SCRS/2002/088 Col. Vol. Sci. Pap. ICCAT, 55(3): 1055-1079 (2003)

A SCENARIO BASED FRAMEWORK FOR THE STOCK ASSESSMENT OF NORTH ATLANTIC BLUEFIN TUNA TAKING INTO ACCOUNT TRANS-ATLANTIC MOVEMENT, STOCK MIXING AND MULTIPLE FLEETS*

P. Apostolaki[1], E. A. Babcock[2] and M. K. McAllister[1]

SUMMARY

The assessment of North Atlantic bluefin tuna has been based on the assumption that two separate populations of bluefin tuna exist in the North Atlantic, one on the west and another on the east part of the Atlantic (including the Mediterranean Sea), and that the mixing of the two populations is limited. Management measures have been adopted on the basis that the management regime imposed in the western Atlantic does not affect the population of bluefin tuna in the eastern Atlantic and vice versa. Recent tagging data suggest that the migratory patterns of fish from the two populations are much more complex and extensive than it was previously believed. If the degree of mixing of the two stocks is greater than the 1-2% which is currently assumed, then the recovery of the depleted western stock might not be possible under the existing management regime. A multi-area, fleet-disaggregated, age-structured population dynamics model is used to test this hypothesis and evaluate the effectiveness of existing and alternative management measures under different mixing scenarios. The model simulates the dynamics of the two bluefin tuna stocks in the North Atlantic and of the fisheries that target them and explicitly models the trans-Atlantic migration of the fish.

RÉSUMÉ

L'évaluation sur le thon rouge de l'Atlantique nord s'est fondée sur l'hypothèse selon laquelle deux populations distinctes de thon rouge existent dans l'Atlantique nord, une à l'ouest et l'autre à l'est de l'Atlantique (mer Méditerranée comprise), et que le mélange des deux populations est limité. Des mesures de gestion ont été adoptées étant entendu que le régime de gestion imposé dans l'Atlantique ouest n'affecterait pas la population de thon rouge dans l'Atlantique est et vice-versa. Les récentes données de marquage suggèrent que les schémas migratoires des poissons des deux populations sont bien plus complexes et étendus qu'on ne l'avait cru auparavant. Si le degré de mélange des deux stocks est supérieur à 1-2%, ce qui constitue l'hypothèse actuelle, le rétablissement du stock décimé de l'ouest risque alors de ne pas être possible en vertu du régime de gestion existant. Un modèle dynamique de population structuré par âge, par flottille individualisée et à zones multiples est utilisé pour tester cette hypothèse et évaluer l'efficacité des mesures de gestion existantes et alternatives selon différents scénarios de mélange. Le modèle simule la dynamique des deux stocks de thon rouge dans l'Atlantique nord et des pêcheries qui les ciblent et modélise explicitement la migration transatlantique du poisson.

RESUMEN

Las Jornadas de Trabajo ICCAT de septiembre de 2001 sobre mezcla de atún rojo identificaron una estructura espacial (el estrato seis en la figura 3 del informe de dicha reunión) como punto de partida para el desarrollo del modelo preliminar encaminado a la incorporación de un mayor realismo biológico en futuras evaluaciones. Se aplica un enfoque de modelo de producción agregado por edad simple con mezcla entre estratos (superposición) para

---

[*] This document presents preliminary results. Please contact the authors for information on updated versions of the model and further results

[1] Renewable Resources Assessment Group, Department of Environmental Science and Technology, Imperial College, Royal School of Mines
Building, Prince Consort Road, London SW7 2BP UK. +44 (0) 207 594 9330 fax +44 (0) 207 589 5319

