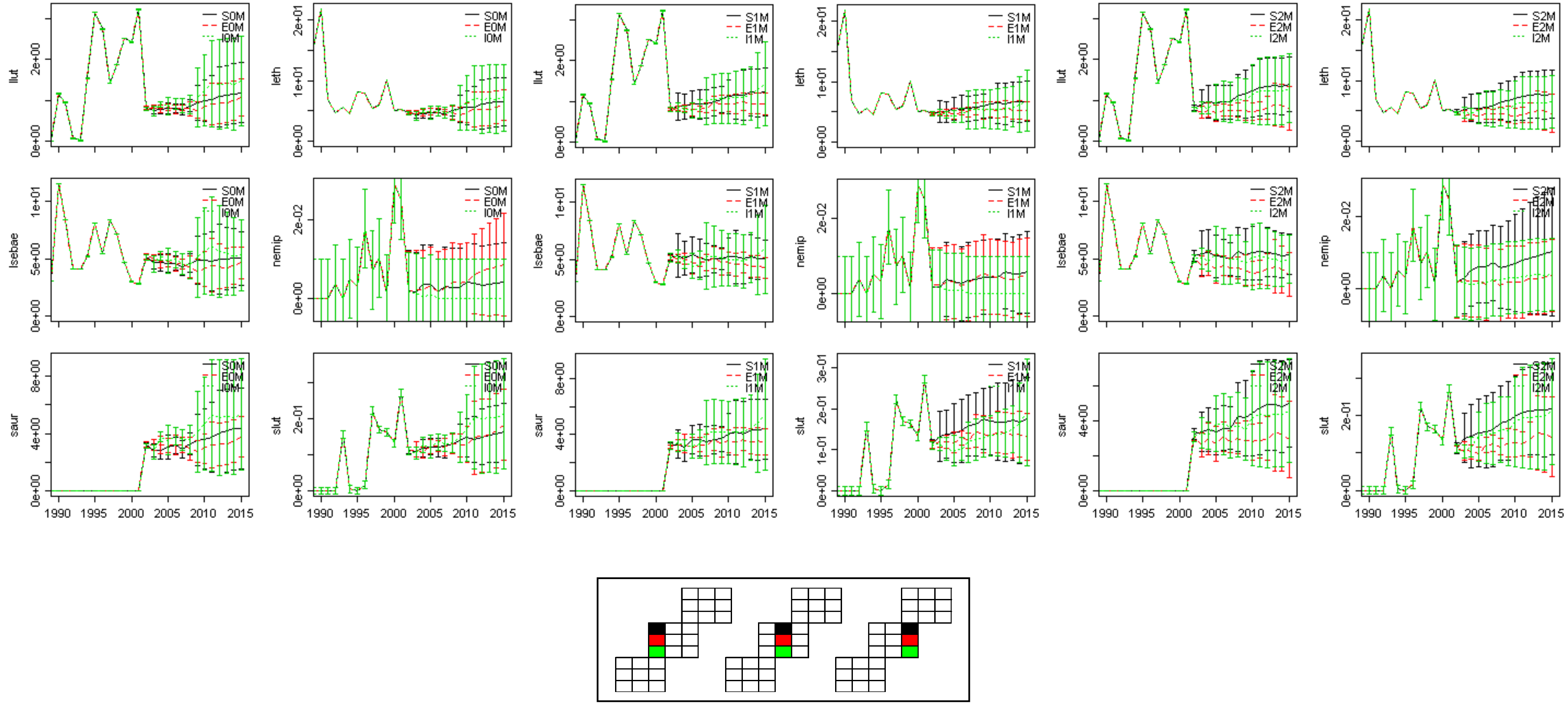
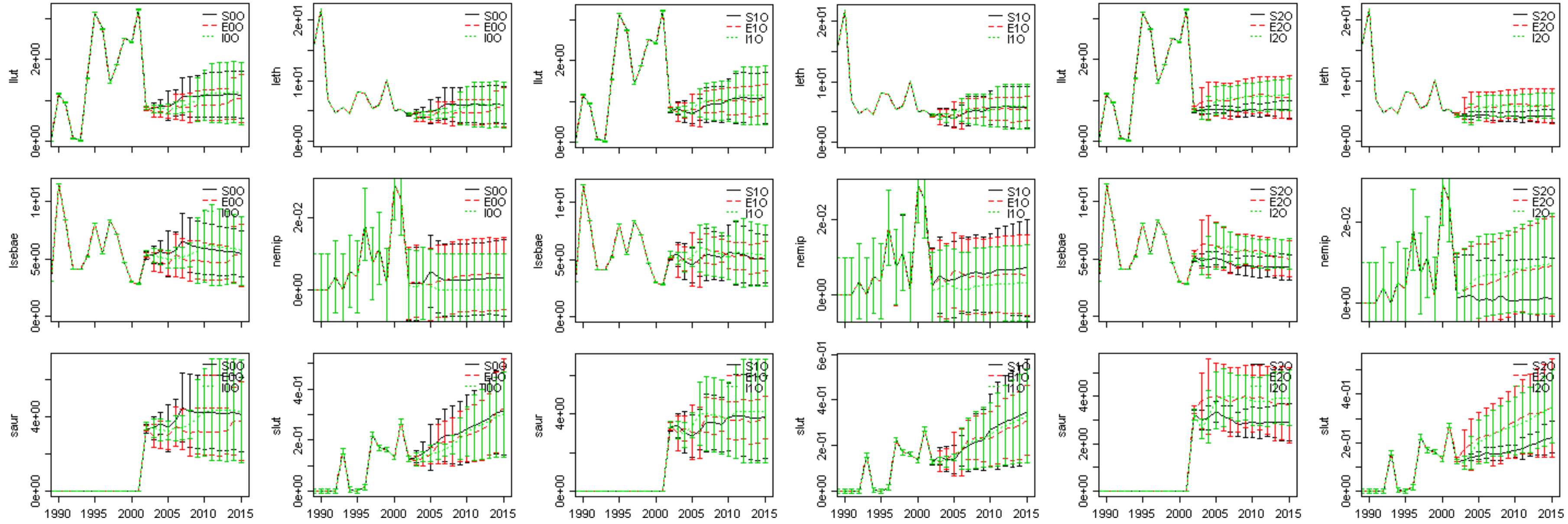


Figure D.80: Comparison of management strategies for trap CPUE (kg per trap soak hour) of different species groups under the base case model specification (leth = lethrinid, llut = large lutjanids, lsebae = *L. sebae*, nemip = nemipterids, slut = small lutjanids, saur = saurids).



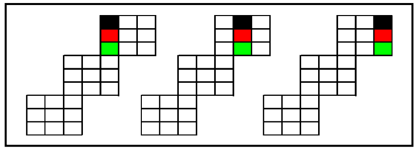


Figure D.81: Comparison of management strategies for trap CPUE (kg per trap soak hour) of different species groups under the optimistic model specification (leth = lethrinid, llut = large lutjanids, lsebae = *L. sebae*, nemip = nemipterids, slut = small lutjanids, saur = saurids).

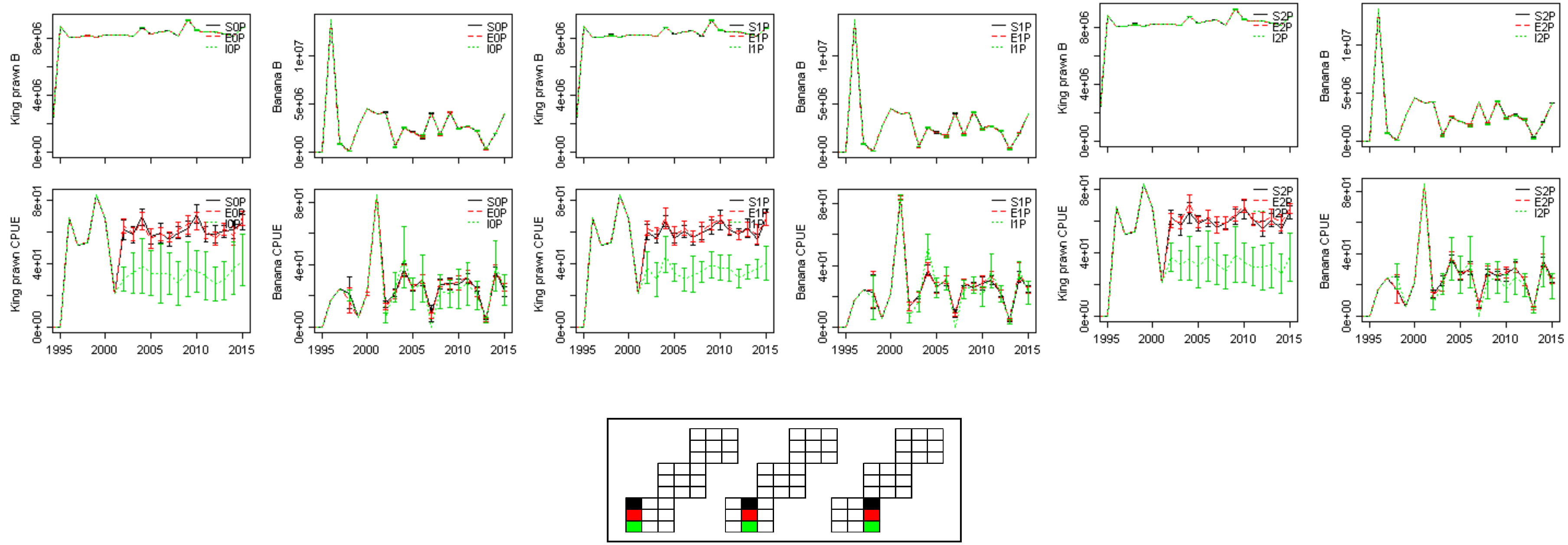
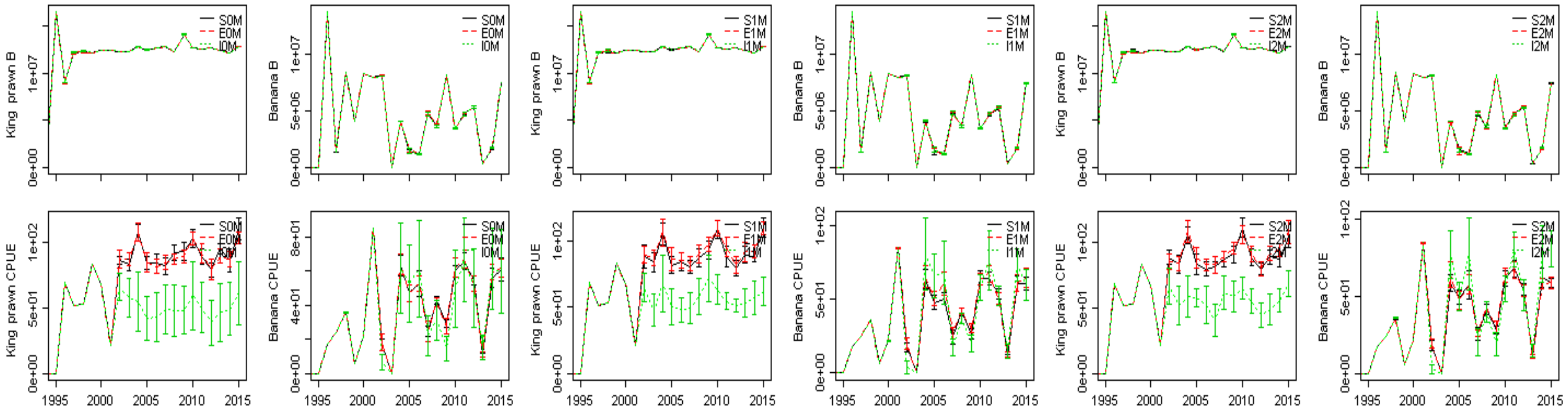


Figure D.82: Comparison of management strategies for total biomass (kg) and CPUE (kg per trawl hour) of the two prawn species under the pessimistic model specification.



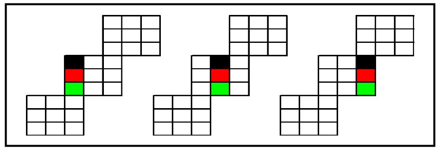


Figure D.83: Comparison of management strategies for total biomass (kg) and CPUE (kg per trawl hour) of the two prawn species under the base case model specification.

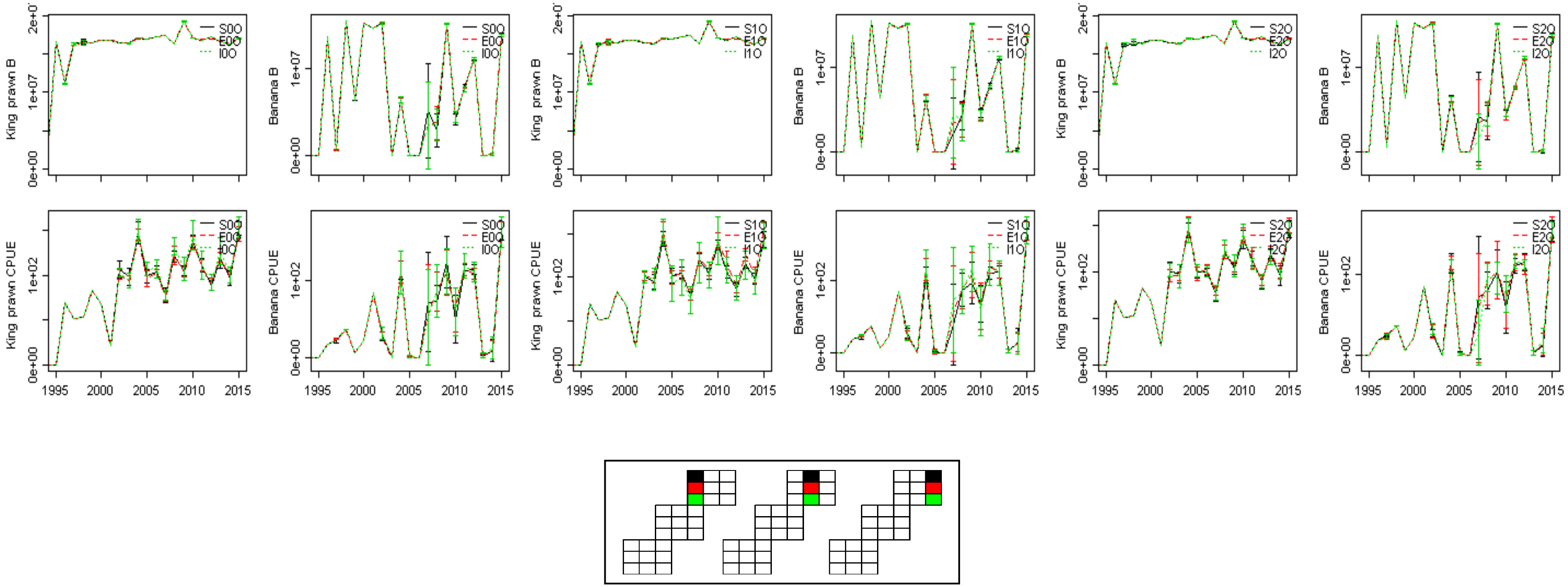
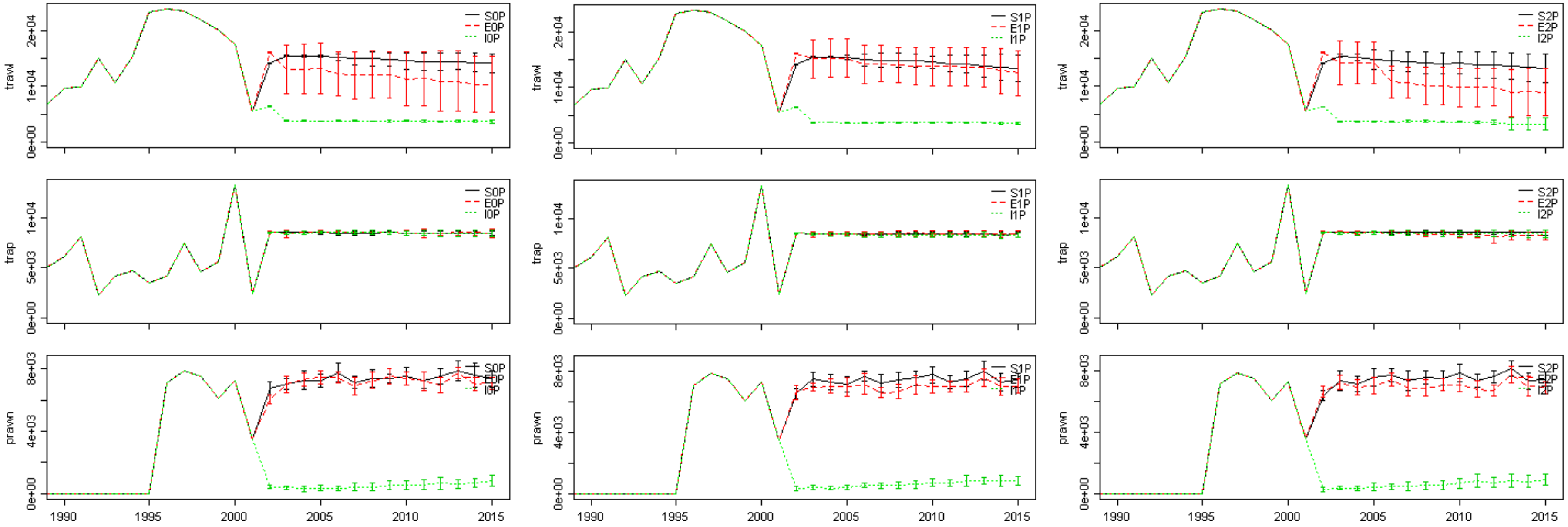


Figure D.84: Comparison of management strategies for total biomass (kg) and CPUE (kg per trawl hour) of the two prawn species under the optimistic model specification.



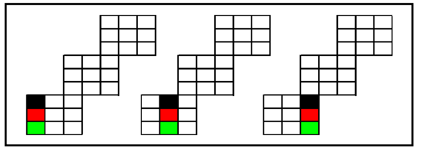


Figure D.85: Comparison of management strategies for total effort (fishing hours) for the different fisheries under the pessimistic model specification.

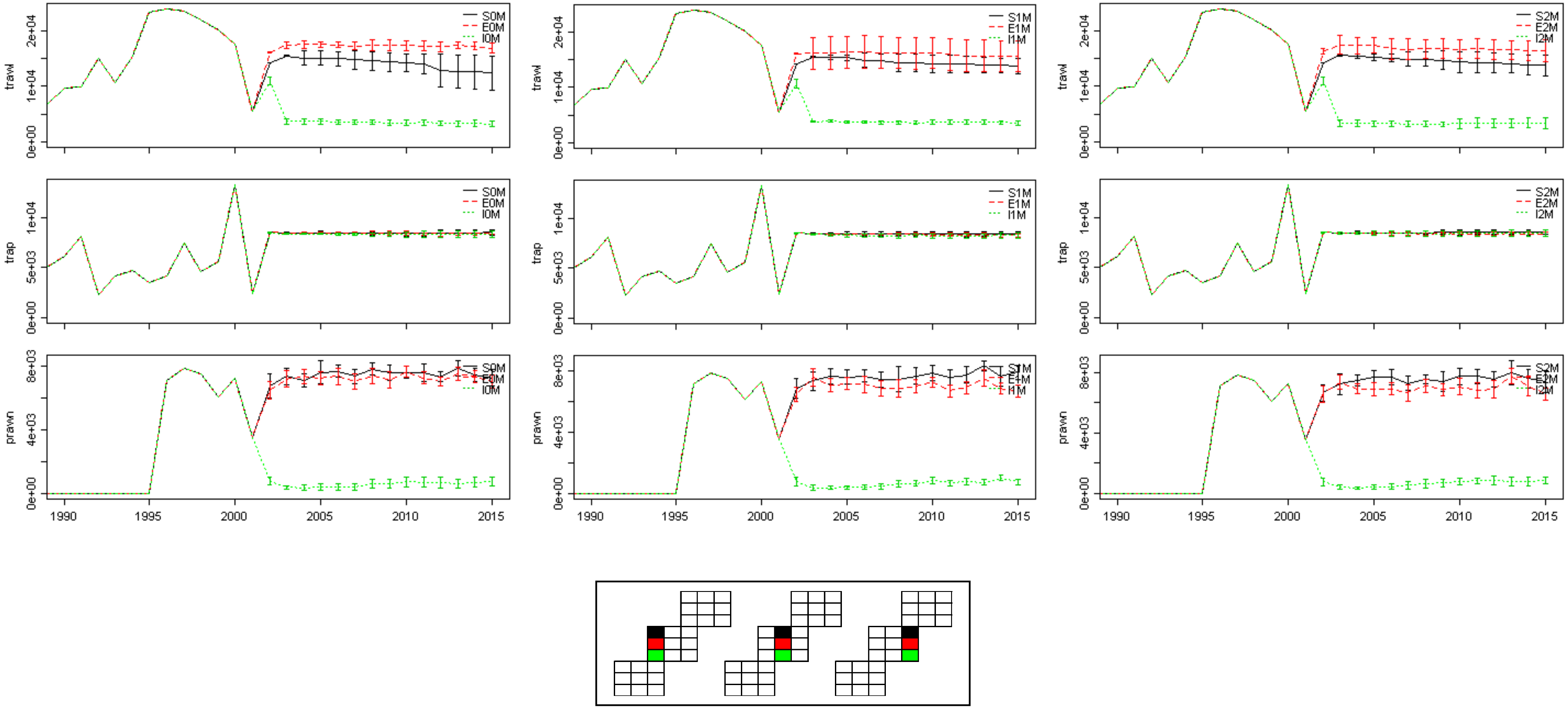


Figure D.86: Comparison of management strategies for total effort (fishing hours) for the different fisheries under the base case model specification.

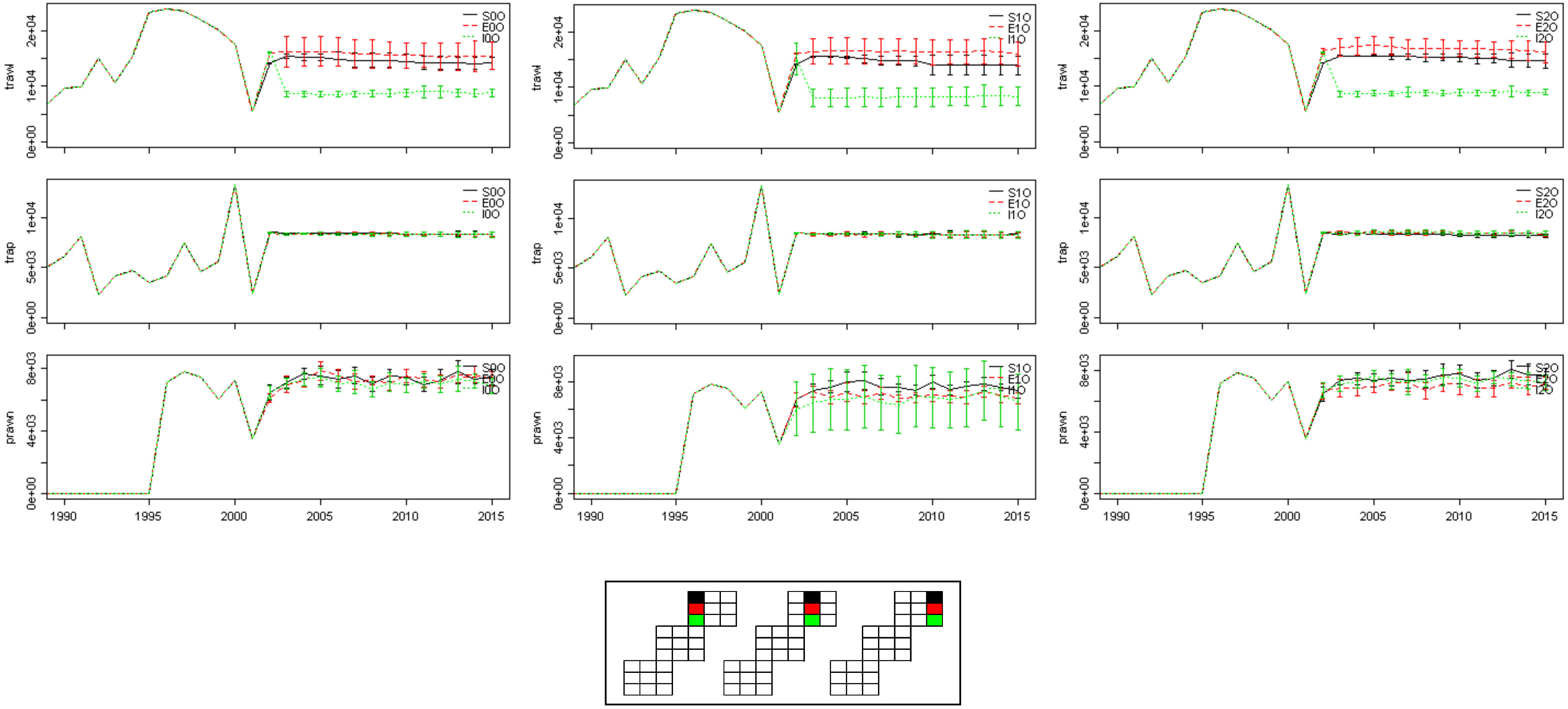
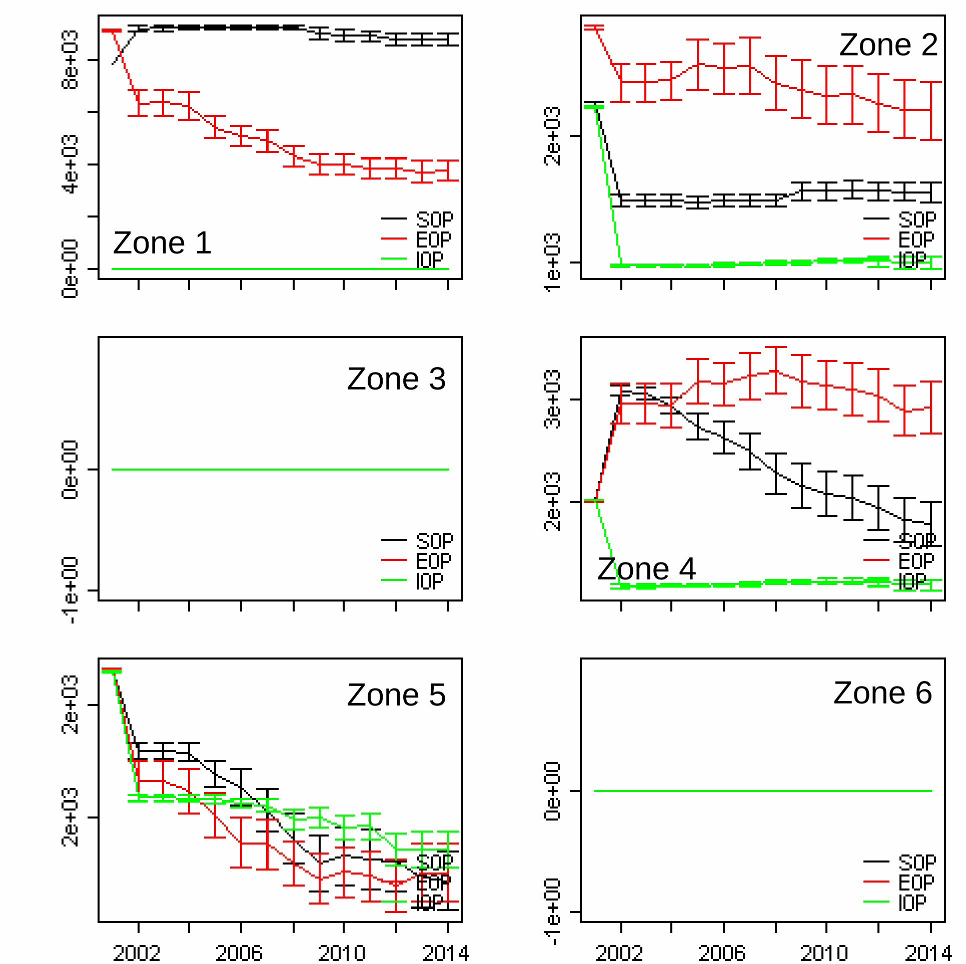


Figure D.87: Comparison of management strategies for total effort (fishing hours) for the different fisheries under the optimistic model specification.



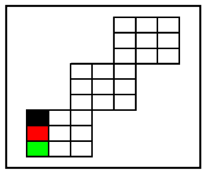


Figure D.88: Comparison of management strategies for finfish trawl effort (trawl hours) in the six trawl areas under the zero-pulse development scenario and the pessimistic model specification.

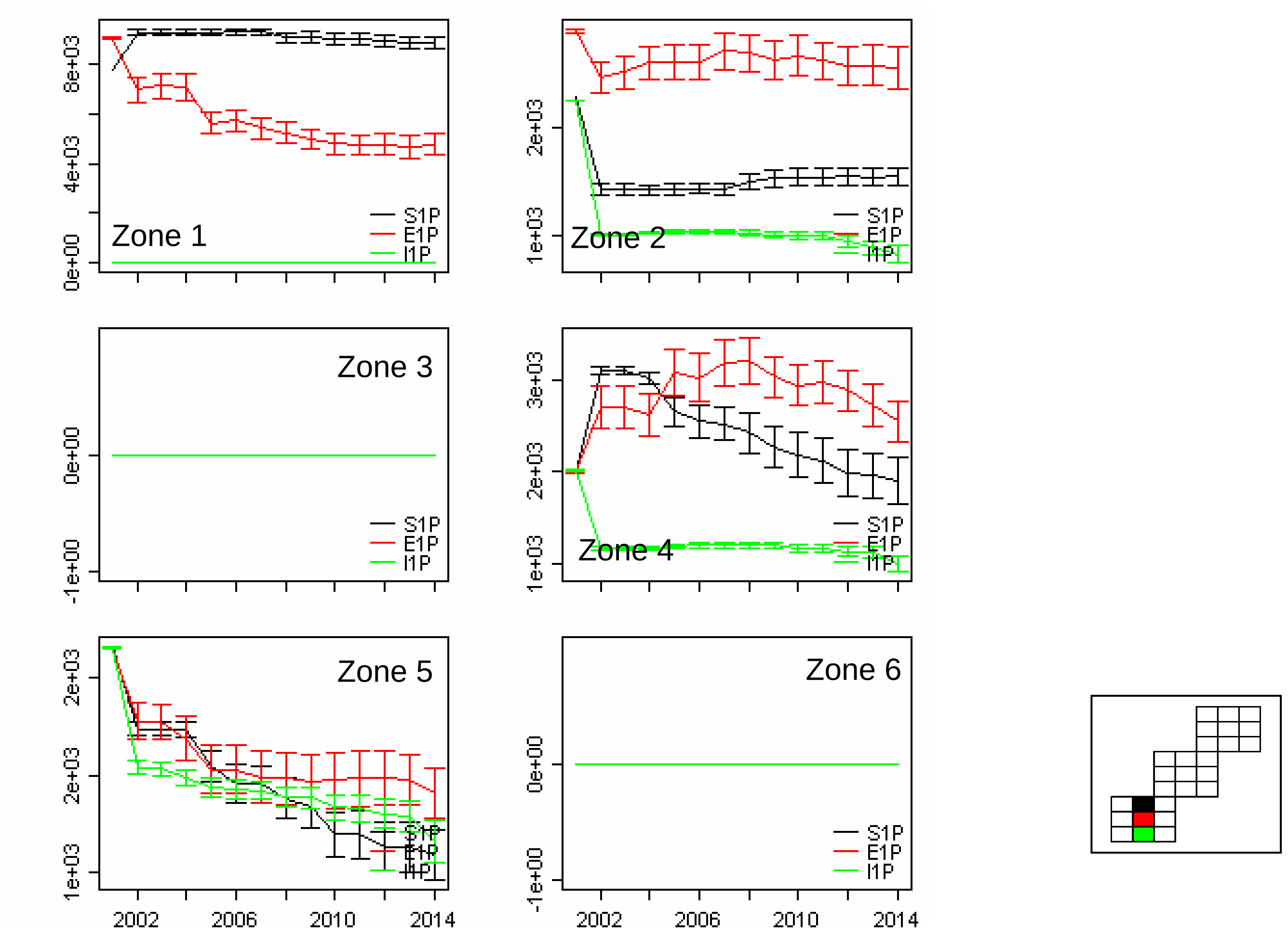


Figure D.89: Comparison of management strategies for finfish trawl effort (trawl hours) in the six trawl areas under the one-pulse development scenario and the pessimistic model specification.

