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Process modelling and uncertainty estimation in fishery resource dynamics: An analysis using Bayesian techniques

Modelado de procesos y estimación de incertidumbre en la dinámica de recursos pesqueros: análisis mediante técnicas bayesianas.

TESIS DOCTORAL

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“To all young scientists out there: It is your job to prove that we were wrong”

John Pope

A mi madre María Isabel Hidalgo/ en su memoria

Contents

Resumen

En esta tesis se aborda el problema de cuánto pescar maximizando el beneficio y disminuyendo el riesgo de colapso mediante una aproximación matemática a tres stocks diferentes, la anchoa en el mar de Alborán, la anchoa en el golfo de Cádiz y la merluza del Atlántico Norte. Teniendo en cuenta las condiciones y particularidades de cada stock, el enfoque para los tres ha sido diferente. Para la anchoa del golfo de Cádiz y del mar de Alborán, aunque se ha utilizado principalmente la interacción entre el medio y el ciclo de vida de la especie, los tipos de forzamiento ambiental y su relación con el ciclo vital son diferentes. Sin embargo, para la merluza se ha tenido en cuenta la relación entre la pesca y su biología, que no se conoce totalmente, ya que el efecto del medio ambiente es menos representativo.

En el golfo de Cádiz, ya se conoce la dinámica del forzamiento ambiental causada principalmente por la temperatura, los fuertes vientos y las descargas del río Guadalquivir, y por lo tanto se procede directamente a modelar dichas interacciones con un modelo de doble resolución temporal: Una resolución semanal para las primeras etapas vitales, y mensual para juveniles y adultos. Este modelo logra mejorar estimaciones previas de juveniles y provee estimaciones coherentes de la distribución mensual por tallas de la población mostrando que la doble resolución incorpora adecuadamente la variabilidad del tamaño de la población causada por la influencia del medio ambiente en las etapas tempranas y la dinámica de crecimiento.

En el mar de Alborán era necesario analizar primero los factores que podrían estar causando el forzamiento y una indagación exhaustiva logró revelar una conexión entre su sistema circulatorio y el nivel de capturas, donde se ve claramente que el usual alto nivel de energía del sistema circulatorio de la zona no es favorable para el reclutamiento, y que cuando este colapsa es posible la existencia de reclutamientos excepcionales de esta especie.

No obstante, la herramienta estadístico-matemática que está presente en todos es el análisis Bayesiano que permitió la incorporación de elementos complejos, desde el forzamiento ambiental a la dinámica de capturas y descartes con diferentes flotas, cuantificando la incertidumbre subyacente en todos los procesos involucrados. Las técnicas Bayesianas proveen en este trabajo una gran herramienta para asesorar pesquerías con una aproximación más realista a la dinámica biológica y ecológica de las poblaciones. Además, el conocimiento derivado de la aplicación de dichas técnicas se puede proyectar sobre elementos socioeconómicos, diseñando herramientas de gestión que tengan en cuenta el impacto del ecosistema y evaluando su funcionamiento.

Por este motivo fue posible proponer en el caso del golfo de Cádiz, una herramienta de evaluación de diversas estrategias para la gestión del recurso, resaltando la importancia de aquellas que tienen en cuenta la interacción entre el ecosistema y la biología de la especie estudiada. La herramienta se basa en la aplicación de un esquema de seguros que permite calcular el valor de la información ambiental aplicada a la gestión, usando conceptos como ingreso medio, prima y riesgo de colapso. Los resultados de una estrategia propuesta que incluye el forzamiento ambiental muestran que el riesgo económico no se disminuye, dado que la volatilidad del ingreso y el valor de la prima son mayores, pero si disminuye el riesgo de colapso y se genera un monto de ingresos tal que permite compensar dicha volatilidad. El aumento considerable de ingresos obtenidos bajo esta estrategia hacen que esta herramienta sugiera la posibilidad de estabilizar ingresos sobre un recurso inherentemente fluctuante. Por tanto, representa un precedente para la posibilidad de un manejo cooperativo del riesgo que responda a una cuota variable determinada por el medio ambiente.

A pesar de las múltiples ventajas de las técnicas Bayesianas aplicadas tanto al modelado del ecosistema y sus interacciones con la pesca, como a la gestión del recurso, el tiempo computacional es demasiado elevado para modelos con un gran número de parámetros y procesos como el de la merluza. El rápido avance tecnológico resolverá este inconveniente y hará que esto sea posible en el futuro, permitiendo que la medida de incertidumbre que provee esta herramienta pueda ser la base de la toma de decisiones relevantes para el sector pesquero.

Introducción General

La explotación indiscriminada de los recursos naturales durante muchos años se ha convertido en una gran problemática que abarca dimensiones económicas, políticas y sociales (Hopwood et al., 2005). La idea de un manejo sostenible de los recursos ha venido tomando fuerza como la forma más eficaz de preservar el medio ambiente sin renunciar a obtener un beneficio económico del mismo (Ludwig et al., 1993). Aunque en muchos lugares del planeta ya existían políticas de sostenibilidad locales desde hace muchos años, estas iniciativas frente al nivel de explotación actual han sido insuficientes y han requerido la intervención conjunta de los países mediante el diseño de leyes que restrinjan la explotación y una vasta inversión en investigación.

El caso de la pesca como importante motor social y económico (12.5 millones de personas empleadas en actividades relacionadas con la pesca y un total de ventas estimado en alrededor de 40 millones de dólares a principios de los noventa (FAO)), no es la excepción a este patrón de explotación de los recursos ambientales. Hay intentos de gestión pesquera que datan de cientos de años atrás. Por ejemplo, se cree que los maoríes, residentes en Nueva Zelanda desde hace 700 años, restringían la pesca en ciertas zonas según la estación del año motivados por sus creencias religiosas (Barber, 2004). Sin embargo, estas iniciativas sostenibles han sido pocas y no se compensan con el crecimiento económico del sector en los últimos siglos. Los primeros intentos políticos de regulación empezaron en el siglo XIX en las pesquerías del Norte de Noruega con el establecimiento de leyes que delimitaban los espacios de pesca. No obstante, una visión integradora entre política y ciencia para la conservación y protección de los recursos pesqueros por parte de los entes gubernamentales no empezó sino a mediados del siglo XX.

Los países con pesquerías en el Atlántico noreste fueron pioneros en organizarse para lograr una mejor gestión, cabe resaltar al respecto, la convención multilateral del mar del Norte en 1882, la convención del Báltico en 1929 y la International Overfishing Conference en 1946. Las dos primeras sirvieron sólo para hacer llamados de atención a los gobiernos de los delegados y la mayoría simplemente ignoró la situación, mientras que a la última asistieron miembros de 12 paises y un observador estadounidense que reconocieron por primera vez la necesidad imperante de un control internacional sobre la pesca principalmente en el Atlántico noreste (Johnston, 1987). La preocupación creciente permitió la creación del Instituto Internacional para la explotación del mar (ICES) en 1902, que es la organización científica intergubernamental más antigua del mundo y que en aquella época estaba conformada por 8 países del norte de Europa mientras que actualmente la conforman 20 países, incluyendo España. Es sólo hasta 1946 durante la International Overfishing Conference donde los gobiernos de los países asistentes empiezan a involucrarse activamente en la gestión comprometiéndose a penalizar la comercialización de ejemplares que estuviesen por debajo de las tallas mínimas establecidas para 12 especies de peces. Aunque hubo ciertas iniciativas por parte de los gobiernos, las medidas tomadas en muchos casos no fueron suficientes para luchar contra la sobre-explotación y el deterioro ecológico de varias zonas pesqueras a nivel global. Son conocidos los colapsos de la anchoa peruana en 1970 y del bacalao en los caladeros de Terranova en 1992, entre otros. Sin embargo, los momentos de crisis en las pesquerías han sido el motor que ha impulsado a los gobiernos y a las pesquerías a reforzar la investigación científica en el campo.

Aún a principios de este milenio hay poca evidencia de sostenibilidad para los recursos marinos (Caddy and Seijo, 2005), y aunque se ha desarrollado cierta conciencia por parte de científicos, políticos y gestores de pesca, las fallas en la comunicación entre ellos hacen que los aspectos ecológicos, económicos y sociales de la pesquería se vean como disciplinas diferentes (Johnson and Walker, 2000; Lundquist and Granek, 2005). Se presenta entonces la necesidad de un manejo cooperativo de la pesca, y un reto para el científico, ya que debe tener en cuenta todos estos aspectos para que sus investigaciones sean pertinentes al sector y ser efectivo y claro cuando vaya a comunicar sus resultados.

En el caso de la pesquería de la anchoa en el golfo de Cádiz, que es un componente nuclear de esta tesis, el primer estudio científico es publicado en 1977 (Rodríguez-Roda, 1977) y allí se ve claramente cómo los primeros acercamientos al funcionamiento de la pesquería se hacen desde la biología y con un enfoque básicamente descriptivo, mediante el análisis de patrones en pequeñas series temporales de capturas, relaciones talla-peso, talla-edad, donde la edad es estimada a partir de la lectura de escamas y patrones estacionales para la reproducción.

El ICES empieza a asesorar científicamente la pesquería en el año 1990 (ICES, 1990) y en sus informes se limita a presentar datos de capturas y esfuerzo pesquero junto con información sobre la biología de la anchoa, hasta 1995, cuando la pesquería sufre un colapso inexplicable sólo por las capturas ya que estas no habían sido notablemente altas en los años previos. El informe anual del ICES para ese año (ICES, 1996), después de mencionar la caída en las capturas de 3036 toneladas en 1994 a 571 toneladas en 1995, en el apartado de medidas recomendadas para la gestión se limita a decir que "Given the reduced knowledge of the biology and dynamic of this population, it is recommended that the precautionary total admisible catches (TAC) at the level of recent catches would be appropriate to avoid an increase in effort".

Sin embargo, más inexplicable resultó el gran aumento de las capturas en 1996 y 1997, con 1780 y 4600 toneladas, respectivamente. La pesca en 1997 se incrementó en un 258% respecto al año anterior registrando el valor más alto de capturas de los últimos 6 años (ICES, 1998). En este año, el comité científico del ICES afirma por primera vez que cree que la cuota total admisible (TAC) excede el potencial de captura sostenible y que el sistema de cuotas no parece adecuado para esta especie de vida corta, ya que las variaciones en la supervivencia de los primeros estadios vitales son causadas principalmente por factores ambientales.

Una situación similar se había observado en 1987 con la anchoa en el mar Adriático, donde se determinó que el tamaño de la población explotable cada año estaba determinada más por el reclutamiento durante los dos años precedentes, que por el esfuerzo pesquero (Cingolani et al., 1996). El reclutamiento según la FAO (Cochrane and Organització de les Nacions Unides per a l'Agricultura i l'Alimentació, 2005) es: "El número de peces (reclutas) agregados a la población explotable en el área de pesca, cada año, por medio del proceso de crecimiento (es decir, el pez crece hasta una talla a la cual se puede capturar)". La supervivencia de los reclutas está determinada por el proceso de crecimiento y todo lo que pueda entorpecer la supervivencia desde el huevo hasta el adulto. Para esta época ya había evidencias de que el medio ambiente afectaba severamente la supervivencia en estas primeras etapas vitales de la anchoa, tanto en el mar Adriático, como en el Mediterráneo (Caddy et al., 1995; Regner, 1996; Sabates, 1990), así que no era extraño que el comité científico del ICES atribuyese la situación extremadamente fluctuante de la anchoa en el golfo de Cádiz a procesos similares influenciados por los factores ambientales.

Estaba claro que el medio ambiente tenía un impacto relevante en pequeños pelágicos (Basilone et al., 2006; Guisande et al., 2004; Nakata et al., 2000), particularmente, la anchoa. Sin embargo es sólo hasta el 2006 cuando se establecen factores meteorológicos y oceanográficos que afectan las primeras etapas vitales de la anchoa en el golfo de Cádiz (Ruiz et al., 2006), identificándose la temperatura superficial del mar, la intensidad y duración de los vientos de levante (vientos que vienen del Este) y las descargas del río Guadalquivir como las variables medioambientales responsables de las fluctuaciones en el reclutamiento.

Una vez se conoce el efecto del medio ambiente, es preciso establecer un modelo matemático que permita decidir el nivel de captura que mantendrá la sostenibilidad del recurso en un momento futuro. En Ruiz et al. (2009) se presenta el primer modelo que integra dichas variables ambientales con el desarrollo de la anchoa en el golfo de Cádiz, un modelo bayesiano que utiliza una serie de datos de esfuerzo pesquero desde 1988 hasta 2004 con el objetivo de conocer las distribuciones de los parámetros relacionados con el medio ambiente. Este enfoque es apropiado para resolver la incertidumbre inherente en la dinámica de ecosistemas pesqueros (Ruiz and Kuikka, 2012) y ha sido ampliamente utilizado en la disciplina (Michielsens and McAllister, 2004; Millar and Meyer, 2000; Punt and Hilborn, 1997). Estos modelos toman las observaciones y el conocimiento previo sobre los parámetros para calcular una distribución de probabilidad para las estimaciones (Gelman et al., 2013), específicamente, en el ámbito pesquero, proporcionan estimaciones de abundancia consistentes con la dinámica del stock incluyendo la incertidumbre asociada al proceso.

El modelo del 2009 ha servido como evidencia de la influencia del medio ambiente en la abundancia del stock y es una referencia importante para entender el desarrollo vital de la anchoa. Sin embargo, este modelo no incorpora explícitamente la mortalidad por pesca, la distribución por tallas y el crecimiento. Además, la escala temporal mensual para los primeros meses de vida no logra incorporar adecuadamente la resolución temporal que gobierna las primeras fases del ciclo vital (frecuencia de puestas y el régimen meteorológico que condiciona la supervivencia). Por este motivo se desarrolla un nuevo modelo Bayesiano en el marco del proyecto europeo ECOKNOWS, basado en un modelo geneneral de dinámica de población (GPDM) desarrollado por Samu Mäntyniemi en la Universidad de Helsinki. Dicho modelo forma parte de esta tesis y ha sido aceptado para su publicación en el Canadian Journal of Fisheries and Aquatic Sciences, es un modelo con resolución temporal semanal para las primeras etapas vitales, y mensual para juveniles y adultos que incorpora la influencia del medio ambiente para etapas tempranas y una estructura de crecimiento que permite estimar la distribución mensual de tallas.

Este modelo, además, provee una distribución mensual de las capturas a partir de los parámetros estimados, lo que permite simular series temporales y comparar como se comportarían las capturas usando diferentes estrategias de pesca para diseñar una que sea óptima. Teniendo en cuenta que las fluctuaciones en esta pesquería dependen fuertemente del medio ambiente, una estrategia basada únicamente en la reducción del esfuerzo de pesca no sería suficiente, la pesquería estaría expuesta principalmente a dos tipos de riesgo (Hannesson et al., 1993). El primero, que ante condiciones medio ambientales óptimas la población se infraexplote generando ineficiencias económicas. El segundo, que ante unas condiciones medio ambientales especialmente adversas se sobreexplote y no se permita el reemplazo de la población para la siguiente temporada. Una estrategia que incorpore el efecto del medio ambiente podría ser la solución ya que permitiría reducir ambos tipos de riesgo. Sin embargo, esta afirmación que proviene naturalmente del conocimiento de la dinámica de la pesquería carece de una medida científicamente objetiva: ¿Cómo medir el riesgo asociado a esta estrategia?

El trabajo desarrollado en el capítulo 2, también en el marco del proyecto ECOKNOWS, permite responder a esta pregunta desde un enfoque inspirado en la gestión del sector agrícola. La pesquería de la anchoa y la agricultura resultan similares en cuanto a que presentan severas fluctuaciones en la cantidad del recurso causadas por numerosos factores biofísicos y ambientales que están por fuera del control humano. Sin embargo, el sector agrícola ha encontrado alternativas frente a la vulnerabilidad del recurso con el objetivo de disminuir su impacto socio-económico. Una de estas alternativas ha sido la de la contratación de seguros agrarios, que en España tienen aproximadamente unos 30 años de vigencia y que han demostrado ser un instrumento altamente eficaz en la gestión de riesgos. Actualmente no existe una figura similar para la pesca. En algunas pesquerías tales como la del salmón rojo en Alaska se ha analizado que su implementación sería inviable debido al poco conocimiento que se tiene de la dinámica de la población y la dificultad de seguimiento del riesgo moral asociado, donde los contratantes de la póliza cambian su producción para obtener pagos por parte de la aseguradora, entre otros (Greenberg et al., 2004). Sin embargo, aparte de la noción práctica de compensación de riesgo que tiene una póliza de seguro, a nivel teórico el precio de la prima que debe pagar el contratante es una medida del riesgo que la aseguradora está dispuesta a cubrir. De esta manera, la simulación de un esquema de seguros permite calcular la prima y el ingreso asociado a series de capturas que han sido simuladas siguiendo diferentes estrategias de manejo (Mumford et al., 2009). Así, en el capítulo 2 se compara una estrategia que tiene en cuenta el medio ambiente con otra que lo ignora en diversos escenarios usando un patrón de medida que facilita la comunicación de resultados a los gestores del recurso.

En contraposición a la pesquería de anchoa en el golfo de Cádiz que tiene un nivel de capturas anuales de entre 1780 y 8200 toneladas aproximadamente exceptuando el colapso del año 1995, se encuentra la pesquería del mar de Alborán que tiene un nivel de capturas anuales de entre 200 y 2000 toneladas, salvo en los años 2001 y 2002, donde hay una inexplicable abundancia y las capturas ascienden a 2900 y 4100 toneladas respectivamente.

Nuevamente, estas fluctuaciones inexplicables, han sido las que han permitido arrojar luz sobre las variables ambientales que afectan el ciclo de vida de la anchoa en esta particular zona geográfica. El mar de Alborán es la puerta de entrada de aguas provenientes del Atlántico hacia la cuenca del Mediterráneo y estas reemplazan aguas más salinas que van en sentido contrario hacia el Atlántico a gran profundidad. Este reemplazo se realiza gracias a una corriente de agua con dirección Este, denominada comúnmente en el argot científico como el "chorro atlántico", pasando por el Estrecho de Gibraltar. La energía persitente de esta corriente se distribuye en dos giros anticiclónicos cuya intensidad puede variar de acuerdo a la presión atmosférica y a la fuerza del viento. La circulación derivada de la potencia del chorro está asociada a un aumento en la producción primaria, que a su vez podría verse reflejada en un aumento en las capturas. Sin embargo, en el capítulo 3, se muestran claros indicios de que la disminución en la fuerza del chorro atlántico permite una mayor supervivencia de la anchoa en sus estadios más tempranos aumentando las probabilidades de un reclutamiento exitoso y en consecuencia un alto número de capturas.

La vinculación de la energía de la circulación y el reclutamiento en el mar de Alborán, ha sugerido un trabajo preliminar que se presenta en el capítulo 4. Allí se puede ver la aplicación de las redes bayesianas a la pesquería del mar de Alborán mediante un ejemplo sencillo donde se integran la energía cinética del sistema, el volumen de capturas y el ingreso percibido gracias a esas capturas. El enfoque de redes Bayesianas permite la explicitación de las relaciones causa-efecto, lo que resulta clave en un entorno donde el gestor necesita identificar los elementos del sistema sobre los que puede actuar (causas) y las consecuencias de estas actuaciones (efectos). Además, la comunicación de resultados a los gestores se facilita al incorporar el factor económico dentro del modelo.

Junto a estos dos stocks altamente influenciados por el medio ambiente, debido a la vulnerabilidad de la anchoa en sus primeras etapas vitales, en el capítulo 5, se presentan los resultados de un modelo Bayesiano para la merluza del Atlántico norte, una especie que es poco vulnerable a cambios medio ambientales pero cuya biología todavía no es completamente conocida, ya que el crecimiento de la especie aún no se ha determinado con exactitud. A principios de este siglo se demostró mediante el estudio de otolitos, que las tasas de crecimiento de la merluza duplicaban las estimadas previamente (de Pontual et al., 2003*a*; Depontual et al., 2006) y recientes estudios abordan dicho problema usando estimas a partir de la longitud de maduración (Cerviño, 2014). Los resultados presentados comparan escenarios donde se utiliza información de diversos stocks de merluza para estimar parámetros biológicos como la mortalidad natural, la tasa de crecimiento y el reclutamiento máximo, con otros donde estos parámetros se asumen constantes.

Estructura de la tesis			
	Anchoa golfo de Cádiz	Anchoa mar de Alborán	Merluza Atlántico Norte
Impactos biológicos y medio ambientales	Ruiz et al. (2006)	Capítulo 3	Casey and Pereiro (1995), de Pontual et al. (2013), Depontual et al. (2006), de Pontual et al. (2003*a*) entre otros
Modelado	Capítulo 1	Capítulo 4	Capítulo 5
Gestión	Capítulo 2	Capítulo 4	

Table 1: Estructura de la tesis

En resumen, esta tesis presenta una aproximación matemática a tres stocks diferentes, la anchoa en el golfo de Cádiz, la anchoa en el mar de Alborán y la merluza del atlántico Norte (Ver Tabla 1). Partiendo del conocimiento que se tiene sobre la biología de la especie y la influencia del medio ambiente sobre sus poblaciones. Además, tal y como se recomienda crecientemente en este ámbito de la ciencia (Harwood and Stokes, 2003) se incorpora el hecho de que todo este conocimiento tiene una incertidumbre asociada que debe ser cuantificada. Esta incertidumbre se cuantifica en la tesis mediante técnicas Bayesianas. Este enfoque permite asimilar múltiples fuentes de información, incluyendo datos incompletos e imprecisos debido a diferentes fuentes de error (Buckland et al., 2007) y permite cuantificar la incertidumbre procedente de la estocasticidad demográfica y meteorológica, y de los errores de observación suministrando una medida del error asociado a los parámetros estimados (Michielsens and McAllister, 2004). Esta flexibilidad hace de los modelos Bayesianos, una gran herramienta para asesorar pesquerías con una aproximación más realista a los procesos biológicos y ecológicos subyacentes (Kuparinen et al., 2012). En en el caso del golfo de Cádiz se propone también una herramienta de evaluación de diversas estrategias para la gestión del recurso teniendo en cuenta la importancia de la comunicación de los resultados científicos, en especial si se tiene en cuenta la necesidad que tiene el gestor de entender los resultados de los cuantiosos estudios que subvenciona la Unión Europea y el papel decisivo tanto del científico, como del gestor, en la consecusión de una pesca sostenible y económicamente rentable.

Objetivos

El principal objetivo de esta tesis es desarrollar herramientas que sean útiles para la mejor comprensión gestión de las pesquerías de anchoa en el golfo de Cádiz y el mar de Alborán, y de la merluza en el Atlántico Norte usando para ello la información biológica y ambiental disponible. Los objetivos específicos de cada capítulo son:

Capítulo 1

Desarrollar un modelo Bayesiano para la anchoa en el golfo de Cádiz que:

- Integre los cambios drásticos en el tamaño de la población causados por el medio ambiente durante las primeras etapas vitales
- Incluya crecimiento, distribución por tallas, mortalidad natural y mortalidad por pesca
- Genere resultados coherentes con las fuentes de información utilizadas y con datos independientes que no hayan tenido contacto con el modelo
- Permita simular series temporales de capturas como resultado de la integración del ciclo vital de la especie y del esfuerzo pesquero

Capítulo 2

- Desarrollar una estrategia de pesca que incluya el efecto del medio ambiente sobre las etapas vitales previas al reclutamiento (Environmental Harvest Control Rule, EHCR)
- Simular series temporales de capturas, unas usando la EHCR y otras manteniendo constante la mortalidad por pesca.

- Aplicar un esquema de póliza de seguros a las series temporales simuladas.
- Analizar la viabilidad de la aplicación del esquema actuarial midiendo los riesgos ambientales y económicos mediante la comparación de las probabilididades de colapso, el ingreso medio y la prima media anual.
- Comparar los resultados entre las simulaciones que utilizaron la EHCR y las que mantuvieron constante la mortalidad por pesca.

Capítulo 3

Analizar la influencia que tienen los patrones de circulación en el mar de Alborán en el ciclo de vida de la anchoa, incluyendo la energía cinética y modos de variabilidad conjunta entre la clorofila y la topografía de la superficie del océano relacionada con la dinámica de su propio flujo (Absolute Dynamic Topography, ADT).

Capítulo 4

Analizar la relación existente entre la energía cinética del sistema del mar de Alborán con las capturas y el ingreso que estas generan al sector usando redes Bayesianas

Capítulo 5

Desarrollar un modelo Bayesiano para la merluza del Atlántico Norte que:

- Integre información biológica proveniente del estudio de otros stocks de merluza usando *priors* informativas
- Incluya crecimiento, distribución por tallas, mortalidad natural y mortalidad por pesca, descartes, patrones de selección y retención de 7 y 3 flotas pesqueras, respectivamente y patrones de estimación de 4 flotas pesqueras.
- Genere distribuciones posteriores coherentes con los datos existentes
- Permita comparar los resultados del modelo para diferentes escenarios, sobre todo entre aquellos que incluyen información biológica a través de *priors* y aquellos que parten de *priors* no informativas.

CHAPTER

1

Embedding anchovy survival in the environment with a dual time resolution : A Bayesian state-space size-structured population dynamics model

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Abstract: Many studies underscore the importance of incorporating the effect of environmental data within a stage-specific frame in small pelagic fish. In the Gulf of Cádiz (NE Atlantic), intense easterlies, stratification of the water column and discharges from the Guadalquivir River have been identified as the main factors driving population dynamics of anchovy (*Engraulis encrasicolus*) during early life stages (Ruiz et al. (2006)). We have developed a new Bayesian model with weekly resolution for early life stages and monthly for juveniles and adults. This dual time step resolution is appropriate to resolve environmental effects on pre-recruits and anthropogenic effects like fishing on recruited fish. Our estimates for juvenile abundances are validated with in situ data. The model of growth provides consistent length frequency estimates and the Bayesian approach supplies the uncertainty measure, providing a plausible environmentally driven stock-recruitment relationship.

Key words: Bayesian statistics, Marine fisheries, Models, Population dynamics, Stock assessment.

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Introduction

The physical environment impacts fish stocks and landings (Erzini, 2005; Lloret et al., 2001), particularly for short-lived small pelagic species (Basilone et al., 2006; Guisande et al., 2004; Lindegren et al., 2013; Nakata et al., 2000). This effect is observed at different time-scales (Fréon et al., 2005). Short-term synoptic events affect mostly the early life stages engendering recruitment failures which are thought to drive inter annual fluctuations of catches more than variations in fishing effort (Cingolani et al., 1996; Dimmlich et al., 2004). Variability and instability characterize the dynamics of small pelagics (Fréon et al., 2005). Their position in the food web and the prominent role of recruitment in the population dynamics partly explain the aforementioned dynamics. The inclusion of environmental drivers in predictive recruitment models for these (and other) species has been advocated in the past and is increasing (Barange, 2001; Durant et al., 2013), but their adoption in management is not too frequent (Fréon et al., 2005, 2009).

Intense easterlies, stratification of the water column and the influence of the Guadalquivir river have been identified as the main environmental factors influencing anchovy (*Engraulis encrasicolus*) early life stages (Ruiz et al., 2006) in the Gulf of Cádiz. The synoptic time-scales of these forcings and the nature of the spawning process suggest that eggs and larvae abundances can change drastically within a timescale of days (Catalán et al., 2006). Since many environmental data bases provide one-week composites, both the natural scale of the process and the availability of data suggest that it is sensible to model these early stages under a weekly resolution.

However, in small pelagics fishing mortality may become a dominant element of the population dynamics after recruitment (Lindegren et al., 2013; Pinsky et al., 2011). Fisheries data are frequently aggregated into monthly statistics at the publicly available databases. Thus, the availability of landing or catch per unit effort (CPUE) data and the decreased sensitivity of fish individuals to short-term synoptic-events suggests that it is sensible to model post-recruit processes with a time resolution longer than a week. The change of time-scale for the natural processes governing the dynamics of clupeoids during ontogenetic development poses significant challenges for modelling purposes. Restricting the whole model to a resolution only suitable for post-recruits (e.g. monthly) would result in a model that misses the impact of oceanographic synoptic events on the recruitment (Ruiz et al., 2009). A trivial option would be to select the maximum resolution (e.g. weekly) for the whole life cycle. However, this might render the model numerically intractable owing to the large number of time steps involved. A double resolution model, with shorter time steps for earlier stages, offers a compromise between the need to resolve the synoptic scales that force eggs and larvae while keeping tractable the numerical burden.

A double resolution model should be able to encompass the change of time-scale inherent to the ontogenic development. However, the suitability of such a model does not imply the ability to resolve the intrinsic uncertainty that characterizes ecosystem dynamics. This uncertainty demands an approach based on probabilistic rather than deterministic grounds (Ruiz and Kuikka, 2012). In fishery research, state-space models coupled with Bayesian Markov chain Monte Carlo (MCMC) methods provide estimates for abundance while measuring the uncertainty pervasive in all the life-cycle. State-space models separates the problem into two stochastic models (Meyer and Millar, 1999; Rivot et al., 2004). The first one, the process model, accounts for the unobservable stochastic variations that govern the internal population dynamics. The second one, the observation model, describes how the population state is observed and with what uncertainty. The linking of these two stochastic models provides consistent simulation of stock-dynamics and computes uncertainty as a natural output (Millar and Meyer, 2000; Punt and Hilborn, 1997).

We describe in this paper the implementation of a state-space size-structured population dynamics model for anchovy in the Gulf of Cádiz. It assumes that the environment affects early stages of the life cycle at different time-scales and includes a von-Bertalanffy growth process providing consistent recruitment and length frequency estimates. The first section is devoted to the description of the conceptual framework necessary to accommodate a double resolution environmentally forced formulation into the general population dynamics model (GPDM) developed in the ECOKNOWS project by Samu Mäntyniemi. The second section describes the model outputs and the third presents a discussion regarding the validation of our hypothesis and the effectiveness of the tool proposed.

Bayesian state-space size-structured population dynamics model

The process model has two modules in order to integrate both the environmentally forced recruitment and the size-structured stock dynamics. The first one is implemented here for the environmental conditions in the Gulf of Cádiz but could be extended to other small pelagic whose recruitment is mainly forced by the environment at the earliest life stages. The second one describes mainly growth and mortality processes. The observation model is defined with data from catch in numbers, CPUE and acoustic surveys. The notation for data and model parameters is summarized in Table 1.

Process model

Ruiz et al. (2009) created a first Bayesian model for the effect of the environmental covariates (discharges from Guadalquivir River, sea surface temperature and intense easterlies) on the anchovy population at the Gulf of Cádiz. They provided there solid evidence of the tight control exerted by the environment on the fraction of the population between 0 (eggs) and 6 months old. Nevertheless, they also showed the difficulties associated to the time resolution of the model when simulating egg and larvae abundances. It was evident in that exercise that monthly time steps were not enough to fully resolve the environmental influence on these early stages. In order to overcome this mismatch between the time step of the model and the time scale of early-stage processes, we describe below a weekly resolution model for anchovy eggs and larvae in the Gulf of Cádiz. The model includes the impact of the environment on these early stages and it is designed to be embedded in a general population dynamics model that runs under longer time steps.

Environmentally forced recruitment

According to the anchovy spawning dynamics described in Motos et al. (1996) and García and Palomera (1996), it is reasonable to consider that the production of anchovy eggs in the Gulf of Cádiz occurs when there is a sea surface temperature increase of at least one degree between consecutive months and it is above $16°C$ (Ruiz et al., 2006, 2009). To resolve the weekly heating triggering of egg production we assume that it occurs when there is an increment of at least a quarter degree in a week, thus consistent with the proposal of a degree per month in Ruiz et al. (2009). Empirical data from other areas suggest that females may spawn on average each three days under suitable temperature conditions (Somarakis et al., 2004). After spawning, strong currents created by easterlies can advect eggs and larvae away from favorable conditions (Catalán et al., 2006). Hence, the number of individuals that survive is negatively influenced by the occurrence of easterlies during the following two months after spawning. After these two months individuals have better capacity to control their position in the water and are less vulnerable to currents.

Indexes	
k and l	Size class, $k, l = 1, \ldots, 6$
t	Month, $t = 1, \ldots, 222$
j	Week, $j = 1, \ldots, 4$
i	Age, only specified for individuals between 3 and 5 months old
Data	
T_t^j	Sea surface temperature during week j in month t ($^{\circ}C$)
W_t^j	Number of days that strong easterlies have blown during week j in month t
D_t	Discharges from Alcalá del Río dam at month t (Hm^3)
$CPUE_t$	Catch per unit effort at month t ($Tons/fishing$ trip)
A_t	Acoustic estimates in numbers of the stock size at time t
c_t	Catch in numbers at month t in the Gulf of Cádiz
Parameters	
λ	Parameter for the effect of easterlies
ρ	Parameter for the effect of discharges
Q	Monthly Catchability (*fish caught per effort unit*)
$Linf$	Expected size of large individuals (cm)
$sdLinf$	Standard deviation for the size of large individuals (cm)
g	Monthly somatic growth rate
F	Monthly fishing mortality
M	Monthly natural mortality
N^*	Initial population
σ_A	Standard deviation for acoustic surveys
l_1	Size composition by length of fishes at the beginning of the first time step
Fixed Parameters	
$minLinf$ and $maxLinf$	Bounds for $Linf$ in cm (see Table 2)
$minsdLinf$ and $maxsdLinf$	Bounds for $sdLinf$ in cm (see Table 2)
$ming$ and $maxg$	Bounds for the expected somatic growth rate (see Table 2)
w_k	Weight (g) for a fish in size class k, ($a = 0.0029, b = 3.3438$)
fec	Number of eggs per gram spawned by a female $fec = 450$ *eggs* g^{-1}
$sexr$	Proportion of females in the population, $sexr = 0.5$
mat_k	Maturity at length k. If fish in size class k is mature ($> 11.2cm$) is equal to 1, or, 0 otherwise
Others	
$B_t(i)$	Number of anchovies between i and $i + 1$ months old at time t
N_t	Population in the stock at month t
R_t	Recruits at month t
d_t	Death fishes at month t
p_t	Proportion of the population that survives to the next month $t{+}1$
q_t	Proportion of caught fish from dead fish at month t

Table 1. List of symbols used in the model specification

The model resolves spawning triggering by sea surface temperature and egg/larvae survival depending on easterlies through weekly time steps running during two months (see equation (1) below). Monthly time steps seem enough to resolve the dynamics of anchovy from juveniles stages onward (Ruiz et al., 2009) and that is the resolution the model implements for these stages. This implies to move the resolution from weekly towards monthly time steps as the ontogeny moves anchovy individuals from eggs/larvae towards juveniles/recruits stages. This coupling between two different time resolutions is achieved by making the eggs produced in the first, second, third and fourth week to become first juveniles at the 9th, 10th, 11th and 12th week, respectively. Consequently, $B_t(2)$, defined as the number of individuals that are two months old in month t (first juveniles), is modelled following a truncated normal distribution using data from weekly sea surface temperature at the times of spawning (9, 10, 11 or 12 weeks before) and weekly effect of easterlies in the preceding 2 months, as follows:

$$B_t(2) \sim N(\overline{B_t(2)}, 200000)\mathbf{I}\{B_t(2) \geq 0\}$$

where $\mathbf{I}$ denotes an indicator variable and $\overline{B_t(2)}$ is defined as follows:

$$\overline{B_t(2)} = Eggs_{t-3}(\mathcal{M}_t^1 + \mathcal{M}_t^2 + \mathcal{M}_t^3 + \mathcal{M}_t^4), \tag{1}$$

where

$$\mathcal{M}_t^1 = \begin{cases} e^{-\lambda(W_{t-1}^4 + \cdots + W_{t-1}^1 + W_{t-2}^4 + \cdots + W_{t-2}^1)} & \text{if } T_{t-2}^1 > 16, T_{t-2}^1 - T_{t-3}^4 > 0.25 \\ 0 & otherwise \end{cases},$$

$$\mathcal{M}_t^2 = \begin{cases} e^{-\lambda(W_t^1 + W_{t-1}^4 + \cdots + W_{t-1}^1 + W_{t-2}^4 + \cdots + W_{t-2}^2)} & \text{if } T_{t-2}^2 > 16, T_{t-2}^2 - T_{t-2}^1 > 0.25 \\ 0 & otherwise \end{cases},$$

$$\mathcal{M}_t^3 = \begin{cases} e^{-\lambda(W_t^2 + W_t^1 + W_{t-1}^4 + \cdots + W_{t-1}^1 + W_{t-2}^4 + W_{t-2}^3)} & \text{if } T_{t-2}^3 > 16, T_{t-2}^3 - T_{t-2}^2 > 0.25 \\ 0 & otherwise \end{cases},$$

and

$$\mathcal{M}_t^4 = \begin{cases} e^{-\lambda(W_t^3 + W_t^2 + W_t^1 + W_{t-1}^4 + \cdots + W_{t-1}^1 + W_{t-2}^4)} & \text{if } T_{t-2}^4 > 16, T_{t-2}^4 - T_{t-2}^3 > 0.25 \\ 0 & otherwise \end{cases}$$

For T_t^j and W_t^j the temperature and the number of days that strong easterlies ($> 30 \quad kmh^{-1}$) have blown respectively, during week j in the $t-th$ month. Parameter λ accounts for the effect of strong winds and $Eggs_{t-3}$ is the number of eggs at time $t-3$ relative to the population size at the first time step (N^*), whose calculation will be explained in the second part of the model. It means that the real number of eggs is calculated as $Eggs_{t-3} * N^*$ and the corresponding real variance is $200000(N^*)^2$. This variance is large enough to avoid any constrain on parameters while the Gibbs sampling is exploring their space. Note that $\mathcal{M}_t^j$ corresponds to the assumption of birth in the j-th week of month $t-2$.

Freshwater regulation in the dam of Alcalá del Río has a significant impact on the survival of juveniles at their second (3-4 months old), third (4-5 months old) and fourth (5-6 months old) stages (Ruiz et al., 2009). The lack of discharge, D_t, implies low fertilization, and excessive discharges urge the individuals to leave the estuary and a loss of the protection it provides. The concentration of anchovy as a function of discharges can be enveloped by the standardized normal density function as $\phi(ln(D_t) - 4.6052)$ taking the maximum value when $D_t = 100Hm^3$ (Ruiz et al., 2009), consequently, the model for second, third and fourth juvenile (3, 4 and 5 months old, respectively) stages at time $t+1, t+2$ and $t+3$, respectively $B_{t+1}(3), B_{t+2}(4)$ and $B_{t+3}(5)$ is formulated as:

$$B_{t+i-2}(i) \sim N(\overline{B_{t+i-2}(i)}, 2000)\mathbf{I}\{0 \leq B_{t+i-2}(i) \leq B_{t+i-3}(i-1)\} \quad i = 3,4,5$$

with

$$\overline{B_{t+i-2}(i)} = B_{t+i-3}(i-1)\rho\phi(ln(D_t) - 4.6052)) \tag{2}$$

$$i = 3,4,5$$

Where parameter ρ is associated to monthly discharges D_t. The variance chosen (2000) is large enough to not constrain the model in the look for appropriate parameter values while keeping population within sensible limits.

The number of individuals in age group $5, B_{t+3}(5)$ represents the recruits at month $t+3$. Therefore, $B_t(5)$ acts as the link between the environmental forcing of anchovy life stages as modelled in Ruiz et al. 2009 and the dynamics of the stock as modelled in GPDM, where the change in total population size equation is defined as:

$$N_{t+1} \approx p_t N_t + R_{t+1} = p_t N_t + B_{t+1}(5) \tag{3}$$

Where p_t is the expected survival after growth at time t, R_{t+1} is the number of recruits at time $t+1$ and N_t is the stock population size relative to the population size in the beginning of the first time step, N^*, i.e. $N_1 = 1$ and absolute population size is calculated as $N_t N^*$.

Size-structured stock dynamics

Population in the stock (10-22 cm) was assumed to be gathered in 6 length intervals of 2 cms each, $\mathcal{I}_k = [I_k, I_{k+1})$, $k = 1, \ldots, 6$, where I_k and I_{k+1} are the size class limits.

Spawning

As an approximation of the three days spawning frequency, the female population is assumed to spawn once each week if suitable conditions hold. They are supposed to produce a number of eggs computed with the following dot product:

$$Eggs_t = (\mathbf{l}_t \cdot N_t\mathbf{e})$$

Where $\mathbf{l}_t$ and $\mathbf{e}$ are column vectors with six components. The first, denoting the size class frequencies after recruitment, allocating the relative population N_t in the 6 length intervals defined above. The second is the number of eggs per gram spawned by a mature female in each length class. Each component of vector $\mathbf{e}$ is calculated as the product of the fixed parameters: $fec, mat_k, sexr$ and w_k, defined in Table 1. Note that this number of eggs only becomes effective if spawning conditions settled in equation (1) are satisfied.

Growth

Growth of individuals is assumed to take place instantly at the beginning of each month. The length at time t of individuals, which at time $t-1$ were in length class k, L_k, is assumed normally distributed with expected value, μ_{L_k}, and standard deviation, σ_{L_k}, calculated as follows:

$$\mu_{L_k} = Linf(1 - e^{-g}) + \frac{I_{k+1} - I_k}{2} e^{-g}, \tag{4}$$

and

$$\sigma_{L_k} = sdLinf * \sqrt{1 - e^{-g*2}} \tag{5}$$

Where $Linf$ and $sdLinf$ are the asymptotic expected value and standard deviation, respec- tively, for the length distribution of large individuals and g is somatic growth rate. The mean value of L_k is an application of von Bertalanffy growth equation (Quinn and Deriso, 1998) starting from $\frac{I_{k+1}-I_k}{2}$ whereas standard deviation is also motivated by this equation but requires additional calculation and it is detailed in the appendix.

Each individual has the possibility to stay in the same length class or move to larger classes. This transfer is modelled through a transition matrix $\mathbf{G} = (g_{k,l})_{6\times6}$, where $g_{k,l}$ denotes the probability that an individual in class $\mathcal{I}_k$ growths enough in a month to move to class $\mathcal{I}_l$ and it is calculated as:

$$g_{k,l} = \frac{P[I_l < L_k < I_{l+1}]}{P[I_1 < L_k < I_7]}.$$

After growth, column vector $\mathbf{l}_t$ becomes $\mathbf{l}_t^{(\mathbf{G})} = (\mathbf{l}_t^T \mathbf{G})^T$ describing a modified size distribution of the population.

Length distribution

Once growth process occurs, fishing and natural mortality modifies this distribution. Then the length distribution of surviving fishes, $\mathbf{l}_t^{(S)}$, is computed as $p_t \mathbf{l}_t^{(\mathbf{G})}$. Where p_t is the expected survival after growth as defined in equation (3).

Accordingly, the length distribution in the next time step will be defined as the weighted sum of the known length distribution of recruits (between 10 and 12 cm) and the length distribution of surviving fishes, as follows:

$$\mathbf{l}_{t+1} = (1 - \frac{R_{t+1}}{N_{t+1}})\mathbf{l}_t^{(S)} + \frac{R_{t+1}}{N_{t+1}} * (1,0,0,0,0,0)^T.$$

Mortality and survival

A fish in length class k after growth has three possibilities, to die naturally, being caught or to survive (ρ_t, γ_t and p_t respectively), with respective probabilities given by Baranov (Baranov, 1976; Quinn and Deriso, 1998) as follows:

$$\begin{aligned}
\rho_t &= \frac{M}{F+M}(1-e^{-(F+M)})\sum_{k=1}^{6}\phi_{t,k}^{(G)} && (6)\\
\gamma_t &= \frac{F}{F+M}(1-e^{-(F+M)})\sum_{k=1}^{6}\phi_{t,k}^{(G)} && (7)\\
p_t &= e^{-(F+M)}\sum_{k=1}^{6}\phi_{t,k}^{(G)} && (8)
\end{aligned}$$

With F and M denoting fishing and natural mortality, respectively. Then the proportion of caught fish from all dead fish, considering that $\sum_{k=1}^{6}\phi_{t,k}^{(G)} = 1$, is computed as

$$q_t = \frac{\gamma_t}{1-p_t} = \frac{F}{F+M}.$$

The number of surviving anchovies at time t determined by the probability p_t given in equation (8), together with the environmentally forced recruits at time $t+1$ computed in the first part constitute the population available in the stock for time $t+1$ (equation (3)). This remaining population will spawn, grow and die again.

Observation model

Catch in numbers

Anchovy catches at time t, c_t, are assumed to follow a beta-binomial distribution, as follows:

$$c_t|q_t, d_t \sim Betabin(q_t, 1-q_t, d_t) \quad t = 1, \ldots, 222. \tag{9}$$

Where q_t, as defined above, is the probability of being captured once the anchovy is dead and $d_t \approx N_t(1-p_t)$ represents all dead fishes (by natural and fishing mortality) at time t. This choice corresponds to an overdispersed alternative to binomial distribution (Gelman et al., 2013). A binomial distribution is too restrictive considering the schooling and clustering behavior (Mäntyniemi and Romakkaniemi, 2002) of anchovy and a beta-binomial distribution reflects the fact that all individuals do not have the same probability of being captured. Note that the expected value of the distribution ($q_t d_t$) corresponds to Baranov's catch equation.

CPUE

The Catch per Unit Effort at time $t, CPUE_t$ is applied only for the spawning times i.e when the mean sea surface temperature of the month is bigger than $16°C$ and it has increased at least $1°C$ compared with the mean temperature of the last month. As extensively discussed in Ruiz et al. (2009), this value is reported yearly but most of the signal is produced during the spawning period. The correct use of CPUE data into a Bayesian model under these circumstances is the implementation of a fixed value for each year that only operates during the spawning period (Ruiz et al., 2009). $CPUE_t$ is normally distributed with mean proportional to the stock size at time t, N_t, and a very high variance reflecting a vague knowledge about this variable, as follows:

$$CPUE_t|Q, N_t \sim N(QN_t, 10^5) \tag{10}$$

Where Q, is the catchability coefficient. Compared to previous formulations (Ruiz et al., 2009), and owing to the large variance selected as well as the intimate connection that equation (9) defines between landings and N_t, it is expected that $CPUE$ has a lesser role (in favor of landings) to connect fishery information with the model. As an example, the connection in equation (9) is implemented 222 times (number of months) in the whole model while the $CPUE$ is only implemented a total of 63 times.

Acoustic surveys

Estimations of the population through acoustic surveys are available for two specific months: June 1993 and 2004, as in Ruiz et al. (2009). These acoustic data for stock size, $A_t, t = 71, 215,$ provide absolute abundance estimates. They are assumed lognormally distributed with unknown variance, as follows:

$$A_t|N_t, \sigma_A \sim LN(ln(N_t), \sigma_A^2) \quad t = 71, 215.$$

T are the only contact of the model with non-fishery estimates of stock size. We decided to let variance as a non-fixed parameter to be determined a posteriori by the Gibbs sampling. This implies an additional numerical burden to the exercise, but not excessive owing to the low number of estimates and justified given the important role of this non-fishery source of data.

Directed Acyclic Graph, DAG

Figure 1 shows the Directed Acyclic Graph (DAG) for the model. The DAG represents random quantities as elliptical nodes connected by arrows that indicates conditional dependencies. Data are introduced as rectangles and the arrows could be dotted or solid lines corresponding to logical and stochastical dependencies, respectively. If parameter A follows a distribution dependent on parameter B, there is a solid arrow pointing from B to A. If parameter A is a function of parameter B, there is a dotted arrow pointing from B to A (Meyer and Millar, 1999). For example in Figure 1 the relationship of Catches, c_t with dead individuals, d_t, and the total probability of being caught, q_t, is detailed in equation (9).

Priors

After extensive literature search on parameters values for this particular species and area, the data was filtered, preprocessed and interpreted in terms of reliability by expert knowledge. This reliability determines the informativeness of the prior distributions (Table 2). When reliability on previous information was considered low, uniform or large variance distributions were thus selected. In general, the use of the lognormal distribution was considered adequate for informative priors given the underlying processes of variability and the scarcity of data. The source of information to derive biological and exploitation-related data was based on anchovy stocks from European waters, and expert-knowledge on those stocks. For some parameters (e.g. ρ) the PDF was modelled coherently with previous work, whereas for others, such as natural and fishing mortality (F and M), no reliable information was available for the area, hence selected information from similar stocks was used.

Identical monthly distributions for F were chosen based on the assumption of a mean annual F of 1.1 corresponding to age^{-1} fish in the close-by Alboran Sea stock (Giráldez et al., 2009). The Alboran Sea stock is the most genetically similar to the Gulf of Cádiz stock (Zarraonaindia et al., 2012). Further, age 1 is the reference age in ICES division IXa (ICES, 2012) and also depicts well the average age composition of most close-by stocks (Pertierra and Lleonart, 1996). A large standard deviation was supplied, so that maximum accumulated (annual) F values might reach the maximum F values reported in the literature for the aforementioned stocks (around $F = 2$). The prior distribution was constrained at the lower end to 0.05, which corresponds to aprox 50% of the selected average F value for age 1. The PDF for M, for which even less data exist, was based on the age-specific M estimates for age 1 of anchovy in the near Alboran Sea (Giráldez et al., 2009), following the same reasoning as before. Those authors estimated M following the ProdBiom method (Abella et al., 1997) based on Caddy (1991). The large variance given to M was bounded in the upper part to 0.08, which would yield theoretical annual mortality rates close to $M = 1$, which is 15% higher than the M value for age-0 anchovy reported from 5 years of surveys of an unfished anchovy stock (Gulf of Biscay,(ICES, 2010)).

The bounds for growth parameters $Linf$, $sdLinf$ and g (Logitnorm function) were constructed based on a single work performed in the Gulf of Cádiz (Table 2) in which biological data were collected fortnightly for 4 years in individuals from 4 cm to maximum length. $Linf$ and g extremes were estimated directly from that series, whereas bounds for $sdLinf$ can be considered uninformative and embrace the mean of the standard deviation of $Linf$ also approximated from that series.

Lower bound for λ was chosen considering the negative effect of winds on recruitment (Ruiz et al., 2006) while the upper bound was chosen based on preliminary analysis where, without fishing, average environmental conditions (as determined by combinations of λ and ρ) allow a replacement rate of at least one recruit per female. This assumption prevents collapse in the absence of fishing and adverse environmental conditions.

Deterministic values of the model were taken from the literature through agreed (by two) expert's knowledge, following the assumption that if data were not available from the same stock, they should be taken from the closest (genetically and geographically) stock under a similar exploitation pattern. From data of the Gulf of Cádiz systematically sampled during 4 years (Millán, 1999), we extracted constant parameter values including a 1/1 sex-ratio ($sexr = 0.5$), an average length of maturity equal to 11.2 cm (for females) to define maturity at length class k, mat_k (See Table 1) , and $a = 0.0029$ and $b = 3.3438$ for the power length-weight relationship, $w_k = a(\frac{I_{k+1} - I_k}{2})^b$. The number of eggs spawned per gram $fec = 450\ eggs\ g^{-1}$ was approximated from a review on spawning traits of 22 anchovy stocks in European waters (Somarakis et al., 2004).

Parameters	Form of the prior	Source
λ	$\sim Unif(0,1)$	
ρ	$\sim N(0.1, 0.1)$	Ruiz et al. (2009)
σ_A^{-1}	$\sim Gamma(0.001, 0.001)$	
$ln(F)$	$\sim N(ln(0.09), 0.04)\mathbf{I}\{F > 0.05\}$	Giráldez et al. (2009)
$ln(M)$	$\sim N(ln(0.035), 0.05)\mathbf{I}\{M < 0.08\}$	Giráldez et al. (2009)
N^*	$\sim N(ln(1), 10000)$	
$pLinf$	$\sim Logitnorm(0,1)$	
$maxLinf = 20$		Bellido et al. (2000)
$minLinf = 18$		Bellido et al. (2000)
pg	$\sim Logitnorm(0,1)$	
$maxg = 0.08$		Bellido et al. (2000)
$ming = 0.05$		Bellido et al. (2000)
$psdLinf$	$\sim Logitnorm(0,1)$	
$maxsdLinf = 3$		
$minsdLinf = 0.1$		
$ln(Q)$	$\sim N(ln(2000000), 500)$	
$\mathbf{l}_1$	$\sim Dirich([1/1, 2/2, \ldots, K/K])$	

Table 2. Prior probability density functions (PDFs) of the parameters. $pLinf$ is such that $Linf = minLinf + (maxLinf - minLinf)pLinf$, and analogically pg and $psdLinf$.

Data

Observation model is defined using quarterly *catch in numbers* data and yearly *CPUE* from January 1988 to December 2004 extracted from ICES reports. Monthly *Catch in numbers* data results from the assumption that the same amount of fish is landed every month of the quarter. *CPUE* data was transformed to monthly data based on the knowledge that most of anchovy landings comes from the spawning season. Thus, it was assumed that CPUE is only known for spawning months and equal to the CPUE in the respective year. Acoustic estimates were provided by ICES (ICES, 2006) for the June of years 1993 and 2004. *Length frequency of the catches* for the same years from ICES annual reports was used for validation.

Transformation of monthly to weekly data requires assuming months of 28 days, 13 months per year, approximately. Then the 204 months from January 1988 to December 2004 become 222 months ($T = 222$).

The environmental covariates, sea surface temperature (SST), discharges from the Alcalá del Río dam and wind, were obtained as follows: SST was extracted from the Advanced Very High Resolution Radiometer (AVHRR) sensor data. The nighttime AVHRR PATHFINDER SST v5 weekly means with $4 \times 4 \quad km^2$ pixel resolution were taken from NASA PO.DAAC website (http://podaac.jpl.nasa.gov/). The interest region was acquired from the global image and arithmetic means were calculated based on all pixels within this region. Discharges were provided by Confederación Hidrográfica del Guadalquivir. They correspond to the monthly accumulated cubic hectometers that are discharged from the dam each month. Wind data are the weekly accumulated time (in days) that easterlies faster than 30 $\quad kmh^{-1}$ have been recorded in the meteorological station of Cádiz.

Implementation and posterior analysis

The model has been run in the Centre of Supercomputing of Galicia (CESGA) using the SVG cluster with an AMD Opteron and AMD Bulldozer Processors. The software used was R 2.14.1 (R Development Core Team, 2011) and JAGS 3.3.0 (Just Another Gibbs Sampler) (Plummer, 2013). The code is written in R linking with the MCMC sampler through the package rjags (Plummer, 2012). It spent 488.5 hours for 170000 iterations of two chains running in different cores. The first 10000 iterations were for adaptation without thinning and then a thinning of 100 was applied. After a burn-in period of 80000, potential scale reduction factors (Gelman et al., 2013) and Heidelberg and Welch convergence diagnostic (Heidelberger and Welch, 1981, 1983) were calculated for all monitored parameters using the coda package (Plummer et al., 2006). Potential scale reduction factor remain below 1.1 for all of them. Heilderberg and Welch tests were passed for the second chain of all parameters while the first chain failed for parameter λ. Considering that these tests are designed for single chains, random samples from the second chain were used for results as samples from the target distribution.

We use the Kullback-Liebler (KL) divergence (Kullback and Leibler, 1951) as a measure of statistical distance between the distributions obtained. The KL divergence measure the loss of information when the predicted distribution is used instead of the real. It is also considered as a basis for valid inference in ecological bayesian approaches (Burnham and Anderson, 2001). It was calculated using KLdiv function from the R package flexmix (Grün and Leisch, 2008). In order to compare estimated and observed time series for the observation model, the square root of the expected value of the quadratic loss i.e. root mean squared error (RMSE) was calculated. Standardization was necessary to compare the mean square error (MSE) between model outputs and *in situ* data for juveniles since they express juvenile abundance in different scales.

Results

Posterior distributions and joint posterior of the parameters are displayed in Figures 2 and S1, respectively. Posterior for initial population N^* is coherent with the initial modelled population in Ruiz et al. (2009) where an uninformative prior was also implemented. The annual fishing mortality is lower than annual natural mortality in coherence with the restrictions set to the priors. Parameters as $Linf$, and growth rate g for von Berttalanfy growth model remains in the limits established by the priors following Bellido et al. (2000). Easterlies parameter, λ, had a slow convergence process (not shown) but the iterations mode is in a range between 0.8 and 1, and the discharges parameter ρ remains in low values with 0.005 as the mode of the distribution.

In coherence with Ruiz et al. (2009) mortality was assumed constant in Baranov's catch equation (The expected value of c_t in equation (9)). This is equivalent to consider catches proportional to abundance. Figure 3b reflects this assumption showing a consistent evolution of catches compared to modelled stock population size. In Figure 3a a temporary decay in the modelled recruitment time series from 1992 to 1995 is observed together with a sudden recovery in the next year.

A detailed representation of the juvenile population is presented in Figure 4 to asses the performance of the higher temporal resolution for the first life stages. The dual time resolution results in a consistent relation between the model output for juvenile population ($B_t(3) + B_t(4), t = 1, \ldots, T$) and *in situ* data (Drake et al., 2007). There are also some misestimates, the most remarkable in year 2003 where the model estimates that there is a considerable amount of juveniles at the beginning of the year and few at the end when *in situ* data reflect the opposite. See table 4 for a detailed analysis.

An additional contrast of the output vs data not used in the model formulation or parametrization comes from the length structure of the population. The growth module, included through the matrix $\mathbf{G}$, allows to simulate the length frequency in the stock for each month ($\mathbf{l}_t$). The KL divergence between modelled and ICES data was smaller than 2 in the 81.08% of the months considered (Figure 5), showing that a von Berttalanfy-based matrix could model the length frequency of the population without a significant loss of information in many cases. A lower KL divergence was obtained in the last years where the sensitivity to initial values is reduced. Main differences are in the two first length classes as could be seen in the comparison between modelled and observed length distributions for each month in Figure S2. Length distributions reported by ICES are between the $5th$ and $95th$ percentiles of estimated distributions for first and second length class in the 66% and 67% of all the 222 months compared with 85, 84, 96 and 99% for the other length classes.

Discussion

Bayesian models have proven their value to assess the underlying stock-recruitment relationship of exploited species as well as the errors and uncertainties associated to this assessment (Dorn, 2002; Michielsens and McAllister, 2004; Mäntyniemi and Romakkaniemi, 2002). In many stocks and particularly in small pelagic fish, the sensitivity of recruitment to the environment impedes the use of traditional relationships (e.g. Ricker or Beverton Holt) as the unique driver of small pelagic populations (Erzini, 2005; Fréon et al., 2005). However, attempts to include the environment into Bayesian models of recruitment (Ruiz et al., 2009) are hampered by the short time-scale response of early-stages to this forcing.

The dual time resolution implemented in this work overcomes this handicap. The approach is able to integrate within the same model the traditional formulations and parameters of fishery management (e.g. von Bertalanffy, Baranov, $M, F, \ldots$) with the most advanced tools in oceanographic research (e.g. remote sensing) and to perform this merging in a consistent manner with existing observables (e.g. CPUE, landing or acoustic data).

The proposed dual time resolution does not bear a significant numerical burden to the computational effort demanded by a model fully formulated under monthly resolution. The (weekly) forcing of early stages is implicitly resolved through the $\mathcal{M}_t^j$ terms (equation (1)) and the whole MCMC sampling is resolved at monthly time steps. The computational time required by a monthly-resolved model is already very high (above 488 hours in our case, see also Ruiz et al. (2009)), which renders intractable the numerical burden necessary to approach convergence if this were to be formulated with weekly time-steps.

Even though the additional numerical burden of implicitly resolving weekly time scales for early stages is negligible, its incorporation results in a better coherence between modelled and observed abundances. Figure 4 of this paper, in contrast to Figure 7 of Ruiz et al. (2009), illustrates this for the seasonal variations and inter-annual tendencies of juveniles in the Gulf of Cádiz. This improvement is evident if we assess the performance of Ruiz et al. (2009) versus the present model as shown in Tables 3 and 4. These tables synthesize deviations between model outputs and all available data. These data includes those that are incorporated in the modeling exercise (catch, CPUE and acoustics) as well those that are not (juveniles). Table 4 analyzes the capacity of the models to reproduce the seasonal evolution of the juveniles. The dual-resolution performs better than the monthly model to estimate juveniles abundance in five out of the eight years. In addition, the difference between CPUE residuals for both models is very small, what can be thought as an improvement of the current model compared with the former, considering that CPUE is the main source of data of the model in Ruiz et al. (2009) and the high variance defined in equation (10). Another enhancement is the possibility to calculate catches as a model output, the small RMSE between observed and estimated catches (6 million corresponding to 4.54 % of the maximum value of observed catches) is a preliminary condition to construct a forecast model for management purposes.

	Current model	Model from Ruiz et al.(2009)	Difference
Catches (million)	6.1865		
CPUE (tons/fishing trip)	0.2752	0.2734	0.0018
Ac. 1993 (million)	199.3359	185.3100	14.0259
Ac. 2004 (million)	171.5417	180.7900	-9.2483

Table 3. Interannual performance of dual-time versus monthly resolution models. The table shows the RMSE between monthly means of estimations and observations. The model of Ruiz et al. (2009) did not estimate catches. Maximum and minimum values for observed catches are 0 and 136 million, respectively, while maximum and minimum values for observed CPUE are 0.138 and 1.148 tons/fishing trip, respectively.

	Current model	Model from Ruiz et al.(2009)	Difference
1997	1.2001	1.9435	-0.7433
1998	1.5529	1.2814	0.2715
1999	1.3627	1.5284	-0.1657
2000	1.0511	0.6572	0.3939
2001	1.6420	1.8253	-0.1833
2002	1.0984	1.9506	-0.8522
2003	2.0806	1.2811	0.7995
2004	1.6805	2.0485	-0.3680

Table 4. Seasonal performance of dual-time versus monthly resolution models. The table shows the expected value of the quadratic loss (MSE) between predicted and observed juvenile abundance for each of the years when the latter is available. Predictions and observations were standardized with the mean and variance of each year (12 values per year) before MSE is calculated.

The dual resolution also facilitates the embedding of environmental forcing into generalist models, such as the GPDM for fishery management. This integration results in model-observation coherence beyond the initial stages of the life cycle, see for instance Figures 5 and S2. These figures show coherence between the size structures produced by the model and those reported by ICES. The coherence seems to indicate the suitability of von Bertalanffy model used for equations (4) and (5), and the bounds settled for growth parameters provided by Bellido et al. (2000) (see Table 2). Other features observed in the population size-structure also seem to be well reproduced by the model. Thus, absence of large sizes and high concentration of individuals between 10 and 14 cm is consistent with the BOTTOP control suggested in Ruiz et al. (2007), i.e. fishing pressure hampers adults to survive beyond a year and population relies on the youngest fishes. Nevertheless, model-observation discrepancies frequently occur in the first two length classes (10-12 and 12-14 cm, Figure S2). This probably reflects the need to ameliorate the transition matrix $\mathbf{G}$ in future versions of the model. To this respect, the inclusion of another length class in the model (e.g. 8-10 cm, mostly immature) seems reasonable according to the recent report of landings data (ICES, 2014). Further, the use of a seasonal growth model incorporating temperature effects might improve the observed results.

To explore the influence of λ samples from chain 1, all the results were repeated using both chains. There were few small changes in Figures 4 and 3a and no changes in Figures 3b, 5 and S2. Values for Table 4, also changed, but the conclusions are the same. This exercise evidences that correlation of λ samples from chain 1 with other unknown parameters is not relevant for all the results presented here.

It is worth to underscore that the model had no previous contact with the in situ data for early-stage abundance presented at Figure 4 or with the population size-structured reported by ICES (and used in model versus observation contrast of Figures 5 and S2). Therefore, the Bayesian integration of environmental forcing in traditional formulations of fishery management results in outputs coherent with observations. This coherence holds in the whole life cycle, even when those observations have had no previous contact with the model.

The main feature of the time series, the collapse and recovery between 1994 and 1996 is described in previous works pointing to the combined effect of wind and discharges over recruitment (Ruiz et al., 2006, 2009). This drastic variation on landings is also well resolved by the model. The posteriors of λ and ρ in Figure 2 indicate, nevertheless, a higher role of the wind regime in driving the dynamics of the population. In coherence with a recruitment-driven fishery, the model transfers these major changes of recruits abundance (Figure 3a) into large fluctuations of landings (Figure 3b).

The model presented here confirms the critical role of the environment in shaping recruitment and landings of anchovy in the Gulf of Cádiz. Compared to previous models, its dual time resolution improves coherence between model output and observations throughout the life cycle of anchovy, including independent observations that represent a genuine validation of the approach (Pauly et al., 2013). The environment starts to influence the future recruitment several months ahead. For managing proposes this implies that the model could be used as a tool to estimate recruitment based on the observation of wind, temperature and discharges conditions before the fishing season has started. It could be then feasible to define a harvest control rule incorporating this anticipated knowledge to reduce risks.

Although the implementation is designed for anchovy in the Gulf of Cádiz, this validation suggest a strong capacity of the approach to simulate the dynamics of small pelagics. Since equations (1) and (2) can be easily modified for other species and stocks, this capacity suggest that the approach can be extrapolated to other small pelagic where the recruitment is key to explain surplus or collapse.

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Appendix

Derivation of equation (5)

Considering the von Bertalanffy growth equation with an additional error term, ε_τ, as follows:

$$L_\tau = Linf(1-e^{-g}) + L_{\tau-1}e^{-g} + \varepsilon_\tau, \tag{11}$$

where L_τ is the length of an individual at age τ and $\varepsilon_\tau \sim N(0, \sigma_L^2)$. If $c = Linf(1-e^{-g})$ and $\varphi = e^{-g}$, equation (11) can be rewritten as an AR(1) process

$$L_\tau = c + \varphi L_{\tau-1} + \varepsilon_\tau.$$

Assuming $\tau > M$ and $M \to \infty$, $E(L_\tau) = Linf$ and $Var(L_\tau) = sdLinf^2$. By properties of AR(1) processes, if $|\varphi| < 1$ then

$$Var(L_\tau) = \frac{\sigma_L^2}{1-\varphi^2}$$

and

$$\sigma_L^2 = sdLinf^2(1-e^{-2g})$$

Figure captions

Figure 1: Directed acyclic graph of the bayesian state-space size-structured population dynamics model.

Figure 2: Posterior distributions of the model parameters (solid lines). Dotted lines are for the prior distributions except for parameters $Linf$ and g where they represent upper and lower bounds.

Figure 3: a. Modelled recruits (Individuals between 5 and 6 months old). b. Modelled population size (lines) versus catches reported by ICES (bars). In all figures the dotted lines are for the 5 and 95 percentiles while the solid line is for the median of the posterior distribution. Quarterly reported catches were transformed in order to preserve the monthly scale.

Figure 4: Bars from juvenile data in Drake et al. (2007) never in contact with the model and black circles for the mean of modelled juvenile population relative to initial population N^*. Second and third juveniles population corresponds to individuals that are 3 and 4 months old, respectively $(B_t(3) + B_t(4))$.