[2] Wildlife Conservation Society, Marine Conservation Program, 2300 Southern Blvd., Bronx, NY 10460. +1 718 741 8212. fax +1 718 364 4275

proporcionar una visión de las implicaciones de los diferentes historiales de capturas en el estrato seis que se ha definido. Se consideraron nueve escenarios, para diferentes valores de merma de 1998 en el Atlántico oeste (estrato 1-3) y este (estrato 4-6), oscilando cada uno entre 0,2 y 0,4. Los resultados para estos escenarios sugieren que con o sin mezcla, los niveles de captura de atún rojo de 1997 en el Atlántico oeste son sostenibles, sin embargo, los del este para 1997 están muy por encima de los niveles sostenibles y necesitan una reducción sustancial. Incluso en niveles relativamente modestos de mezcla, la pesquería del Oeste se verá negativamente afectada a menos que se produzca dicha reducción en el Este. Esta conclusión es robusta en una amplia gama de opciones para la productividad del recurso y se superpone a los valores de los parámetros.

KEYWORDS

Migrations, spawning grounds, age-structured population dynamics model, fishery boundaries, stock mixing, fishery management, tuna fisheries

1. INTRODUCTION

Recent tagging studies show that the mixing of the bluefin tuna from the western and eastern part of the North Atlantic could be much greater than the trivial 1-2% that was originally assumed. If this is so, then the current management approach for North Atlantic bluefin tuna fisheries might not provide effective management and additional measures might be needed to achieve the sustainable exploitation of the population and the recovery of the depleted western stock. Nonetheless, the adoption of additional/alternative management measures depends on the degree of mixing assumed which means that, given the high uncertainty about tuna migratory behaviour, consensus regarding the best management approach can be difficult to achieve.

Here, we utilise population dynamics modelling to test the effectiveness of alternative management regimes under different biological and exploitation scenarios, which are based on previous assessments and published biological data. The population model simulates the dynamics of the two bluefin tuna stocks in the North Atlantic and of the fisheries that target them. It accounts for differences in the biology of the two populations and explicitly models their trans-Atlantic migration.

A brief description of the North Atlantic bluefin tuna fisheries management regime and of the current problems that their management presents is given in the first part of the paper. The problem that this paper focuses on and the framework used to deal with the problem are discussed in the second part of the paper. The last part of the paper comprises the presentation of the results and a discussion of our findings. Advantages and weaknesses of the framework are discussed and some recommendations for its improvement are made.

1.1. Background

North Atlantic bluefin tuna fisheries are currently managed on the basis of two separate stocks of tuna; the western and the eastern stock. A management line placed at 45° W defines the area that each of the two stocks occupies (ICCAT, 1982). In 1982, the existence of separate spawning grounds for the western and eastern Atlantic stocks, the discontinuity in catch in the central Atlantic and an assumed low rate of mixing led the Scientific Committee on Research and Statistics (SCRS) to adopt this boundary and the two stock hypothesis (ICCAT, 2001). Almost two decades later it seems that there is enough evidence to challenge the rationale for using this boundary. Catch data show that the distribution of catch of bluefin tuna in the North Atlantic is much more continuous now than it was in 1982 (ICCAT, 2001). Recent tagging data also show that the rate of trans-Atlantic movement could be up to an order of magnitude greater than the 1-2% that was originally assumed (de la Serna, 2001).

The management implications of this new information could be considerable especially for the western stock. In 2000, the Commission, in the light of the new tagging data, resolved that the effects of bluefin tuna mixing for stock assessment and for the choice of management boundaries should be examined by the SCRS. Bluefin tuna mixing, catch distribution and spawning-site fidelity and the management issues that are associated with them were discussed in the 2001 ICCAT workshop on bluefin mixing (ICCAT, 2001). Taking into account the recent biological, exploitation and tagging data, scientists were requested to re-evaluate the existing management boundaries and examine alternative assessment models that could be used for the stock assessment of tuna. Three short-term options for the management units were suggested in the meeting; a. the *status quo* management units b. a separate management area in the Central Atlantic, and c. one boundary line which is placed further to the east than the *status quo* management boundary (ICCAT, 2001). A more fine-scale division of North Atlantic area for assessment purposes was also considered (Fig. 1). Which of the three management options is preferable with respect to rebuilding western Atlantic bluefin tuna depends on the rate of migration assumed and the potential of each option to achieve the recovery of the western stock given an assumed mixing rate (ICCAT, 2001).