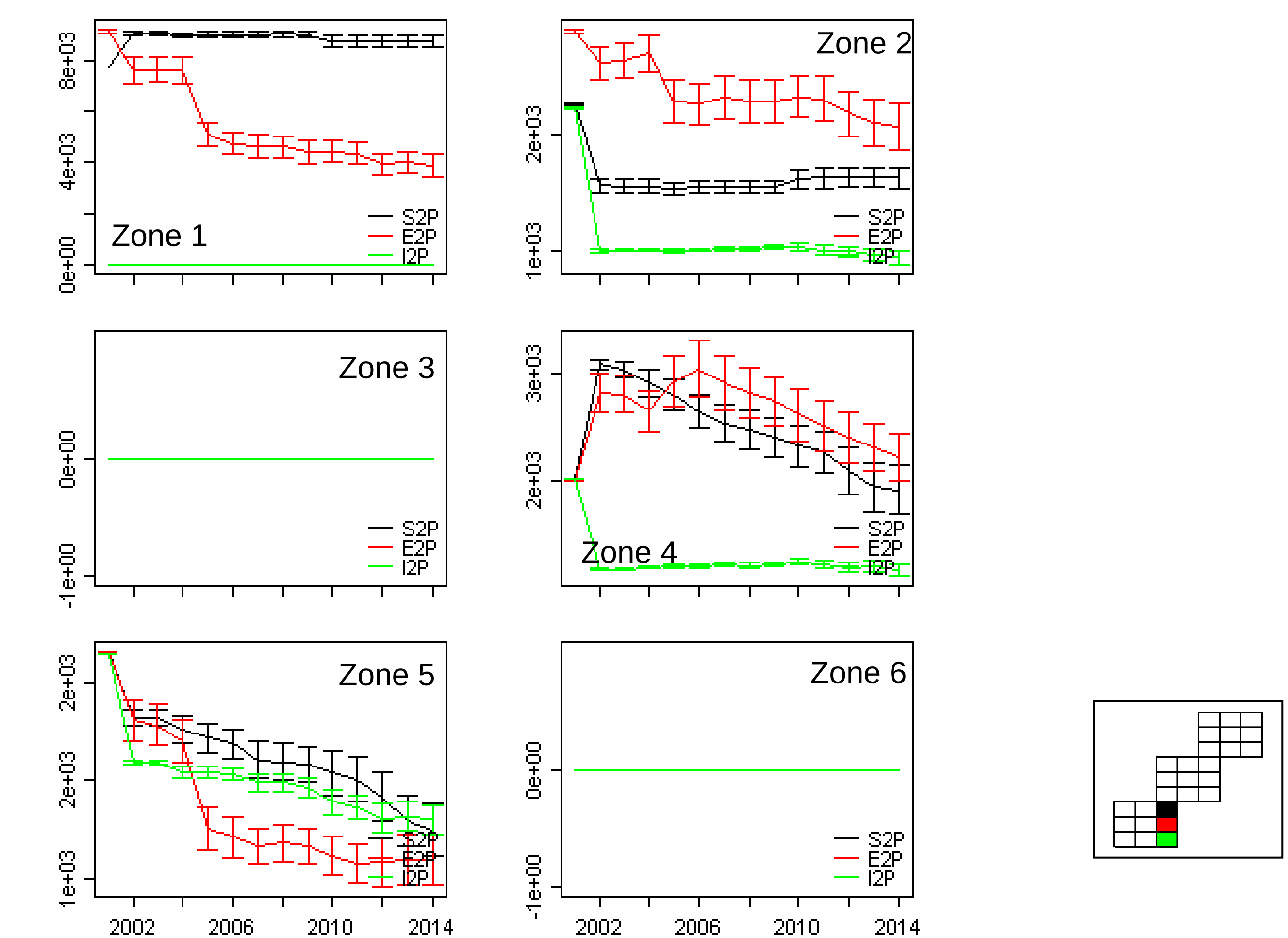
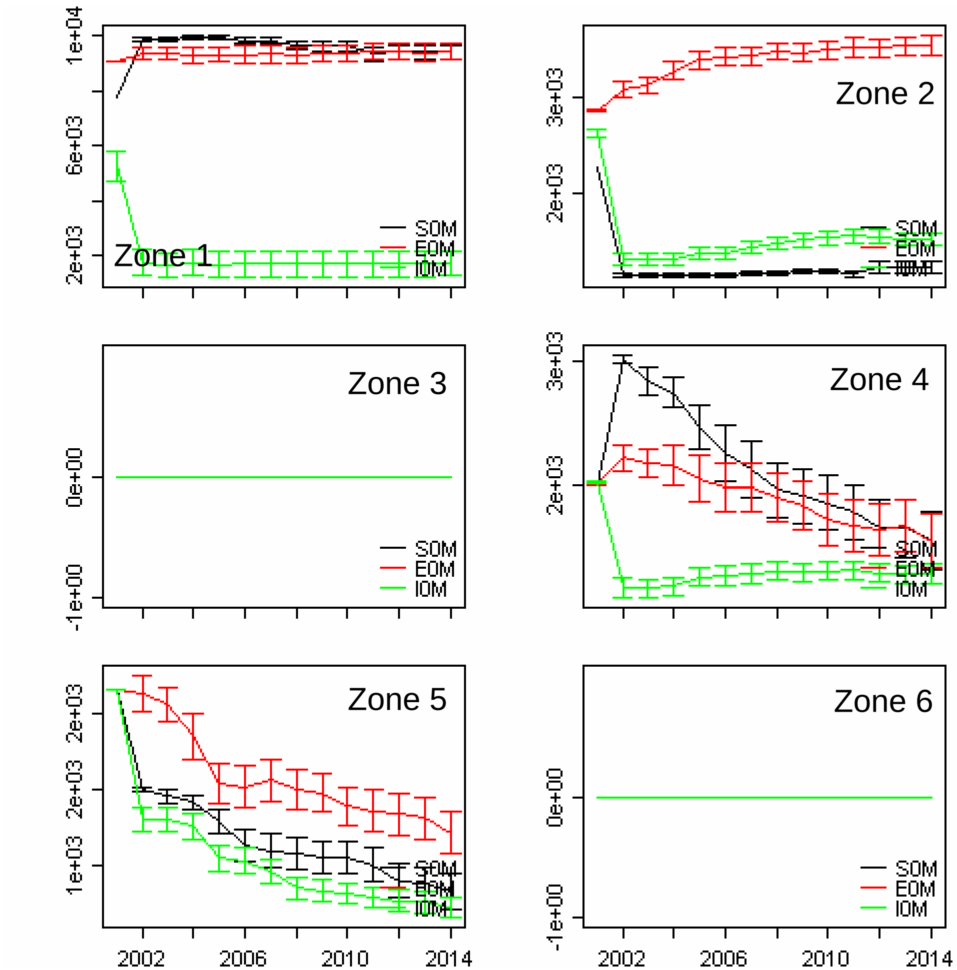


Figure D.90: Comparison of management strategies for finfish trawl effort (trawl hours) in the six trawl areas under the two-pulse development scenario and the pessimistic model specification.



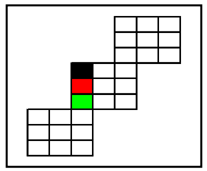


Figure D.91: Comparison of management strategies for finfish trawl effort (trawl hours) in the six trawl areas under the zero-pulse development scenario and the base case model specification.

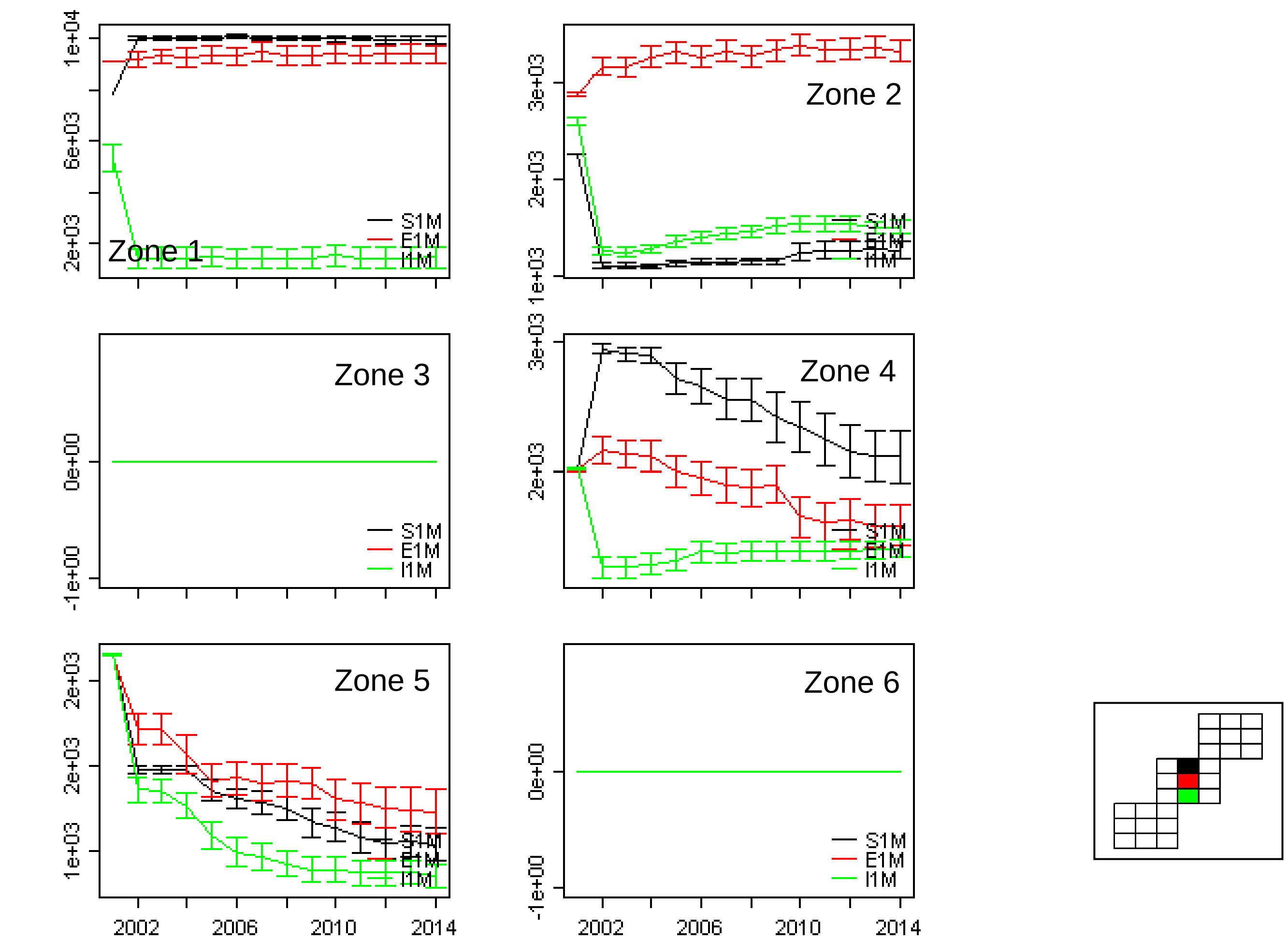
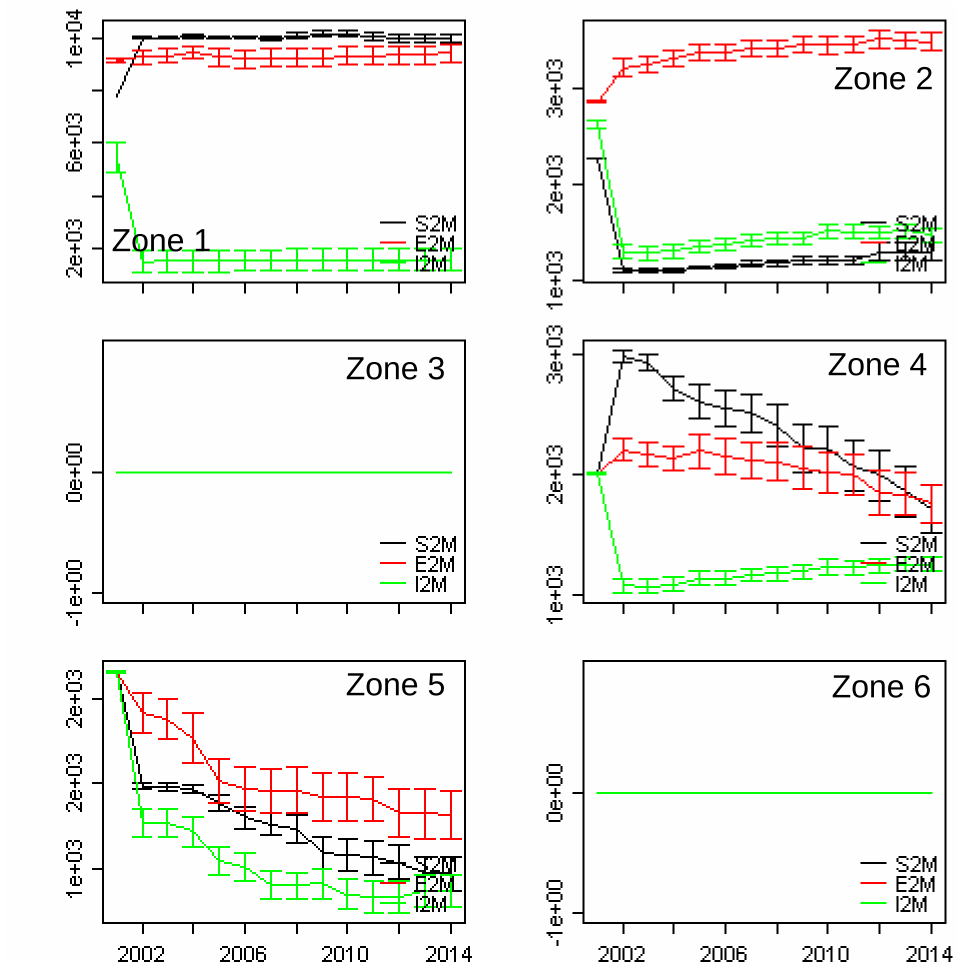


Figure D.92: Comparison of management strategies for finfish trawl effort (trawl hours) in the six trawl areas under the one-pulse development scenario and the base case model specification.



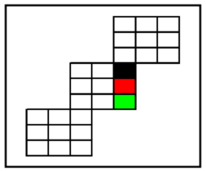
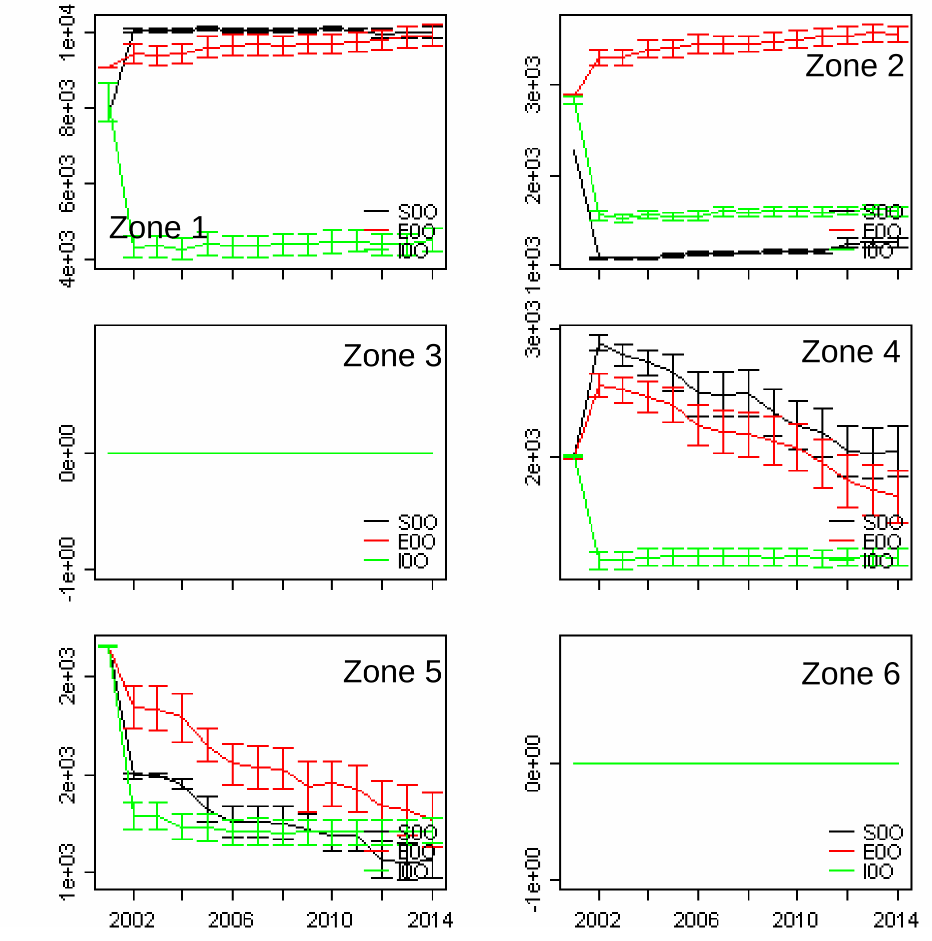


Figure D.93: Comparison of management strategies for finfish trawl effort (trawl hours) in the six trawl areas under the two-pulse development scenario and the base case model specification.



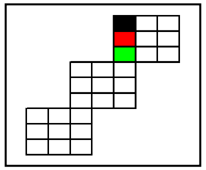
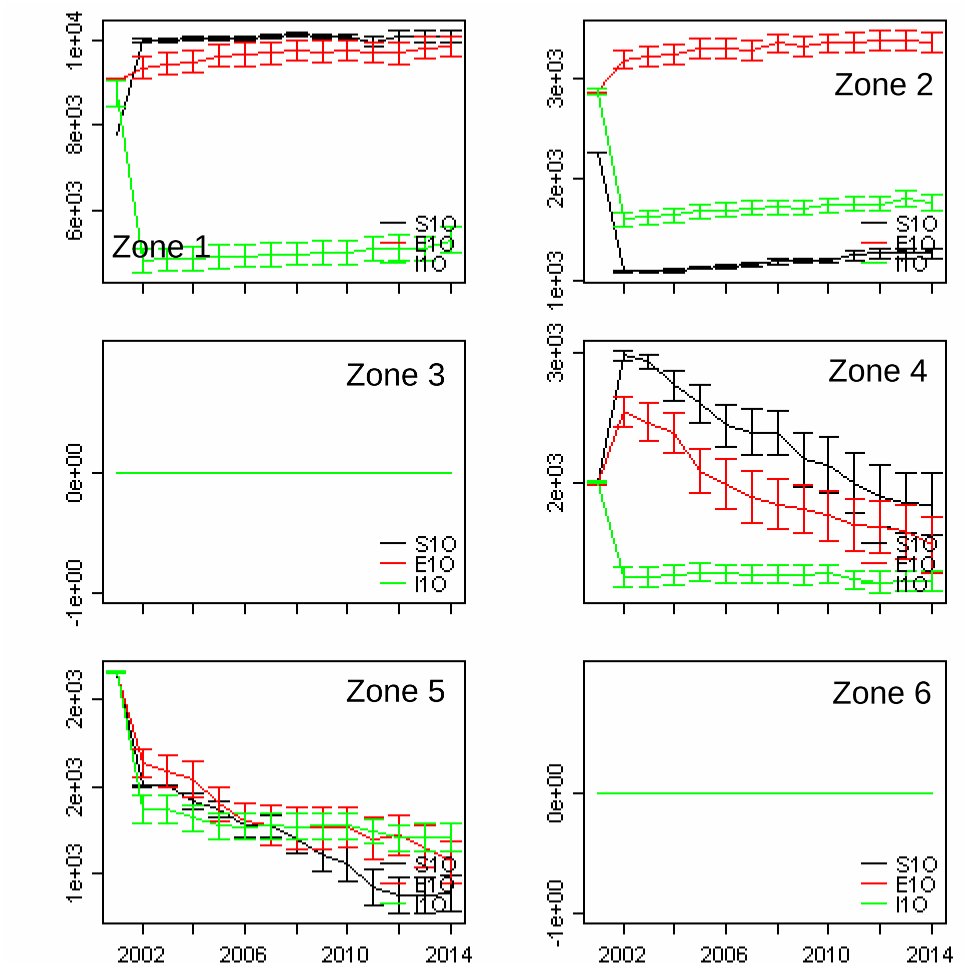


Figure D.94: Comparison of management strategies for finfish trawl effort (trawl hours) in the six trawl areas under the zero-pulse development scenario and the optimistic model specification.



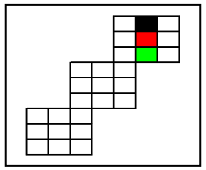


Figure D.95: Comparison of management strategies for finfish trawl effort (trawl hours) in the six trawl areas under the one-pulse development scenario and the optimistic model specification.

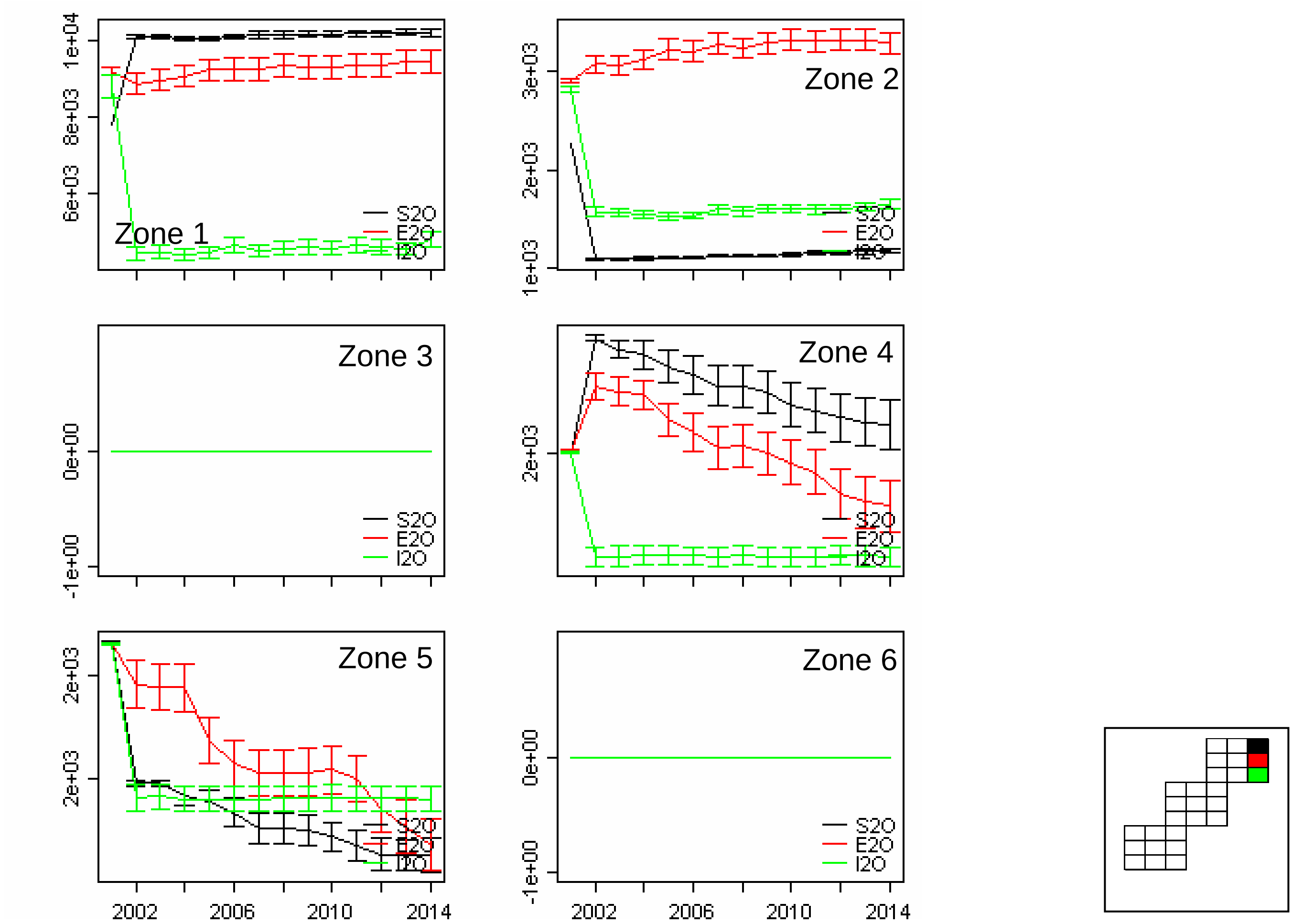


Figure D.96: Comparison of management strategies for finfish trawl effort (trawl hours) in the six trawl areas under the two-pulse development scenario and the optimistic model specification.

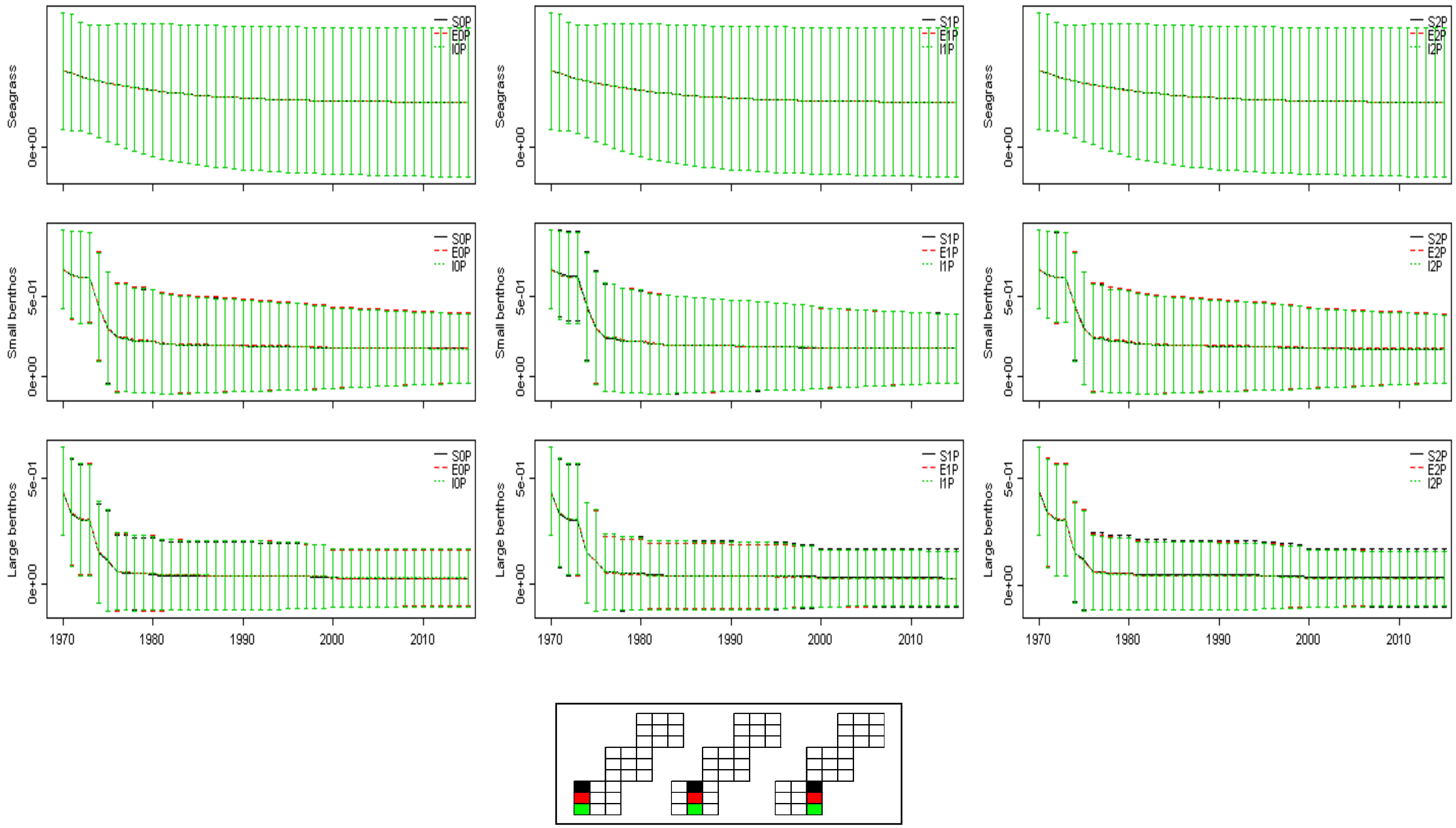


Figure D.97 (a): Comparison of management strategies for the spatial extent of three habitats under the pessimistic model specification for seagrass and large and small benthos.