Figure 5: Bars represent the KL divergence between the modelled and real length frequency distribution of the population grouped in 6 length classes of size 2 cm from 10 cm to 22 cm. Black circles identify the values less than 1.5

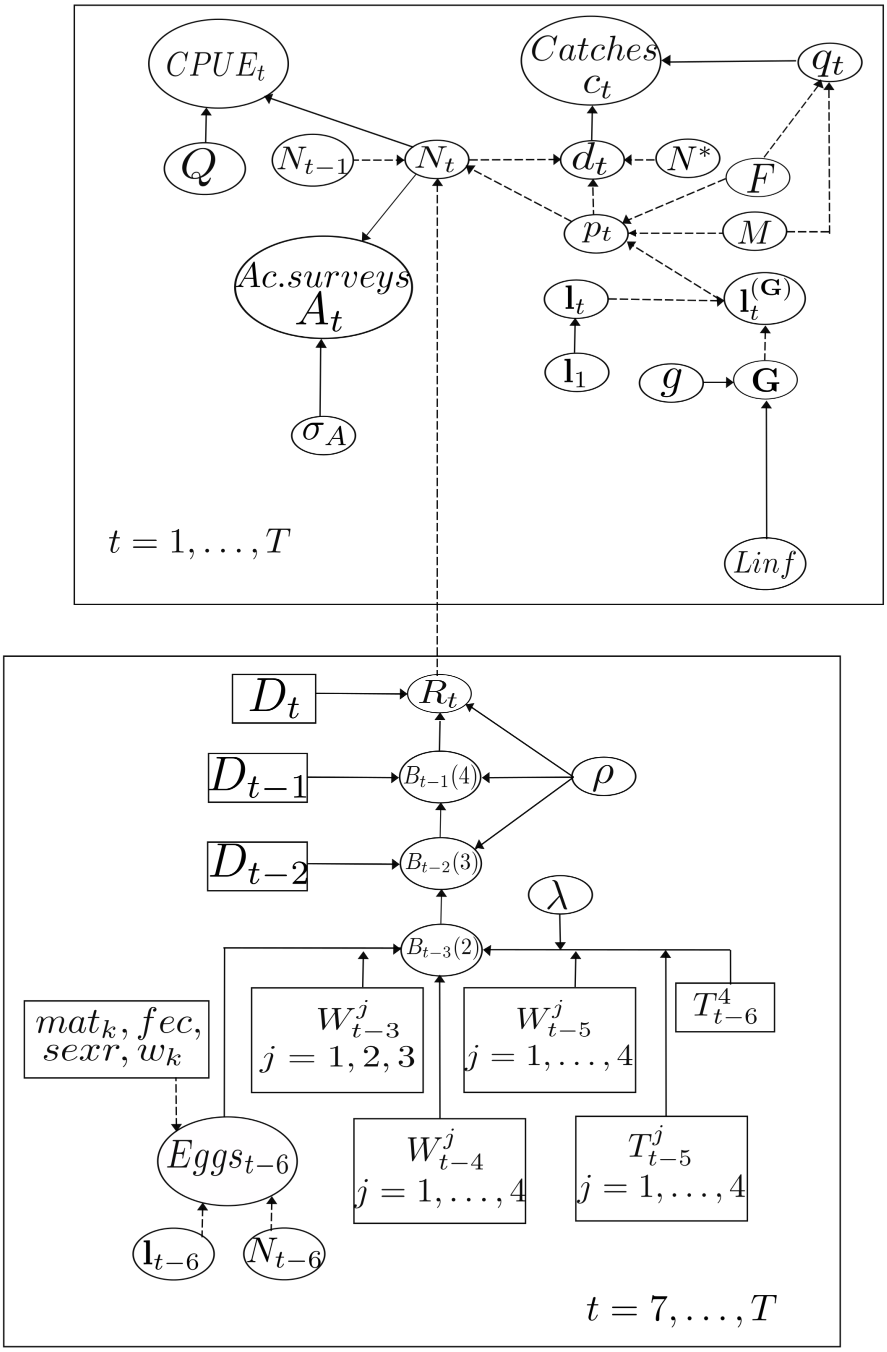
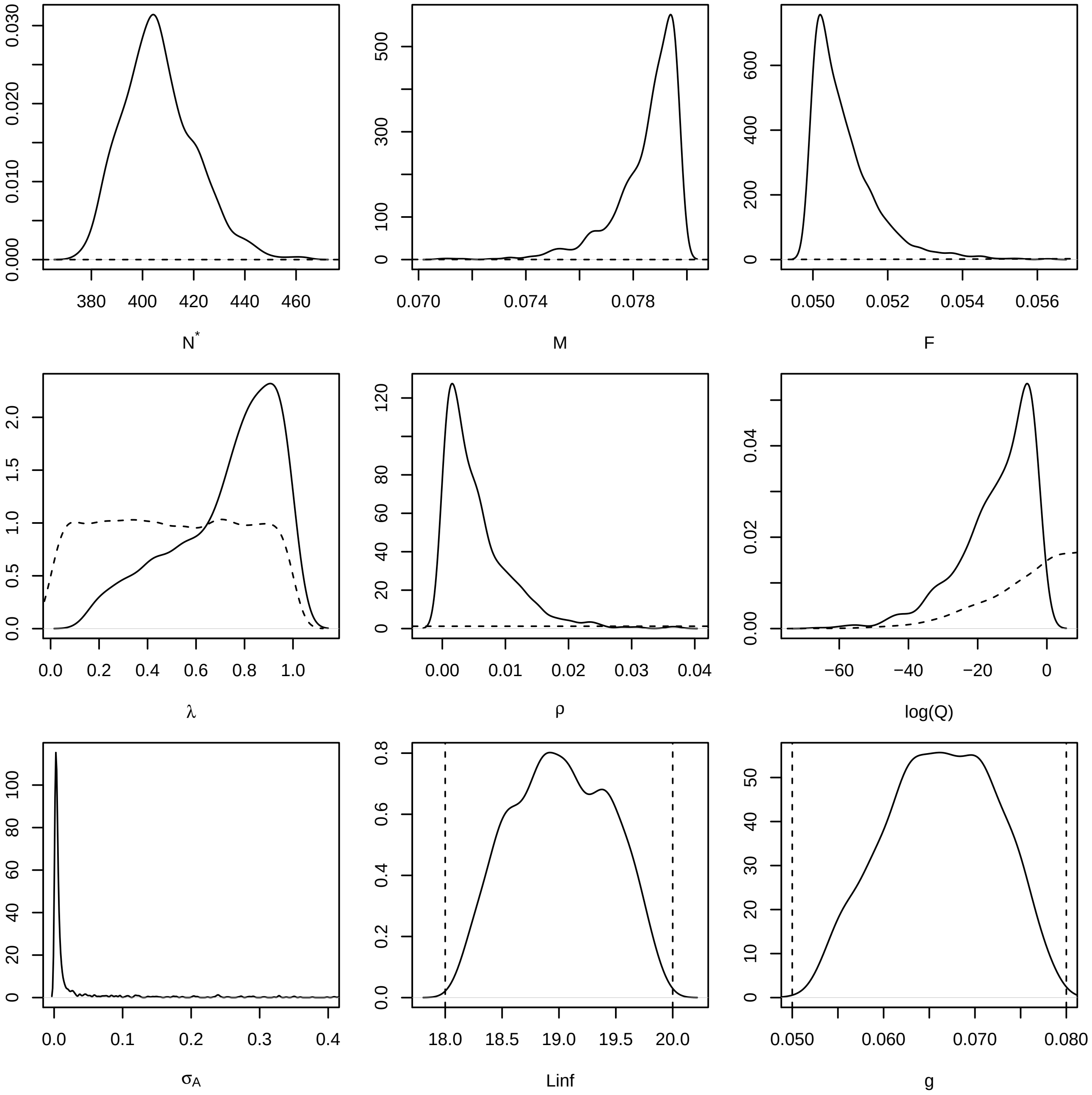


FIGURE 1. Directed acyclic graph of the bayesian state-space size-structured population dynamics model



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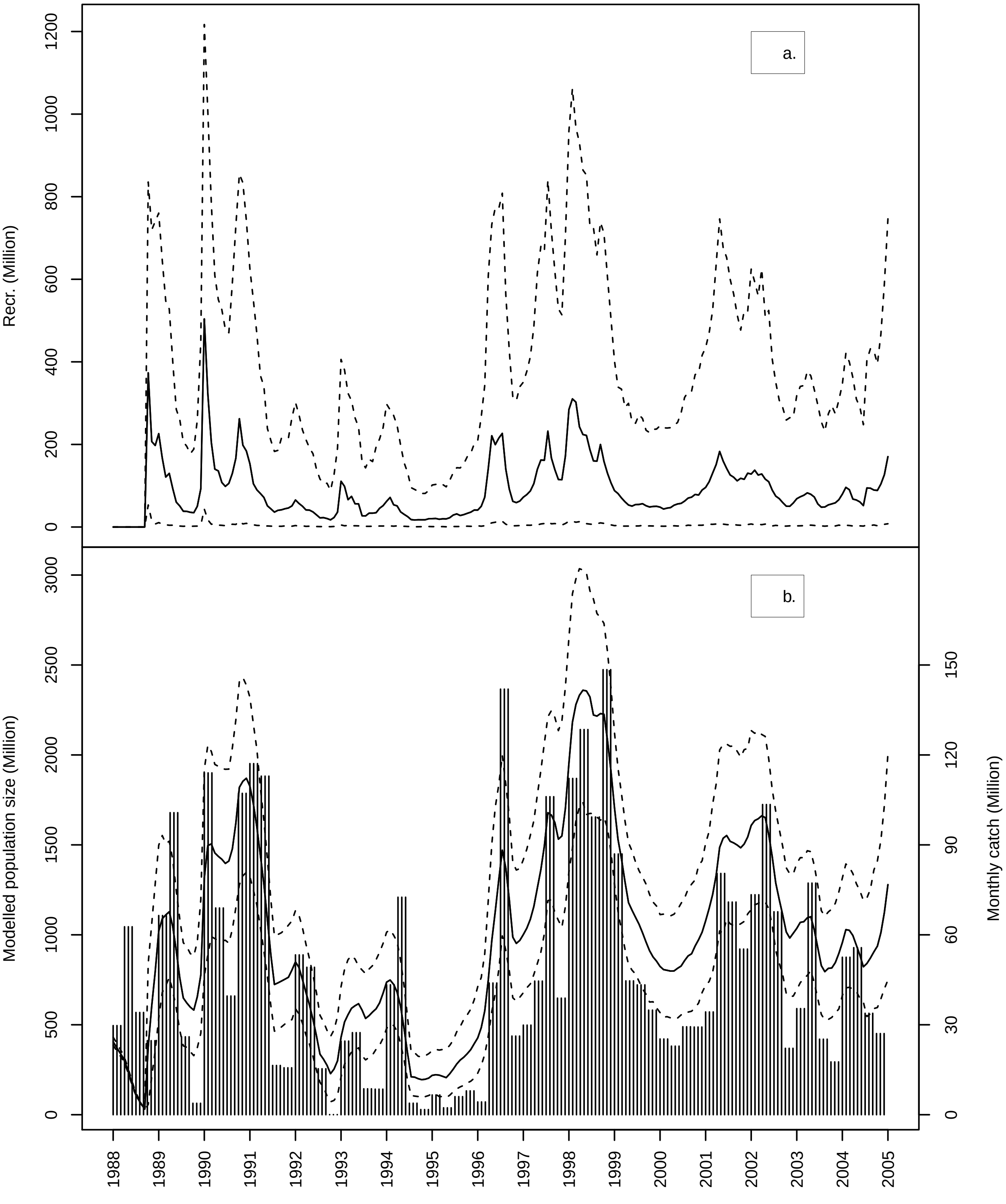

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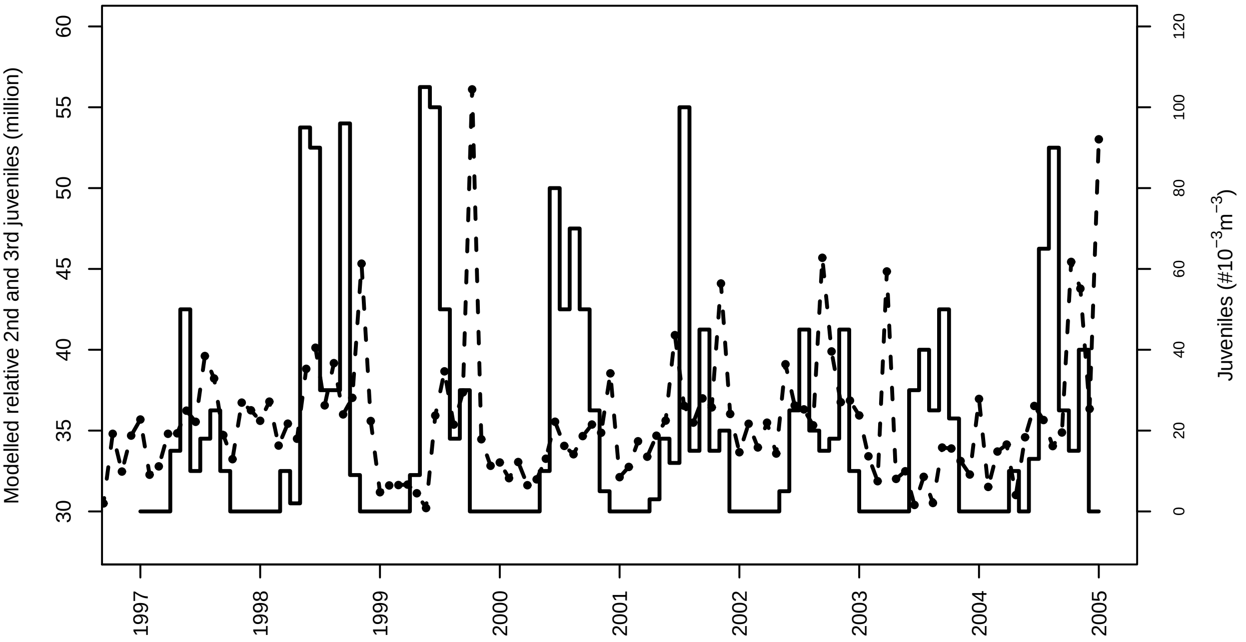

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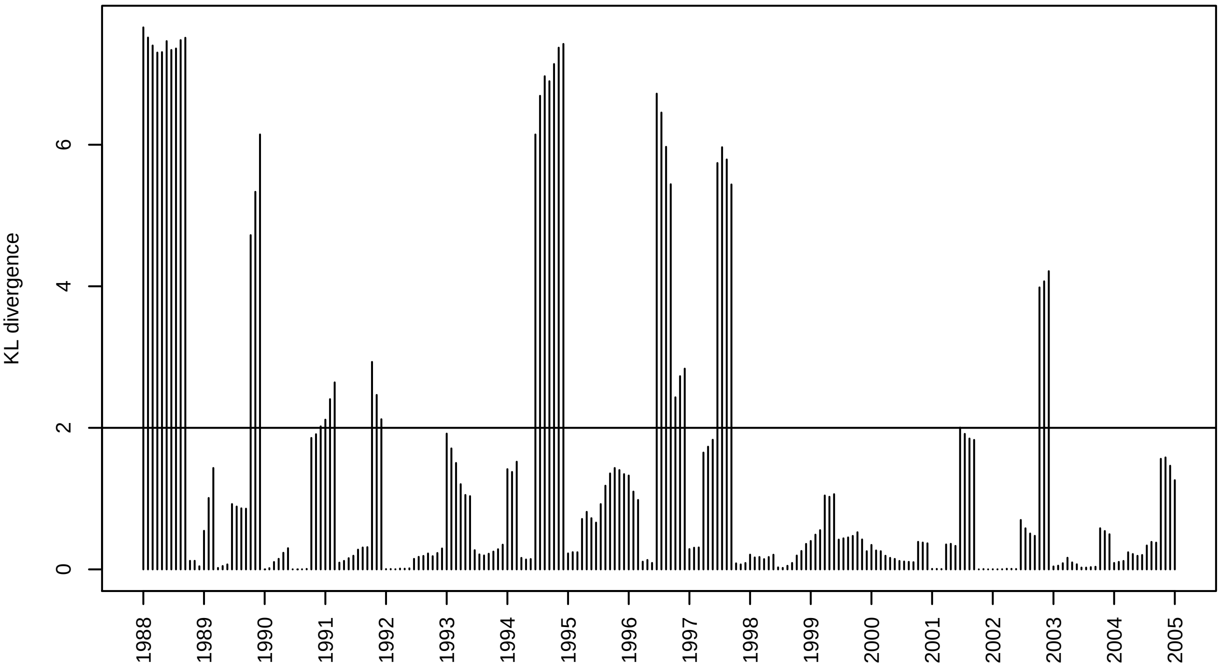

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Embedding anchovy survival in the environment with a dual time resolution : A Bayesian state-space size-structured population dynamics model

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Supplementary Figures

Figure S1: Joint posterior of key parameters for second chain output.

Figure S2: Boxplots are for modelled length distributions for individuals after recruitment and blue lines for ICES reported data, the lengths in the horizontal axis are divided in 6 groups from 10cm to 22cm, the first: 10-12 cm, the second: 12-14 cm, the third: 14-16 cm, the fourth: 16-18 cm , the fifth: 18-20 cm and the sixth: 20-22 cm (ICES data never in contact with the model).

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Figure S1

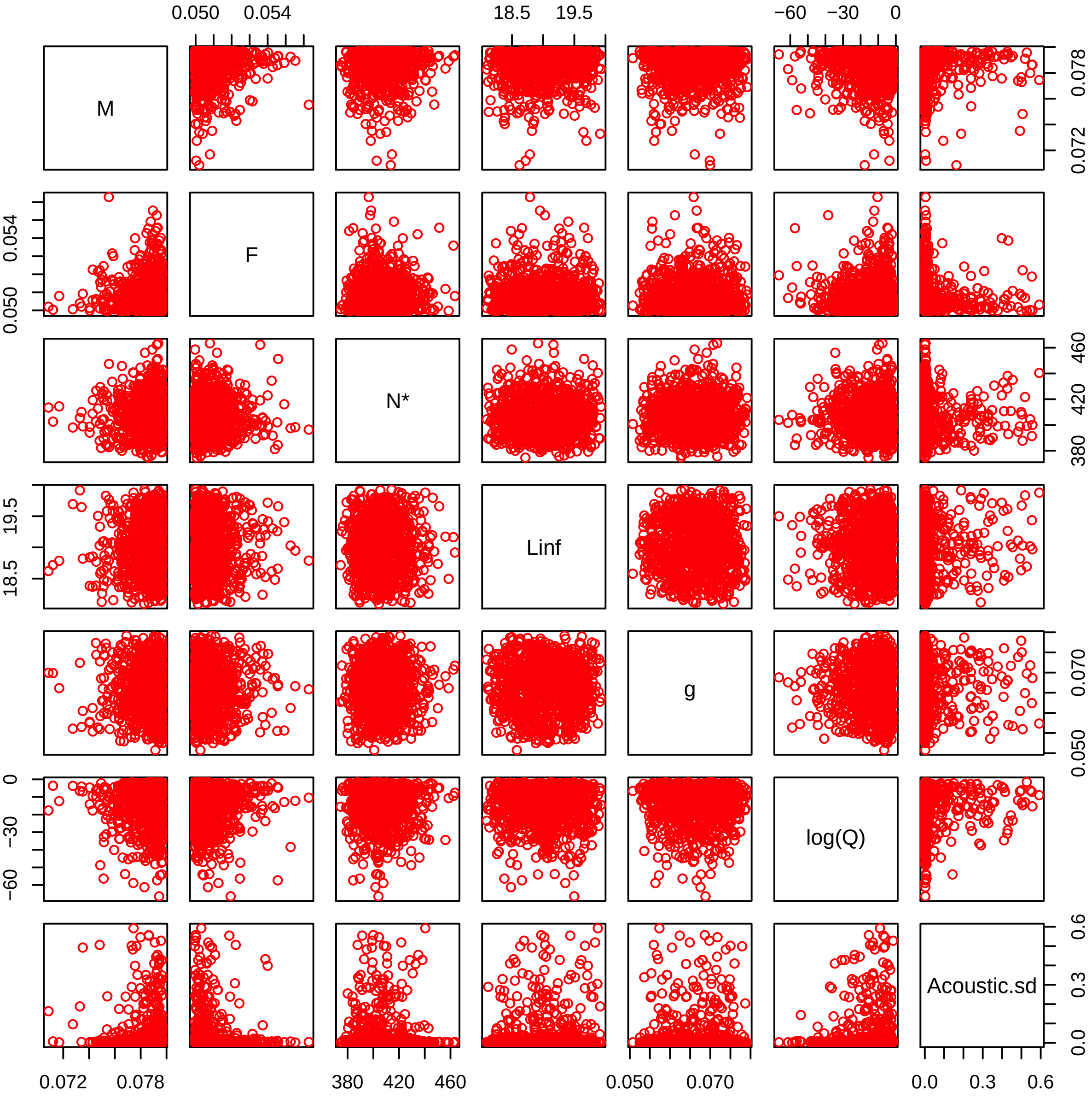
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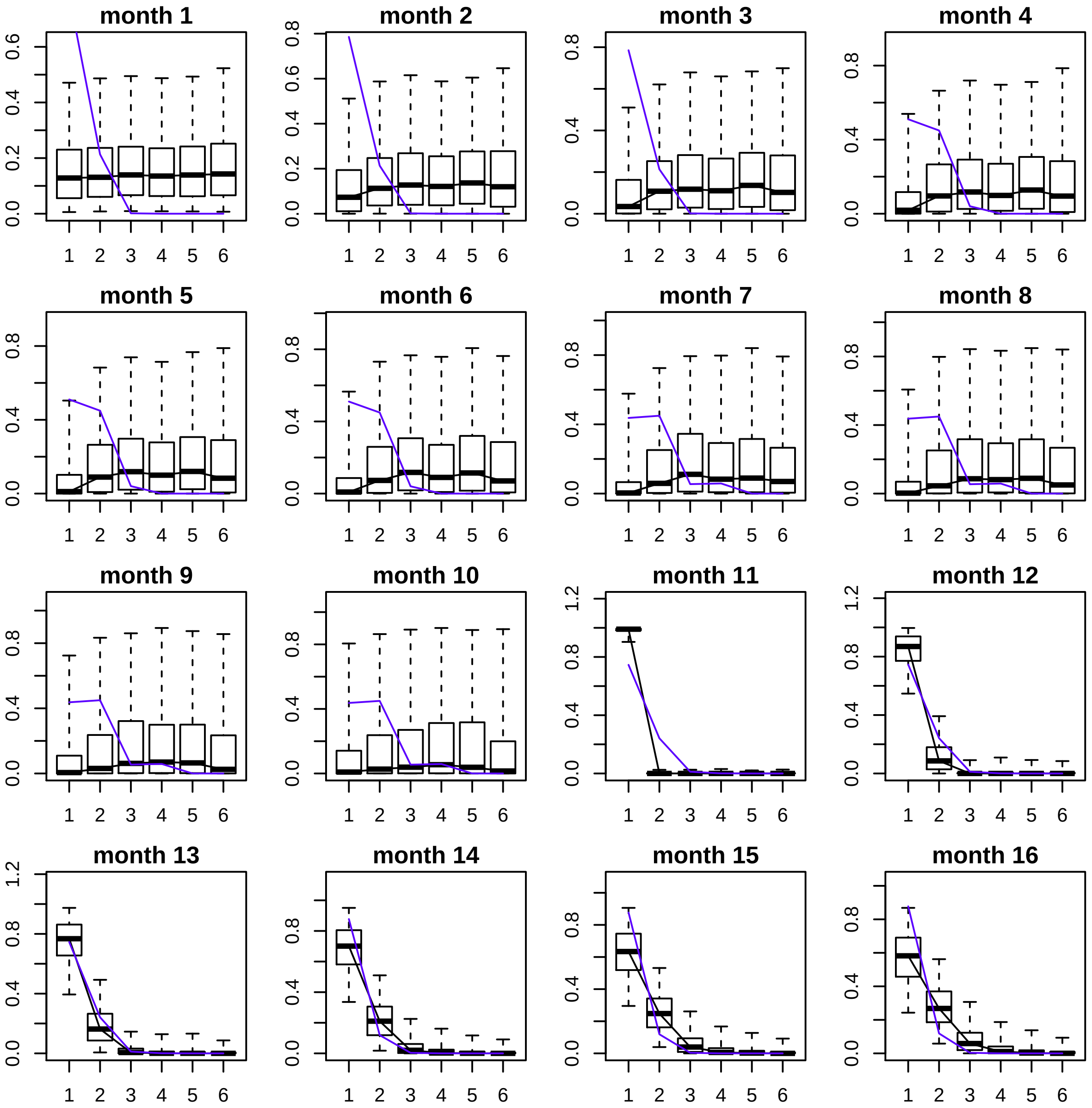
Figure S2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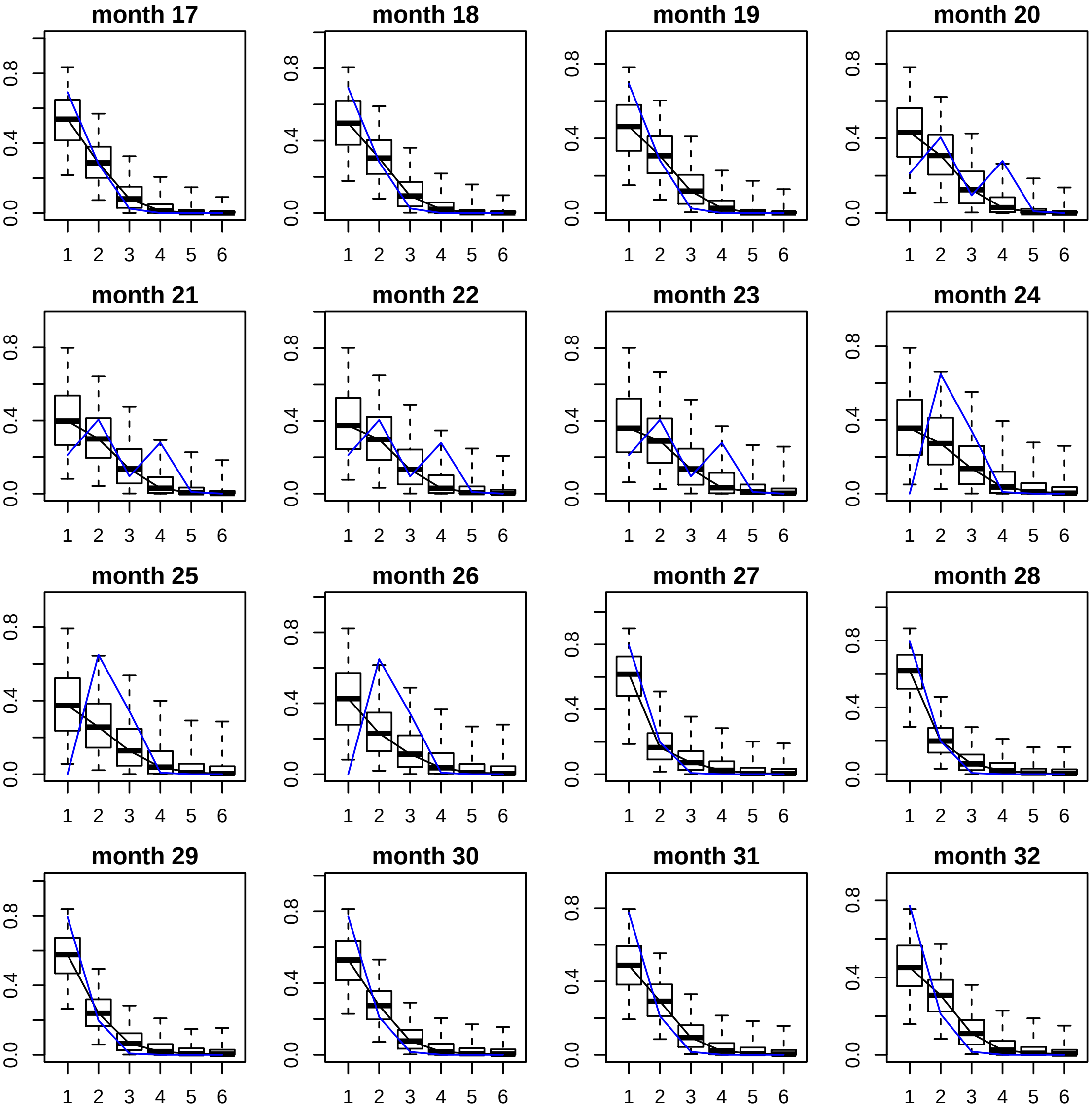
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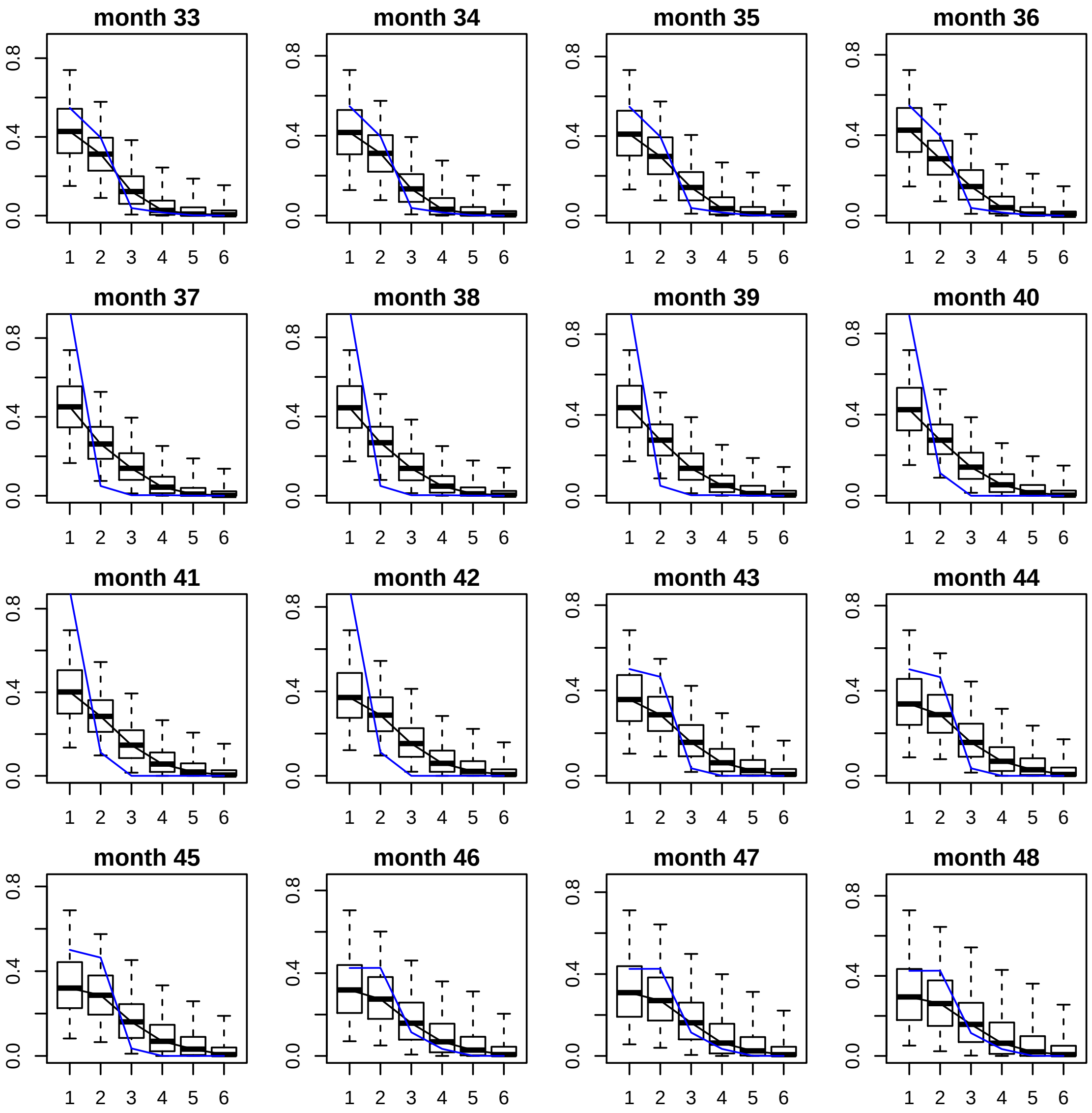
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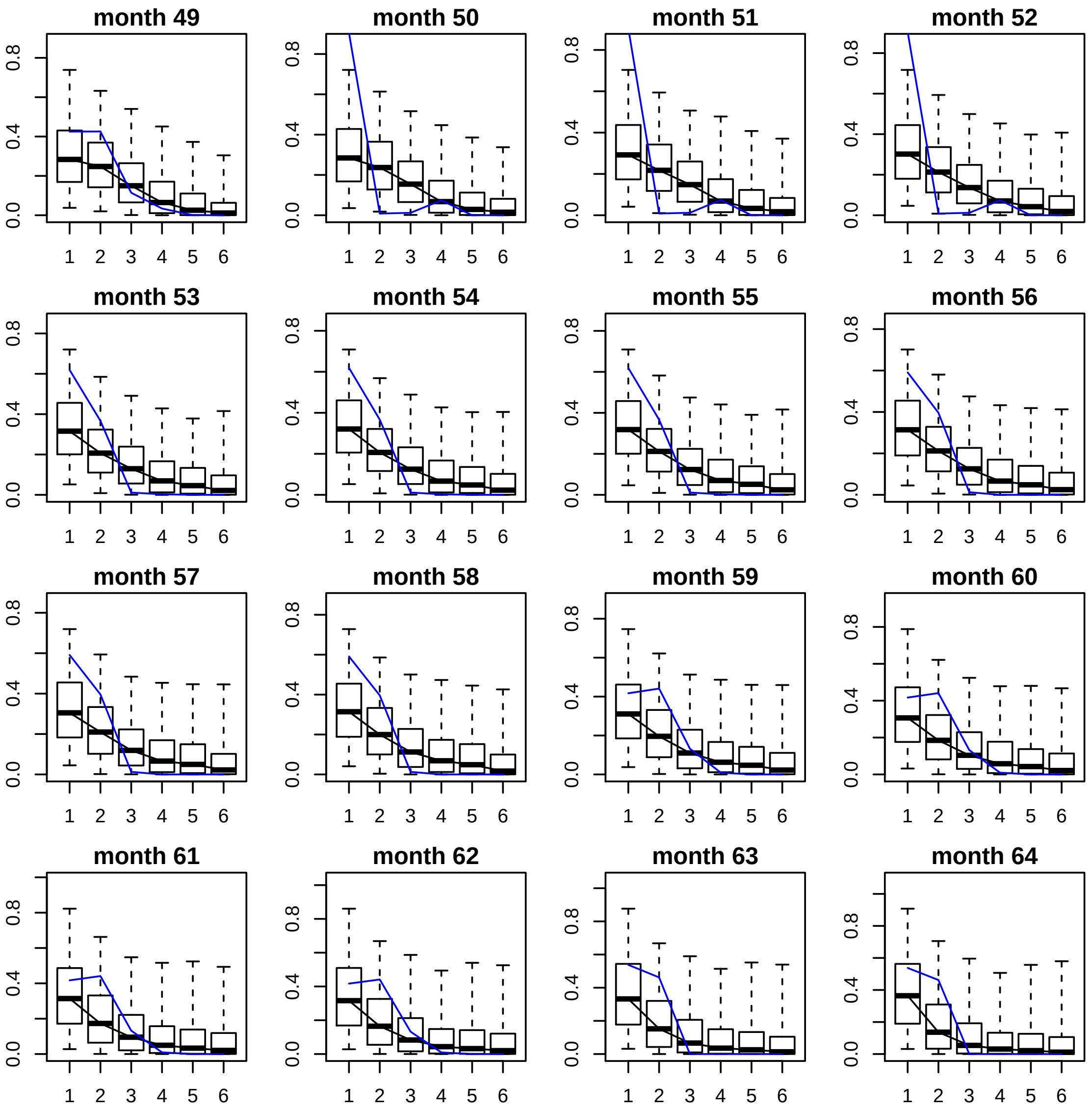
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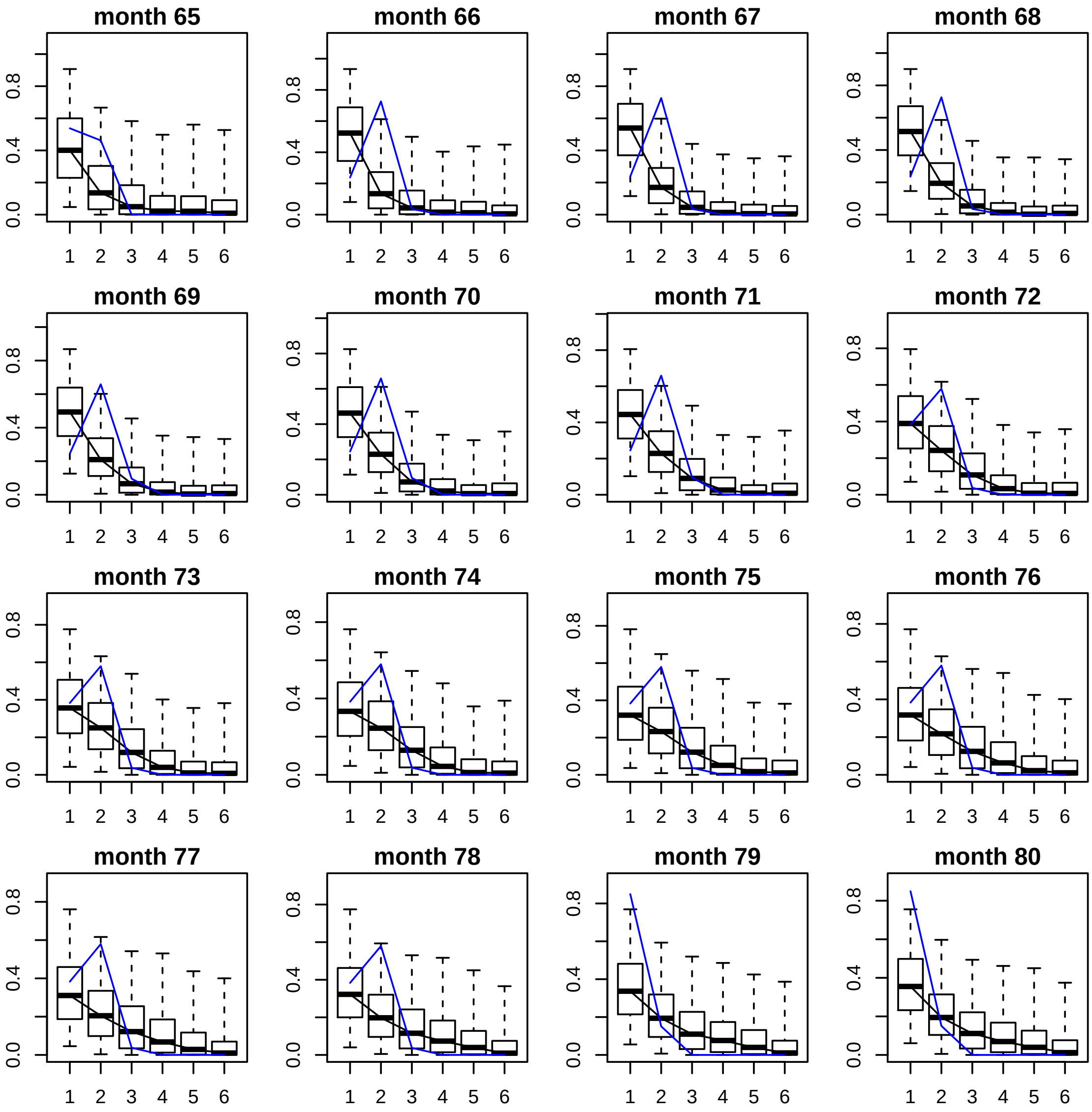
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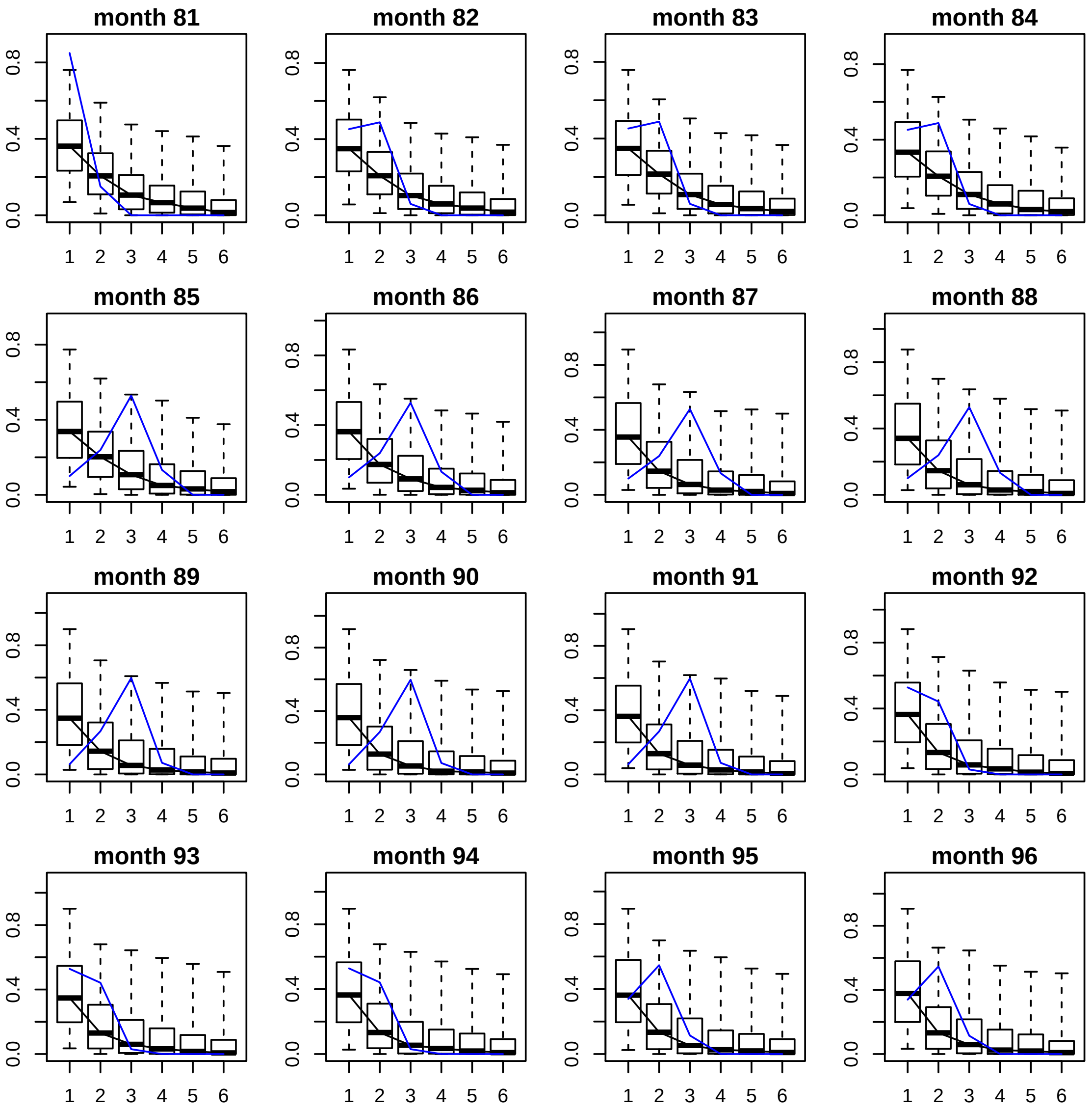
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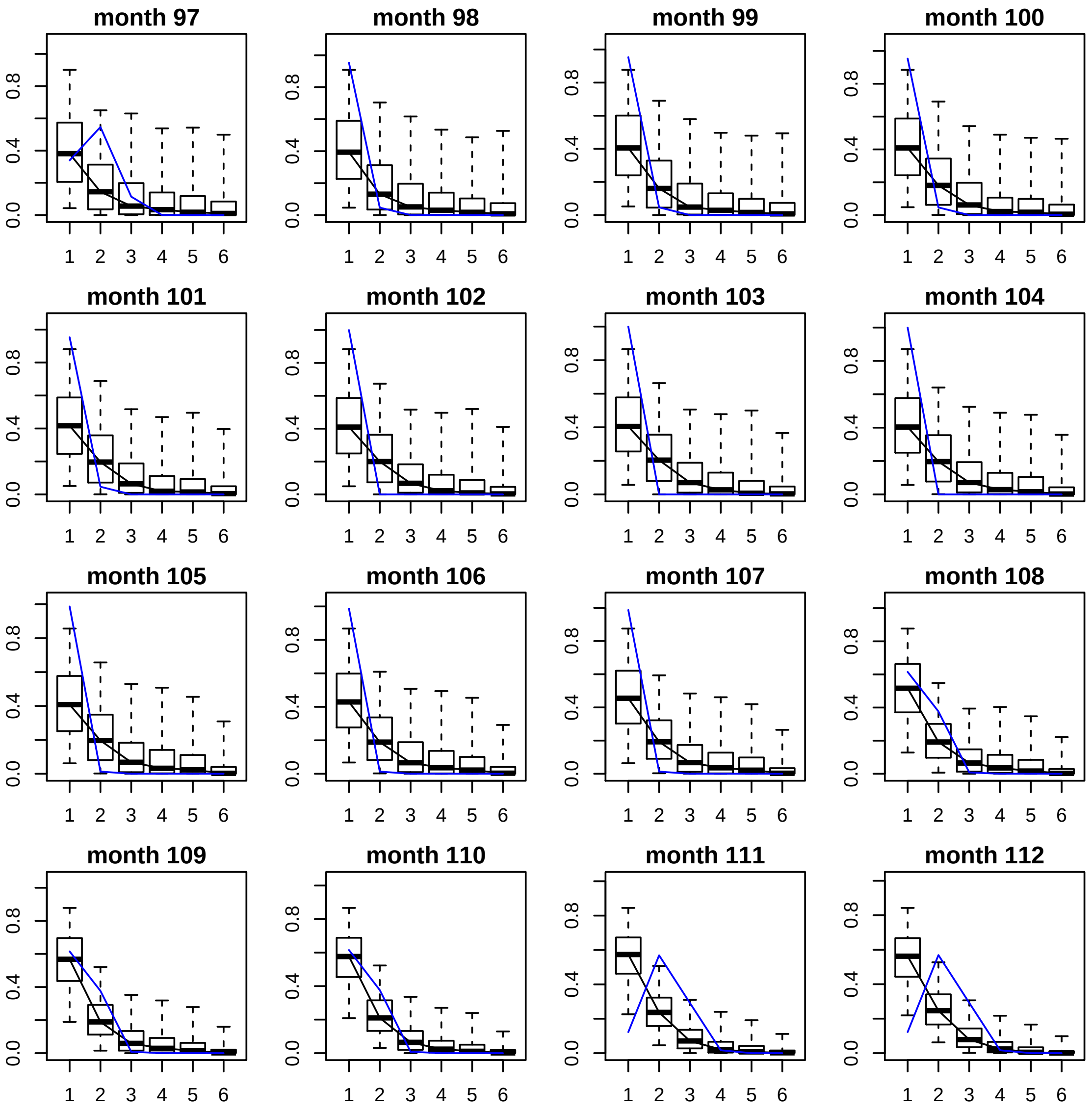
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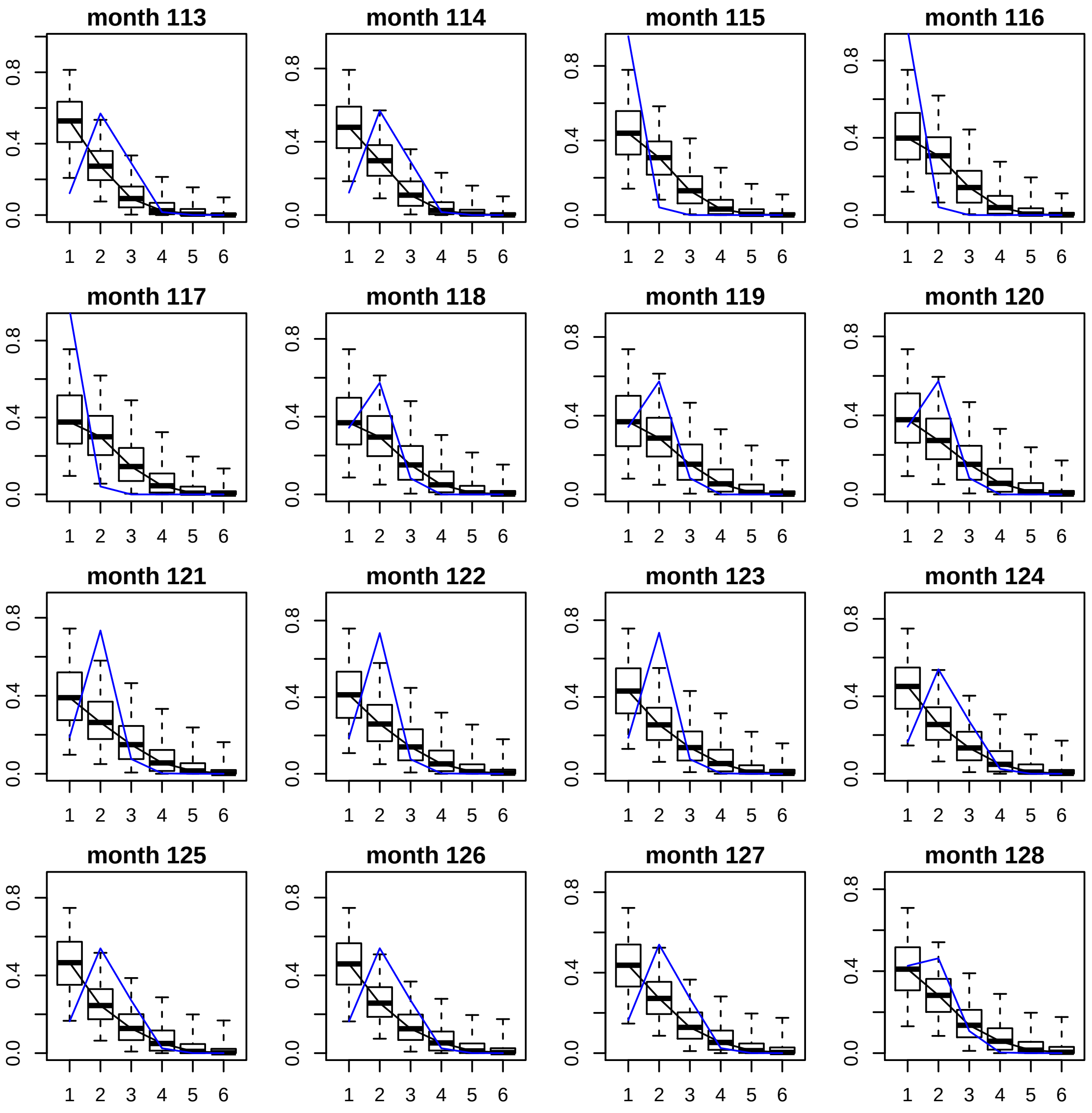
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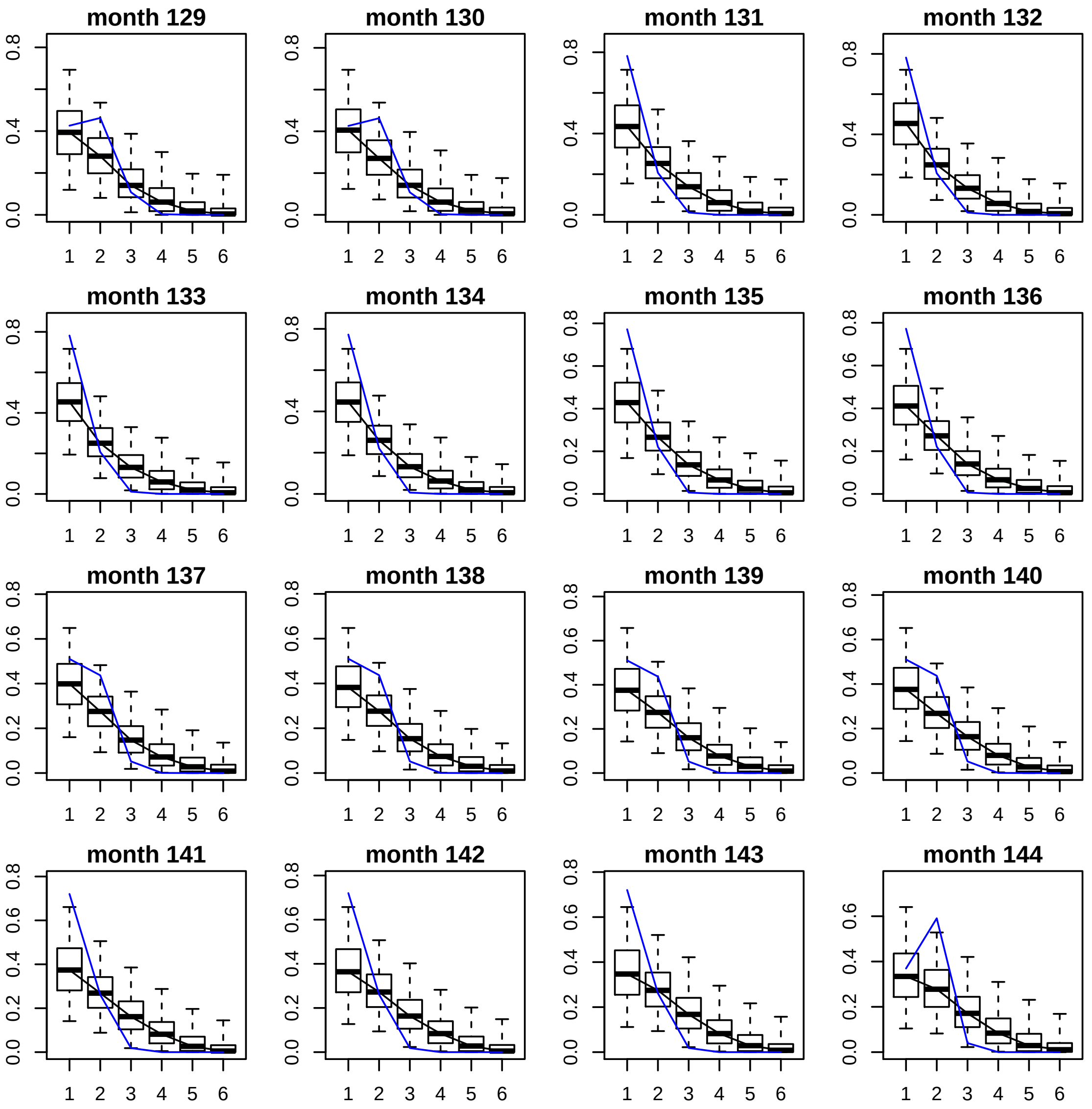
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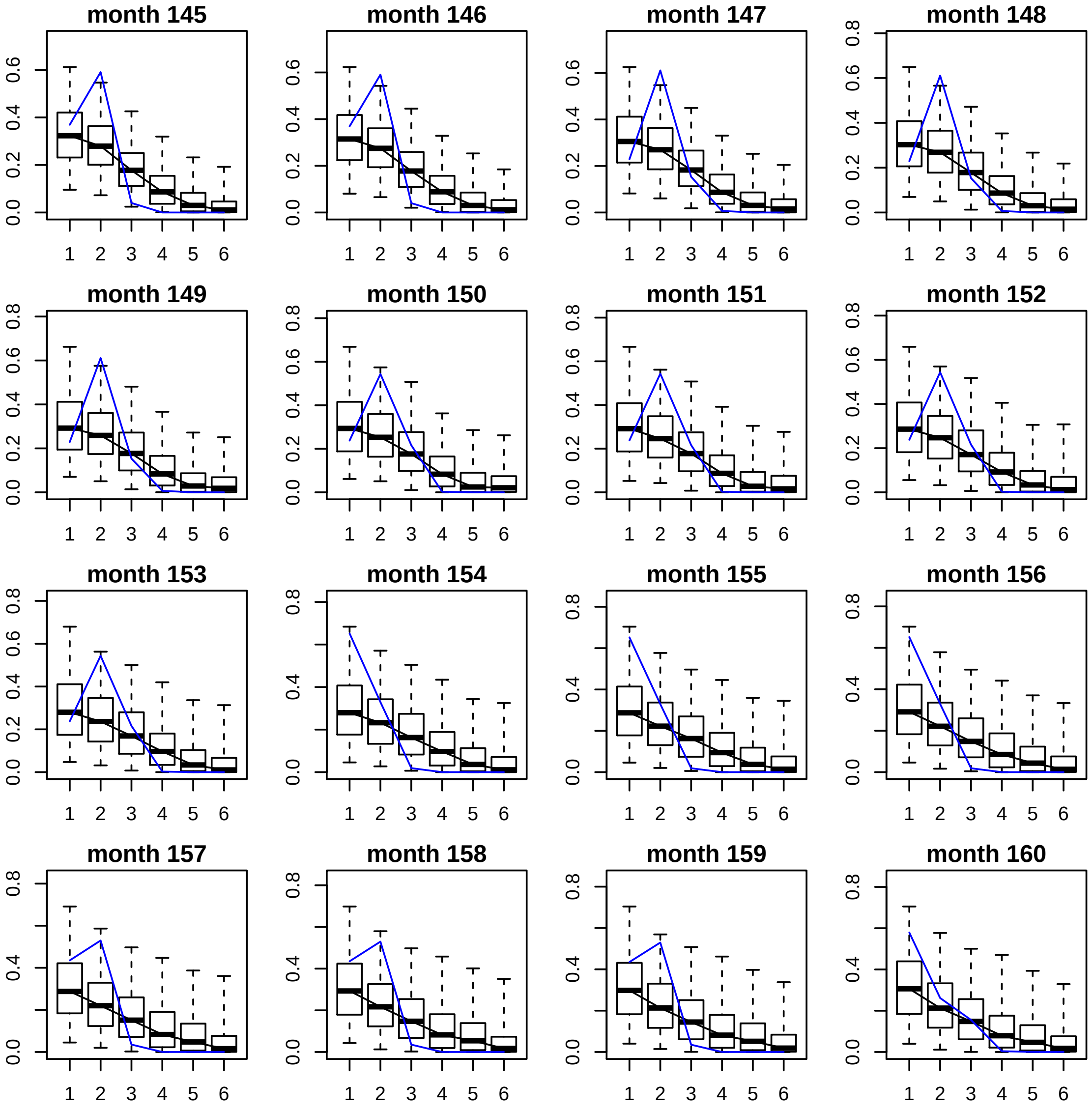
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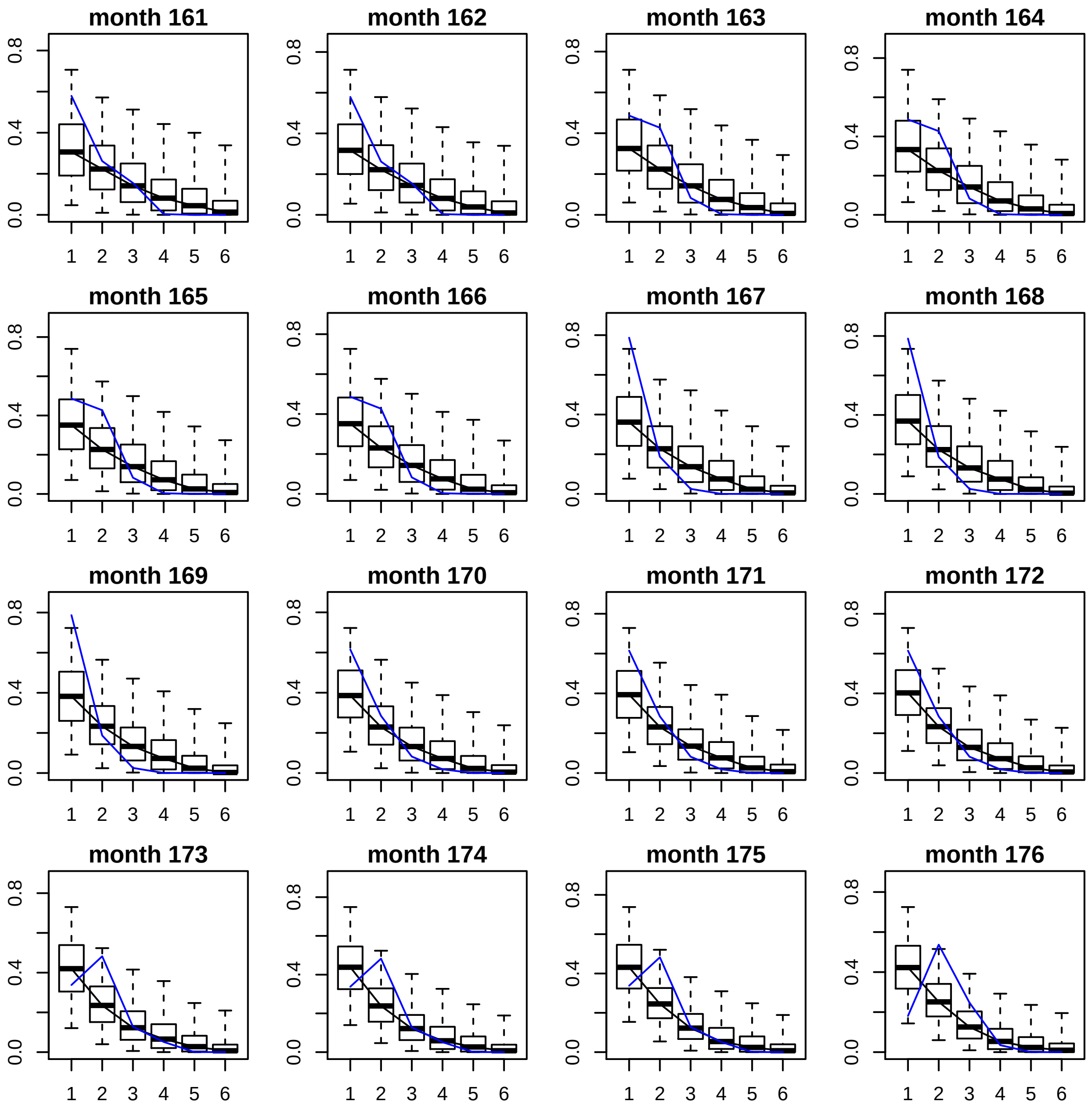month 161
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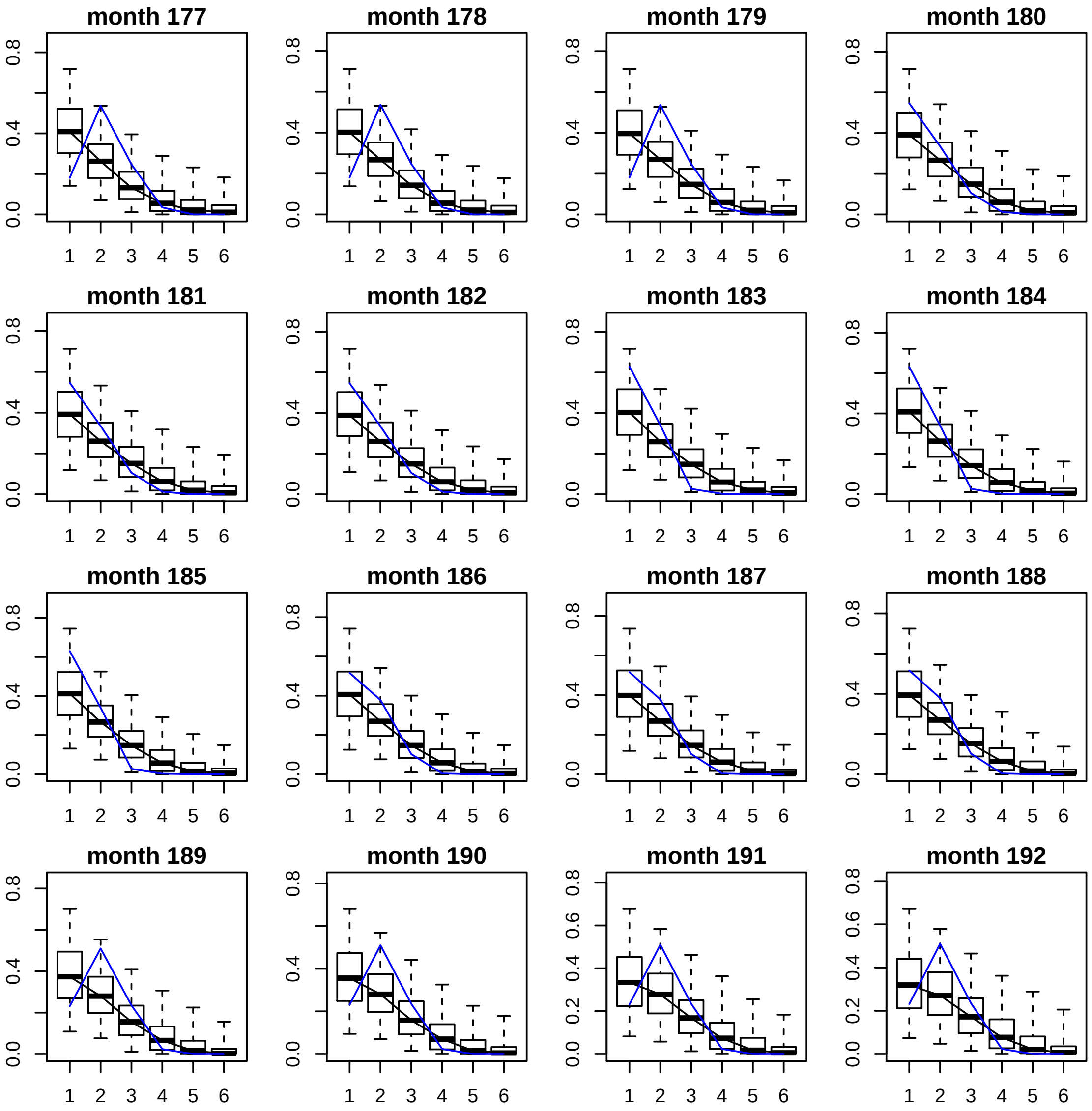
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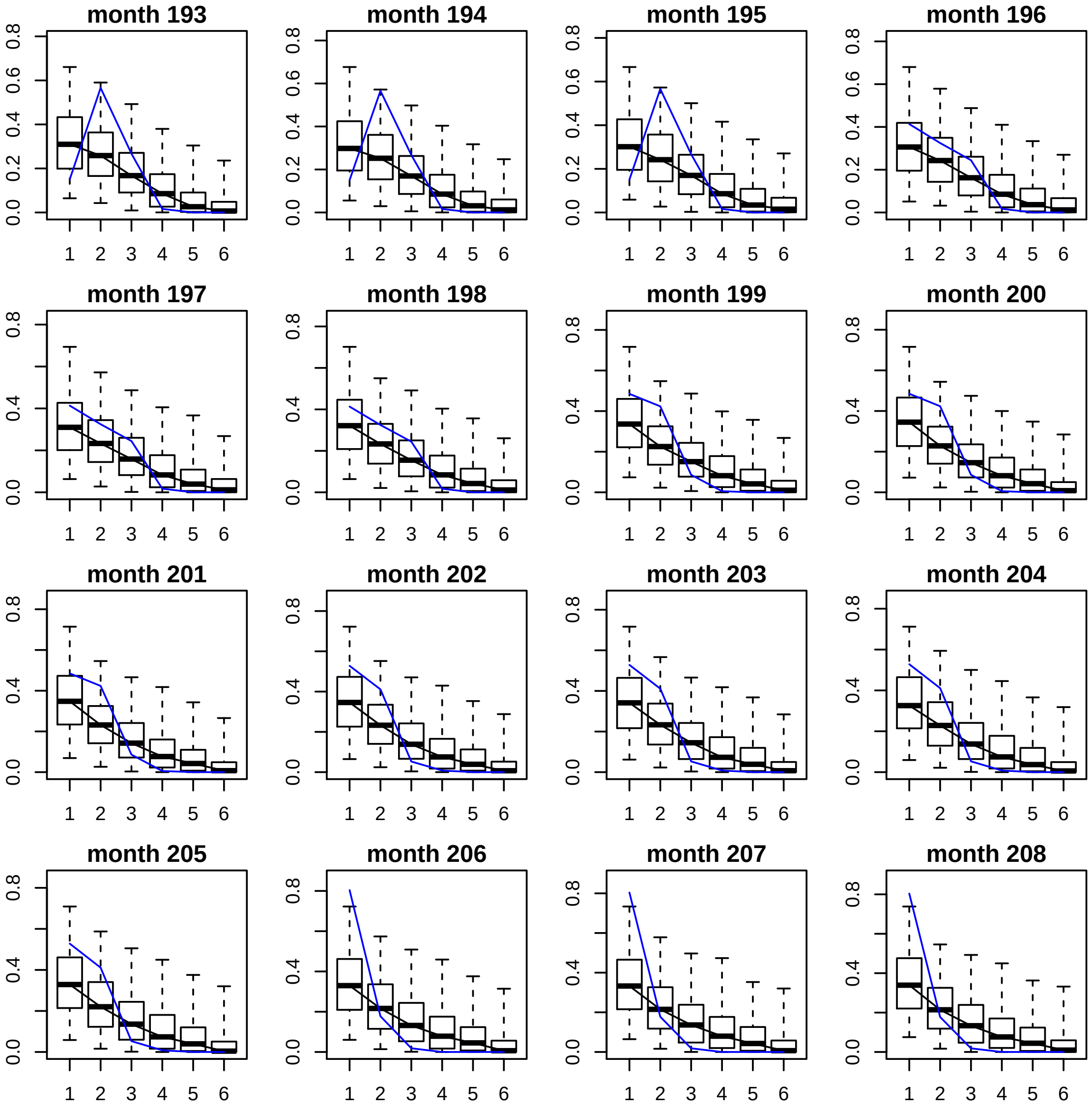
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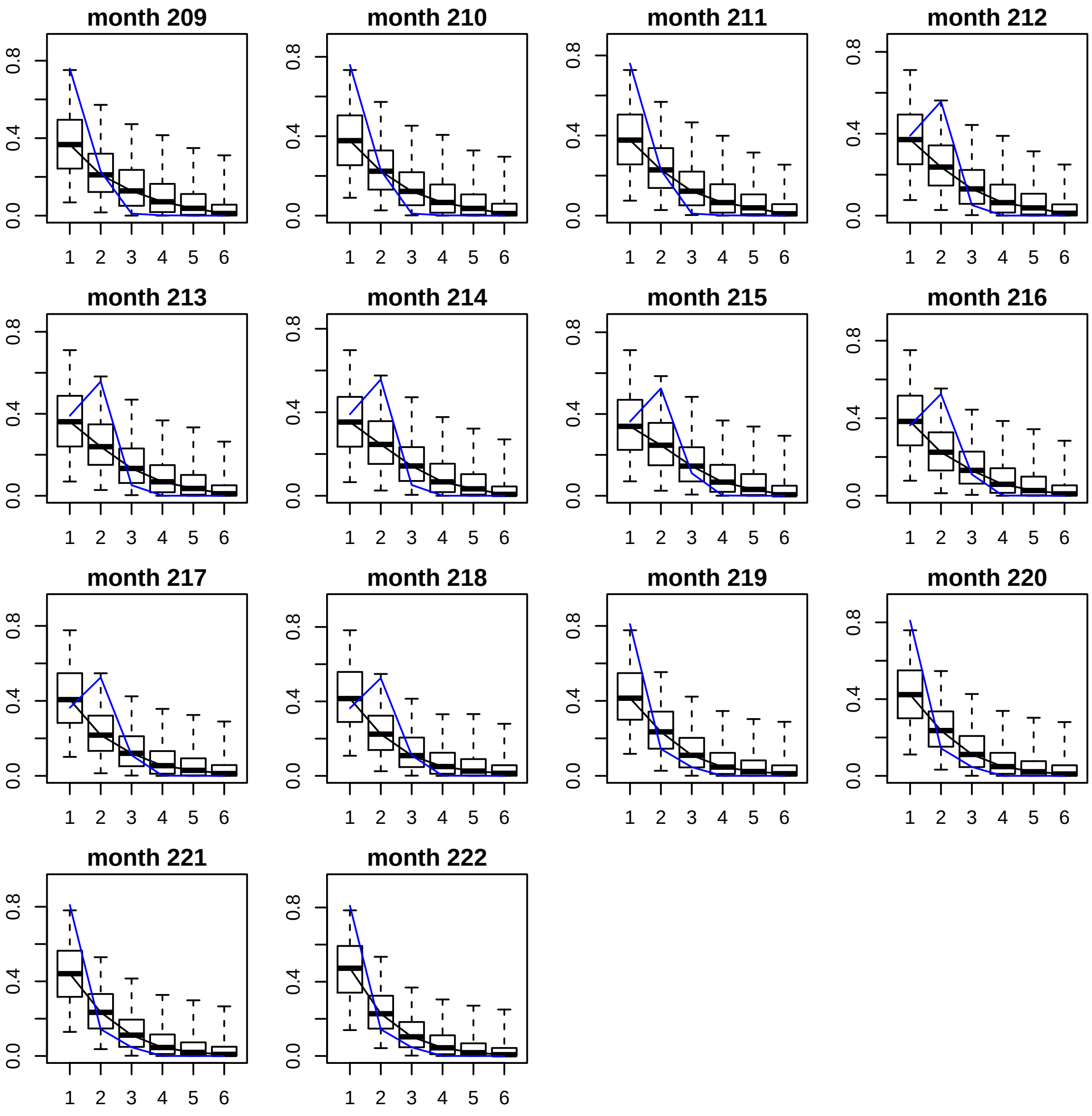
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CHAPTER

2

The economic value of environmental data: A notional insurance scheme for the European anchovy

Margarita María Rincón, Polina Levontin, Adrian Leach, Javier Ruiz & John Mumford.

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The economic value of environmental data: A notional insurance scheme for the European anchovy.

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Abstract

To explain atypical events in anchovy population dynamics in the Gulf of Cádiz, it is crucial to consider environmental processes in a different way from how these are traditionally included in stock-recruitment relationships. In the Gulf of Cádiz, sea surface temperature, intense easterlies and discharges from the Guadalquivir River have been identified as key factors determining early life stage mortality in anchovy. We have constructed an environment-based recruitment model that simulates the abundance of juveniles under alternative parameters representing plausible biological hypotheses. We are able to evaluate how modelling environment-based recruitment can affect stock assessment and how responding to environmental information can benefit fisheries management. Further, simulating a notional insurance scheme we can measure the value of using environmental information within a specific management regime defined by a harvest control rule. The main questions are whether incorporating the knowledge of environment in the management of anchovies in the Gulf of Cádiz is likely to increase the mean harvest or reduce the volatility of harvests and how this could benefit the commercial fishery and

ecosystem management policies.