Detailed population models need to be developed to allow scientists to account for the revised spatial management structure (Fig. 1) and evaluate the effectiveness of each of the management options suggested above under different scenarios for fish movement. These models also need to accommodate more biological realism and allow for more spatial and temporal heterogeneity in fisheries and population dynamics (ICCAT, 2001).

2. THE FRAMEWORK

In this section we outline the stock assessment modelling framework that we propose to apply for the evaluation of the effects of different migration scenarios and management measures on predictions of bluefin tuna abundance and yield in the western and eastern Atlantic.

Four different types of migratory behaviour have been observed in tuna tagged in the western part of the North Atlantic: western Atlantic residency without visiting a known spawning ground, western Atlantic residency including a visit to a known spawning ground, trans-Atlantic movement from west to east and back, and trans-Atlantic movement to the east after 1 to 3 years of residency in the west (Block et al. 2001). The eastern population also seems to travel very long distances but some of the mature fish tend to remain in the Mediterranean Sea for long time (De Metrio et al., 2001).

The simulation of such complex migratory behaviour requires a model that will allow for age-dependent movement and will be more detailed than the two-area model. In addition, the spatial and temporal heterogeneity in catches can only be simulated with the aid of a model that uses a fine temporal and spatial scale. This paper presents an alternative approach to stock assessment of North Atlantic bluefin tuna that takes into account the complex dynamics of this species and can be used to investigate the potential of alternative management regimes under different biological and exploitation hypotheses.

In accordance with the suggestions of the SCRS (ICCAT, 2001), we have developed a six-area age-structured model that simulates the dynamics of the two tuna stocks. The six areas that constitute the North Atlantic are the same as those presented in the report of the 2001 ICCAT workshop on bluefin mixing (Fig. 1). The use of a two-stock model allows us to account for differences in the behaviour and biological characteristics between the two stocks. The use of an age-structured model allows for differences in the biology and exploitation among fish of different ages to be considered. Movement of fish is explicitly modelled and the temporal and spatial heterogeneity in the catch is taken into account. The model also can assign a unique gear selectivity pattern for each different fishery fleet.

We have assumed that only two spawning areas exist, however, the model can be extended to include a third spawning area, e.g., if tagging and other studies suggest that a spawning ground exists in the central Atlantic (Lutcavage and Luckhurst, 2001). Currently, only indirect use of the information of tagging studies is made in the selection of the values of the coefficients that describe fish movement. However, a future version of the model will incorporate statistical analysis of tagged fish.

The use of a detailed model requires additional information such as catch by area and time period, selectivity per gear and movement rates of fish per age, area and time. Some of this information is not yet available or is characterised by considerable uncertainty and therefore, assumptions need to be made. The population dynamics model could be used in conjunction with Bayesian statistics to test the credibility of different movement hypotheses (McAllister and Ianelli, 1997; Punt and Hilborn, 1997) and the implications of different biological and exploitation scenarios. However, the present model is not fit to data.

2.1 Discrete model

We assume that the North Atlantic bluefin tuna population is comprised of two stocks; the western and the eastern, and that North Atlantic is separated into 6 areas (e.g., 1: Gulf of Mexico, 6: Mediterranean Sea), (Fig. 1). Fish from the two stocks are allowed to move to any part of the North Atlantic but have separate spawning grounds. It is supposed that fish from the western stock do not move to the spawning ground of the eastern stock and vice versa. The number of fish is calculated on a quarterly basis so a year consists of four time steps. Fishing is taking place in the middle of each time step and the movement is an instantaneous process that takes place at the beginning of each time-step. If the number of fish, $N_{s,r,a,t}$, of age a and stock s, in area r, at the beginning of time step, t, after movement has occurred is known, the number of fish in the middle of the time step, will be:

$$(1) \qquad N_{s,r,a+\frac{\delta}{2},t+\frac{\delta}{2}} = N_{s,r,a,t} \cdot e^{-M_{s,a}/2} - \sum_{g=1}^{g_{\max}} C_{s,r,a,t,g} \, ,$$

where δ is the duration of the time step (3 months), $C_{s,r,a,t,g}$ denotes number of fish from stock, s, which were caught with gear, g, in area, r, and $M_{s,a}$ is the natural mortality rate at age by stock per time step (see also Table 1 for parameter symbols).