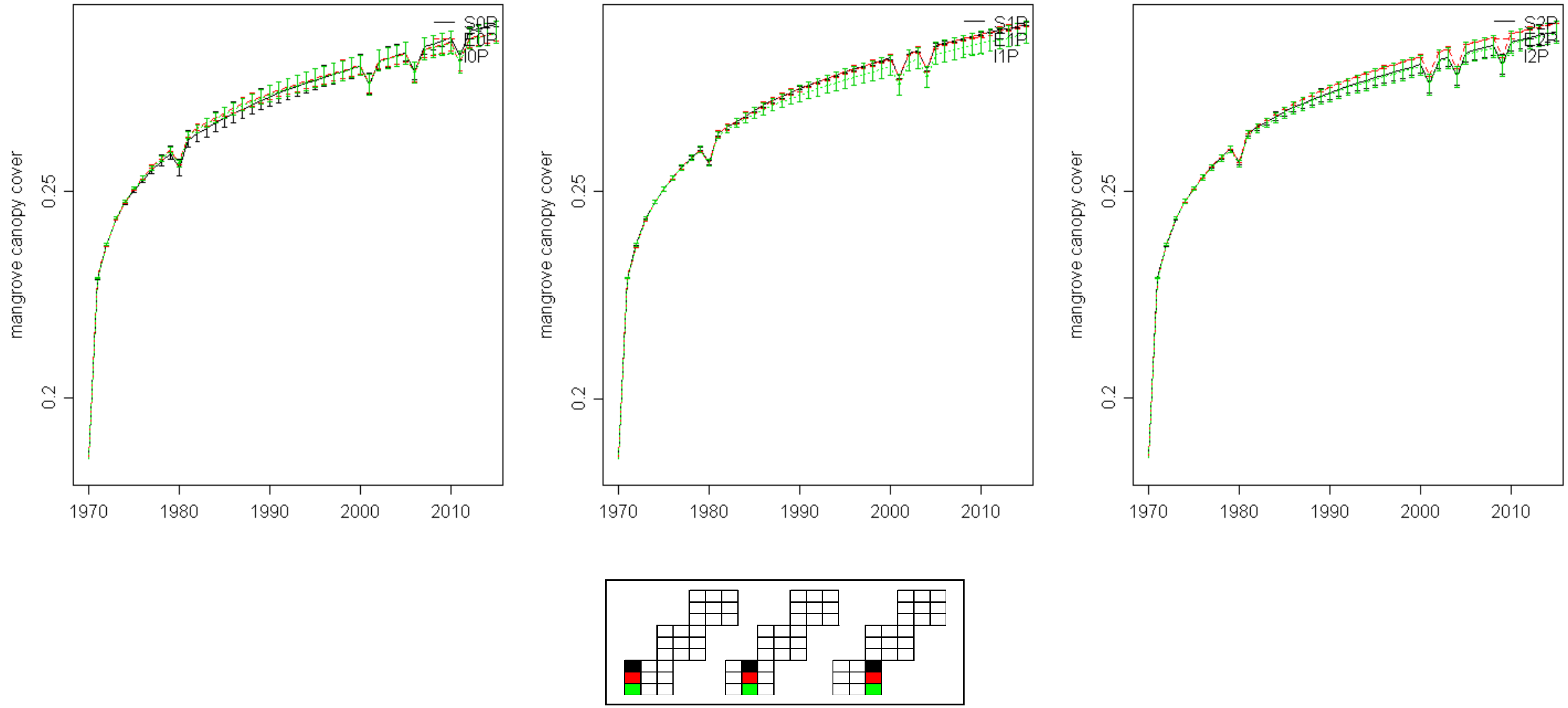


Figure D.97 (b): Comparison of management strategies for the spatial extent of three habitats under the pessimistic model specification for mangroves and large and small benthos.

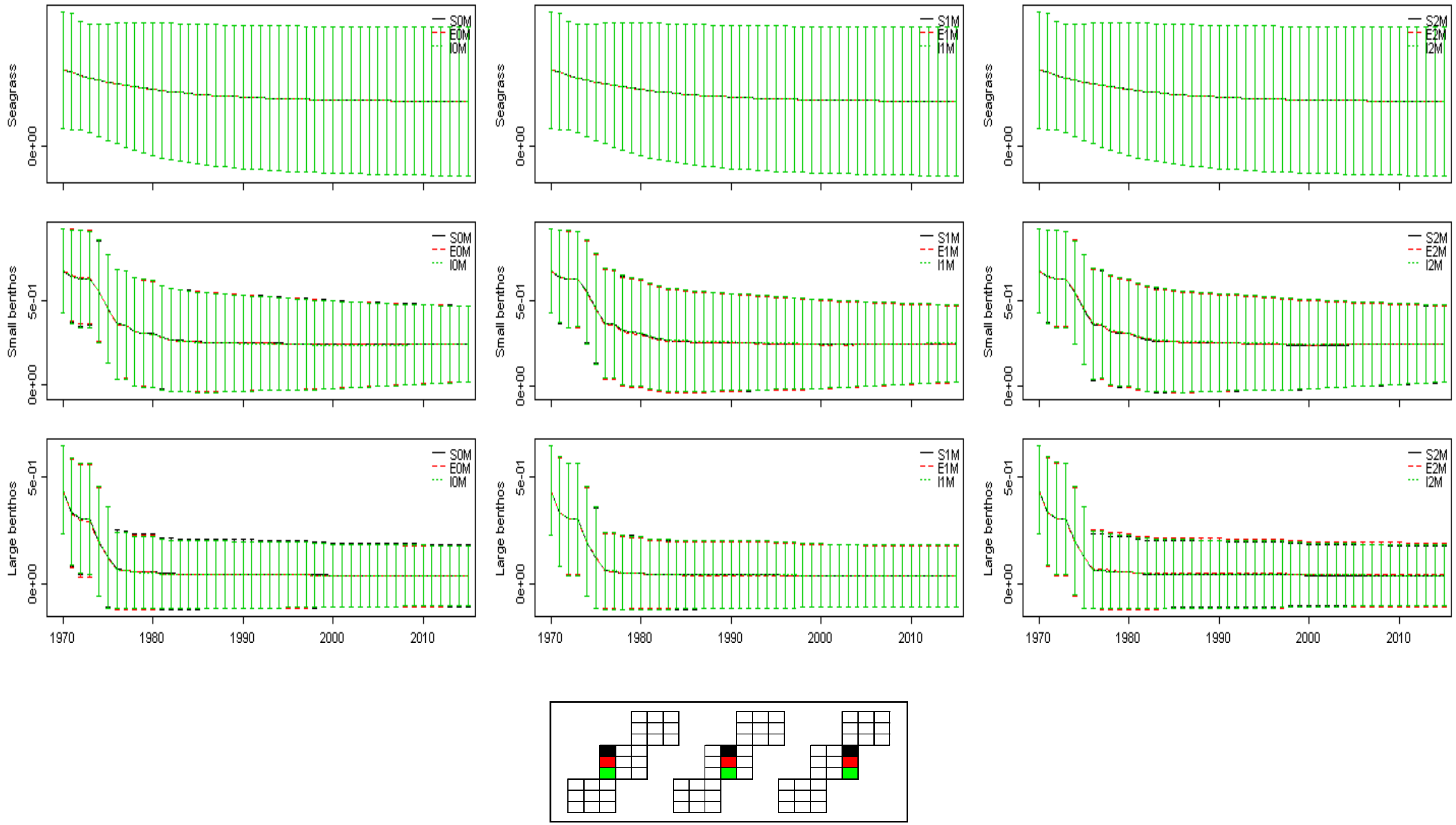


Figure D.98 (a): Comparison of management strategies for the spatial extent of three habitats under base case model specification for seagrass and large and small benthos.

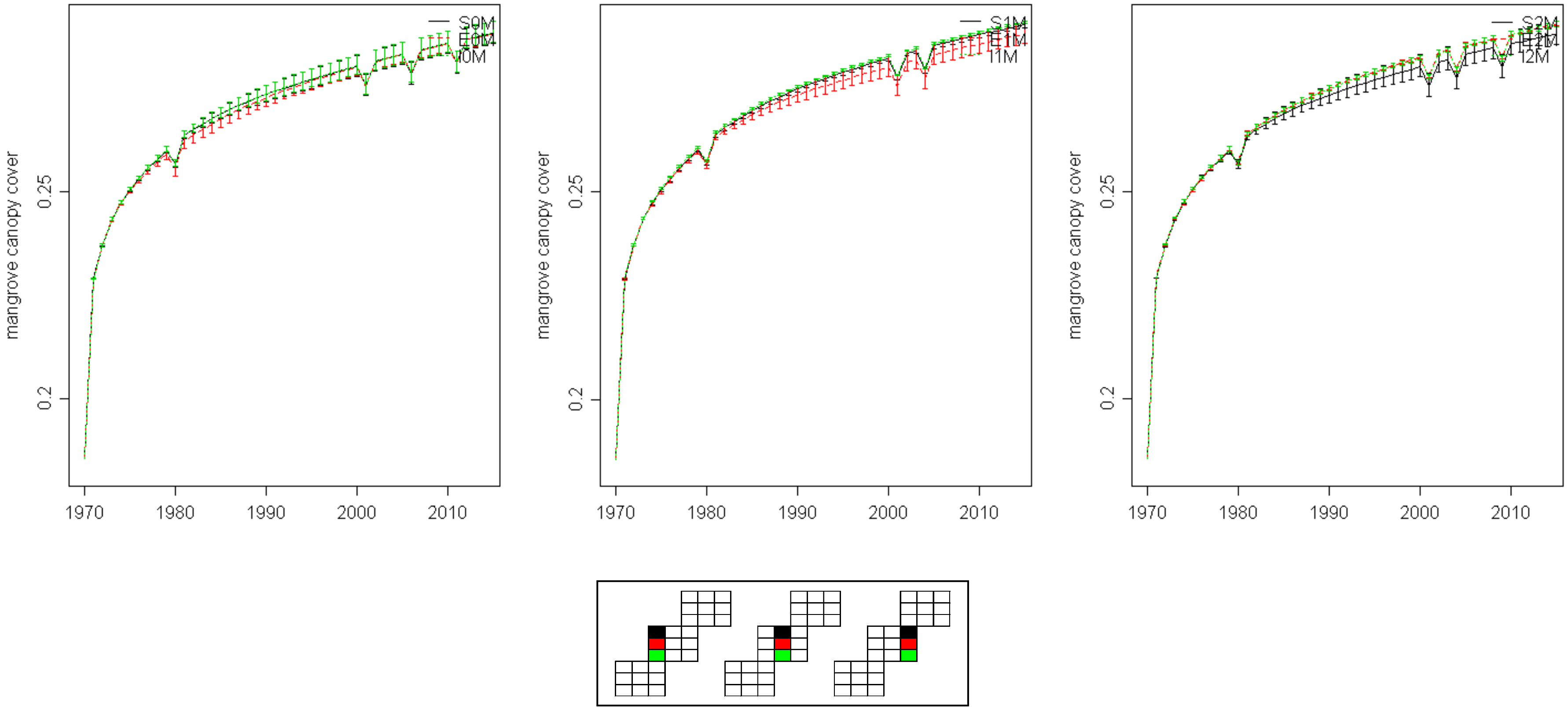


Figure D.98 (b): Comparison of management strategies for the spatial extent of three habitats under the base case model specification for mangroves and large and small benthos.

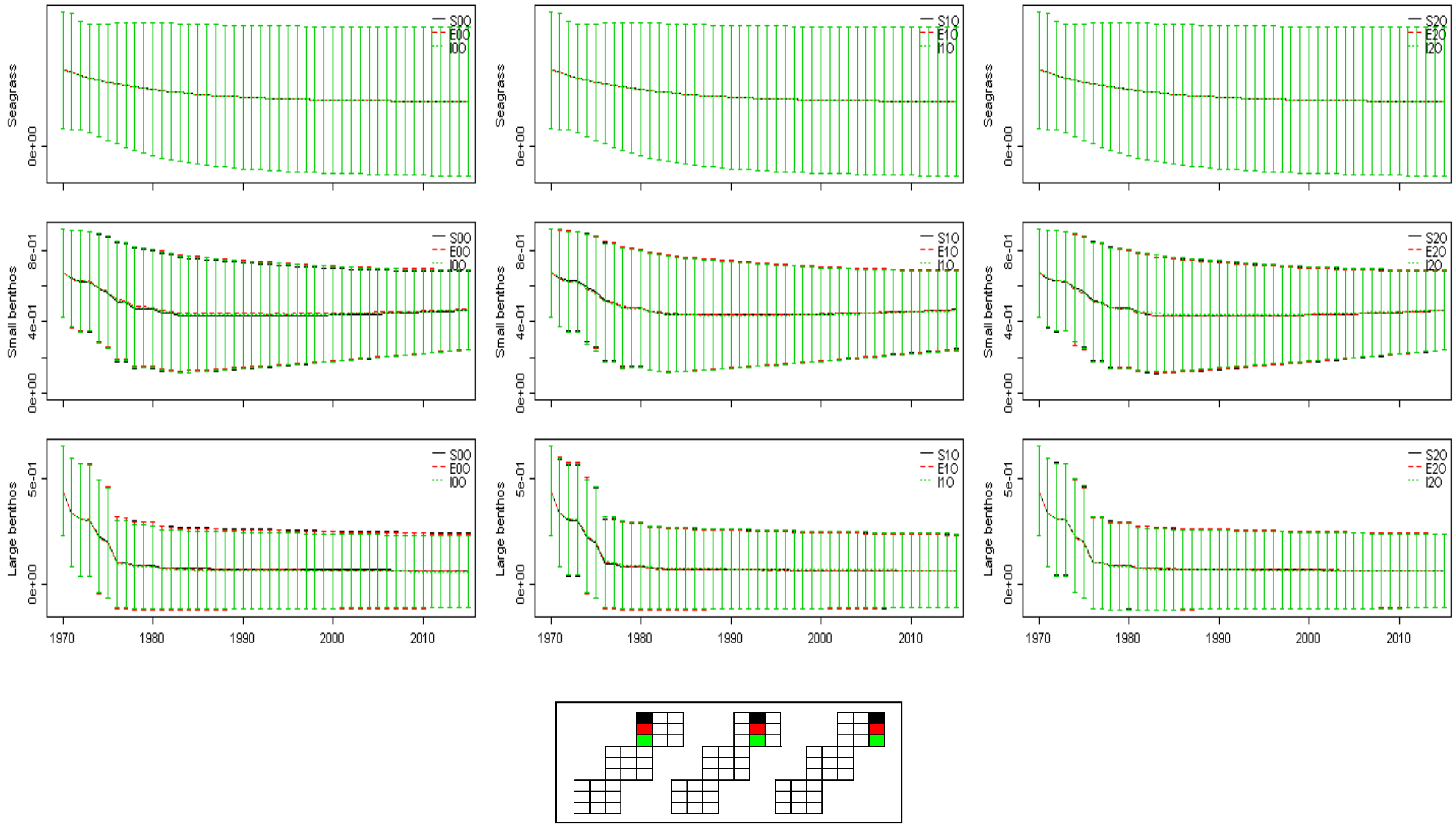


Figure D.99 (a): Comparison of management strategies for the spatial extent of three habitats under the optimistic model specification for seagrass and large and small benthos.

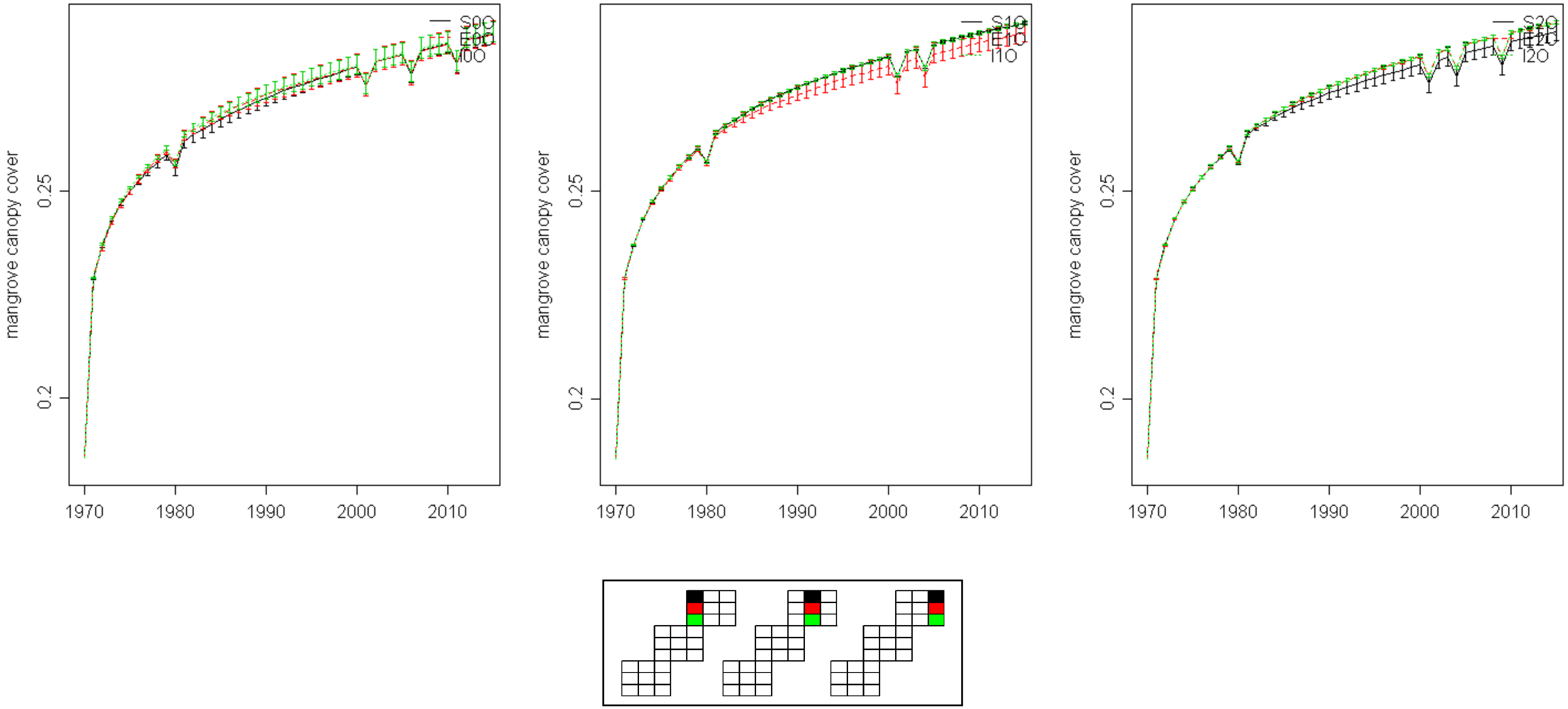


Figure D.99 (b): Comparison of management strategies for the spatial extent of three habitats under the optimistic model specification for mangroves and large and small benthos.

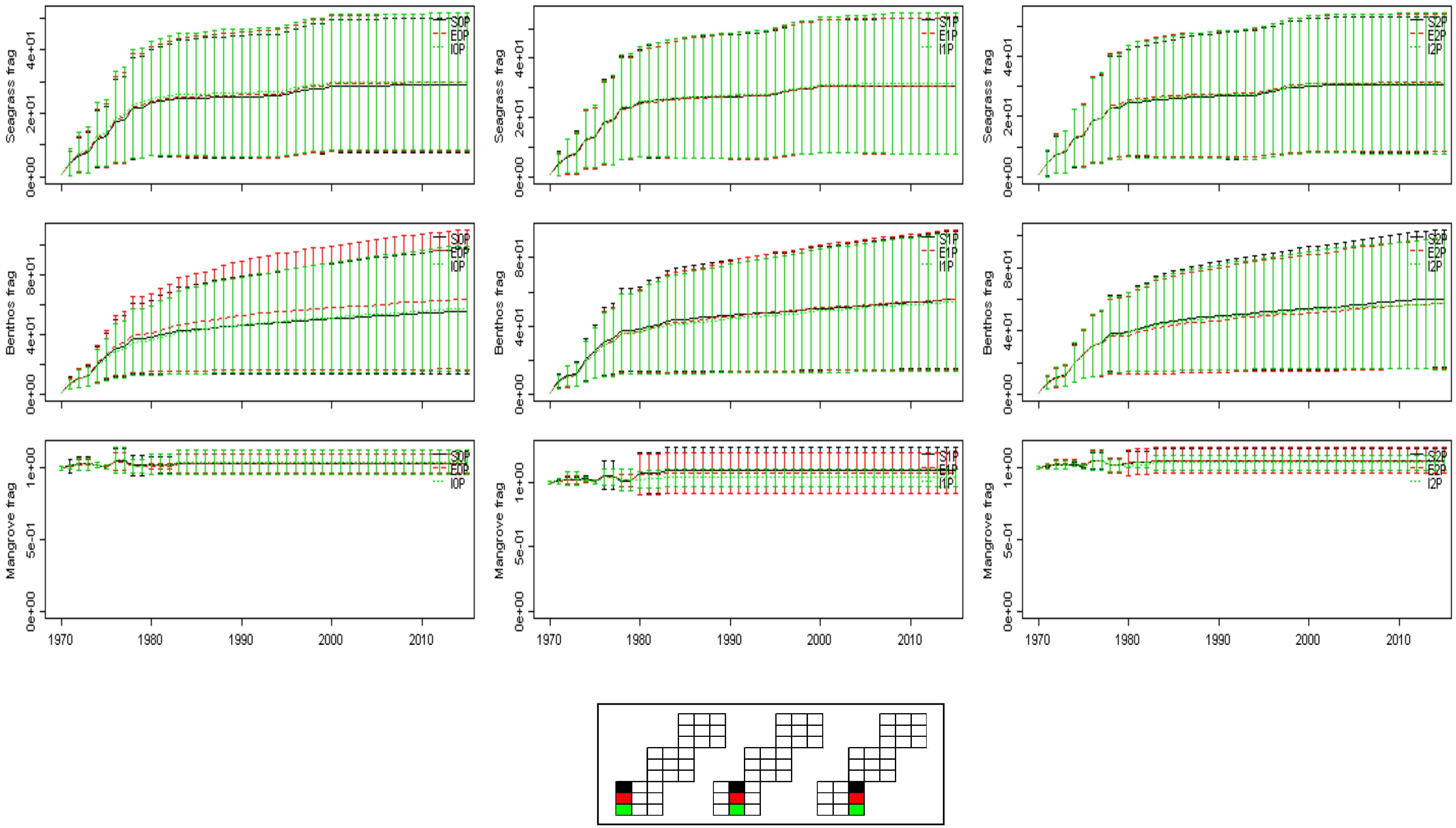


Figure D.100: Comparison of management strategies for the spatial fragmentation of three habitats under the pessimistic model specification.

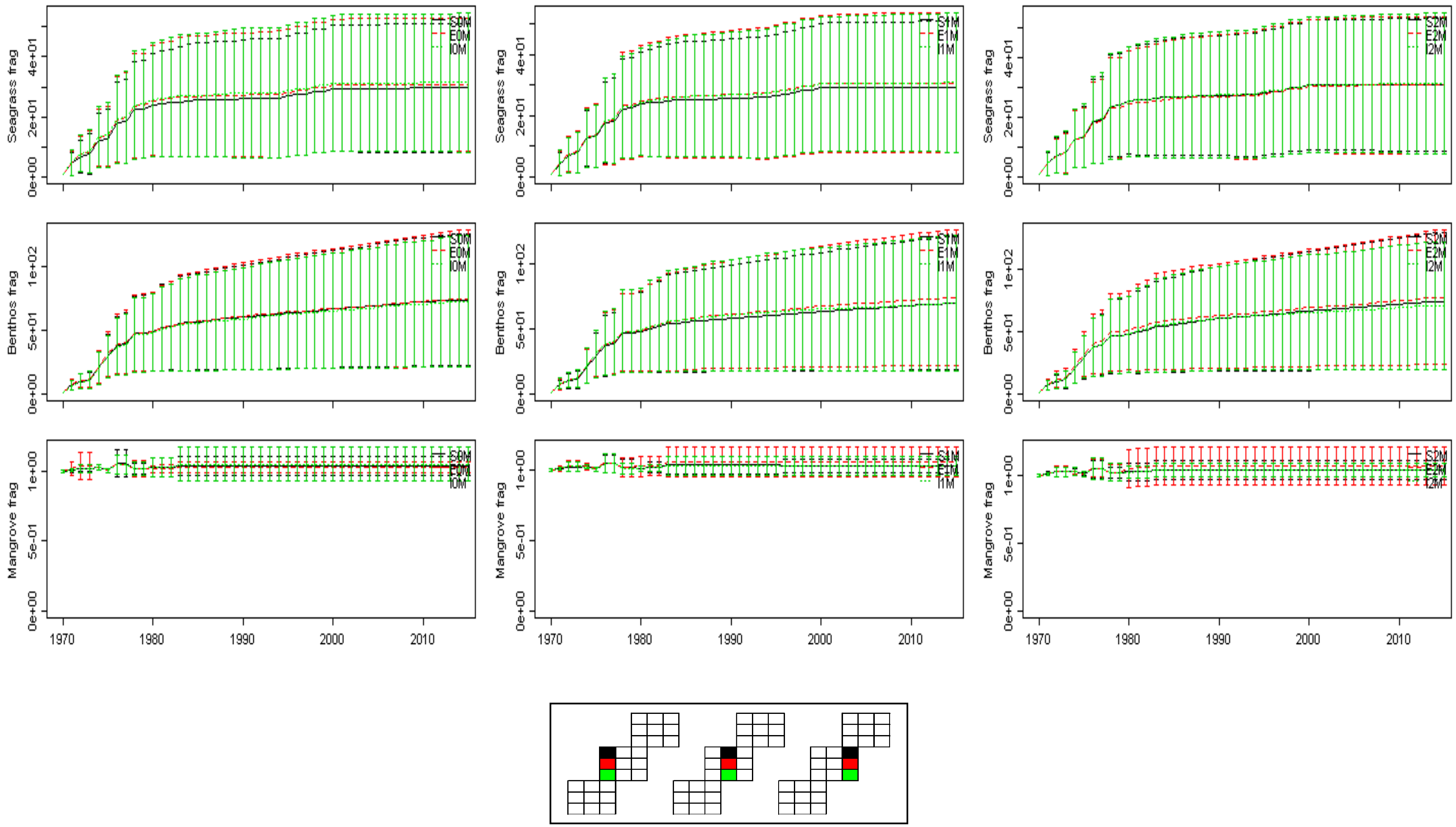


Figure D.101: Comparison of management strategies for the spatial fragmentation of three habitats under the base case model specification.

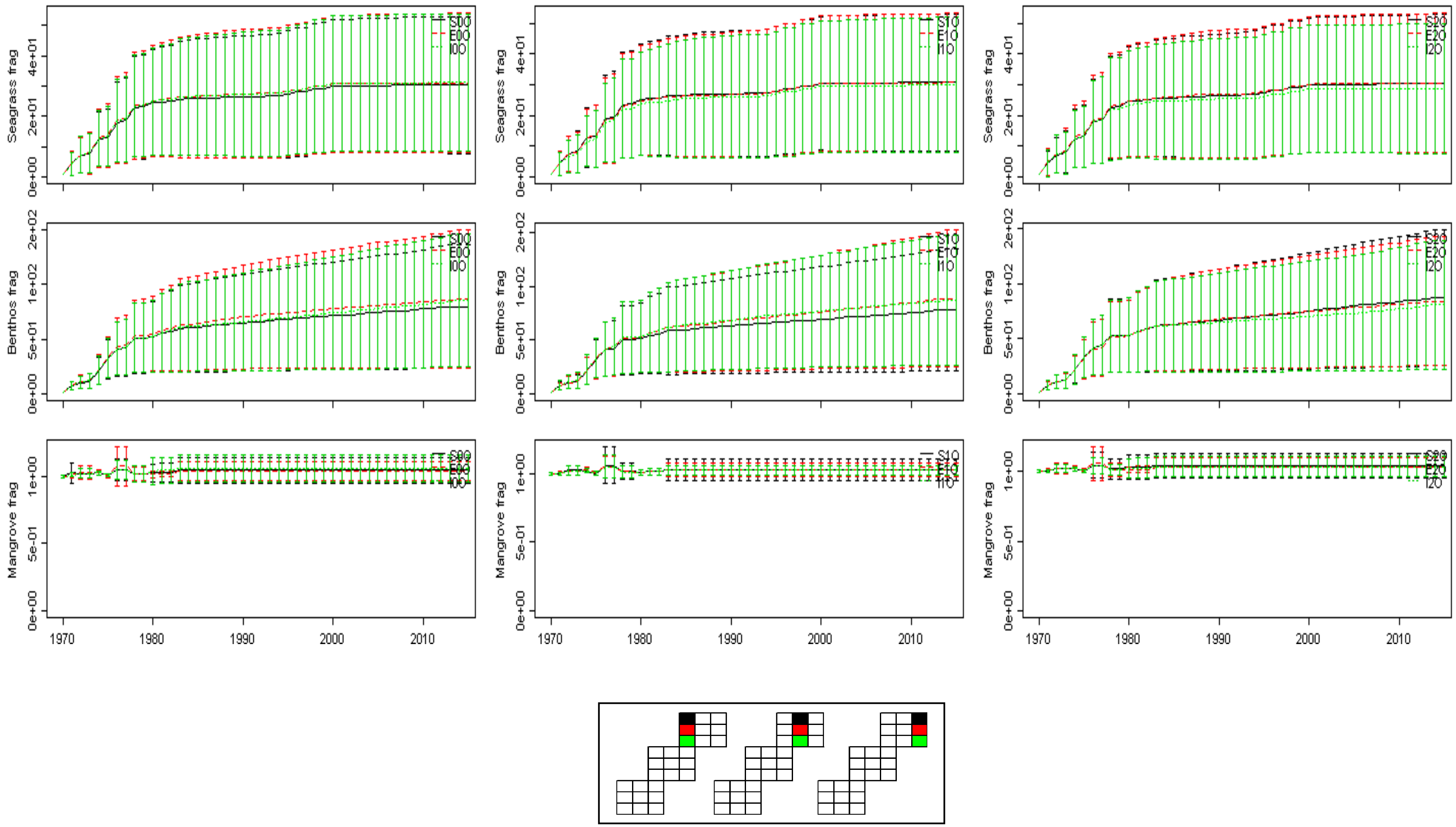


Figure D.102: Comparison of management strategies for the spatial fragmentation of three habitats under the optimistic model specification.