Keywords: Harvest Control Rule; insurance; risk; Gulf of Cádiz and European anchovy.

Introduction

The state of European anchovy (*Engraulis encrasicolus*) in the Gulf of Cádiz is described by ICES (2012) as “not known precisely because of the inadequacy of the available information to evaluate the spawning stock or fishing mortality relative to risk”. This assertion is based on data limitations compounded by large inter-annual fluctuations in abundance and the high dependence upon recruitment which is unpredictable using traditional stock-recruitment relationships not accounting for environmental variability (Ricker or Beverton-Holt models).

The great variability of the stock has led to several attempts to understand the mechanisms that govern population dynamics. Important results were presented in Ruiz *et al.* (2006) reiterating the importance of environmental forcing when modelling small pelagic dynamics (Fréon *et al.*, 2005) and identifying the sea surface temperature (SST), intense easterly winds and discharges from the Guadalquivir River as the main influences on early life stage mortality for the Gulf of Cádiz anchovy stock.

The Ruiz *et al.* (2009) paper describes a Bayesian population model that links environmental covariates to recruitment dynamics. Using that population dynamics structure it is possible to evaluate different harvest control rules by simulating long series of landings under diverse environmental scenarios. This framework allows evaluation of different management strategies that use knowledge of environmental covariates. This approach, termed management strategy evaluation (MSE), which was pioneered by the International Whaling Commission (Kirkwood, 1997; Butterworth and Punt, 1999; Kell *et al.*, 1999, 2005) found wide application in fisheries (Kell *et al.*, 2007). This paper shows how knowledge of environmental conditions could be used to improve in-season management in stocks that are highly dependent on easily monitored environmental variables.

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The Environment-based Harvest Control Rules (EHCR) takes advantage of scientists' ability to use environmental parameters to estimate unusually large year classes of anchovy. EHCR responds to unfavourable conditions by reducing fishing pressure on the affected year class. This is a novel approach contrasting with the management strategy of the last ten years that has been setting an annual threshold for catches (TAC) based on surveys and 17-year averages of the recorded landings (ICES, 2012).

In order to compare both approaches, those that use the knowledge of the dependencies between environment and recruitment and those management rules that don't, we simulate a notional insurance scheme following Mumford *et al.* (2009). Insurance policies have been widely used in agriculture to reduce risk, but the cost of insurance is also an effective measure of risk. In fisheries, these policies are very hard to implement (Greenberg *et al.*, 2004) with current regulations but they could be used as a theoretical tool to compare and measure the efficiency with which different HCR deal with economic risk. Calculating the difference in required premiums under the hypothetical insurance scheme allows the value of using environmental information to be calculated.

Population dynamics model

In order to simulate anchovy dynamics, it is relevant to understand the environmental processes behind early-stages anchovy survival in the Gulf of Cádiz (see Fig 1). Before recruitment, stock dynamics are mainly driven by the environment, and after that it is mainly determined by natural and fishing mortality (Ruiz *et al.*, 2006, 2009).

Environmentally forced recruitment

Recruit survival is highly affected by the wind and the discharges from the Guadalquivir River (Ruiz *et al.*, 2006) while spawning depends mainly on SST (Motos *et al.*, 1996; García and Palomera, 1996). In other areas it has been observed that females may spawn on average each three days if suitable temperature conditions hold (Somarakis *et al.*, 2004). As an approximation, spawning can be assumed to follow a weekly time

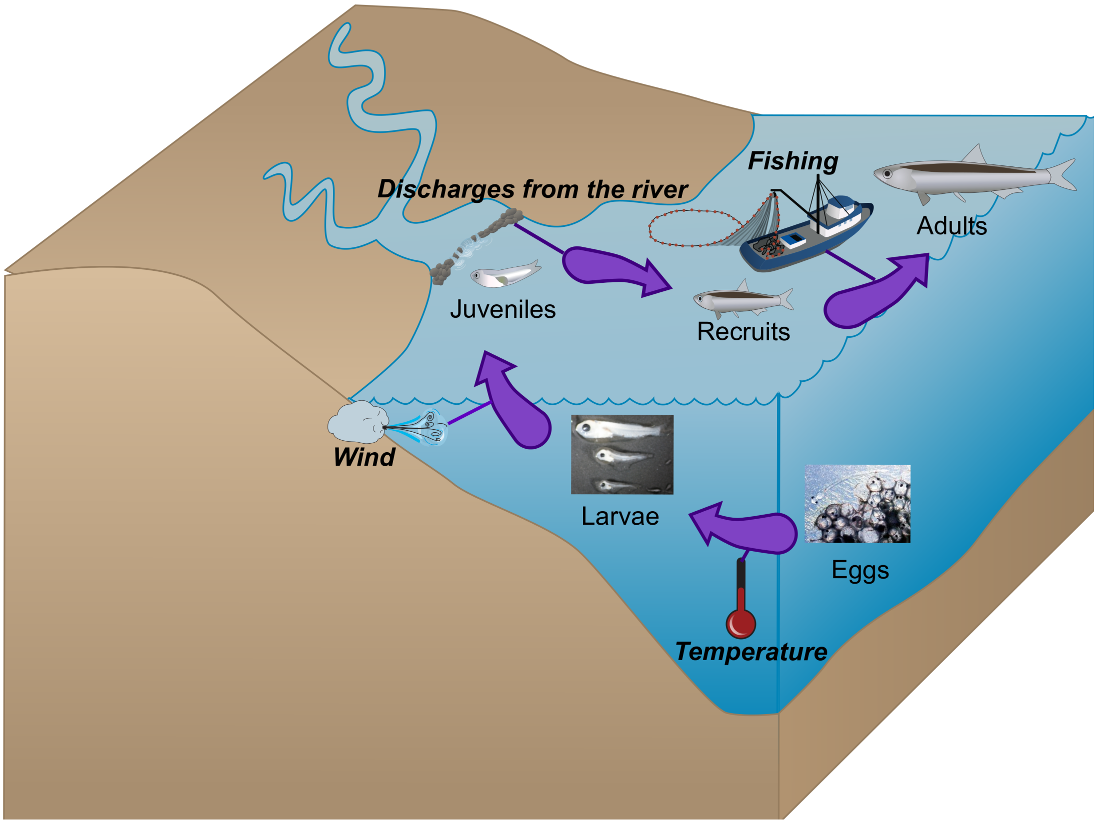

Figure 1: Diagram of anchovy life-cycle in the Gulf of Cádiz including environmental factors affecting different life stages. Courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/).

scale taking place when a minimum of $16°C$ sea surface temperature is reached and an increase of at least a quarter of a degree occurs from one week to another, consistent with the increase of a degree per month considered in Ruiz *et al.* (2009). These conditions hold with higher probability from May to September when individuals from nine to twenty-four months old could spawn up to four times per month.

When spawning occurs, the eggs and larvae can be advected by the effect of the easterlies on currents with a negative impact on survival (Ruiz *et al.*, 2006). The negative impact of advection is considered negligible after three months, when first juveniles are able to swim, controlling their position. These first juveniles are affected by freshwater regulation in the reservoir of Alcalá del Río during the following two months of development, with a positive effect on survival when discharges are closer to $100Hm^3$. This source of environmental variability can be modelled as a standardized normal density function of the natural logarithm of river discharges (Ruiz *et al.*, 2009).

Individuals that have survived for five months, are considered recruits and are included in the stock population size owing to their availability to the fishery. The fishery closes from November to February approximately each year to allow growth of individuals spawned from May to September (ICES, 2012).

Simulated model

We used four-dimensional arrays storing number of individuals by age (a), year (y), month (k) and simulation (s), where every year is supposed to start in May ($k = 1$) and a goes from 0 to 24 because negligible amounts of anchovies surpass this age in this stock (Ruiz *et al.*, 2009).

Initial state of the fishery is simulated assuming that the number of individuals of age 1 in spawning months, May to September, for the first three years of each simulation is $N_{1,y,k,s} = ME = 286 \times 10^{10}, k = 1, \ldots, 5, y = 1, 2, 3$. Then, the following equations determine the population size:

$$\begin{aligned} N_{a+1,y,k+1,s} &= N_{a,y,k,s} e^{(-M-F_{y,s})}, \quad a = 1, \ldots, 23, k = 1, \ldots, 11. && (1) \\ N_{a+1,y+1,1,s} &= N_{a,y,12,s} e^{(-M-F_{y-1,s})}, \quad a = 1, \ldots, 23. && (2) \end{aligned}$$

Where $N_{a,y,k,s}$ is the number of individuals of age a at month k of year y, M represents the natural mortality and $F_{y,s}$, the fishing mortality. Maximum number of eggs, ME, is calculated such that simulated catches are consistent with historical catches records (see Figure 5 below). The value corresponds to 1000 times the abundance estimate provided by an acoustic survey in 2007 (ICES, 2012). It is the highest of the values recorded.

During the first three years, $M + F_{y,s}$, is considered equal to 1 in equations (1) and (2). It is an arbitrary number to initialize population dynamics but these first years are not considered in the simulations. Since year four, the number of eggs produced by mature females (i.e. older than 11 months, bigger than 11 cm) from May to September is calculated as follows:

$$Eggs_{y,k,s} = fec \times sexr \times s_{y,k,s} \sum_{a=11}^{24} N_{a,y,k,s} w_a, \quad k = 1, \ldots, 5$$

Where $fec = 500\ eggs/g$, is the number of eggs that a female could spawn per gram, $sexr = 0.5$, is the proportion of sexually mature anchovy and, $s_{y,k,s}$ and w_a, corresponding to the number of spawns in a month and the weight at age, respectively.

We calculate the probability of spawning events that occur once, twice, three or four times in a month from a SST time series available from 1996 to 2004. They were respectively, 0.37, 0.37, 0.22 and 0.04 during the spawning season from May to September. Then, to calculate $s_{y,k,s}$ at each month, during the spawning season, we sampled randomly from $\{1, 2, 3, 4\}$ with the corresponding probability.

Weight at age, w_a, is calculated using a linear regression from the seasonal von Bertalanffy growth model (Bellido *et al.*, 2000) to transform age to length, and then the weight at length relationship $w = aL^b$ with $a = 0.0029$ and $b = 3.3438$.

The $Eggs_{y,k,s}$ are vulnerable to wind in the first three months and to the discharges from the Guadalquivir River, during the following three months, accordingly, population at month $k + 5$ is computed as:

$$\begin{aligned} N_{6,y,k+5,s} &= Eggs_{y,k,s}(e^{-\lambda W_{y,k,s}})(e^{-\lambda W_{y,k+1,s}})(e^{-\lambda W_{y,k+2,s}})\rho\phi(ln(D_{y,k+3}) - ln(100))\ldots \\ &\quad \rho\phi(ln(D_{y,k+4,s}) - ln(100))\rho\phi(ln(D_{y,k+5,s}) - ln(100)) \end{aligned}$$

Where $W_{y,k,s}$ is the number of days that strong winds blow, and $D_{y,k,s}(hm^3)$ represents the discharges from the Guadalquivir River ($\lambda = 0.15$ and $\rho = 0.4$.). They are randomly sampled from $W \sim Unif(2.25, 15)$ and $D \sim LN(ln(102), 0.4)$, respectively. These distributions were chosen based on historical records of wind and discharges from 1996 to 2004. Considering the seasonal pattern of discharges and the period when the juveniles occupy the estuary, mean and standard deviation of the logarithm were calculated using only the discharges from March to October of each year. Parameters λ and ρ were calculated to avoid collapse, such that the replacement rate was close to one.

Starting from year four, the change in population for individuals older than 6 months is driven by equations (1) and (2) with $M = 0.075$ and $F_{y,s}$ determined by a harvest control rule explained below. Annual catches, $C_{y,s}$, are calculated from Baranov equation as:

$$\begin{aligned} C_{y,s} &= \sum_{k=1}^{12}\sum_{a=6}^{24} N_{a,y,k,s}(1-e^{-(M+F_{y,k,s})})\frac{F_{y,k,s}}{M+F_{y,k,s}} \\ &\quad -\sum_{k=7}^{10}\sum_{a=6}^{24} N_{a,y,k,s}(1-e^{-(M+F_{y,k,s})})\frac{F_{y,k,s}}{M+F_{y,k,s}} \end{aligned}$$

Note that the second term corresponds to the closure of the fishery.

Environmental Harvest Control Rule

The ability to predict anchovy recruitment in the Gulf of Cádiz based on environmental data is used to test a harvest control rule that takes into account the influence of strong winds in the months preceding anchovy recruitment. Simulations produce dynamics largely dependent on wind, where the year class strength is determined by the number of days extreme easterly winds so that abnormally large year classes occur when the eggs are not disturbed. Survival of juveniles is more sensitive to an absolute change in the number of windy days at the lower end of the scale, hence seasons with few windy days coincide with exceptionally high survival resulting in larger cohorts (Figure 2, left panel). The impact of discharges on survival is substantial but more constant from season to season, having less impact on variability of cohort sizes than the wind (Figure 2, right panel). These features suggest the use of harvest control rules where fishing mortality can be modified by only taking into account wind conditions and not the effects of discharges.

For the environmental control rule, a reference monthly fishing mortality $F^* = 0.04$ is modified once each year before March and it is applied each month from March to October, according to the number of days strong winds blow from May to September in the previous year.

If the number of days that strong winds blow from May to September is low, conditions are favourable for survival of individuals spawned in those months (the cohort of the year).

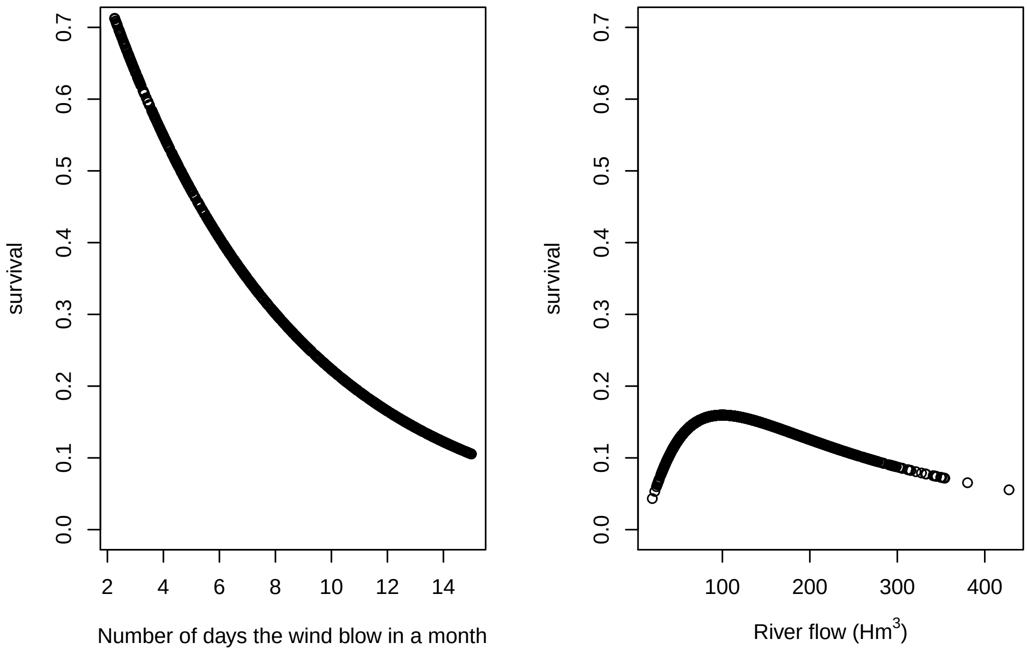

Figure 2: Left: Effect of wind on survival ($e^{-\lambda W}$) after one month for 1000 values of wind sampled from $W \sim Unif(2.25, 15)$. Right: Effect of discharges on survival ($\rho\phi(ln(D) - ln(100))$) after 1 month for 1000 values of discharges sampled from $D \sim LN(ln(102), 0.4)$.

On the contrary, if this number is high then conditions are adverse. This favourable or adverse conditions for recruitment are translated to a rule where the monthly fishing pressure in the period March to October of the next year is allowed to reach a value double or half the reference F* (See Figure 3). Thus, as the number of days with strong winds increases the reference limit value $2F^*$ decreases linearly to $F^*/2$. The fishing pressure is reduced from F^* to $F^*/2$ when the number of windy days in those months is more than five times μ_W, the expected value of W according to the uniform distribution described above ($\mu_W = 8.62$). As follows:

$$F_{y,k,s} = max(-0.0314F^* * (\sum_{k=1}^{5} W_{y,k,s}) + 2.35F^*, F^*/2) \quad k = 7, \ldots, 12$$

We chose the effect of wind during these months as representative for environmental conditions and apply a harvest control rule for the period March to October because it is the time when the fishery is open. In addition, there is a strong correlation between this

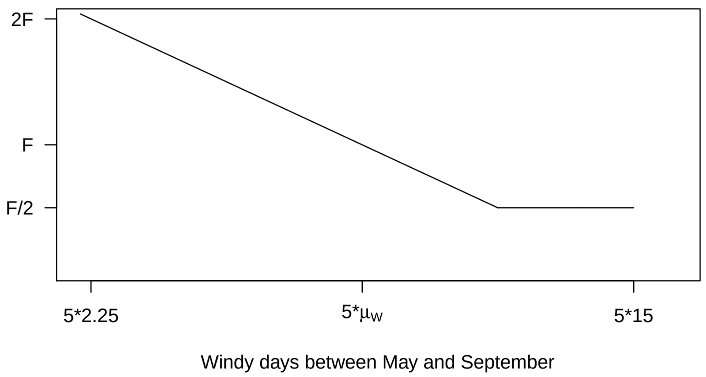

Figure 3: Fishing pressure of the EHCR as a function of windy days during the spawning season (May to September).

wind and simulated catches from March to October of the next year when F is constant and equal to F^* (see section below).

Insurance scheme

The notional insurance scheme presented here is similar to that presented in Mumford *et al.* (2009) and it is based on insurance plans used for agricultural management. It provides some representation of how an insurance regime can perform in fisheries as an indicator of the value of uncertainty. Insurance payouts are calculated from simulated revenue time series to define a maximum insurance payout and a premium. Premiums are saved in a mutual fund with a pre-set limit and the excess above that cap is covered by commercial reinsurance. The cost of premiums for this notional insurance plan is a comparator for the value of different rules that affect the mean and variability of yields.

Insurance calculation

A constant price ($\mathbf{p}$) was assumed of 0.23 euros for one individual anchovy. The annual revenue (in millions of euros) is calculated by multiplying the simulated annual catch in numbers (millions of individuals) by the fixed price. Average revenue ($\overline{\Pi}_{y,s}$) is calculated based on the preceding five years, as follows:

$$\overline{\Pi}_{y,s} = \mathbf{p} * mean(C_{y-6,s}, \ldots, C_{y-1,s})$$

Where $C_{y,s}$ represents annual catches. Compensation, $IP_{y,s}$, (annual Insurance Payout) from the notional insurance scheme is paid if this annual revenue falls below the the average revenue and it is calculated as the difference between the values:

$$IP_{y,s} = \begin{cases} \overline{\Pi}_{y,s} - C_{y,s} * \mathbf{p} & \text{if } C_{y,s} * \mathbf{p} < \overline{\Pi}_{y,s} \\ 0 & otherwise. \end{cases}$$

The 75th percentile of all simulated payouts is set as the maximum compensation paid by the insurance scheme ($MaxIP$), the upper tail of compensation payouts is paid by a reinsurance fund. Annual premiums paid directly by the policy holders are saved in a mutual fund that is allowed to grow to an arbitrary pre-set limit, set at twice the maximum compensation ($2 * MaxIP$). Premium contributions are suspended while the fund is at or above its limit that year. The fund works in the following way: it is allowed to borrow money if needed during the first 10 years at 8% interest; conversely, the money not used for payouts is invested at a 5% annual rate of interest and surplus interest dividends are returned to policy holders yearly:

$$Fund_{y+1,s} = \begin{cases} Fund_{y,s}(1 + BR) + Premium - IP_{y,s} & \text{if } Fund_{y,s} < 0 \\ Fund_{y,s}(1 + IR) + Premium - IP_{y,s} & \text{if } 0 \leq Fund_{y,s} < 2 * MaxIP \\ Fund_{y,s} - IP_{y,s} & \text{if } Fund_{y,s} > 2 * MaxIP \end{cases}$$

Where BR and IR stand for borrowing and investment rates, respectively. In the third case (when $Fund_{y,s} > 2 * MaxIP$) a dividend equal to $Fund_{y,s} * IR$ is paid to the policy holders to bring the fund back down to its pre-set limit (see Figure 4).

Hence, the annual premium is defined as the minimum premium required such that the insurance fund raised is enough to cover up to the maximum compensation for all simulations and all years except for the first ten years. In those ten years if there is

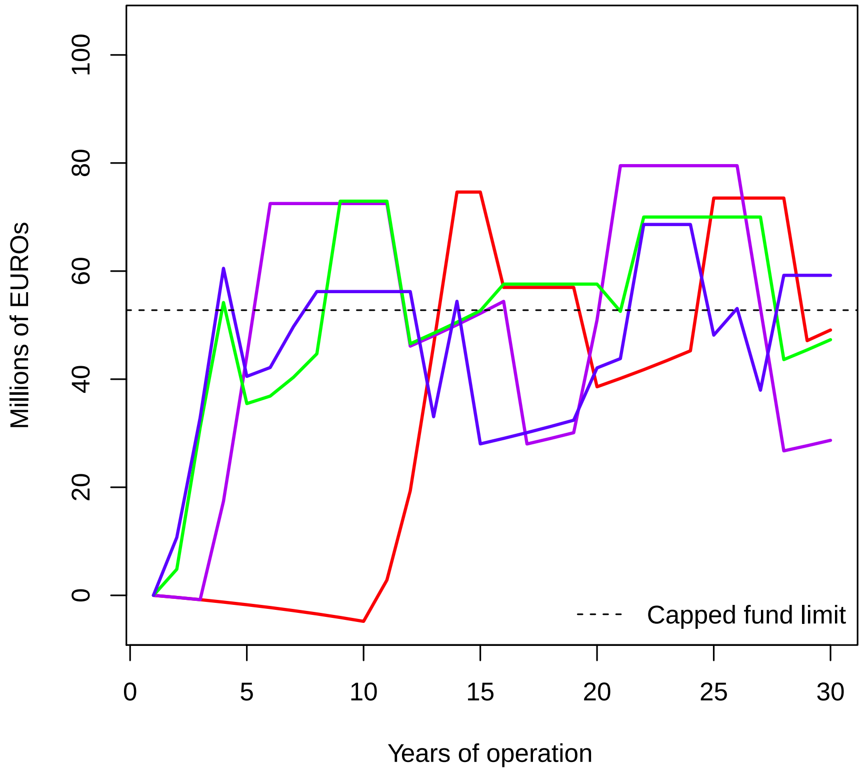

Figure 4: Building an insurance fund over 30 years under EHCR regime. Each coloured line represents a simulation. Note that the fund value (y-axis) sometimes exceeds the pre-set upper limit of the fund because of the fixed premium level, but it drops back to the pre-set limit soon after because premiums stop until the fund falls below the limit again as a result of payouts.

any shortfall and money in the fund plus the fixed premium is not enough to cover the payment, it is possible to borrow money, aiming to reach the fund limit by year ten.

The upper 25% of annual payouts are covered with a reinsurance plan which makes it a bit more expensive, but less likely to collapse. Reinsurance payout ($ReP_{y,s}$) is the difference between any annual payout and maximum compensation paid by the fund:

$$ReP_{y,s} = \begin{cases} IP_{y,s} - MaxIP & \text{if } MaxIP < IP_{y,s} \\ 0 & otherwise. \end{cases}$$

Finally, reinsurance premium ($RePremium$) is calculated as the expected value of all annual reinsurance payouts plus the 25% of that value, where the 25% is the profit for the reinsurance plan:

$$RePremium = mean_{y,s}(ReP_{y,s}) * 1.25$$

Data

Catches and *CPUE* data were extracted from ICES reports. Deterministic values of the model were taken from the literature and two experts were consulted for their knowledge, following the assumption that if data were not available from the same stock, they should be taken from the closest (genetically and geographically) stock under a similar exploitation pattern. From data of the Gulf of Cádiz systematically sampled during 4 years (Millán, 1999), we extracted constant parameter values including a 1/1 sex-ratio ($sexr = 0.5$), an average length of maturity equal to 11.2 cm (for females) corresponding to 11 months old individuals, and $a = 0.0029$ and $b = 3.3438$ for the power length-weight relationship. The number of eggs spawned per gram $fec = 500\ eggs\ g^{-1}$ was approximated from a review on spawning traits of 22 anchovy stocks in European waters (Somarakis *et al.*, 2004).

Historical records from 1996 to 2004 used to simulate environmental covariates, sea surface temperature (SST), discharges from the Alcalá del Río reservoir and wind, were obtained as follows: SST was extracted from the Advanced Very High Resolution Radiometer (AVHRR) sensor data. The nighttime AVHRR PATHFINDER SST v5 weekly means with $4 \times 4\ \ km^2$ pixel resolution were taken from NASA PO.DAAC website (http://podaac.jpl.nasa.gov/). The region of interest was acquired from the global image and arithmetic means were calculated based on all pixels within this region. Discharges were provided by Confederación Hidrográfica del Guadalquivir. They correspond to the monthly accumulated cubic hectometers that are discharged from the reservoir each month. Wind data are the weekly accumulated time (in days) that easterlies faster than 30 kmh^{-1} have been recorded in the meteorological station of Cádiz.

Implementation

Population and insurance models were implemented in R (R Development Core Team, 2011) to simulate 1000 iterations. The model was initialised with values taken from a run long enough to stabilise the model values, and the results for a period of a further thirty simulated years were analysed in this paper.Simulations were implemented for two different approaches, one using the environmental harvest control rule (EHCR), and other with a constant $F, F = F^*$ (HCR1) in 5 different scenarios:

- **Base model:** Standard deviation of discharges equal to 0.4, reference monthly fishing mortality equal to 0.04, and environmental parameters, λ for wind and ρ for discharges, equal to 0.15 and 0.4, respectively.

- **Greater discharge variability:** Standard deviation of discharges equal to 0.6, reference monthly fishing mortality equal to 0.04, and environmental parameters, λ for wind and ρ for discharges, equal to 0.15 and 0.4, respectively.

- **Higher F:** Standard deviation of discharges equal to 0.4, reference monthly fishing mortality equal to 0.045, and environmental parameters, λ for wind and ρ for discharges, equal to 0.15 and 0.4, respectively.

- **Sensitivity to λ:** Standard deviation of discharges equal to 0.4, reference monthly fishing mortality equal to 0.04, and environmental parameters, λ for wind and ρ for discharges, equal to 0.13 and 0.4, respectively.

- **Sensitivity to λ and ρ:** Standard deviation of discharges equal to 0.4, reference monthly fishing mortality equal to 0.04, and environmental parameters, λ for wind and ρ for discharges, equal to 0.12 and 0.3, respectively.

The base case was arbitrarily chosen as a default in order to have something to compare other scenarios to. Other combinations of parameters might be plausible and we explored some of those during model testing. Several alternatives are presented, in particular with respect to early survival. The combined effect of lambda and rho parameters define juvenile survival, which needs to be high enough for the population not to collapse.

Results

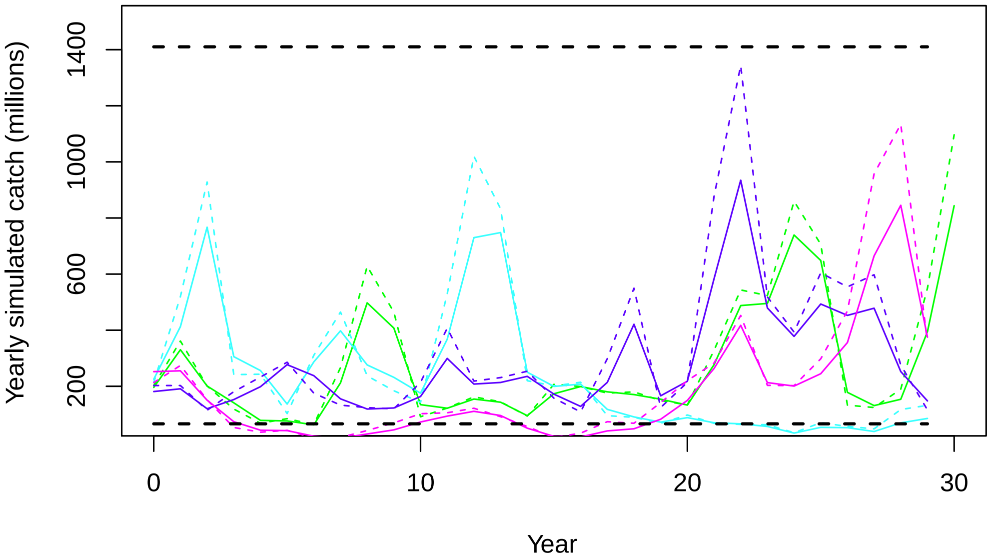

Figure 5: Random simulated catches under two regimes, one with a constant fishing mortality (solid lines) and the other with an environmental harvest control rule (dotted lines). The black dashed lines represent minimum and maximum of annual catches in millions of individual fish registered by ICES from year 1988 to 2005.

As an example of simulated annual catches, Figure 5 shows some random trajectories of simulated catches under the two management regimes in the base model (Solid lines for HCR1 and dotted for EHCR). Maximum number of eggs (ME) was chosen such that 96 % of simulated catches under EHCR have values below 1410 million of individual fish, which is the maximum annual catches registered by ICES (dashed black lines).

The aforementioned strong correlation between windy days from May to September and simulated catches from March to October in the next year for all the simulations is showed in Figure 6. Also, the Pearson's product moment correlation coefficient is equal to -0.66 with $p < 2.2 * 10^{-16}$, which is consistent with the choice of windy days from May to September in the environmental harvest control rule.

To measure the value of environmental information, average annual yield, average

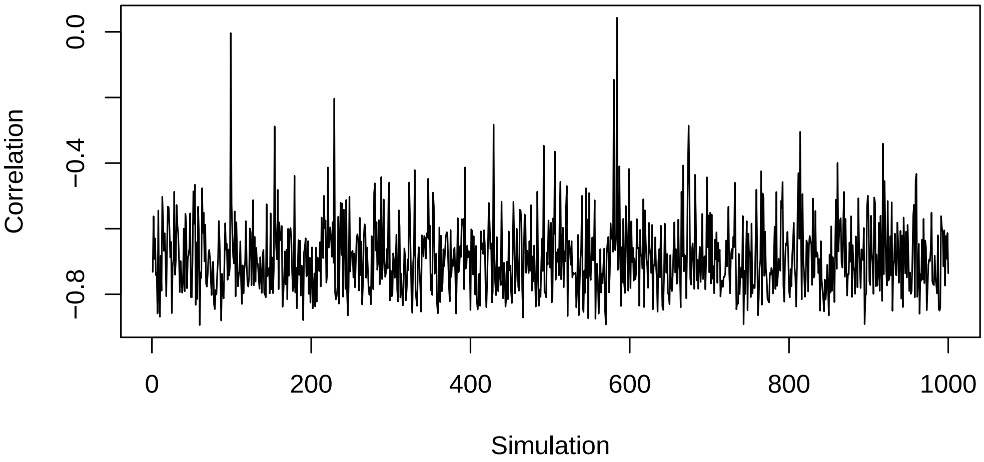

Figure 6: Correlation between wind from May to September and simulated catches from March to October in the next year for all the simulations.

insurance premium, reinsurance premium, difference between average annual yield and premiums, standard deviation and coefficient of variation for annual yield, and probability of collapse, were calculated for both approaches in all the scenarios (Tables 1 and 2). Probability of collapse was defined as the probability of having a spawning season with a number of eggs less than 10 % the maximum number of eggs.

	Base model		Greater disch. var. Disch.sd=0.6		Higher F Ref. $F = 0.045$	
	HCR1	EHCR	HCR1	EHCR	HCR1	EHCR
Ave. Annual Yield in mil of euros	52.70	59.00	17.20	18.80	52.60	59.30
Ave. Premium mil euros	8.64	10.90	2.47	2.75	8.34	10.40
ReIns Premium mil euros	6.31	8.39	4.45	5.49	7.08	9.19
Ave. yield - Ave. premiums	37.70	39.70	10.30	10.60	37.20	39.60
SD Yield	39.20	49.50	23.90	28.00	42.50	52.40
CV %	74.40	83.80	139.00	149.00	80.90	88.40
Prob. of annual stock crash %	3.98	2.54	43.00	41.30	6.43	4.19

Table 1: Comparison between using and not using an environmental HCR. First two columns are for the base model, the other columns are for test of values for standard deviation of simulated discharges and reference F in the base model. Annual yield and premiums are in millions of euros while coefficient of variation (CV) and probability of annual stock crash are in percentages.

In all the cases EHCR produces a higher average annual yield and a higher difference between yield and premiums when compared with HCR1. Although the variability and

	Sensitivity to λ $\lambda = 0.13$		Sensitivity to λ and ρ $\lambda = 0.11$ and $\rho = 0.3$	
	HCR1	EHCR	HCR1	EHCR
Ave. Annual Yield in mil of euros	81.40	89.70	28.50	31.70
Ave. Premium mil euros	12.60	16.50	4.01	4.91
ReIns Premium mil euros	7.42	10.20	3.80	4.98
Ave. yield - Ave. premiums	61.40	63.10	20.70	21.80
SD Yield	46.30	61.30	23.90	28.50
CV %	56.90	68.40	83.80	89.80
Prob of annual stock crash %	0.14	0.05	13.50	10.30

Table 2: Comparison between using and not using an environmental HCR. Test of values for λ (two first columns) and, ρ and λ (last two columns) in the base model. Annual yield and premiums are in millions of euros while coefficient of variation (CV) and probability of annual stock crash are in percentages.

premiums cost increases under this approach, the probability of stock crash is reduced in all the scenarios, in particular when the fishing mortality is increased.

When there is a greater discharge variability, the difference between annual yield and premiums is higher under the environmental approach but with a very small difference compared with the non-environmental approach. In addition, the collapse probability and coefficient of variation are the highest compared with the other scenarios. These facts suggest that if discharge variability increases, perhaps it will be necessary to consider a harvest control rule including the effect of discharges on survival.

The highest average yield is obtained when λ value is reduced, but premiums also increase. This scenario shows a lower coefficient of variation and reduces substantially the collapse probability.

Discussion

The management scenarios considered in this paper represent a risk-based precautionary approach which differs from the current strategy. The target fishing mortality is chosen to lie below F_{MSY} which was a value found by performing simulations with different fishing mortalities to find the one that on average produced highest average yield in stochastic simulations over the period of 30 years. However, the notion of F_{MSY} itself may not be applicable in highly dynamic fisheries such as Anchovies. In our model, we assumed that most mortality is caused by discharges since historical records show stock collapse during periods of catastrophic droughts. However, during standard years when these exceptional catastrophes are not present, the variability from cohort to cohort is mainly driven by the frequency of strong winds. Given such variability, a constant fishing mortality aimed at MSY management will either over-exploit a given cohort or under-exploit it. We attempted to introduce a more flexible management by varying exploitation in tandem with environmental factors which strongly influence cohort strength. Unlike other attempts to include ecosystem concepts in fishery management (Pikitch *et al.*, 2012), we have not considered ecological interactions arising from the need to account also for predator conservation, instead our criteria for management involved only economic criteria and a desire to avoid stock collapse. In this paper we attempt to use a simulated insurance scheme in order to measure the value of using environmental information that can predict recruitment strength. Lower insurance premiums would indicate a lower economic risk. The preliminary results indicate that making the HCR responsive to the environmental information does not lower economic risk in the sense that profit volatility increases. However, adapting to environment appears to benefit biological sustainability as measured by lower risk of recruitment failure and also mean yield increases sufficiently to allow insurance to compensate for the increased volatility using EHCR. These findings seem to be robust to alternative scenarios regarding environment and fishing. The relevance of this analysis to actual management practice depends strongly on the plausibility of assumptions in the operating model. We have tried to develop a model that describes anchovy dynamics in accordance with scientists' beliefs and consistent with available data, but there remains a possibility that the model differs from reality in ways crucial to the inferences made from the analysis. We have considered several alternatives to the base case, but such analysis is limited. For instance, we have looked at single deviations from the base case thus ignoring interactive potential of such differences. Further, we have relied on a narrow range of scientific expertise and have not sought opinions of other stakeholders. A more inclusive evaluation could have relied on a wider range of opinions about the modelling of Anchovy population in the Gulf of Cádiz which could have led to a different description of processes both in terms of parameters and functional relationships. Discussions with managers could have yielded alternative ideas for including environmental information with the decision making. Such evaluations, albeit higherly desirable are unfortunately beyond the resources available to us at this time. However, the examples discussed in this paper are sufficient to demonstrate the principles of the approach.

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CHAPTER

3

Recruiting at the Edge: Kinetic Energy Inhibits Anchovy Populations in the Western Mediterranean

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Recruiting at the Edge: Kinetic Energy Inhibits Anchovy Populations in the Western Mediterranean

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Abstract

The Strait of Gibraltar replenishes the Mediterranean with Atlantic waters through an intense eastward current known as the Atlantic Jet (AJ). The AJ fertilizes the southwestern Mediterranean and is considered to be the ultimate factor responsible for the comparatively high fish production of this region. Here, we perform an analysis of the available historical catches and catch per unit effort (CPUE), together with a long series of surface currents, kinetic energy and chlorophyll concentration. We show that the high kinetic energy of the AJ increases primary production but also negatively impacts the recruitment of anchovy. We contend that anchovy recruitment in the region is inhibited by the advection and dispersion of larvae and post-larvae during periods of strong advection by the AJ. The inhibitory impact of kinetic energy on anchovy landings is not a transient but rather a persistent state of the system. An exceptional combination of events creates an outbreak of this species in the Alboran Sea. These events depend on the Mediterranean-Atlantic exchange of water masses and, therefore, are highly sensitive to climate changes that are projected, though not always negatively, for fish landings.

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Introduction

The Alboran Sea (Figure S1) is the door to replenish with Atlantic waters the Mediterranean basin, where evaporation rates and deep outflow cannot be compensated by river discharges and atmospheric precipitations. Replenishment occurs via an intense eastward current, commonly named the Atlantic Jet (AJ), through the Strait of Gibraltar. The persistence and energy of the AJ, with standard velocities of $1ms^{-1}$, drive the circulation of the Alboran Sea [1]. The climatological features of this basin typically include a western and an eastern anticyclonic gyre (WAG and EAG, respectively; see Figure S1), but circulation snapshots with one, three or even no gyres are also common [2–4]. This diversity emerges from changes in the intensity and direction of the AJ that are driven by seasonal oscillations [5], by variations in the atmospheric pressure of the western Mediterranean [6] and by the wind stress in the Strait of Gibraltar [7].

Circulation instabilities manifest as complex meso- and sub-mesoscale processes that fertilize the surface waters of the basin [8]. Positive vorticity enhances the production in offshore waters between WAG and EAG [9]. Cyclonic circulation forced by the AJ at the northwestern shelf of the Alboran Sea also increases the production of this area, particularly under westerly winds that strengthen the jet [10] and trigger coastal upwelling [11]. Vertical dynamics at the WAG edge [12,13] and horizontal advection from the shelf or even from the Atlantic side of the strait [8,14,15] create a strip of high chlorophyll levels following the AJ around the anticyclonic gyres. All together, these mechanisms make the Alboran Sea a productive sub-basin [16] that eludes the severe oligotrophy that characterizes the Mediterranean [17].

The elevated primary production of the Alboran Sea should result in potential fish landings that are comparatively high when contrasted to the oligotrophic Mediterranean, particularly for small pelagic species [18]. Due to its economic value, European anchovy (*Engraulis encrasicolus*) has been the main target species for purse seines since the late 1960 s [19]. Similar to other anchovy fisheries [20], landings in the Alboran Sea are mainly based on age-0 recruits and have strong interannual variability [19]. However, major freshwater inputs known to force anchovy catches at the nearby Gulf of Cadiz [20], the Bay of Biscay [21] and the Catalan Sea [22] are absent in the Alboran basin, and the origin of landing fluctuations has remained largely unknown.

The fish in this area have most likely adapted to the prevailing hydrodynamic regime and narrow shelf. In the Alboran Sea, anchovy spawn from late spring to early autumn at $T > 19^{o}C$, and recruits enter the fishery in the same year [23,24]. Several authors identify the protection from intense currents provided by Malaga Bay as being an important factor for spawning and nursery grounds for small pelagic species in the north Alboran Sea [25–29]. However, these areas are strongly affected in their southern regions by the AJ, which alters the composition of the ichthyoplanktonic fish assemblage by transporting early stages away from the coast into the highly dynamic Alboran Sea and is able to transport mesopelagic larvae inshore via vertical upwelling [30]. It is expected that the AJ dynamics, including north-south excursions, will have an impact on the subsequent recruitment of species, particularly on small pelagic, which are known to be very sensitive to the physical environment [31]. However, the available knowledge on the environmental control of anchovy recruitment in the area, which seems largely unconnected to the spawning stock biomass in the last decades [24], remains speculative and based upon short-term analyses of growth and/or condition [27].

In this paper, we perform an extensive analysis based on the joint signals provided by available historical fisheries records and data from remote sensors for surface currents, kinetic energy (KE), temperature and chlorophyll. Based on this analysis, we conclude that anchovy recruitment in the Alboran Sea is highly linked to the dynamics of the AJ and the associated circulation features in the basin. An anomalous environment results in success rather than failure in recruitment. The standard state of the basin is highly energetic because of the jet. This jet enhances primary production but consistently creates adverse conditions because it advects and disperses the early life-stages of anchovy. Anomalous years with lower levels of kinetic energy result in high recruitment and subsequent landings.

Results

Figure 1.a shows a manifest peak in the yearly landings and catches per unit effort (CPUE) during 2001 and 2002. Variations in landing and CPUE are not originated by changes in the effort since fluctuations in the gross registered tonnage of purse seiners are small (Figure S2) and the number of vessels targeting anchovy shows a smooth decreasing tendency along these years [24]. Despite the March/April closure of the fishery, monthly landings for the peaking years (insert in Figure 1.a) identify a strong recruitment in 2001 that was able to sustain high catches throughout the winter until February of 2002. Figure 1.a shows that the Julian calendar creates an artifact in the analysis of recruitment data. The high landings of 2002 are the consequence of a successful recruitment in the spawning season of 2001, not in the year 2002 (insert in Figure 1.a). Monthly landings were then aggregated from August to the next July (Figure 1.b), accumulating the production after each spawning season. This representation indicates the very anomalous recruitment of the year 2001 that resulted in landings more than twice the size of the second maxima in the series. Figure 1.b also shows the sensitivity of the stock to environmental conditions: high recruitment occurs during years of negative phase in the North Atlantic Oscillation (NAO) but the NAO alone is not enough to fully explain the recruitment fluctuations. Thus, the main peak of 2001 is not associated with the lowest NAO and the negative NAO in 2006, 2009 or 2010 does not result in high landings.

The potential connection of this high-recruitment signal with enhanced primary production or a thermal change in the basin is explored in Figure 2. The figure shows the primary production of the shelf dynamical region [32], where anchovy nurse and recruit [33]. Figure 2.a shows the monthly average of sea surface temperature (SST) in the same region as derived from the Pathfinder data. No remarkable feature seems evident in the thermal signal of 2001. Figure 2.b shows the concentration of chlorophyll for the same area as derived from the GlobColour project. The high recruitment of 2001 did not coincide with sustained high concentrations of chlorophyll throughout that year. Instead, chlorophyll fell abruptly in autumn toward the persistent minima of the series.

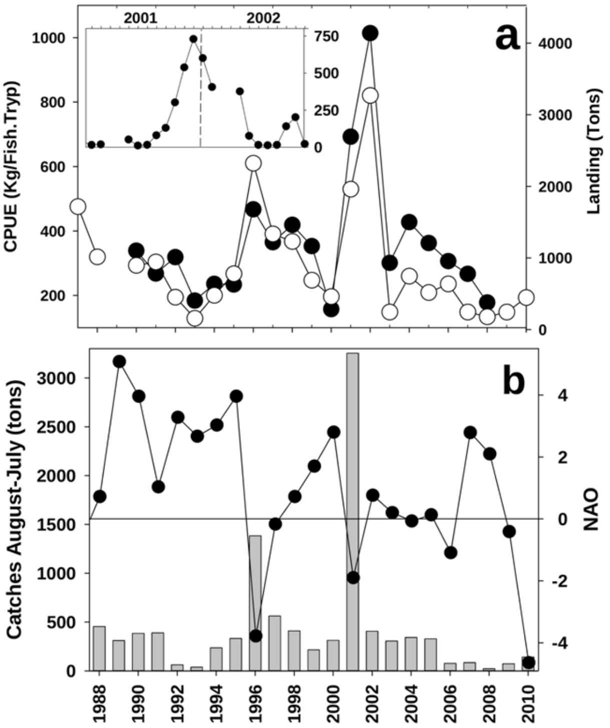

Figure 1. Anchovy fishery at the Alboran Sea. a) White and black circles are landings and CPUE respectively. The insert shows monthly landing (Tons) at the period of maximum catches. b) Bars show the accumulated catches between August and July of the next year (assigned to the first of the two years involved) and circles the value of the NAO index.
doi:10.1371/journal.pone.0055523.g001

Chlorophyll in the western Alboran Sea is highly sensitive to the circulation of the AJ-WAG system [32]. Singular value decomposition (SVD) of the absolute dynamic topography (ADT) and sea surface chlorophyll (CHL) fields synthesizes this sensitivity in the expansion coefficient of the ADT second mode [17]. Figure 2.c shows the temporal evolution of this mode. This mode is also atypical in 2001, with an abrupt downward shift after spring and summer toward the minima of the series. Low values of the expansion coefficients of this mode imply a weakening of the circulation system [17].

Figure 3 explores this weakening through monthly composites of the geostrophic circulation and kinetic energy in the Alboran Sea during the period of these abrupt changes. As a contrast with a more standard situation, Figure 3 also shows composite images of the year 2000. From March 2000 to February 2001, the circulation stabilizes in the typical pattern of the basin. The AJ encircles the WAG and then meanders northeastward after reaching Cape Tres Forcas in the African coast ($\sim 3^{\circ} W$) to round the eastern anticyclonic gyre (only partially seen in the figures), cyclonic circulation is observed between both of the gyres. From March 2001 to January 2002, the circulation is very different. During this period, the AJ does not meander northward after Cape Tres Forcas but remains flowing eastward close to the African coast. The energy of the system decreases, particularly after October 2001, when the AJ is not strong enough to activate stable structures in the basin circulation. The consequences for the chlorophyll distribution of these circulation features during 2001 are explored in Figure 4 (Figures S3 S4, S5, S6, S7, S8, S9, S10, S11, S12 provide the full series of chlorophyll and SST from 1998

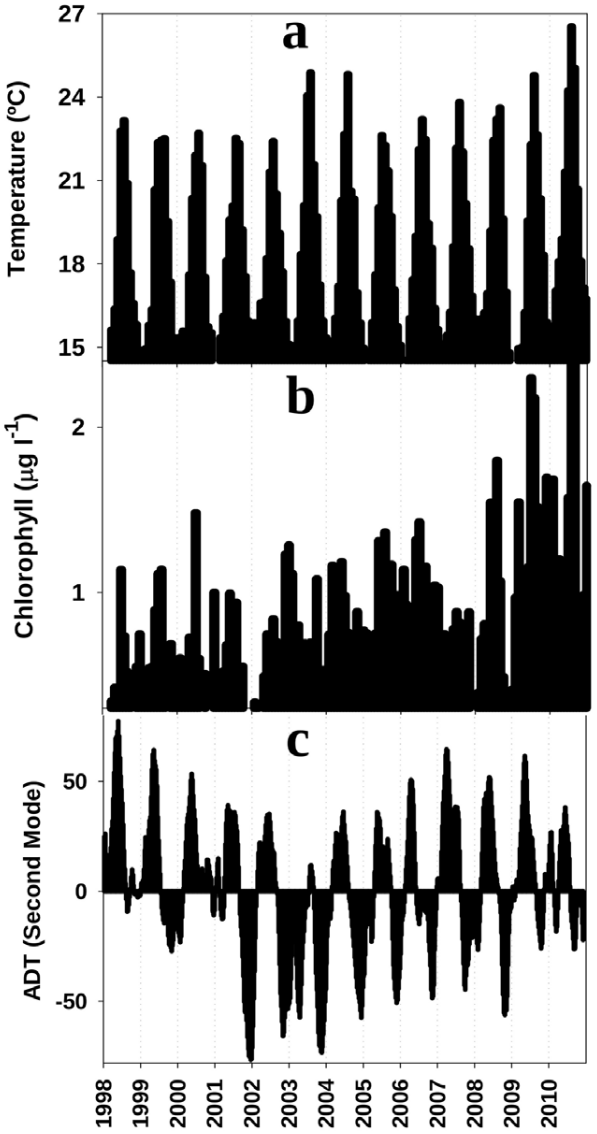

Figure 2. Time series of SST, chlorophyll and ADT mode. Monthly averages of (a) SST and (b) chlorophyll concentration in the northwestern shelf of the Alboran Sea. b) Temporal evolution of the expansion coefficients of the ADT second mode after a coupled singular value decomposition between ADT and CHL fields. Data of this mode were obtained from [17].
doi:10.1371/journal.pone.0055523.g002

to 2011). Chlorophyll remains high during spring and early summer, when the AJ is visible as an elongated zone of high chlorophyll. This feature diminishes after July and disappears after October.

There is no evident connection between proxies for abundance (CPUE) and chlorophyll at the time of spawning (Figure 5.c; $r=-0.403, p>0.15$), when early stages demand high food concentrations. Despite the control that temperature may exert on the survival of fish larvae [34], the correlation between SST during the spawning season and subsequent catches is also low (Figure 5.a; $r=-0.332, p>0.20$). Large-scale environmental indexes, such as NAO, also exhibit poor explanatory power (Figure 5.b; $r=-0.295, p>0.30$), and only ADT at the time of recruitment seems to be connected with catches (Figure 5.d; $r=-0.625; p<0.05$). Moreover, a time-lag analysis of recruitment shows that this (0-lag) correlation between ADT and recruitment is the only significant correlation in the series.

In addition to this correlational analysis, a test for one outlier based on a chi-squared distribution of squared differences between the data and sample means [35] was applied to the series of recruitment, SST, chlorophyll and ADT. As in Figure 5, the analysis was implemented for the period between 1998 and 2010, when information is available for all of the environmental variables. The test does not identify as an outlier the chlorophyll in the spawning period of 2001. Additionally, the test does not identify as an outlier the SST in 2001 either at the period of spawning or during the recruitment period. In contrast, the ADT and recruitment during 2001 are the unique outliers of their respective series, with $p<0.05$ and $p<0.01$, respectively. The conditional distribution for the number of coincidences, K, of two outliers in two independent discretized paths of length N is described by the following hypergeometric distribution [36]:

$$P(K=k|C_1=c_1,C_2=c_2)=\frac{\binom{c_1}{k}\binom{N-c_1}{c_2-k}}{\binom{N}{c_2}} \qquad (1)$$

where C_1 and C_2 are the number of outliers in each series. For the analysis presented here, $N=13$, k,c_1, and $c_2=1$ because the chi-squared test detected only one outlier for each of the ADT and recruitment series. This combination results in a low probability (0.077) of ADT and recruitment outliers to randomly coincide in the same year of the series.

Discussion

The year 2001 stands out in the time series analyzed as a strong outlier in both circulation and anchovy recruitment. No coherent signal is observed in other small-pelagic fisheries like sardine and mackerel (Figure S13) or round sardinella [37] what might have suggested an interspecific-interaction origin for the anchovy peak. The landings of these species in 2001 and 2002 are around the series average and there is no evidence of any particular direct, inverse or lagged relationship between anchovy and sardine, mackerel or round sardinella populations at the short term. Together with the correlations emerging from Figure 5, this pattern is an improbable random coincidence that provides evidence to ground the extreme recruitment in that year on the exceptional environment forced by circulation. Indeed, the recruitment of short-lived pelagic species, such as anchovy, is very sensitive to hydrodynamics because of the hydrodynamic control over the trophic environment at spawning areas [38,39]. Hydrodynamics also have the potential to advect early life stages with reduced motility away from environments that are suitable for recruitment. Marine areas that are optimal for the successful recruitment of clupeoids frequently have relatively high primary production but low advection and turbulence [40,41].

These conditions do not easily occur together in the Alboran Sea. This basin is productive but as a result of the very intense dynamism forced by the AJ. Thus, the fertilization necessary to produce food for early stages is accompanied by strong currents that are able to advect these stages away from the spawning place. The intensity of this egg and larval transport is well known. There are reported cases of advection within the AJ of fish larvae from the north coast toward deep waters south in the basin [42]. Three-dimensional displacements of anchovy larvae in the intense

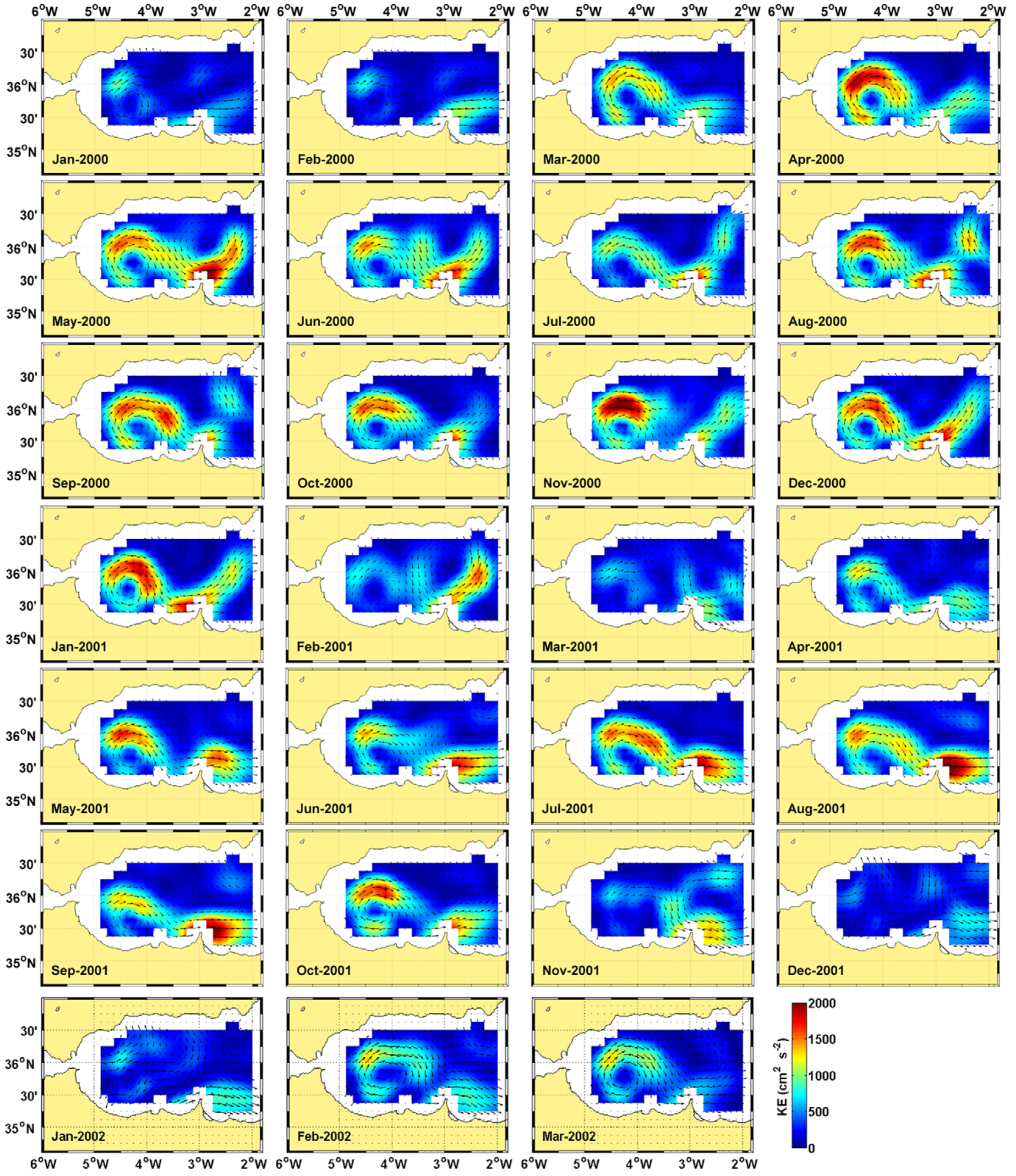

Figure 3. Circulation in the Alboran Sea. Monthly composites of geostrophic circulation and kinetic energy derived from altimetry data.
doi:10.1371/journal.pone.0055523.g003

mesoscale circulation forced by the AJ have also been reported [30]. Larvae removal from the shelf is only activated during northward excursions of the AJ, whereas a jet flowing away from the north shelf contain no anchovy larvae [30]. Indeed, the capacity of a northward-oriented AJ to remove anchovy larvae from the Iberian shelf is very strong. Events of neritic fish-larvae being massively swept away from the northwestern shelf by the AJ are frequently recorded [43]. During these events, most of the shelf is occupied by oceanic larvae that are advected from the open ocean within the AJ.

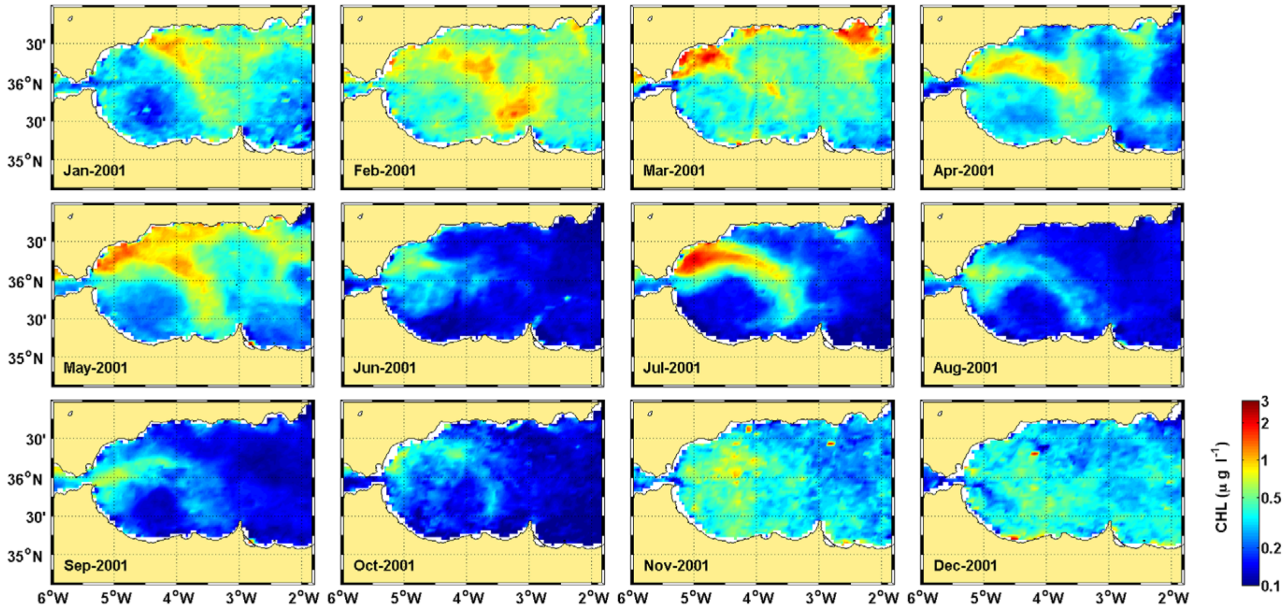

Figure 4. Monthly composites of chlorophyll concentration in 2001.
doi:10.1371/journal.pone.0055523.g004

We postulate that these reported cases and the results presented here reveal the tight control that the AJ exerts over the anchovy recruitment in the Alboran Sea. The field studies of ichthyoplankton in the area demonstrate beyond question the capacity of a strong AJ to sweep neritic larvae from the shelf. This capacity depends on the strength of the AJ-WAG system, as diagnosed in Figures 2, 3 and 5. Its operation over the years analyzed here, 1998 to 2010, connects the signals of AJ-WAG strength/weakness

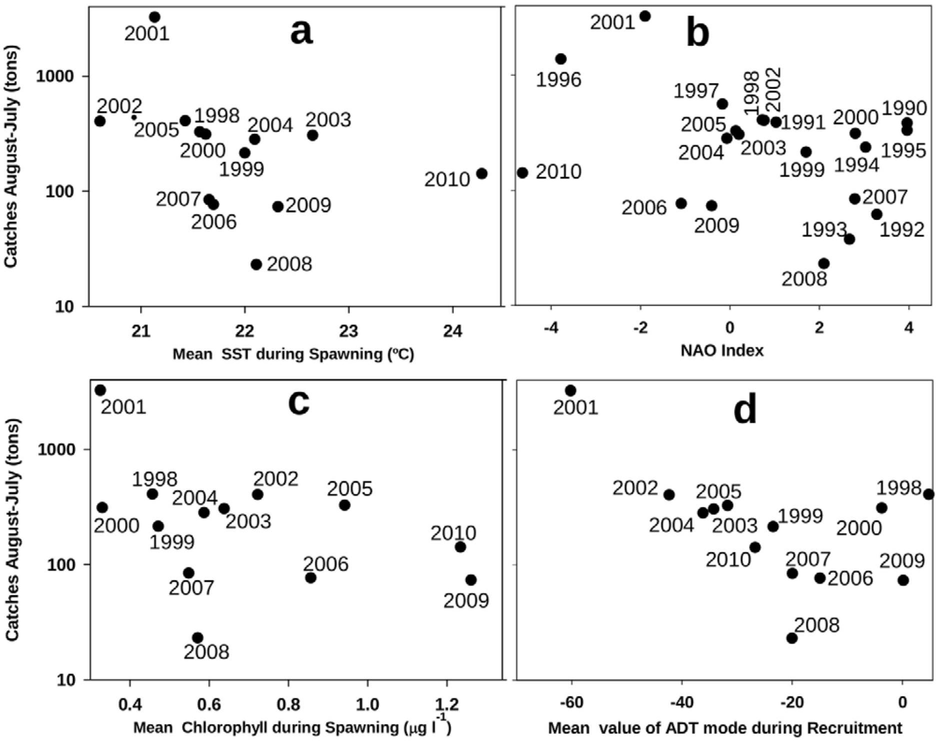

Figure 5. Recruitment versus SST, NAO, chlorophyll concentration and ADT mode. The figure shows the landing of Fig. 1.b versus the mean of (a) SST and (c) chlorophyll concentration at the shelf during spawning period (June to September) as well as (b) the NAO index and (d) the expansion coefficient of the ADT second mode during recruitment (October to December).
doi:10.1371/journal.pone.0055523.g005

(Figures 2.b and 3) and recruitment failure/success (Figure 1.b) during this period. The AJ-WAG system is too energetic during standard years to favor a successful recruitment. The intense AJ-WAG system forces surface fertilization and high chlorophyll concentration during typical years (Figure 2). However, the positive influence of this fertilization on recruitment is strongly counterbalanced by the advection resulting from energetic currents. Recruitment might be dampened due to spatial constraints imposed by the AJ on the spawning and nursery grounds, most likely affecting the amenable area rather than the available food. Other environmental factors, such as temperature, seem to play a minor role in the process (Figure 5.a–b). The weakness of the AJ-WAG system during the year 2001 creates an exceptional setting over this background scenario of high productivity and high advection. The unusual circulation releases most of the northern Alboran Sea from the intense currents of the eastern Alboran gyre, the cyclonic circulation between anticyclones and even of the WAG after October (Figure 3). During late spring and summer, the AJ-WAG is weak but is not totally shut down (April to October 2001 in Figure 3) and still allows high chlorophyll concentrations (Figures 2 and 4). After summer, the AJ-WAG system weakens to such an extent that it disappears from the basin, and the amount of energy is too low to firmly activate fertilization mechanisms. This cessation of the AJ-WAG system during three months (from November 2001 to January 2002) is exceptional in the series of altimetry images (Figures S14, S15, S16, S17, S18). The exceptionality of this period in the circulation of the Alboran Sea is also confirmed by the time series of basin currents as reconstructed through modeling [44]. Under these conditions, the production of the shelf persistently decreases toward the lowest values of the series (Figure 2). The lack of fertilization at the northwestern shelf is also evident from field studies in this period [45]. Therefore, there seem to be two phases of the AJ-WAG system in 2001: a first period of anomalous weakness during spawning in spring/summer and a full collapse during recruitment in autumn/winter.

The amount of production during spawning cannot explain the successful recruitment of 2001 because the mean chlorophyll of that year is the lowest of the series (Figure 5). The phytoplankton data suggest a profound trophic shift at the northern shelf of the Alboran Sea during 2001 and early 2002, as revealed by the substitution of the diatom-dominated community by a coccolithophorid and dinoflagellate community [45]. This shift agrees with a less dynamic environment in which diatom-based communities are not favored [46]. Further, dinoflagellates and protists have been found in other areas at greater proportions than diatoms in the gut of young anchovy [47,48], thereby reinforcing the evidence that the food environment was not adverse for anchovy larvae during the spring and summer of 2001. This situation is also supported by estimates of the daily growth (based on otoliths) of anchovy larvae in the northern Alboran Sea, with enhanced growth in the 2001 spawning season [27]. Consequently, the weakening of the AJ-WAG system favors retention in the shelf but, despite the concomitant decrease of primary production, apparently had no negative effect on the food available to anchovy larvae and postlarvae during early 2001.

However, the trophic environment becomes very adverse in autumn/winter because primary production collapses with the collapse of the AJ-WAG system (Figure 2). Post-larval stages stay near the coast, but juveniles increasingly spread over the shelf as the season progresses, and a larger size provides these juveniles more motility [49]. As their motility drives their behavior away from the planktonic realm, this change decreases the sensitivity to food concentration relative to that of earlier stages [50]. If physical forcing is relaxed, post-larval spread over stable areas may favor faster than usual growth even if production is reduced [21]. Several authors propose that small pelagic species use “continual testing” of the environment to take advantage of profitable spatial configurations that contribute to population resilience [51]. Indeed, during 2001, the northwestern shelf of the Alboran Sea had very low fertilization after summer, the period when the juvenile stages explore the shelf (Figures 3 and 4 [45]). Apparently, this lack of fertilization had no negative impact on the recruitment (Figure 1.b). The juvenile season of 2001 is the only period in the series when the AJ-WAG system persistently collapsed (Figures 2.b and 3). The consequences of this collapse on the survival of juveniles should be explored in the context of juvenile vs. larval stages as modulators of recruitment. The role of late larvae/early juveniles in shaping class 0 strength has received little attention but has supporting evidence and is frequently interpreted in terms of density-dependent mechanisms [52]. The velocities involved in a well-developed AJ-WAG system are too high ($\sim 1ms^{-1}$) for the system to be a suitable habitat for these stages. Thus, a severe weakening or cessation of the AJ-WAG system not only prevents the offshore transport of early stages with limited motility but also widens the portion of the shelf without energetic currents, thus providing a reduced density-dependent competition by increasing the amount of calm areas that are available to early stages. Anchovy largely constrains its recruitment to the northwestern shelf of the Alboran Sea what makes the stock extremely sensitive to the fluctuations of the local environment there, as described above. Other small pelagics with a broader distribution, like sardine, seem to be less sensitive to the local regime generated by the AJ as it enters the Mediterranean (Figure S13).

In summary, we contend here that anchovy recruitment in the region is inhibited by the advection and dispersion of larvae and post-larvae during periods of strong advection by the AJ. Food availability is not the primary limiting factor in the region. During standard years, the intense currents fertilize the region and sustain this anchovy stock but also keep recruitment very low. Exceptional years involve a weakening, but not a total collapse, of the AJ-WAG during spring and summer. This weakening provides adequate food and stability to larvae and postlarvae. The total collapse of the AJ-WAG after summer seems to have a positive effect on recruitment. These exceptional years open an optimal window (*sensu* Cury and Roy [40]) for a recruitment that is quasi-permanently kept at the edge by the AJ to shift to the right of the dome-shaped curve of [40] hypothesis. However, this shift involves such an improbable combination of events in the Alboran Sea that this window can only be qualified as extremely narrow in time and very sensitive to the circulation in the Strait of Gibraltar. This circulation is in a transient state due to modifications in the thermal and hydric balances of the Mediterranean [53], a scenario that will have consequences, though not necessarily negative, on future anchovy landings in the western Mediterranean.

Materials and Methods

Environmental control of the recruitment of small pelagic fishes is frequently analyzed in the context of meteorological records. This approach implicitly assumes that atmosphere-sea interaction somehow reflects the meteorological information into ocean circulation and biological production. Sea surface topography derived from satellite altimetry is more directly connected to ocean dynamics as a tracer of synoptic and high-resolution geostrophic circulation [54]. However, this information is less frequently explored despite now being available to the scientific community as accessible products and maps. This section describes the sources and nature of altimetry information in the context of its explanatory power for proxies for anchovy abundance in the Alboran Sea. This section also describes the sources of fishery records in the Alboran Sea as well as the origin of sea surface temperature and color data. The length of the time series is shorter for environmental (13 years) than for fishery (23 years) or NAO index data because the operation of the color sensor began in late 1997. Although the long set of catch data is used in the manuscript to show time tendencies and their connection with NAO, the joint analysis of recruitment and environment is restricted to the eleven years when a consistent set of data is available for both the fishery and environment.

Fisheries data

The anchovy recruitment in the North Alboran Sea is strongly dependent on the 0 age-class, and both landings and CPUE are frequently used as abundance proxies in the area ([24] and references therein). Several data sources have been used to compile the time series of anchovy landings and CPUE in the Alboran Sea. In addition, a precise analysis of the historical information for the small pelagic fishery in the basin is also available [55]. This analysis dates back to initial landings data from 1925, with increasing detail for more recent records. The continuation of that work [19,56] provided exhaustive information, including monthly landing and CPUE data disaggregated by species and port, for the period between 1985 and 1995. The General Fisheries Commission for the Mediterranean, through its annual assessment made by the Working Group on the stock assessment of small pelagic species, provides yearly landing and CPUE data since 1990. Monthly landing (but not CPUE) data are again available since the year 2000 from the website of the Regional Government (IDAPES database; www.juntadeandalucia.es/agriculturaypesca/idapes). Since 1999, the fishery is affected by closures during March and April; thus, the data contain gaps for these months and are excluded from the seasonal analysis.