Although, in reality, fisheries which use different gears operate simultaneously in each area, the model assumes that fishing using different gears is a successive process such that, at any given time fish are caught with only one gear (Punt and Walter, 1998). This is a simplification and is used to make easier the calculation of the number of fish caught in each fishery. Thus,

$$(2) \qquad C_{s,r,a,t,g} = (N_{s,r,a,t} \cdot e^{-M_{s,a}/2} - \sum_{g'=1}^{g-1} C_{s,r,a,t,g'}) \cdot v_{a+\frac{\delta}{2},s,g,t} \, u_{g,r,t} \, ,$$

where $v_{a,s,g,t}$ denotes fish vulnerability to gear g at age a, and $u_{g,r,t}$ is the exploitation rate per gear, g, in area r, at time, t. The results when the above formula is used approach the values we get when fishing is modelled as a continuous process as the time step becomes smaller.

The exploitable biomass available for each gear in each area is calculated after half of the catches that correspond to the gear of interest have been removed from the population:

$$(3) \quad B^{\exp l}_{s,r,t,g} = \sum_{a=a_{rec}}^{a_{\max}} (N_{s,r,a,t} \cdot e^{-M_{s,a}/2} - \sum_{g'=1}^{g-1} C_{s,r,a,t,g'} - \frac{C_{s,r,a,t,g}}{2}) \cdot v_{a+\frac{\delta}{2},s,g,t} \cdot w_{s,a+\frac{\delta}{2}}$$

The biomass of fish caught per unit of effort is calculated by multiplying the above expression by the catchability, $q_{t,g}$. The weight (w) of fish is calculated as a function of length while the length of fish at age, a, is:

$$(4) \qquad L_{s,a} = L_{s,\infty}(1 - e^{k_s \cdot (a - t_{s,0})}),$$

where $L_{s,\infty}$, k_s and $t_{s,0}$ are constants for each stock.

The number of fish in each area at time $t+\delta$ will be:

$$(5) \quad N_{s,r,a+\delta,t+\delta} = \sum_{r'=1}^{r_{\max}} (N_{s,r',a+\frac{\delta}{2},t+\frac{\delta}{2}} \cdot e^{-M_{s,a}/2}) T_{s,a+\delta,t+\delta,r',r} \cdot$$

$T_{s,a,t,r',r}$ is a matrix with the percentage of fish in area r' at time t that move to area, r, at time $t + \delta$ and remain there for at least one time step. The values of $T_{s,a,t,r',r}$ are different for each stock and season and for fish of different age. If the probability that a fish moves from one area to an adjacent one, $P^{s}_{r,r_{adj},a,t}$, (and stay in it or move to another one) can be specified, the values of $T_{s,a,t,r',r}$ will be calculated in the way shown in Table 2. We assume that movement from area 3 through area 4 to area 5 and vice versa do not occur in one time step. Also, it is assumed that fish from the western stock do not move to the Mediterranean Sea while fish from the eastern stock do not move to the Gulf of Mexico.

If the time step, t, corresponds to the spawning period, the population of each stock is divided to two parts, the spawners and non-spawners. The dynamics of the two parts are governed by equations which are similar to those above but the calculations are taking place in two steps. The time step is divided into two and it is assumed that half of the spawners spawn in the first half of the time step while the rest of the spawners remain outside the spawning area and move to it only at the beginning of the second half of the time step to spawn. In this way, we seek to simulate a continues process in a more precise way and also take into account the fact that some spawners are caught in areas other than their spawning ground before they spawn.