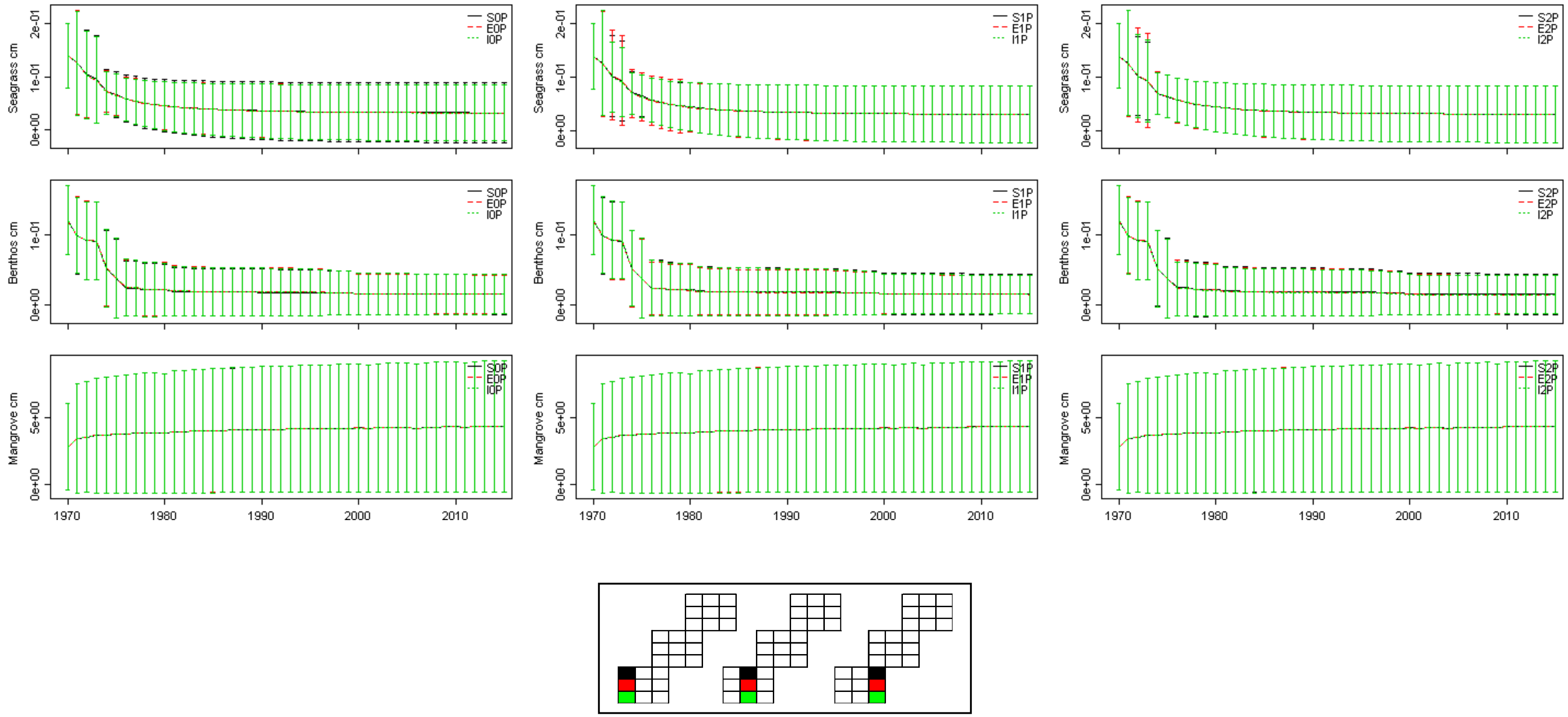


Figure D.103: Comparison of model specifications for the average vertical height of three habitats under the pessimistic model specification.

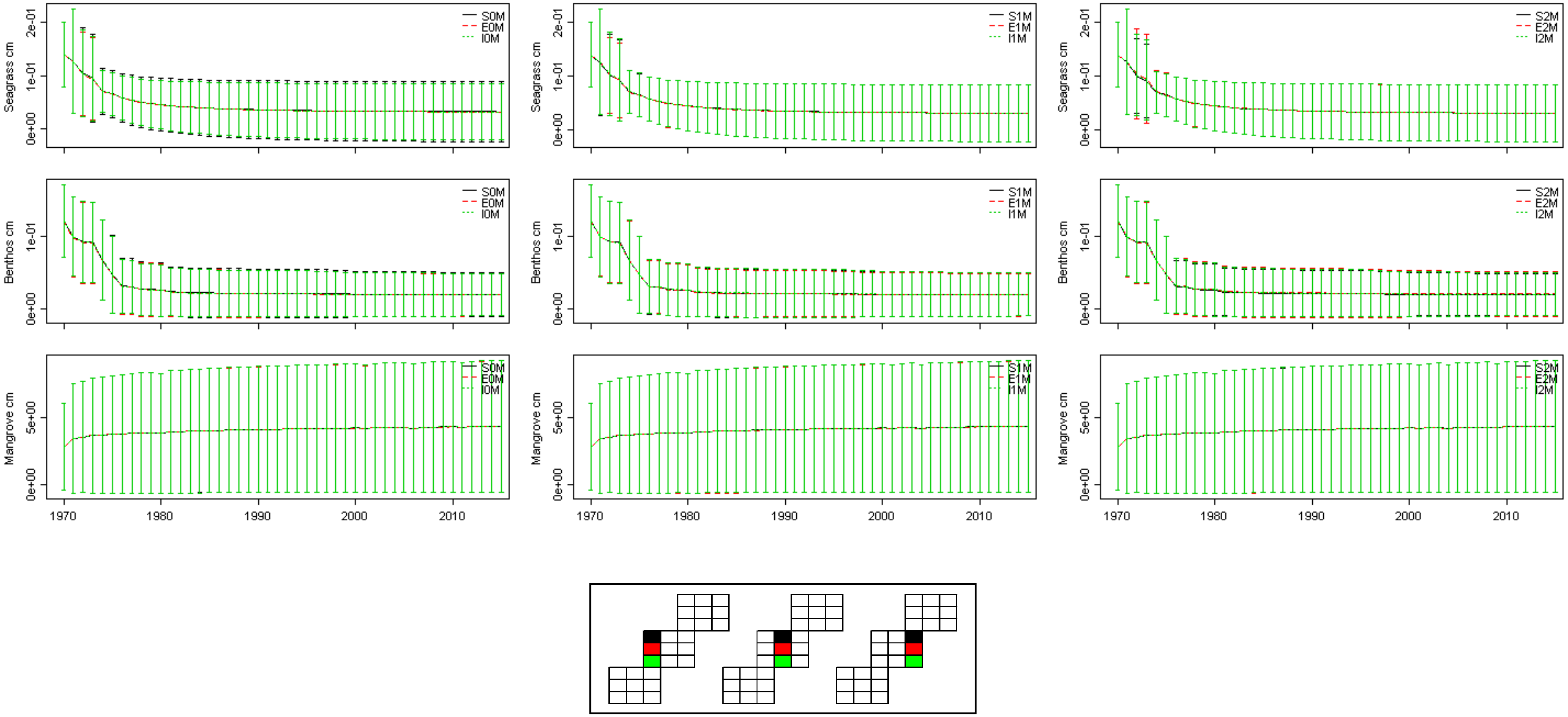
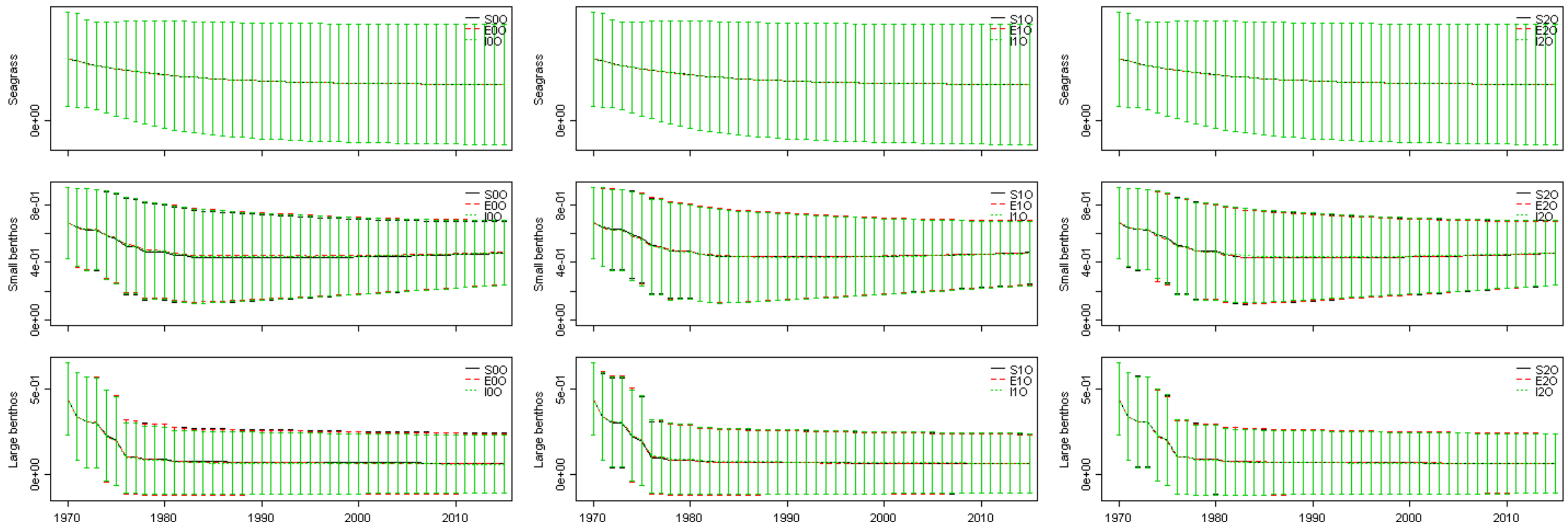


Figure D.104: Comparison of model specifications for the average vertical height of three habitats under the base case model specification.



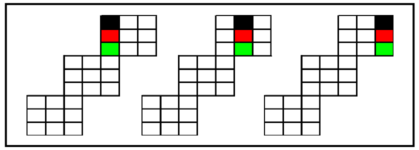


Figure D.105: Comparison of model specifications for the average vertical height of three habitats under the optimistic model specification.

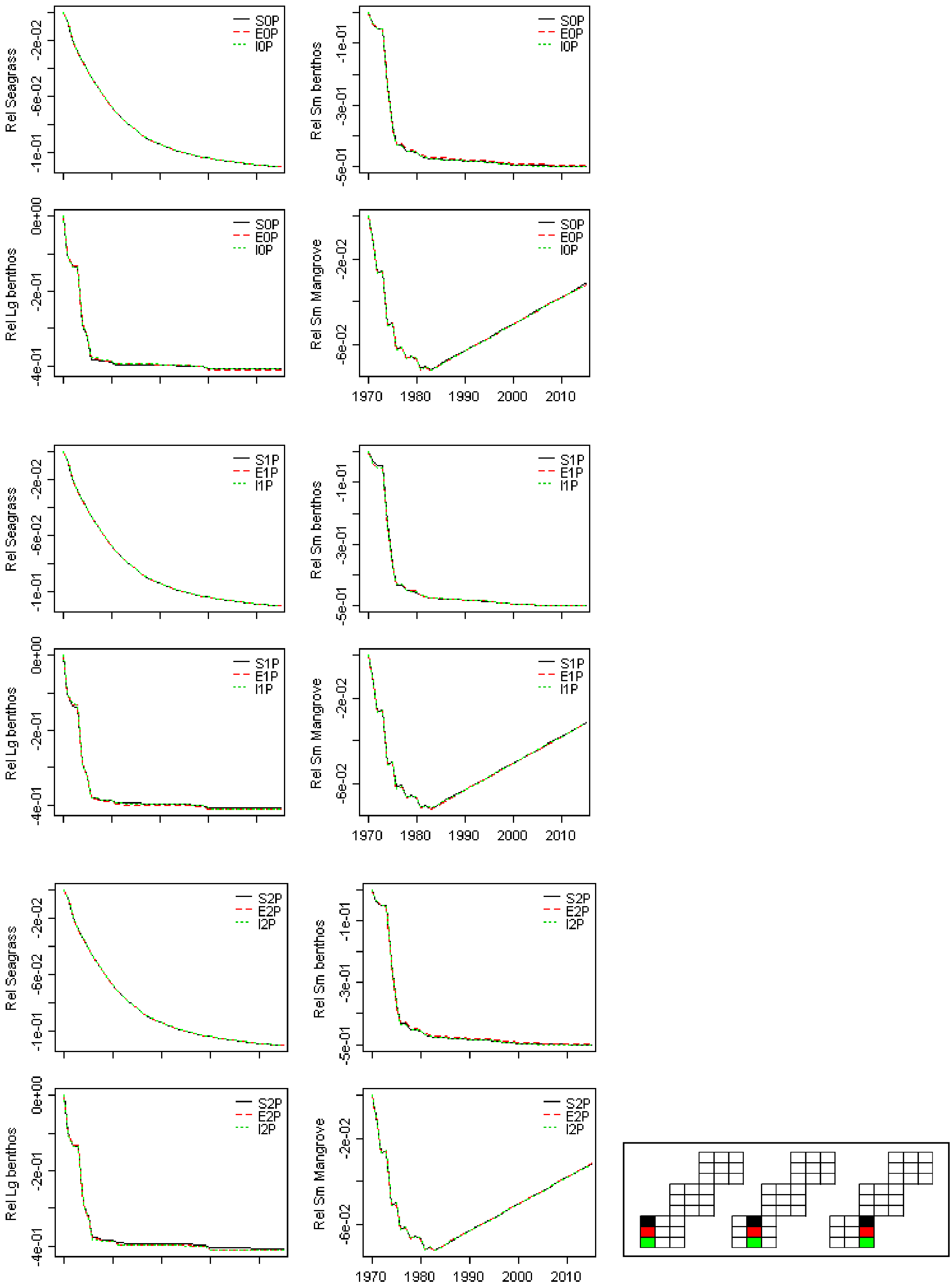


Figure D.106: Comparison of management strategies for habitat cover relative to initial amount in 1970 of seagrass, mangrove, large and small benthos under the pessimistic model specification.

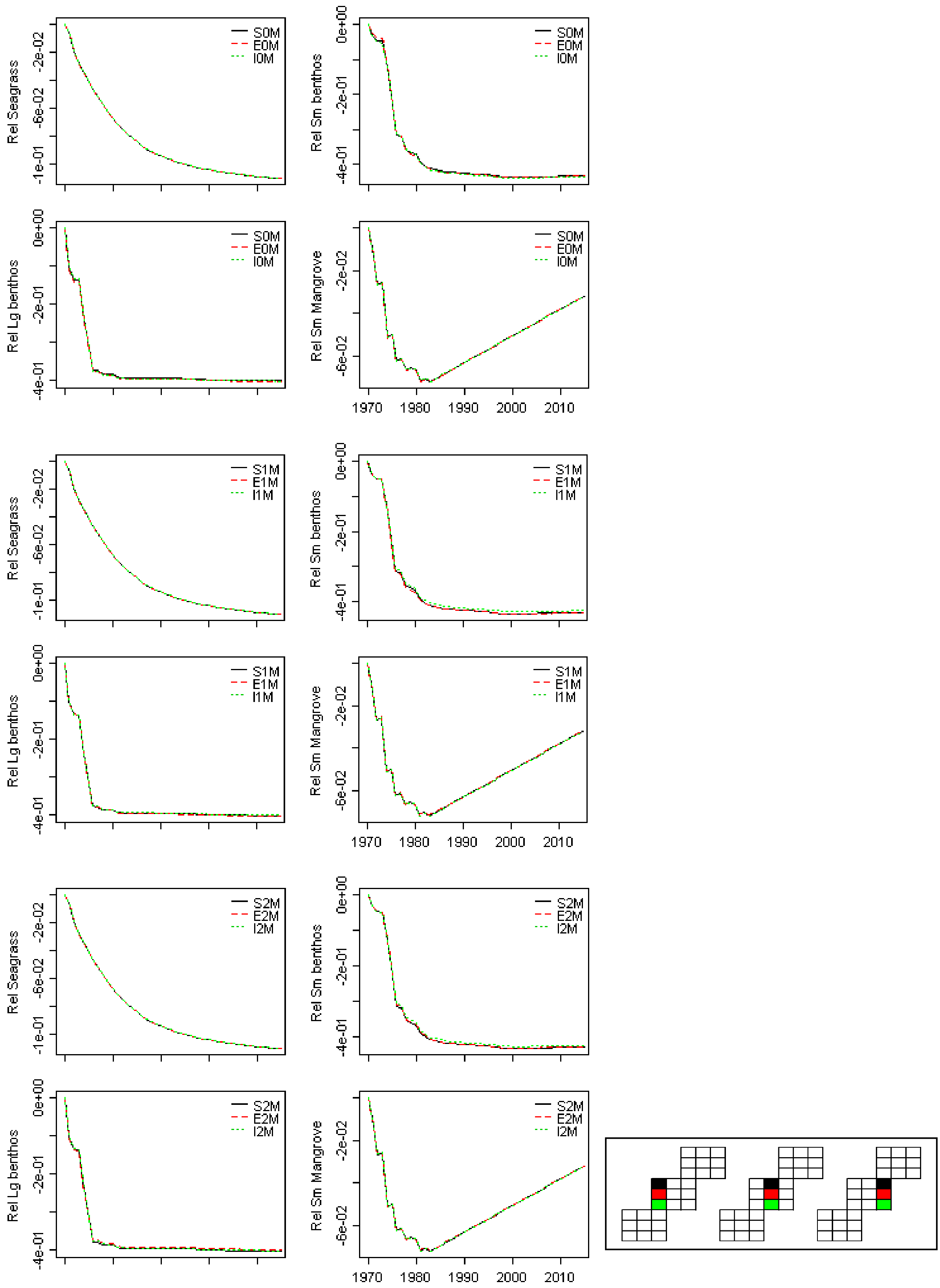


Figure D.107: Comparison of management strategies for habitat cover relative to initial amount (in 1970) of seagrass, mangrove, large and small benthos under the base case model specification.

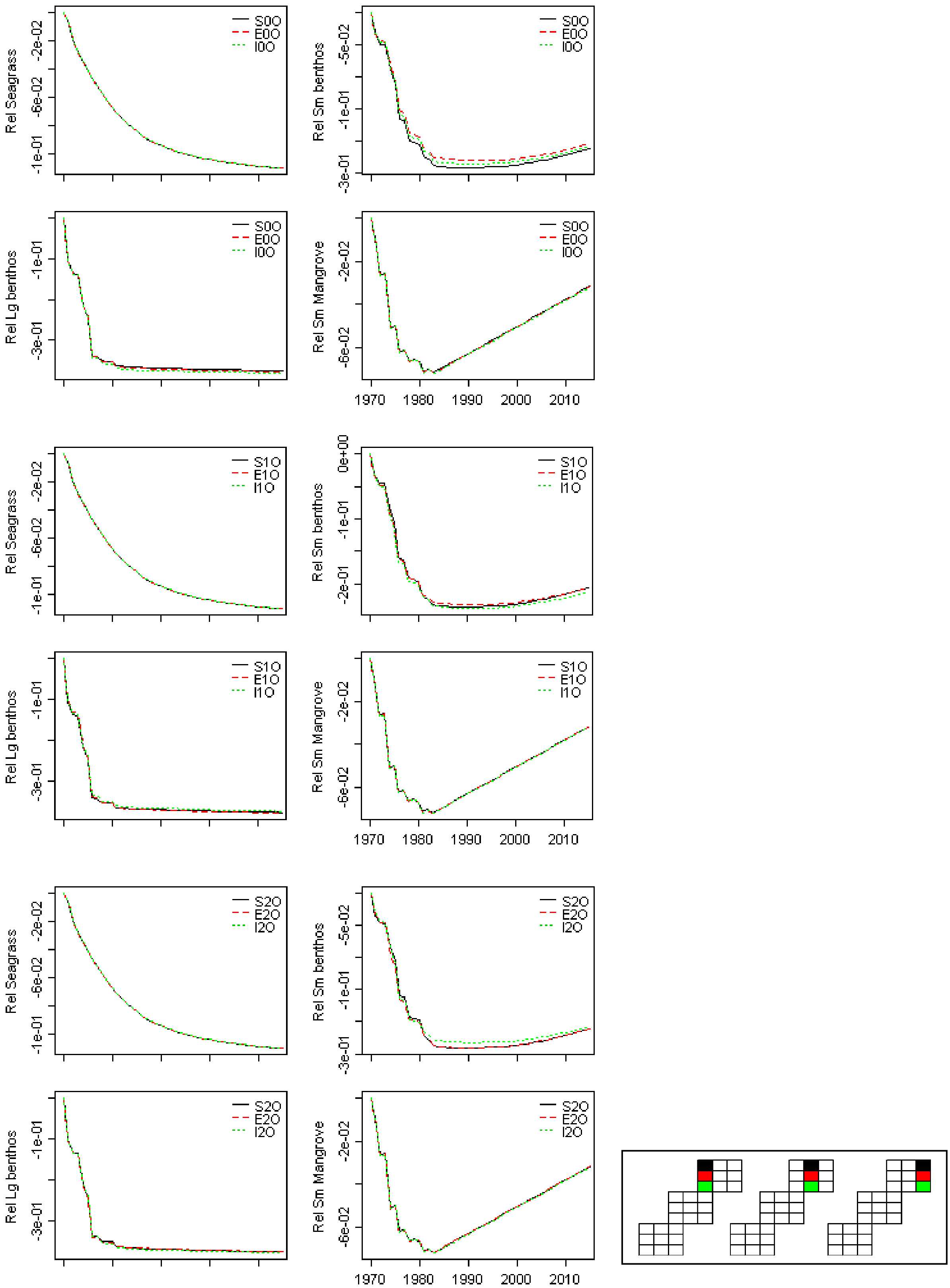


Figure D.108: Comparison of management strategies for habitat cover relative to initial amount (in 1970) of seagrass, mangrove, large and small benthos under the optimistic model specification.

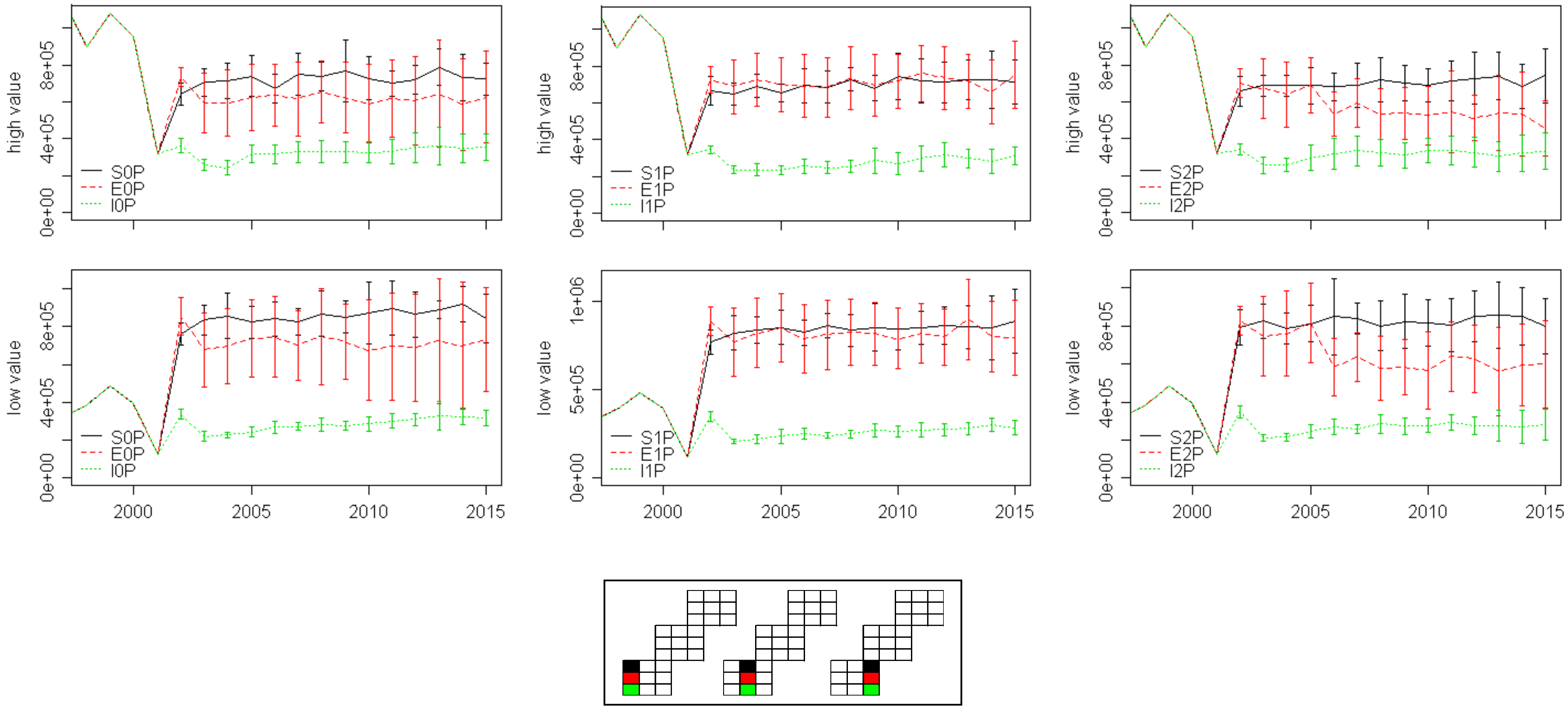


Figure D.109: Comparison of management strategies for total catch (kg) of high valued and low valued species under the pessimistic model specification.

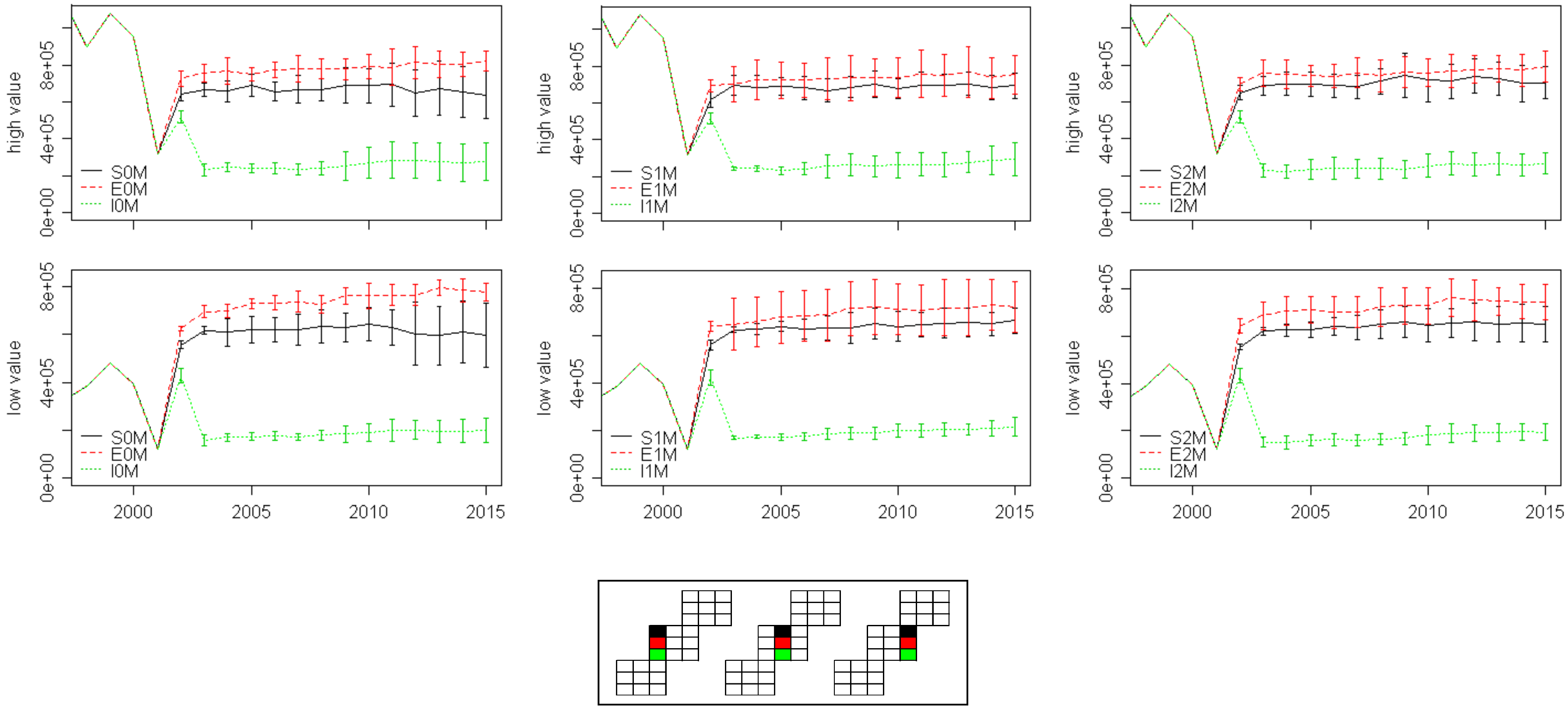


Figure D.110: Comparison of management strategies for total catch (kg) of high valued and low valued species under the base case model specification.

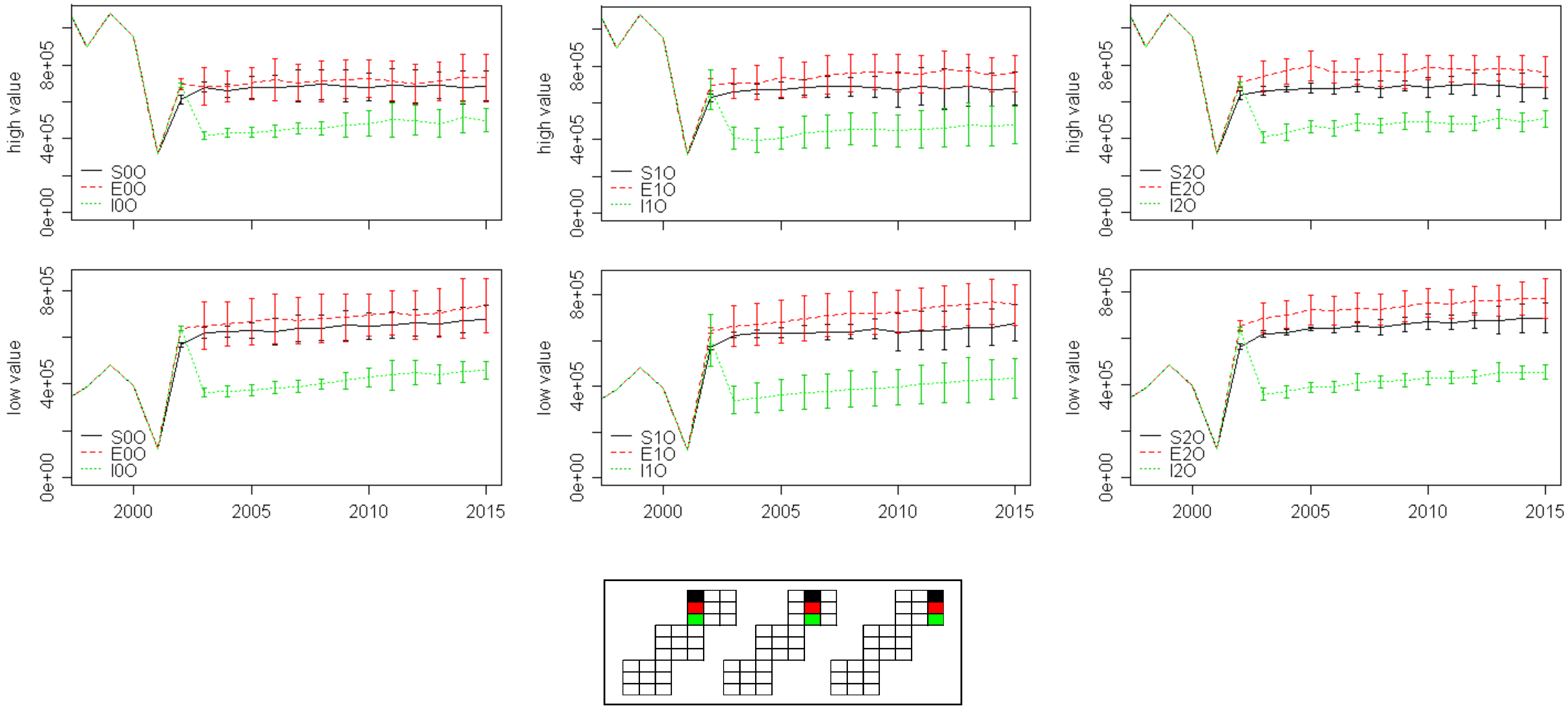


Figure D.111: Comparison of management strategies for total catch (kg) of high valued and low valued species under the optimistic model specification.