The yearly catches analyzed in this paper include data after 1986, when this fleet only landed catches from fishing grounds north of $36^{\circ}N$ [55]. The port of Malaga registers almost 85% of all of the anchovy landings of the northern Alboran Sea, and after several corrections for anchovy fished elsewhere but disembarked at Malaga port, the data of anchovy landed in the Port of Malaga are routinely used to assess landings in the N. Alboran Sea [57]. The CPUE data from the General Fisheries Commission for the Mediterranean (GFCM) and other reports [19] exactly coincide at the years of overlapping (1990 to 1995), indicating that both are the same series of data. Since the late 1990s, the fishery has been closed between March and April, and the seasonal analyses presented in this paper exclude these years. All of the available assessments of this fishery indicate that recruits (age 0) support the bulk of the fishery [24], and therefore, that the peak of catches in autumn/winter are the result of spawning in the preceding spring/summer [24]. In addition, these assessments also indicate that CPUE is a good index for the relative abundance of spawners in the area [58], what is also evident in the averages of both age in catches ($0.63 \pm 0.23SD$) and the percentage of mature individuals at age 0 and 1 ($60.7 \pm 18.8SD$ and $95.8 \pm 6.6SD$ respectively) [24].

Altimetry data

The ADT data are delayed-time (dt) gridded and merged products with a spatial resolution of $1/8^{\circ}$ and weekly temporal resolution [59,60]. These data were provided by AVISO (http://www.aviso.oceanobs.com), covering the entire Mediterranean Sea and combining information from different missions, significantly improving the estimation of mesoscale signals [61,62].

The KE is calculated as:

$$KE = \frac{u^2 + v^2}{2}$$

where the velocity components, u and v, were derived from the geostrophic approximation:

$$u = -\frac{g}{f}\frac{\partial h}{\partial y}$$

$$v = -\frac{g}{f}\frac{\partial h}{\partial x}$$

where h is the ADT, g is the gravitational acceleration, and f is the Coriolis parameter.

To investigate the combined spatial and temporal covariability between ADT data and CHL, an SVD technique was employed [17]. The SVD was performed on the cross-covariance matrix between the non-normalized values of each field (CHL anomalies and ADT anomalies) to identify pairs of coupled spatial patterns and their temporal variation. The first SVD mode is associated to changes in the sea level of the whole basin in response to variations of atmospheric pressure, whereas the second mode synthesizes the dynamics of circulation structures that are able to control anchovy recruitment in the Alboran Sea [17].

Sea Surface Temperature data

The SST data used in this study correspond to AVHRR Ocean Pathfinder SST and MODIS L3 SST 4μ. The AVHRR Ocean Pathfinder SST data were obtained from the Physical Oceanography Distributed Active Archive Center at the NASA Jet Propulsion Laboratory, (http://podaac.jpl.nasa.gov/). We used the 4 km Pathfinder version 5 SST Project, which is a new reanalysis of the earlier AVHRR version of the Pathfinder data set that has been distributed since the early 1990s [63]. We used the monthly nighttime data and the period was comprised between 1998 and 2009. The MODIS L3 SST 4μ were obtained from the Oceancolor website (http://oceancolor.gsfc.nasa.gov). We used the monthly nighttime data with 4 km of spatial resolution for years comprised between 2010 and 2011.

Sea Surface Color data

Sea surface chlorophyll a data were downloaded from the GlobColour Project (http://www.globcolour.info/). This source produces global ocean color maps (Level-3) by merging data since 1998 from the three sensors SeaWiFS, MODIS and MERIS. Surface chlorophyll a data correspond to a product of chlorophyll a case I water based on the GSM merging method [64,65]. This method provides the best fit to in-situ chlorophyll a concentration and has the added advantages of providing other products and allowing researchers to calculate pixel-by-pixel error bars. With these data sets, the cloud cover is reduced, and therefore, more useful images become available. The spatial and temporal resolutions of these composite images were 4.6 km and monthly, respectively.

North Atlantic Oscillation index

The winter (December through March) index of the NAO is based on the difference of normalized sea level pressure between

Lisbon, Portugal, and Stykkishol- mur/Reykjavik, Iceland, since 1864. The NAO index data were provided by the Climate Analysis Section(NCAR) [Boulder, USA], (http:// www.cgd.ucar.edu/cas/jhurrell/indices.html) [66].

Supporting Information

Figure S1 Map of the Alboran Sea with standard circulation structures. AJ, WAG and EAG stand respectively for the Atlantic Jet as well as the western and Eastern anticyclonic gyres.
(TIFF)

Figure S2 Evolution of the total GRT of purse seiners in the NW Alboran (CopeMed II, 2011).
(TIFF)

Figure S3 Monthly composites of chlorophyll concentration (CHL, in $\mu g l^{-1}$) between 1998 and 2000.
(TIFF)

Figure S4 Monthly composites of chlorophyll concentration (CHL, in $\mu g l^{-1}$) between 2001 and 2003.
(TIFF)

Figure S5 Monthly composites of chlorophyll concentration (CHL, in $\mu g l^{-1}$) between 2004 and 2006.
(TIFF)

Figure S6 Monthly composites of chlorophyll concentration (CHL, in $\mu g l^{-1}$) between 2007 and 2009.
(TIFF)

Figure S7 Monthly composites of chlorophyll concentration (CHL, in $\mu g l^{-1}$) between 2010 and 2011.
(TIFF)

Figure S8 Monthly composites of Sea Surface Temperature (SST, in ^oC) between 1998 and 2000.
(TIFF)

Figure S9 Monthly composites of Sea Surface Temperature (SST, in ^oC) between 2001 and 2003.
(TIFF)

Figure S10 Monthly composites of Sea Surface Temperature (SST, in ^oC) between 2004 and 2006.
(TIFF)

Figure S11 Monthly composites of Sea Surface Temperature (SST, in ^oC) between 2007 and 2009.
(TIFF)

Figure S12 Monthly composites of Sea Surface Temperature (SST, in ^oC) between 2010 and 2011.
(TIFF)

Figure S13 Yearly catches of small pelagic fish in the NW Alboran Sea during the last decade (data only reliable since 2000). Source: Andalusian Regional Government IDAPES database (http://www.juntadeandalucia.es/agriculturaypesca/idapes/). Black and white circle are anchovy and sardine respectively while the white square is mackerel.
(TIFF)

Figure S14 Monthly composites of geostrophic circulation and kinetic energy (KE, in $cm^2 s^{-2}$) derived from altimetry between 1998 and 2000.
(TIFF)

Figure S15 Monthly composites of geostrophic circulation and kinetic energy (KE, in $cm^2 s^{-2}$) derived from altimetry between 2001 and 2003.
(TIFF)

Figure S16 Monthly composites of geostrophic circulation and kinetic energy (KE, in $cm^2 s^{-2}$) derived from altimetry between 2004 and 2006.
(TIFF)

Figure S17 Monthly composites of geostrophic circulation and kinetic energy (KE, in $cm^2 s^{-2}$) derived from altimetry between 2007 and 2009.
(TIFF)

Figure S18 Monthly composites of geostrophic circulation and kinetic energy (KE, in $cm^2 s^{-2}$) derived from altimetry between 2010 and 2011.
(TIFF)

Author Contributions

Jointly debated the new hypothesis described in this manuscript: JR DM MR AP IC GN. Conceived and designed the experiments: JR DM IC MR. Analyzed the data: DM JR IC MR GN AP. Contributed reagents/materials/analysis tools: GN AP MR. Wrote the paper: JR DM IC.

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Recruiting at the edge: Kinetic energy inhibits anchovy populations in the western Mediterranean

Javier Ruiz, Diego Macías, Margarita M. Rincón, Ananda Pascual, Ignacio A. Catalán and Gabriel Navarro

SUPPLEMENTARY MATERIAL

Figure S1. Map of the Alboran Sea with standard circulation structures. AJ, WAG and EAG stand respectively for the Atlantic Jet as well as the western and Eastern anticyclonic gyres.

Figure S2. Evolution of the total GRT of purse seiners in the NW Alborán (CopeMed II, 2011).

Figure S3. Monthly composites of chlorophyll concentration (CHL, in μg l^{-1}) between 1998 and 2011.

Figure S4. Monthly composites of Sea Surface Temperature (SST, in ºC) between 1998 and 2011.

Figure S5. Yearly catches of small pelagic fish in the NW Alboran Sea during the last decade (data only reliable since 2000). Source: Andalusian Regional Government IDAPES database (http://www.juntadeandalucia.es/agriculturaypesca/idapes/). Black and white circle are anchovy and sardine respectively while the white square is mackerel.

Figure S6. Monthly composites of geostrophic circulation and kinetic energy (KE, in cm^2 s^{-2}) derived from altimetry between 1998 and 2011.

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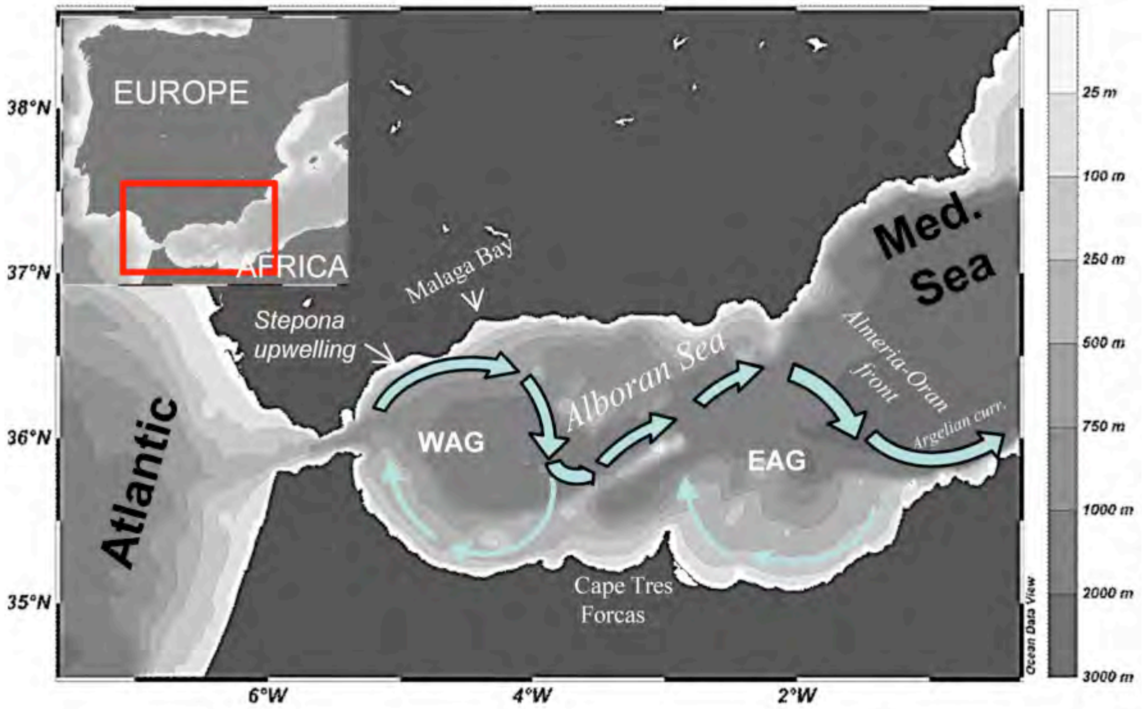

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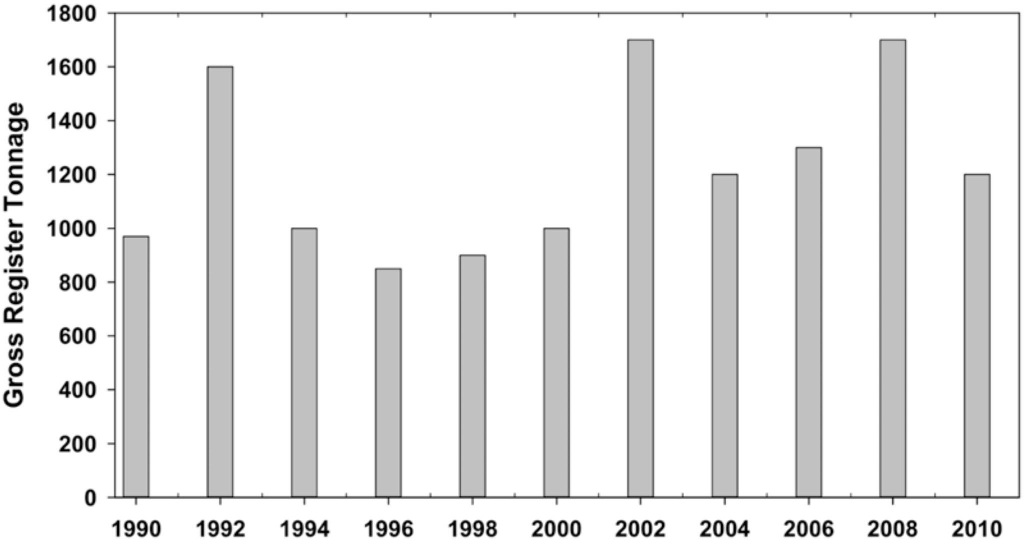

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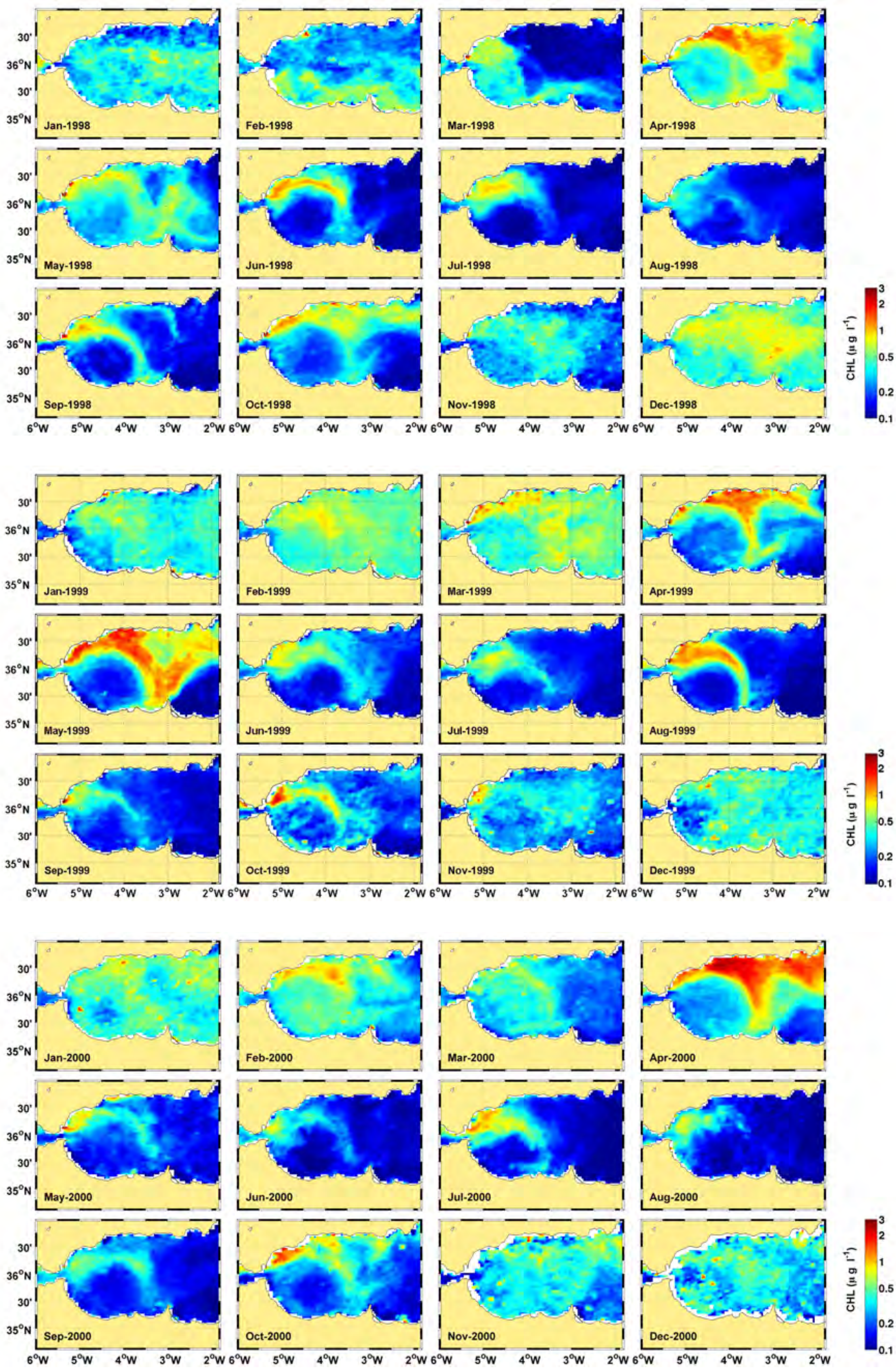

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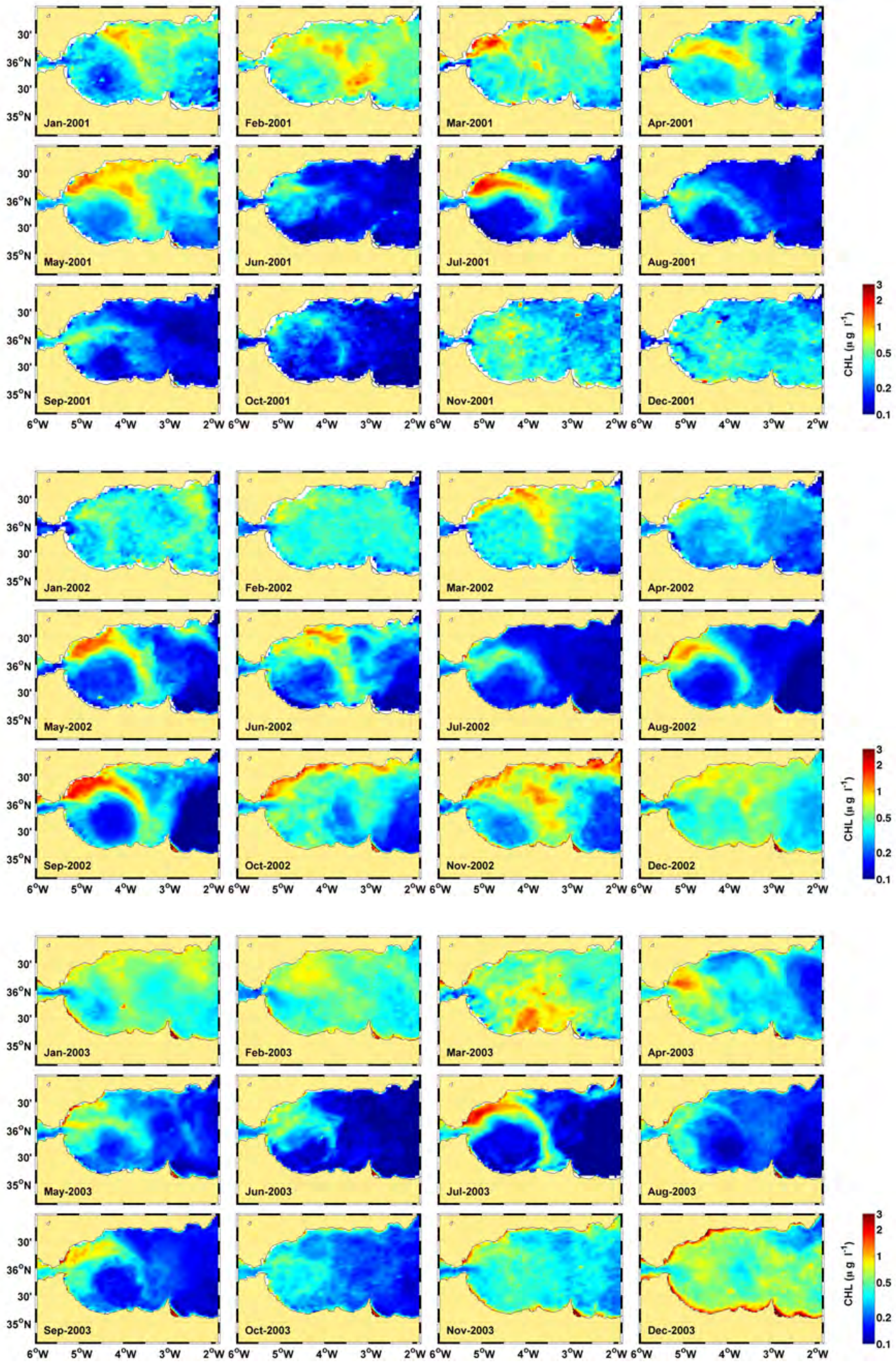

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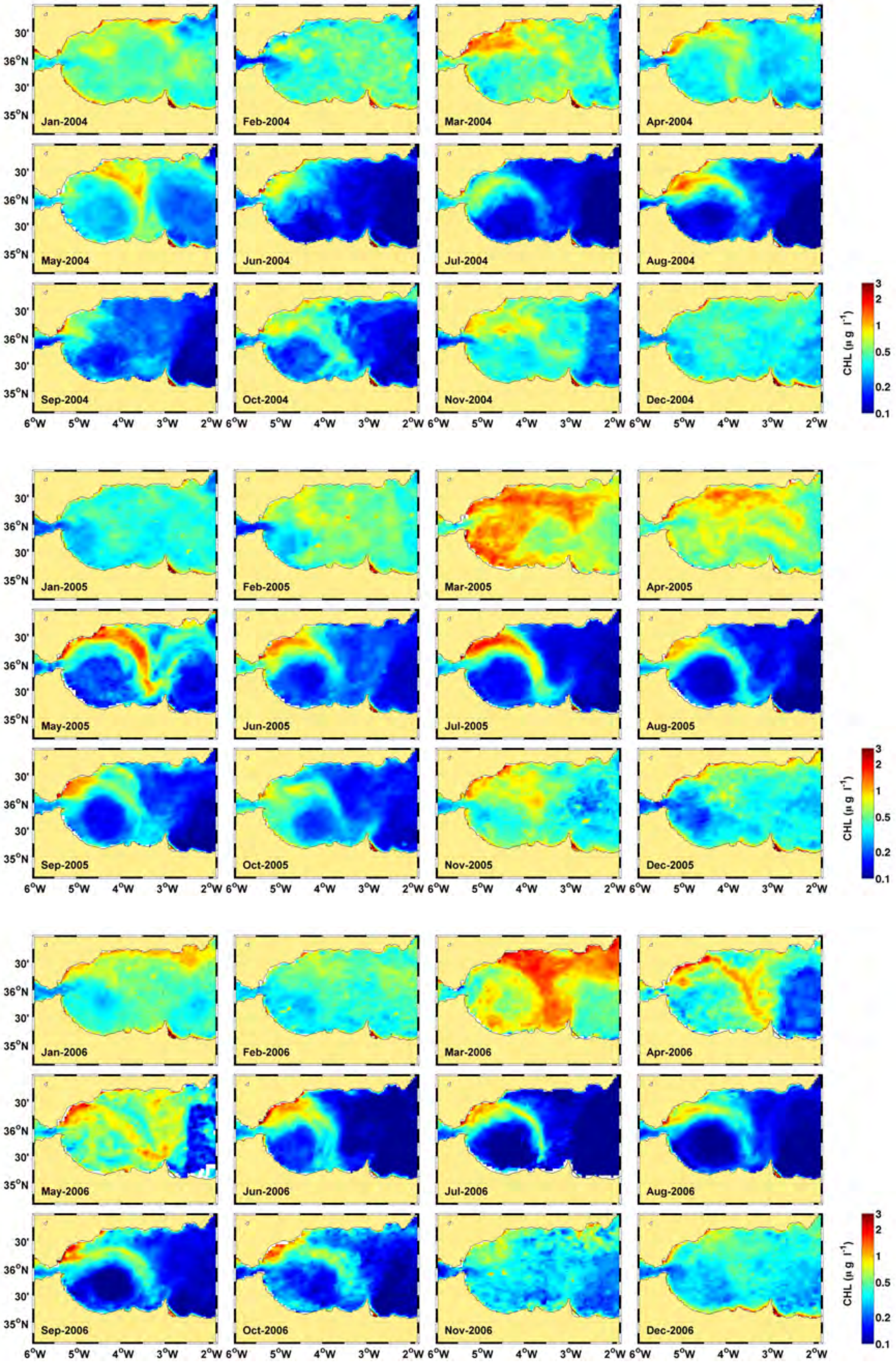

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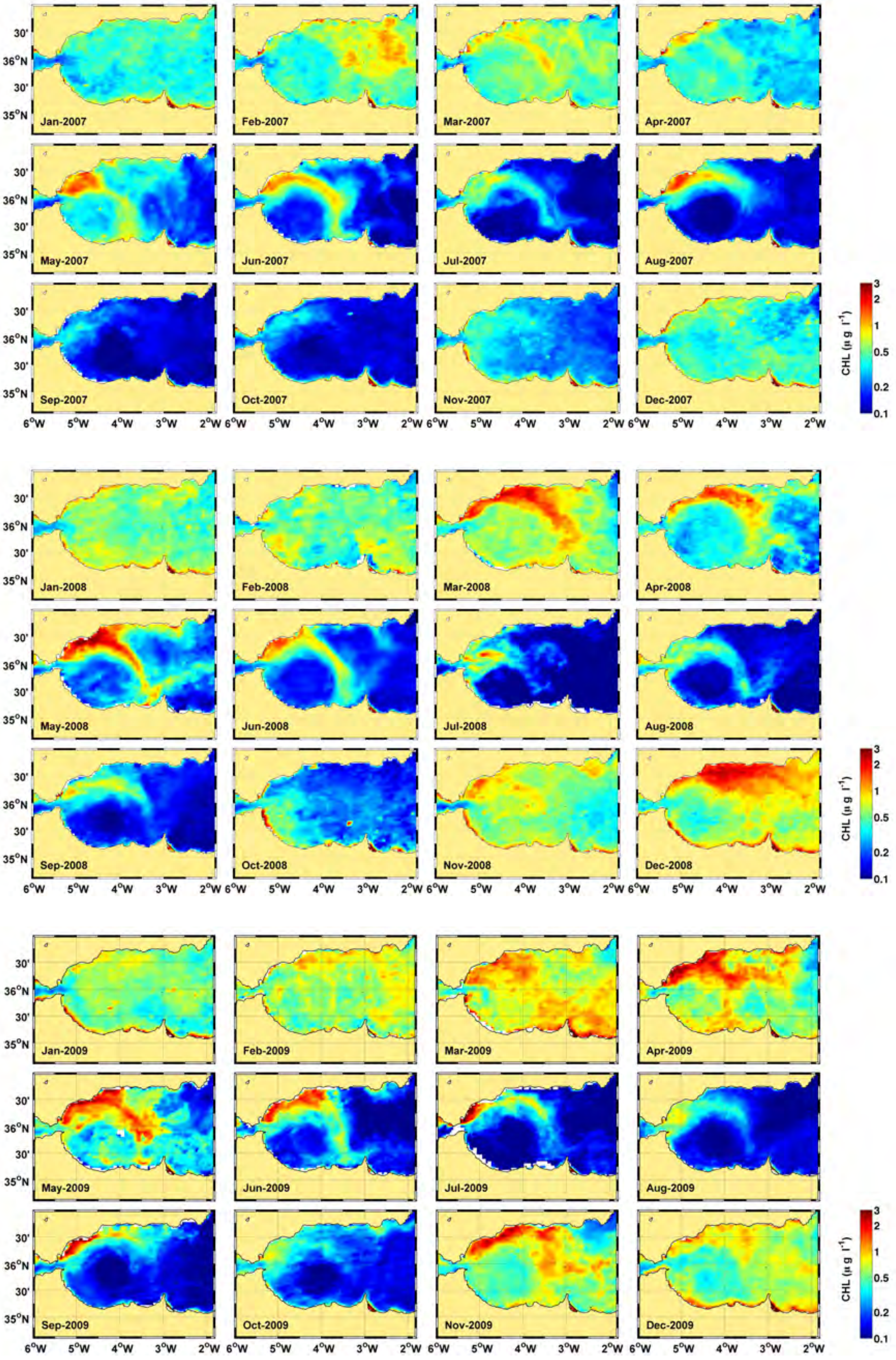

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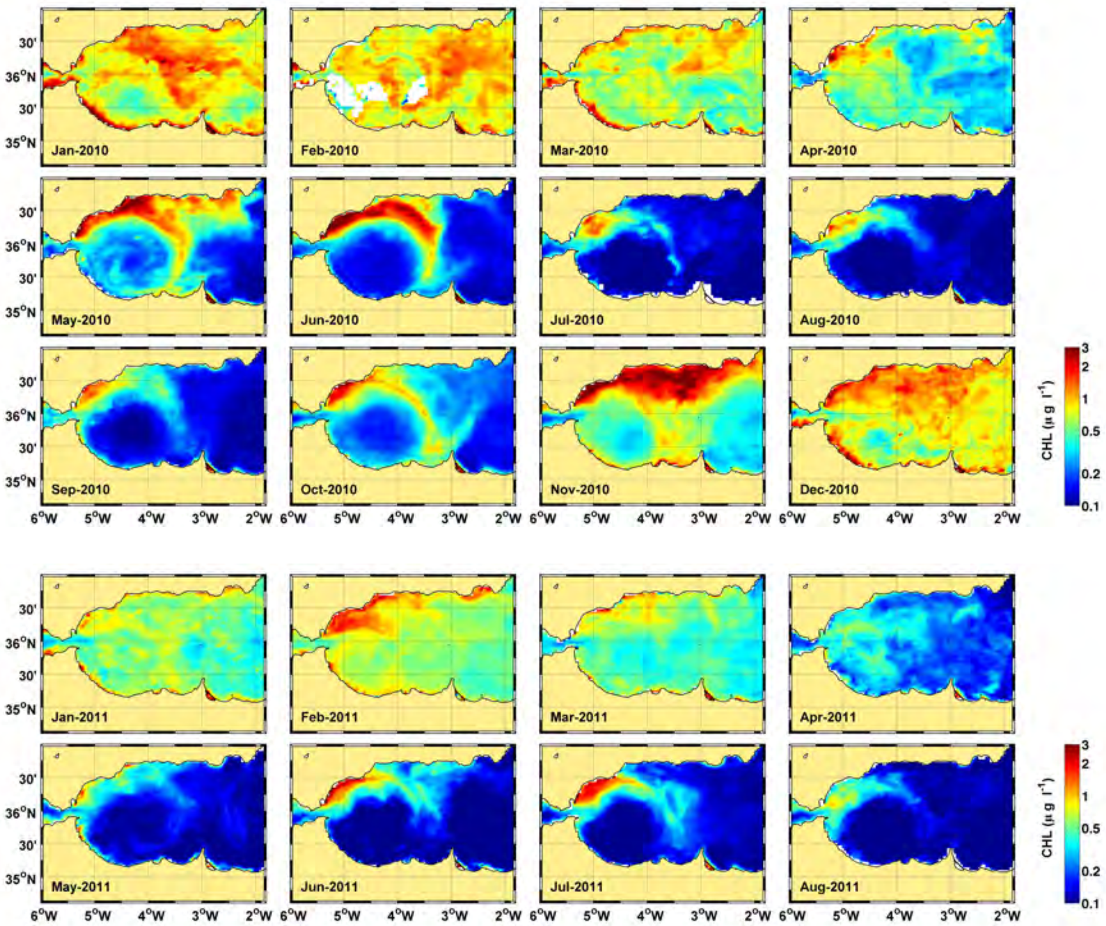
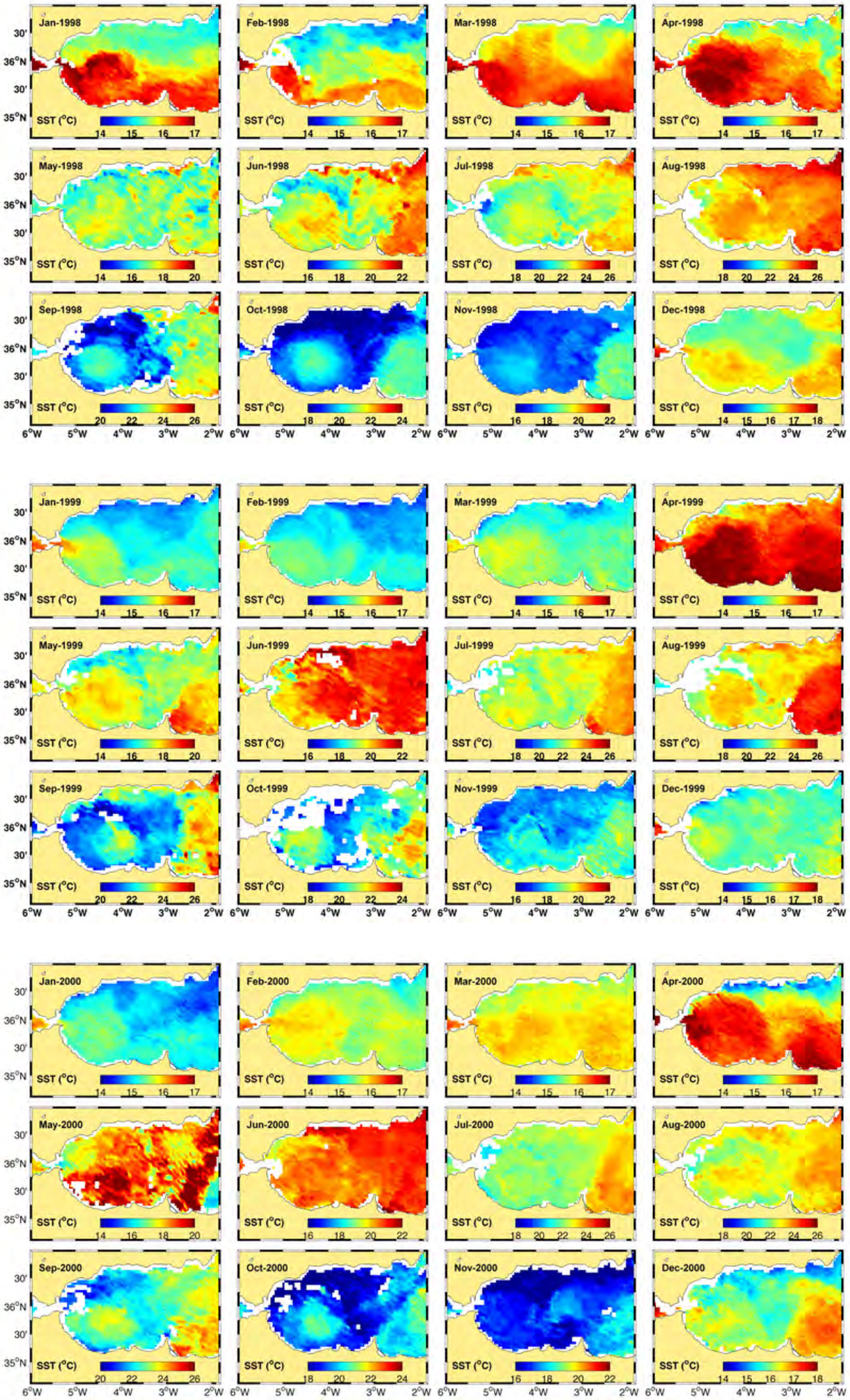


Figure S3. e) Monthly composites of chlorophyll concentration (CHL, in μg l^{-1}) between 2010 and 2011.



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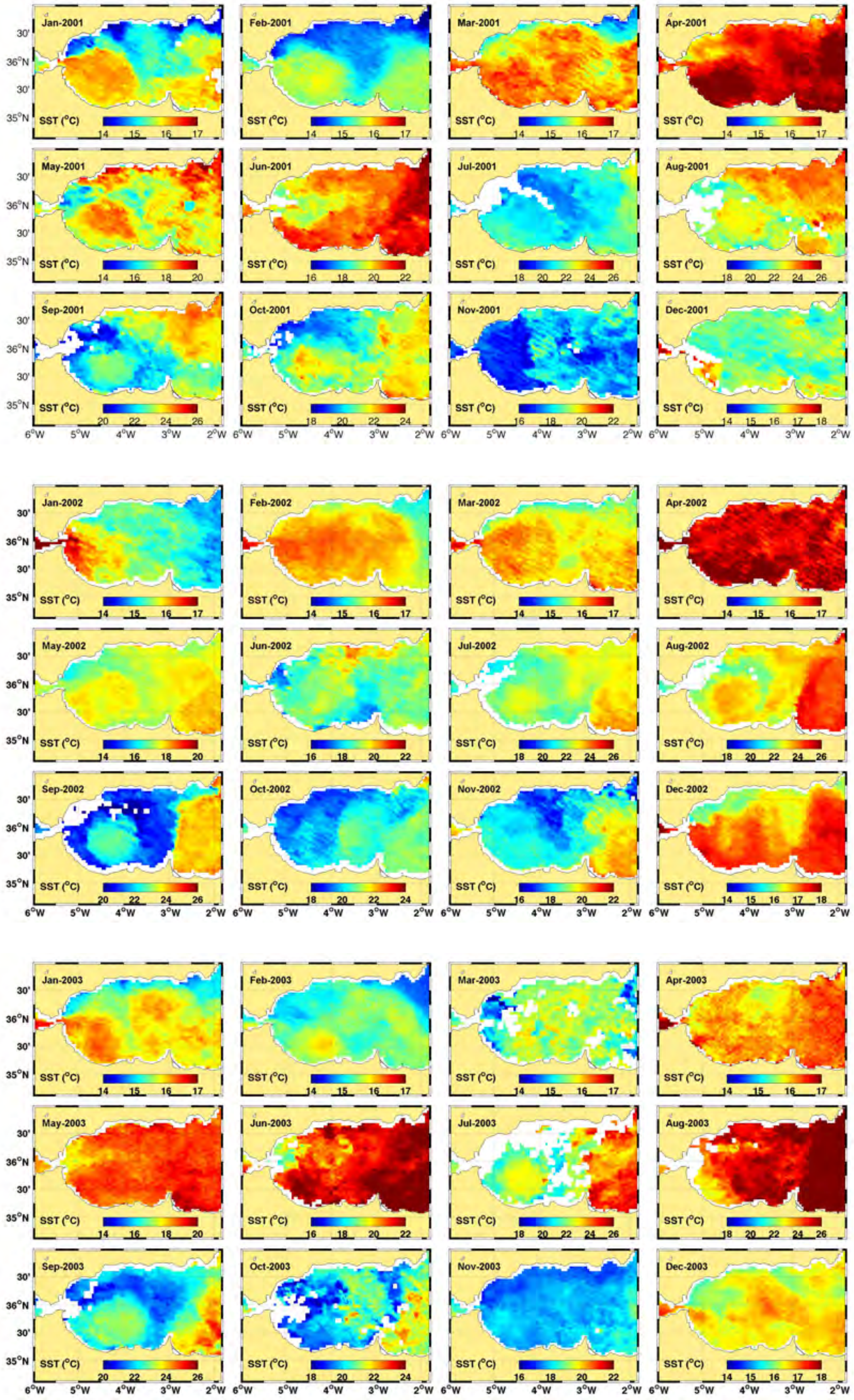

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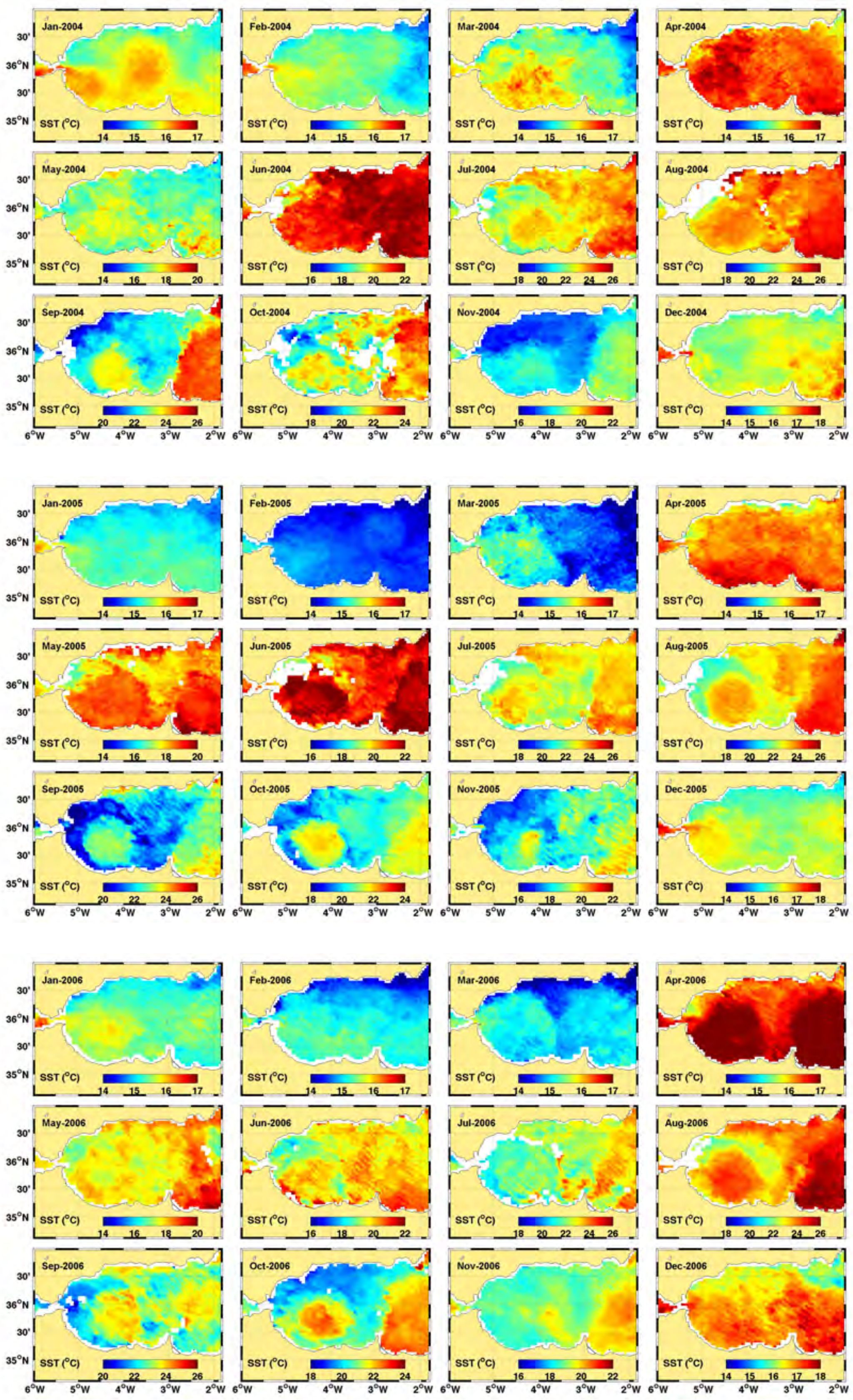

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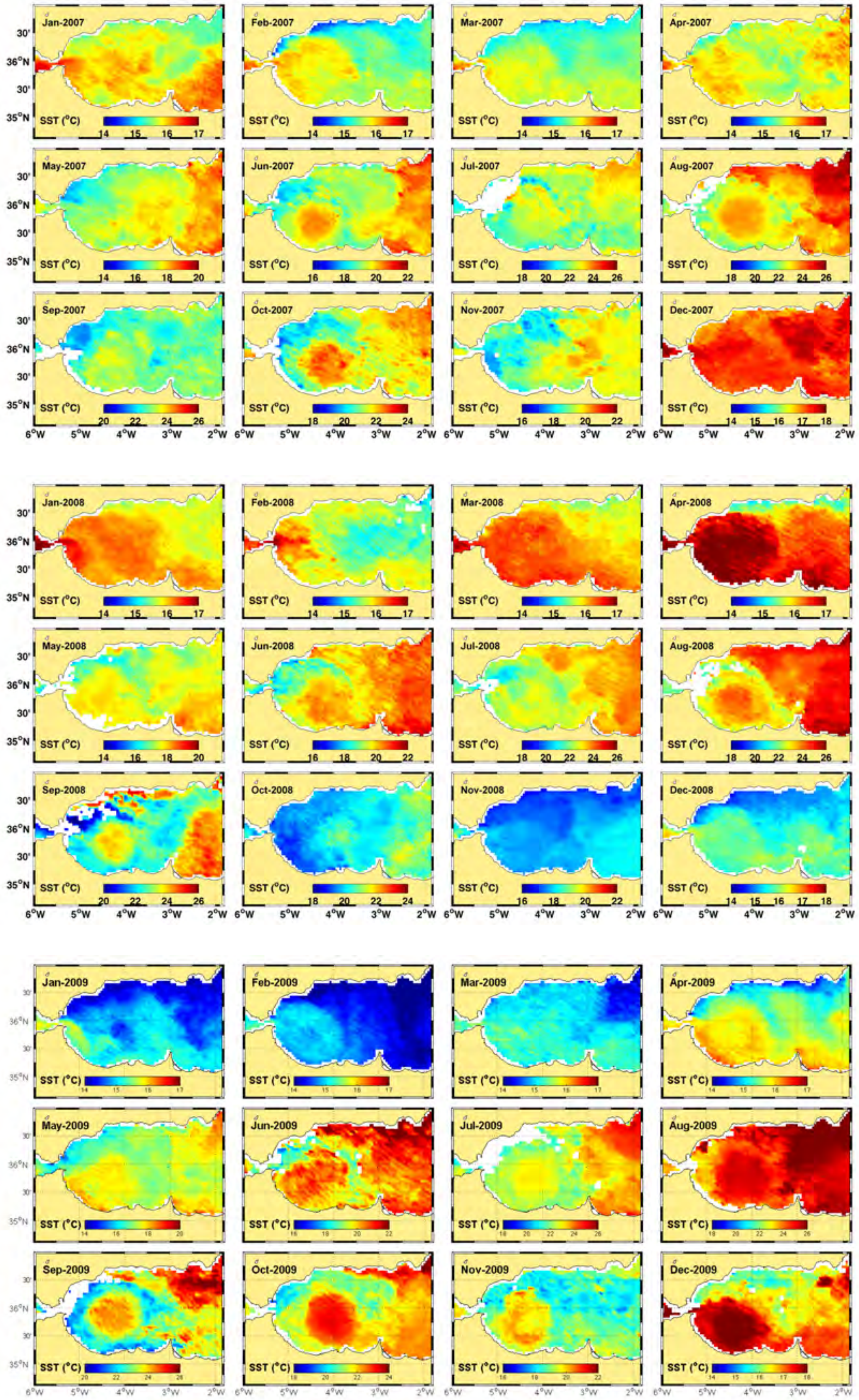

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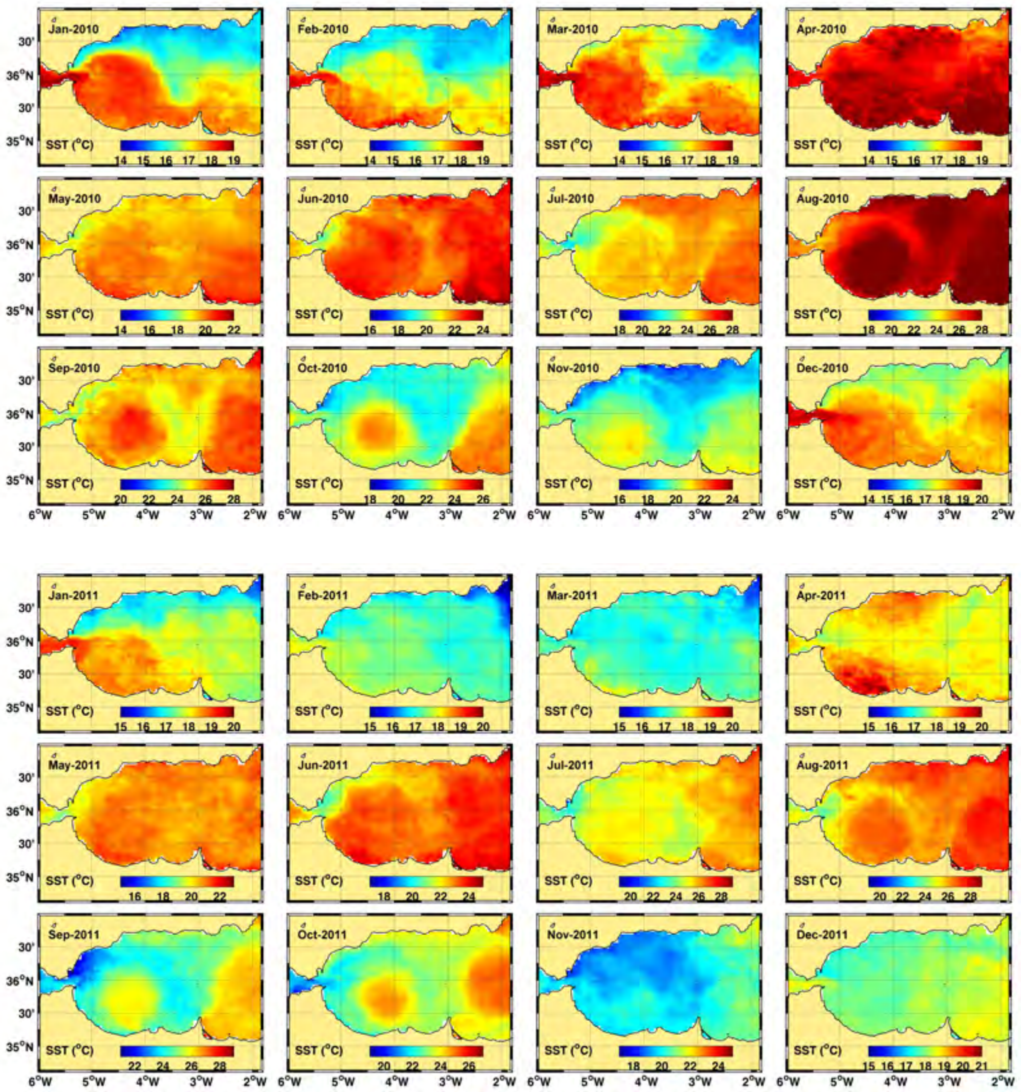

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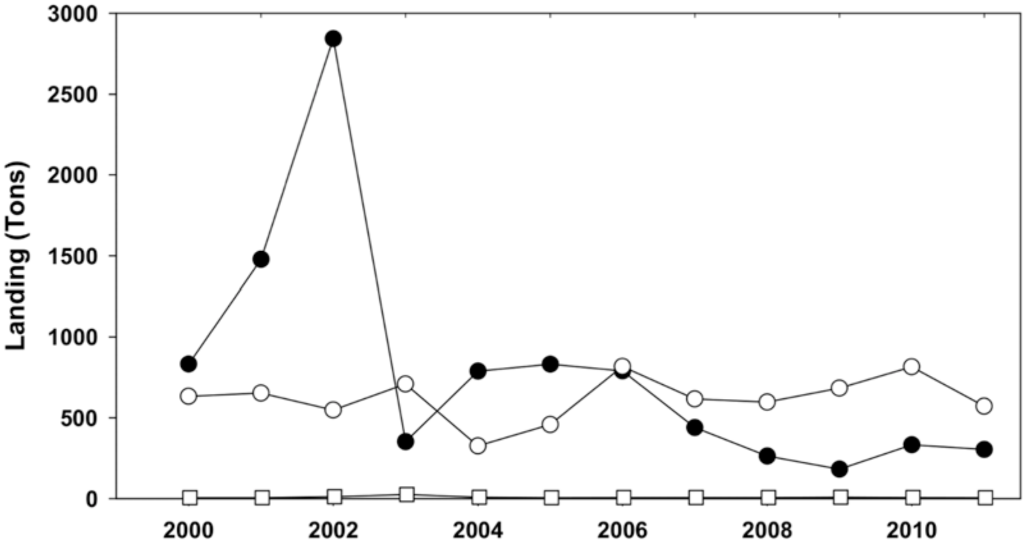

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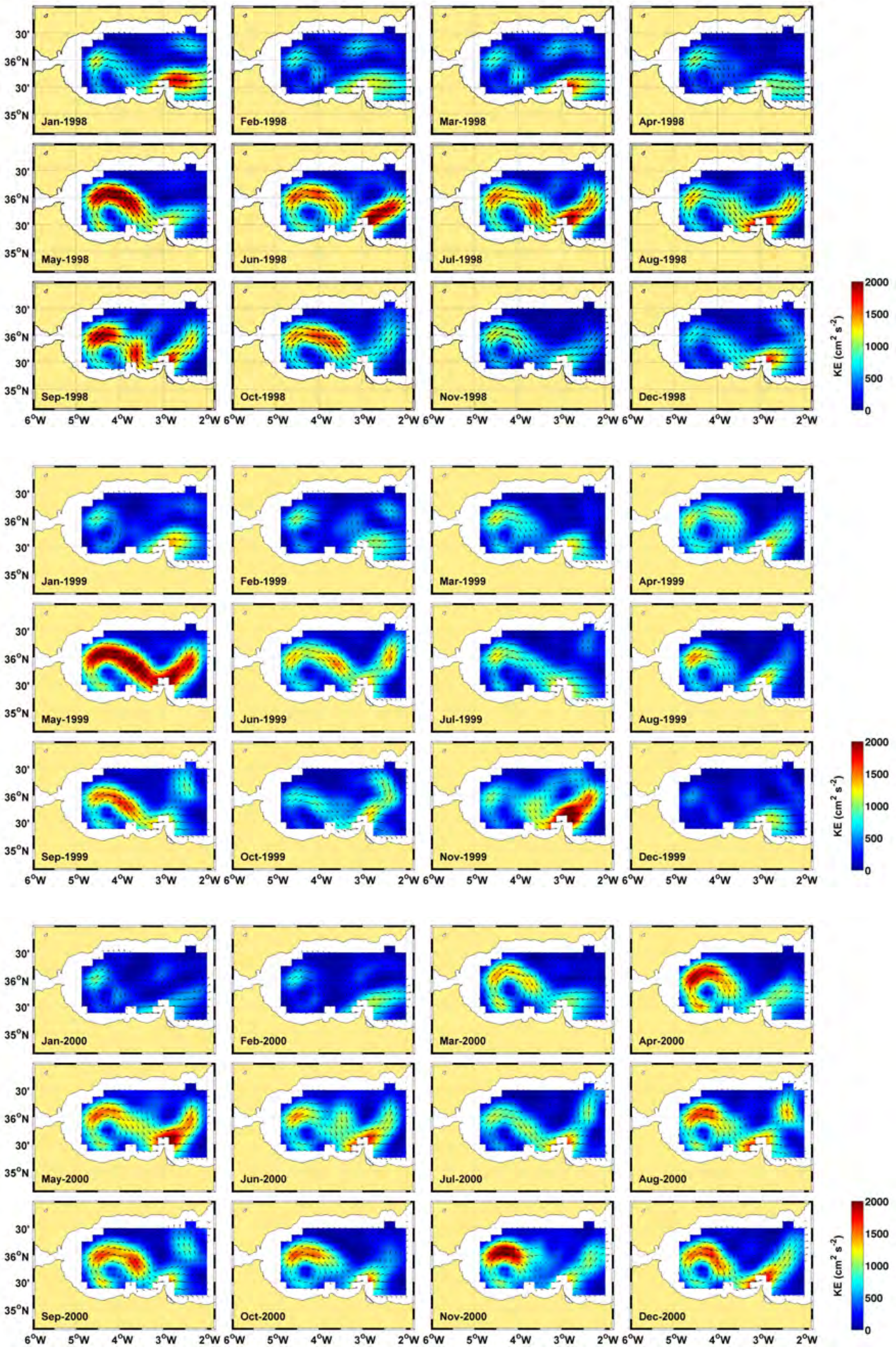

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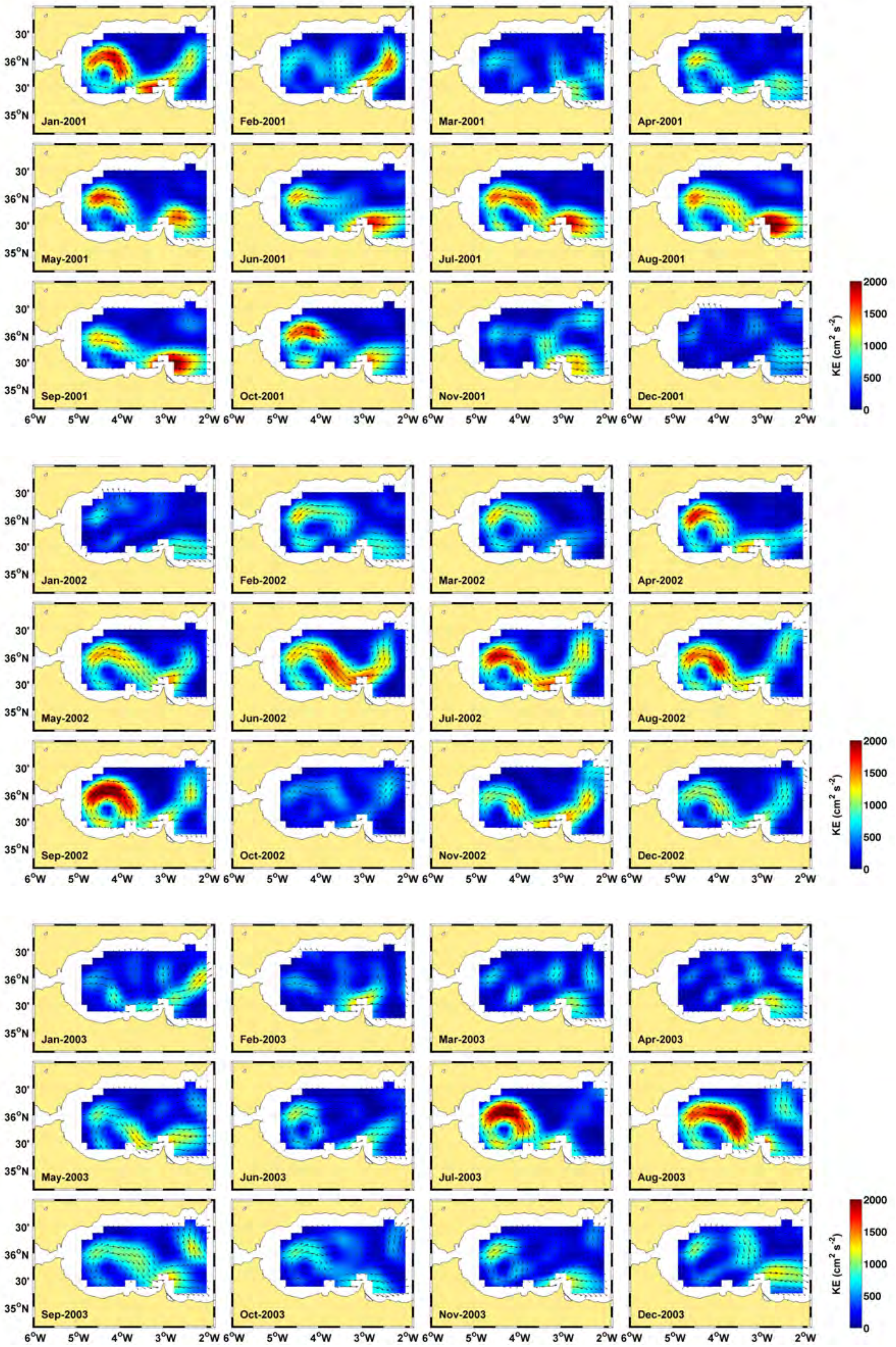

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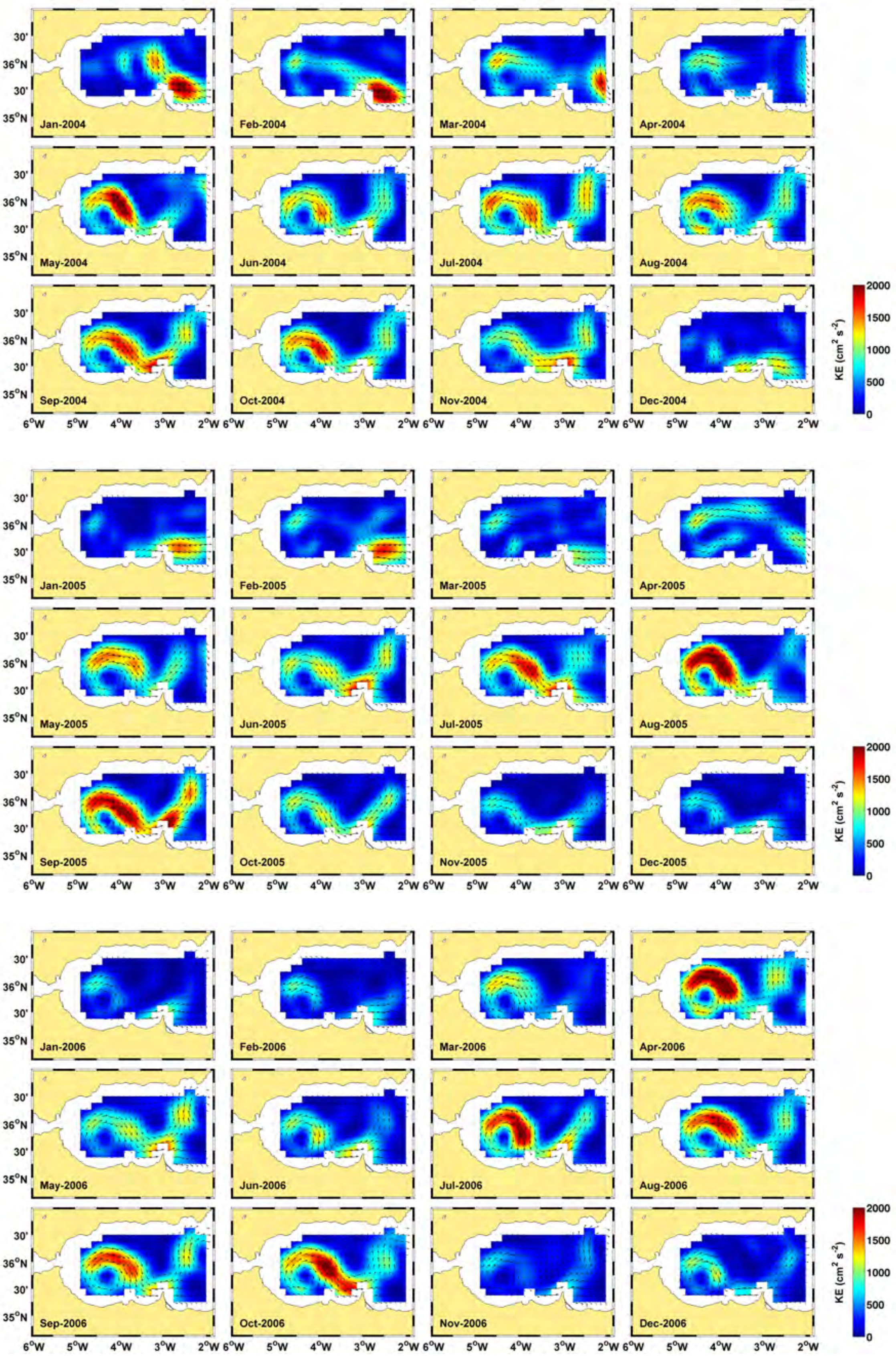

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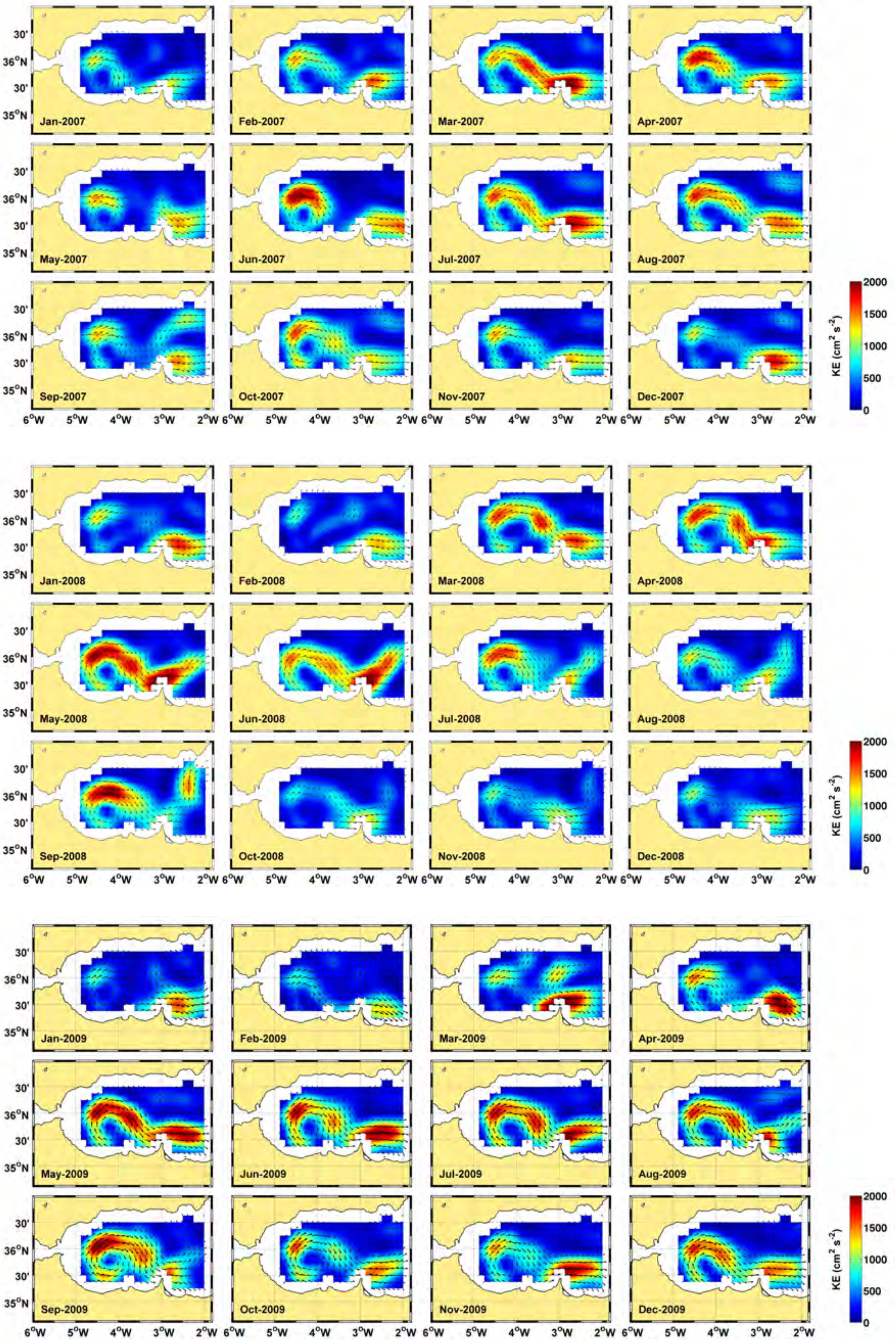

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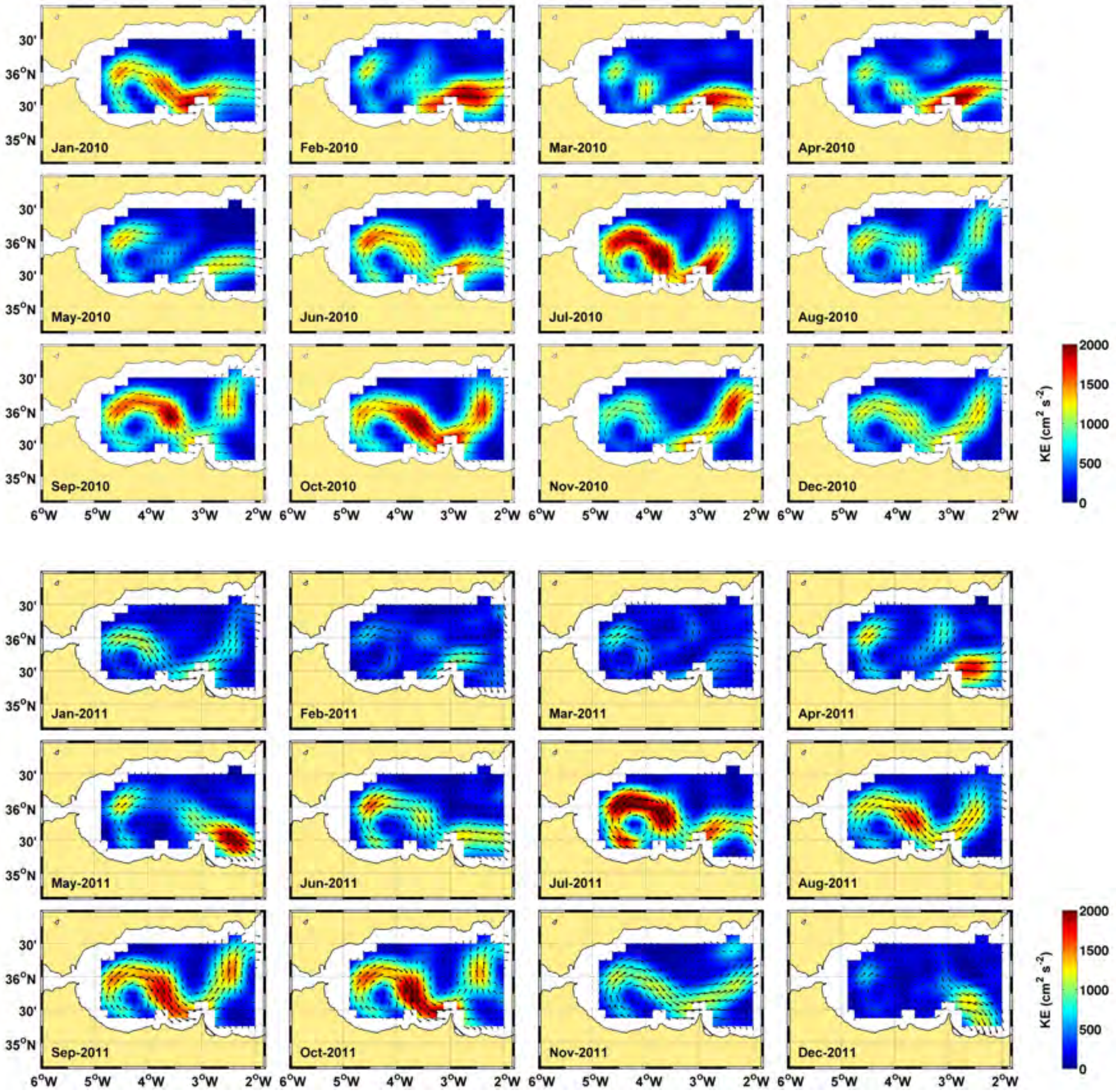

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CHAPTER

4

Transformando el conocimiento en herramientas de gestión: Redes Bayesianas aplicadas a la pesquería de boquerón en el Mar de Alborán

Margarita María Rincón & Javier Ruiz.
Trabajo preliminar.

Convirtiendo el conocimiento en herramientas de gestión: Redes Bayesianas aplicadas a la pesquería de boquerón en el Mar de Alborán

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Introducción

El capítulo anterior se identificó el control que la circulación general del mar de Alborán ejerce sobre las capturas que se obtenían de un pequeño pelágico como el boquerón.