In the first step of the calculations, the number of spawners and non-spawners is calculated at the beginning of the spawning period after movement has taken place. It is assumed that some of the spawners move to the spawning area at the beginning of the spawning period and the rest of the spawners move to the area in the middle of the period. The spawners which occupied the spawning ground during the first part of the spawning period move out of the area in the middle of the season. Thus, movement of spawners to the spawning ground takes place in two stages; at the beginning of the spawning season and in the middle of the season after half of the catches have been taken. Non-spawners stay in the area that they occupied at the beginning of the spawning period. Spawners from the western stock move to the Gulf of Mexico to spawn while spawners from the eastern stock move to the Mediterranean Sea.

The number of fish that move to each area is calculated as described above. However, the values of the transport coefficients that are used for the group of spawners are different from the values that are used for the non-spawners group; the former values depend on the assumptions used regarding the proportion and spatial distribution of mature fish that spawn each year. The number of fish in each group (spawners, non-spawners) is calculated in the middle of the time step when half of the total catches have been taken. The spawner biomass for the first half of the spawning period is calculated as the mean of the spawning biomass in the spawning area at the beginning of the spawning period and in the middle of the same period. Therefore, the number of fish which spawn is smaller than the number of spawners that moved to the spawning area since some of them are caught before they spawn.

In the second step, the rest of the spawners that occupy areas other than the spawning areas are assumed to move to the spawning areas while those in the spawning areas move to other areas. Thus, in the second step of the calculation, we calculate the number of fish in each area after the middle period movement of spawners has taken place and the second half of the catch that corresponds to each area has also been taken. The spawning biomass for the second half of the spawning period is calculated as the mean of the biomass of spawners that enter the spawning area in the middle of the spawning season and the biomass of spawners at the end of the spawning period. The formulas used for the calculations are described below:

First step:

The number of fish that do not spawn at time t is:

$$(6) \qquad N^{non-sp}_{s,r,a,t} = \sum_{r'=1}^{r_{\max}} (N_{s,r',a-\frac{\delta}{2},t-\frac{\delta}{2}} \cdot e^{-M_{s,a-\delta}/2}) \cdot (1-\vartheta_{s,t} \cdot \Omega_{s,a}) \cdot T_{s,a,t,r',r},$$

while the number of spawners at the beginning of the spawning season in each area will be:

$$(7) \qquad N^{sp}_{s,r,a,t} = \sum_{r'=1}^{r_{\max}} (N_{s,r',a-\frac{\delta}{2},t-\frac{\delta}{2}} \cdot e^{-M_{s,a-\delta}/2}) \cdot \vartheta_{s,t} \cdot \Omega_{s,a} \cdot T^{sp}_{s,a,t,r',r}.$$

$\vartheta_{s,t}$ is the proportion of mature fish from each stock that spawn at time, t, and $\Omega_{s,a}$ is the proportion of fish at age a that are mature. When the ages a_{50} and a_{95}, at which 50% and 95% of the fish are mature, respectively, are known the proportion of mature fish at age a is calculated as follows:

$$(8) \qquad \Omega_{s,a} = \frac{1}{1+\exp(-k_m(a-a_{s,50}))}, \qquad k_m = \frac{\ln(19)}{a_{s,95}-a_{s,50}}$$

The number of fish caught is calculated as above assuming that only half of the total catches are taken during the first half of the spawning season:

$$(9) \qquad C^{(1)}_{s,r,a,t,g} = [(N^{non-sp}_{s,r,a,t} + N^{sp}_{s,r,a,t}) \cdot e^{-M_{s,a}/2} - \sum_{g'=1}^{g-1} \frac{C_{s,r,a,t,g'}}{2}] \cdot v_{a+\frac{\delta}{2},s,g,t} \, u^{(1)}{}_{g,r,t}$$