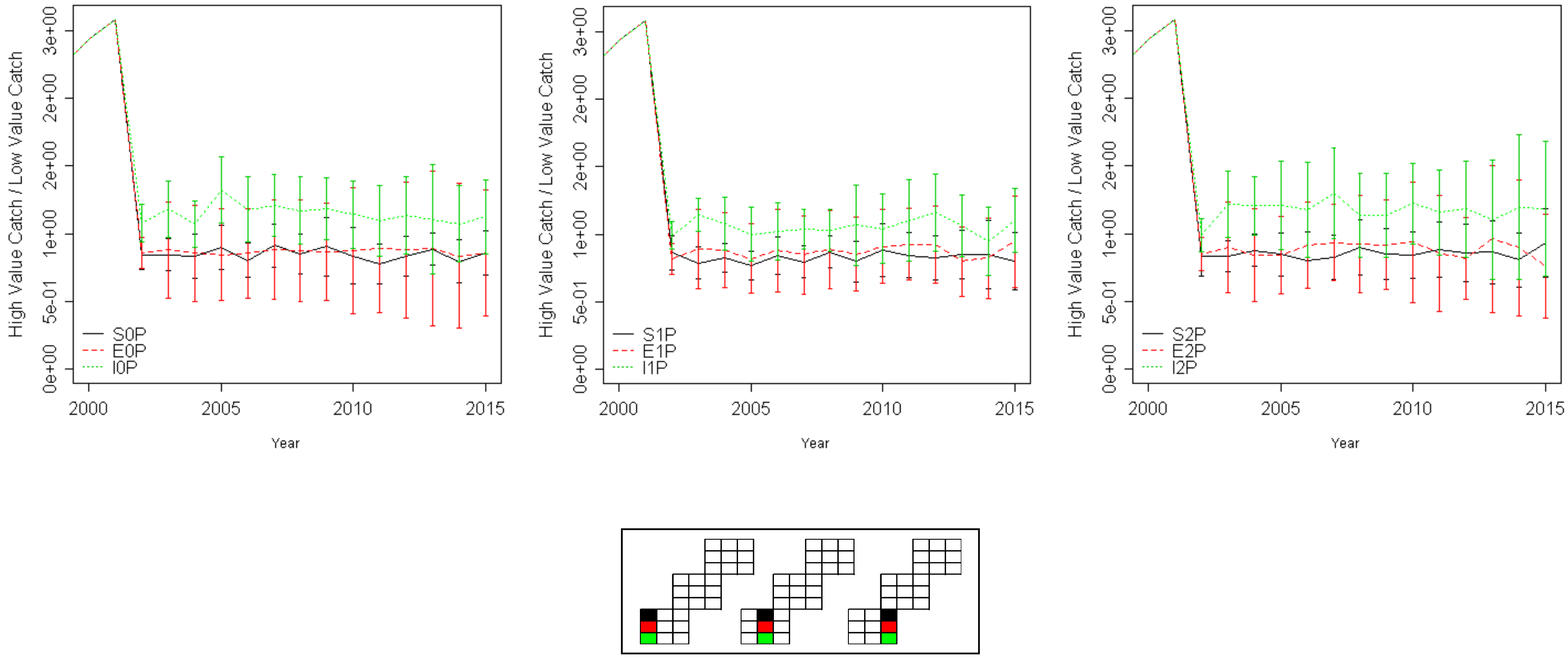


Figure D.112: Comparison of management strategies for the ratio of high-valued species catch to low-valued species catch under the pessimistic model specification.

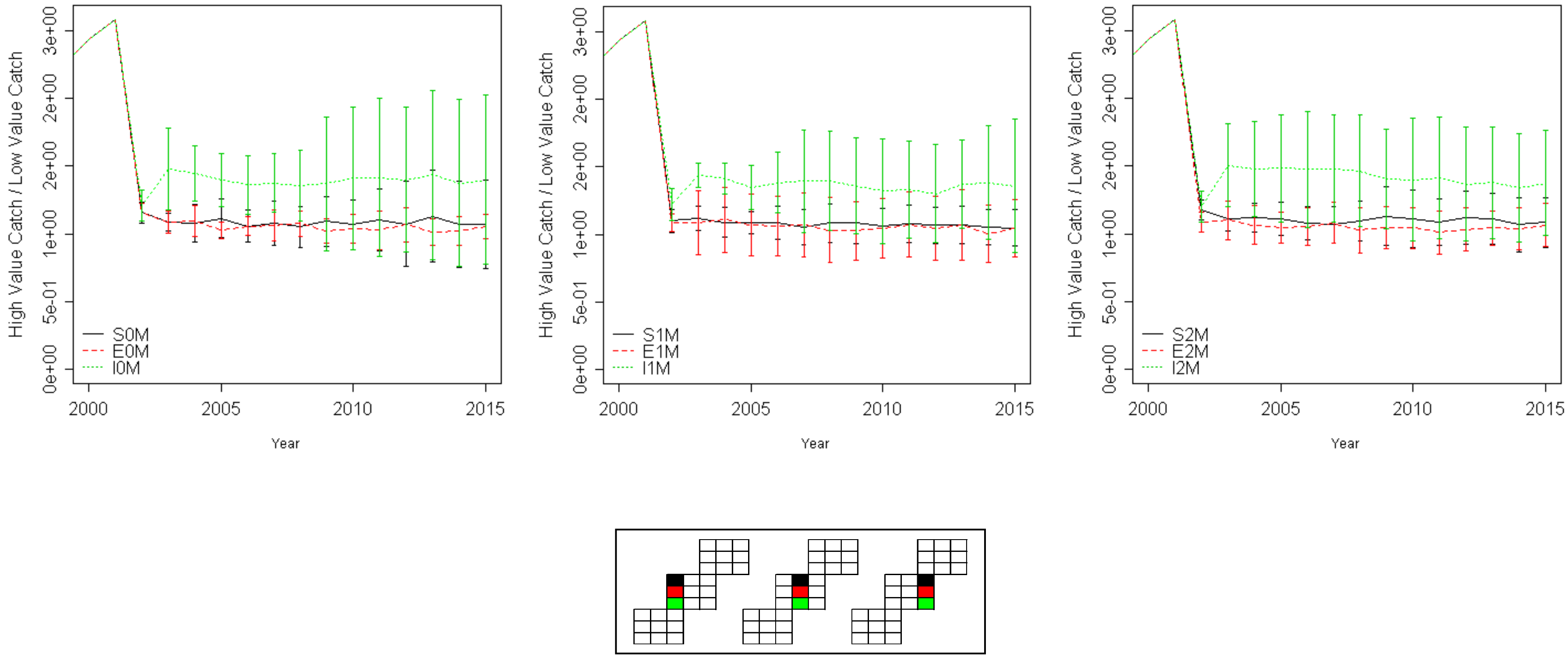
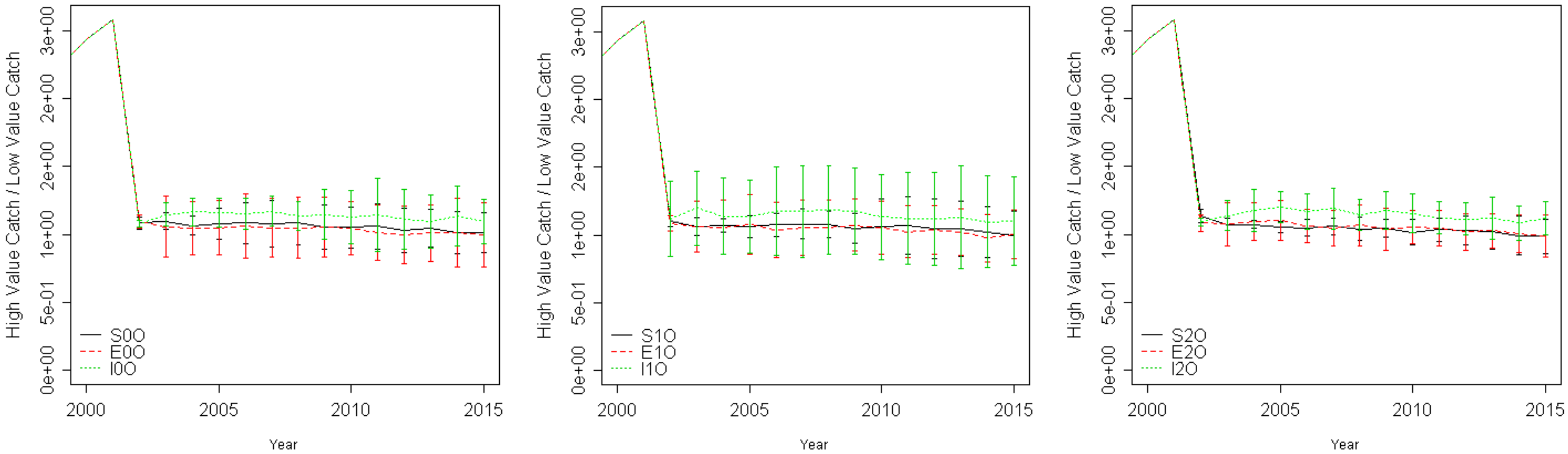


Figure D.113: Comparison of management strategies for the ratio of high-valued species catch to low-valued species catch under the base case model specification.



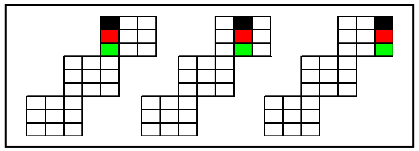


Figure D.114: Comparison of management strategies for the ratio of high-valued species catch to low-valued species catch under the optimistic model specification.

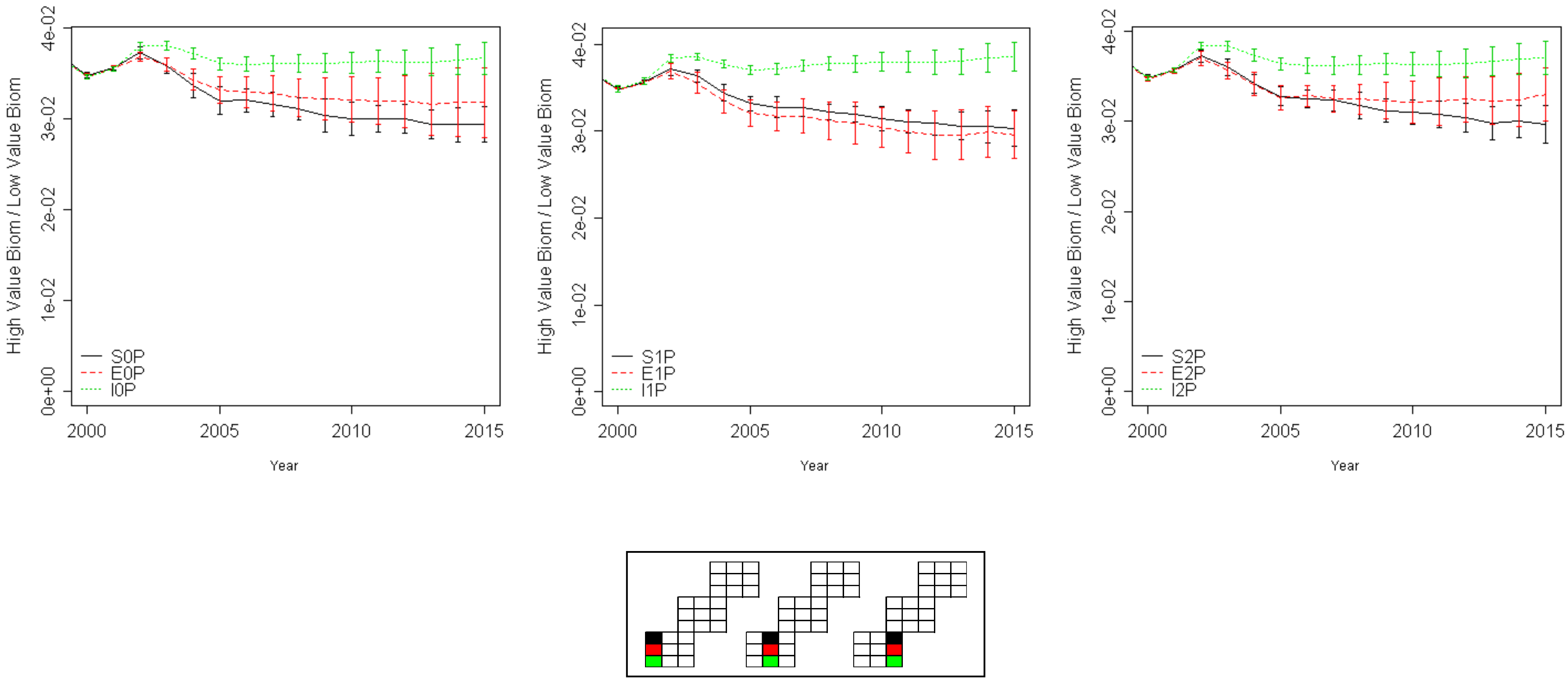
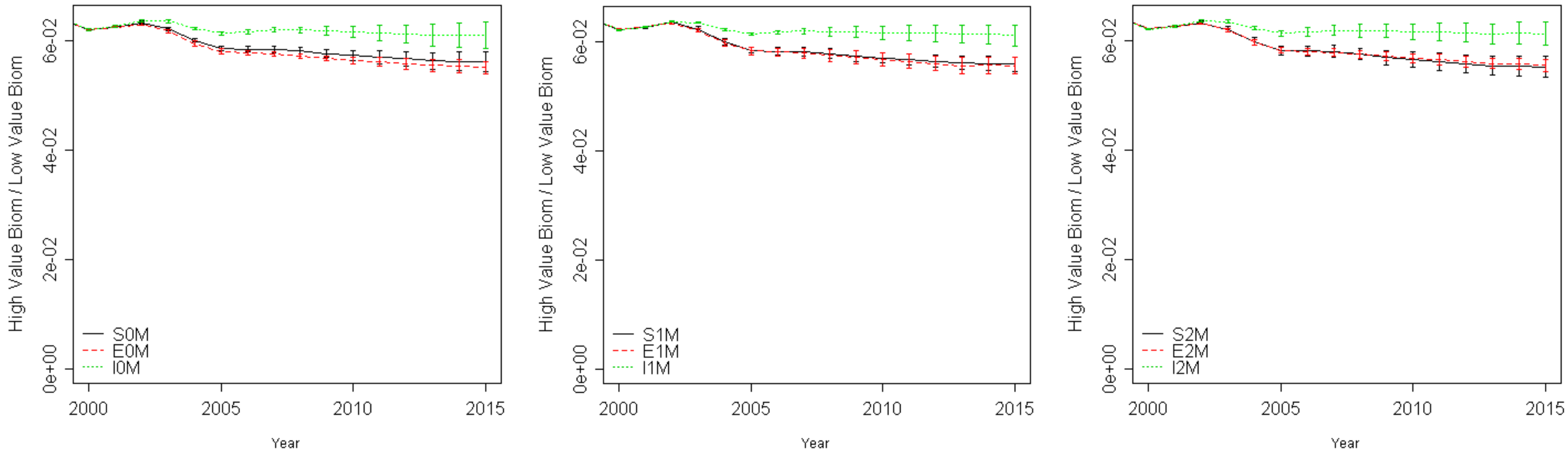


Figure D.115: Comparison of management strategies for the ratio of high-valued species biomass to low-valued species biomass under the pessimistic model specification.



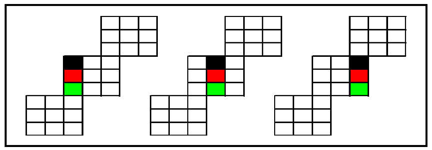


Figure D.116: Comparison of management strategies for the ratio of high-valued species biomass to low-valued species biomass under the base case model specification.

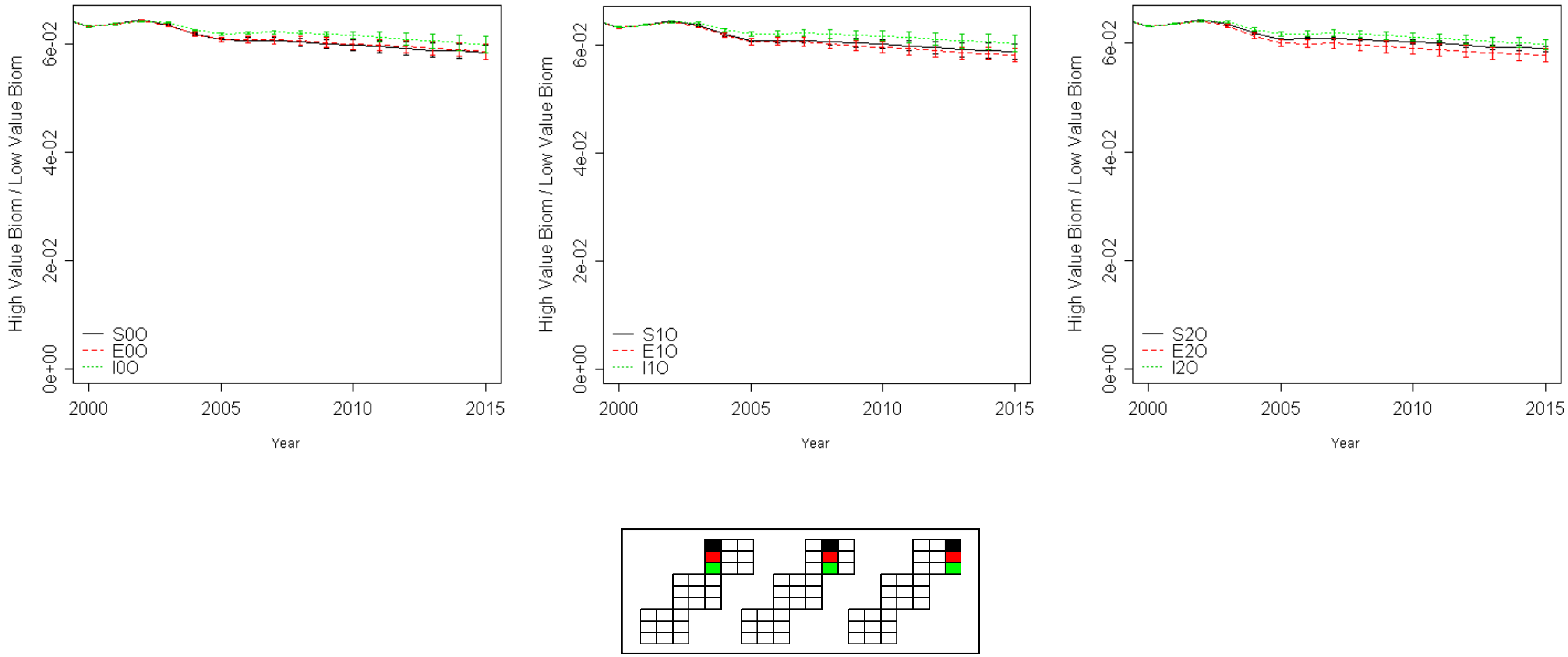
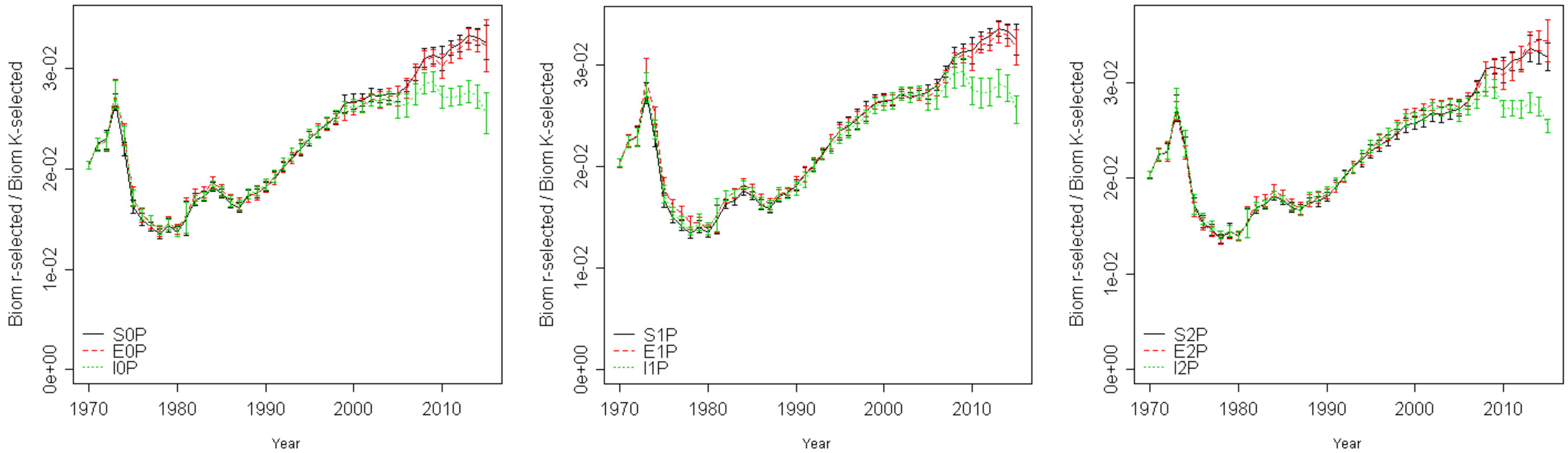


Figure D.117: Comparison of management strategies for the ratio of high-valued species biomass to low-valued species biomass under the optimistic model specification.



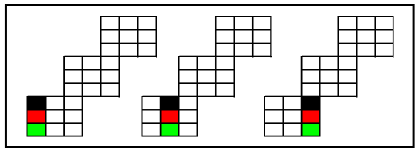


Figure D.118: Comparison of management strategies for the ratio of r-selected species biomass to K-selected species biomass under the pessimistic model specification.

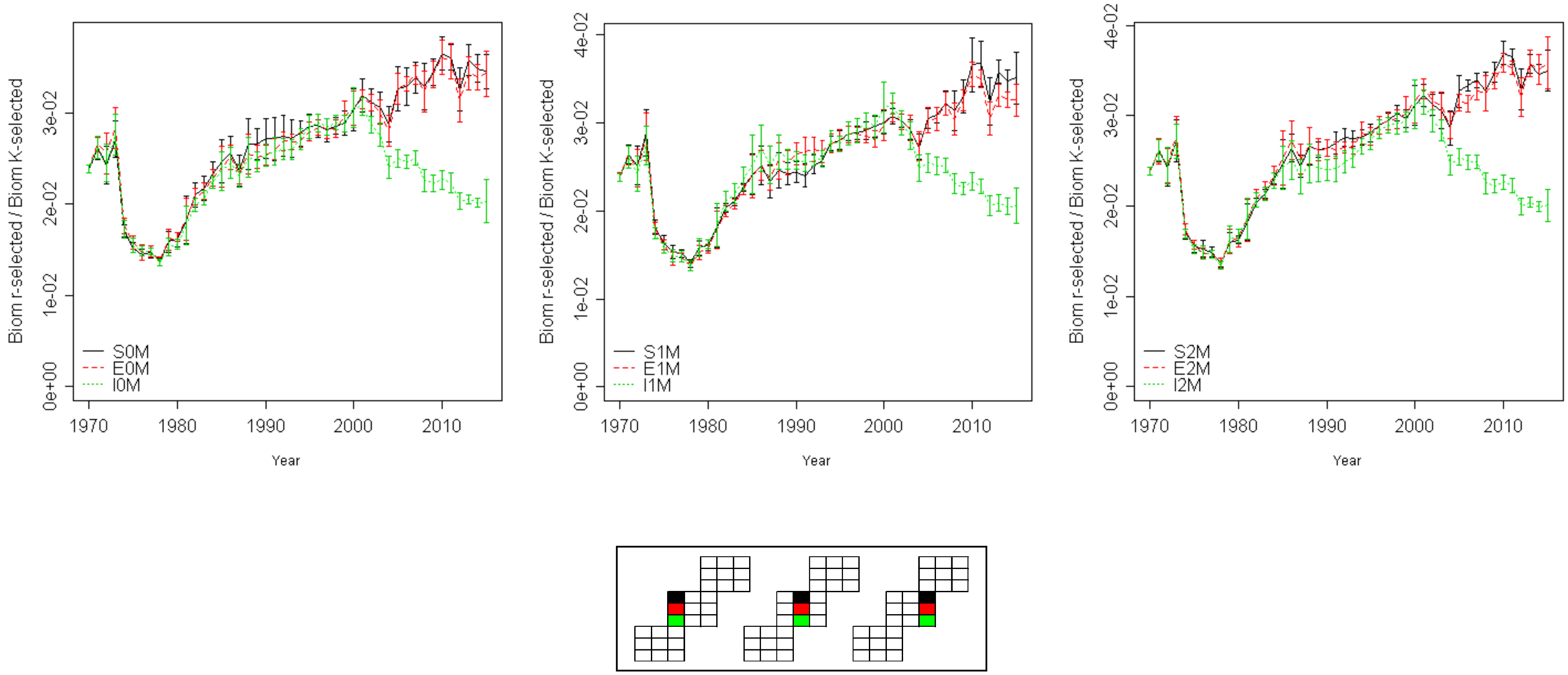


Figure D.119: Comparison of management strategies for the ratio of r-selected species biomass to K-selected species biomass under the base case model specification.

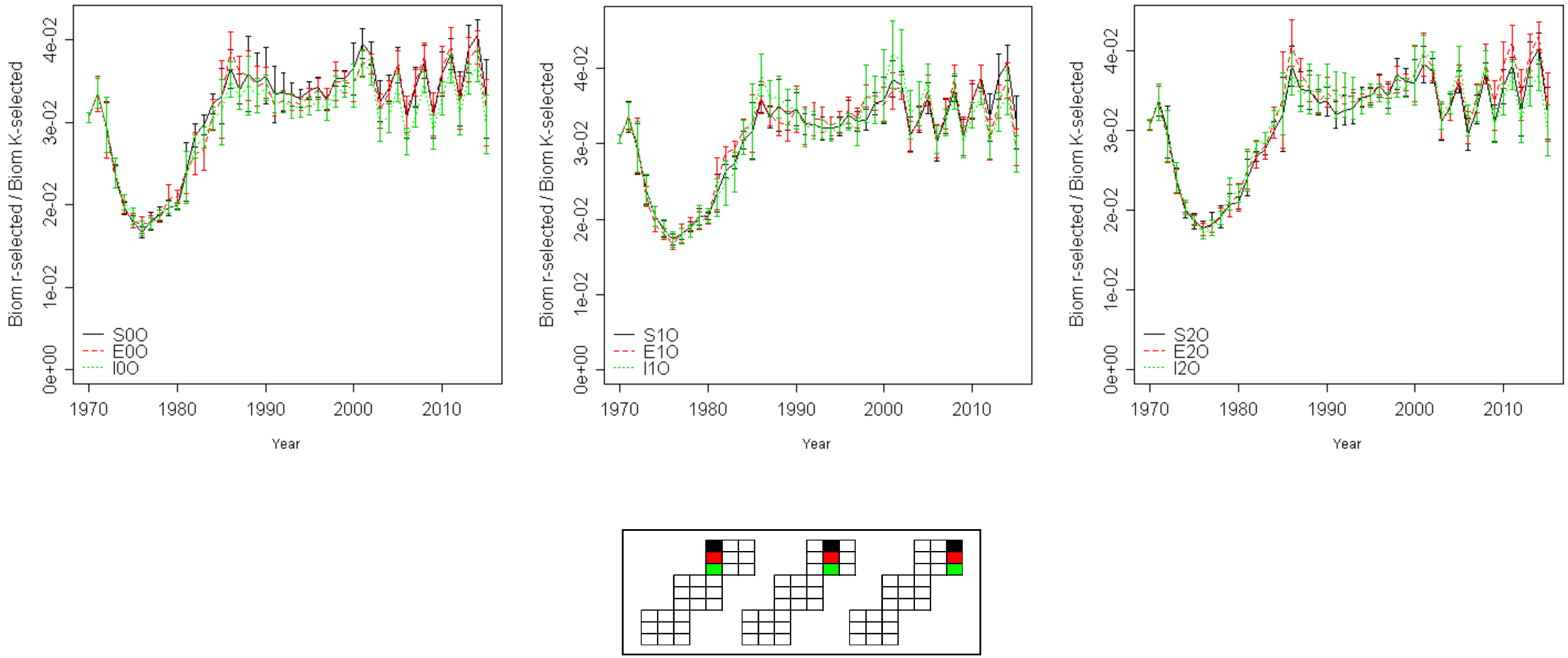


Figure D.120: Comparison of management strategies for the ratio of r-selected species biomass to K-selected species biomass under the optimistic model specification.