El medio ambiente influencia tanto el reclutamiento, que la señal de capturas de boquerón en el mar de Alborán en un año determinado tiene muy poca correlación con la señal de capturas del año siguiente (Figura 1). Esta escasa correlación muestra la escasa validez de modelos clásicos como el de Beverton-Holt o el de Ricker para explicar el reclutamiento a la pesquería en función de la cantidad de biomasa reproductora (Cury and Roy, 1989). Es una característica común a otras pesquerías de pequeños pelágicos por la fuerte influencia que sobre su reclutamiento tienen los procesos medioambientales (Fréon et al., 2005). En el mar de Alborán estos procesos son tan intensos que, como se describe en el capítulo 3, tienen una importante capacidad para explicar las oscilaciones que se producen en la pesquería de esta especie.

La conexión que existe entre las oscilaciones de pesca y medio ambiente, en este caso la energía cinética que contiene el sector norte del mar de Alborán en forma de estructuras estables de circulación, implica la posibilidad de generar modelos sencillos con los que entender, simular y pronosticar oscilaciones de esta pesquería; y transformar ese conocimiento en herramientas que apoyen a la toma de decisiones sobre su gestión. Como se ha visto en capítulos anteriores, los modelos Bayesianos son muy útiles para la generación de estas herramientas porque integran conocimientos e informaciones muy diversas en rigurosos marcos conceptuales y matemáticos (Ruiz et al., 2009). Sin embargo, como se menciona en los capítulos 1 y 5, esta rigurosidad matemática tiene una contrapartida en el importante coste computacional que se necesita para la convergencia de las distribuciones posteriores cuando el modelo se formula en su totalidad mediante variables continuas.

Discretización

La formulación mediante variables continuas es más cercana a la estructura original del proceso que se quiere representar. En el caso de forzamiento ambiental de pesquerías, las variables que intervienen son de naturaleza continua en su totalidad pues incluyen elementos tales

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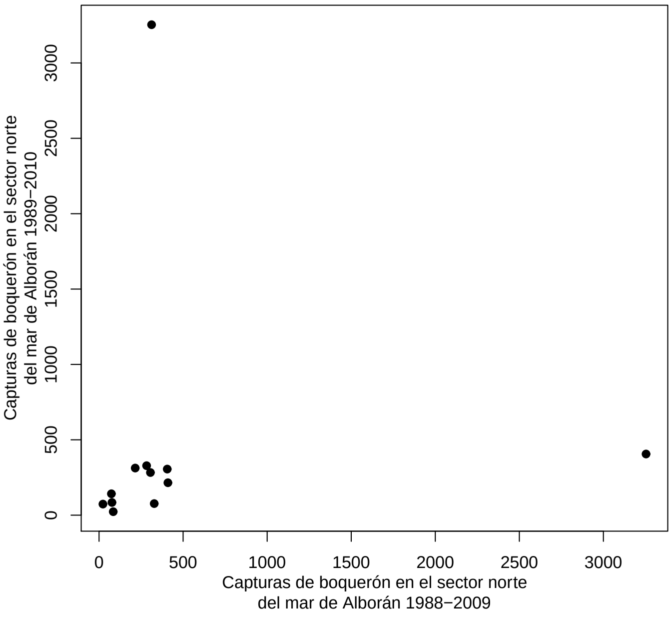

Figura 1: Relación de capturas en el tiempo t con capturas en el tiempo $t+1$

como energía cinética, kilogramos desembarcados o mortalidad natural entre otras muchas que pueden definir este proceso. Por tanto, resulta más fácil al modelador definir las variables y las relaciones entre ellas en un marco en el que las primeras ocupan la recta real sin más limitaciones que las que la naturaleza les impone. Es probable que el rápido incremento de la potencia computacional permita en un futuro no muy lejano que esta formulación natural en forma completamente continua sea acompañada de implementaciones rápidas donde muchas cadenas se puedan iterar simultáneamente durante millones de veces. De esta forma se podría tener una convergencia de los posteriores con la eficiencia de tiempos que a menudo demanda el proceso de toma de decisiones. Igualmente, el incremento de potencia computacional permitirá que ese ejercicio de convergencia analice simultáneamente muchos escenarios de gestión con sus incertidumbres asociadas. De esta forma el gestor tendrá opciones de decisión sobre la mejor de las soluciones posibles con base en herramientas que incorporan todo el conocimiento científico disponible.

Una alternativa actual a esa posibilidad futura es la discretización de parte del problema desde su formulación original como proceso continuo. La discretización permitiría entender mejor la situación general en términos sencillos que podrían ser entendidos fácilmente por los gestores. Utilizando el método de discretización de Hartemink (Hartemink, 2001), IPD (Information-preserving discretization), se transforman las variables continuas en variables ordinales, que sería una forma de representar fielmente las variables propias del ecosistema que suelen fluctuar con valores que se corresponden más con la recta de números reales que con una serie de clases discretas.

El método IPD consiste en discretizar todas las variables involucradas de modo conjunto, de esta manera se maximiza la cantidad de información mutua retenida y se preservan las interdependencias que son la base del modelado posterior. Este proceso de discretización suele utilizarse frecuentemente en el entorno de las redes Bayesianas debido a su capacidad de

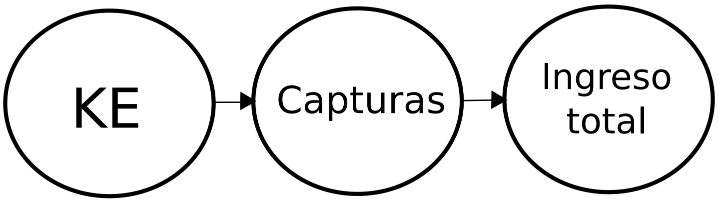

Figura 2: Grafo aciclíco dirigido de la red Bayesiana implementada para el forzamiento ambiental del boquerón en el mar de Alborán

conservar las dependencias condicionales entre variables.

Las redes Bayesianas

Las redes Bayesianas modelan un fenómeno mediante un conjunto de variables y las relaciones de dependencia entre ellas, que en ocasiones pueden ser interpretadas como relaciones causa-efecto. Se representan mediante un grafo acíclico dirigido en la cual los nodos representan variables aleatorias y los arcos representan relaciones de dependencia directa entre las variables. Se ha empezado a utilizar frecuentemente en diversos campos (genética, bioinformática, epidemiología, etc ...) debido a a lo fácil que resulta trasladar la información a un modo gráfico de flechas y nodos, así como la extracción de resultados a partir de la misma.

En el caso más simple, un experto especifica la forma de la red, sin embargo para evadir la visión subjetiva del ser humano, es recomendable que la estructura de la red y los parámetros de las distribuciones locales sean aprendidos de los datos mediante un procedimiento de “aprendizaje de máquina”(machine learning). Dicho procedimiento construirá una red que satisfacerá la propiedad local de Markov (Russell and Norvig, 2003) que consiste en que cada nodo es independiente de todos sus nodos no-descendientes dados los padres, donde la la distribución de probabilidad conjunta de todos los nodos se puede obtener mediante el producto de distribuciones de probabilidades condicionales.

A nivel computacional resulta muy eficiente ya que puede asimilar y procesar con mucha rapidez la información proporcionada al modelo (Castillo et al., 1997),y además, el paquete *bnlearn* de *R* (Scutari, 2009) provee las rutinas necesarias para el modelado de redes Bayesianas.

Red Bayesiana para el control medio ambiental del boquerón en Alborán: Un ejemplo sencillo

A modo de ejemplo, la figura 2 presenta un diagrama (gráfico acíclico dirigido) de red Bayesiana coherente con el forzamiento medioambiental sobre las capturas de boquerón en el mar de Alborán que se describe en el capítulo 3. Esta red es capaz de proyectar el modelo más allá de los elementos conceptuales que se identifican en dicho capítulo al incluir los beneficios económicos obtenidos por el sector.

En esta estructura tan sencilla, el medio ambiente (Kinetic Energy) fuerza la cantidad de recurso que existe en un año determinado (Capturas) y ésta a su vez el ingreso total.

A pesar de su sencillez, su calificación comparativa frente a otros modelos en test de Minimum Description Length (Lam and Bacchus, 1994) sería muy alta, en esta red bayesiana subyace un modelo conceptual sobre los procesos que controlan la abundancia de biomasa de boquerón en el mar de Alborán y cómo ésta determina los ingresos que por esta especie recibe el sector.

KE	(-60.2,-26.3]	(-26.3,-23.5]	(-23.5,4.78]
Capturas (Toneladas)	(23.1,119]	(119,283]	(283,3250]
Ingreso Total (Miles de Euros)	(125,385]	(385,692]	(692,3050]

Cuadro 1: Discretización de las variables consideradas para la red bayesiana

La conexión entre KE y las capturas ya se discutió en el capítulo anterior. Igualmente cabe esperar que un incremento de las capturas según la ley de oferta y demanda resulte en una reducción del precio unitario de cada kilogramo de boquerón en las lonjas del mar de Alborán (Samuelson and Nordhaus, 2010), aunque en general se suele mantener una relación directamente proporcional entre las capturas y el precio total. Esta explicitación de las relaciones causa-efecto en las redes Bayesianas las diferencia claramente de otro tipo de redes como las neuronales en las que las conexiones entre variables se producen dentro de una caja oscura al modelador. Esta diferencia no es trivial para la formulación de modelos destinados a la toma de decisiones porque en este contexto el modelador debe poder transmitir al gestor la hipótesis subyacente en su herramienta, y no resulta válido justificar los resultados con base en una caja negra como ocurre con las redes neuronales. Igualmente, la explicitación de las relaciones causa-efecto resulta clave en un entorno donde el gestor necesita identificar los elementos del sistema sobre los que puede actuar (causas) y las consecuencias de estas actuaciones (efectos). Esta explicitación de las relaciones causa-efecto es también importante en entornos de gestión donde las relaciones entre ambas pueden verse modificadas por una alteración del escenario que las produjo, por ejemplo como resultado del proceso de cambio climático que altere los mecanismos de interrelación de un ecosistema determinado.

La red Bayesiana de la Figura 2 se implementó con el paquete bnlearn. En este caso se implementa el aprendizaje estructural de la red usando un algoritmo Hill-climbing (Margaritis, 2003). El proceso de discretización usando el método IPD, transformó todas las variables en variables ordinales con tres categorías cada una como se observa en la tabla 1, donde la biomasa está expresada en toneladas de boquerón descargadas en las lonjas del mar de Alborán y el precio por kilo está en euros.

La implementación de esta simple red demanda muy pocas líneas de código:

```
> BN_alboran

        KE  Capturas Ingreso total
1    4.7819  409.6356      636.3279
2  -23.4549  215.1600      329.4745
3   -3.7480  312.5100      700.5849
4  -60.2231 3253.6956     3050.9904
5  -42.3231  405.6900      628.4138
6  -34.2461  305.7000      956.2602
7  -36.1912  282.8676      686.2085
8  -31.7156  328.1964     1088.0367
9  -14.9486   76.8420      342.9074
10 -19.9663   84.3384      355.9080
11 -20.0298   23.0856      124.6622
12   0.0000   73.4580      269.5909
13 -25.0000  141.9880      391.8869

> BN_alboran_d<-discretize(BN_alboran, method = "hartemink", breaks = 3)
> bn.hc <- hc(BN_alboran_d)
> fit_BN_alboran<-bn.fit(bn.hc,BN_alboran_d)
```

Con este código es posible construir una estimación de la probabilidad de desembarco de boquerón en las lonjas del mar de Alborán condicionada al nivel de energía cinética en el sistema (Figura 3). Es evidente en la diagnosis que realiza la red, y en coherencia con los resultados del capítulo 3, que es muy probable obtener una cantidad importante de boquerón

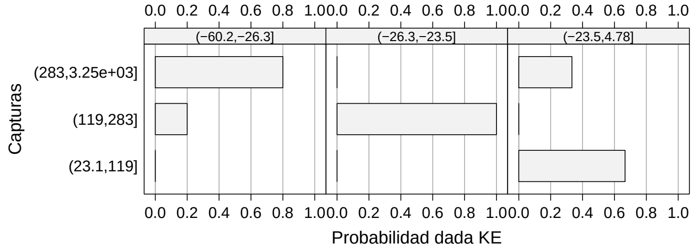

Figura 3: Probabilidad condicional de las capturas descargadas (Eje x) dada la energía cinética (Eje y)

(más de 283 toneladas) cuando la KE es menor que -26.3. Entre -26.3 y -23.5 hay una gran probabilidad de obtener una captura media (entre 119 y 283 toneladas) mientras que para valores superiores a una KE de -23.5, la probabilidad de tener una pesca desastrosa (entre 23.1 y 119 toneladas) es apróximadamente 3 veces mayor que la de tener una captura exitosa o media.

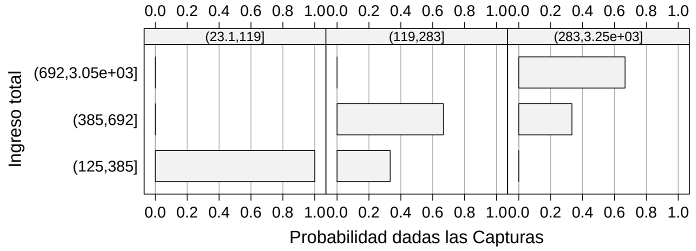

Figura 4: Probabilidad condicional del ingreso total (Eje x) dadas las capturas descargadas (Eje y)

La gráfica de la función de probabilidad condicional del ingreso total dada la biomasa de capturas (Figura 4) muestra que las capturas son proporcionales al ingreso total, cabe resaltar que para un nivel alto de capturas hay una probabilidad de casi un 4 % de tener un ingreso medio y que esto seguramente esté relacionado con la ley de oferta y demanda. Además, un número medio de capturas tiene una probabilidad dos veces mayor de corresponder a un precio medio, que a un precio bajo.

La función de probabilidad condicionada del ingreso total dada la cantidad de energía que contiene el sistema circulatorio del mar de Alborán se puede calcular mediante el producto matricial de $P(Ingreso|Capt.)$ con $P(Capt.|KE)$ y se muestra en la Figura 5.

La Figura 5 tiene importantes derivaciones desde la perspectiva de la gestión de esta pesquería. Indica que cuando el sistema circulatorio pasa de un estado que contiene poca energía a uno con mucha, es altamente probable que el ingreso total disminuya, lo que muestra que la influencia del chorro de agua atlántica más el giro anticiclónico sobre el reclutamiento, se acentúa cuando se proyecta sobre el marco económico. Cuando la KE es menor a -26.3 es más probable que el ingreso total sea alto, mientras que cuando la KE es mayor a -23.5 es más probable que el ingreso sea muy bajo. Entre -26.3 y -23.5 la mayor probabilidad se concentra en un precio medio. Le corresponde al gestor teniendo en cuenta la biomasa de capturas (Figura 3) y el ingreso total esperados, tomar decisiones respecto a si se debe disminuir o aumentar el nivel de capturas en la búsqueda del mayor beneficio.

Macías et al. (2014) identifica la necesidad de considerar la variabilidad ambiental en relación

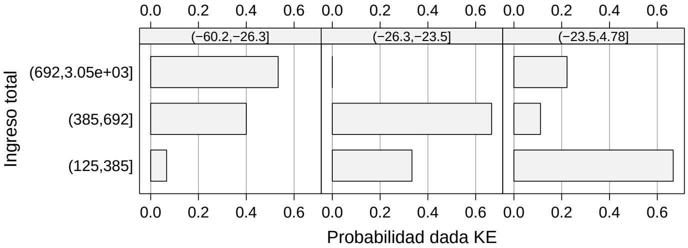

Figura 5: Probabilidad condicional del ingreso total (Eje x) dada la energía cinética (Eje y)

con las decisiones de gestión de esta pesquería. Se trata de un recurso que ha ido progresivamente disminuyendo el tamaño de su flota ante el bajo rendimiento económico que el mismo produce. Las figuras 3 y 4 hacen comprensible esta evolución pues incluso cuando la cuenca produce niveles intermedios de capturas éstas se distribuyen entre un precio medio y uno bajo, lo que se podría traducir en escasos rendimientos económicos. En este contexto no parece tener sentido invertir en el sostenimiento de esta actividad. Sin embargo, el sistema tiene capacidad de oscilar bruscamente a un estado en el que ese rendimiento económico podría aumentar significativamente si la KE baja de -50, ya que aunque el precio sea menor podría compensar si el número de capturas es alto. En el pasado estos eventos de baja KE han sido excepcionales pero en un entorno de cambio climático al que la circulación del mar de Alborán es extremadamente sensible (Boutov et al., 2014) esta situación puede cambiar. Desde la perspectiva de la gestión, probablemente tiene poco sentido apoyar a un sector cuyo recurso tiene una probabilidad altísima de caer si el cambio climático nos conduce a un incremento de KE. Igualmente, tiene poco sentido no apoyar al sector si aparece la oportunidad económica que puede representar este recurso si la evolución de KE es decreciente en un escenario de cambio climático.

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CHAPTER

5

Improving hake advice considering stock-recruitment uncertainty: A Bayesian state-space size-structured population dynamics model for northern hake

Margarita María Rincón, Santiago Cerviño, Samu Mäntyniemi, José Castro & Javier Ruiz.

Delivered to the European Commission.

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A Bayesian state-space size-structured population dynamics model for northern hake. Improving hake assessment considering biological uncertainty

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Abstract

In fisheries research bayesian state-space models have been proved to be very useful because of their capacity to include new data while measuring the uncertainty associated to biological and physical processes. The ECOKNOWS (Effective use of ecosystem and biological knowledge in fisheries) project proposes to use Bayesian analysis in a general population dynamics model GPDM as a tool to include biological information in fisheries management. Results of Bayesian models under different assumptions for northern hake population dynamics are presented here. The model intends to reproduce as far as possible the structure and main assumptions of the current ICES assessment model. Prior information obtained from several hake stocks for growth, natural mortality and recruitment variability were also inserted in the model. Including informative priors for the biological processes provides a way to consider additional information that is not taken into account avoiding assumption of constant values for this unknown parameters. However, assessment models require short computing time to be operative. This is the main handicap of model developed. Given the biological limitation in the current hake assessment, a Bayesian model may be a good and operational alternative if computing times could be reduced.

Introduction

European hake (*Merluccius merluccius*) is widely distributed over the Northeast Atlantic shelf, from Norway to Mauritania, with a larger density from the British Islands to the south of Spain (Casey and Pereiro, 1995; Murua, 2010) and in the Mediterranean and Black sea. ICES

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assumes two different stock units, the Northern stock and the Southern stock, to the north and south of Cape Breton Canyon (Bay of Biscay) respectively. Northern stock corresponds to ICES Division IIIa, Subareas IV, VI and VII and Divisions VIIIa,b,d. Northern hake is caught by different countries (Spain, France, Ireland, UK, etc) and different fleets (trawlers, gillnetters, longlinners, etc) in a mixed fishery where the other main species are megrims, anglerfishes, neprhops, etc. The mean landings have been around 45 thousand tonnes in the first decade of XXI century although these have risen to 73 thousand tonnes in 2010 (ICES, 2012). Discards have accounted for around 2 thousand tonnes in recent years. Catch data from 1978 are used for assessment purposes.

Hake is an important species for the fishing activity in the area and also has an important role in the ecosystem as a top predator. Despite this, its biology has many unknowns making an accurate assessment difficult. Allometric length-weight relationship ($W(g) = 0.00513 * L(cm)^{3.074}$) and maturity-at-length parameters ($L_{50} = 42.85 cm$ and $slope = -0.2$) are assumed to be constant on time as in the current ICES assessment. Hake growth is relatively unknown. Studies developed in the first years of XXI century showed that hake grows about two times faster than assumed under previous otolith ring interpretation (de Pontual et al., 2003, 2006; Piñeiro et al., 2007). Since age interpretation was wrong and there is not an alternative to assign ages, ICES decided to move to a length based assessment model with SS3 (Methot, 2000). Because the tagging information reported growth rates about two times higher than previously assumed, the natural mortality rate was corrected following Hewitt and Hoenig (2005) from 0.2 to 0.4 year -1. For modelling purposes at a first stage, M was set as 0.4; the growth follows Von Bertalanffy functions with $Linf$ as 130 and k estimated by the model was 0.177 $year^{-1}$.

ECOKNOWS (Effective use of ecosystem and biological knowledge in fisheries) is a FP7-KBBE project in the topic "Improving fisheries assessment methods by integrating new sources of biological knowledge". The main aim of the project is to develop models that use all the available biological information which is likely to be useful for the management of specific stocks in a bayesian statistical context. Classical statistical methods do not allow combining existing information with new data. Bayesian statistics, uses prior knowledge, that is knowledge we have before we start to analyze any new data. If the new data includes more information about the parameters, then the Bayesian calculus combines the prior information with the new information in a process that can be called scientific learning (Gelman et al., 2003; Congdon, 2003).

The goal of this work is to develop a Bayesian model for Northern hake able to deal with the biological process and stock-recruitment uncertainty. We used the General Population Dynamics Model described in Mäntyniemi (2012) as base model and we adjust it for northern hake including ICES assumptions and also biological knowledge coming from other hake species related with carrying capacity, growth and mortality. We have run 56 model versions . Here we present an output comparison of 5 of them, where there are different assumptions associated to the model, such as number of length classes, number of fleets or process errors. We explain the progress of the model in terms of convergence and estimated posterior distributions coherence.

Materials and methods

The data used for this work were extracted from the input file used in the ICES assessment with SS3. This data ranges from 1978 to 2010 split by quarters and considers 7 fleets and 4 surveys. 3 of the fleets have also discards. These data consist on total landings in weight and length distribution for all fleets and surveys. Length distributions available are grouped by 2 cm length classes from 4 to 100 cm. The approach to develop this Bayesian model begins with a simpler data grouping. The first model version presented here uses 10 years (2001-2010), four quarters per year, 19 length groups (1, 5, 10, 15, 20, 23, 26, 29, 32, 35, 38, 41, 44, 47, 50, 60, 70, 80, 100) and 5 fleets (Table 1).

Fleet	Selection	ICES fleet	Discards	Retention
1	Double Normal	SPTRAWL7	Yes	Logistic
2	Double Normal	FRNEP8	Yes	Logistic
3	Double Normal	SPTRAWL8	Yes	Logistic
4	Logistic	TRAWLOTH+OTHERS	No	
5	Double Normal	GILLNET+LONGLINE	No	

Table 1: Fleets used in hake Bayesian GPDM. SPTRAWL7 and SPTRAWL8 are for spanish trawls used in VII and VIII ICES divisions, FRNEP8 is for french trawl targeting Nephrops in division VIII and TRAWLOTH is for all other trawl operating in Northern stock.

Model description

Process model

Spawning

At the beginning of each month the female population is assumed to spawn once each quarter. They are supposed to produce a number of eggs computed with the following dot product:

$$Eggs_t = (\mathbf{\Phi_t} \cdot N_t \mathbf{eggs_t})$$

Where $\mathbf{\Phi_t} = (\phi_{t,1}, \ldots, \phi_{t,k})$ denotes the relative size class frequencies allocating the population N_t in K length classes and $\mathbf{eggs_t} = (e_{t,1}, \ldots, e_{t,K})$, is the number of eggs per kilogram spawned by a mature female of length class K (aprox 1000 eggs by kilogram). In order to calculate the kilograms equivalent to a determined length, the weight-length relationship with $a = 0.00000531$ and $b = 3.074$ was used.

For simplicity, we assume that $N_1 = 1$ and that population at time t is $N^* * N_t$, where N^* is a parameter denoting initial population at the beginning.

Recruitment and population dynamics

Recruitment is determined by K_{bh} and α parameters in the following Beverton-Holt model:

$$R_t = \frac{K_{bh} Eggs_t}{\frac{K_{bh}}{\alpha} + Eggs_t}$$

The recruits are incorporated to the change in total population size using the following equation:

$$N_{t+1} \approx p_t N_t + R_{t+1}$$

Where N_t and p_t are the number of individuals into the stock and the expected survival at time t, respectively, while R_{t+1} is the number of recruits at time $t + 1$.

Growth

Growth of individuals is assumed to take place instantly in the beginning of each month. Each individual has the possibility of stay in the same length class or move higher. This movement is modelled through a transition matrix $\mathbf{g_t} = (g_{t,i,j})_{K \times K}$, where $g_{t,i,j}$ denotes the probability of and individual to move from length class i to length class j at time t. A normally distributed growth from each length class is assumed following the von Bertanlanffy growth function, such that length at time t is $l_t = Linf * (1 - exp(-k_g * (t - t_0)))$, where k_g is a parameter for somatic growth rate and $Linf$ is maximum size (see Appendix A in Mäntyniemi (2012)).

After growth, vector $\mathbf{\Phi_t}$ becomes $\mathbf{\Phi_t^{(G)}} = \mathbf{\Phi_t} \times \mathbf{g_t}$ describing a modified size distribution of the population.

Mortality and survival

A fish in length class $k, k = 1, \ldots, K$, after growth could be caught by fleet $j, j = 1, \ldots, F$, or to survive, with respective probabilities given by Baranov (see for example Quinn and Deriso,

1998) as follows:

$$\begin{aligned}\gamma_{t,k,j} &= \frac{F_{t,k,j}}{\sum_{j=1}^{F} F_{t,k,j} + M}(1 - e^{-(\sum_{j=1}^{F} F_{t,k,j}+M)})\phi_{t,k}^{(G)} \\ p_t &= \sum_{k=1}^{K}(1 - e^{-(\sum_{j=1}^{F} F_{t,k,j}+M)})\phi_{t,k}^{(G)}\end{aligned}$$

With $M = 0.1$ as the natural mortality and

$$F_{t,k,j} \approx propF_j \cdot Fsel_{k,j} \cdot F, \tag{1}$$

the fishing mortality for the $j - th$ fleet, where $propF_j$ is a parameter for the proportion of fishing mortality corresponding to fleet j, $Fsel_{k,j}$ is the fishing selectivity for fleet j and F the parameter for total fishing mortality.

When the hake is caught it has two posibilities: either to be landed with probability $\gamma_{t,k,j}Rsel_{k,j}$ or to be discarded with probability $\gamma_{t,k,j}(1 - Rsel_{k,j})$, both determined by the retention pattern of the $j - th$ fleet, $Rsel_{k,j}$.

Then the proportion of landed fish and discarded fish from all dead fish, q_t^l and q_t^d, is computed respectively, as:

$$\begin{aligned}q_t^l &= \frac{1}{1-p_t}\sum_{j=1}^{F}\sum_{k=1}^{K}\gamma_{t,k,j}Rsel_{k,j} = \frac{1}{1-p_t}\sum_{j=1}^{F} q_{t,j}^l \\ q_t^d &= \frac{1}{1-p_t}\sum_{j=1}^{F}\sum_{k=1}^{K}\gamma_{t,k,j}(1 - Rsel_{k,j}) = \frac{1}{1-p_t}\sum_{j=1}^{F} q_{t,j}^d\end{aligned}$$

Fishing selectivity, survey selection and retention patterns

Table 1 summarizes the descriptions of the functions chosen for the fishing selectivity, $Fsel_{k,j}$, survey selection, $Ssel_{k,s}$ and retention patterns, $Rsel_{k,j}$, for each fleet. The particular case of northern hake includes 5 fleets for fishing selectivity and retention ($F = 5$) and 3 different ones for survey selectivity. Fishing selectivity for fleets 1,2,3 and 5 is modelled with a double normal function, while for fleet 4 a logistic function was used. Retention applies only for the first three fleets and each one is modelled with a logistic function, for the other two fleets the retention is assumed constant and equal to 1. The double normal selection function is defined by parameters τ_{1j}, τ_{2j} and $l_j, j = 1, 2, 3, 5$, as follows:

For $\mathbf{M} = (M_1, \ldots, M_K)$ a vector with the midpoints of each length class k

$$Fsel_{k,j} = \begin{cases} e^{-\tau_{1j}(M_k - l_j)^2} & \text{if } M_k < lj, \\ e^{-\tau_{2j}(M_k - l_j)^2} & \text{if } M_k \geq lj, j = 1, 2, 3, 5 \end{cases}, \tag{2}$$

The logistic function with parameters α_j^f and $\beta_j^f, j = 4$ or α_j^r and $\beta_j^r, j = 1, 2, 3$ is used for fishing selectivity and retention, respectively:

$$\begin{aligned}logit(Fsel_{k,j}) &= \beta_j^f(M_k - \alpha_j^f), j = 4 \\ logit(Rsel_{k,j}) &= \beta_j^r(M_k - \alpha_j^r), j = 1, 2, 3\end{aligned}$$

The survey selection patterns are modelled as double normal analogously to equation (2) , with parameters $I\tau_{1s}, I\tau_{2s}$ and $Il_s, s = 1, 2, 3$.

Observational model

Landings and discards in numbers

Landings and discards at time t, l_t and dis_t, respectively, are assumed to follow a beta-binomial distribution.

$$\begin{aligned}l_t &\sim Betabin(q_t^l * \eta^*, (1 - q_t^l) * \eta^*, d_t) \quad t = 1, \ldots, T \\ dis_t &\sim Betabin(q_t^d * \eta^*, (1 - q_t^d) * \eta^*, d_t) \quad t = 1, \ldots, T\end{aligned}$$

For q_t^l and q_t^d as defined before, $d_t \approx N_t(1-p_t)$ representing all the dead fishes (by natural and fishing mortality) at time t and η^* accounting for process error.

Proportion of landings and discards by fleet

From available data for landings and discards numbers by fleet, the vector of proportions $\mathbf{Pl_t} = (Pl_{t,1},\ldots,Pl_{t,F})$ and $\mathbf{Pd_t}$, respectively, are calculated. They are modelled with a Dirichlet-Multinomial distribution.

$$\begin{aligned} \mathbf{Pl_t} &\sim DM(l_t, \frac{1}{q_t^l}(q_{t,1}^l,\ldots,q_{t,F}^l)) \quad t=1,\ldots,T \\ \mathbf{Pd_t} &\sim DM(dis_t, \frac{1}{q_t^d}(q_{t,1}^d,\ldots,q_{t,F}^d)) \quad t=1,\ldots,T \end{aligned}$$

For speed up computational time the Dirichlet approximation described in Mäntyniemi (2012) was implemented.

Length Distribution of landings and discards by fleet

Vector of length distribution of landings by fleet, $\mathbf{Ll_{t,j}} = (Ll_{t,j,1},\ldots,Ll_{t,j,K})$, and discards, $\mathbf{Ld_{t,j}}$, are presented in percentages, and assumed to be multinomially distributed.

$$\begin{aligned} \mathbf{Ll_{t,j}} &\sim Multi(100, \frac{1}{q_{t,j}^l}(\gamma_{t,1,j}Rsel_{1,j},\ldots,\gamma_{t,K,j}Rsel_{K,j})) \\ \mathbf{Ld_{t,j}} &\sim Multi(100, \frac{1}{q_t^d}(\gamma_{t,1,j}(1-Rsel_{1,j}),\ldots,\gamma_{t,K,j}(1-Rsel_{K,j})) \end{aligned}$$

Survey indexes

Estimations of the population by length through surveys are available for some quarters with three different fleets $I_{t,s}, s=1,2,3$. They are assumed lognormally distributed with a coefficient of variation $CV = 0.2$, as follows:

$$I_{t,k,s} \sim LN(log(q_s N_t \phi_{t,k} Ssel_{k,s}) - log(CV^2+1)/2, 1/log(CV^2+1)) \quad k=1,\ldots,K, s=1,2,3.$$

Prior distributions

Most of the prior distributions have been chosen uninformative but with plausible boundaries in order to allow parameters to move in a wide range of values.

Informative priors were also developed for some model parameters ($Linf$, M and recruitment variance) based on previous studies on hake biology. $Linf$ priors were estimated based on the life history invariant for the ratio $Linf/Lmat$ (Charnov, 1993), where $Lmat$ is the length at maturity. The total number of hake studies records with $Linf$ and $Lmat$ data was 33 resulting in a final prior for $Linf$ that follows a normal distribution with mean 100.42 cm and s.d. 9.48 cm. Priors for M were estimated based on the life history invariant for the ratio k_g/M (Charnov, 1993). The total number of hake studies with $Linf$ and $Lmat$ information were 25 resulting in a final prior for M that follows a lognormal distribution with parameters (in log scale) mean, -0.64 and s.d., 1.5. Finally, relative carrying capacity, K_{bh}, (absolute carriying capacity is K_{bh} multiplied by initial population, N^*) for recruitments was also estimated from 13 hake studies. Coefficient of variance for recruitment follows a normal distribution with mean, 0.56 and s.d., 0.41.

Implementation

The model have been run in the Centre of Supercomputing of Galicia (CESGA) using the SVG cluster with an AMD Opteron and AMD Bulldozer Processors. The software used was R 2.14.1 (R Development Core Team, 2011) and JAGS 3.3.0 (Just another Gibbs sampler) (Plummer, 2013). The code is written in R linking with the MCMC sampler through the package *rjags* (Plummer, 2012).

Function	**Priors**
Initial abundance	log(N[1])~N(dnorm(muN,s2N), muN=0, s2N=10000
F	F~dunif(0,0.5)
Fleet 1-Selection Double normal	tau11~dunif(0,0.3), tau21~dunif(0.0005,0.01) l11~dunif(20,40)
Fleet2 - Selection Double normal	tau12~dunif(0.002,0.3), tau22~dunif(0.002,0.3) l12~dunif(10,30)
Fleet3 -Selection Double normal	tau13~dunif(0,0.3), tau23~dunif(0.00005,0.01) l13~dunif(20,60)
Fleet 4- Selection Logistic	alphaFsel~dnorm(-40,1/400)T(-60,-10) betaFsel~dunif(0.1,0.99)
Fleet 5- Selection Double normal	tau15~dunif(0.002,0.01), tau25~dunif(0.0005,0.005) l15~dunif(50,90)
Fleet 1 retention pattern – Logistic	alphaGsel[1]~dnorm(-27,0.01), betaGsel[1]~dunif(0.001,3)
Fleet 2 retention patters – logistic	alphaGsel[2]~dnorm(-27,0.01) betaGsel[2]~dunif(0.001,3)
Fleet 3 retention pattern - logistic	alphaGsel[3]~dnorm(-27,0.01) betaGsel[3]~dunif(0.001,3)
Survey1- double normal	Itau11~dunif(0.0001,0.01), Itau21~dunif(0.0005,0.005) Il11~dunif(40,80), q1~dunif(5e-5,10e-3)
Survey2- double normal	Itau12~dunif(0.001,0.5), Itau22~dunif(0.001,0.1) Il12~dunif(1,30), q2~dunif(10e-3,10e-1)
Survey3- double normal	Itau13~dunif(0.001,0.5), Itau23~dunif(0.00001,0.1) Il13~dunif(5,30), q3~dunif(10e-5,10e-3)
Growth (Logit)	Gk = mink+(maxk-mink)*pk, mink=0.025; maxk = 0.075; logit pk ~ dnorm(0,1)
Beverton-Holt	log(K)~dnorm(muK,s2K), muK=log(0.2), s2K=25

Figure 1: Prior distributions for parameters in first and second model version

Results

We performed 56 runs. The main reason to perform only 56 runs was the long time of every individual run. Each run might lasting up to 600 hours in the supercomputers. To explain the evolution of the model along all these runs we have selected 5 out of them each one following from different assumptions regarding running time, data aggregation, processes structure, length classes, number of fleets and prior distributions. This is the description of these 5 runs:

- **1st model version:** Data grouped in 19 length classes, 5 fleets and prior distributions as in Figure 1. Running takes 562.68 hours for 520000 iterations. The first 20000 for adaptation without thinning and after that a thinning of 100 was applied.
- **2nd model version:** Data grouped in 14 length classes, 5 fleets, Fishing mortality $F_{t,j,k}$, is bounded by 0.5 and prior distributions are defined as in Figure 1. Running takes 195.05 hours for 220000 iterations. The first 20000 for adaptation without thinning and after that a thinning of 100 was applied.
- **3rd model version:** Data grouped in 19 length classes, 5 fleets grouped in three

fleets (see Table 1), the first group with SPTRAWL7, FRNEP8 and SPTRAWL8, assumed as double normal for selection and logistic for retention, the second group with TRAWLOTH + OTHERS modelled logistic for selection and the third group with GILLNET + LONGLINE modelled double normal for selection. A multivariate normal prior was defined for initial population and fishing mortality parameters, instead of univariate normal for both in order to speed up sampling. F prior was transformed from uniform ($U(0, 0.5)$) to normal using a logit transformation. Priors for selection patterns parameters were also modified from priors in Figure 1 because of the mixture of fleets, as follows:

$$\begin{aligned} tau11 &\sim dunif(0, 0.3) \\ tau21 &\sim dunif(0.00005, 0.3) \\ l11 &\sim dunif(10, 60) \\ tau12 &\sim dunif(0.002, 0.01) \\ tau22 &\sim dunif(0.0005, 0.005) \\ l12 &\sim dunif(50, 90) \end{aligned}$$

Running takes 177.2 hours for 220000 iterations. The first 20000 for adaptation without thinning and after that a thinning of 100 was applied.

- **4th model version:** The same as the third model version but variance of prior for relative carrying capacity K_{bh} ($K_{bh} = K^*/N^*$ where K^* is the absolute carrying capacity and N^* is the initial population) and coefficient of variation for the total recruitment is defined from 13 hake recruitment data series with a mean coefficient of variation equal to 0.56 and standard deviation 0.41. Also k, the annual growth rate is assumed as constant and equal to 0.17 as ICES did in the last assessment. Process error term in equation 3, η^*, was modified as follows:

$$\begin{aligned} l_t &\sim Betabin(q_t^l * \eta^*, (1 - q_t^l) * \eta^*, d_t) \quad t = 1, \ldots, T \\ dis_t &\sim Betabin(q_t^d, 1 - q_t^d, d_t) \quad t = 1, \ldots, T \end{aligned}$$

  a. With $Linf = 130cm$ and $M = 0.1$. Fishing mortality $F_{t,j,k}$, is bounded by 0.8. Running takes 252.34 hours for 220000 iterations. The first 20000 for adaptation without thinning and after that a thinning of 100 was applied.
  b. With priors for Linf and M based on previous studies. $Linf \sim N(100.42, 9.48)$ and $M \sim LN(log(0.23), sqrt(log(185.4164))$. Prior for alphaGsel, the length where 50% of the retention occurs (α_1^r) is bounded by 20 and 30 cms. Fishing mortality $F_{t,j,k}$, is bounded by 0.5. Running takes 259.81 hours for 200000 iterations. The first 20000 for adaptation without thinning and after that a thinning of 100 was applied. JAGS code for model is in Supplementary material IV.

Observed-expected (total numbers)

GPDM works by minimizing the catch and discards in numbers in every time step. The coherence between the time series data and the estimations could be interpreted as a partial validation of the model definition. We can see how this fit performs in each model version in Figures 2 and 3.

We can see a general good performance fitting landings, except for year 2009 where the model overestimate the values in all the model versions . The best landings estimation is achieved in model version 4b and the worst in the third model version.

Discards are well fitted in model versions 1,2 and 4b, also with a remarkable difference in year 2009. In model versions 3 and 4a, they are understimated and overstimated, respectively.

Selection and Retention plots

Selection and retention patterns are displayed in Supplementary material I. For the first two model versions including 5 fleets for selection and three for retention, the patterns estimation

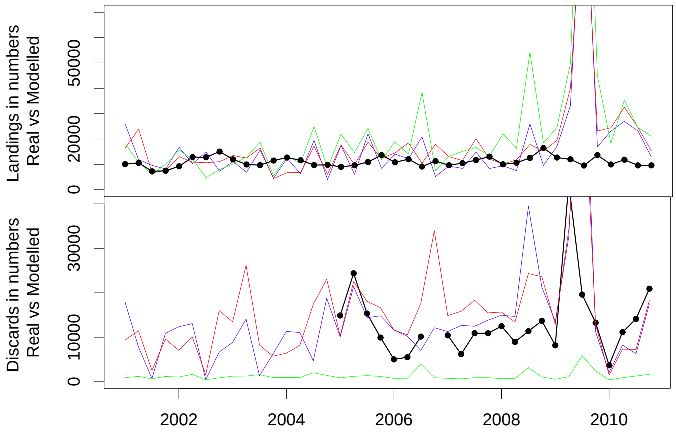

Figure 2: Comparison between modelled and observed quaterly data for landings and discards in numbers (thousands) for model versions 1 (blue), 2 (red) and 3 (green). Black line with circles corresponds to observed numbers transformed from ICES landings biomass data using the lenght at weight relationship. Solid coloured lines correspond to the modelled median.

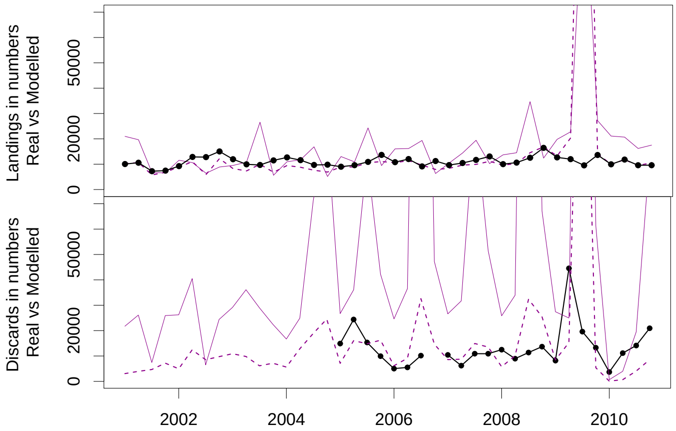

Figure 3: Comparison between modelled and observed quaterly data for landings and discards in numbers (thousands) for model versions 4a (magenta) and 4b (magenta dashed). Black line with circles corresponds to observed numbers transformed from ICES landings biomass data using the lenght at weight relationship. Coloured lines correspond to the modelled median.

results very similar to the one obtained in ICES model. The model reproduces propperly the selection and retention patterns except for retention pattern of fleet SPTRAWL8 in first and second model version. This lack of fit is coherent with the mixing problems associated to the parameters involved, alphaGsel[3] and betaGsel[3], see Figures 5 and 11 in Supplementary material II.

For model versions 3, 4a and 4b, where fleets SPTRAWL7, FRNEP8 and SPTRAWL8 where grouped into one fleet, the selection pattern estimation is very similar in all the model versions except for the first fleet, where the maximum of the function is achieved approximately at 40, 20 and 35 cms, respectively. The retention pattern which is assumed logistic as a mixture of the three discarding fleets, in model version 3, is coherent with the pattern of fleet SPTRAWL8 in model versions 1 and 2. In model versions 4a and 4b retention is similar to the pattern of fleet FRNEP8.

Growth plots

The modelled von-Betallanfy growth curve corresponding to black and coloured lines in left panel of Figure 4 was calculated assuming $Linf = 130$. The somatic growth rate k_g was estimated in the first three model versions following a logit normal prior distribution bounded by 0.025 and 0.075. This curve results similar to the ICES estimation (black line) in model versions 1,2 and 3. In first model versionthe estimation of this curve is the best even when the posterior distribution for the annual somatic growth rate parameter is bimodal (Right panel of Figure 4). Traceplot for quaterly parameter k_g in Figure 1 of Supplementary material II shows two chains without mixing but with a very small difference between their means. The first one centres around 0.0425 and the other one around 0.0445. When they are transformed into annual values they result also in different but closer values, which lead us to conclude that an annual somatic growth rate between 0.17 and 0.178 will be adequate to model the growth dynamics, which is coherent with ICES that assumes this rate as constant and equal to 0.17.

Second and third model versions estimate a von-Betallanfy growth curve similar to ICES but not as close as in first scenario. The second underestimate and the third overestimate the curve with a bigger difference in third scenario.

Results for this curve in model version4a are not plotted, because the parameters involved, $Linf$ and k_g where assumed constant.

In model version 4b, where $Linf$ is considered as a parameter and k_g as constant, an unrealistic estimation is obtained. The median of the posterior of $Linf$ (Right panel in Figure 5) is close to 80 cm and far away from the prior $Linf \sim N(100.42, 9.48)$.

Summary plots (Recruits, SSB, landings, discards and fishing mortality)

The Figure 6 shows a comparison between modelled (coloured lines) and ICES estimations (black line) of recruitment, SSB, landings, discards and fishing mortality by year for individuals between 15 and 80 cms, for model versions 2 (red), 4a (magenta) and 4b (magenta and dotted). We choose these scenarios in order to see how the reduction in the number of fleets and the inclusion of environmental priors affects the population size estimations at different stages (red vs. magenta and solid magenta vs. dotted magenta).

In model versions 2 (red) and 4a (magenta) the fishing mortality and discarded biomass are higher than the one estimated by ICES in most of the years considered, the discarded biomass trend is consistent with the estimations in numbers of individuals (Figures 2 and 3) . For model version 2, year 2005 is the only year where F is bigger than ICES estimate and for model version 4a, there is a minimum at that year. Also spawning biomass in that year is higher in both scenarios. The overestimation in landings in numbers in the last two years and discards in numbers in year 2009 showed in Figures 2 and 3 is coherent with the increase in spawning biomass during that years.

For model version 4b where biological information is included, the number of fleets is reduced and observed discards error is modified, the discards biomass estimation improves considerably while landings estimation is in a reasonable level. The reduction in fishing mortality matches with the increase in spawning biomass.

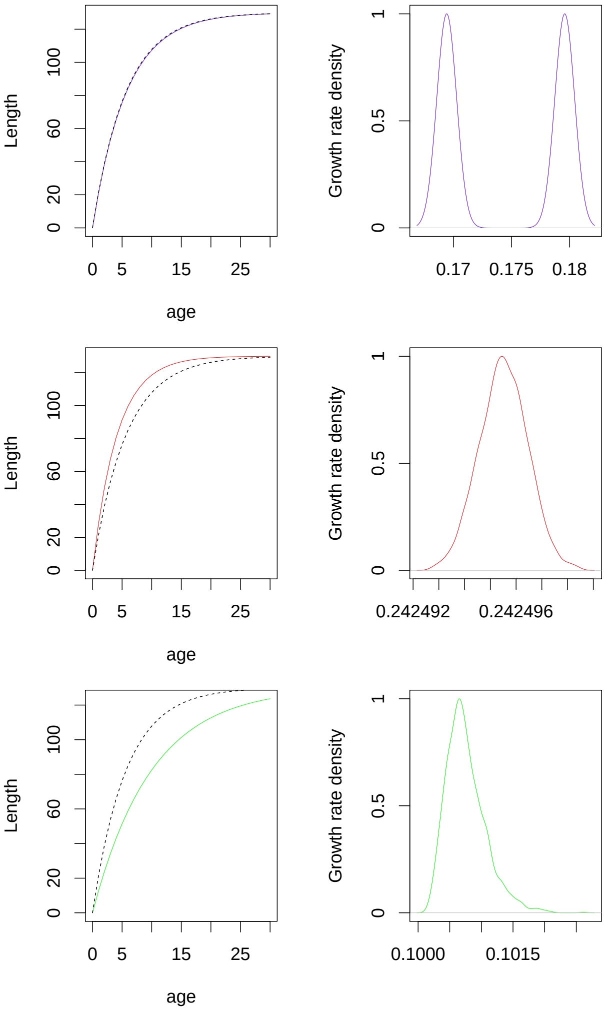

Figure 4: Left:Comparison between modelled von-Bertallanfy growth curve (dotted) and the one estimated by ICES (black and dotted). Right: Posterior distribution for the annual somatic growth rate parameter, k_g. Every row represents one scenario, 1 (blue), 2 (red) and 3 (green)

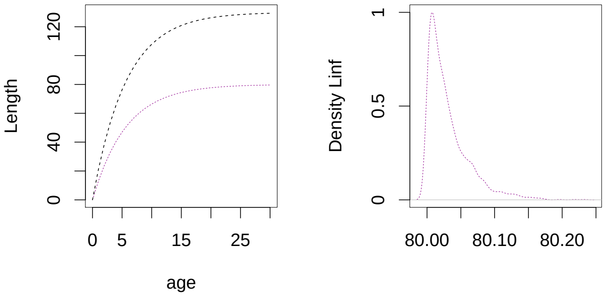

Figure 5: Left:Comparison between modelled von-Bertallanfy growth curve (dotted and magenta) and the one estimated by ICES (black and dotted). Right: Posterior distribution for $Linf$. (Model version 4b)

Big difference between F in model versions 4a and 4b is coherent with the corresponding bounds of 0.8 and 0.5.

The recruitment in all scenarios remain close to ICES estimation. Similarity between model version 2 and ICES estimation is remarkable while there are big differences with model version 4a (Perhaps due to the reduction of fleets).

Beverton Holt stock-recruitment parameter

The maximum recruitment parameter, K_{bh}, was calculated using prior information of different stocks in model versions 4a and 4b, corresponding to the fourth and fifth rows of Figure 7. There is a significant variance reduction when this information is taken into account. Without prior information for M and $Linf$ as in model version 4a, posterior is between 0 and 0.8 while including prior information it is between 0 and 0.15.

MCMC sampling traces

Diagnostics (traces) are presented in Supplementary material II. An acceptable level of convergence is achieved when traces are random and horizontal with overlapping in all chains.

It can be seen in first model version that chains for growth rate are not mixing, however the distance between both chains is not bigger than 0.0025 (Figure 1 in Supplementary material II). Fleet selection and retention patterns parameters in this model version are not showing a general good mixing performance. Chains for tau13 and SPTRAWL8 fleet retention parameters (alphaGsel[3] and betaGsel[3]) are not mixing at all. Chains for l11, l12, tau11, alphaFsel, betaFsel, alphaGsel[1], betaGsel[2], Itau11 and Il11 are close but not overlapping (Figures 2,3,4 and 5 in SM II). Parameters tau22 and F are bounded in the limit of the prior distribution. This means that the model is trying to find a solution out of credible limits.

In second model version the problems with F, tau13 and l12 persist (Figures 7 and 8) but most of the selection patterns parameters achieve convergence. Retention patterns chains for fleet SPTRAWL8 remain with no mixing and also betaGsel[2] is low bounded by the prior (Figure 11). Survey fleet parameters, Il11 and Itau11 achieves convergence but Itau13 and Il13 get worst (Figure 12).

In third scenario, convergence improves substantially, all chains mix and overlap, and F chains are not bounded anymore by the prior (Figure 13). There are only problems with initial population and one catchability parameter. Mixing for initial population parameter is

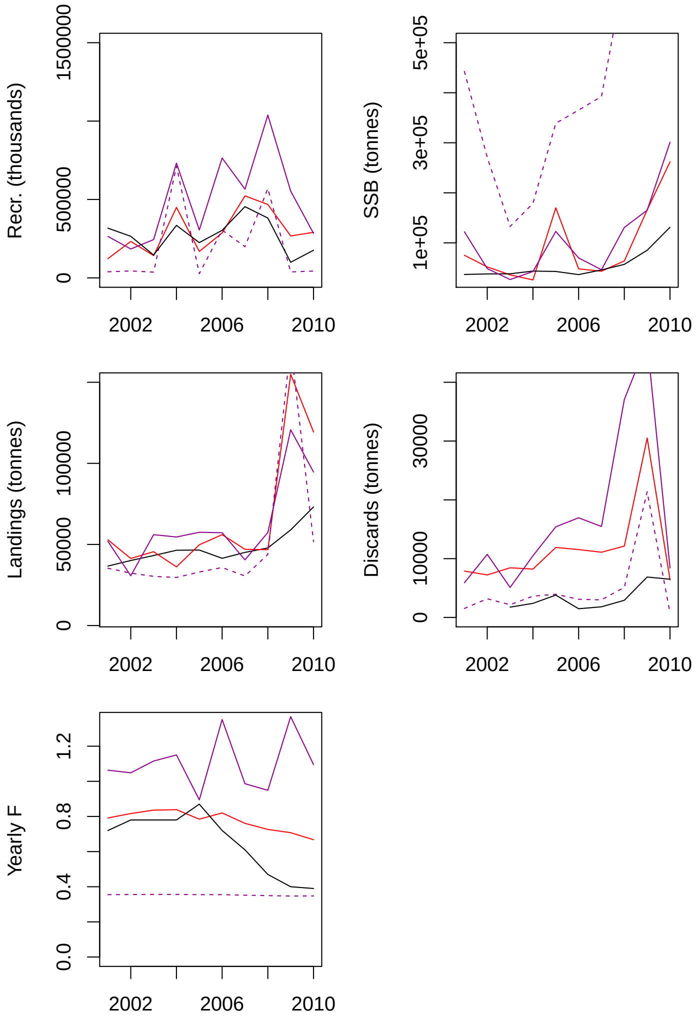

Figure 6: Comparison between model estimations (medians, model version 2 (red), model version 4a (magenta) and model version 4b (magenta and dotted)) and ICES estimations (black line) by year

not as good as in the first two model versions (Figure 13) and catchability chains for survey fleet 2, q2 (Figure 15) is low bounded by the prior.

The situation for fourth a model version is similar to the one in third scenario, most of the parameters converge, except for F (Figure 18) and tau11 (Figure 21) which are bounded by the priors. Also initial population parameter chains remain close but mixing are not quite good.

When including biological priors, mixing situation get worst, there are mixing problems with initial population, F, M, alphaGsel, q1, q2, q3, Itau12 and Itau13.

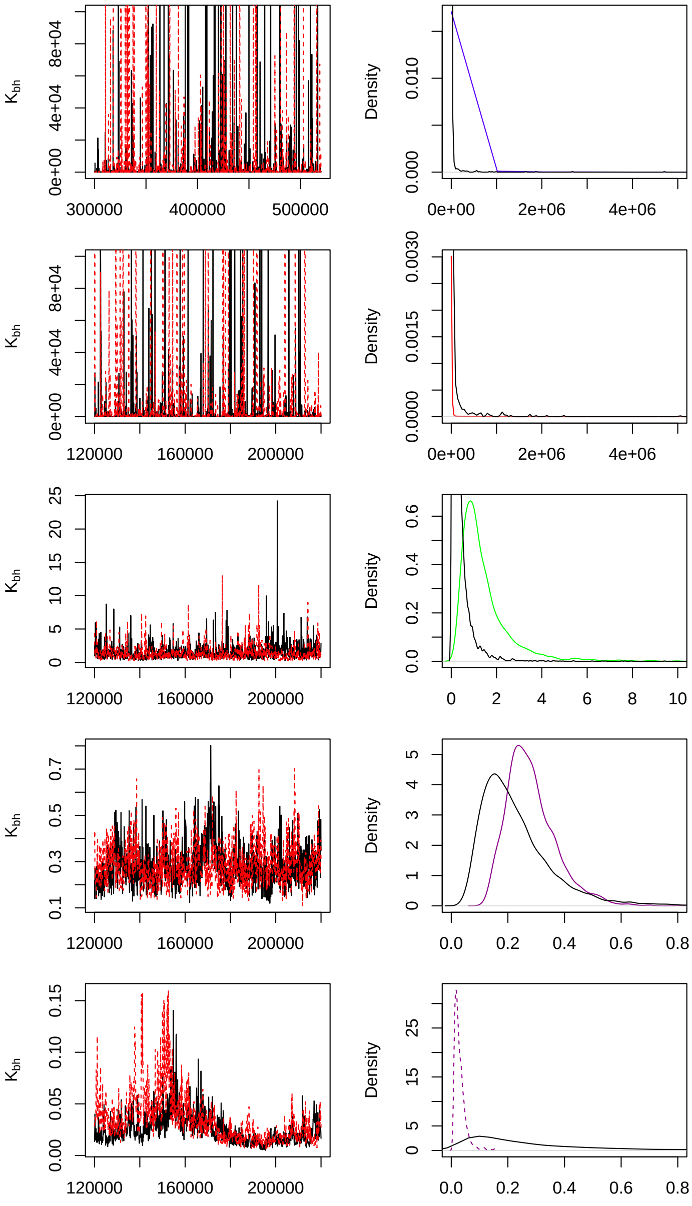

Figure 7: In left panel the traces and in right panel the comparison between prior (black line) and posterior (coloured lines) for the carrying capacity parameter. Each row represents one scenario, colors are respectively blue,red, green, magenta and magenta dotted for model versions 1,2,3,4a and 4b.

Length frequency

The modelled length frequency of the population at each quarter is displayed in Supplementary material III.

Most of the population relies between 3 and 30 cms in all the scenarios, except for quarter 7 in the first two model versions and quarters 37 and 38 in all the scenarios. This missbehavior in quarters 37 and 38 can be driven by the overestimation of landings and discards in numbers in quarters 35 and 36 (Figures 2 and 3). Length frequency of the population moves to big sizes in order to fit the overestimated numbers.

Discussion

Bayesian theory provides a well grounded way to develop population dynamic models for stock assessment purposes implementing two main features: a straightforward method of dealing with uncertainty and a innovative system to combine the knowledge based on observed data (the likelihoods) with the previous knowledge we have about model parameters (what in Bayesian models is called "a priori"). This second feature is a useful way to improve the biological knowledge in fish population dynamic models since there is a lot of information about fish biology that cannot be used in non Bayesian models. This additional information can be extracted from different sources like previous studies published which can belong to the same or similar species, public data sources like FishBase (www.fishbase.org; Froese and Pauly (2013)); furthermore this information might be combined with through meta-analysis (Liermann and Hilborn, 1997; Myers and Mertz, 1998)

Hake is evaluated by ICES (ICES, 2012) with a length based model named SS3 (Methot Jr. and Wetzel, 2013). This model has implemented the biological knowledge in a quite simple way. Main biological process parameters have been estimated outside the assessment model framework and have been fixed before running the SS3 model. These main biological processes are: the growth, which follows a von Bertalanfy model with parameters $Linf$=130 cm and $k_g = 0,168\ year^{-1}$; the natural mortality with value 0.4 $year^{-1}$ equal for all years and ages and the recruitment that follows a Beverton-Holt model with steepness equal to 1 and high CV. These make the Beverton-Holt model to produce a mean recruitment independent of the spawning stock biomass. The high CV makes that good or bad yearly recruitments will be estimated based on the observed catches. The advantages of the ICES approach are the simplicity in the biological implementation making the model convergence easy. Other advantage of the ICES approach are the platform used, SS3. This software implements a searching algorithm called "automatic differentiation" quite efficient and faster for (Methot Jr. and Wetzel, 2013). The current ICES hake model does not last more than 4 hours to get a converged solution. The disadvantages are the lack of biological realism given the poor available knowledge to estimate growth, natural mortality and recruitment. One of the goals of this work is to improve this realism.

The strategy followed when developing the Bayesian model for hake was: first to replicate the ICES model in a Bayesian context and afterwards implement biological priors based on hake studies. To replicate the ICES model we started with a Bayesian model already developed called General population dynamics model (GPDM) developed by Samu Mäntyniemi (Mäntyniemi, 2012). However this model does not have the required slots for some processes already implemented in the ICES model. These processes are the fleet selection at length for different fleets and the retention pattern for the fleets discarding fish, i.e. the trawlers. Furthermore, the process to calibrate surveys data (length distribution) was also required. All these process were implemented in the GPDM as described in the "Methods" section allowing a model implementation similar that those developed by ICES.

With this model on the hand we started to implement the hake data. The data availability was the same that used by ICES (2012) assessment with data until 2010 including landings, discards and surveys by quarter. Total biomass and length distribution were also available. ICES landings were split in 7 different fleets and 3 out of them had also discarded data. Length distribution of these data were grouped by 1 cm (from 4 to 40 cm) and by 2 cm from 40 to 100 making a total of 76 length groups. The ICES modelled population follows this same length structure adding lengths groups from 1 to 4 cm each cm and from 100 to 130 cm each 10 cm to accomplish the maximum length of 130 cm. These data disaggregation were not operational in a bayesian context given the long computing time. To be operative we had to reduce the data complexity to be able to test and develop the needed processes first and also to be able to implement the statistical processes needed to test the biological informative priors afterwards.

As a starting point, a general rule to develop models is to start with a simple one and to evolve eventually towards a complexity level that allows answering the relevant questions. The Bayesian implementation has huge computational requirements expending many days for a single run. This makes the initial model development impossible in a feasible time since every run provide the clues for the next runs. Our first data structure was made of 10 years (2001-2010) every quarter (40 time steps); 1 fleet (instead of the 7 fleets implemented by ICES) and 13 length groups (instead of 76). Main model assumptions were similar than those in the ICES model, i.e. constant biological parameters (as described before), non-informative priors for other parameters such us fleet selection, retention pattern or survey catchability. This simple structure allowed us to compile the model, to identify problems in the code, to improve the definition of un-informative priors and to define Bayesian settings such us the iterations number, the adaptation period, the burning and the thinning. However after extending the model, the number of iterations was not enough to get model convergence in a reasonable time in our computers, thus compromising the development of the hake model.

Given the time limitation of our personal computers we needed access to better computers that eventually would give us two different advantages: first, faster processors to reduce computing time and second, more processors to run different model versions at the same time . We got these computers in the Center of Supercomputation of Galicia (CESGA – www.cesga.es). We expected these computers to run the hake model faster. However the convergence was not achieved after near 600 hours running two Bayesian chains in parallel. The maximum time that CESGA allow us to run the model. The working strategy should consist on playing with the model complexity. To do that, two different approaches were taken: first playing with data complexity (fleets and length classes) and second playing with model structure in two ways: simplifying processes and simplifying statistical priors (e.g using normal proxies for beta-binomial priors and Dirichlet for Dirichlet-Multinomials) since normal priors are less computing demanding.

We can see the convergence problems in the traces presented in the Supplementary material II where some parameters are not able to mix and some others are bounded in the limit of the prior distribution. This means that the model is trying to find a solution out of credible limits. Figures 2 and 3 also show the huge difference between the observed catches (landings and discards) and the modelled ones in recent years (2009 and 2010) driving the model to catches in weight well above the ICES estimated catches (Figure 6). Since the estimation of biological parameters requires a high amount of length classes to be able to follow the growth dynamics through the quarterly length distribution, we kept the model version with the 19 length classes but reduced the amount of fleets from 5 to 3. Some changes in priors and fishing mortality process were also implemented. The idea was to give more flexibility to F to allow a good fit in recent years. With this new model version the convergence clearly improves although still remain some problems of mixing (see Figure 13 in Supplementary material II). However the estimation of discard abundance is now well below the observed one and still remains the problem of huge modelled landings in recent years. This situation was quite similar in the most of the performed runs; when a problem in a particular parameter is addressed through data structure, process design or this problem is apparently solved but other different appears. Results with non-informative priors were not totally satisfactory. The great number of parameters makes very difficult to find what is the piece of knowledge that is steering the posteriors to right direction. Perhaps the decrease in the number of fleets and length classes produces some incompatibilities in used information or some of the observations are not what they are supposed to be.

Model versions 4a and 4b are examples of the implementation of biological priors. Biological priors for growth, natural mortality and variability in the Beverton-Holt carrying capacity were developed from meta-analysis with data taken from the literature (Cerviño and Michielsens, 2014). The 4a model version implements the prior for the variance in the carrying capacity. Figure 7 shows the impact in this prior on the 5 different scenarios. We can see how the prior improves the mixing (left panel), although the posterior is dominated by the prior (right panel), not by the data. This is an additional diagnostic about the difficulties of the model to fit the data without well defined priors. When more biological priors were added (model version 4b) the convergence gets worst. Model version 4b added two more priors for M and $Linf$ giving more freedom to the model to find a solution; however, at the same time the model is able to find unrealistic solution. This indicates that the model is over the limit of what can be estimated.

The model development have had two well differentiated parts: along the first part the modifications introduced, mainly different data aggregation levels and prior definition did not allow reaching model convergence in a reasonable time. Along the second part, the simplification applied to the model, mainly alternative process definition including statistical distribution of priors. In this second period model convergence was quite improved although some unrealistic results had been got. For instance, those related with catches like big amounts of catches or extreme ratios of landings/discards. The insertion of biological priors for recruitment through the carrying capacity resulted in a posterior distribution with less variance, however this variance increased when adding priors for M or $Linf$. Further work is needed to better understand how different priors interplay between each other and what is required to be assumed about observations when the structure of the data is changed. Also to find more mechanisms to improve convergence and mixing.

In summary, the hake model is a complex model based on lengths and length population dynamic model are quite computing demanding. In a Bayesian context this computing requirements are even bigger. The analysis performed showed the difficulties to develop this model given the time required to take every decision. Even though, the insertion of biological knowledge in the Bayesian model helps to achieve model stability in some cases, for instance with the recruitment variance, other biological priors reduced that stability and much time was required to readjust the model. Even though the model evolved until a stable design where convergence was achieved, this design turned out to be oversimplified (10 years, 3 fleets and 19 length classes) limiting its usefulness to management.

The current power of computers makes this model implementation hard and slow. However the progress developed shows the way to follow and given the speed at with computing power is increasing, it is possible that a better implementation, more useful for management purposes, will be feasible in a short time.

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A Bayesian state-space size-structured population dynamics model for northern hake. Improving hake assessment considering biological uncertainty

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Suplementary material I

Selection and rettention patterns estimations

Fleet	Selection	ICES fleet	Discards	Retention
1	Double Normal	SPTRAWL7	Yes	Logistic
2	Double Normal	FRNEP8	Yes	Logistic
3	Double Normal	SPTRAWL8	Yes	Logistic
4	Logistic	TRAWLOTH+OTHERS	No	
5	Double Normal	GILLNET+LONGLINE	No	

Table 1: Fleets used in hake Bayesian GPDM. SPTRAWL7 and SPTRAWL8 are for spanish trawls used in VII and VIII ICES divisions, FRNEP8 is for french trawl targeting Nephrops in division VIII and TRAWLOTH is for all other trawl operating in Northern stock.

- **1st model version:** Data grouped in 19 length classes, 5 fleets. Running takes 562.68 hours for 520000 iterations. The first 20000 for adaptation without thinning and after that a thinning of 100 was applied.
- **2nd model version:** Data grouped in 14 length classes, 5 fleets, Fishing mortality $F_{t,j,k}$, is bounded by 0.5. Running takes 195.05 hours for 200000 iterations. The first 20000 for adaptation without thinning and after that a thinning of 100 was applied.
- **3rd model version:** Data grouped in 19 length classes, 5 fleets grouped in three fleets (see Table 1), the first group with SPTRAWL7, FRNEP8 and SPTRAWL8, assumed as double normal for selection and logistic for retention, the second group with TRAWLOTH + OTHERS modelled logistic for selection and the third group with

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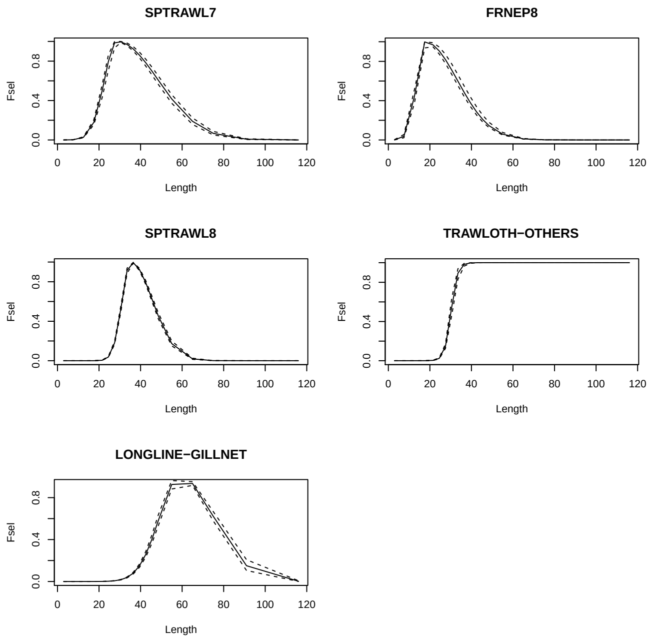

Figure 1: Modelled selection patterns for the five fleets considered in model version 1. Black solid line corresponds to the median while dotted black lines represent the 0.05 and 0.95 percentiles

GILLNET + LONGLINE modelled double normal for selection. A multivariate normal prior was defined for initial population and fishing mortality parameters. Running takes 177.2 hours for 200000 iterations. The first 20000 for adaptation without thinning and after that a thinning of 100 was applied.

- **4th model version:** The same as the third model version but variance of prior for relative carrying capacity K_{bh} ($K_{bh} = K^*/N^*$ where K^* is the absolute carrying capacity and N^* is the initial population) and coefficient of variation for the total recruitment is defined from 13 hake recruitment data series with a mean coefficient of variation equal to 0.56 and standard deviation 0.41. Also k, the annual growth rate is assumed as constant and equal to 0.17 as ICES did in the last assessment. Fishing mortality $F_{t,j,k}$, is bounded by 0.8 and process error term η^*, was modified as follows:

  $$\begin{aligned} l_t &\sim Betabin(q_t^l * \eta^*, (1-q_t^l) * \eta^*, d_t) \quad t = 1, \ldots, T \\ dis_t &\sim Betabin(q_t^d, 1-q_t^d, d_t) \quad t = 1, \ldots, T \end{aligned}$$

  a. With $Linf = 130cm$ and $M = 0.1$. Running takes 252.34 hours for 200000 iterations. The first 20000 for adaptation without thinning and after that a thinning of 100 was applied.
  b. With priors for Linf and M based on previous studies. $Linf \sim N(100.42, 9.48)$ and $M \sim LN(log(0.23), sqrt(log(185.4164))$. Running takes 259.81 hours for 200000 iterations. The first 20000 for adaptation without thinning and after that a thinning of 100 was applied.