The number of spawners and non-spawners in each area after half of the catches have been taken is:

$$(10) \qquad N^{non-sp,(1)}_{s,r,a+\frac{\delta}{2},t+\frac{\delta}{2}} = N^{non-sp}_{s,r,a,t} \cdot e^{-M_{s,a}/2} - \frac{N^{non-sp}_{s,r,a,t}}{N^{non-sp}_{s,r,a,t} + N^{sp}_{s,r,a,t}} \sum_{g=1}^{g_{\max}} C^{(1)}_{s,r,a,t,g}$$

$$N^{sp,(1)}_{s,r,a+\frac{\delta}{2},t+\frac{\delta}{2}} = N^{sp}_{s,r,a,t} \cdot e^{-M_{s,a}/2} - \frac{N^{sp}_{s,r,a,t}}{N^{non-sp}_{s,r,a,t} + N^{sp}_{s,r,a,t}} \sum_{g=1}^{g_{\max}} C^{(1)}_{s,r,a,t,g} \tag{11}$$

In the second step spawners that were not in the spawning areas during the first half of the spawning season move to the spawning areas while spawners that are already in the spawning areas move out of them:

$$N^{sp,(2)}_{s,r,a+\frac{\delta}{2},t+\frac{\delta}{2}} = \sum_{r'=1}^{r_{\max}} N^{sp,(1)}_{s,r',a+\frac{\delta}{2},t+\frac{\delta}{2}} \cdot T^{sp}_{s,a+\frac{\delta}{2},t+\frac{\delta}{2},r',r} \tag{12}$$

The catch per age for each stock in each area for the second half of the spawning season will be:

$$C^{(2)}_{s,r,a,t,g} = [(N^{non-sp,(1)}_{s,r,a+\frac{\delta}{2},t+\frac{\delta}{2}} + N^{sp,(2)}_{s,r,a+\frac{\delta}{2},t+\frac{\delta}{2}}) - \sum_{g'=1}^{g-1} \frac{C_{s,r,a,t,g'}}{2}] \cdot v_{a+\frac{\delta}{2},s,g,t}\, u^{(2)}_{g,r,t} \tag{13}$$

and the number of spawners and non-spawners in each area after the second half of the catches has been taken will be:

$$N^{non-sp}_{s,r,a+\frac{\delta}{2},t+\frac{\delta}{2}} = N^{non-sp,(1)}_{s,r,a+\frac{\delta}{2},t+\frac{\delta}{2}} - \frac{N^{non-sp,(1)}_{s,r,a+\frac{\delta}{2},t+\frac{\delta}{2}}}{N^{non-sp,(1)}_{s,r,a+\frac{\delta}{2},t+\frac{\delta}{2}} + N^{sp,(2)}_{s,r,a+\frac{\delta}{2},t+\frac{\delta}{2}}} \sum_{g=1}^{g_{\max}} C^{(2)}_{s,r,a,t,g} \tag{14}$$

$$N^{sp}_{s,r,a+\frac{\delta}{2},t+\frac{\delta}{2}} = N^{nsp,(2)}_{s,r,a+\frac{\delta}{2},t+\frac{\delta}{2}} - \frac{N^{sp,(2)}_{s,r,a+\frac{\delta}{2},t+\frac{\delta}{2}}}{N^{non-sp,(1)}_{s,r,a+\frac{\delta}{2},t+\frac{\delta}{2}} + N^{sp,(2)}_{s,r,a+\frac{\delta}{2},t+\frac{\delta}{2}}} \sum_{g=1}^{g_{\max}} C^{(2)}_{s,r,a,t,g} \tag{15}$$