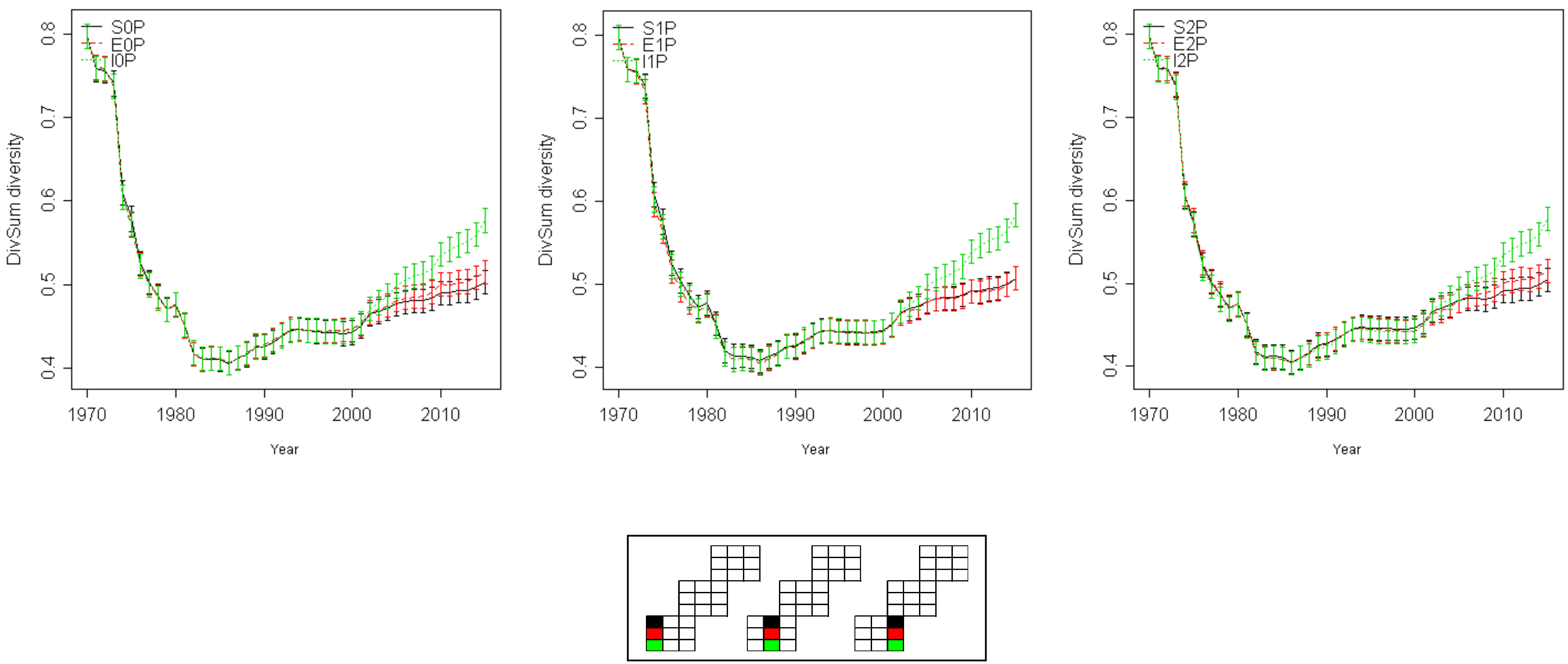


Figure D.121: Comparison of management strategies for the biodiversity proxy under the pessimistic model specification.

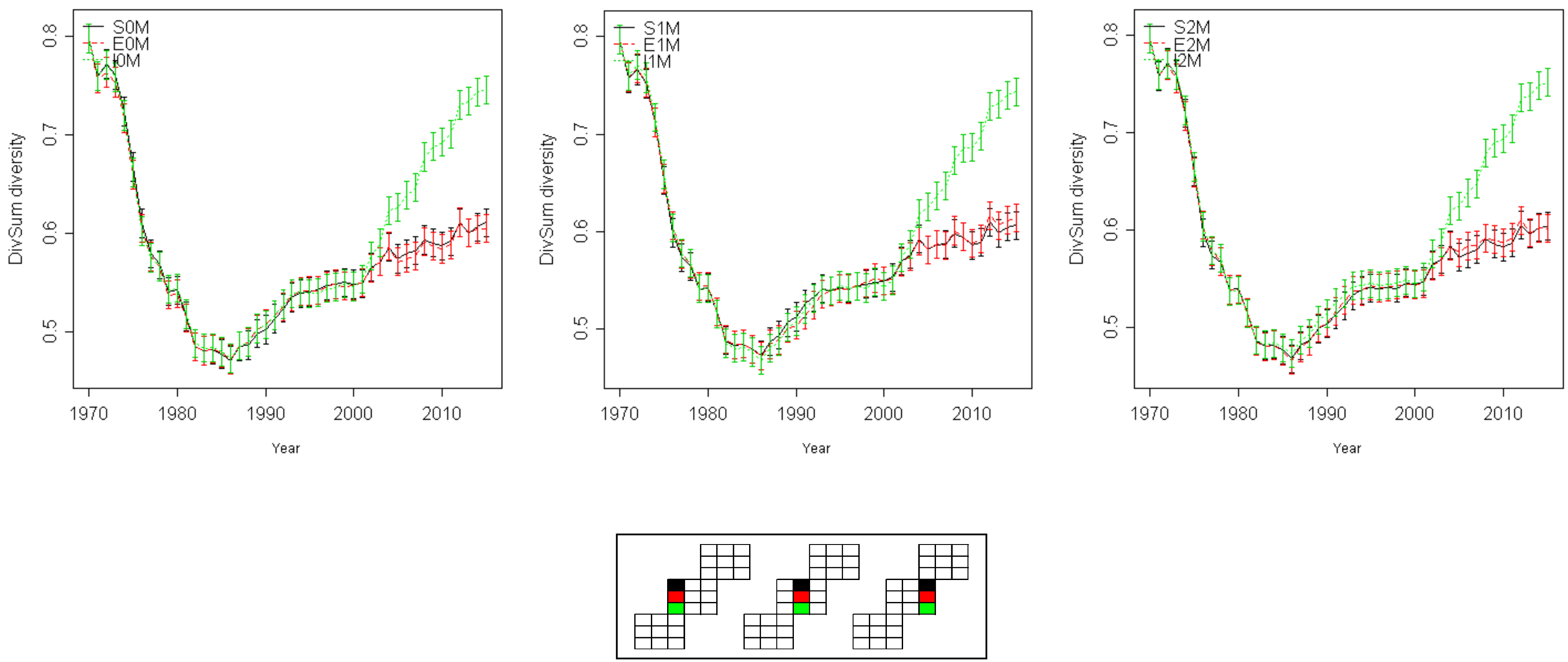


Figure D.122: Comparison of management strategies for the biodiversity proxy under the base case model specification.

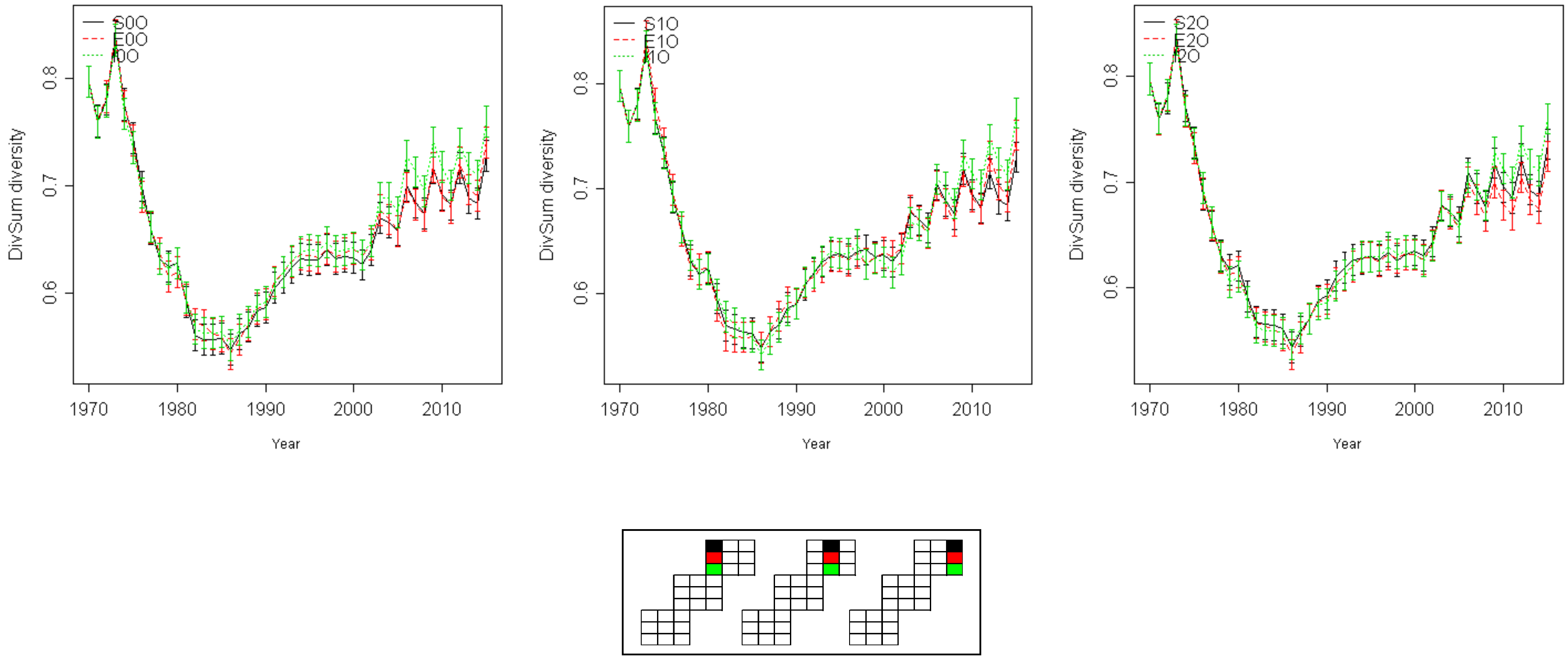


Figure D.123: Comparison of management strategies for the biodiversity proxy under the optimistic model specification.

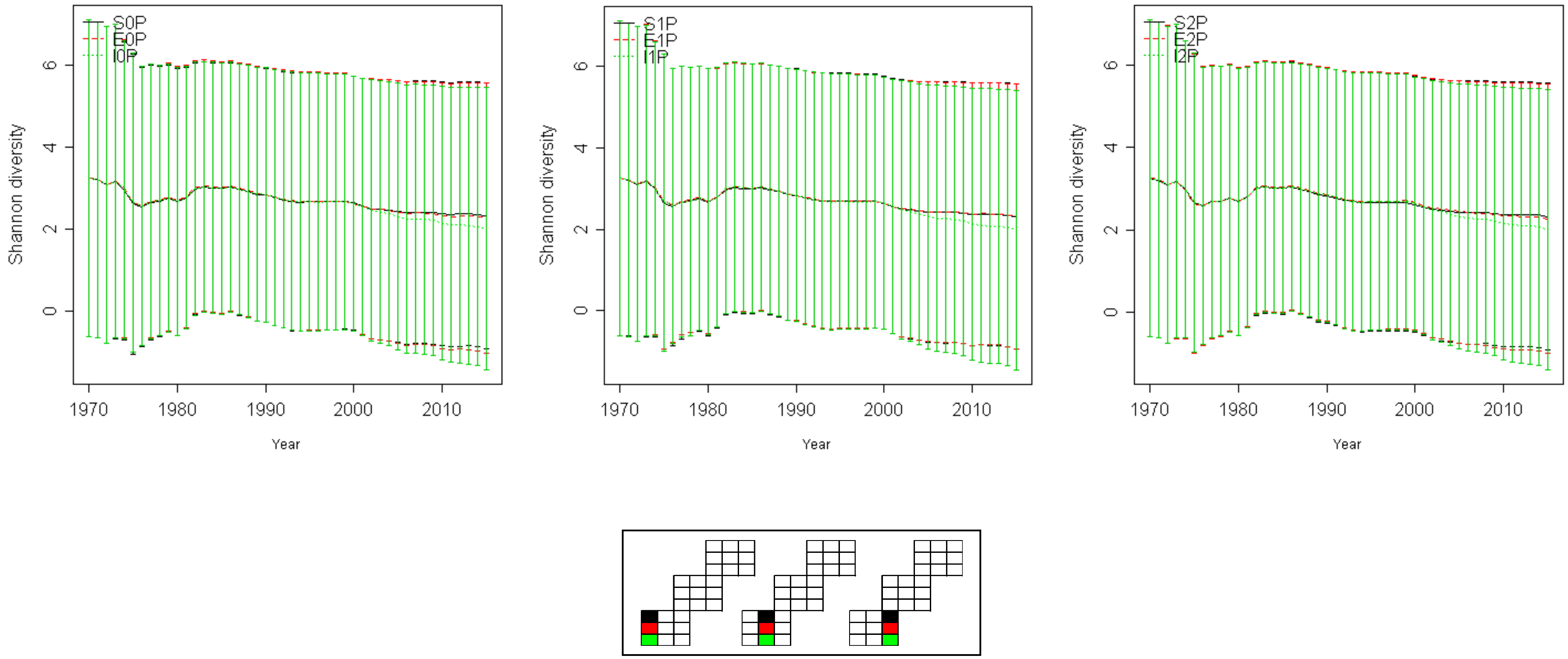


Figure D.124: Comparison of management strategies for the Shannon diversity index under the pessimistic model specification.

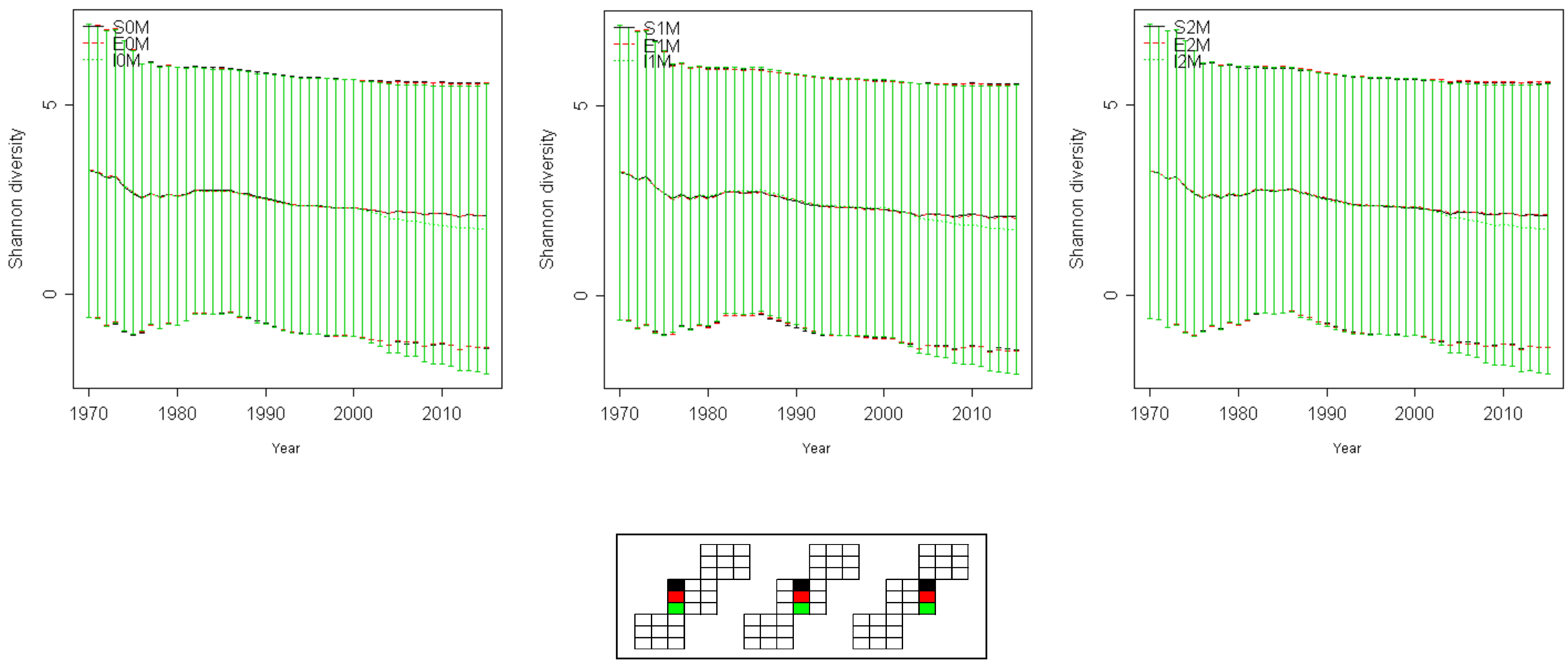


Figure D.125: Comparison of management strategies for the Shannon diversity index under the base case model specification.

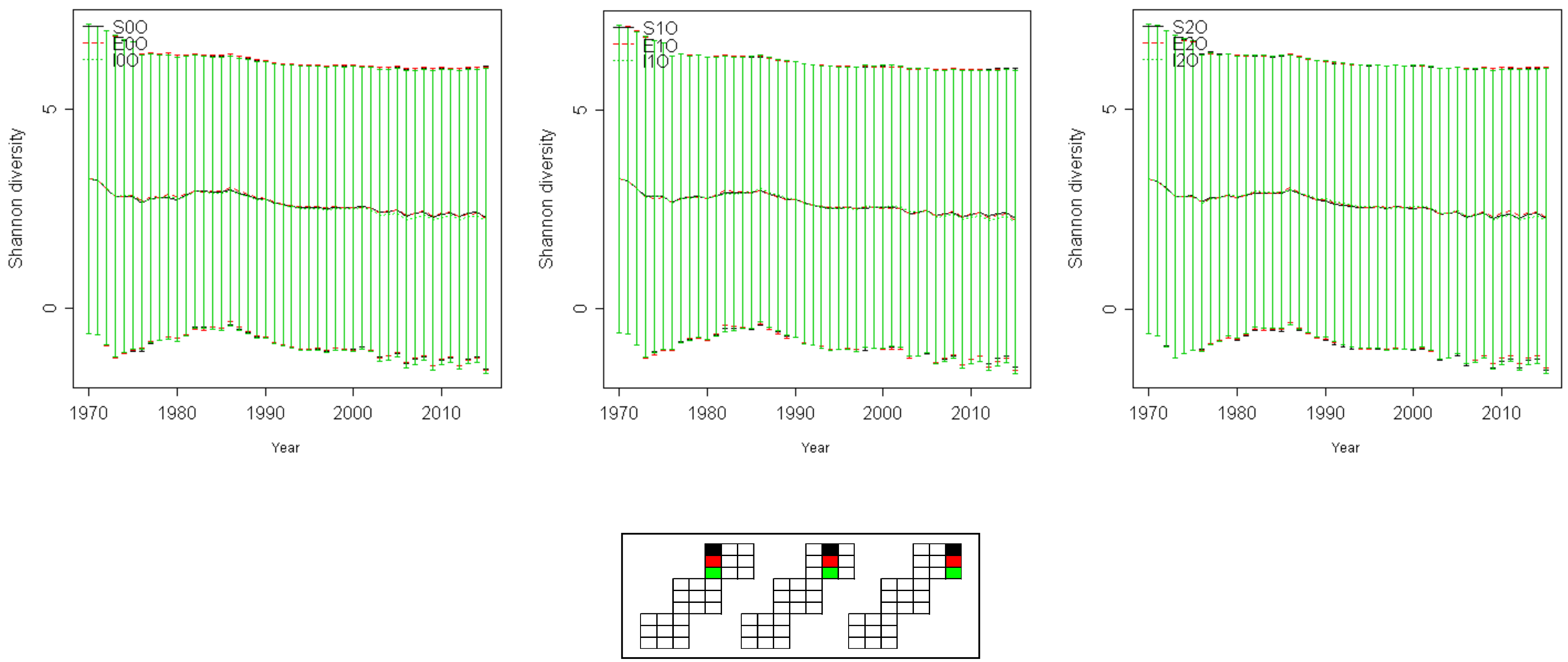


Figure D.126: Comparison of management strategies for the Shannon diversity index under the optimistic model specification.

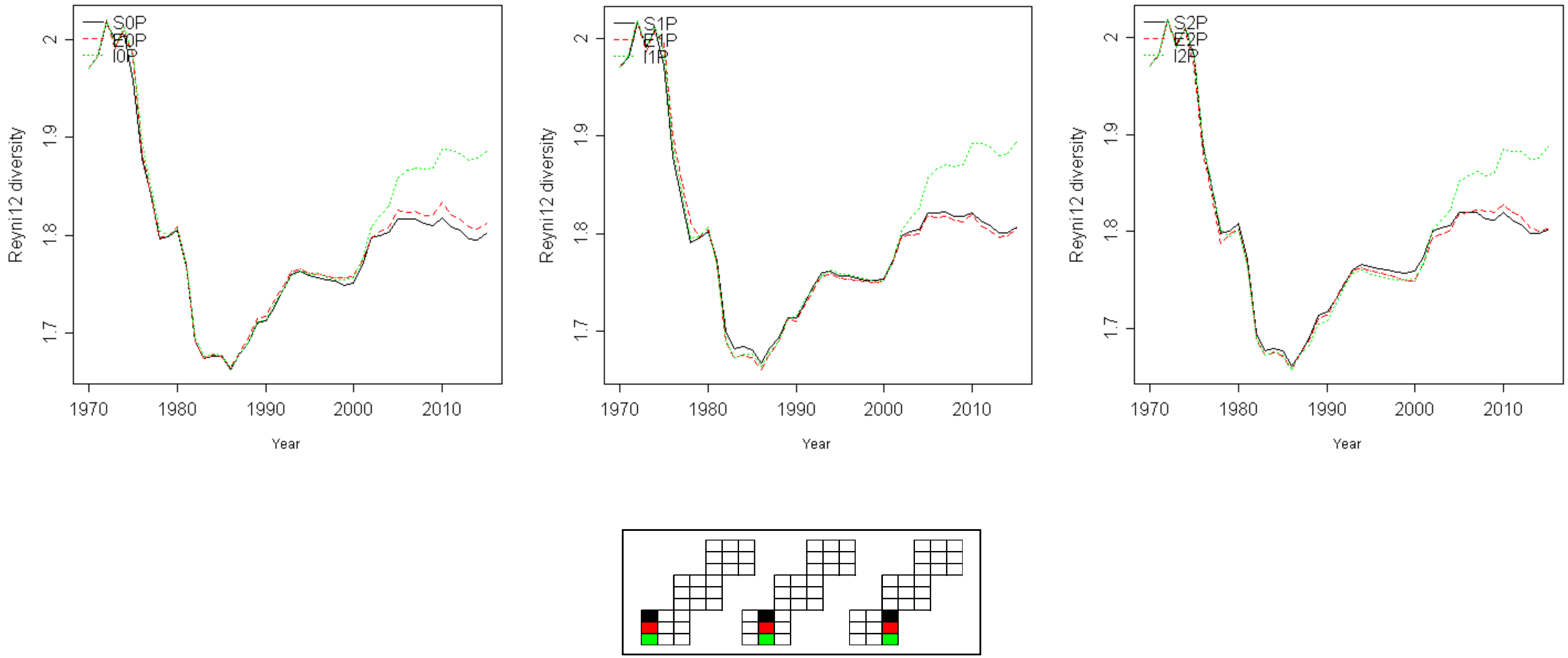


Figure D.127: Comparison of management strategies for Renyi generalised diversity of order 12 under the pessimistic model specification.

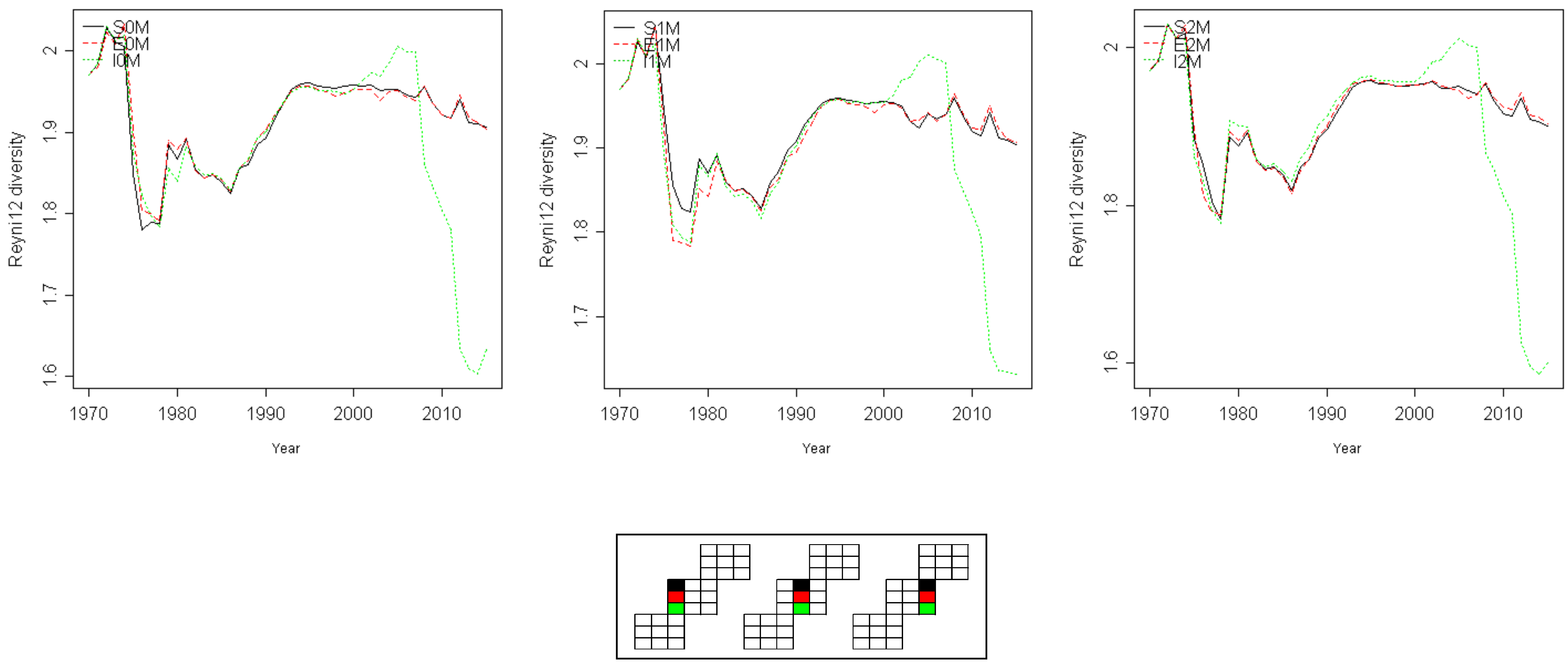


Figure D.128: Comparison of management strategies for Renyi generalised diversity of order 12 under the base case model specification.

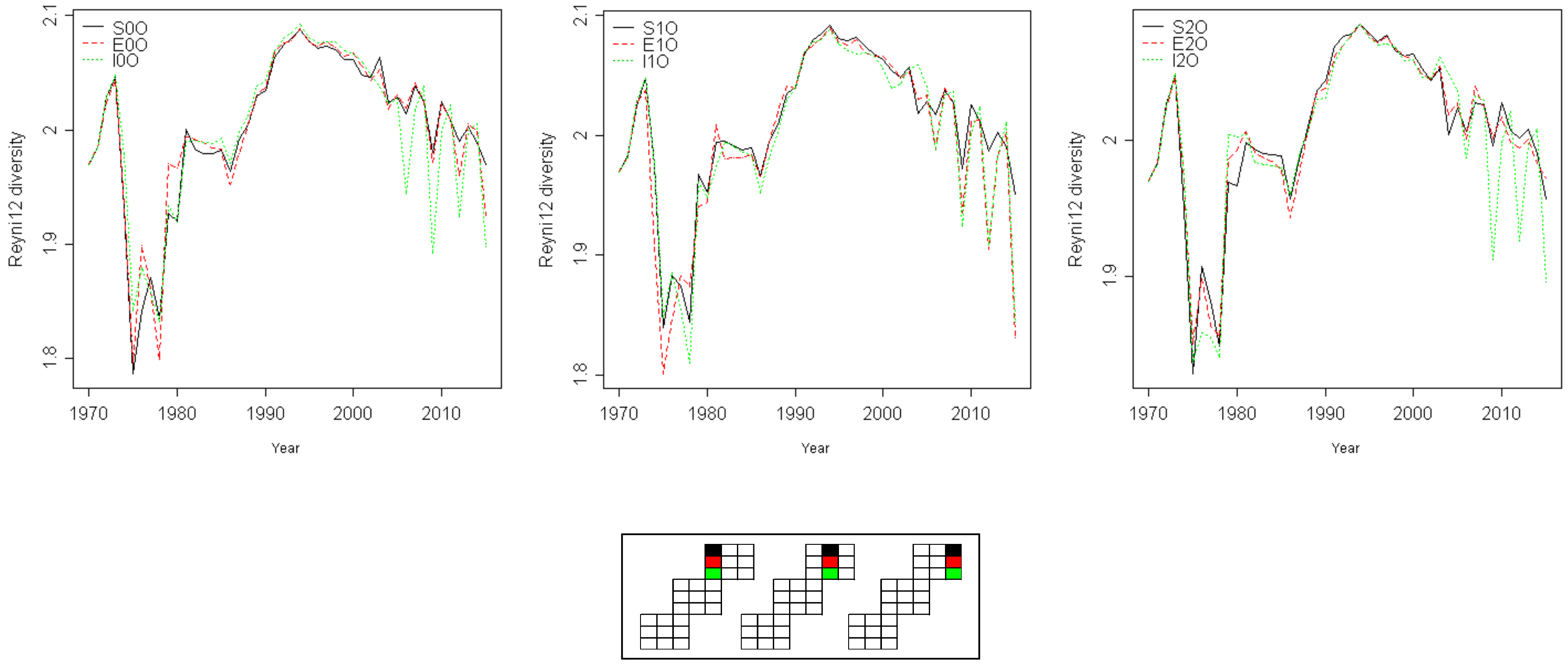


Figure D.129: Comparison of management strategies for Renyi generalised diversity of order 12 under the optimistic model specification.