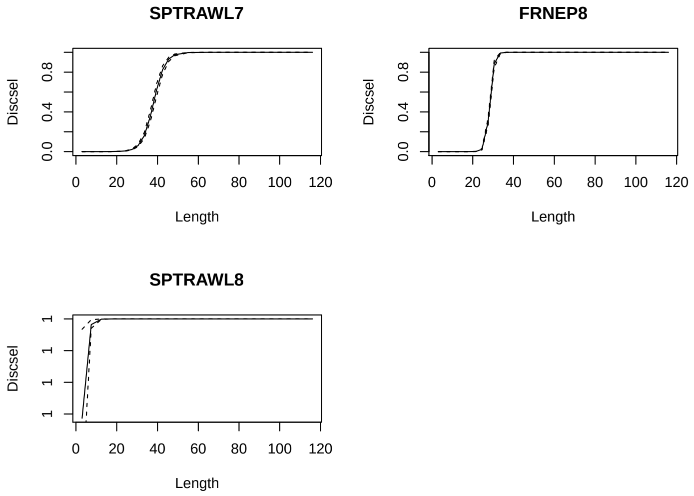

Figure 2: Modelled retention patterns for the fleets discarding in model version 1. Black solid line corresponds to the median while dotted black lines represent the 0.05 and 0.95 percentiles

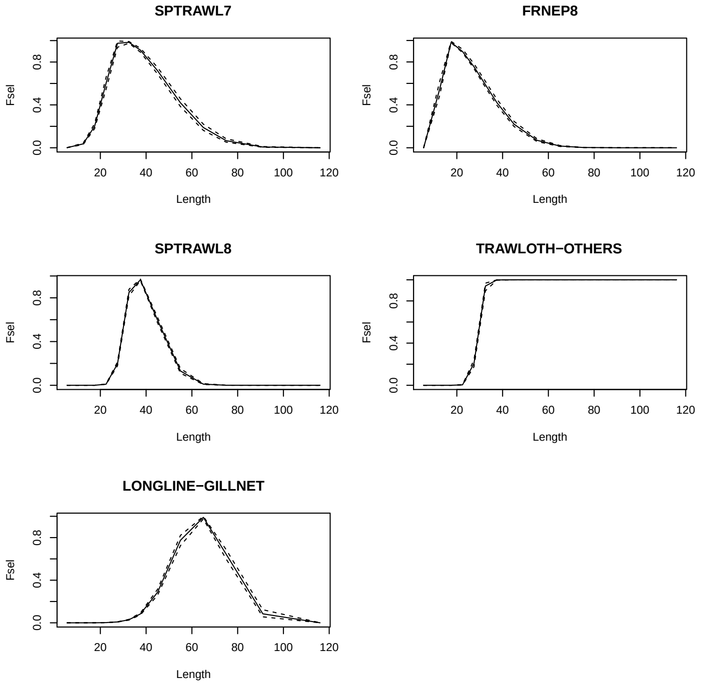

Figure 3: Modelled selection patterns for the five fleets considered in model version 2. Black solid line corresponds to the median while dotted black lines represent the 0.05 and 0.95 percentiles

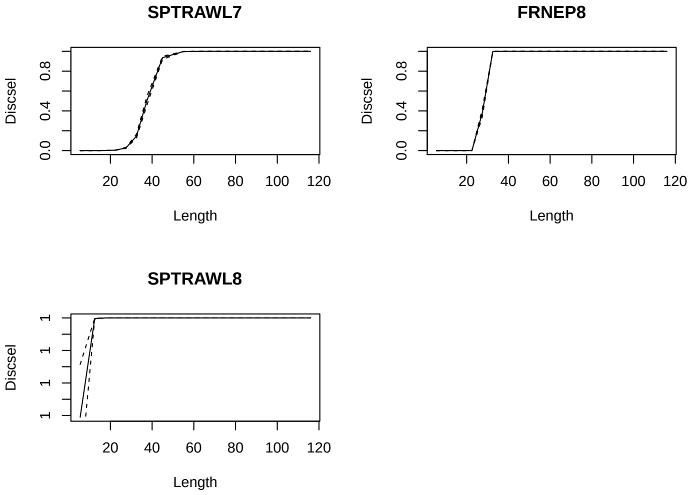

Figure 4: Modelled retention patterns for the fleets discarding in model version 2. Black solid line corresponds to the median while dotted black lines represent the 0.05 and 0.95 percentiles

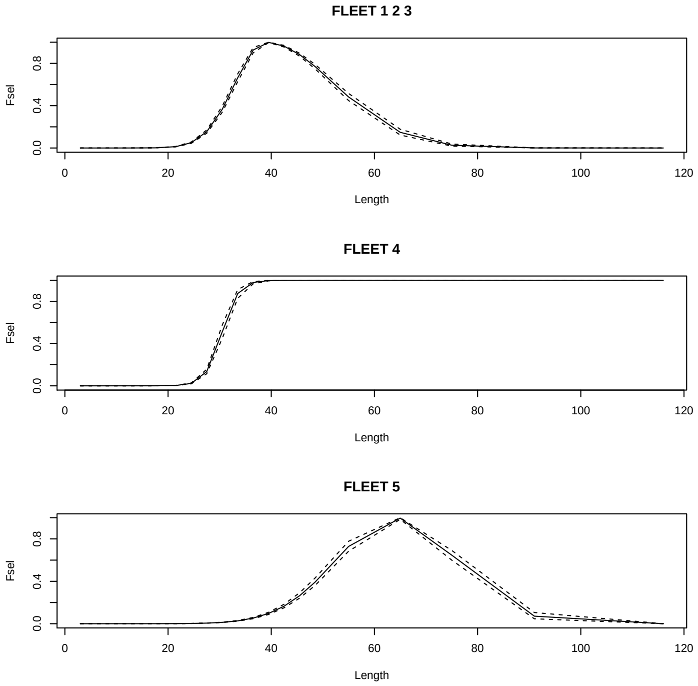

Figure 5: Modelled selection patterns for the three fleets considered in model version 3. Black solid line corresponds to the median while dotted black lines represent the 0.05 and 0.95 percentiles

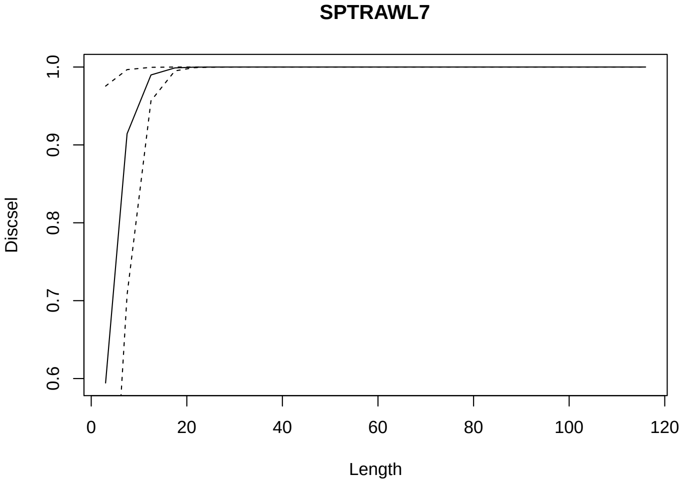

Figure 6: Modelled retention patterns for the fleet discarding in model version 3. Black solid line corresponds to the median while dotted black lines represent the 0.05 and 0.95 percentiles

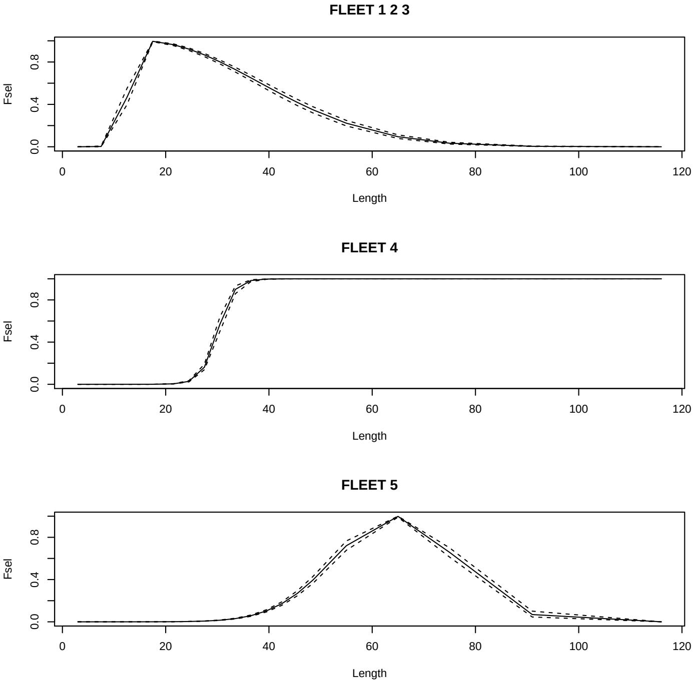

Figure 7: Modelled selection patterns for the three fleets considered in model version 4a. Black solid line corresponds to the median while dotted black lines represent the 0.05 and 0.95 percentiles

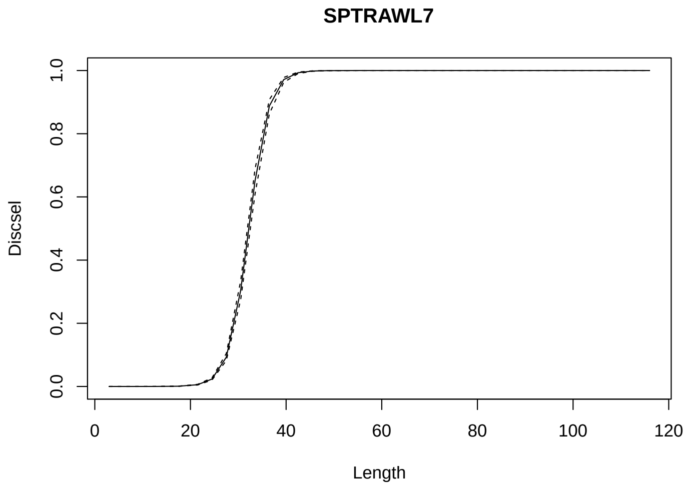

Figure 8: Modelled retention patterns for the fleet discarding in model version 4a. Black solid line corresponds to the median while dotted black lines represent the 0.05 and 0.95 percentiles

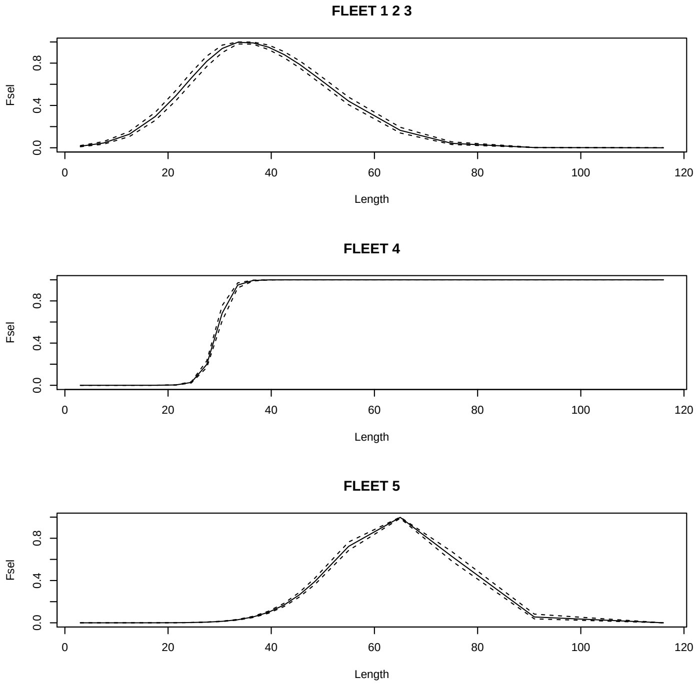

Figure 9: Modelled selection patterns for the fleets considered in model version 4b. Black solid line corresponds to the median while dotted black lines represent the 0.05 and 0.95 percentiles

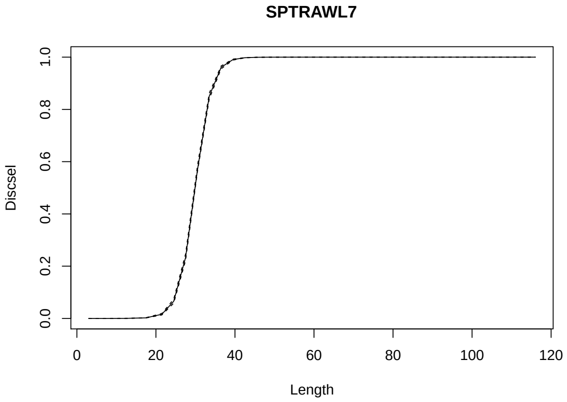

Figure 10: Modelled retention patterns for the fleets discarding in model version 4b. Black solid line corresponds to the median while dotted black lines represent the 0.05 and 0.95 percentiles

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Suplementary material II

Traces of parameters

An acceptable level of convergence is achieved when traces are random and horizontal with overlapping in all chains.

Fleet	Selection	ICES fleet	Discards	Retention
1	Double Normal	SPTRAWL7	Yes	Logistic
2	Double Normal	FRNEP8	Yes	Logistic
3	Double Normal	SPTRAWL8	Yes	Logistic
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First model version Traces

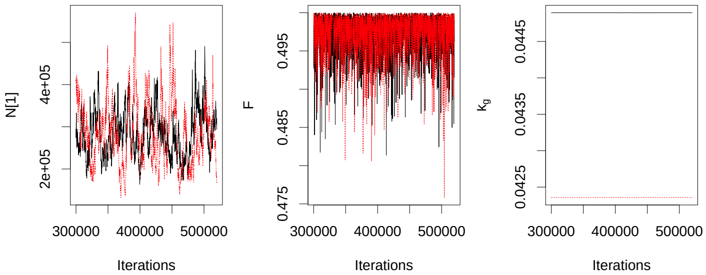

Figure 1: Traces of two MCMC chains (one red and the other black) for initial population, fishing mortalityand growth rate in model version 1.

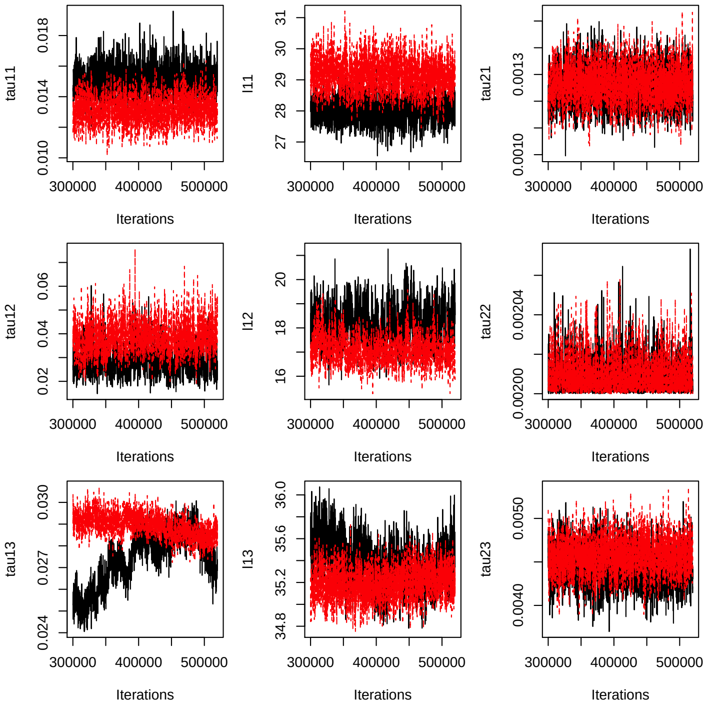

Figure 2: Traces of two MCMC chains (one red and the other black) for fleet selection patterns parameters in model version 1.

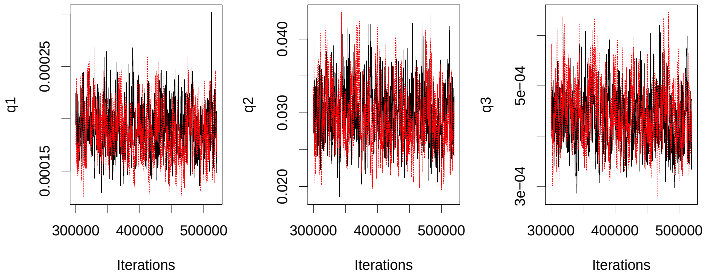

Figure 3: Traces of two MCMC chains (one red and the other black) for fleet survey catchability parameters in model version 1.

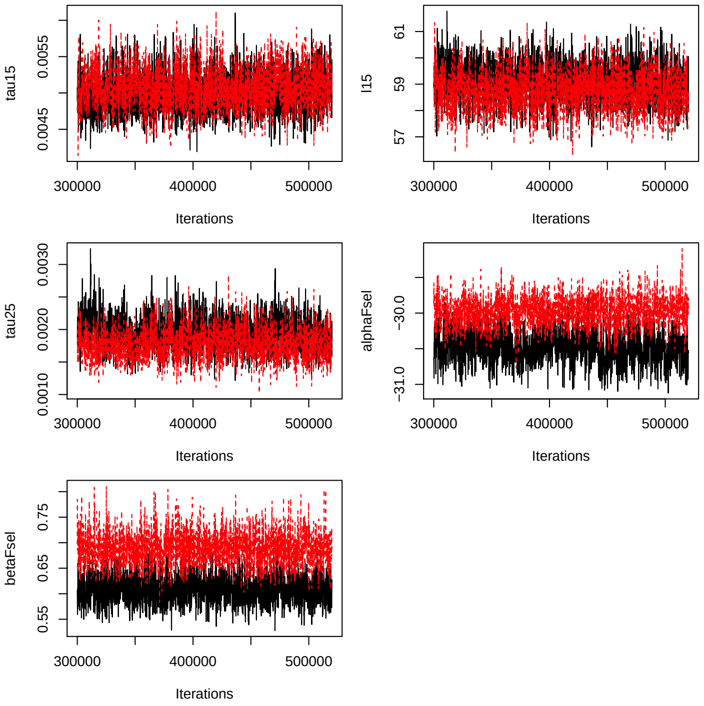

Figure 4: Traces of two MCMC chains (one red and the other black) for fleet selection patterns parameters in model version 1.

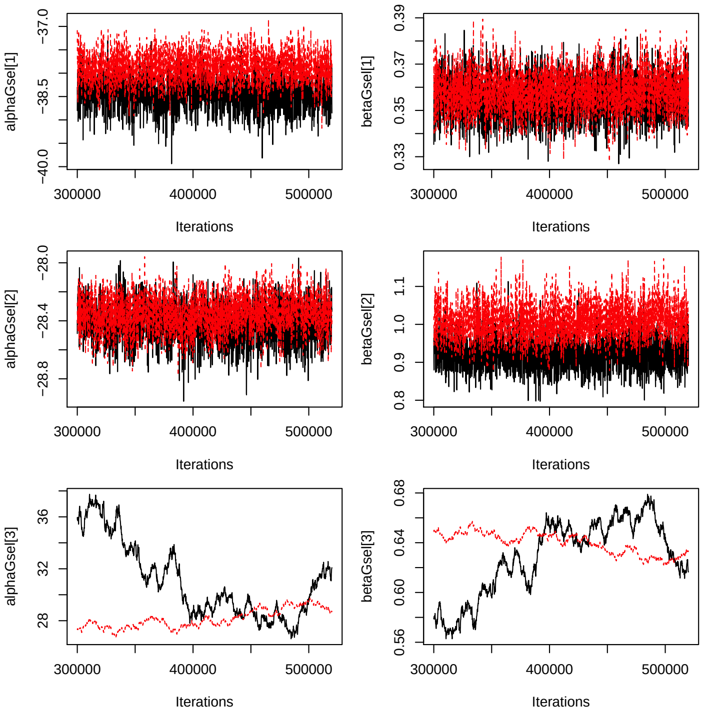

Figure 5: Traces of two MCMC chains (one red and the other black) for fleet retention patterns parameters in model version 1.

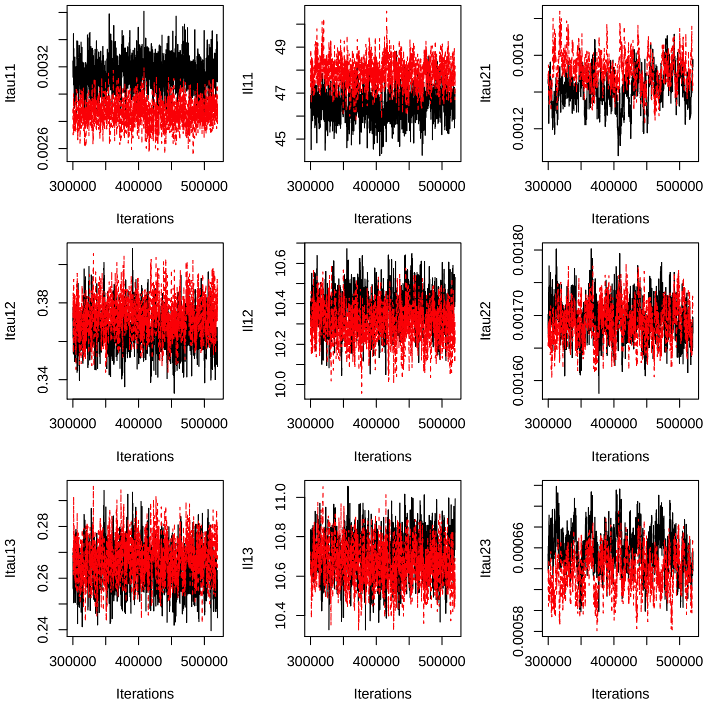

Figure 6: Traces of two MCMC chains (one red and the other black) for fleet survey patterns parameters in model version 1.

Second model version Traces

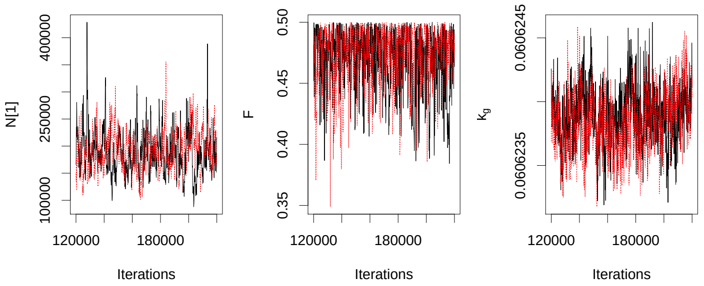

Figure 7: Traces of two MCMC chains (one red and the other black) for initial population, fishing mortalityand growth rate in model version 2.

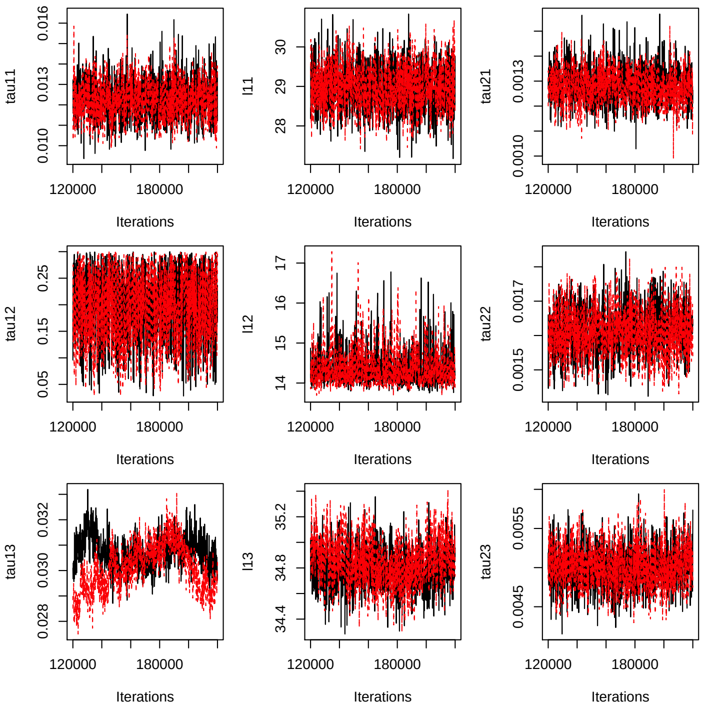

Figure 8: Traces of two MCMC chains (one red and the other black) for fleet selection patterns parameters in model version 2.

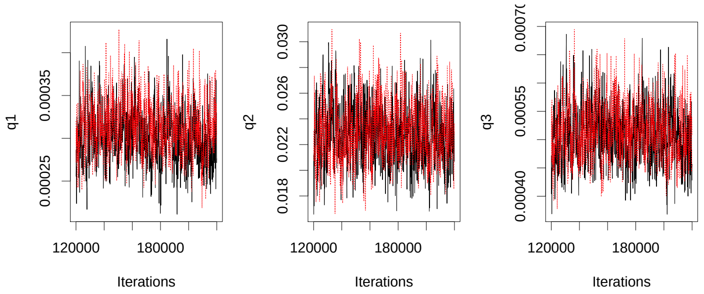

Figure 9: Traces of two MCMC chains (one red and the other black) for fleet survey catchability parameters in model version 2.

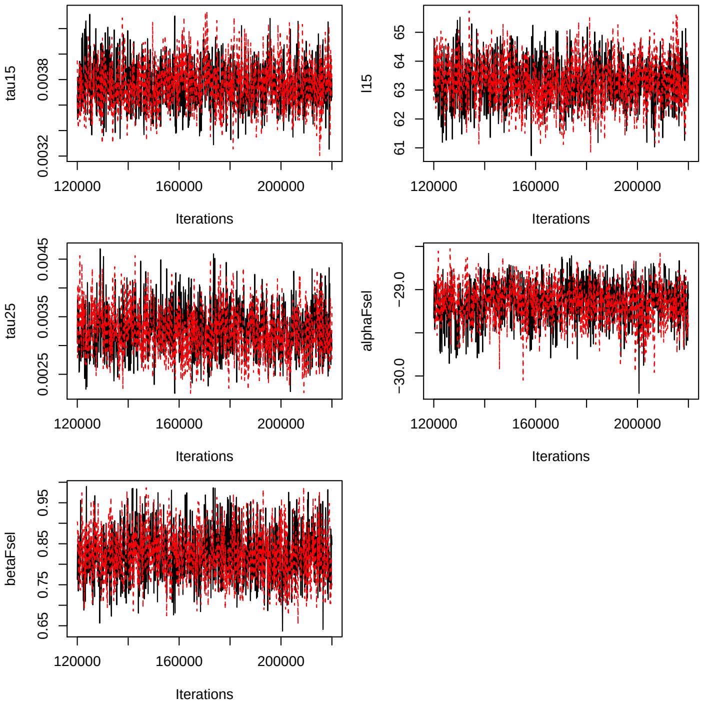

Figure 10: Traces of two MCMC chains (one red and the other black) for fleet selection patterns parameters in model version 2.

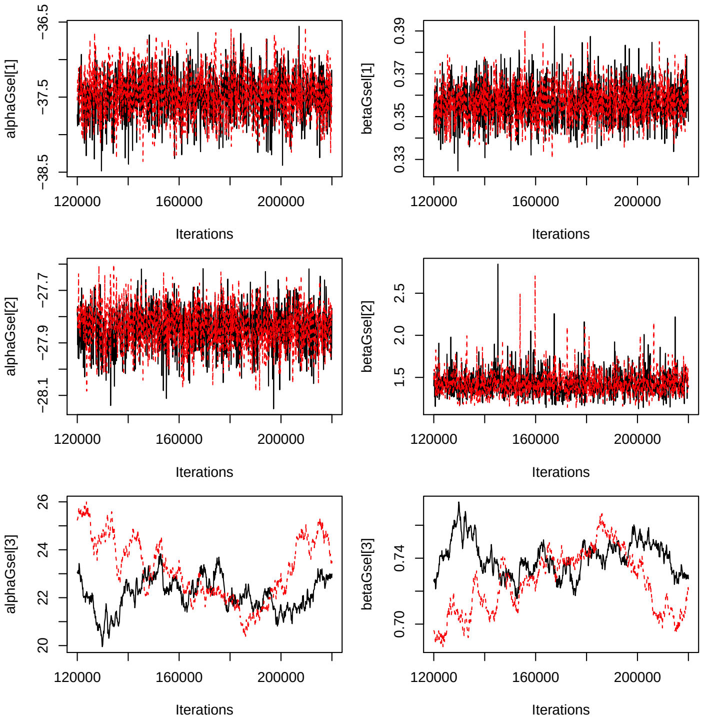

Figure 11: Traces of two MCMC chains (one red and the other black) for fleet retention patterns parameters in model version 2.

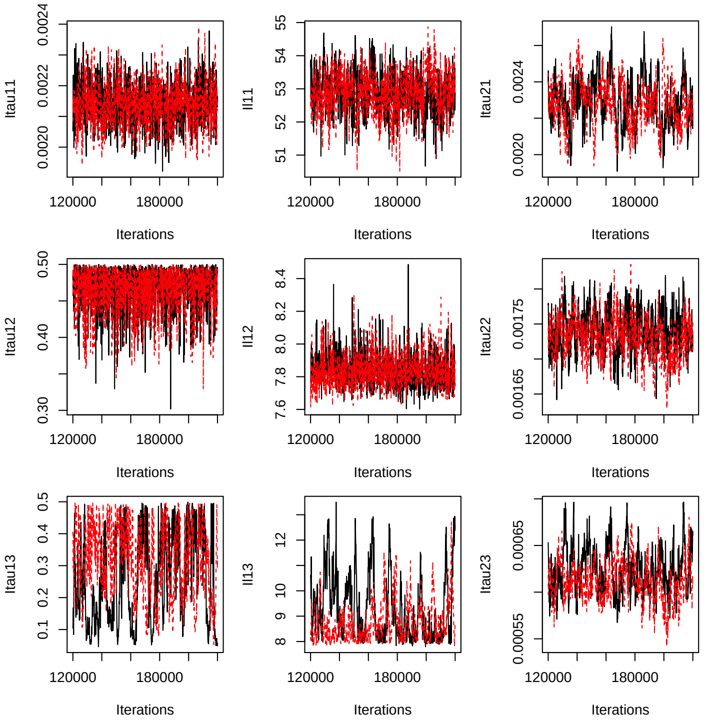

Figure 12: Traces of two MCMC chains (one red and the other black) for fleet survey patterns parameters in model version 2.

Third model version Traces

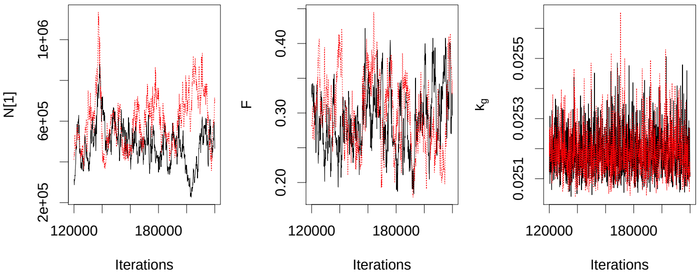

Figure 13: Traces of two MCMC chains (one red and the other black) for initial population, fishing mortalityand growth rate in model version 3.

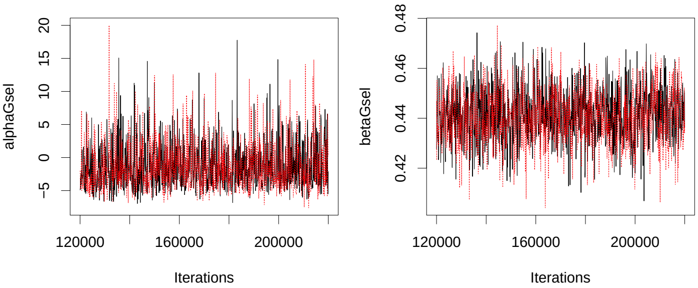

Figure 14: Traces of two MCMC chains (one red and the other black) for fleet retention patterns parameters in model version 3.

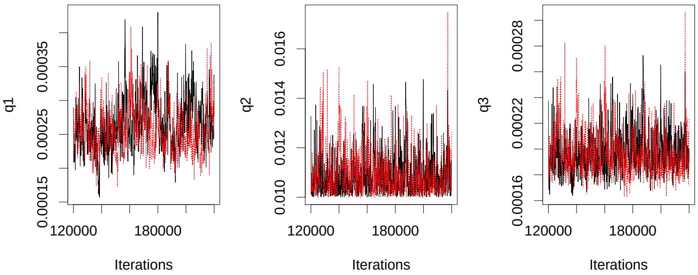

Figure 15: Traces of two MCMC chains (one red and the other black) for fleet survey catchability parameters in model version 3.

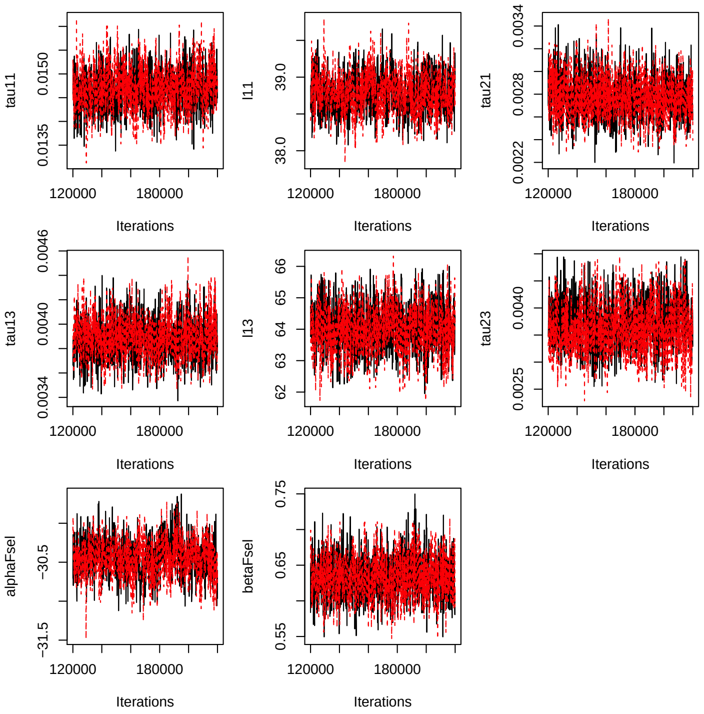

Figure 16: Traces of two MCMC chains (one red and the other black) for fleet selection patterns parameters in model version 3.

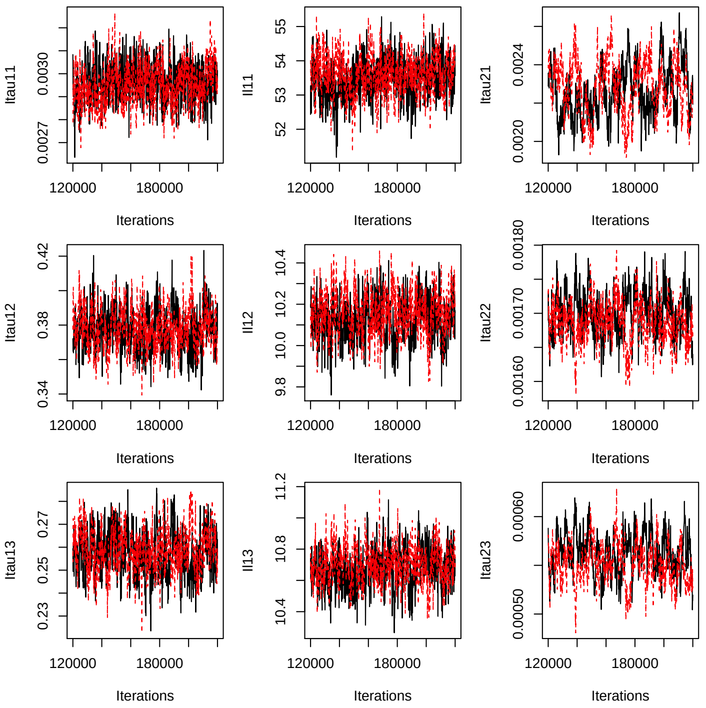

Figure 17: Traces of two MCMC chains (one red and the other black) for fleet survey patterns parameters in model version 3.

Fourth a. model version Traces

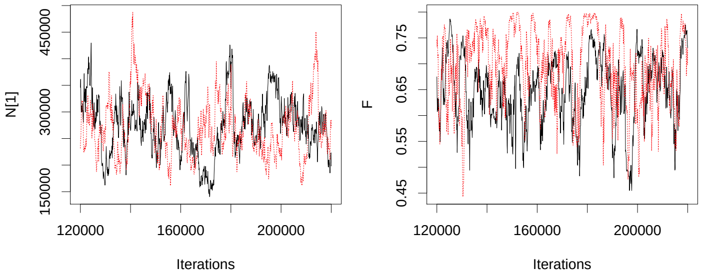

Figure 18: Traces of two MCMC chains (one red and the other black) for initial population, fishing mortalityand growth rate in model version 4a.

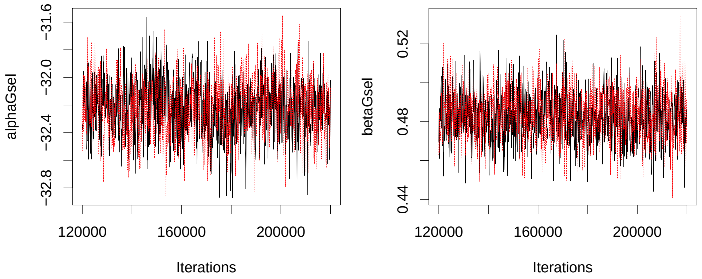

Figure 19: Traces of two MCMC chains (one red and the other black) for fleet retention patterns parameters in model version 4a.

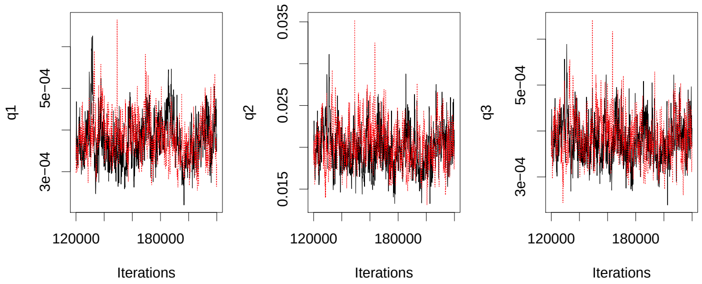

Figure 20: Traces of two MCMC chains (one red and the other black) for fleet survey catchability parameters in model version 4a.

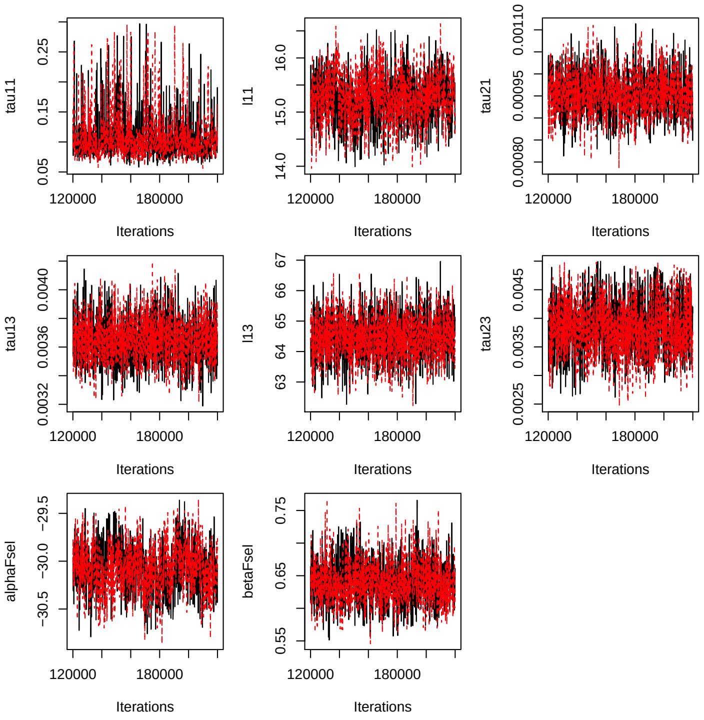

Figure 21: Traces of two MCMC chains (one red and the other black) for fleet selection patterns parameters in model version 4a.

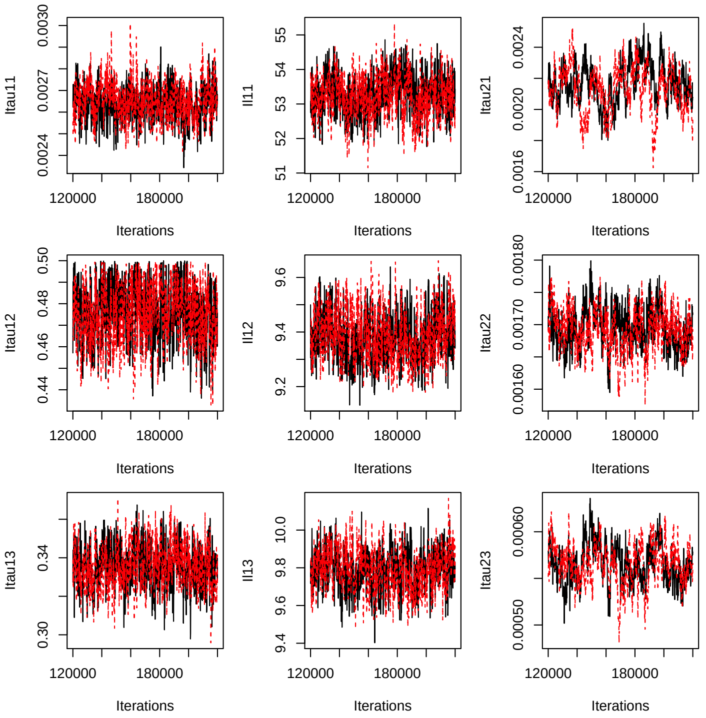

Figure 22: Traces of two MCMC chains (one red and the other black) for fleet survey patterns parameters in model version 4a.

Fourth b. model version Traces

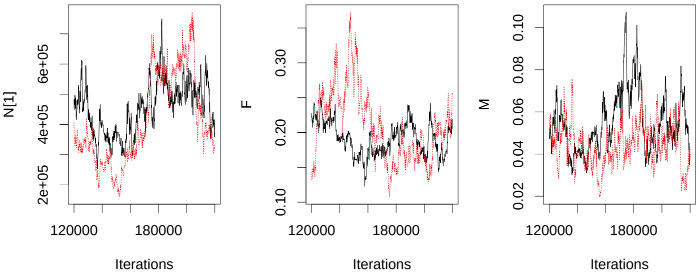

Figure 23: Traces of two MCMC chains (one red and the other black) for initial population, fishing mortalityand growth rate in model version 4b.

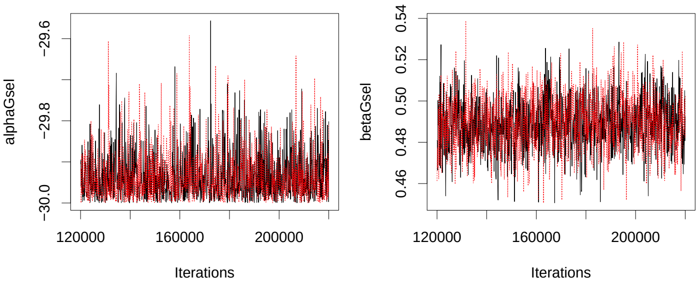

Figure 24: Traces of two MCMC chains (one red and the other black) for fleet retention patterns parameters in model version 4b.

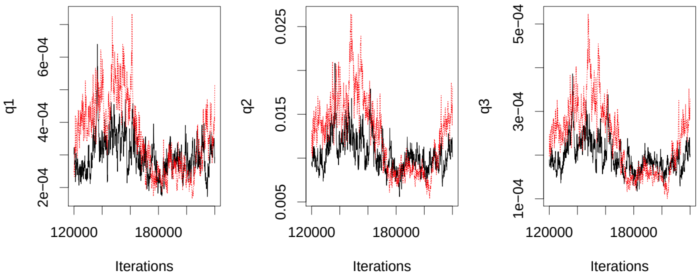

Figure 25: Traces of two MCMC chains (one red and the other black) for fleet survey catchability parameters in model version 4b.

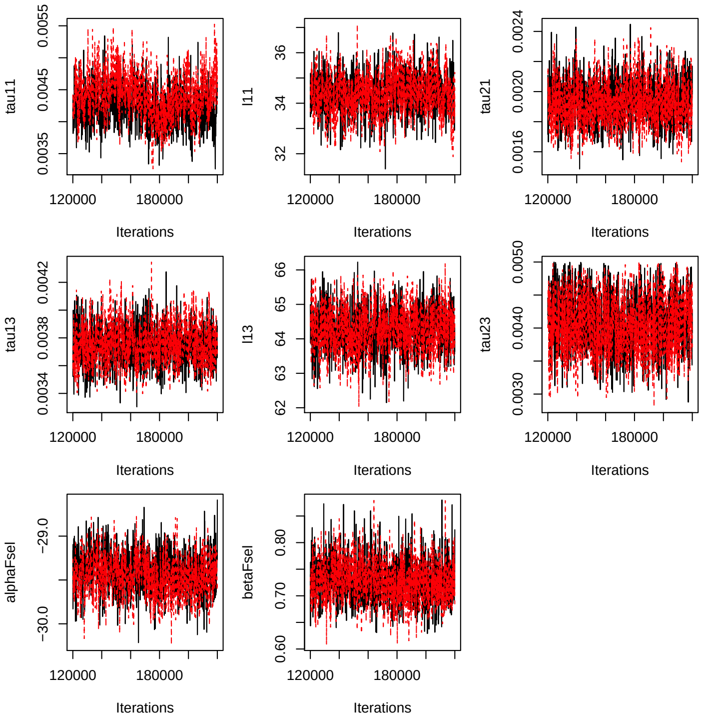

Figure 26: Traces of two MCMC chains (one red and the other black) for fleet selection patterns parameters in model version 4b.

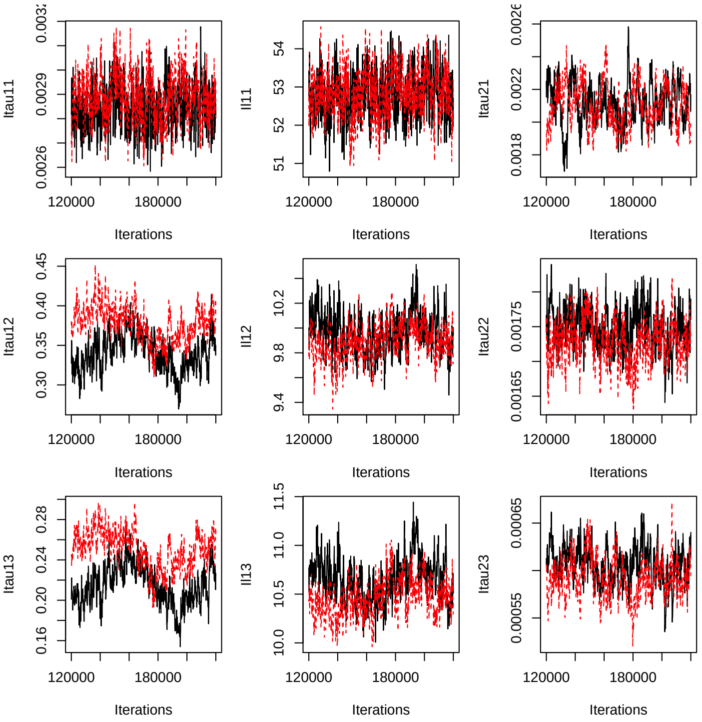

Figure 27: Traces of two MCMC chains (one red and the other black) for fleet survey patterns parameters in model version 4b.

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Suplementary material III

Estimated length distribution of the population

The initial length distribution assuming 19 length classes, $\mathbf{\Phi_1} = (\phi_{1,1}, \ldots, \phi_{1,19})$ was sampled from the corresponding Bayesian posterior, when individuals grow $\mathbf{\Phi_1}$ becomes $\mathbf{\Phi_1^{(G)}} = \mathbf{\Phi_1} * \mathbf{g}$ describing the length distribution after growth. Once growth process occurs, fishing and natural mortality (F and M) modifies this distribution. Assuming mean survival as $p = e^{-F-M}$ the length distribution of surviving fishes, $\mathbf{\Phi_1^{(S)}}$, is computed as randomly sampled from a Dirichlet distribution $Dirich(p * \mathbf{\Phi_1^{(G)}})$.

Accordingly, the length distribution in the next time step will be defined as the weighted sum of the known length distribution of recruits and the length distribution of surviving fishes, as follows:

$$\mathbf{\Phi_{t+1}} = (1 - \frac{R_{t+1}}{N_{t+1}}) * \mathbf{\Phi_t^{(S)}} + \frac{R_{t+1}}{N_{t+1}} * (1, 0, 0, 0, \ldots, 0).$$

- **1st model version:** Data grouped in 19 length classes, 5 fleets. Running takes 562.68 hours for 520000 iterations. The first 20000 for adaptation without thinning and after that a thinning of 100 was applied.
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2	Double Normal	FRNEP8	Yes	Logistic
3	Double Normal	SPTRAWL8	Yes	Logistic
4	Logistic	TRAWLOTH+OTHERS	No	
5	Double Normal	GILLNET+LONGLINE	No	

Table 1: Fleets used in hake Bayesian GPDM. SPTRAWL7 and SPTRAWL8 are for spanish trawls used in VII and VIII ICES divisions, FRNEP8 is for french trawl targeting Nephrops in division VIII and TRAWLOTH is for all other trawl operating in Northern stock.

GILLNET + LONGLINE modelled double normal for selection. A multivariate normal prior was defined for initial population and fishing mortality parameters. Running takes 177.2 hours for 200000 iterations. The first 20000 for adaptation without thinning and after that a thinning of 100 was applied.

- **4th model version:** The same as the third model version but variance of prior for relative carrying capacity K_{bh} ($K_{bh} = K^*/N^*$ where K^* is the absolute carrying capacity and N^* is the initial population) and coefficient of variation for the total recruitment is defined from 13 hake recruitment data series with a mean coefficient of variation equal to 0.56 and standard deviation 0.41. Also k, the annual growth rate is assumed as constant and equal to 0.17 as ICES did in the last assessment. Fishing mortality $F_{t,j,k}$, is bounded by 0.8 and process error term η^*, was modified as follows:

$$\begin{aligned} l_t &\sim Betabin(q^l_t * \eta^*, (1-q^l_t) * \eta^*, d_t) \quad t = 1, \ldots, T \\ dis_t &\sim Betabin(q^d_t, 1-q^d_t, d_t) \quad t = 1, \ldots, T \end{aligned}$$

a. With $Linf = 130cm$ and $M = 0.1$. Running takes 252.34 hours for 200000 iterations. The first 20000 for adaptation without thinning and after that a thinning of 100 was applied.
b. With priors for Linf and M based on previous studies. $Linf \sim N(100.42, 9.48)$ and $M \sim LN(log(0.23), sqrt(log(185.4164))$. Running takes 259.81 hours for 200000 iterations. The first 20000 for adaptation without thinning and after that a thinning of 100 was applied.

Length distribution-model version 1

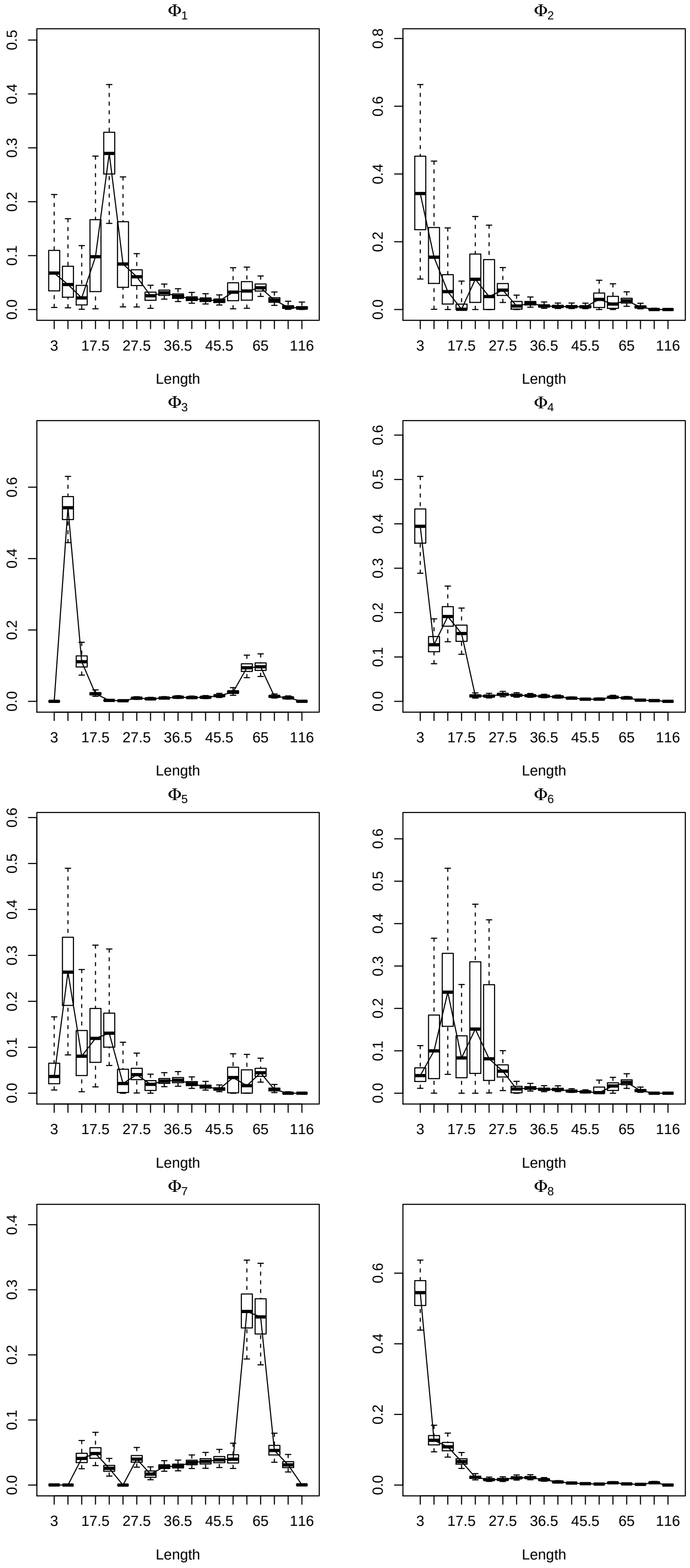


Figure 1: Estimated length distribution of population from quarter 1 to quarter 8. Limits of the box are for quantiles 25 and 75 while the middle is for the median.

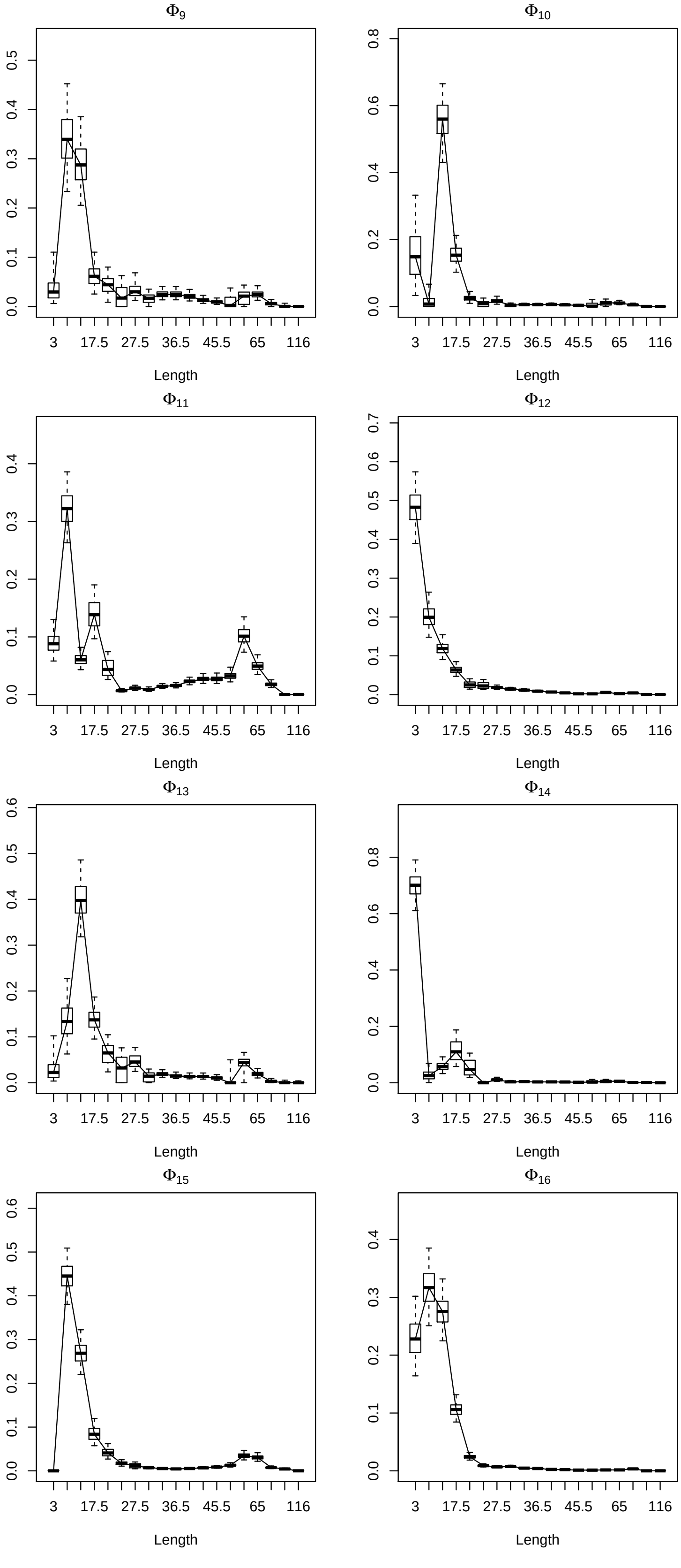


Figure 2: Estimated length distribution of population from quarter 9 to quarter 16. Limits of the box are for quantiles 25 and 75 while the middle is for the median.

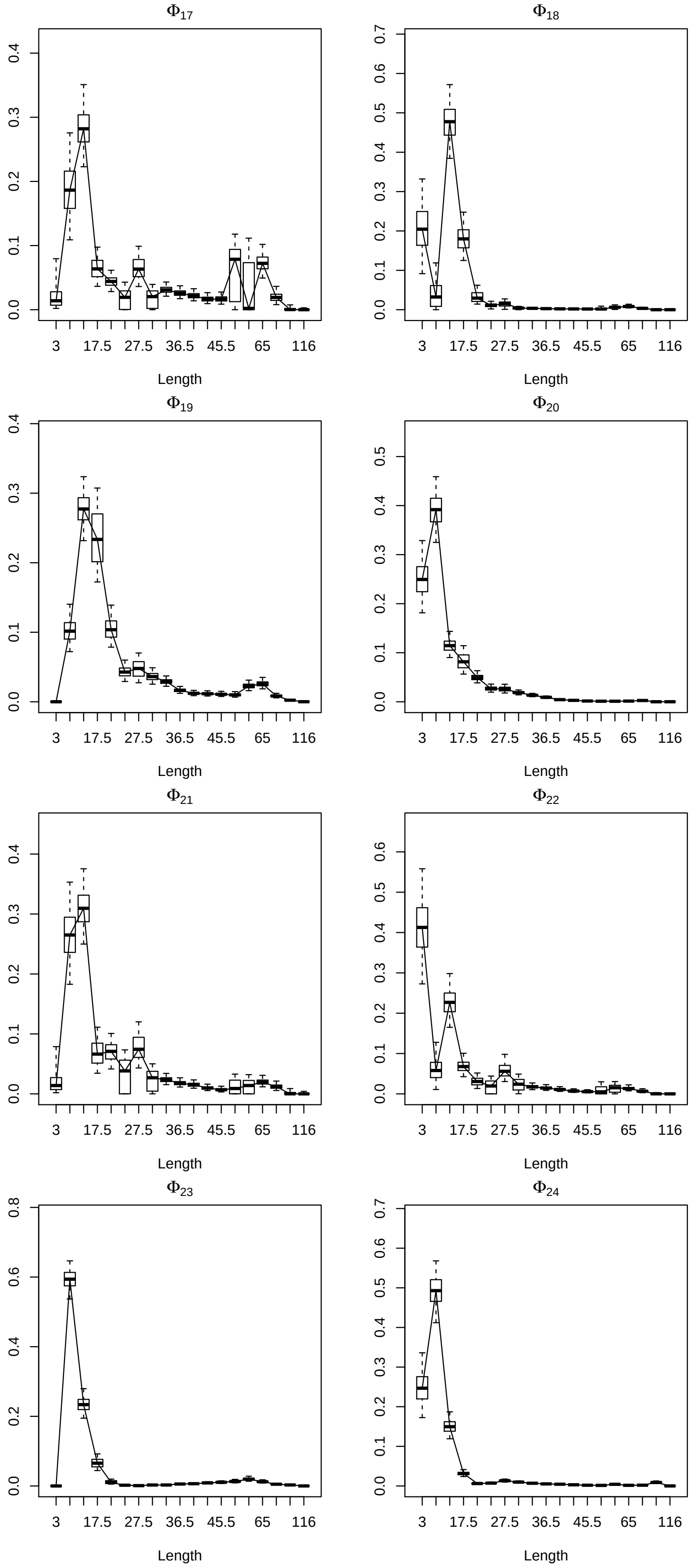


Figure 3: Estimated length distribution of population from quarter 17 to quarter 24. Limits of the box are for quantiles 25 and 75 while the middle is for the median.

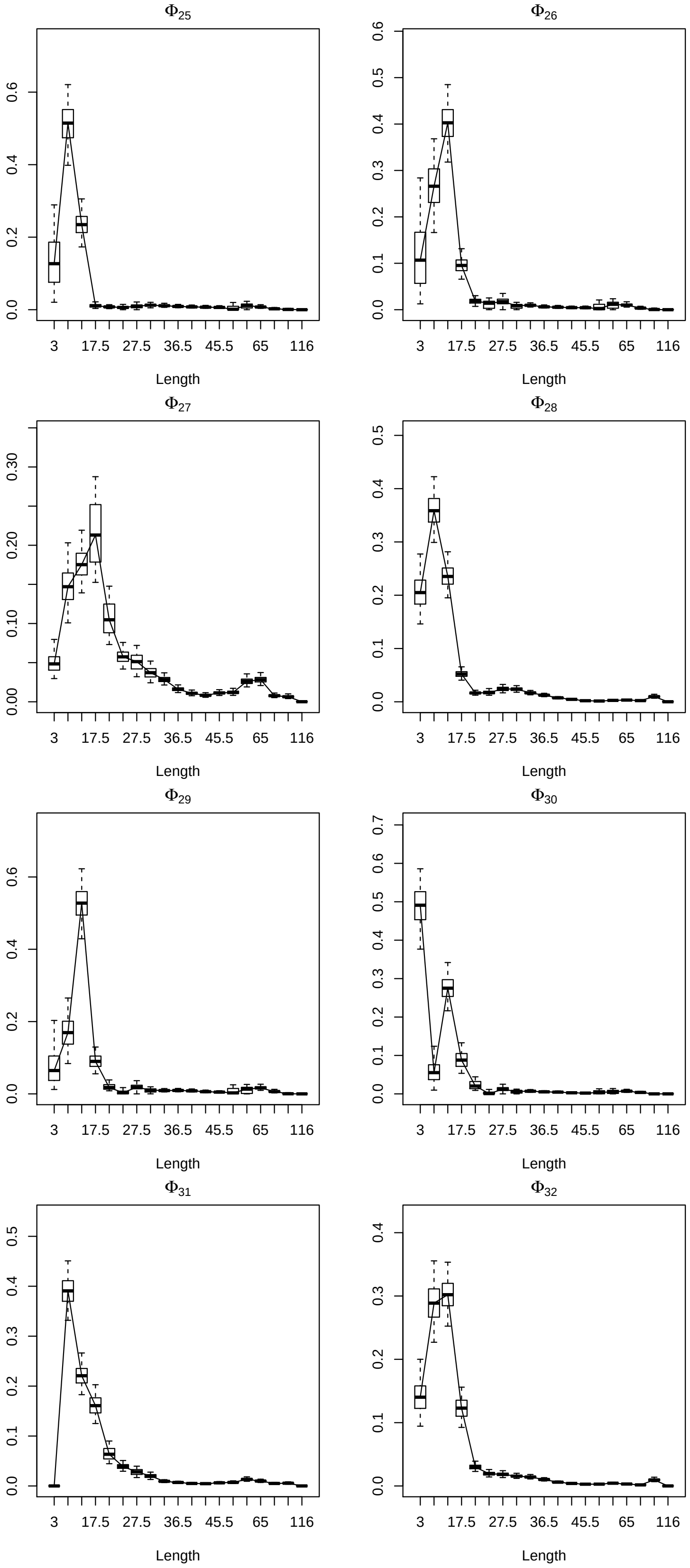


Figure 4: Estimated length distribution of population from quarter 25 to quarter 32. Limits of the box are for quantiles 25 and 75 while the middle is for the median.

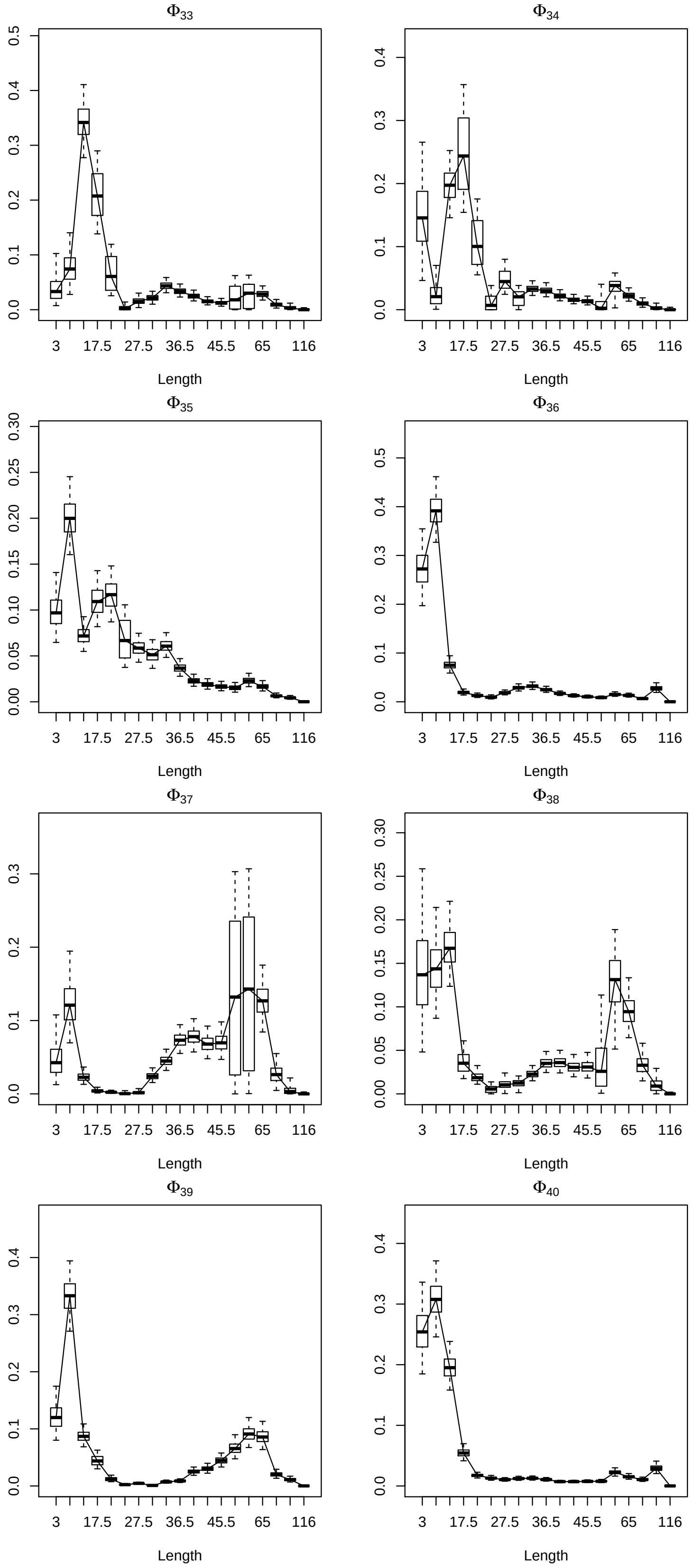


Figure 5: Estimated length distribution of population from quarter 33 to quarter 40. Limits of the box are for quantiles 25 and 75 while the middle is for the median.

Length distribution-model version 2

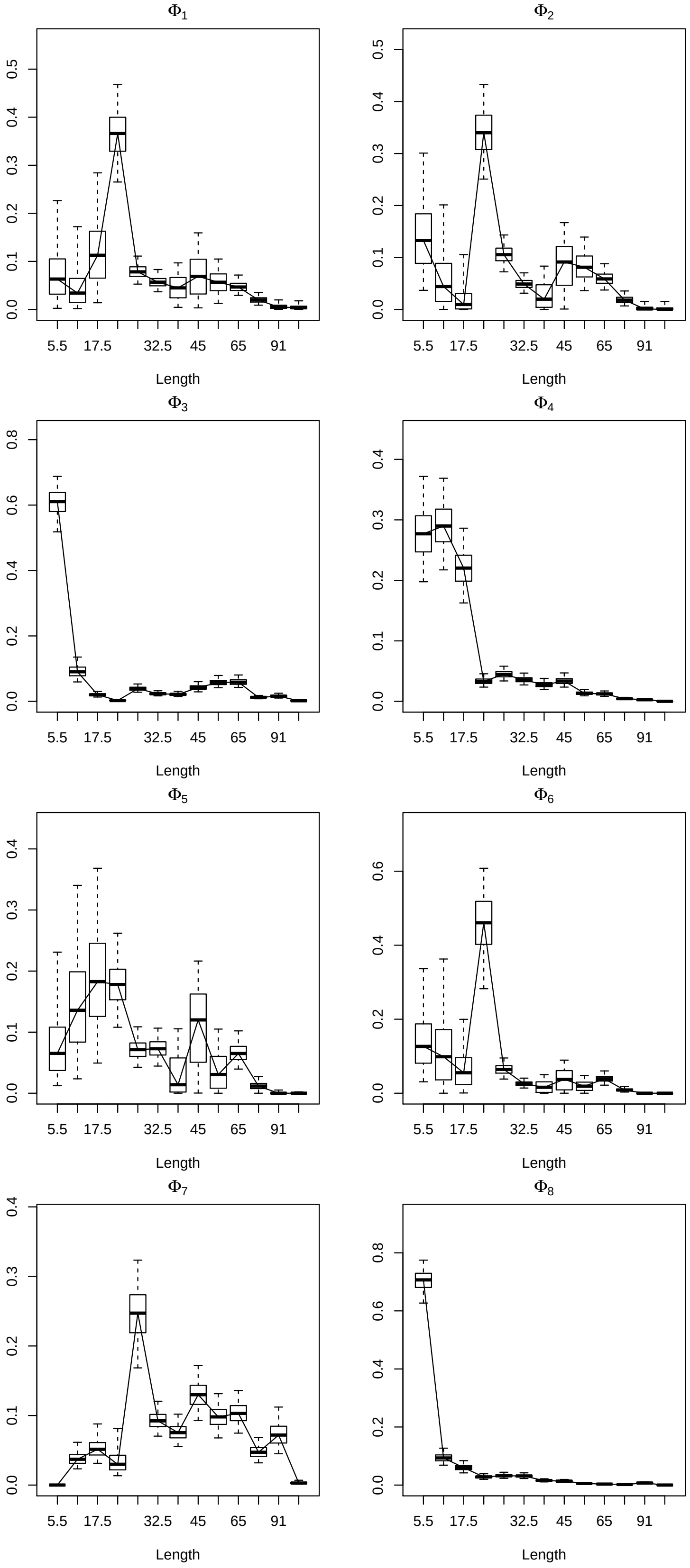
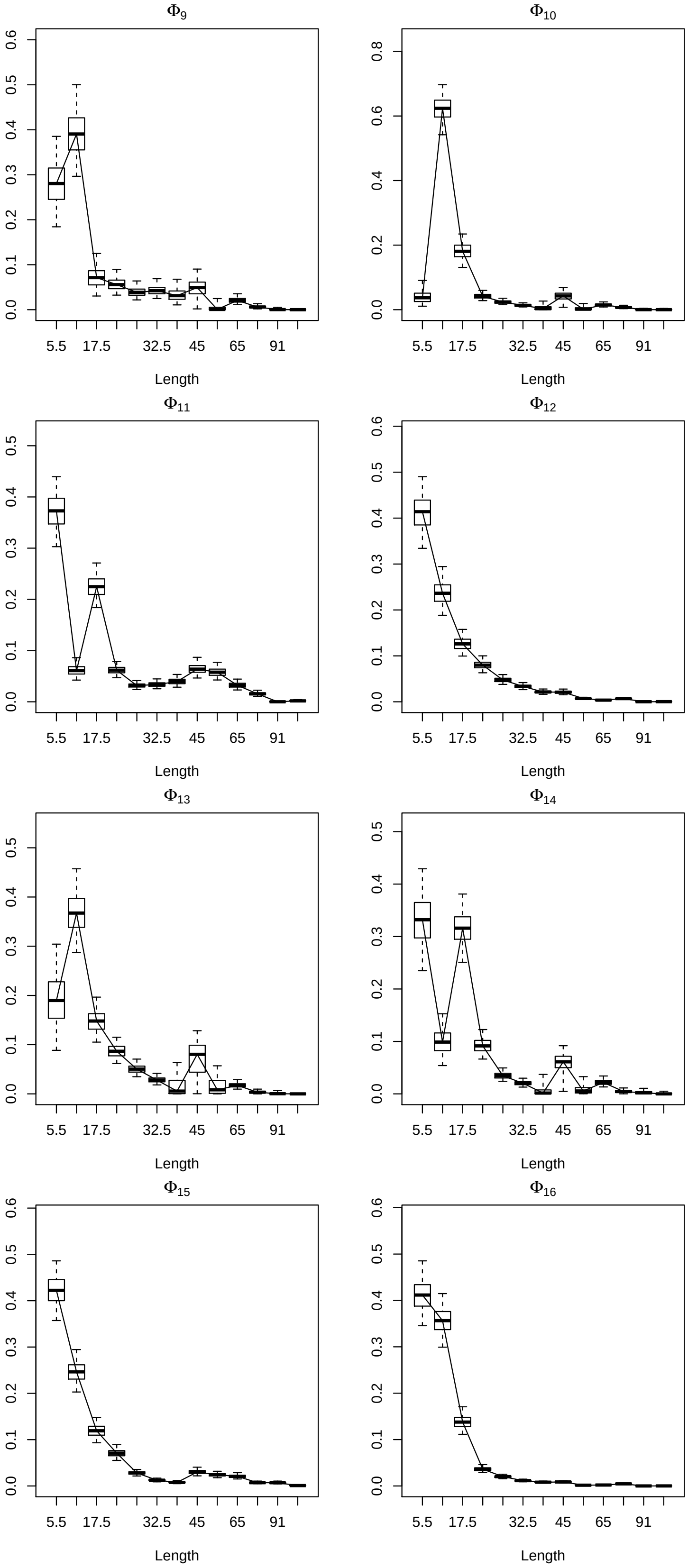


Figure 6: Estimated length distribution of population from quarter 1 to quarter 8. Limits of the box are for quantiles 25 and 75 while the middle is for the median.