The biomass of fish that spawn in each of the spawning areas at time t is calculated as the product of the total number of spawners in the spawning area (r=1 and s=1 for the western stock and r=6 and s=2 for the eastern stock) times the corresponding weight, $w_{s,a}$:

$$B^{sp}_{s,t} = \sum_{a=1}^{a_{\max}} \left(\frac{N^{sp}_{s,r,a,t} + N^{sp,(1)}_{s,r,a+\frac{\delta}{2},t+\frac{\delta}{2}}}{2} + \frac{N^{sp,(2)}_{s,r,a+\frac{\delta}{2},t+\frac{\delta}{2}} + N^{sp}_{s,r,a+\frac{\delta}{2},t+\frac{\delta}{2}} \cdot e^{-M_{s,a}/2}}{2} \right) \cdot w_{s,a+\frac{\delta}{2}} \tag{16}$$

The Beverton-Holt stock recruitment function (Beverton and Holt, 1957) relates the biomass of spawners (only the females are used in the calculations) to the number of recruits at time t:

(17) $$R_{s,t} = \frac{B^{sp}_{s,t-t_{rc}}}{\alpha + \beta \cdot B^{sp}_{s,t-t_{rc}}},$$

where t_{rc} is equal to the age at recruitment and α and β are constants that can be calculated if the virgin spawning biomass (females only), B_o, and recruitment, R_o, are known:

(18) $$\alpha = B_o^{sp} \cdot \frac{(1-h)}{4 \cdot h \cdot R_o}$$

(19) $$\beta = \frac{(5 \cdot h - 1)}{4 \cdot h \cdot R_o},$$

where h is the steepness of the stock-recruit relationship and is equal to the fraction of the recruits under virgin conditions, R_o (the recruitment corresponding to B_o^{sp}), that are expected when the spawning biomass is reduced to 20% of B_o^{sp}. It has been assumed that originally, recruits occupy the spawning area and the areas adjacent to it, but then are allowed to move to other area as well. The model allows the use of the hockey stick stock-recruit relationship (Barrowman and Myers, 2000) as an alternative to the Beverton –Holt one.

If R_o is known then the number of fish at age, under virgin conditions, is calculated as:

(20) $$N^{vg}_{s,a} = \begin{cases} R_o & a = a_{rec} \\ N^{vg}_{s,a-\delta} \cdot e^{-M_{s,a-\delta}} & a_{rec} + \delta \le a \le a_{\max} - \delta \\ \dfrac{N^{vg}_{s,a_{\max}-\delta} \cdot e^{-M_{s,a_{\max}-\delta}}}{1 - e^{-M_{s,a_{\max}}}} & a = a_{\max} \end{cases}$$

The above equation assumes that all fish of each stock occupy a single area. The spatial distribution of fish under virgin conditions, $N^{vg}_{s,r,a}$, can be calculated using the transport coefficients described above.

The population in the earliest year when catch data exist, y_1, is assumed to be a fraction of the virgin population:

(21) $$N_{s,r,a,y_1} = \phi_{s,r,a} \cdot N^{vg}_{s,r,a},$$

where $\varphi_{s,r,a}$ takes values between 0 and 1.

2.2 Values of the $P^s_{r,r_{adj},a,t}$

The movement rate of fish depends on fish age. Older fish travel much more than young fish and it is more likely that they will exhibit trans-Atlantic movement. For this reason the movement of the western stock toward the east and of the eastern stock toward the west will be described with the aid of a sigmoid function. The values of $P^s_{r,r_{adj},a,t}$ for the combination of areas, that correspond to such movement, for a given age *a* and time *t* will be:

$$P^s_{r,r_{adj},a,t} = \frac{\lambda_{r,t}}{1+e^{-\rho(a-a_{mat})}}, \tag{22}$$

where $\lambda_{r,t}$ is a constant and is equal to the maximum value of $P^s_{r,r_{adj},a,t}$ for each *r* and *t* and ρ is a constant that changes the rate at which the maximum of the equation is reached (Fig. 2). A fish from the western stock is more likely to move from area 2 to 3 than from area 3 to 4 so λ could take its greatest value (for a given *t*) for $r=1$ and its lowest for r=5/4. The opposite is true for fish from the eastern stock. All mature fish from the western stock move out of area 1 but mature fish from the eastern stock could remain in the Mediterranean Sea after the spawning season. Thus, the value of λ has been chosen equal to 1 for area 1 but the corresponding value of λ for the eastern stock (area 6) will be less than 1. The values of $P^s_{r,r_{adj},a,t}$ for combinations of *r* and r_{adj} that describe movement of the western stock back to the west part of North Atlantic and of the eastern stock back to the east part of the North Atlantic must be chosen such that fish could stay in areas other than their spawning ground for more than a year.