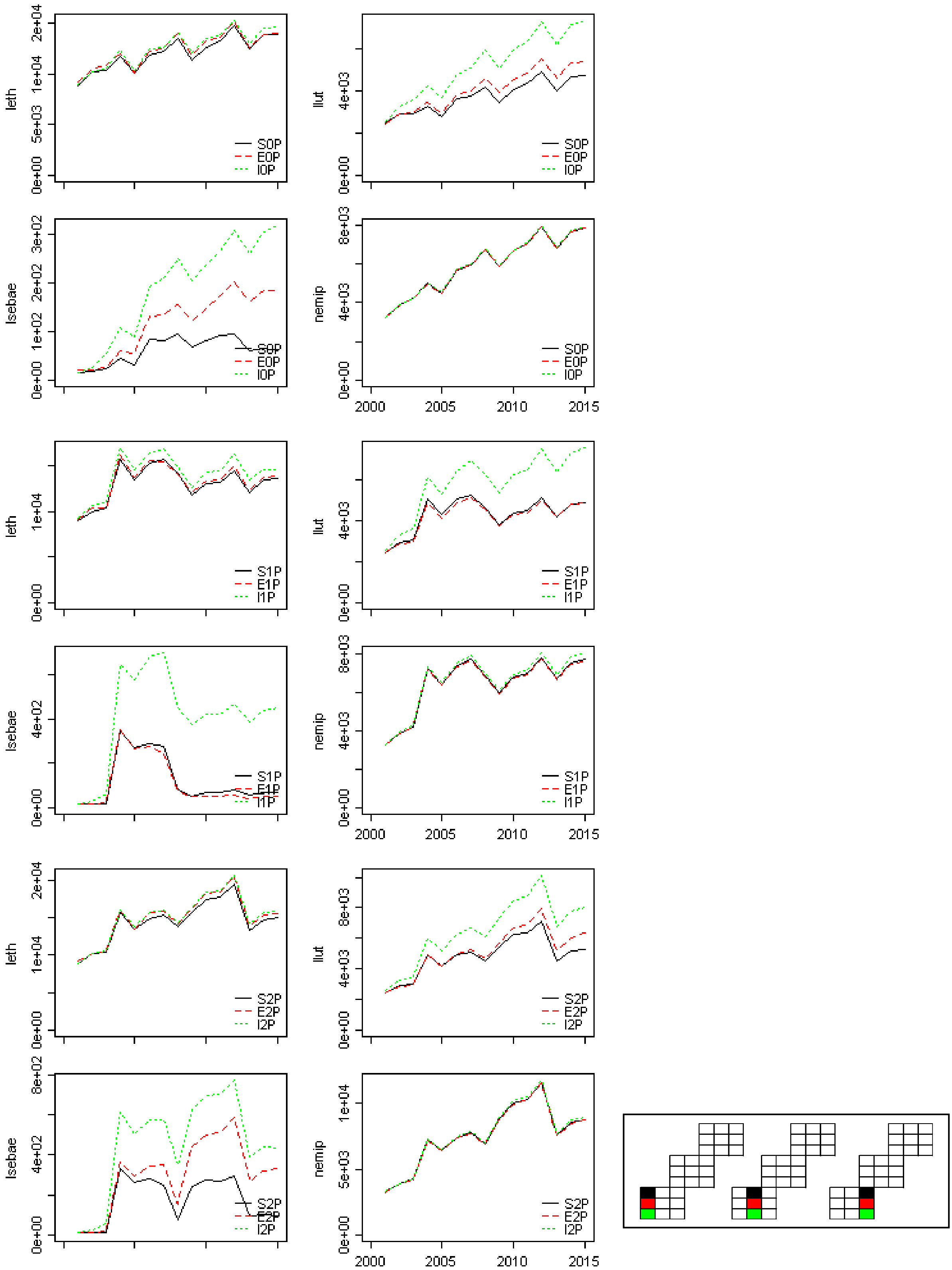


Figure D.130: Comparison of management strategies for total recreational catch (kg) under the pessimistic model specification (leth = lethrinid, llut = large lutjanid, lsebae = *L. sebae*, nemip = nemipterid).

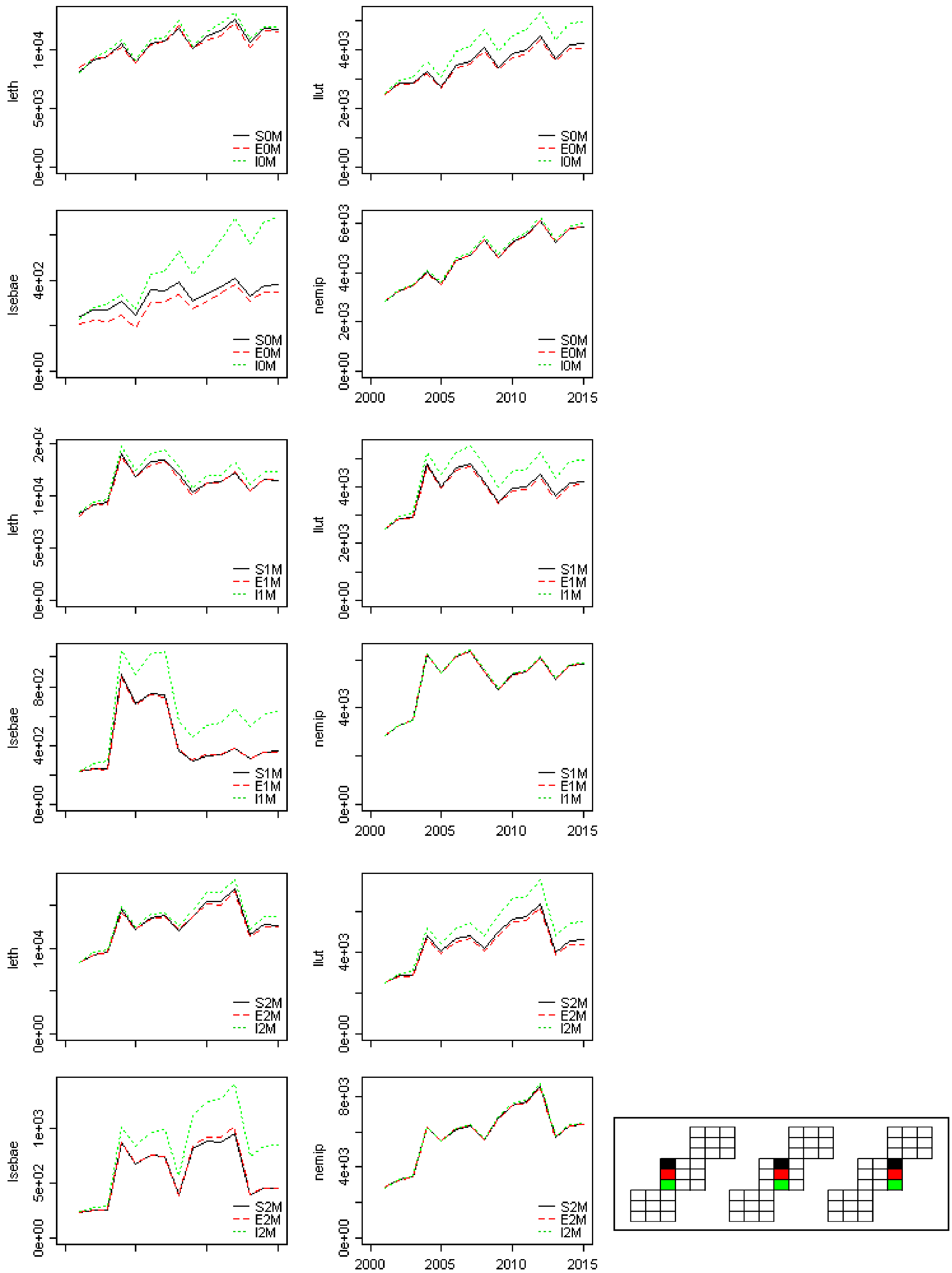


Figure D.131: Comparison of management strategies for total recreational catch (kg) under the base case model specification (leth = lethrinid, llut = large lutjanid, lsebae = *L. sebae*, nemip = nemipterid).

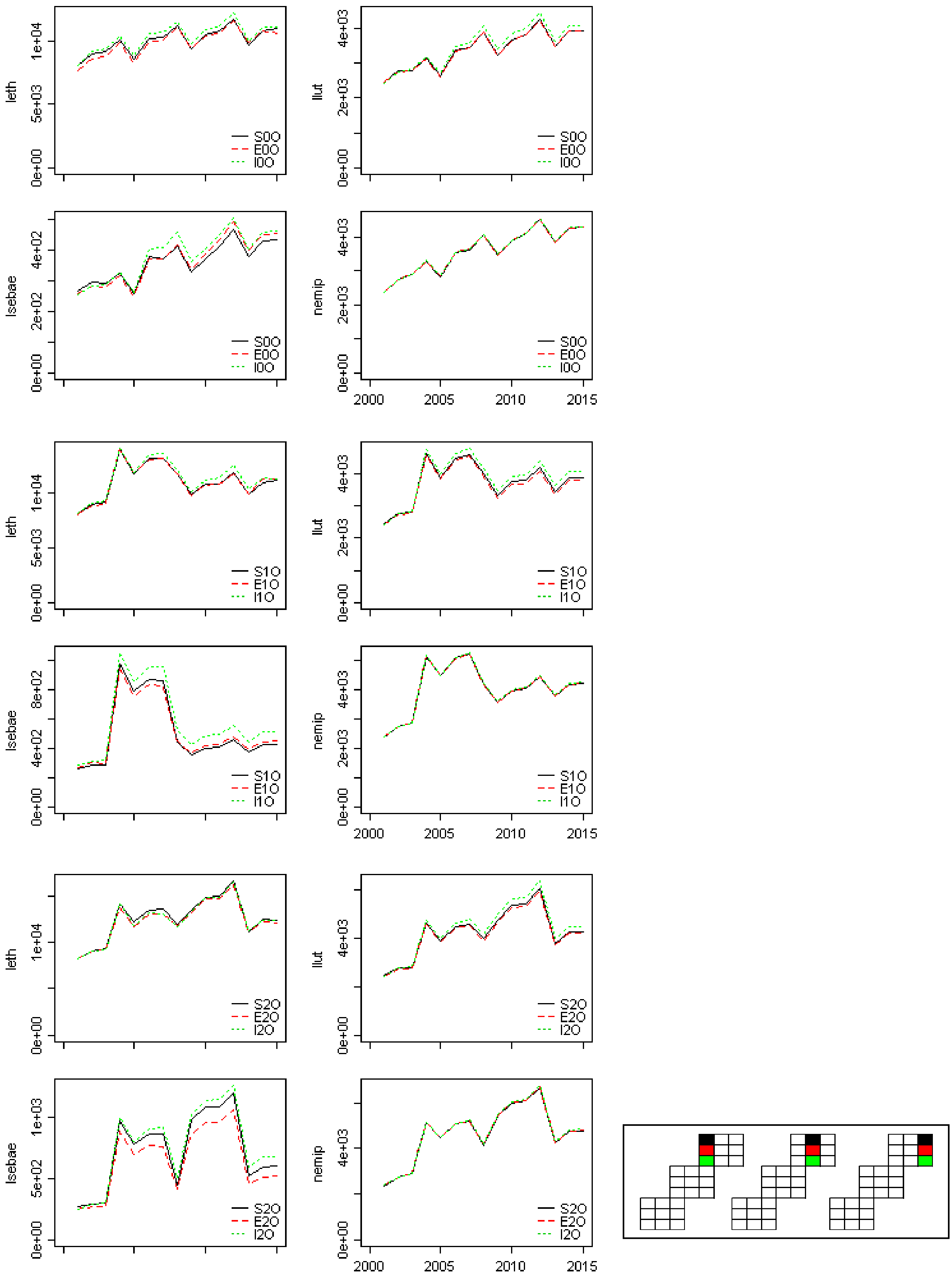


Figure D.132: Comparison of management strategies for total recreational catch (kg) under the optimistic model specification (leth = lethrinid, llut = large lutjanid, lsebae = *L. sebae*, nemip = nemipterid).

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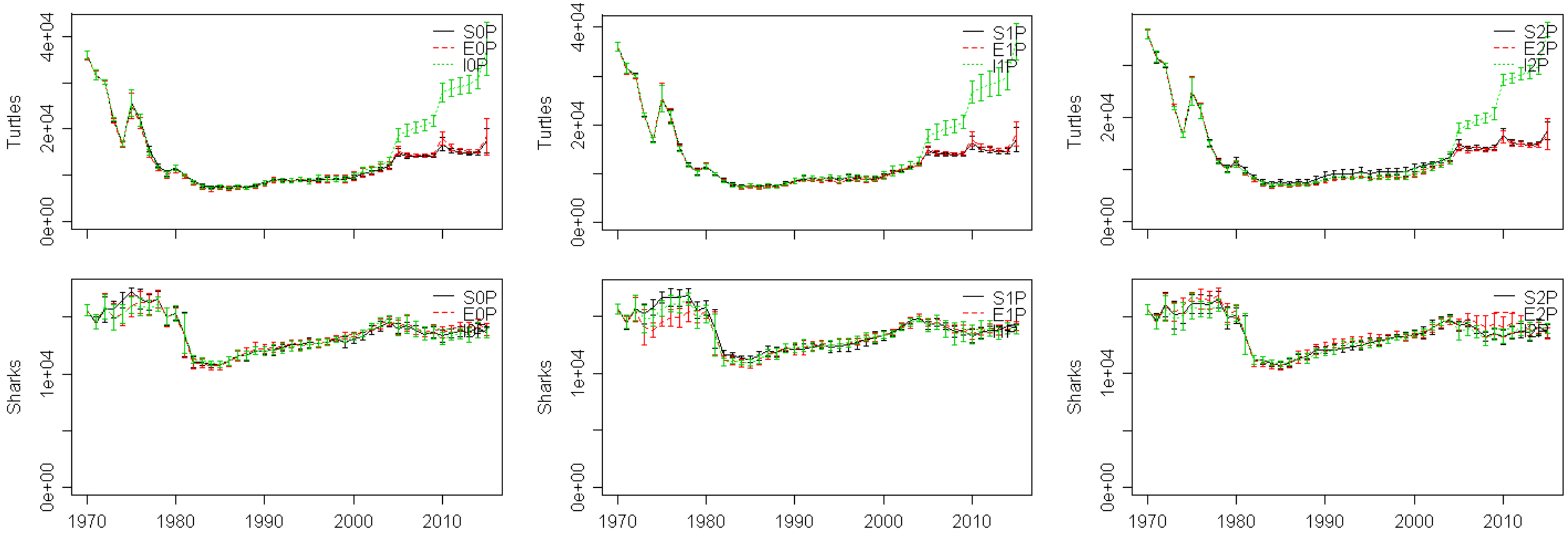


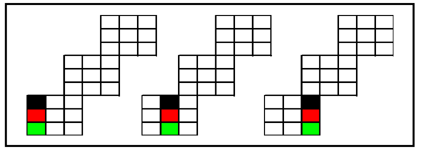


Figure D.133: Comparison of management strategies for total shark biomass (kg) and total turtle biomass (kg) under the pessimistic model specification.

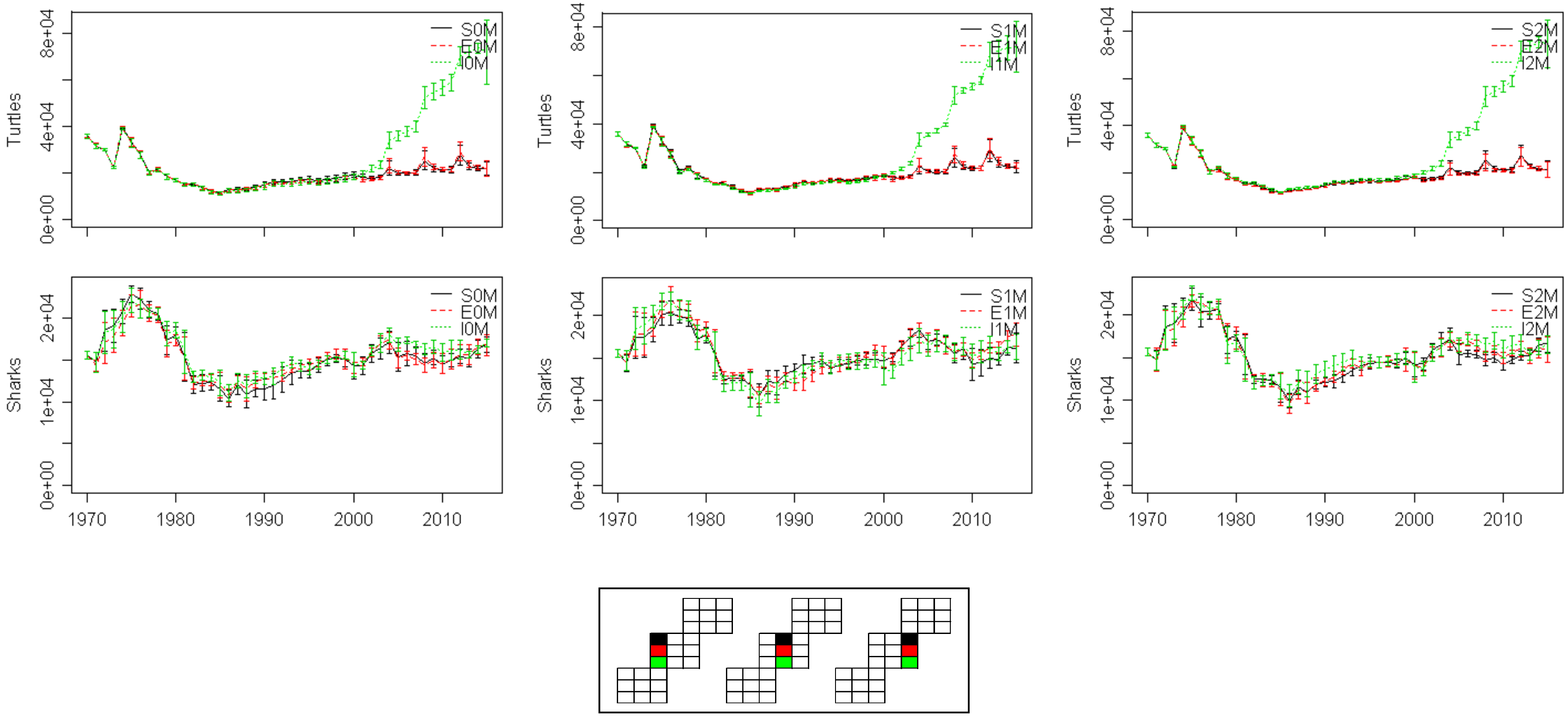


Figure D.134: Comparison of management strategies for total shark biomass (kg) and total turtle biomass (kg) under the base case model specification.

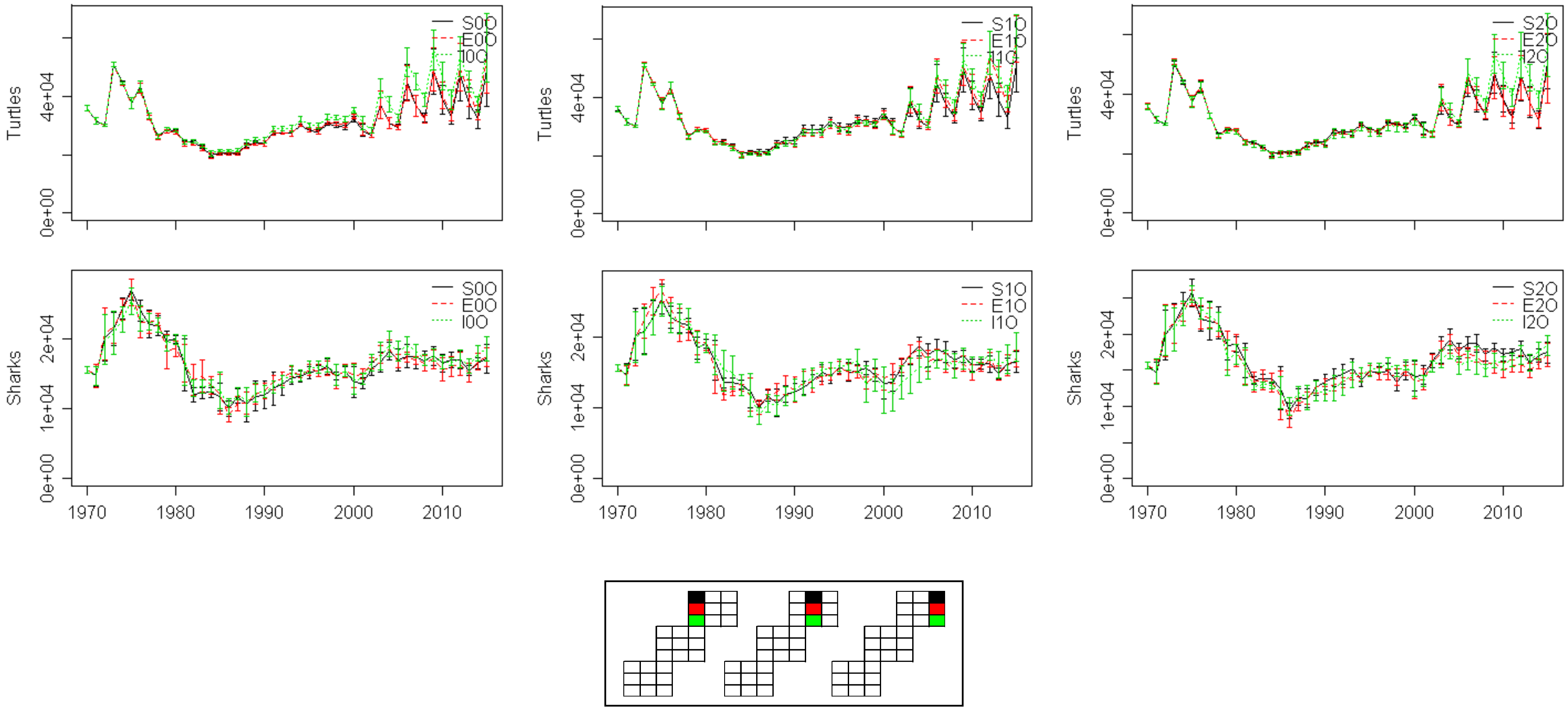


Figure D 135: Comparison of management strategies for total shark biomass (kg) and total turtle biomass (kg) under the optimistic model specification.

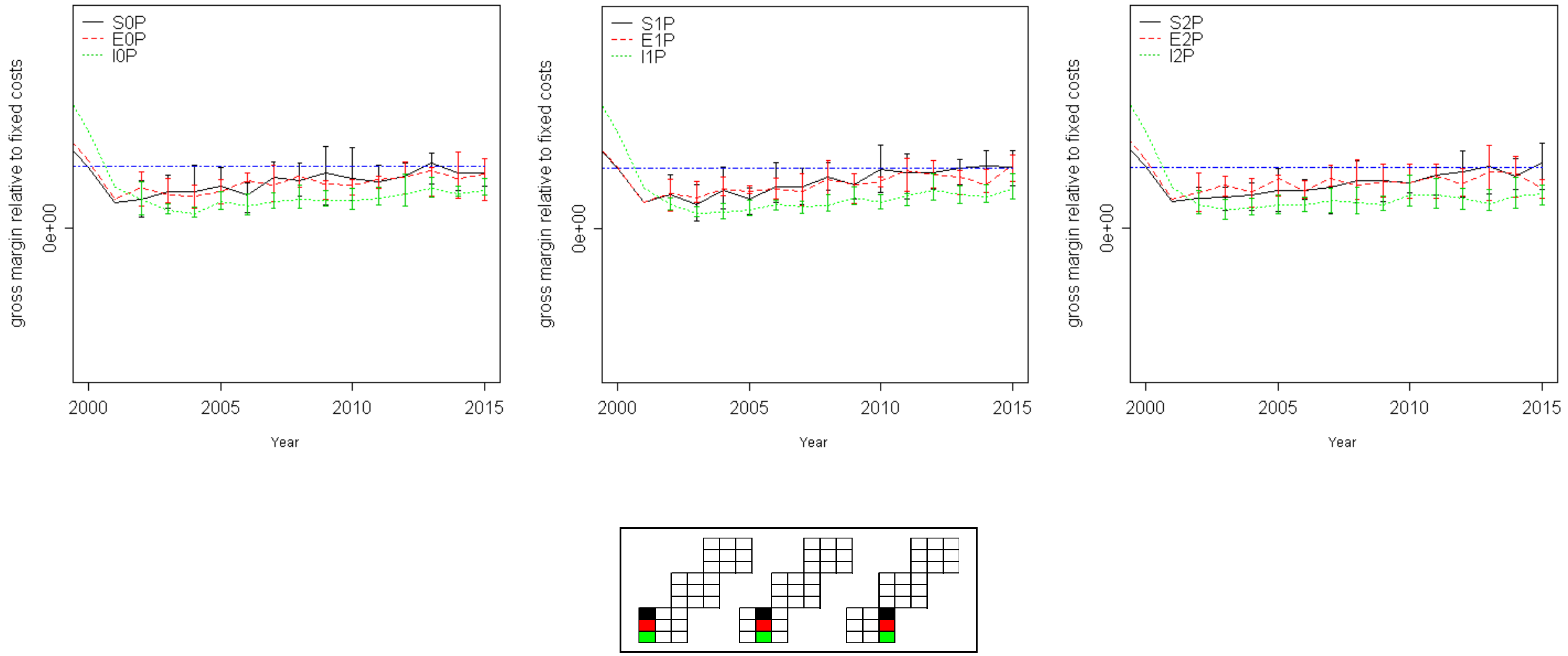


Figure D.136: Comparison of management strategies for the gross margin of the finfish trawl fishery under the pessimistic model specification. The broken blue reference line represents fixed cost. Fleet gross margin is scaled (divided) by fleet fixed cost.

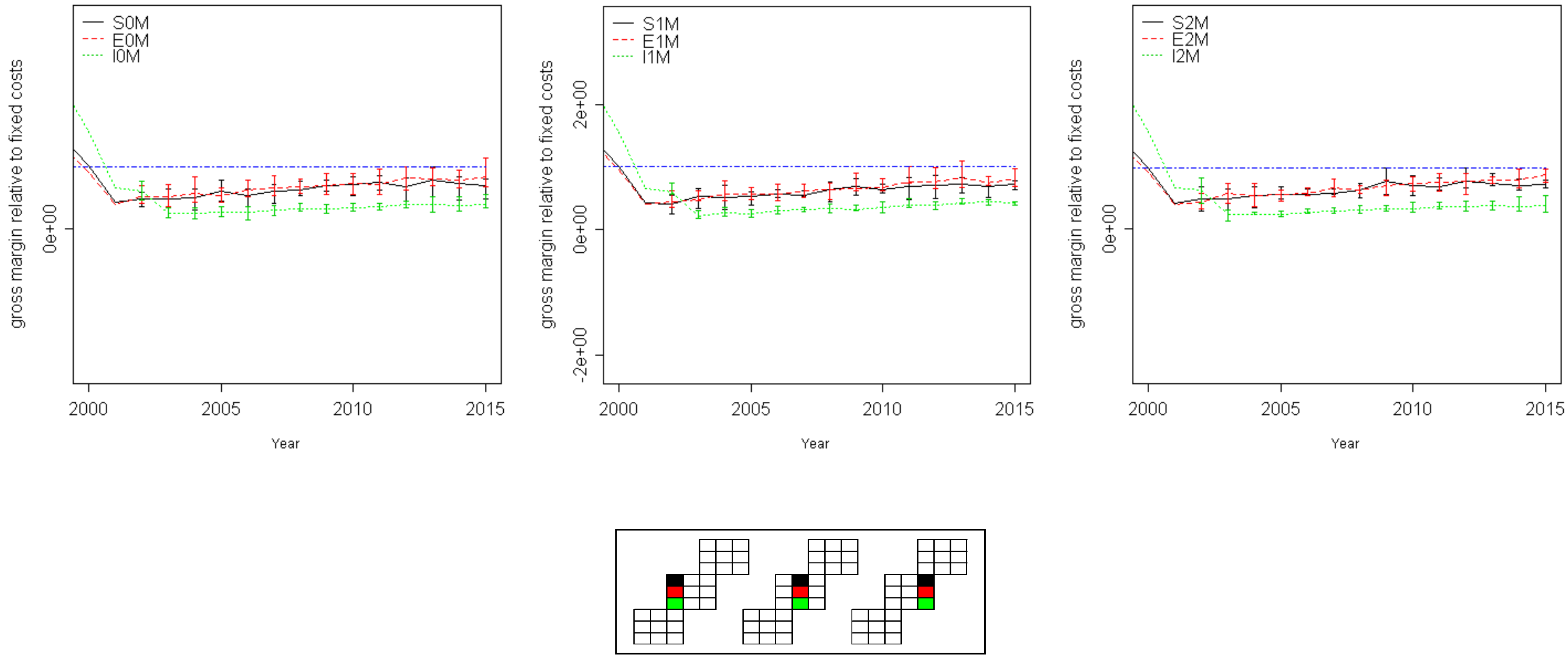
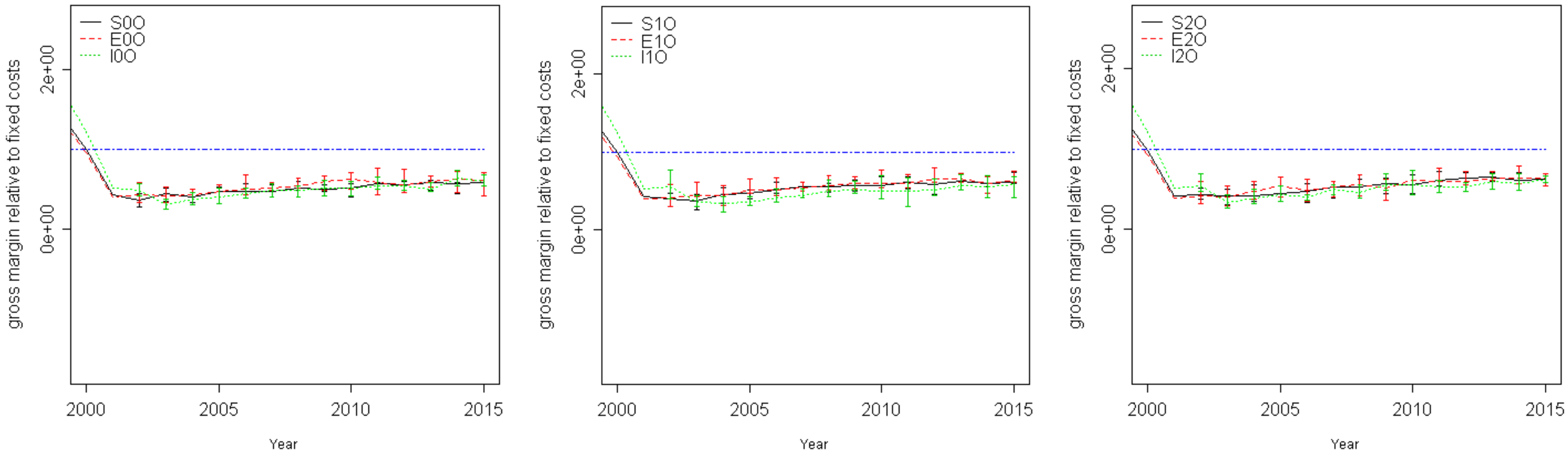


Figure D.137: Comparison of management strategies for the gross margin of the finfish trawl fishery under the base case model specification. The broken blue reference line represents fixed cost. Fleet gross margin is scaled (divided) by fleet fixed cost.



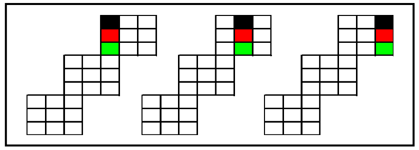


Figure D.138: Comparison of management strategies for the gross margin of the finfish trawl fishery under the optimistic model specification. The broken blue reference line represents fixed cost. Fleet gross margin is scaled (divided) by fleet fixed cost.