Φ_9 Φ_{10} Φ_{11} Φ_{12} Φ_{13} Φ_{14} Φ_{15} Φ_{16}

Figure 7: Estimated length distribution of population from quarter 9 to quarter 16. Limits of the box are for quantiles 25 and 75 while the middle is for the median.

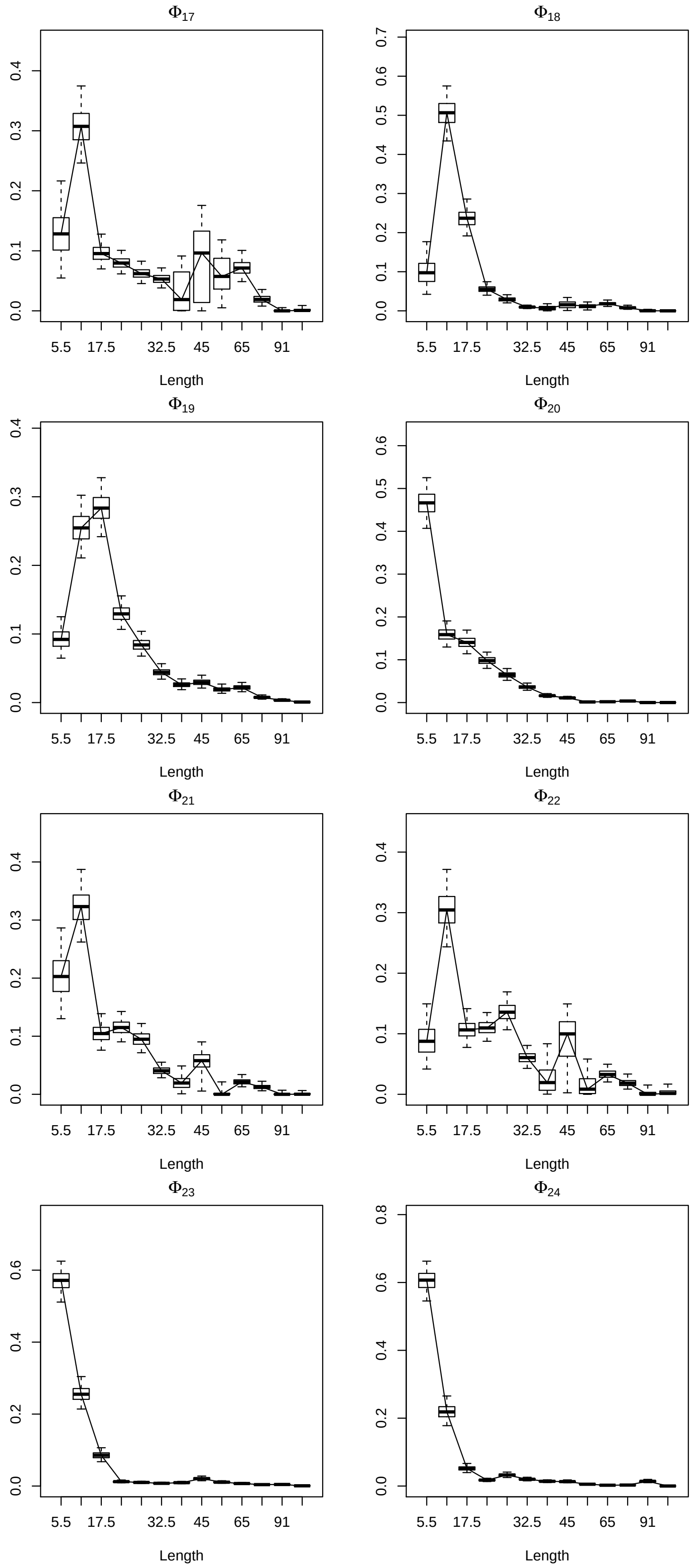


Figure 8: Estimated length distribution of population from quarter 17 to quarter 24. Limits of the box are for quantiles 25 and 75 while the middle is for the median.

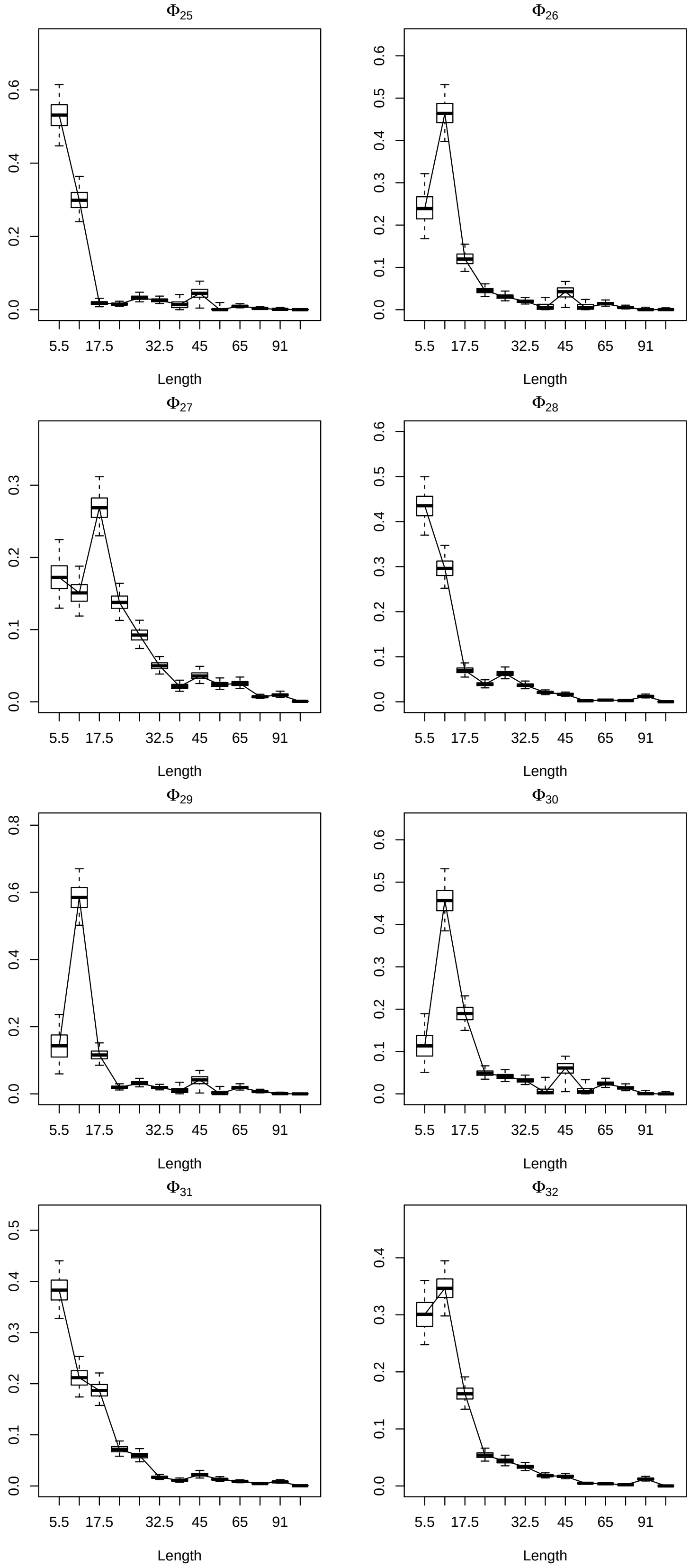


Figure 9: Estimated length distribution of population from quarter 25 to quarter 32. Limits of the box are for quantiles 25 and 75 while the middle is for the median.

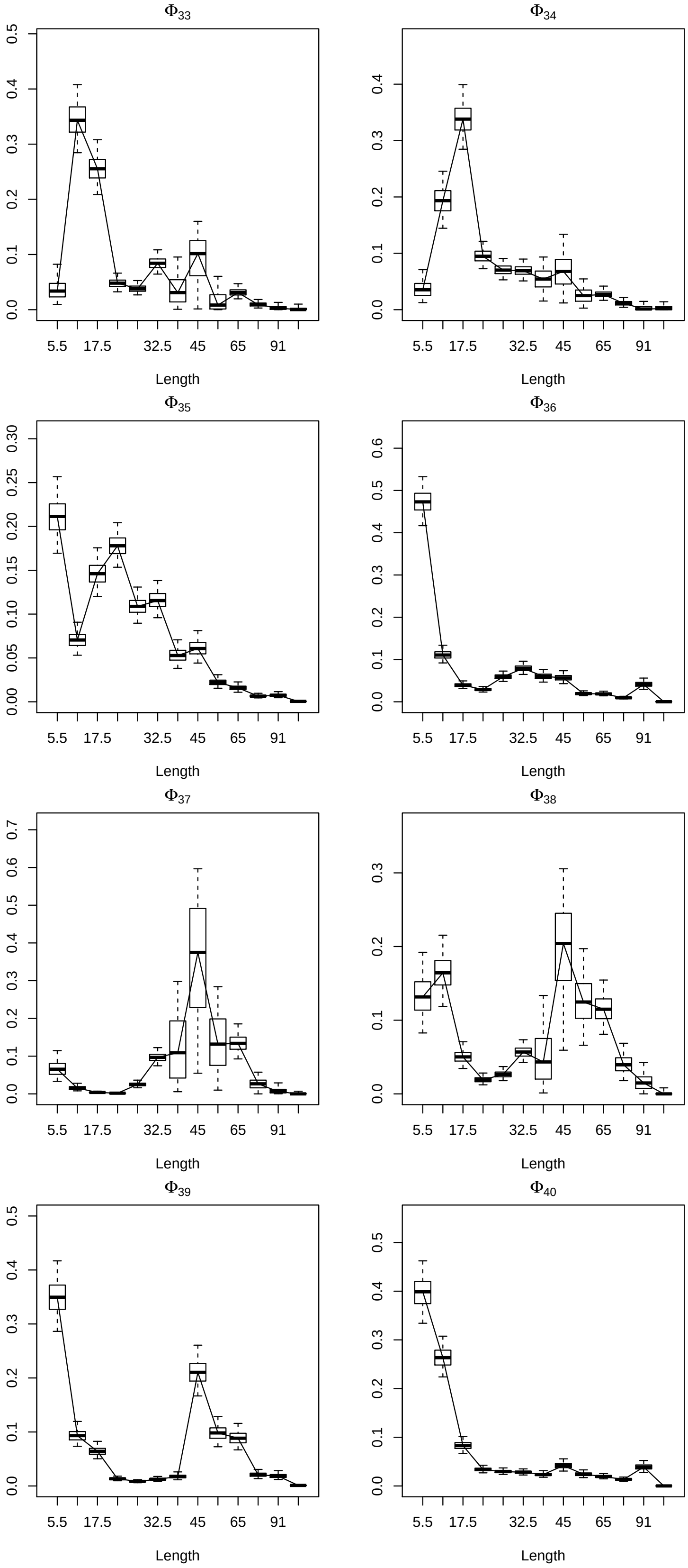

Φ_{33} Φ_{34} Φ_{35} Φ_{36} Φ_{37} Φ_{38} Φ_{39} Φ_{40}

Figure 10: Estimated length distribution of population from quarter 33 to quarter 40. Limits of the box are for quantiles 25 and 75 while the middle is for the median.

Length distribution-model version 3

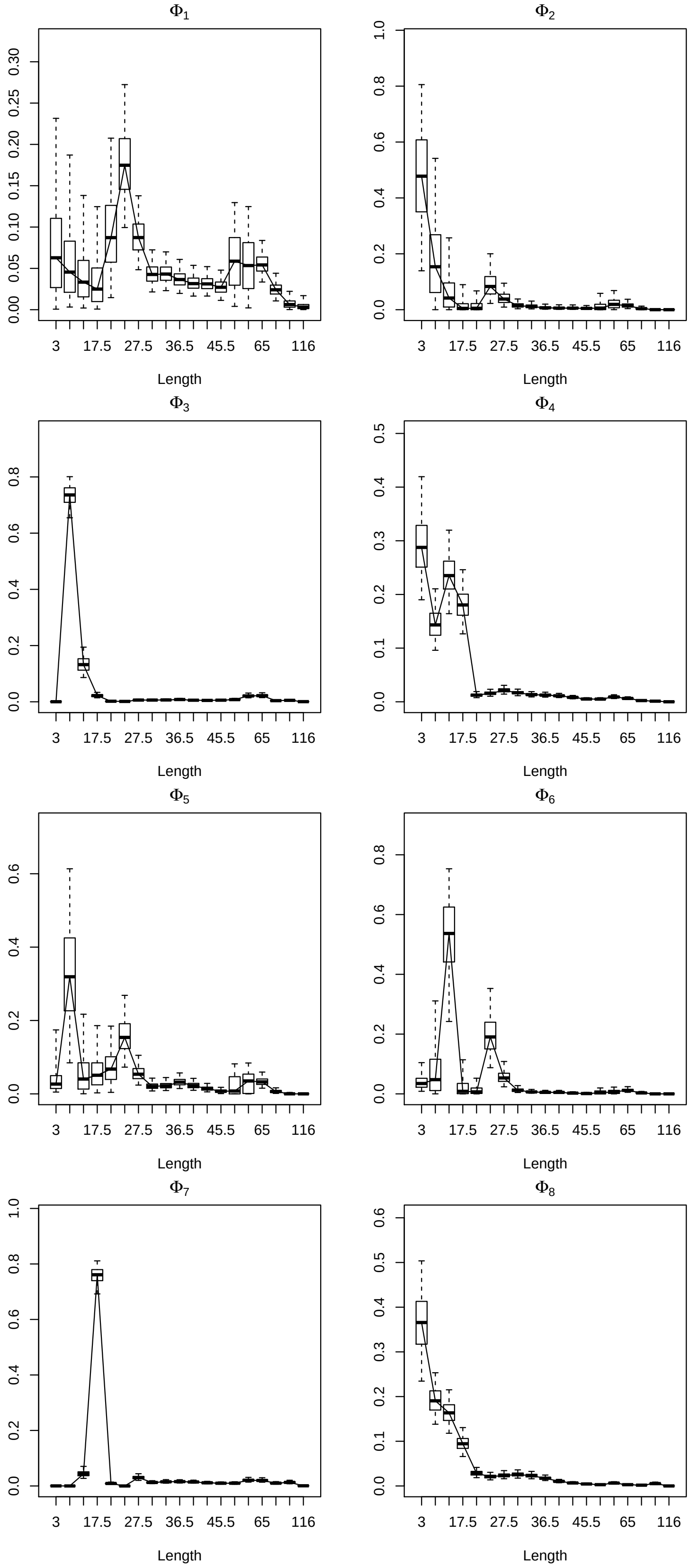


Figure 11: Estimated length distribution of population from quarter 1 to quarter 8. Limits of the box are for quantiles 25 and 75 while the middle is for the median.

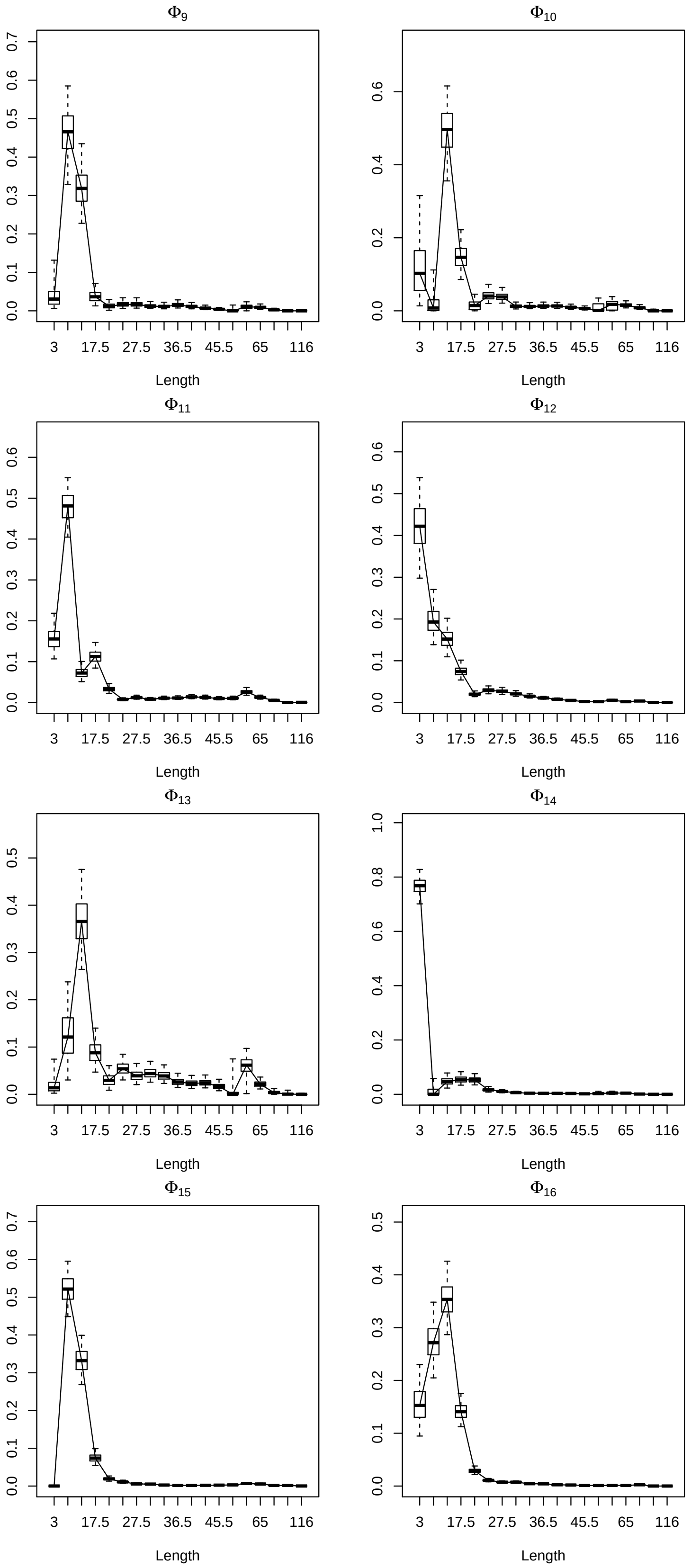


Figure 12: Estimated length distribution of population from quarter 9 to quarter 16. Limits of the box are for quantiles 25 and 75 while the middle is for the median.

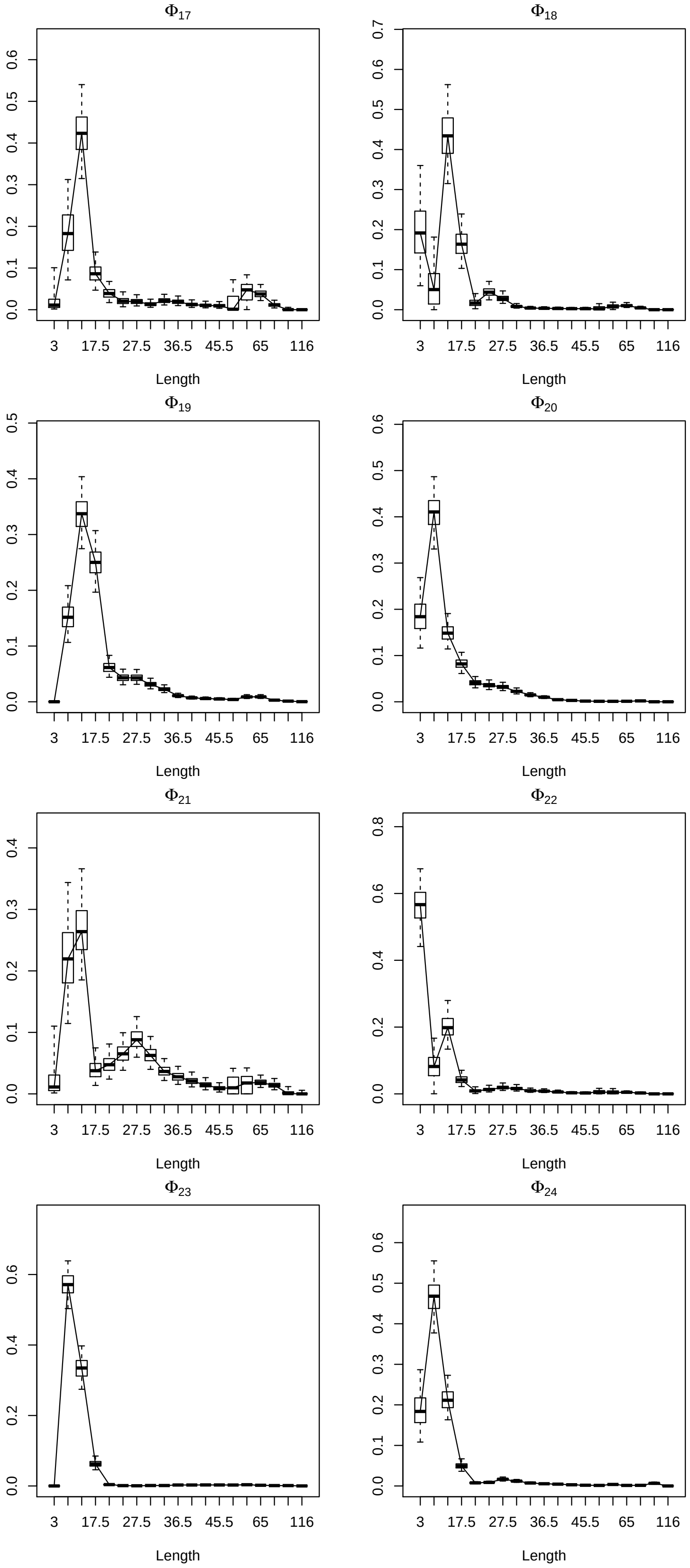


Figure 13: Estimated length distribution of population from quarter 17 to quarter 24. Limits of the box are for quantiles 25 and 75 while the middle is for the median.

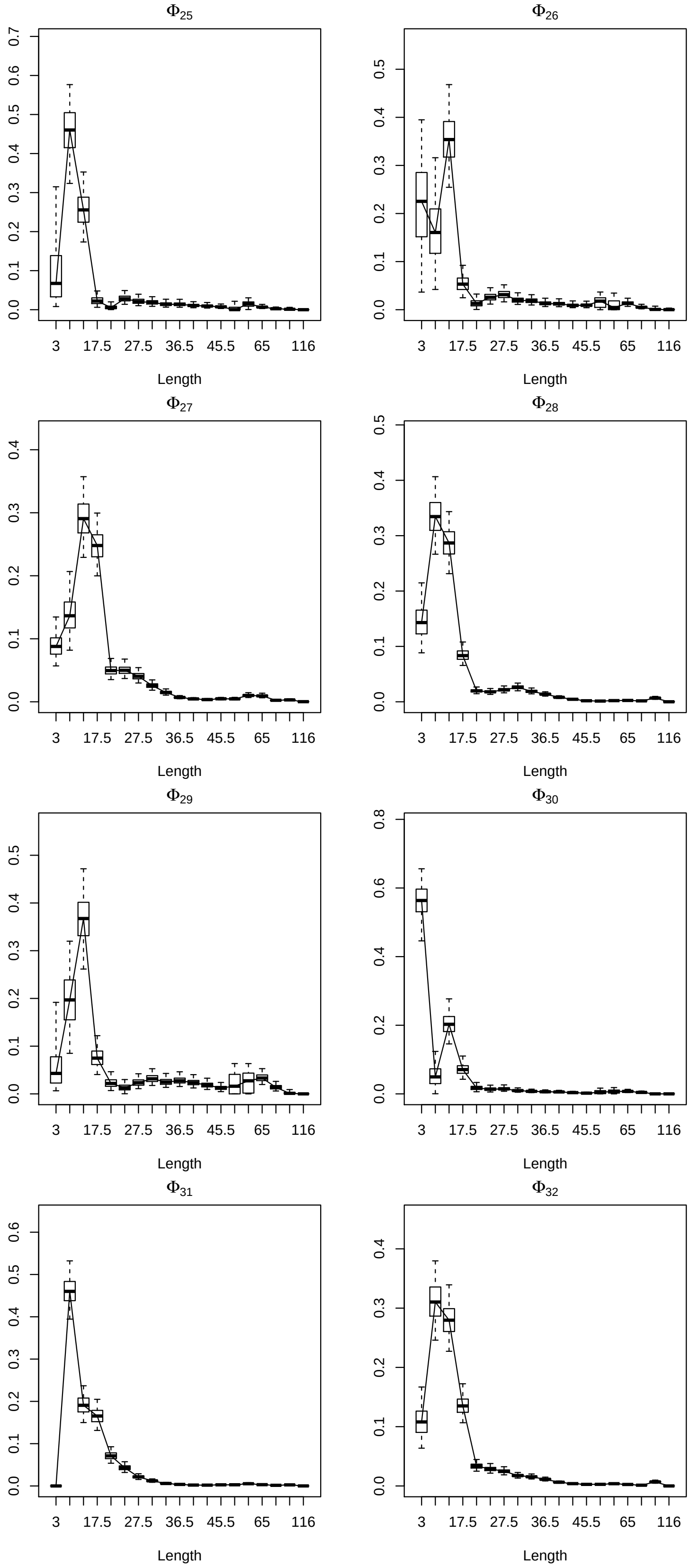


Figure 14: Estimated length distribution of population from quarter 25 to quarter 32. Limits of the box are for quantiles 25 and 75 while the middle is for the median.

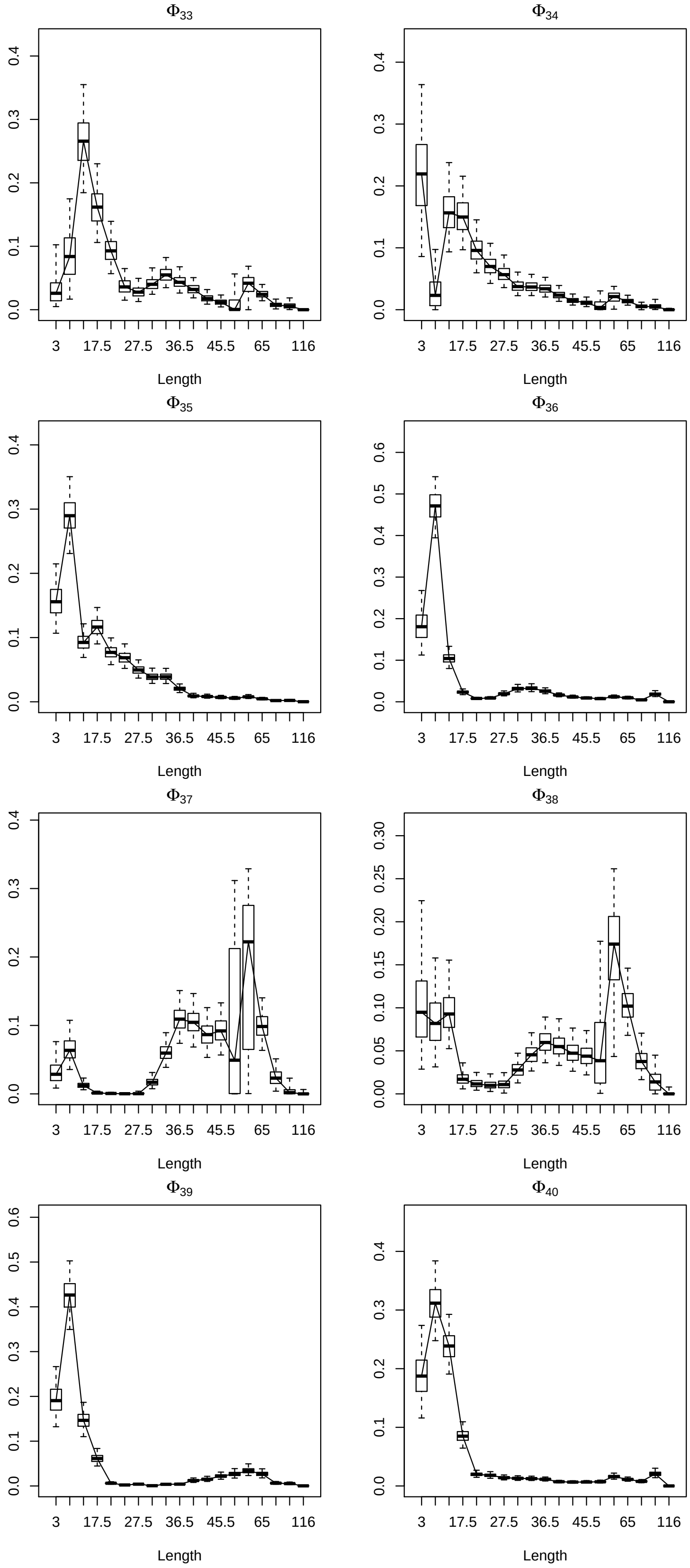

Φ_{33} Φ_{34} Φ_{35} Φ_{36} Φ_{37} Φ_{38} Φ_{39} Φ_{40}

Figure 15: Estimated length distribution of population from quarter 33 to quarter 40. Limits of the box are for quantiles 25 and 75 while the middle is for the median.

Length distribution-model version 4a.

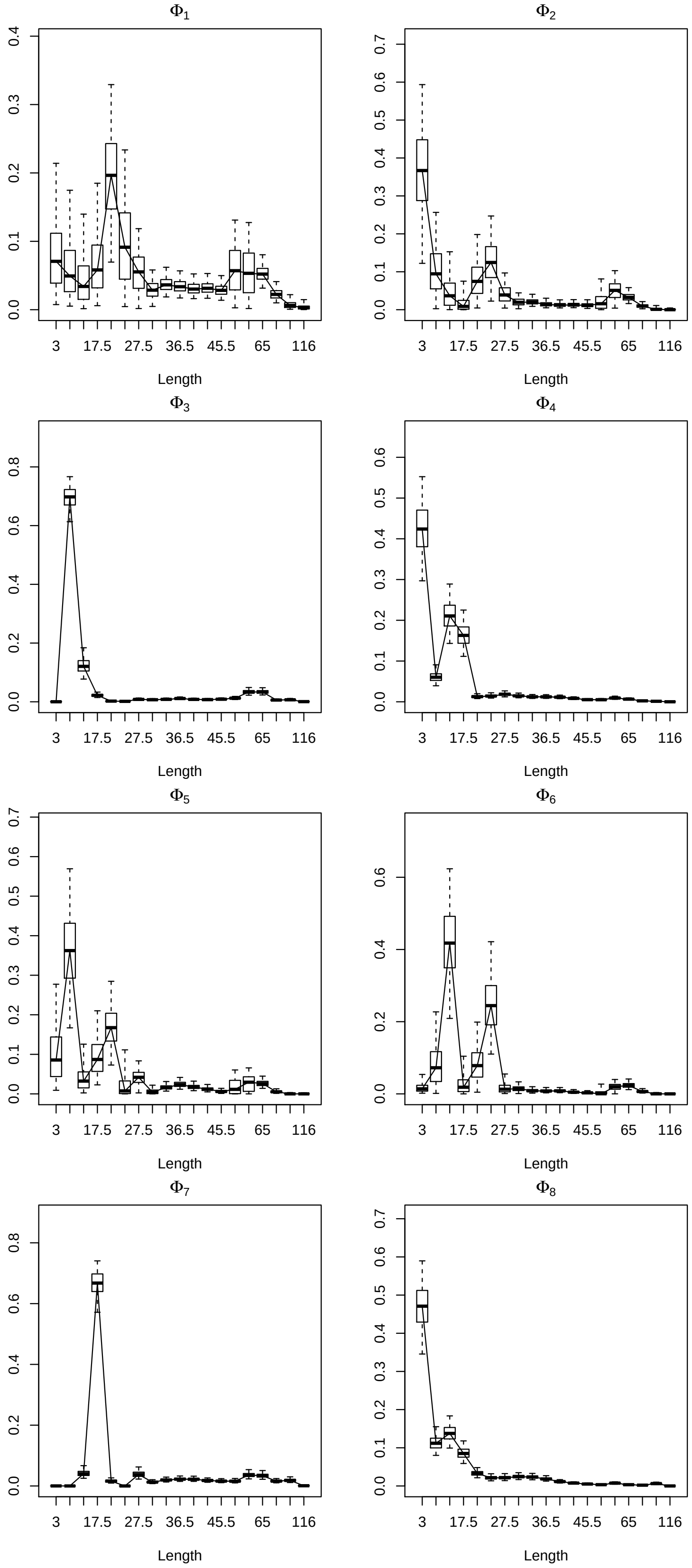


Figure 16: Estimated length distribution of population from quarter 1 to quarter 8. Limits of the box are for quantiles 25 and 75 while the middle is for the median.

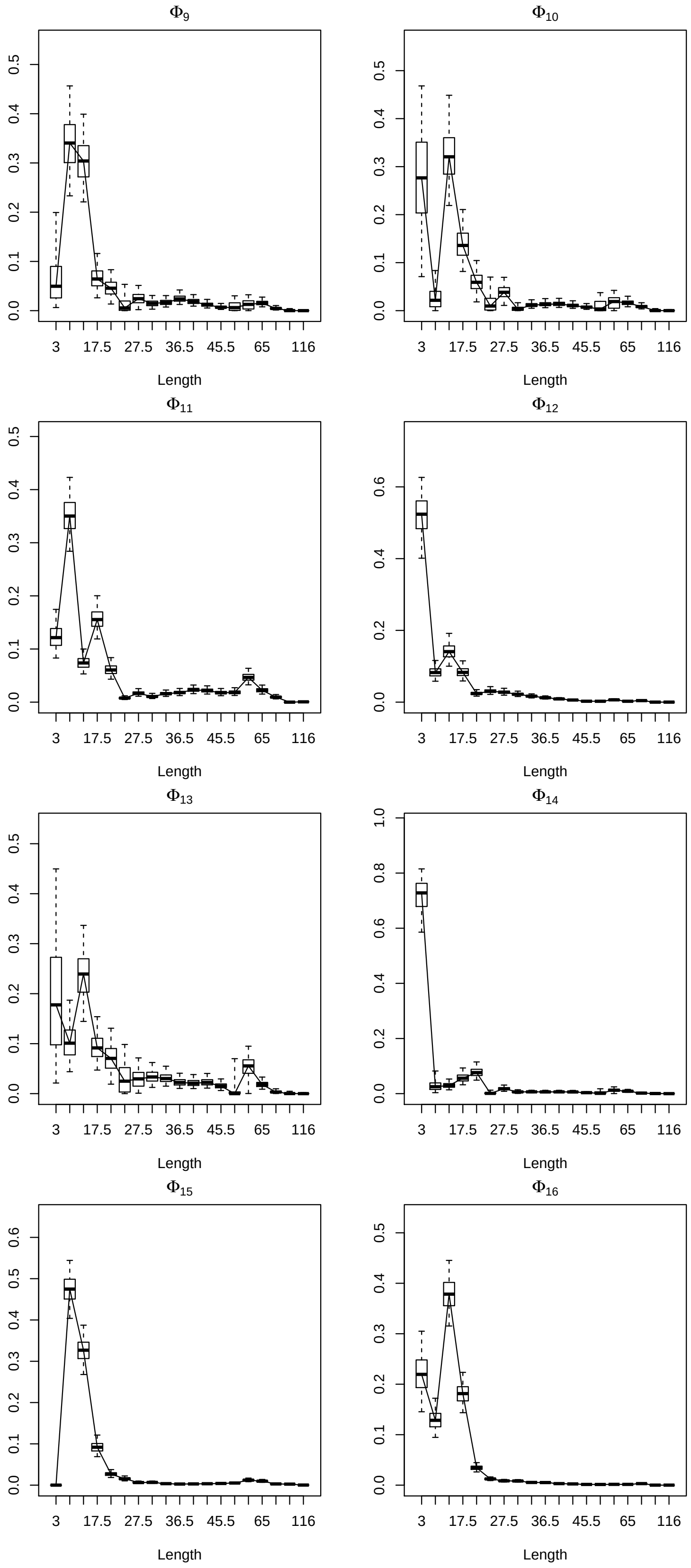


Figure 17: Estimated length distribution of population from quarter 9 to quarter 16. Limits of the box are for quantiles 25 and 75 while the middle is for the median.

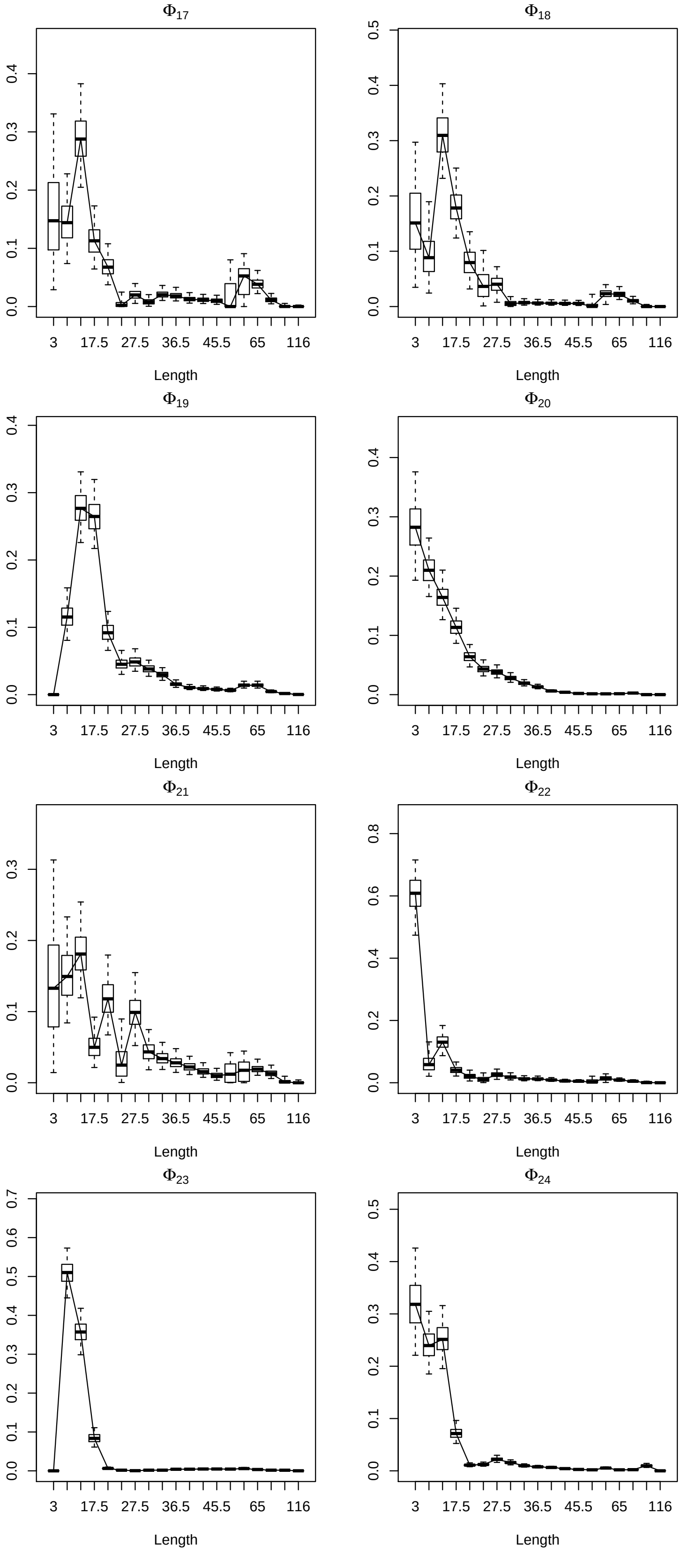


Figure 18: Estimated length distribution of population from quarter 17 to quarter 24. Limits of the box are for quantiles 25 and 75 while the middle is for the median.

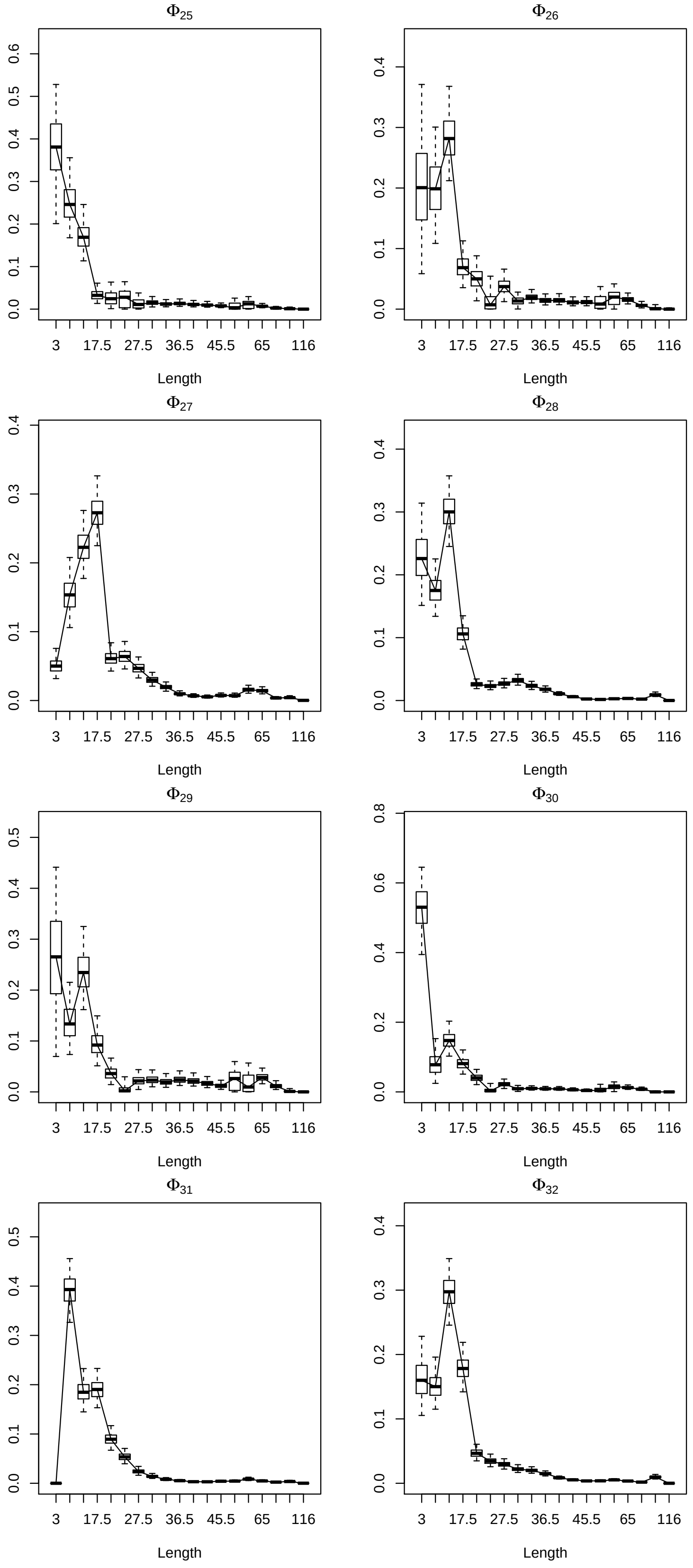


Figure 19: Estimated length distribution of population from quarter 25 to quarter 32. Limits of the box are for quantiles 25 and 75 while the middle is for the median.

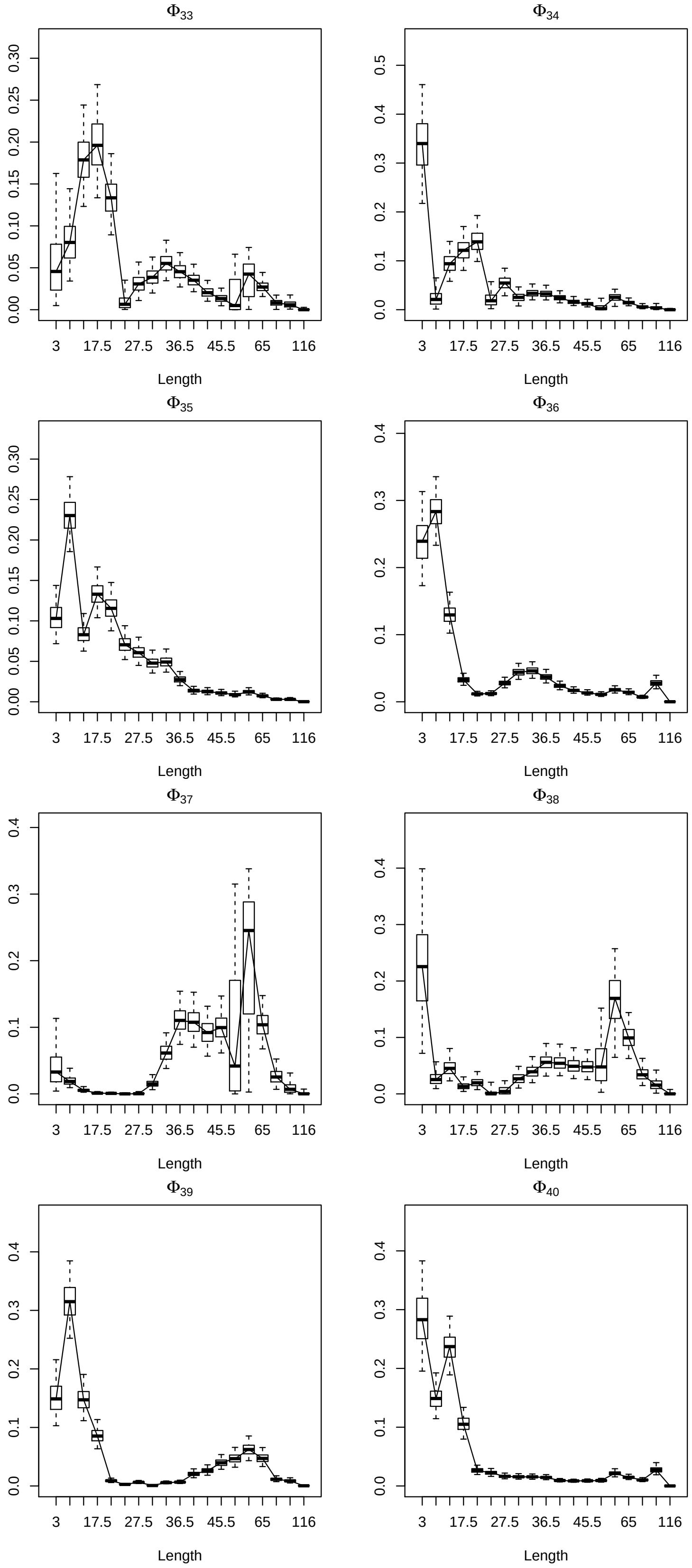
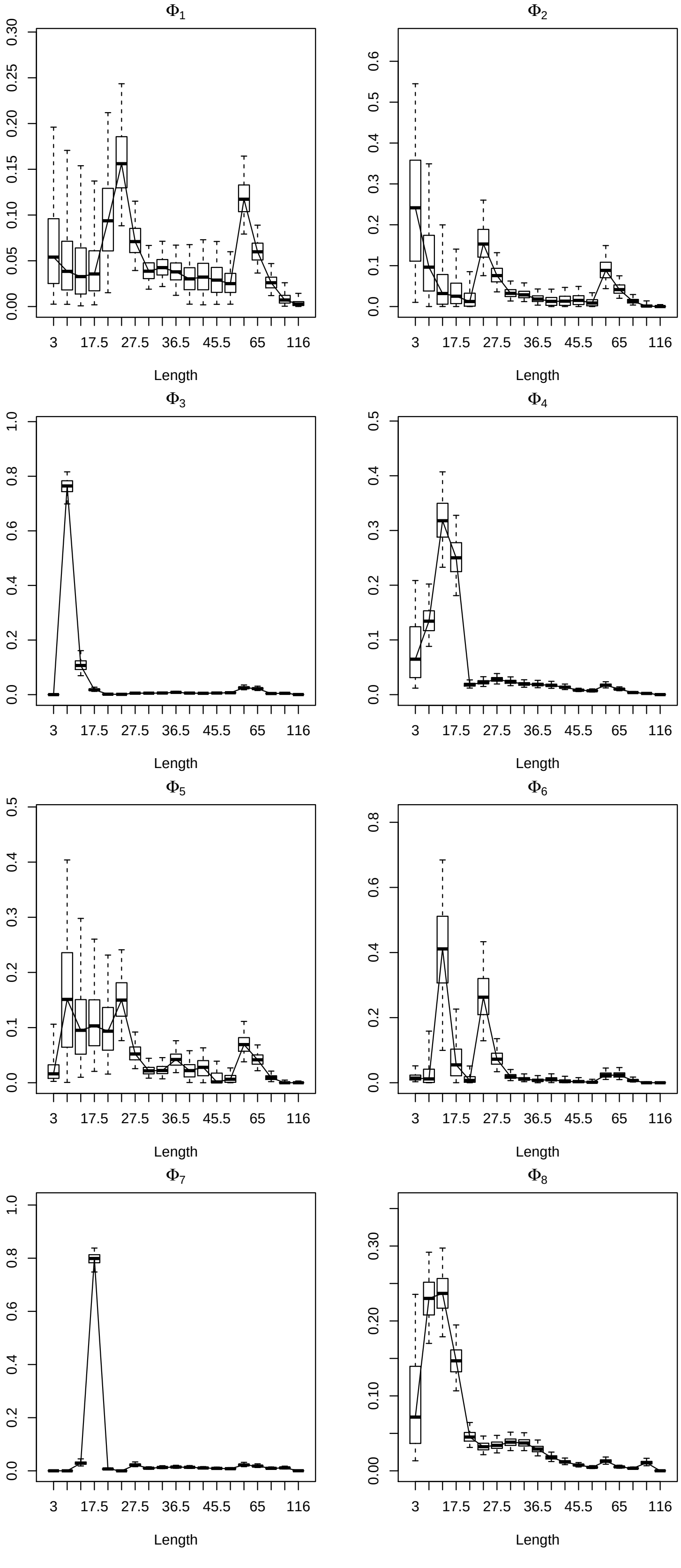


Figure 20: Estimated length distribution of population from quarter 33 to quarter 40. Limits of the box are for quantiles 25 and 75 while the middle is for the median.

Length distribution-model version 4b.



Φ_1 Φ_2 Φ_3 Φ_4 Φ_5 Φ_6 Φ_7 Φ_8

Figure 21: Estimated length distribution of population from quarter 1 to quarter 8. Limits of the box are for quantiles 25 and 75 while the middle is for the median.

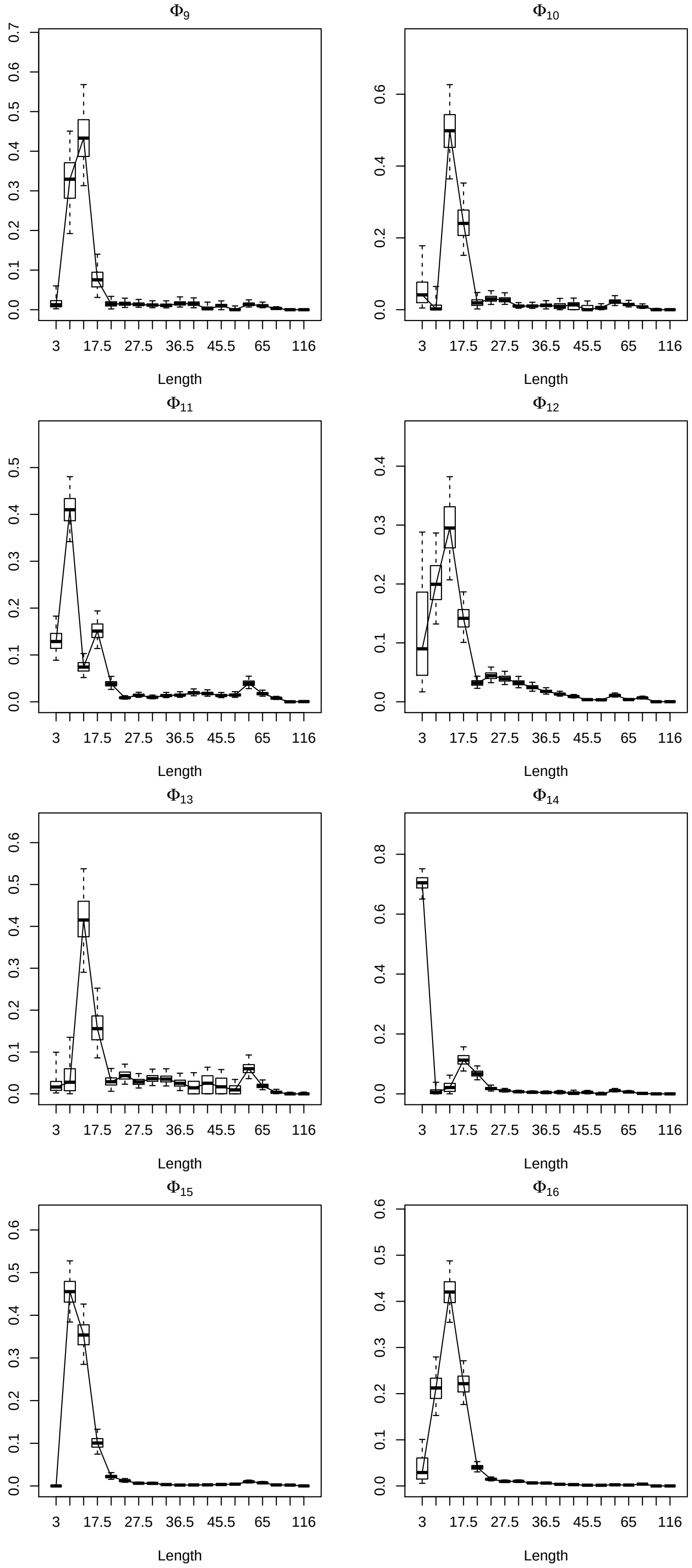


Figure 22: Estimated length distribution of population from quarter 9 to quarter 16. Limits of the box are for quantiles 25 and 75 while the middle is for the median.

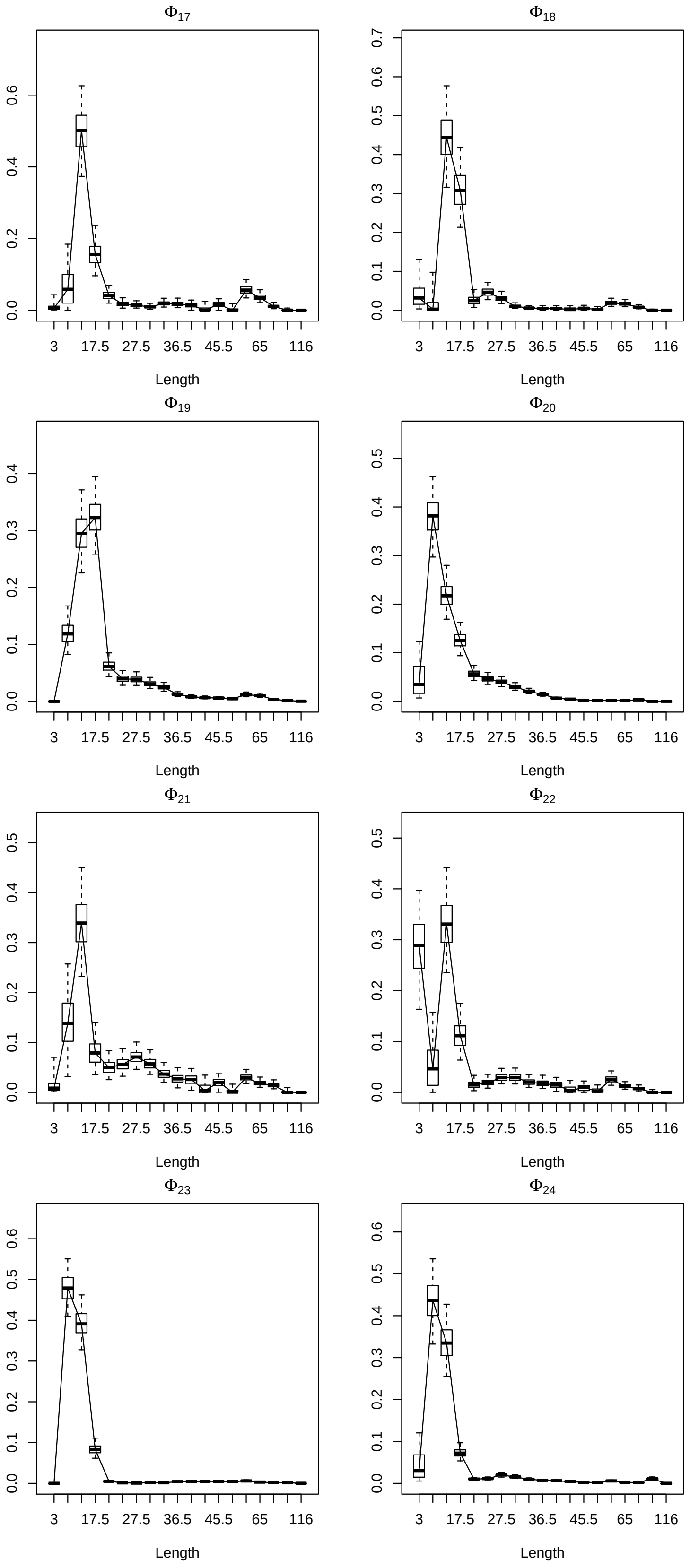


Figure 23: Estimated length distribution of population from quarter 17 to quarter 24. Limits of the box are for quantiles 25 and 75 while the middle is for the median.

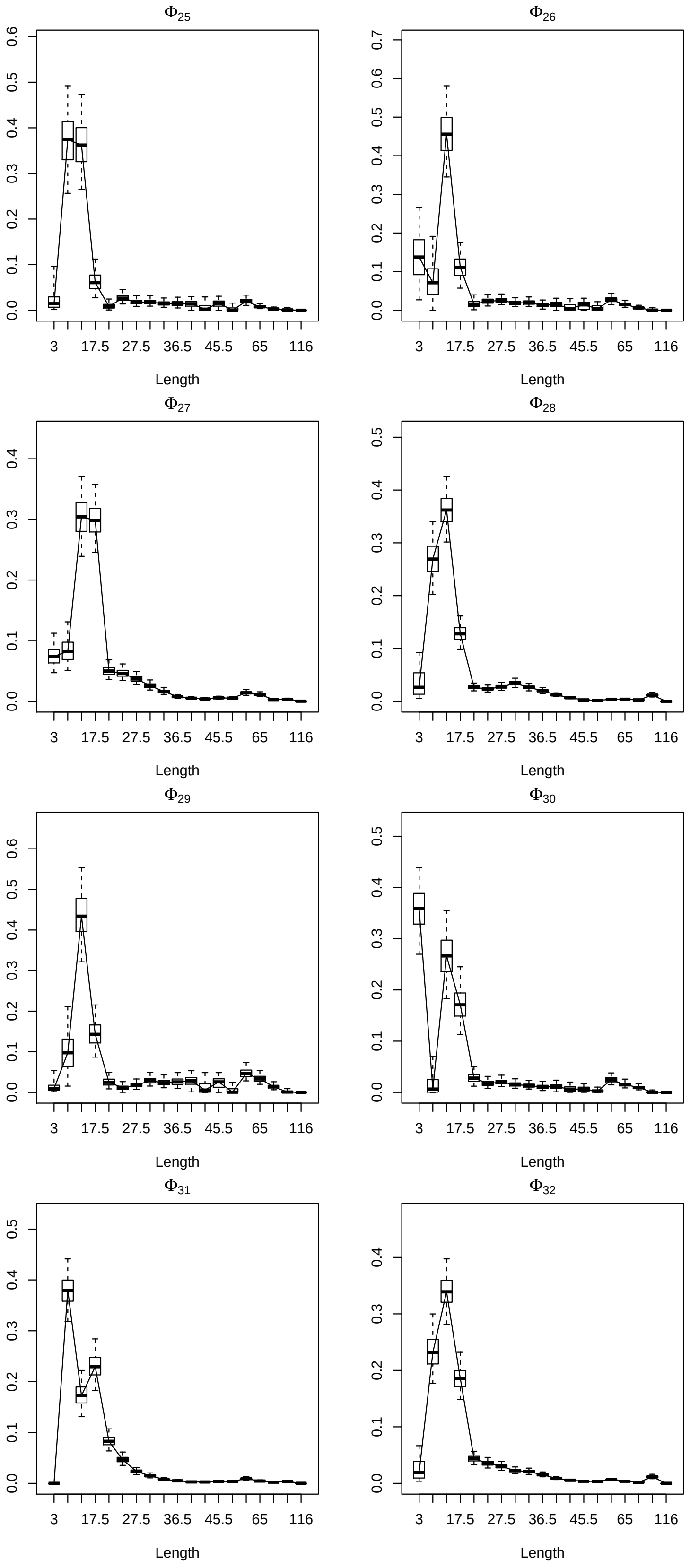


Figure 24: Estimated length distribution of population from quarter 25 to quarter 32. Limits of the box are for quantiles 25 and 75 while the middle is for the median.

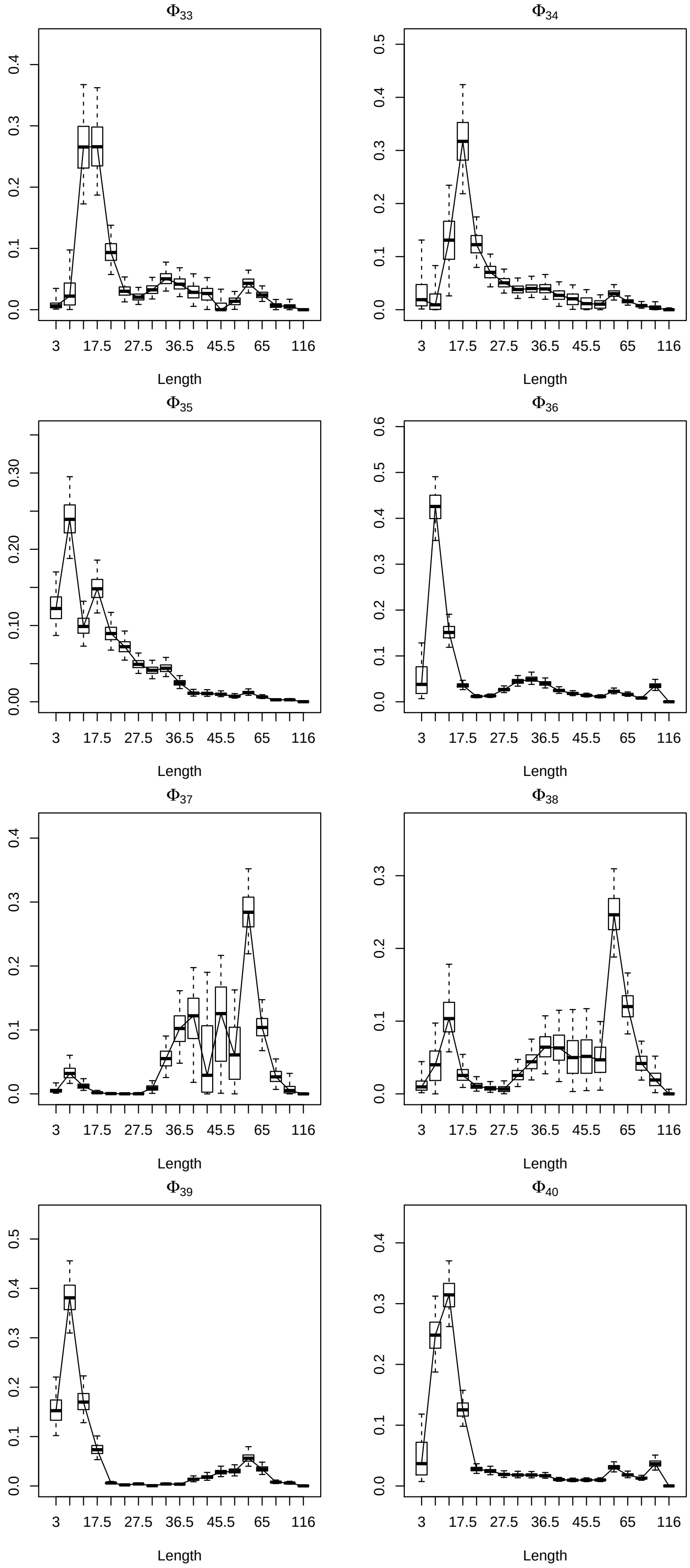


Figure 25: Estimated length distribution of population from quarter 33 to quarter 40. Limits of the box are for quantiles 25 and 75 while the middle is for the median.

A Bayesian state-space size-structured population dynamics model for northern hake. Improving hake assessment considering biological uncertainty

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Suplementary material IV

JAGS code for model version 4b

```
> gpdm<-
+ "
+ model{
+ ################################################################################
+ ## population dynamics
+
+     for(t in 1:Y){                          # T time steps
+     # Change in total population size, scaled to initial population size ni
+
+     n[t+1]<-abs(s[t]*n[t])+abs(R[t+1])+0.006
+     oR[t]<-R[t]*ni # recruitment in original scale
+     on[t]<-n[t]*ni                        # total abundance in original scale
+
+     # survival process
+     s[t]~dbeta(as[t],bs[t])T(,0.9999)       # surviving proportion
+
+     as[t]<-p[t]*eta_star[t]+0.1
+     bs[t]<-(1-p[t])*eta_star[t]+0.1
+     eta_star[t]<-n[t]*ni*qEta
+
+     p[t]<-sum(phiSs[t,1:LC])        # survival probability
+       for(k in 1:LC){
+       #surv[t,k]<-exp(-Z[t,k])
+       Z[t,k]<-Mconstant/4+sum(F[t,k,1:FL]) #M[t,k]F[t,k,1]
+       }
+
```

---

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[**] santiago.cervino@vi.ieo.es
[***] samu.mantyniemi@helsinki.fi

```
+     # Dynamics of the size distribution
+
+     phiG[t,1:LC]<-phi[t,1:LC]%*%G[1:LC,1:LC]        # phi: proportion of fish in size class
+     phiS[t,1:LC]~ddirch(aphiS[t,1:LC]+0.1)
+
+     for(k in 1:LC){
+     aphiS[t,k]<-phiSs[t,k]*eta_star[t]
+     }
+                                                                   # phiS lenght distribution after growth
+     Rratio[t+1]<-R[t+1]/n[t+1]
+       for(k in 1:LC){
+
+       phiSs[t,k]<-exp(-Z[t,k])*phiG[t,k]                      # Expected survival
+
+       phi[t+1,k]<-(1-Rratio[t+1])*phiS[t,k]+Rratio[t+1]*phiR[k]    # lenght distribution after recruitment:
+                                                                     # initial state for the next time step
+       deltas[t,k]<-(1-exp(-Z[t,k]))*phiG[t,k]
+       delta[t,k]<-deltas[t,k]/(1-p[t])                        # length distribution of dead fish
+
+     for(j in 1:FL){
+    F[t,k,j]<-Fmax[t,j]*Fsel[k,j]
+       gammas[t,k,j]<-delta[t,k]*F[t,k,j]*(Gsel[k,j]+0.000000001)/(Z[t,k]+0.00000000001)
+       gamma[t,k,j]<-gammas[t,k,j]/(q[t,j]+0.0000000001) # length distribution in the catch
+       Newps[t,k,j]<-(1-Gsel[k,j])*gammas[t,k,j]/(Gsel[k,j]+0.000000001) #Gsel=1 no discards
+       Newp[t,k,j]<-Newps[t,k,j]/(q_discards[t,j]+0.000000001)
+       }
+ }
+   for(j in 1:FL){
+     q[t,j]<-sum(gammas[t,1:LC,j])  # proportion of caught fish from all the dead fish
+     q_discards[t,j]<-sum(Newps[t,1:LC,j]) # proportion of discard fish from all the dead fish
+       }
+   }
+
+ qEta~dbeta(1,1)T(,0.9999) #cluster size as a proportion of the total population size
+
+ ## Dirichlet prior for the size composition in the beginning of the first time step
+ phi[1,1:LC]~ddirch(aphi[1:LC])
+ for(k in 1:LC){
+ aphi[k]<-1 #mu_phi[k]*eta_phi
+ }
+
+ # Mortality rates and initial abundance: multivariate normal prior for a linear combination
+ #of transformed parameters
+ # -> less correlation between simulated parameters and block updating usingf M-H alg.
+ #-> better mixing
+
+ Mconstant<-exp(LM)  # Natural mortality rate
+ LM<-par[1]+muM
+
+ n[1]<-1
+ ni<-exp(lni)  # Initial population size
+ lni<-par[2]+muN
+ R[1]<-0       # no recruits in the first year: they are already included in the initial
+ #size distribution
+
+ Fconstant<-minF+(maxF-minF)*pF #Fishing mortality rate
+ logit(pF)<-par[3]
+ minF<-0.0001#0.055 #0.1
+ maxF<-0.5 #0.3
+
+ mue[1]<-0
+ mue[2]<-0
```

```
+ mue[3]<-0
+
+ par[1:3]~dmnorm(mue[1:3],tau[1:3,1:3])
+ tau[1:3,1:3]<-inverse(cov[1:3,1:3])
+
+ cov[1,1]<-s2M   # Covariance matrix
+ cov[1,2]<-0    # still have independent priors
+ cov[1,3]<-0
+
+ cov[2,1]<-cov[1,2]
+ cov[2,2]<-s2N
+ cov[2,3]<-0
+
+ cov[3,1]<-cov[1,3]
+ cov[3,2]<-cov[2,3]
+ cov[3,3]<-1 #s2F=1
+
+
+
+ ################################################################################
+ # Von Bertalanffy Growth model: expected length from size class k
+
+     #for(t in 1:Y){
+     #Gk<-0.17/4                                         # growth rate, fixed for now
+             #Lsigma[t]<-sqrt(Linfsigma*Linfsigma*(1-exp(-Gk[t]*2)))
+         Lsigma<-sqrt(1*(1-exp(-Gk*2)))  # Standard deviation of growths over a time step
+    # Linfsigma: standard deviation of lengths of old fish
+   # In time, the length distribution of a cohort converges
+    # to have mean Linf and SD Linfsigma
+
+       for(k in 1:LC){
+
+         Eg[k]<-(Linf-length[k])*(1-exp(-Gk))+length[k]
+       }
+     #}
+
+ ## Scaled and shifted multivariate logit-normal priors for growth parameters: multivariate normal
+ #prior for a linear combination of transformed parameters
+ # -> less correlation between simulated parameters and block updating using M-H alg.
+ #-> better mixing
+
+ Linf~dnorm(muLinf,s2invLinf)T(80,120)
+
+
+ ################################################################################
+ # Growth matrix: normally distibuted growths from each length class. Negative growths are allowed to
+ #counter balance
+ # the too fast growths from small sizes. As a result, the size distribution is kept plausible at the
+ #population level
+ # and the tendency to sink all fish into highest length class becomes avoided.
+ # Of course, this is not an appropriate model for individuals
+
+ # I[j]: lower bound of length class k
+ # l[k]: midpoint of length class k
+  # for(t in 1:Y){
+     for( k in 1:LC){
+       for( j in 1:LC){
+        G[k,j]<-(phi((I[j+1]-Eg[k])/Lsigma)-phi((I[j]-Eg[k])/Lsigma))/(phi((I[LC+1]-Eg[k])/Lsigma)-phi
+ ((I[1]-Eg[k])/Lsigma))
+       }
+     }
+   #}
```

```
+
+ ################################################################################
+ # weight-length relationship
+ # parameters may vary in time, fixed for now
+
+     for( k in 1:LC){
+       log(w[k])<-logawConstant+bwConstant*log(length[k])
+       }
+
+
+
+ # Length weight parameters: fixed dummy values for now
+
+ logawConstant<--12.14592#-5.27490548 #ln(0.00000531)Hake
+ bwConstant<-3.074
+ ################################################################################
+ # # Eggs produced by a length class
+   for(t in 1:Y){
+ SSB[t]<-sum(ssb[t,1:LC])             # Calculating SSB for output, not used in the model
+ BIOM[t]<-sum(biom[t,1:LC])
+     for(k in 1:LC){
+       eggs[t,k]<-mat[k]*fecConstant*sexr*w[k]
+          ssb[t,k]<-mat[k]*w[k]*phiG[t,k]*on[t] # Spawning stock per length. Not used in the model
+         biom[t,k]<-w[k]*on[t]*phiG[t,k]
+     }
+   }
+ ################################################################################
+ # total number of eggs in time t
+   for(t in 1:Y){
+     Eggs[t]<-inprod(eggs[t,1:LC],phi[t,1:LC])*n[t]
+
+   }
+ ################################################################################
+ # Maturity of a length class
+   #for(t in 1:Y){
+     for( k in 1:LC){
+       mat[k]<-step(length[k]-matLength)
+       }
+   #}
+
+ ################################################################################
+ ################################################################################
+ # sex ratio (females)
+ sexr<-0.5
+ ################################################################################
+ #####################################################
+ # Maximum Fishing mortality per fleet. This will be modified using the fishery
+ # selectivity curve
+
+  for( j in 1:FL){                        # Loop over fleets
+
+    for(t in 1:Y){
+
+
+    Fmax[t,j]~dgamma(aF[j],bF[j])T(,0.5)             # Randomly varying F for each fleet
+    reF[t,j]<-Fmax[t,j]/mueF[j]
+         }
+ bF[j]<-1/(CVF[j]*CVF[j]*mueF[j])
+   mueF[j]<-Fconstant *Fprop[j]        # calculate relative changes of F
+   aF[j]<-1/(CVF[j]*CVF[j])
+   #Fpropmean[1:FL]~ddirch(alphaFm[1:FL]) #Just for speed
+   CVF[j]~dbeta(1,1)T(,0.99)
```

```
+ alphaF[j]<-FL}
+
+
+   Fprop[1:FL]~ddirch(alphaF[1:FL]) #Just for speed
+
+ ################################################################################
+ # Fishery selectivity due to availability
+ # this decribes the relative distribution of fishing pressure to different length
+ # groups. Probably more uncertain than the mechanical selectivity of the gear
+
+    for(k in 1:LC){
+ Fsel[k,1]<-exp(-tau11*(length[k]-l11)*(length[k]-l11))*step(l11-length[k])+exp(-tau21*(length[k]-l11
+ )*(length[k]-l11))*step(length[k]-l11)
+   Fsel[k,2]<-SFsel[k,2]/SFsel[LC,2]
+  logit(SFsel[k,2])<-alphaFsel*betaFsel+betaFsel*length[k]
+     #probit(SFsel[k,j])<-(length[k]-mFsel[j])/sdFsel[j] # selection curve
+ #Fsel[k,2]<-exp(-tau12*(length[k]-l12)*(length[k]-l12))*step(l12-length[k])+exp(-tau22*(length[k]-l12
+ )*(length[k]-l12))*step(length[k]-l12)
+ Fsel[k,3]<-exp(-tau13*(length[k]-l13)*(length[k]-l13))*step(l13-length[k])+exp(-tau23*(length[k]-l13
+ )*(length[k]-l13))*step(length[k]-l13)
+ #Fsel[k,5]<-exp(-tau15*(length[k]-l15)*(length[k]-l15))*step(l15-length[k])+exp(-tau25*(length[k]-l15
+ )*(length[k]-l15))*step(length[k]-l15)
+    }
+
+ tau11~dunif(0,0.3)#Mezcla de flotas 1,2 y 3
+ tau21~dunif(0.00005,0.3)#el mínimo de tau23, el máximo de tau22
+ l11~dunif(10,60)#el mínimo de l12 y el máximo de l13
+
+
+
+ tau13~dunif(0.002,0.01)#dunif(0.002,0.3)#la misma de 15
+ tau23~dunif(0.0005,0.005)#dunif(0.0009,0.3)#la misma de 25
+ l13~dunif(50,90)#(10,30)#la misma de l15
+
+
+
+ #tau12~dunif(0.002,0.3)
+ #tau22~dunif(0.0009,0.3)
+
+ #tau11~dunif(0,0.3)
+
+ #tau21~dunif(0.0005,0.01)
+
+ #tau13~dunif(0,0.3)
+ #tau23~dunif(0.00005,0.01)#dunif(0.0005,0.001)
+ #tau15~dunif(0.002,0.01)
+ #tau25~dunif(0.0005,0.005)
+ #l12~dunif(10,30)
+ #l11~dunif(20,40)
+ #l13~dunif(20,60)#dunif(20,40)
+ #l15~dunif(50,90)
+
+    alphaFsel~dnorm(-40,Talpha)T(-60,-10)#T(-45,-15)   # length at 50% selectivity
+    betaFsel~dunif(0.1,0.99)#dunif(0.2,0.4)         # softness of the selection curve
+   Talpha<-1/400
+ ################################################################################
+ # gear selectivity
+ #for( j in 1:3){
+    for(k in 1:LC){
+  logit(Gsel[k,1])<-betaGsel[1]*alphaGsel[1]+betaGsel[1]*length[k]#Gsel=1/(1+exp(-betaGsel*length
+ -betaGsel*alphaGsel))plot(1/(1+exp(-0.8*x+0.8*27))
+ Gsel[k,2]<-1
```

```
+ Gsel[k,3]<-1
+    }
+   alphaGsel[1]~dnorm(-27,0.01)T(-30,-20)  # length at 50% selectivity
+   betaGsel[1]~dunif(0.001,3)         # softness of the selection curve
+    #}
+ #for(k in 1:LC){
+ #Gsel[k,4]<-1
+ #Gsel[k,5]<-1}
+ ################################################################################
+ #recruitment process
+   for(t in 1:Y){
+    R[t+1]<-exp(LR[t+1])
+     LR[t+1]~dnorm(ER[t+1],TR)
+     ER[t+1]<-log(Eggs[t])+log(K)-log(K/alpha+Eggs[t])-0.5/TR
+   # oR[t]<-R[t]*ni # recruitment in original scale
+    }
+
+ # Stock recruitment parameters: multivariate normal prior for a linear combination of transformed
+ parameters
+ # -> less correlation between simulated parameters and block updating using M-H alg. -> better mixing
+ oK<-ni*K      # oK : carrying capacity on original scale
+ K<-exp(LK)    # carrying capacity relative to abundance in 1st year
+ LK<-par2+mu2
+
+ alpha<-1 #for this model we assume it constant
+
+ par2~dnorm(mue2,1/s2K)
+
+ mu2<-muK
+
+ mue2<-0
+ CVR~dunif(0,1) # CV of recruitment residuals
+ TR<-1/log(CVR*CVR+1)
+
+ ################################################################################
+ # fishing process
+
+ for(t in 1:Y){
+
+
+   Total_q[t]<-sum(q[t,1:FL])
+      d1[t]<-round(n[t]*(1-s[t])*ni)      # number of dead fish
+     d[t]<-step(d1[t]-c[t])*d1[t]+step(c[t]-d1[t])*c[t]
+     # Beta-binomial model for catches
+     ac[t]<-Total_q[t]*eta_star[t]+0.1
+     bc[t]<-(1-Total_q[t])*eta_star[t]+0.1
+  c[t]~dbetabin(ac[t],bc[t],d1[t])
+
+ # Distribution of catches to different fleets
+     FleetCatchProp[t,1:FL]~ddirich(AlphaFleetProp[t,1:FL]+0.0000000000001)         # This needs to be
+ #dirich-multi mixture!
+     for(j in 1:FL){
+     AlphaFleetProp[t,j]<-eta_fleet_prop[t]*q[t,j]/Total_q[t]
+     }
+     eta_fleet_prop[t]<-c[t]*(ac[t]+1)/(ac[t]+c[t])-1
+
+
+ Total_q_discards[t]<-sum(q_discards[t,1:FL])
+
+ #Discard process
+     ad[t]<- Total_q_discards[t]#*eta_star[t]
+     bd[t]<-(1- Total_q_discards[t])#*eta_star[t]
```

```
+ dis[t]~dbetabin(ad[t],bd[t],d1[t])
+ }
+ #########################################################################
+ #Observational model for surveys
+ for( k in 1:LC){
+ Isel1[k]<-exp(-Itau11*(length[k]-Il11)*(length[k]-Il11))*step(Il11-length[k])+exp(-Itau21*(length[k]
+ -Il11)*(length[k]-Il11))*step(length[k]-Il11)
+ Isel2[k]<-exp(-Itau12*(length[k]-Il12)*(length[k]-Il12))*step(Il12-length[k])+exp(-Itau22*(length[k]
+ -Il11)*(length[k]-Il12))*step(length[k]-Il12)
+ Isel3[k]<-exp(-Itau13*(length[k]-Il13)*(length[k]-Il13))*step(Il13-length[k])+exp(-Itau23*(length[k]
+ -Il13)*(length[k]-Il13))*step(length[k]-Il13)
+ #Isel4[k]<-exp(-Itau14*(length[k]-Il14)*(length[k]-Il14))*step(Il14-length[k])+exp(-Itau24*(length[k]
+ -Il14)*(length[k]-Il14))*step(length[k]-Il14)
+ #Isel5[k]<-exp(-Itau11*(length[k]-Il11)*(length[k]-Il11))*step(Il11-length[k])+exp(-Itau21*(length[k]
+ -Il11)*(length[k]-Il11))*step(length[k]-Il11)
+ for (i in 1:length(Ins1index)){
+ mean[i,k]<-q1*ni*n[Ins1index[i]]*phi[Ins1index[i],k]*Isel1[k] #Ins1[i,k]<-exp(lnIns1[i,k])
+ Me[i,k]<-log(mean[i,k])-0.5*S2       #log(mean[i,k])-0.5*S2
+ Ins1[i,k]~dlnorm(Me[i,k],T) #lnIns1[i,k]~dnorm(Me[i,k],T)
+ }
+ for (i in 1:length(Ins2index)){
+ mean2[i,k]<-q2*ni*n[Ins2index[i]]*phi[Ins2index[i],k]*Isel2[k] #Ins1[i,k]<-exp(lnIns1[i,k])
+ Me2[i,k]<-log(mean2[i,k])-0.5*S2       #log(mean[i,k])-0.5*S2
+ Ins2[i,k]~dlnorm(Me2[i,k],T) #lnIns1[i,k]~dnorm(Me[i,k],T)
+ }
+ for (i in 1:length(Ins3index)){
+ mean3[i,k]<-q3*ni*n[Ins3index[i]]*phi[Ins3index[i],k]*Isel3[k] #Ins1[i,k]<-exp(lnIns1[i,k])
+ Me3[i,k]<-log(mean3[i,k])-0.5*S2       #log(mean[i,k])-0.5*S2
+ Ins3[i,k]~dlnorm(Me3[i,k],T) #lnIns1[i,k]~dnorm(Me[i,k],T)
+ }
+
+
+
+ }
+ T<-1/S2
+ S2<-log(pow(CV,2)+1)
+ CV<-0.2
+
+ #survey 1 porcupine
+ #prior q1,Itau11, Itau21 y Il11
+ Itau11~dunif(0.0001,0.01)#dunif(0.002,0.01)
+ Itau21~dunif(0.0005,0.005)
+ Il11~dunif(40,80)
+ q1~dunif(10e-10,10e-3)
+ #survey 2 IGFS
+ Itau12~dunif(0.001,0.5)#dunif(0.001,0.2)#dunif(0.001,0.1)
+ Itau22~dunif(0.001,0.1)
+ Il12~dunif(1,30)#dunif(5,30)
+ q2~dunif(10e-4,10e-1)#dunif(10e-6,10e-1)#dunif(10e-10,10e-3)
+ #survey 3 vhoe
+ Itau13~dunif(0.001,0.5)#dunif(0.001,0.1)
+ Itau23~dunif(0.00001,0.1)#dunif(0.001,0.1)
+ Il13~dunif(5,30)
+ q3~dunif(10e-5,10e-3)#dunif(10e-10,10e-3)
+ #survey 4 ressgas
+ ################################################################################
+ # Observation model for length data
+
+   for( k in 1:LC){
+   bandw[k]<-(I[k+1]-I[k])/5  # smoothing bandwidth based on widths of length intervals
+   }
+   for( t in 1:Y){
```

```
+    for( j in 1:OLC){
+   for( pl in 1:FL){
+       newlength[t,pl,j]<-inprod(qlength[j,1:LC],Newp[t,1:LC,pl])
+       plength[t,pl,j]<-inprod(qlength[j,1:LC],gamma[t,1:LC,pl])
+    }
+    }
+ for(jf in 1:FL){
+   x[t,jf,1:OLC]~dmulti(plength[t,jf,1:OLC],SSize[t])
+    }
+
+ xd[t,1,1:OLC]~dmulti(newlength[t,1,1:OLC],SSize[t])
+
+   }
+
+ }
+ "
```

Discusión General

Aunque hace un siglo la abundancia de peces en el mar era tal que parecía impensable que el ser humano tuviese alguna repercusión sobre su abundancia (Huxley, 1884; Roberts, 2010), el rápido agotamiento del recurso llegando incluso a la extinción de varias especies ha demostrado que no es así y que se requiere asesoría científica para que la pesca sea una actividad sostenible tanto económica como medioambientalmente. Esta tesis responde a ese requerimiento científico y aborda el problema de cuánto pescar maximizando el beneficio y disminuyendo el riesgo de colapso. Es un problema que requiere una mirada interdisciplinar desde diversos campos científicos ya que tiene varias dimensiones.

La primera dimensión se refiere a la necesidad de conocer el funcionamiento del ecosistema, cómo son las interacciones del organismo explotado con el medio en sus diferentes etapas vitales. Se trata además de organismos que viven en un hábitat de dificil exploración. De hecho, los ecosistemas marinos están entre los que menos se conocen del planeta (Ramírez-Llodra et al., 2006). El estudio de estos ecosistemas demanda la intervención de diversas ramas de la ciencia, incluyendo la oceanografía física, la biogeoquímica, la ecología y la biología, entre otras. La segunda dimensión incluye el impacto antropogénico en las poblaciones producido por la pesca: Cuál es la proporción capturada respecto al total de la población, cuál es la máxima captura que permite mantener a la población en un nivel sostenible y una vez conocido ese nivel cómo garantizar que de cada puesta sobreviva por lo menos un ejemplar, cómo respetar el ciclo de reproducción si es inevitable capturar por accidente ejemplares que están por debajo de la talla de maduración y qué hacer con esos ejemplares, ya que si se ponen a la venta, dichas capturas dejarían de ser accidentes para convertirse en una fuente de ingresos y si se devuelven muertos al mar, se desaprovecharía una fuente de alimentación. Aquí las dificultades provienen de la imposibilidad de conocer la cantidad exacta de ejemplares, de la diversidad de artes de pesca y el desconocimiento de la forma en que su actividad afecta los patrones de crecimiento y del hecho de no poder evitar las capturas accidentales de ejemplares pequeños, entre otros. La tercera dimensión tiene que ver con la administración y gestión del recurso, en la cual es indispensable la comunicación fluida entre investigadores y gestores para encontrar la forma más eficaz de presentar a los gobiernos los resultados científicos y las decisiones de gestión a la sociedad de forma que sea mas fácil la asimilación de la decision tomada por aquellos que se ven afectados por la misma. Esta dimensión es la que permite aplicar con mínimo conflicto social, el conocimiento generado en las dos dimensiones anteriores al bienestar de aquellos que dependen económicamente de la actividad pesquera.

En esta tesis se han abordado estas tres dimensiones referentes a la actividad pesquera para el análisis de tres stocks diferentes. Empezando por la anchoa en el golfo de Cádiz, luego hacia el Este, atravesando el estrecho de Gibraltar, se estudia el stock de anchoa del mar de Alborán y finalmente en el Atlántico Norte, se analiza la merluza. Teniendo en cuenta las condiciones y particularidades de cada stock, el enfoque para los tres ha sido diferente. Para la anchoa del golfo de Cádiz y del mar de Alborán aunque se ha utilizado principalmente la interacción entre el medio y el ciclo de vida de la especie, los tipos de forzamiento ambiental y su relación con el ciclo vital son muy diferentes. Una captura anual en el mar de Alborán igual a la captura media del golfo de Cádiz es considerada como un evento atípico. En cada caso el modelado de la relación de la captura con el medio se realiza en función al conocimiento de esa relación en cada zona. De esta forma en el golfo de Cádiz, ya se conoce la dinámica de forzamiento ambiental y se procede directamente a modelar dichas interacciones, mientras que en el mar de Alborán es necesario analizar primero los factores que podrían estar causando el forzamiento. Sin embargo, para la merluza se ha tenido en cuenta la relación entre la pesca y el conocimiento que se tiene sobre su biología, que todavía continua actualizándose, ya que el efecto del medio ambiente es menos representativo en una especie cuya máxima edad y máximo tamaño reportados según la base de datos Fishbase (Froese and Pauly, 2013) es de 20 años y 130 cms respectivamente. No obstante, la herramienta estadístico-matemática que está presente en todos es el análisis Bayesiano. Esta metodología ha demostrado ser eficaz a la hora de modelar las relaciones del medio ambiente con la especie, y procesos esenciales cómo son el crecimiento, la reproducción y la mortalidad, ya que permite incluir hipótesis que integran el conocimiento que científicos, pescadores y gestores tienen de la dinámica del stock, además, al ser sólo hipótesis tienen una incertidumbre asociada, un grado de fiabilidad que se puede transformar en probabilidad.

El análisis Bayesiano aplicado al entorno pesquero ha surgido como una sólida alternativa a previos modelos deterministas utilizados en las últimas décadas que no tenían en cuenta la incertidumbre, como el Análisis de población virtual (Virtual population analysis, VPA, Pope (1972)) o las estimaciones de máxima verosimilitud, entre otros. El enfoque frecuentista asume un estado fijo de la población y mediante un gran número de repeticiones del mismo procedimiento, provee intervalos de confianza del estado del stock y erróneamente dichos intervalos suelen asumirse como distribuciones de probabilidad. Para explicar cómo el análisis Bayesiano presenta una medida de la incertidumbre es necesario explicar su funcionamiento: En teŕminos del precursor de la metodología, Thomas Bayes (Bayes and Price, 1763; Bernardo and Smith, 2009), si asumimos que H es la hipótesis y D los datos, se tiene que:

$$P(H|D) = \frac{P(D|H)P(H)}{P(D)} = \frac{P(D|H)P(H)}{\int P(D|H)P(H)dH} \tag{a}$$

Donde $P(H)$ y $P(H|D)$, representan el grado de fiabilidad con respecto a la hipótesis que se tiene antes y después la obtención de los datos, respectivamente. Si se conocen $P(D|H)$ y $P(D)$, el teorema presenta una forma de actualizar el grado de fiabilidad de una hipótesis mediante el contacto con el mundo real a través de la observación y la recolección de datos.

Los métodos Bayesianos presentan una medida de la incertidumbre a través distribuciones de probabilidad de los parámetros en contraposición al análisis frecuentista que provee estimadores puntuales (Punt and Hilborn, 1997; Virtala et al., 1998). Permiten introducir el conocimiento de expertos mediante una distribución previa, que en la ecuación anterior corresponde a $P(H)$, y cuando dicha información no está disponible también una distribución de probabilidad no informativa puede transmitir dicho desconocimiento. Estos métodos suministran una distribución conjunta de todos los parámetros permitiendo medir la correlación entre ellos y la incertidumbre que se va propagando en las relaciones causa-efecto desde la distribución previa hasta la distribución posterior, $P(H/D)$ (Ibaibarriaga et al., 2008; Ruiz and Kuikka, 2012). Conocer la incertidumbre asociada a diferentes hipótesis y a la pérdida inevitable de información en el proceso es crucial para un campo como el pesquero, donde el proceso de modelado culmina en la toma de decisiones.

Las múltiples ventajas del enfoque Bayesiano han permitido modelar la fuerte relación entre el medio ambiente y la supervivencia en las primeras etapas de vida de la anchoa en dos ecosistemas muy diferentes: el golfo de Cádiz y el mar de Alborán. Las poblaciones de ambos ecosistemas están caracterizadas por la influencia del medio ambiente en el reclutamiento. Esta influencia está ampliamente documentada para stocks de pequeños pelágicos (Basilone et al., 2006; Fréon et al., 2005; Guisande et al., 2004; Nakata et al., 2000) y particularmente para la anchoa ya se había estudiado en otras zonas geográficas como Australia (Dimmlich et al., 2004), el mar Adriático (Cingolani et al., 1996) o el Mediterráneo (Caddy et al., 1995). El stock de anchoa en el golfo de Cádiz se ha adaptado a un ecosistema caracterizado por fuertes vientos y una fuerte produccion biológica como consecuencia de los nutrientes que introduce en el ecosistema el río Guadalquivir (Ruiz et al., 2006). Por contraste, esta misma especie en el mar de Alborán, a escasos kilómetros de distancia pero en un entorno ecosistémico completamente diferente, la población convive con un potente régimen de circulación debido al intercambio de agua entre el océano Atlántico y el mar Mediterráneo a través del estrecho de Gibraltar.

El forzamiento medioambiental de la dinámica poblacional de la anchoa en el golfo de Cádiz se modela en detalle mediante una estructura Bayesiana que logra sincronizar la puesta (cada 3 días apróximadamente) y el efecto de los fuertes vientos en los primeros dos meses de vida. Para ello se implementa un modelo que, en esas fases vitales, tiene una resolución cercana a la escala temporal en la que se producen tanto las puestas como los forzamientos meteorológicos. Sin embargo, esta escala semanal sería inoperativa en fases ulteriores del ciclo vital donde no es necesaria tanta resolución. Para estas fases se utiliza una escala temporal semanal que es la más cercana a las fluctuaciones de abundancia en esa etapa, mientras que para el resto del ciclo vital se utiliza una escala temporal mensual que permite modelar adecuadamente los procesos de crecimiento y mortalidad (capítulo 1). La mayor fuente de información para este stock proviene de la pesca que es probablemente la fuente de datos mas infra-utilizada en la generacion de modelos para la gestion pesquera (John Pope, personal communication). Los datos de capturas se convierten en distribución de probabilidad mediante una distribución beta-binomial donde, para un pez muerto, morir por captura representa un éxito, y es gracias a la pesca que se tiene información sobre los parámetros de crecimiento en la ecuación de von Bertallanfy modelados con distribuciones normales a partir de estudios previos (Bellido et al., 2000). El análisis Bayesiano permite que los procesos de captura y crecimiento se nutran del efecto del medio ambiente en el reclutamiento, la mortalidad, la distribución por tallas y la reproducción. De esta forma, el modelo después de su implementación puede simular las capturas sin recurrir a los datos originales.

La potencia de este modelo para reproducir la dinámica real que ocurre en la naturaleza es evidente con el único test que debiera actuar de juez para cualquier modelo: la validación con observaciones independientes que no han tenido ningún contacto previo con el modelo (Jorgensen, 1995). Un contraste entre los resultados obtenidos con una serie temporal de observaciones *in situ* de juveniles y con la distribución mensual por tallas registrada por el ICES revela que el modelo mejora la representación de estas observaciones independientes respecto a ejercicios previos. Además, el modelo logra reproducir claramente la influencia del reclutamiento en las capturas y confirmar una vez más el papel crucial del medio ambiente en el ciclo vital de la anchoa en el golfo de Cádiz.

La coherencia de los resultados indica que las relaciones funcionales que se han construido para modelar la dinámica del stock y su interacción con el medio ambiente tienen un alto grado de fiabilidad y que podría explorarse un modelo similar para otros pequeños pelágicos que también dependen del medio ambiente en sus primeras etapas vitales. Dicha exploración podría incluso ser útil para diseñar sistemas de gestión inter específicos, teniendo en cuenta que en el golfo de Cádiz y en el mar de Alborán conviven la sardina y el boquerón, y que las vedas de captura no son coincidentes.

En el mar de Alborán, la relación del medio ambiente con el reclutamiento no seguía un patrón que estuviera identificado y aunque habían estudios previos que relacionaban la potencia del chorro Atlántico con la advección de larvas de peces

(Rubín et al., 2006; Vargas-Yáñez and Sabatés, 2007), no había suficiente evidencia de la repercusión de este forzamiento en el ciclo vital de la anchoa. El trabajo del capítulo 3 revela la conexión entre un máximo de reclutamiento en el 2001 y una importante disminución en el mismo periodo de energía cinética en la corriente del mar de Alborán y en el segundo modo de la descomposición por valores singulares entre la topografía dinámica y la clorofila. Dicha conexión es un claro indicio de que aunque el chorro atlántico facilita la inyección de nutrientes a la zona fótica, favoreciendo por tanto la producción primaria y las posibilidades de reclutamiento, cuando su potencia es demasiado alta arrastra consigo las larvas hacia mar abierto donde su supervivencia es muy escasa.

Esta conexión también fue trasladada al ámbito Bayesiano en el capítulo 4 a través de las redes Bayesianas. Estas redes son una herramienta que se ha utilizado para la toma de decisiones en diferentes campos como la medicina (Sesen et al., 2013; Su et al., 2013), la ingeniería (Weidl et al., 2005) y últimamente vienen tomando fuerza en el contexto medio ambiental para el manejo de recursos (Uusitalo, 2007; Varis, 1997) y la gestión de pesquerías (Hammond, 2004; Levontin et al., 2011). Debido a su utilidad y a la facilidad de interpretación gráfica, se ha realizado un ejercicio sencillo de implementación con perspectiva a una línea de investigación futura. Después de discretizar los datos, ganando simplicidad pero perdiendo información, se ha efectuado un procedimiento de aprendizaje de máquina (machine learning) que corrobora la relación entre la energía cinética y las capturas. La red Bayesiana obtenida (Figura 2) conecta la energía del chorro directamente con el precio total de las capturas incluyendo el concepto de incertidumbre gracias a una representación gráfica de barras de probabilidad. Las Figuras 3, 4 y 5 del mencionado capítulo confirman el hecho de que hay una alta probabilidad de que dada una mayor energía cinética el ingreso total disminuya debido a la disminución en las capturas que esta energía provoca. La simplicidad de la red Bayesiana construida contrasta con la coherencia de los resultados y, aunque aún no se ha cuantificado la pérdida de información debida al proceso de discretización, se ve claramente la potencialidad de esta herramienta de cara a la gestión.

La gestión y administración del recurso como se dijo anteriormente permiten aplicar el conocimiento derivado del proceso de modelado. Por esa razón en el capítulo 2 se presenta una herramienta de carácter económico para la evaluación de estrategias cuya aplicación puede ser muy útil para los gestores. En este capítulo se explora la evaluación de estrategias de pesca en cuanto a su desempeño respecto a la optimización del beneficio económico y la disminución del riesgo de colapso. Planteamos la necesidad de estrategias que incorporen el conocimiento científico que se tiene de la dinámica poblacional de la anchoa, es decir, que incorporen el efecto del medio ambiente en el reclutamiento, mediante un caso particular donde se incorpora el efecto del viento en la supervivencia de las primeras etapas vitales de la anchoa en el golfo de Cádiz como motor de fluctuación del nivel de capturas. El valor de la inclusión de información ambiental se mide usando un esquema de seguros simulado que proporciona medidas de riesgo e ingreso mediante el coste de la prima y el beneficio económico, respectivamente. Estos conceptos son familiares para los gestores, lo que permite que este esquema sea tanto una herramienta de evaluación como una herramienta de comunicación. Este novedoso esquema se sugirió por primera vez con aplicación a pesquerías en 2009 (Mumford et al., 2009) y podría ser de gran utilidad para la anchoa. Aunque los resultados indican que el riesgo económico no disminuye bajo esta estrategia que incluye el medio ambiente, dado que la volatilidad del ingreso y el valor de la prima son mayores, se concluye que el riesgo de colapso disminuye y que los ingresos aumentan del tal manera que compensan dicha volatilidad.

Es necesario aclarar que este trabajo utiliza los conceptos de riesgo y productividad que aporta la elaboración de una póliza de seguros como herramienta de evaluación y comunicación, ya que es el paso previo y necesario a sugerir su implementación. Trabajos anteriores enfatizan la dificultad de trasladar este concepto ampliamente usado en el sector agrícola a través de subsidios al sector pesquero (Greenberg et al., 2004) y sugieren su implementación usando pequeñas cooperativas (Sethi et al., 2012) ya que en grupos pequeños se evitaría el riesgo de que los beneficiarios alteren su producción para obtener pagos del ente subsidiador. Un subsidio de este tipo permitiría que las fluctuaciones causadas por una cuota flexible que dependa del medio ambiente fuesen mitigadas adecuadamente, ya que el sector no sería rentable si las cuotas variasen drásticamente de un año a otro. La viabilidad de la implementación de subsidios para la anchoa en el golfo de Cádiz va a ser explorada en futuros trabajos, donde se analizará la idea de un manejo cooperativo del riesgo junto con una cuota variable que responda al medio ambiente como alternativa de gestión a los problemas socio-económicos que las fluctuaciones naturales de este recurso generan al sector.

La idea de un subsidio cooperativo puede desarrollarse en este stock ya que la relación entre la pesca y el ecosistema se produce a través de un único arte de pesca: el arte de cerco, pero es más complejo de concebir para un stock como el de la merluza en el Atlántico Norte porque se pesca con 8 flotas diferentes, cada una con un patrón de explotación por tallas específico, y donde 3 de las 8 flotas, descartan con patrones distintos a los patrones de explotación.

Sin embargo, si es posible plantear un modelo Bayesiano que incorpore la información de estas flotas como observación frente a la distribución de tallas de la población (capítulo 5). Una hipótesis para la distribución por tallas se convierte en probabilidad a través de una distribución Dirichlet-multinomial, donde la pertenencia a cierto intervalo de tamaño tiene una probabilidad asociada. Dicha distribución se modifica gracias a la información que proporciona la distribución por tallas de las capturas de cada flota. Dos nuevos módulos que se han incluido al modelo base desarrollado en la Universidad de Helsinki (Dr. Samu Mäntyniemi) permitieron incorporar la información de tamaño de 3 flotas de descartes y 4 de campañas de estimación de abundancia. Todas estas observaciones referentes al tamaño se utilizan para modelar el crecimiento con una estructura similar a la utilizada en el capítulo 1 que no había sido implementada antes en un modelo Bayesiano.

Este modelo es muy complejo ya que es necesario estimar un gran número de parámetros y su complejidad está directamente relacionada con el proceso de disminución del tiempo de cálculo para modelos Bayesianos en los últimos años. La mayor dificultad asociada a los modelos Bayesianos, y la razón por la cual no se han usado extensivamente antes radica en la necesidad de resolver la integral que aparece en el denominador de la ecuación (a) puesto que en la mayoría de casos dicha integral es multi-dimensional dependiendo del número de parámetros a estimar y su cálculo suele ser arduo. A finales del siglo pasado dicha dificultad se solucionó usando una aproximación numérica a la distribución $P(H|D)$ mediante el muestreo de Gibbs que permitía evadir el cálculo de dichas integrales muestreando iterativa y aleatoriamente de distribuciones apropiadas para producir una cadena de Markov que converjiese a la distribución objetivo (Gelfand and Carlin, 1992; Smith and Roberts, 1993). El tiempo de cálculo se redujo considerablemente pero, aún así, el muestreo de Gibbs aplicado a los modelos de los capítulos 1 y 5, tarda 488 y 250 horas, respectivamente. Un tiempo comparativamente superior al de otros modelos utilizados habitualmente para evaluación como *Stock synthesis* (Methot Jr. and Wetzel, 2013) o GADGET (Bartolino et al., 2011; Taylor et al., 2007) que tardan menos de un día en resolverse.

El software escogido para la implementación de los modelos Bayesianos fue JAGS (Just Another Gibbs Sampler, Plummer (2013)). Este es un software reciente y precisamente por esa razón, hemos podido desarrollar una nueva forma de paralelización e implementación en supercomputadores que puede ser una herramienta muy útil para otros usuarios que quieran implementar grandes códigos en supercomputadores (Ver apéndice). Sin embargo, también al ser tan reciente, aún tiene muchas restricciones en la iteracción con el usuario. Las principales radican en la dificultad para encontrar las fuentes de error y la gran cantidad de tiempo de computación, las cuales hacen que el proceso de implementación sea muy extenso y tedioso.

Considerando el hecho de que las correlaciones entre las distribuciones posteriores inducen una lenta convergencia del modelo, se exploraron varias reparametrizaciones del modelo Bayesiano de la merluza y varias alternativas que se resumen en 56 implementaciones diferentes. Finalmente se logró la convergencia en la mayoría de parámetros al reducir el número de flotas de captura de 5 a 3, pero los resultados no coincidían con los del actual modelo de gestión y ciertas inconsistencias eran difíciles de interpretar. El gran número de parámetros y procesos abordados dificultan la identificación de la interacción entre los parámetros y sus distribuciones previas. Para esclarecer dichas interacciones, actualmente, con un avance lento se están implementando nuevos escenarios partiendo de aquellos en donde hay convergencia de la mayoría de parámetros, se están indagando las consecuencias de incluir información biológica y se considera incluso la posibilidad de migrar el código a STAN, un software de análisis Bayesiano que parece ser más eficiente en determinadas situaciones.

También, superando las restricciones de tiempo computacional, se pueden explorar otras alternativas respecto al modelo Bayesiano para la anchoa: realizar un modelo de las mismas características pero con una resolución trimestral incluyendo la resolución semanal para las primeras etapas, utilizar las clásicas relaciones stock-reclutamiento como Ricker o Beverton-Holt sin incluir el medio ambiente para efectos de comparación, entre otros, que serán tenidas en cuenta para futuras publicaciones.

Las técnicas Bayesianas aplicadas a este campo siguen en continua expansión y el rápido avance tecnológico logrará una reducción del tiempo computacional, flexibilizando el proceso de modelado y confirmando que la medida de incertidumbre que provee esta herramienta puede ser la base de la toma de decisiones relevantes para el sector pesquero.

Conclusiones

Conclusiones

El resultado principal de este trabajo es la confirmación de la utilidad de las técnicas Bayesianas para modelar la dinámica de diversas poblaciones explotadas, permitiendo la incorporación de elementos complejos desde el forzamiento ambiental a la dinámica de capturas y descartes con diferentes flotas. Además, el conocimiento derivado de la aplicación de dichas técnicas se puede proyectar sobre elementos socioeconómicos, diseñando herramientas de gestión que tengan en cuenta el impacto del ecosistema y evaluando su funcionamiento.

Conclusiones específicas

- El modelo Bayesiano desarrollado para la anchoa del golfo de Cádiz mediante una doble resolución temporal logra reproducir los cambios drásticos en el tamaño de la población causados por el medio ambiente durante las primeras etapas del ciclo vital, mejorando las estimaciones de abundancia de juveniles respecto a modelos previos. Además, este modelo representa adecuadamente los procesos de crecimiento, mortalidad y reproducción proporcionando estimaciones de la distribución de tallas y del tamaño de la población coherentes con datos observados.

- La estructura matemática del modelo Bayesiano de doble resolución temporal propuesto para la anchoa en el golfo de Cádiz se puede extender fácilmente a otros pequeños pelágicos modificando únicamente el proceso de reclutamiento, donde sería necesario adaptar el forzamiento ambiental que corresponda. Esto permite incorporar para estas especies la capacidad resolutiva que esta estructura matemática ha demostrado para sintetizar en una misma formulación los procesos de reclutamiento, mortalidad, crecimiento y reproducción.

- Usando la información del forzamiento ambiental y la dinámica del stock de la anchoa en el golfo de Cádiz es posible diseñar una estrategia de pesca que incluya el efecto del medio ambiente y evaluar su funcionamiento mediante simulaciones que permitan calcular el ingreso generado, la prima anual y el riesgo de colapso, de esta forma se presenta una medida del valor de la información ambiental en su aplicación a la gestión.

- Un esquema de seguros simulado es una herramienta útil para la evaluación de estrategias de captura. Bajo este esquema, la estrategia de captura sugerida teniendo en cuenta el forzamiento ambiental no disminuye el riesgo económico, dado que la volatilidad del ingreso y el valor de la prima son mayores, pero disminuye el riesgo de colapso y genera un monto de ingresos tal que permite compensar dicha volatilidad.

- Un esquema de seguros simulado se presenta aquí como una herramienta de evaluación de estrategias. Sin embargo, el aumento considerable de ingresos obtenidos bajo estrategias que incluyen el medio ambiente hacen que esta herramienta sugiera la posibilidad de estabilizar ingresos sobre un recurso altamente fluctuante debido a la inestabilidad de la naturaleza. Un precedente para la posibilidad de un manejo cooperativo del riesgo que responda a una cuota variable determinada por el medio ambiente.

- El sistema de circulación que induce la entrada de agua atlántica en el mar de Alborán tiene usualmente un exceso de energía para resultar favorable al reclutamiento de la anchoa. Sólo en años excepcionales, cuando este sistema circulatorio colapsa, es posible la existencia de reclutamientos excepcionales de esta especie.

- La conexión entre el sistema circulatorio del mar de Alborán y el reclutamiento de la anchoa permite representar mediante una red Bayesiana de tres nodos las conexiones existentes entre la energía cinética y el ingreso total del sector. Los resultados de la red muestran que cuando el sistema circulatorio pasa de un estado que contiene poca energía a uno con mucha, es altamente probable que el ingreso total disminuya, evidenciando el gran impacto del sistema circulatorio en el mar de Alborán cuando éste se proyecta sobre un escenario económico.

- En un modelo complejo como el de la merluza, el gran número de parámetros y procesos involucrados hacen que sea difícil identificar la interacción entre los parámetros y sus distribuciones previas, además la correlación en las distribuciones posteriores de algunos parámetros influye en la lenta convergencia del modelo. Una reducción del tiempo computacional podrá permitir en un futuro una mejor exploración de dichas interacciones y correlaciones permitiendo incluir el conocimiento disponible sobre la biología de la merluza en la dinámica del stock.

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Anexos

Anexos

- Recipe for the implementation of a population dynamics Bayesian model for anchovy:Supercomputing using doMC , rjags and coda R packages. Poster presentado en la Conferencia Internacional de R (2013). UseR 2013. Albacete, España.

- Un paso decisivo en la mejora de las predicciones de las pesquerías: resultados del proyecto "ECOKNOWS". Artículo de divulgación presentado en la revista Industrias pesqueras No. 2085 (2014).

- Biología de la merluza europea y su papel en los modelos de evaluación. RESULTADOS DEL PROYECTO “ECOKNOWS”. Artículo de divulgación presentado en la revista Industrias pesqueras No. 2089 (2014).

Recipe for the implementation of a population dynamics Bayesian model for anchovy:

Supercomputing using doMC , rjags and coda *R* packages

CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

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This dish is recommended when you have data on anchovies and you want to know the distribution of the parameters affecting the processes involved.

Ingredients

- Matrices or arrays of observed data (Each one should be in text files using tab between columns: data1.txt, data2.txt, etc.,...)
- A population dynamics model for anchovy written in JAGS languaje relating the parameters of interest with the observed data (In a text file modeldef.txt file starting with mymodel<- "model { and ending with }")
- A list of prior distributions for the parameters.
- A new R script
- Packages rjags, doMC, random and coda (You can get them in the nearest CRAN mirror)
- An account in a supercomputing center (like CESGA, Center of Supercomputing of Galicia)
- A new sheet in a plain text editor (NotePad, gedit, emacs, etc...)

1. Preparation of the R script

- Save the JAGS model, the R script and the observed data in the same folder with the name `Bayesian_Model`. This will be the working directory.
- Rename the R script as `anchovymodel.r`
- Choose the adaptation time `n.adapt`, the number of `samples` per chain to be saved and the thinning period, `thin`.
- Create the object `data1` as follows:

```
data1<-as.matrix(read.table("data1.txt")).
```

Repeat with all the text files.

- Make a list named `Data` with the especification of all data objects used by the JAGS model, including the objects `data1`, `data2`, etc..., and the values needed for the definition of prior distributions.
- Load the R packages required and JAGS modules:

```
require(rjags)  ;require(doMC); registerDoMC();
require(random);load.module("glm");
load.module("lecuyer")
```

- Make a list with the initial values of the parameters named Inits as follows:

```
Inits<-
function(){list(.RNG.name="lecuyer::RngStream",
.RNG.seed=as.numeric(randomNumbers(n=1, min=1,
max=1e+06, col=1)), ...initial values separated by
commas...)}
```

- Load the JAGS model:

```
source("modeldef.txt")
```

- Set the parameters of interest:

```
monitor<-c(...name of the parameters...)
```

- Write the model specification into a text file:

```
cat(mymodel,file="Mymodel.txt")
```

- Compile the model (two chains, one chain by core) and adapt the MCMC samplers. The resulting object should be transform to an mcmc.list object

```
jagsList<-foreach(i=1:2, .combine="c")%dopar%{
jm2<-
jags.model("Mymodel.txt",data=Data,inits=Inits,n.c
hain=1,n.adapt=n.adapt)
chainspre<-
coda.samples(jm2,monitor,n.iter=samples*thin,thi
n=thin)
return(chainspre)})
chainsp<-c(jagsList[])
class(chainsp)="mcmc.list"
```

- Save relevant objects

```
save(Data,chainsp,file="Results.RData")
```

2 Preparation of the shell script

In the folder `Bayesian_Model` using a plain text editor create a file named `job.sh` and write the following:

```
#!/bin/bash
module load R/2.15.2
module load JAGS
Rargs="--no-save -q"
R $Rargs < ./anchovymodel.r
```

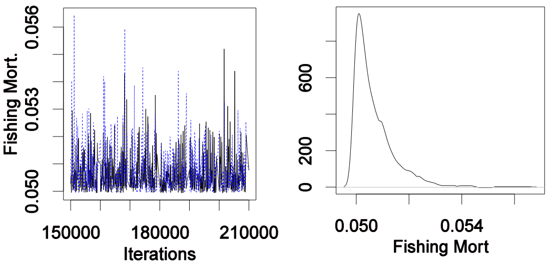
3. Cooking in supercomputer

Connect by ssh with the supercomputing center, copy the folder `Bayesian_Model` to your home directory, open a shell and write:

```
qsub  -l
num_proc=1,s_rt=600:00:00,s_vmem=1.3G,h_fsize=10
G,arch=amd -pe mpi 2 job.sh
```

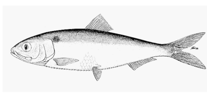
4. Ready to serve with the coda package

```
require(coda); load("Results.Rdata")
traceplot(chainsimp[,"Fconstant"])
d<-as.matrix(chainsimp)
plot(density(d[,"Fconstant"])
```



```
heidel.diag(chainsimp[,"Fconstant"])
```

```
Stationarity start  p-value
test         iter
var1 passed   242      0.156
Halfwidth    Mean Halfwidth
test
var1 passed 0.0507 7.45e-05
```



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Samu Mantyniemi from University of Helsinki, CESGA (Galician Supercomputing Center), the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement n°244706/ECOKNOWS project and Junta de Andalucia, project P09-RNM-5358.

Un paso decisivo en la mejora de las predicciones de las pesquerías: RESULTADOS DEL PROYECTO “ECOKNOWS”





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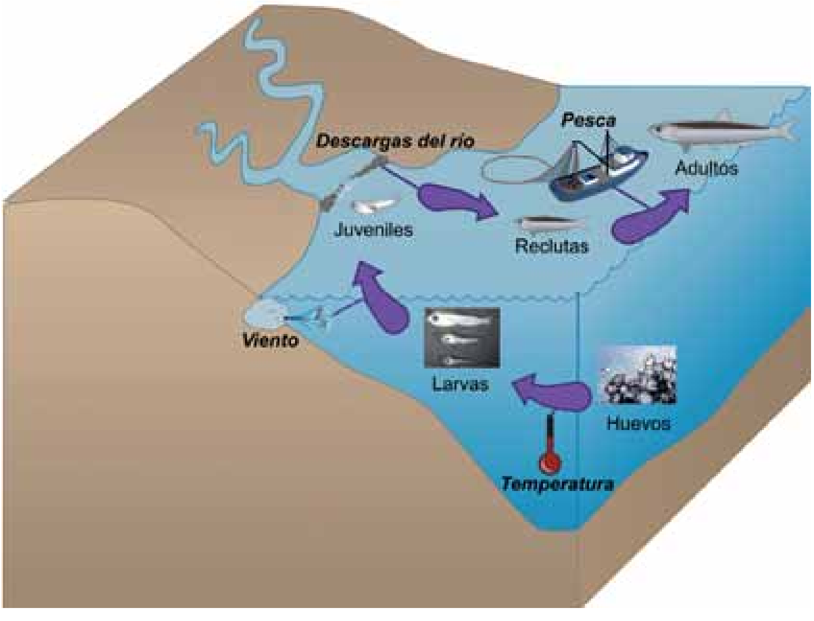
En 2014 finaliza el proyecto Europeo ECOKNOWS. Este proyecto, en el que participan investigadores de 13 centros internacionales entre los que se encuentra España (centros del CSIC e IEO), pretende reducir la incertidumbre en las evaluaciones pesqueras combinando diversos tipos de información, en muchas ocasiones infrautilizada. Para ello, y como relatamos al inicio del proyecto en Industrias Pesqueras (nº 2037, marzo 2012, pp6-10), se han desarrollado métodos estadísticos que permiten combinar, de forma efectiva, grandes volúmenes de datos de múltiples fuentes y características. Mediante la aplicación de estos métodos, el proyecto ECOKNOWS pretende mejorar sensiblemente las herramientas de asesoría pesquera.

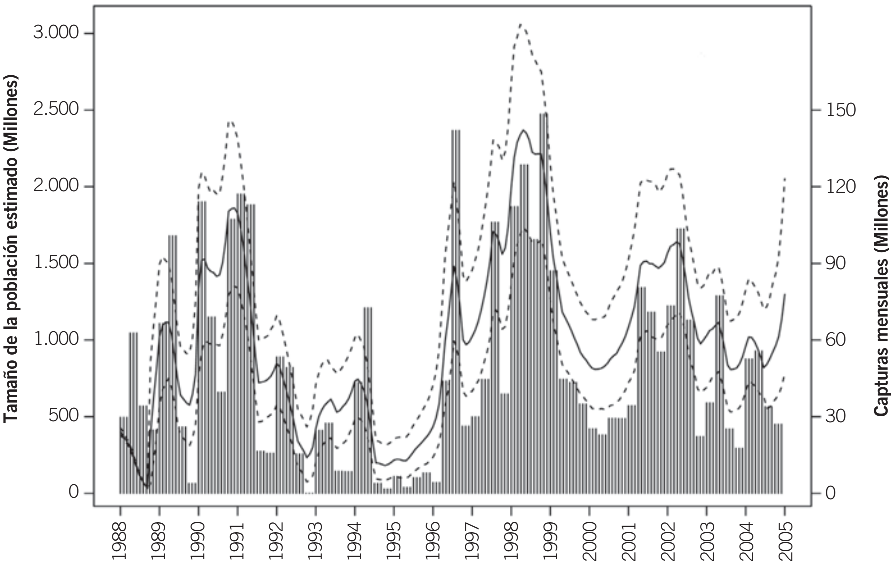
Transcurridos tres años del proyecto, queremos ofrecer a la comunidad pesquera una pincelada sobre los resultados obtenidos. ECOKNOWS cuenta con varios estudios piloto sobre los que se han ensayado estos métodos, que hasta hace pocos años no se podían aplicar de forma efectiva debido a la falta de potencia computacional: los cálculos necesarios excedían la capacidad de los ordenadores usados por los científicos. En España, nos hemos centrado en el estudio del boquerón del Golfo de Cádiz y la merluza del Cantábrico. A modo de ejemplo, en este artículo se explican brevemente los resultados del caso del boquerón, y al finalizar el proyecto se tendrán ya los datos sobre la merluza.

El boquerón del Golfo de Cádiz es un stock muy explotado que se ha caracterizado desde hace años por grandes fluctuaciones en sus capturas. Las evaluaciones convencionales no pueden predecir la evolución de la pesquería de boquerón por falta de datos, lo que normalmente implica actuar mediante el principio de precaución, limitando la pesca ante ciertas señales de alarma.



▲ Diagrama del ciclo de vida del boquerón en el Golfo de Cádiz incluyendo los factores ambientales que influyen en los cambios de fase. Diagrama realizado gracias a Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/).

En ECOKNOWS, ha sido posible incorporar información que antes no era utilizada y que explica en gran parte las oscilaciones del recurso. Varios años de investigación previa han demostrado que la mortalidad del boquerón en sus primeras etapas de vida (pocos meses) depende sobre todo de los vientos de levante (si son demasiado fuertes transportan los individuos fuera de sus zonas de desarrollo óptimo) y de las descargas del Guadalquivir, que regulan el hábitat favorable de las fases juveniles del boquerón. Por otra parte, la época de puesta depende principalmente de la temperatura. Evidentemente la mortalidad de las fases de huevos, larvas y juveniles pequeños no está determinada por la pesca, y cambios ambientales drásticos que ocurran en pocos días pueden dar al traste con una buena parte de la puesta. Sin embargo la pesca sí influye de manera contundente en la mortalidad de los adultos y juveniles grandes. En ECOKNOWS hemos incorporado el efecto de todas estas variables, de forma que podemos



▲ Tamaño de población estimado (líneas) versus capturas registradas por el ICES (barras). Las líneas punteadas representan los percentiles 5 y 95, mientras que la línea sólida representa la media.

predecir, de manera< más precisa y de año en año, la cantidad aproximada de nuevos individuos que se incorporarán al stock.

Los resultados de ECOKNOWS han permitido comprobar que las oscilaciones aparentemente erráticas de las capturas (descargas en lonja) responden a combinaciones de variables ambientales y presión pesquera que operan a diferentes escalas de tiempo y en diferentes momentos de la vida del individuo. Ha sido necesario, para eso, usar varias escalas de tiempo en los modelos de predicción: escalas "rápidas" (semanales) mientras los peces son pequeños y escalas mayores (mensuales) cuando los individuos alcanzan una talla suficientemente grande como para ser pescados. Otra de las grandes ventajas de usar estas herramientas es que también podemos proporcionar una medida razonable de la incertidumbre sobre las predicciones, es decir, lo "seguros" que estamos de esos resultados. De esta forma, los gestores tienen un "campo de riesgo" en el que pueden moverse para adoptar medidas que persigan objetivos específicos.

Los resultados de este trabajo, se basan en un modelo que fácilmente puede ser adaptado a otras pesquerías similares de pequeños pelágicos. Siguiendo la misma filosofía, el método se ha aplicado a la pesquería de merluza del Cantábrico, y los resultados serán públicos en breve. Dado que una de las principales limitaciones de este tipo de estudios era la potencia computacional (el modelo del boquerón tarda en resolverse 488 horas en un supercomputador del Centro de Supercomputación de Galicia CESGA), es previsible que en pocos años gracias al aumento de recursos computacionales, veamos cómo nuestra capacidad de predecir el estado de pesquerías complejas (con muchas flotas, muchas clases de edad y falta de información) aumente significativamente. ●

Los resultados de este trabajo, se basan en un modelo que fácilmente puede ser adaptado a otras pesquerías similares de pequeños pelágicos


iptweets

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GlobPartners4Oceans @GPOceans · 3 h
Healthy oceans are of extreme importance to feed 9 billion people.
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SALVAMENTO MARÍTIMO @salvamentogob · 19 de abr.
En la búsqueda del #Marnosso participarán a lo largo del día Salvamar Capella,, helis de Bomberos, Helimer 211y Pesca II, y buque A. Chaves
11 5

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Búsqueda 2 tripulantes #MardeMarin:
Ya están en #Vigo buques de Salvamento Marítimo Don Inda, que incorpora robot ROV, y SAR Gavia
6

Inseparable @InseparableEU · 18 de abr.
Values of extra-EU exports increased by 80% in the last 6 years. bit.ly/EUFishMarketRe...
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Abierta convocatoria para ocho contratos predoctorales de formación para personal investigador goo.gl/twtR7m
Abrir

Biología de la merluza europea y su papel en los modelos de evaluación. RESULTADOS DEL PROYECTO "ECOKNOWS"




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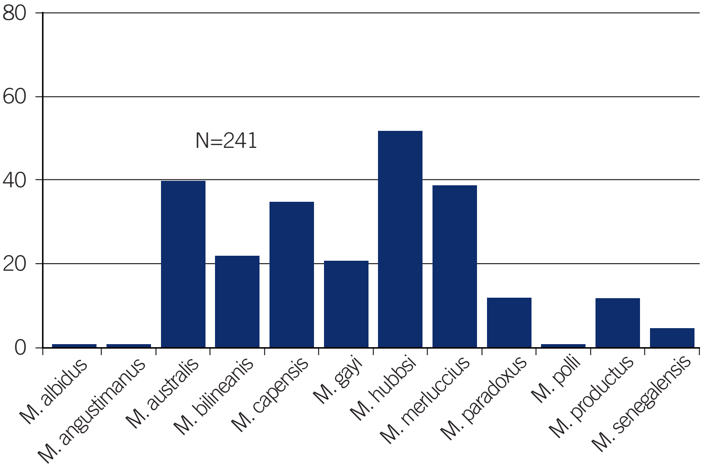
En septiembre de 2011 comenzó el proyecto ECOKNOWS, acrónimo que traducido al castellano significa *Uso efectivo del conocimiento ecosistémico y biológico en pesquerías* (www.ecoknows.eu). Este proyecto está financiado por el VII programa marco de la Unión Europea y tiene por objetivo el desarrollo de métodos que permitan incorporar información biológica al proceso de evaluación reduciendo la incertidumbre de los resultados a través de análisis matemáticos con el fin de mejorar el consejo científico para la gestión de recursos pesqueros. En septiembre de 2012 se presentó el proyecto en esta revista (Catalán et al. 2012). El proyecto está coordinado por la Universidad de Helsinki y participan 13 instituciones científicas de toda Europa. La Universidad de Helsinki era además la responsable del desarrollo de un modelo de evaluación bayesiano y este modelo debía de adaptarse a los distintos casos de estudio. El Instituto Español de Oceanografía coordina del caso de estudio de la merluza, y cuenta con la colaboración del Instituto de Ciencias Marinas de Andalucía (ICMAN), perteneciente al CSIC, para el desarrollo de modelos bayesianos, modelos que se implementaron en el Centro de Supercomputación de Galicia (CESGA).

La idea del caso de estudio surge en un momento en que las dudas sobre el crecimiento de la merluza se confirmaban haciendo que los modelos aplicados en ese momento fueran considerados inadecuados. Mediante experimentos de marcado y recuperación de merluzas se comprobó que la merluza crecía a tasas que duplicaban las que hasta entonces se venían aplicando. Así que inicialmente nos planteamos la realización de distintos estudios biológicos para su posterior implementación en el modelo de evaluación. Llamamos modelos de evaluación a aquellos usados para aconsejar a las administraciones sobre medidas de gestión. Aunque hay una gran variedad de modelos de evaluación, una de sus características es la representación de la evolución histórica de un stock y su explotación pesquera hasta la actualidad. Esto nos permite ver cómo reaccionó este stock en el pasado frente a la actividad pesquera y, bajo ciertos supuestos, prever cómo reaccionará en el futuro frente a distintas opciones de pesca. Esta reacción futura, que en el argot es lo que conocemos como proyecciones, es la base para el consejo científico que

◆**Tabla1** NÚMERO DE REGISTROS DE MERLUZA

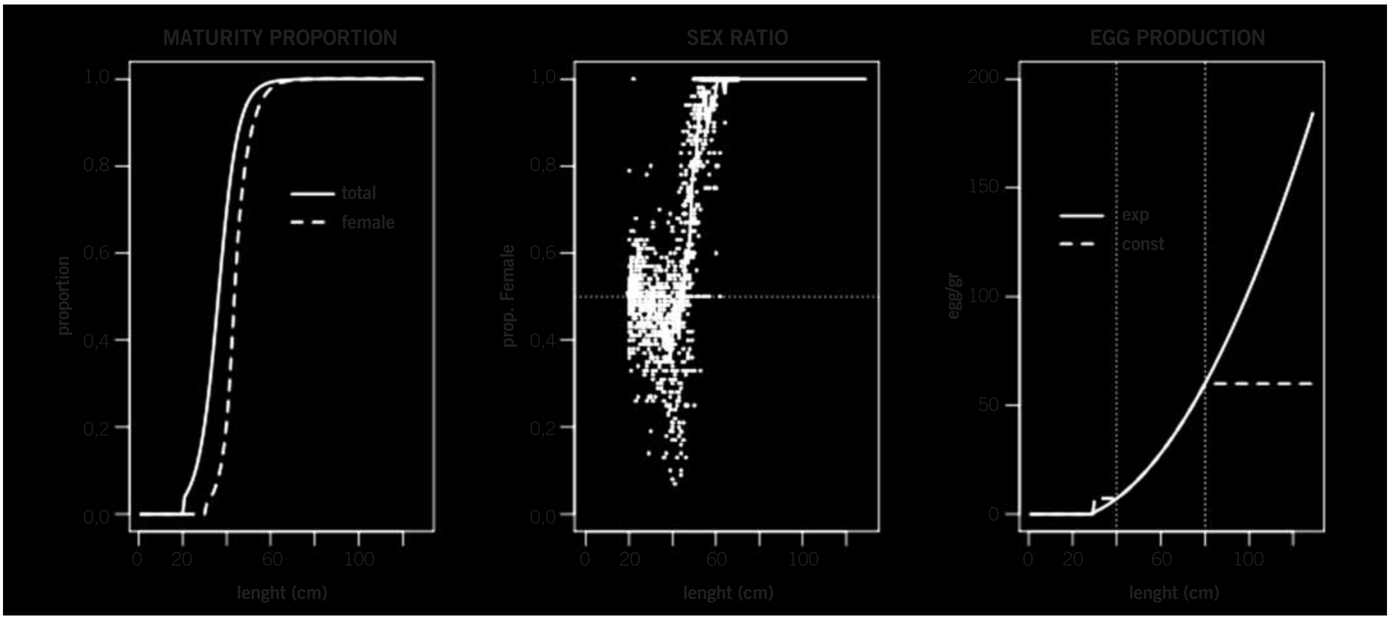


servirá, entre otras cosas, para establecer los TACs y las cuotas del próximo año de un determinado stock. No todos los stocks reaccionan igual a la pesca ya que esto depende de su capacidad productiva. Esta capacidad depende a su vez de las propiedades biológicas de la especie que son fundamentalmente tres: crecimiento, mortalidad natural y reproducción. El crecimiento contribuye positivamente a la producción mediante el aumento en peso de los individuos a lo largo del tiempo; la mortalidad natural contribuye negativamente a la producción debido a la disminución de la abundancia del stock por muerte, principalmente predación, y finalmente la reproducción que contribuye positivamente aportando los nuevos individuos, los reclutamientos. Con la pesca se introduce un cuarto factor: la mortalidad por pesca. Los niveles de pesca que puede soportar un stock dependerá de la manera cómo interactúan los 3 primeros factores entre sí. Así un stock se estabiliza cuando las ganancias debido a los reclutamientos y el crecimiento se equilibran con las pérdidas debido a la mortalidad (natural y por pesca). Puesto que la actividad pesquera actúa sobre las propiedades biológicas existen múltiples puntos de equilibrio. Y puesto que la actividad pesquera es el único de estos factores sobre el que tenemos un control directo, este es el que modificamos para alcanzar un objetivo determinado. Por ejemplo, el rendimiento máximo sostenible (RMS) es uno de estos puntos que se caracteriza por permitir las máximas capturas sin poner en riesgo la sostenibilidad del recurso. La biología de las especies es, por lo tanto, uno de los factores fundamentales para una gestión sostenible.

Durante el proyecto se realizaron tres estudios orientados a mejorar el conocimiento biológico de la merluza. En un primer estudio exploramos el aspecto reproductivo usando información de estudios previos que mostraba que las merluzas más grandes ponen una cantidad de huevos mucho mayor que las más pequeñas. Esta gran diferencia sugiere que implementar medidas de gestión que incrementen el número de individuos grandes en la población aportará dos mejoras: por un lado aumentará el potencial reproductivo de la población y por lo tanto sus garantías de sostenibilidad; por otra parte aumentará la productividad de la población permitiendo unas mayores capturas (Cerviño *et al.* 2013). En un segundo estudio biológico, partiendo del conocimiento de que los machos maduran primero y crecen menos que las hembras tratamos de interpretar el patrón de proporción de sexos por talla. La proporción de sexos es del 50% para los individuos inmaduros, luego, cuando los machos maduran crecen más lentamente aumentando su proporción en la población hasta alcanzar un máximo sobre los 40 cm; sin embargo, este crecimiento más lento hace que apenas alcancen más de 70 cm con lo que a partir de los 40 cm su proporción disminuye y a partir de los 70 cm el 100 % de las merluzas son hembras. La hipótesis de este trabajo era que si la proporción de sexos en

El proyecto busca reducir la incertidumbre de los resultados a través de análisis matemáticos

◆**Tabla2** BIOLOGÍA DE LA MERLUZA



> No todos los stocks reaccionan igual a la pesca ya que esto depende de su capacidad productiva

la población contiene información sobre el crecimiento podríamos usar esa información barata y fácil de adquirir para mejorar nuestra estimación del crecimiento de la merluza (Cerviño, *in press*). El tercer estudio partía de la idea de que ciertas relaciones biológicas son relativamente constantes entre especies similares. Por ejemplo, los individuos inmaduros destinan la energía que adquieren a través del alimento a dos procesos fundamentales: a mantener su metabolismo basal (lo que cada individuo necesita cada día para seguir funcionando) y al crecimiento; sin embargo, cuando un individuo madura comienza a destinar un parte importante de la energía que adquiere a la reproducción, con un coste importante para el crecimiento. Así, las poblaciones o especies que maduran antes, también alcanzan un menor tamaño. De un modo similar también se observa que los individuos que crecen más rápido también mueren con una tasa mayor. La reproducción, el crecimiento y la mortalidad están relacionados siguiendo un patrón que es más parecido entre especies similares. Con esta idea recopilamos información de estudios de merluza de todo el mundo. Existen 12 especies de merluza repartidas por todos los mares del planeta y conseguimos recuperar 241 estudios con información biológica relacionada **(Tabla1)**. Usamos estos estudios para obtener distintos valores para estas relaciones biológicas y, dado que tenemos buena información de madurez de la merluza europea, combinamos ambas fuentes para obtener estimaciones de crecimiento y mortalidad para la merluza europea (Cerviño y Michaelis, 2014).

Paralelamente a los estudios biológicos se desarrolló un modelo de evaluación bayesiano. Las ventajas de los modelos bayesianos son su facilidad para manejar la incertidumbre y para implementar conocimiento "a priori" como el que acabamos de describir. Por otra parte una de las principales dificultades de los modelos bayesianos era su alta necesidad de computación. El hecho de que no pudiéramos diseñar el modelo por edades debido al problema del crecimiento nos obligó a estructurarlo por tallas, aumentando considerablemente el problema de la computación. Otra dificultad añadida fue la pérdida de nuestro experto bayesiano al año de empezar el proyecto. Encontrar un sustituto nos llevo mucho tiempo y hubo que empezar de cero con mucho tiempo perdido. Cuando conseguimos arrancar la primera versión del modelo, que aun no tenía la parte biológica implementada, nos

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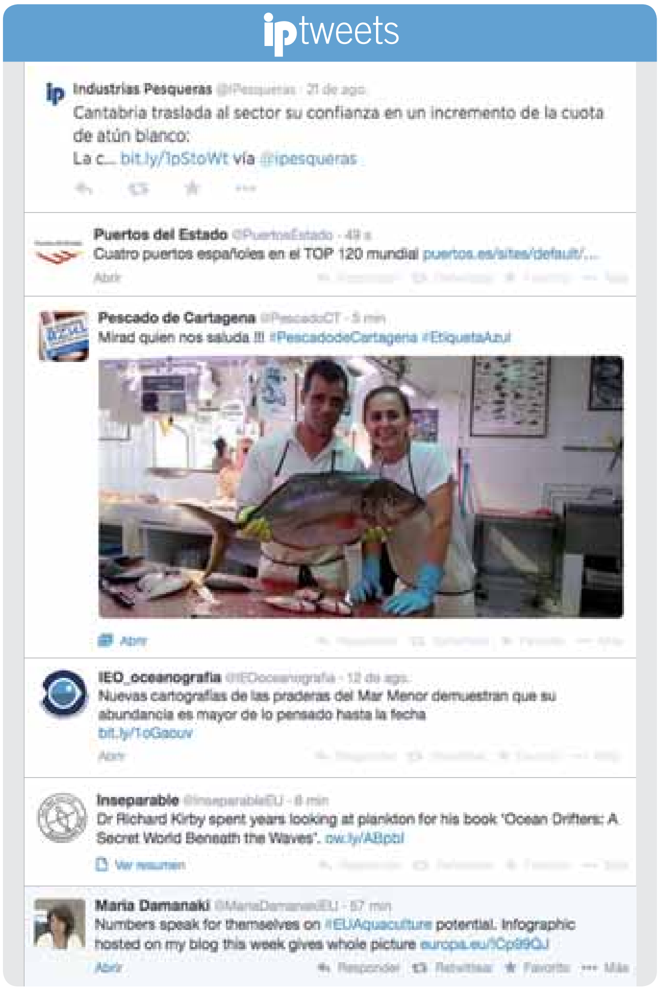
encontramos con que se necesitaba casi un mes en el ordenador. Gracias a la ayuda del Centro de Supercomputación de Galicia (CESGA) conseguimos implementar los modelos en sus ordenadores de una manera más rápida y comenzamos a tratar de simplificar el modelo para hacerlo manejable (Rincón *et al*., 2013). Aun así este proceso fue muy lento debido al tiempo de computación y a día de hoy aún no está totalmente finalizado. Pero, de todas formas, hemos conseguido reducir el tiempo de computación a menos de 10 días y hemos comenzado a implementar la parte biológica. Sin embargo, los proyectos de investigación tienen sus plazos y MareFrame finaliza el 31 de agosto de 2014, así que es el momento de hacer el balance final del proyecto.

En resumen, en lo que respecta a la merluza hemos aprovechado muchos estudios realizados durante los últimos años para hacer una síntesis biológica que aporta importantes novedades al conocimiento actual de la biología de la merluza europea que nos permitirán en un futuro cercano hacer mejorar la evaluación del recurso. También hemos aprendido que la tecnología actual no está aún a la altura para permitir el desarrollo de modelos de evaluación bayesianos complejos, pero a la velocidad a la que aumenta el poder de computación de los ordenadores es muy posible que si lo esté en un plazo relativamente corto. Aunque el proyecto haya acabado, nosotros no renunciamos a la idea y seguimos trabajando sobre ella. ●



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Process modelling and uncertainty estimation in fishery resources dynamics: Analysis using Bayesian techniques

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Granada, 2015