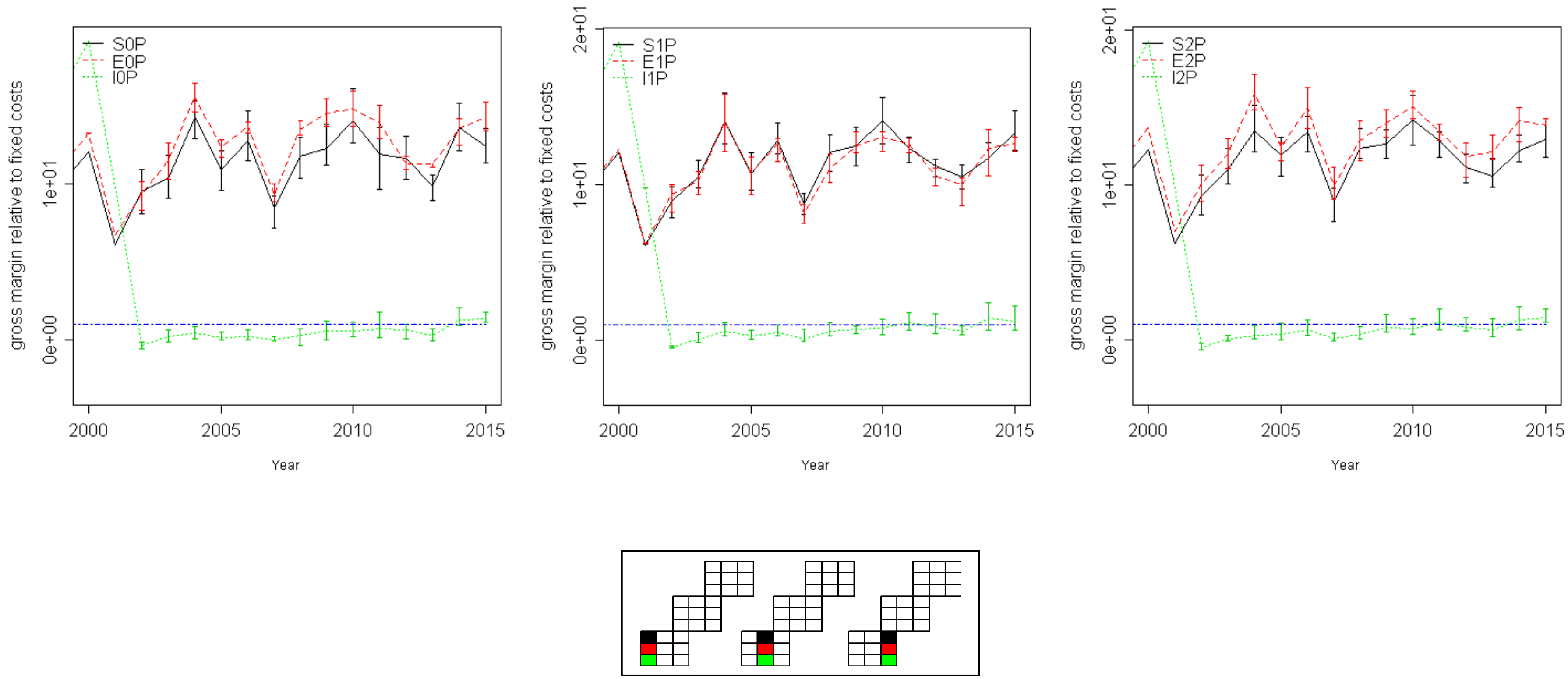
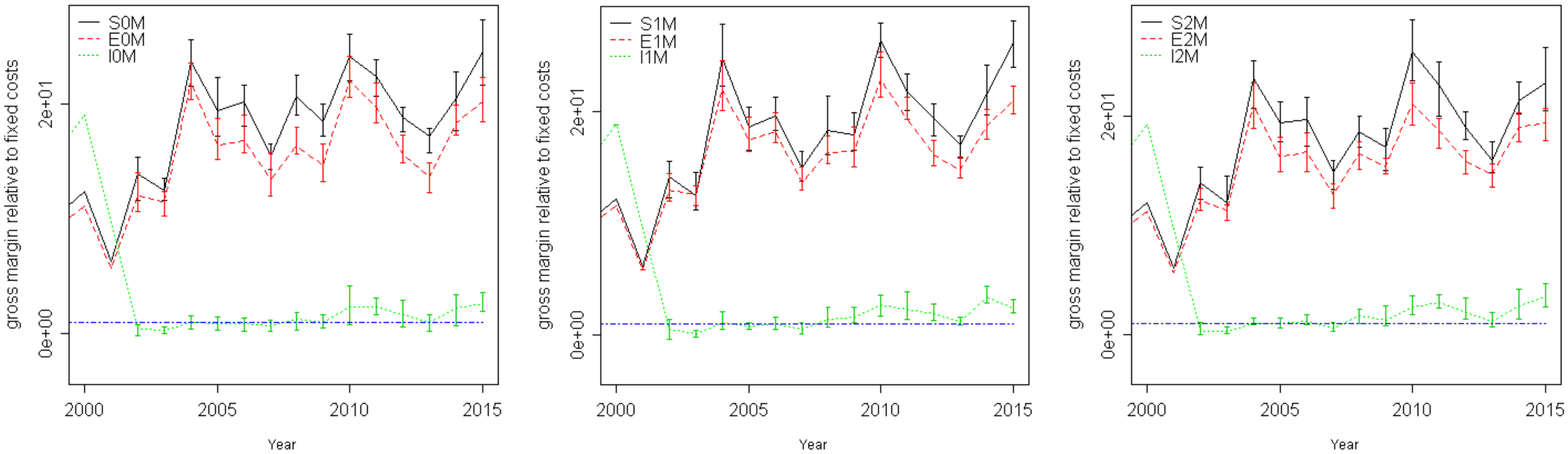


Figure D.139: Comparison of management strategies for the gross margin of the prawn trawl fishery under the pessimistic model specification. The broken blue reference line represents fixed cost. Fleet gross margin is scaled (divided) by fleet fixed cost.



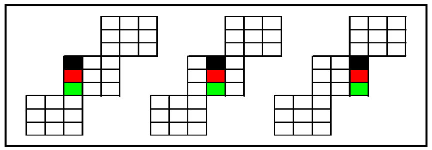


Figure D.140: Comparison of management strategies for the gross margin of the prawn trawl fishery under the base case model specification. The broken blue reference line represents fixed cost. Fleet gross margin is scaled (divided) by fleet fixed cost.

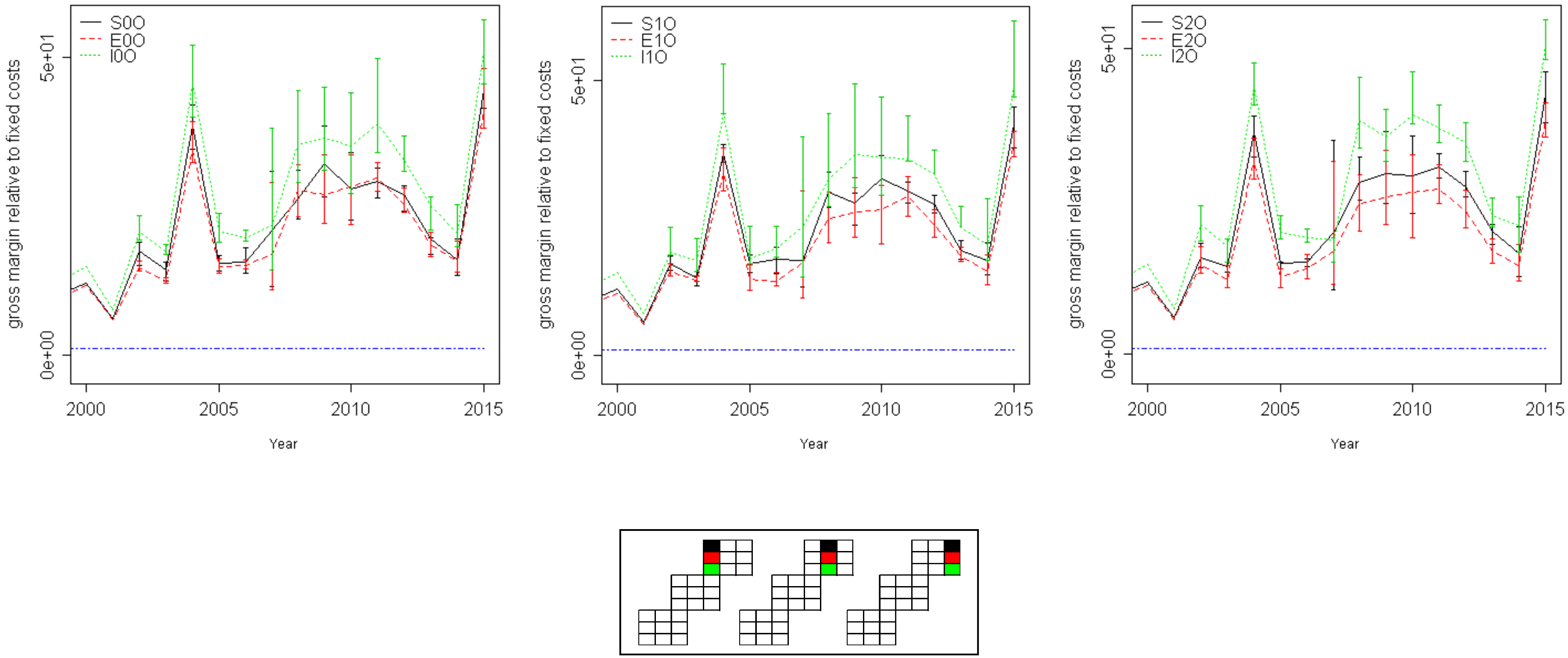


Figure D.141: Comparison of management strategies for the gross margin of the prawn trawl fishery under the optimistic model specification. The broken blue reference line represents fixed cost. Fleet gross margin is scaled (divided) by fleet fixed cost.

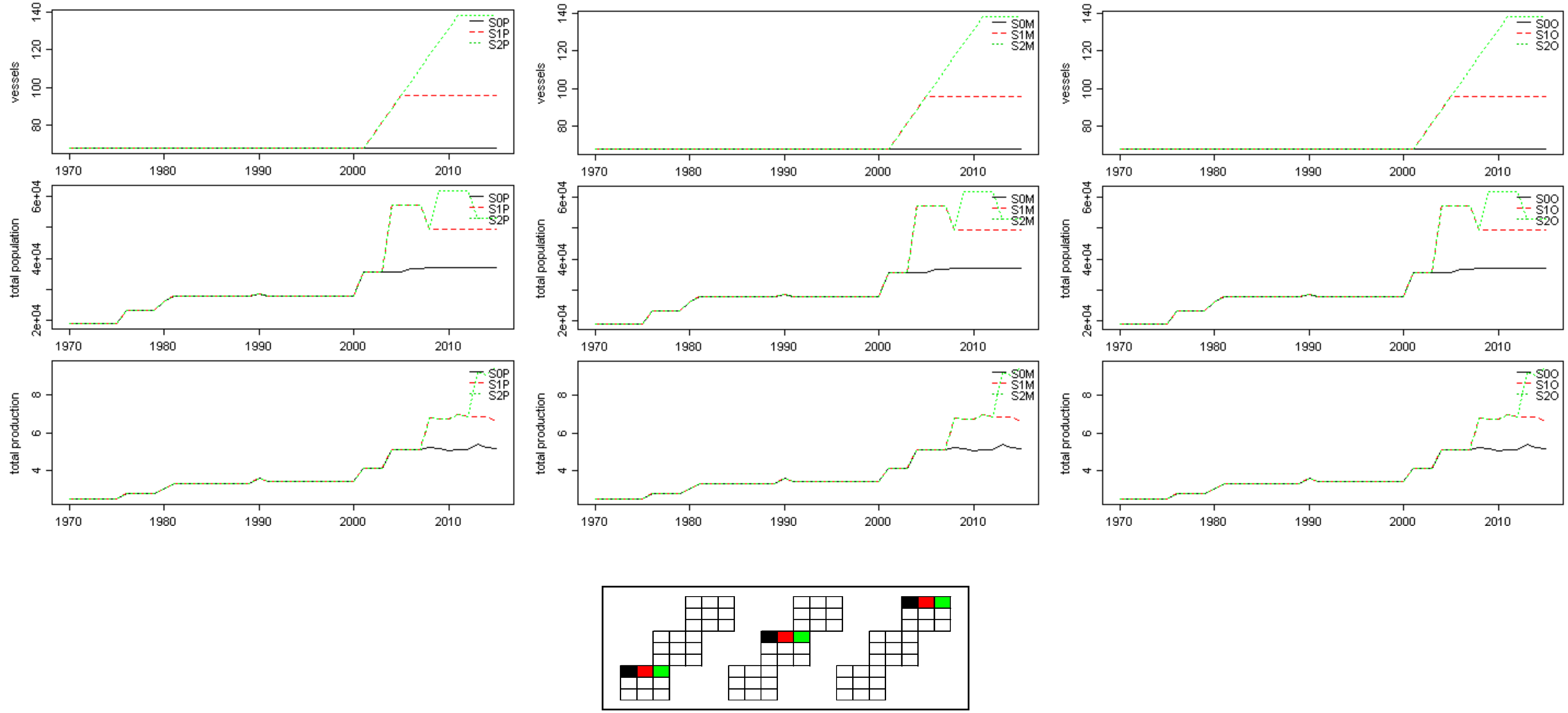


Figure D.142: Comparison of development scenarios for number of cargo vessels, total human population and total production under the status quo management strategy.

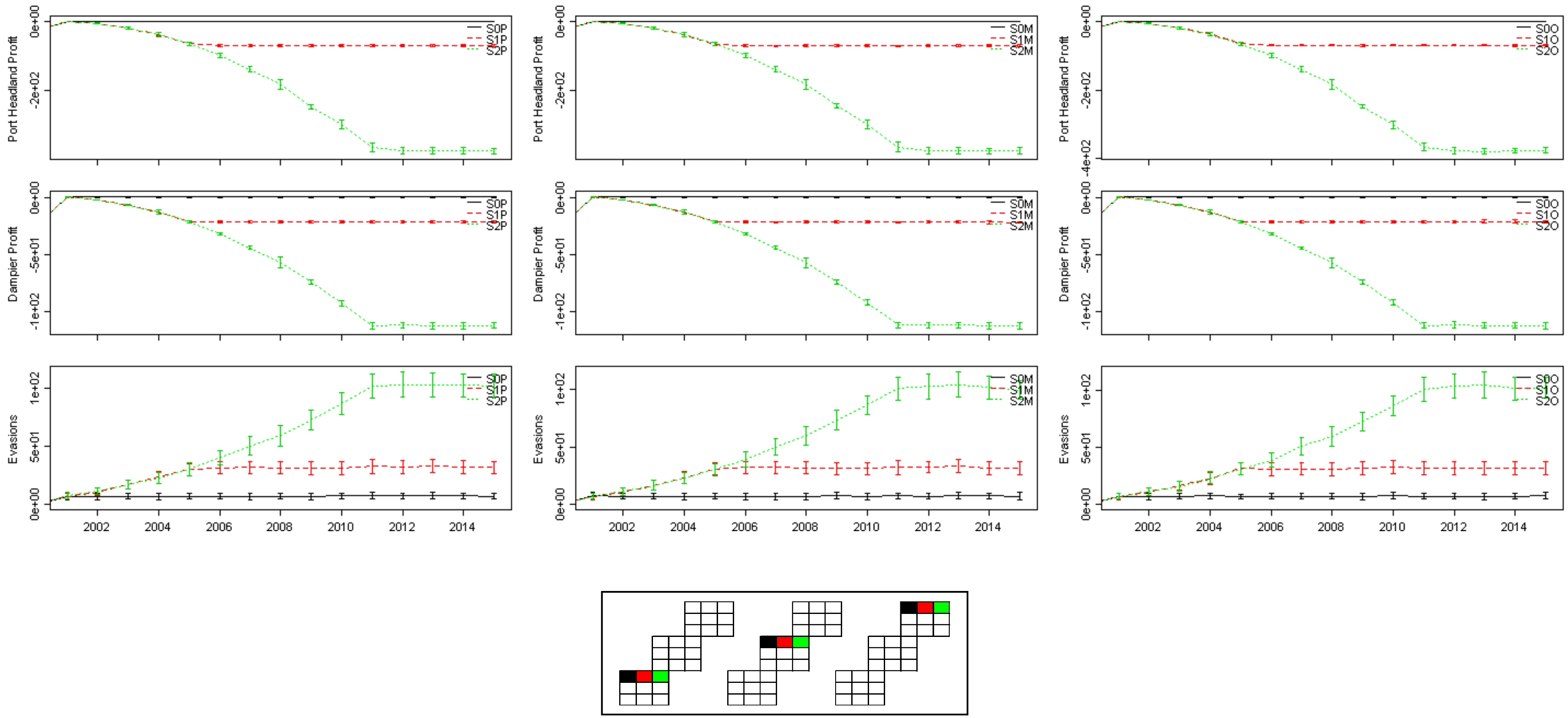


Figure D.143: Comparison of development scenarios for Port Hedland and Dampier port revenue and the number of vessel evasions under the status quo management strategy.

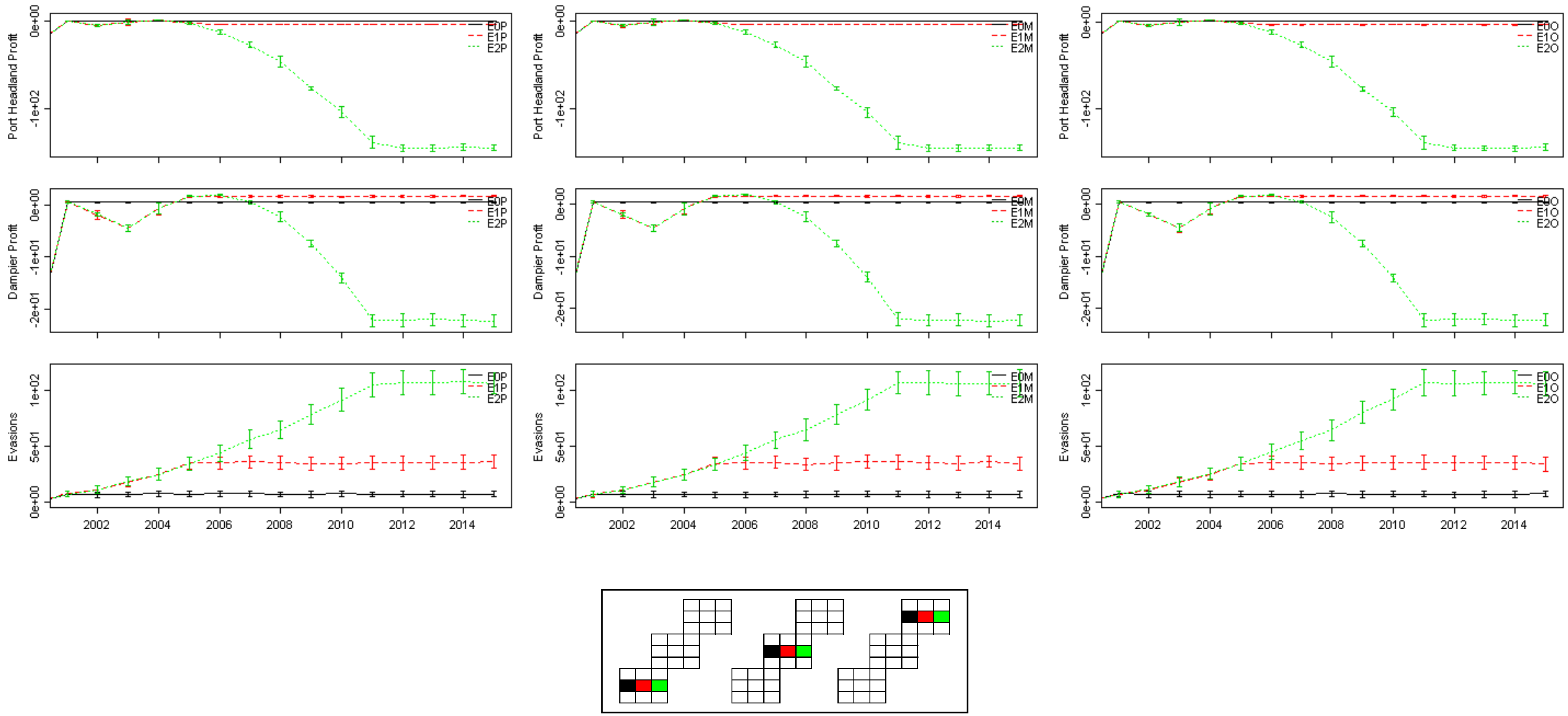


Figure D.144: Comparison of development scenarios for Port Hedland and Dampier port revenue and the number of vessel evasions under the enhanced management strategy.

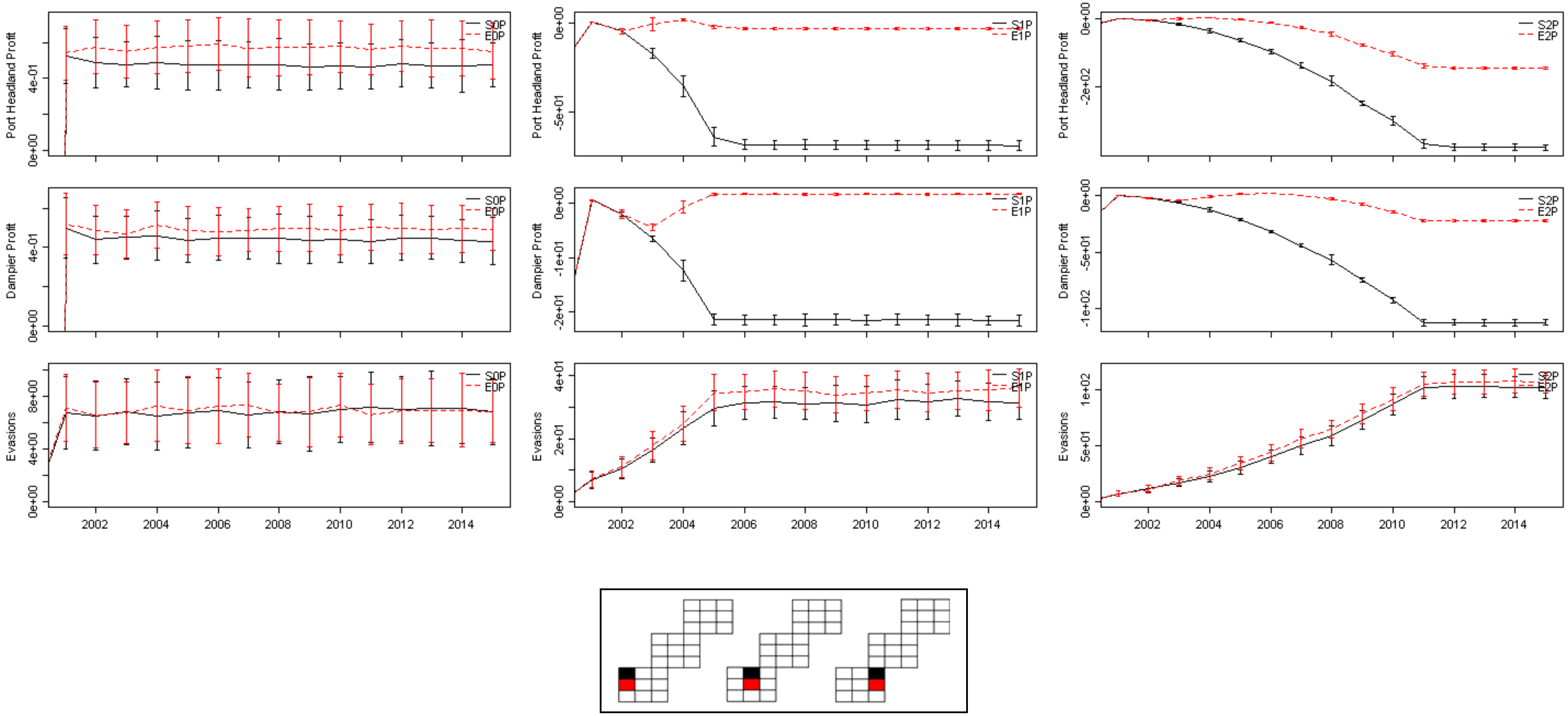


Figure D.145: Comparison of management strategies for Port Hedland and Dampier port revenue and the number of vessel evasions under the pessimistic model specification.

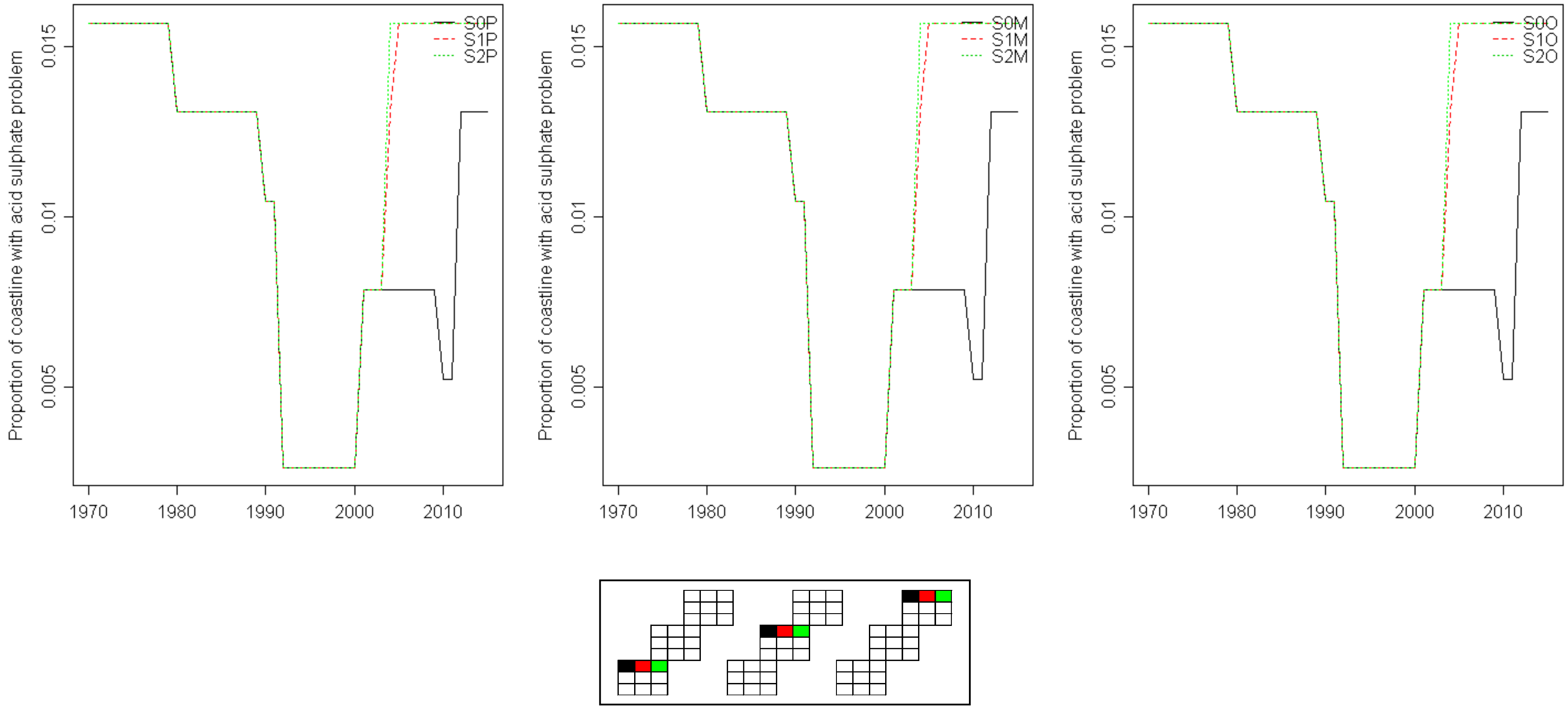


Figure D.146: Comparison of model specifications for acid sulphate soils under the status quo management strategy.

APPENDIX E: ECONOMIC FISHERIES DATA USED IN NWSJEMS

Economic analysis of the finfish fisheries was done using cost data from AFMA logbook and ABARE survey statistics from the South East Trawl Fishery (courtesy of T. Kompas, table E.1). Fish price data were obtained from the Sydney Fish Market monthly price report data for 2004 of six species (Threadfin Bream, Red Emperor, Blue-spotted Emperor, Scarlet Sea Perch, Red Snapper and Spangled Emperor) from Western Australia (table E.2).

Gross margins were calculated as:

$$\pi_y = (1 - c_l)\sum_s C_{y,s} p_s - E_y c_c$$

where

π_y is the gross margin in year *y* per vessel

$C_{y,s}$ is the total trawl catch of species *s* in year *y*

p_s is the price ($/kg) of fish of species *s*

c_l is the average labour and other costs per unit revenue

c_c is the average fuel costs per unit effort

E_y is the total trawl effort (travel hours) expended (h) in year *y*

For the analysis, c_l was set to 0.37, and c_c was 137.25. Gross margin was scaled to fixed costs for graphical presentation in Appendix D. Fixed costs were calculated from the average of the capital and gear costs, multiplied by the average annual effort E_y .

Table E.1: Cost data of the South East Trawl Fishery.

Costs	Unit	Method Values			Average
		Inshore	Offshore	Danish	
Share of labour costs/revenue	$ per 1$	0.31	0.27	0.35	
Share of other/revenue	$ per 1$	0.06	0.06	0.05	
Total		0.37	0.33	0.40	0.37
Average fuel cost/effort	$/hour	103.44	244.65	63.66	137.25
Average capital cost/effort	$/hour	94.40	115.05	80.87	
Average gear cost/effort	$/hour	19.19	68.20	18.56	
Total		113.59	183.25	99.43	132.10

Table E.2: Average price in 2004 for six species of Western Australian fish from Sydney Fish Market, grouped into species grouping used by the NWSJEMS MSE.

Species	NWS species group (code name)	price ($/kg)
red emperor	*Lutjanus sebae* (lsebae)	10.18
blue-spotted emperor	lethrinids (leth)	3.10
spangled emperor	Lethrinids (leth)	6.79
Average		4.95
scarlet sea perch	large lutjanids (llut)	4.94
red snapper	large lutjanids (llut)	4.54
Average		4.74
threadfin bream	nemipterids (nemip)	5.08

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Department of Industry and Resources (Department of Mineral and Petroleum Resources)
Department of Land Information
Department for Planning and Infrastructure (Department of Transport)
Pilbara Tourism Association
Shire of Roebourne
Town of Port Hedland
Tourism Western Australia
Western Australian Land Information System
Western Australian Museum

Commonwealth agencies
Australian Institute of Marine Science
Geoscience Australia (formerly Australian Geological Survey Organisation)

Consultants
Cognito Consulting
David Gordon International Risk Consultants
METOCEAN Engineers (formerly Weather News International, Perth)
Oceanica (formerly DA Lord and Associates)

Industries
Australian Petroleum Production Exploration Association (APPEA)
Apache Energy
BHP Petroleum
Chevron Australia
Dampier Salt
Hamersley Iron
Mermaid Marine
Woodside Energy

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