2.3 Assumptions regarding fish spatial distribution

Four movement scenarios were considered. They were:

- West stock occupies the western part of Atlantic and the east stock occupies the eastern part; limited mixing occurs (movement scenario 1).

- Fish from the west stock move to the central part of the North Atlantic but few fish from the east stock move to the central part. Two cases were examined:
  a. Fish from the west stock move to the central part of the North Atlantic (area 3) and a similar number of fish from the east stock also move to this area (movement scenario 2). Thus, the two stocks equally sustain the fishery in area 3. Fish from the east stock do not move to area 2.
  b. A much smaller number of fish from the east stock moves to area 3 so the fishery in this area is mainly sustained by the fish from the west stock (movement scenario 3).

- The probability to move to the central part of the North Atlantic is the same for the two stocks. Some fish from the east stock could cross the 45° W line and some fish from the west stock could move further east crossing the 30° W line. One case examined:
  a. The central part of the North Atlantic is mainly occupied by fish from the east stock and some of the eastern fish also move to the western part of Atlantic (movement scenario 4).

2.4.Input parameters and assumptions

The values of the input parameters used for the calculations are shown in Table 3. These values were intended to accurately reflect current knowledge about bluefin tuna biology and fisheries, except for the virgin biomass level. Virgin biomass level was assumed to be much higher than the value estimated in the 1998, so that the population would not go extinct in any of the scenarios considered. Thus, the results should not be considered to reflect the actual status of the stock; however, the qualitative differences between the movement and management scenarios, and between the eastern and western stocks would not be affected by this scale parameter.

Seven gears were used for the calculations the selectivity of which is shown in Figure 3. The fisheries that were assumed to operate in each area are longline and other for area 1, purse seine, rod and reel, longline and other for area 2, Japanese longline for area 3, purse seine, Japanese longline, and other for area 4, baitboat, purse seine, longline, trap and other for area 5, and purse seine, trap, Japanese longline and other for area 6. The first year of the calculations is 1950 and the final year is the latest year for which catch data were available for both the eastern and western stocks (1997). The population is assumed to be at its virgin state at the beginning of 1950. The ratio of female to male fish in the population is taken to be equal to 1 and therefore, the biomass of female spawners which is used for the calculation of recruits is half of the biomass which is given by equation 16.

Historical catches east and west of 45° were taken from ICCAT (1998) and ICCAT (2001). The assumption we used to split the data from catches per year to catches per quarter was that the proportion of the catch in an area that are taken in each quarter was equal to the fraction of the population that occupied the area each quarter. Four different assumptions were used for the catch in the future; status quo, 50% increase in catches in area 1 and 2, 50% in catches in area 1 and 2 and catch in area 3 at the 1996 levels (~3.5 times the status quo) and no fishing in areas 1 and 2. Three other hypothesis were also examined when no mixing of the population occurred; 20% increase in the catch in all areas, decrease in the catch in area 5 and 6 from purse seine fishery (smaller fish) or the same level of decrease in catches from traps (larger fish). We also examined the recovering rate of the two stocks by setting all the catches equal to 0.

3. RESULTS

The distribution of fish of two different ages (1 and 15 year old) under virgin conditions, for each of the movement scenarios, are shown in figure 4-7. The fish are assumed to move to areas 2, 3 and 4 (feeding grounds) during spring and summer and return to areas 1, 2 and 5 in winter. Mainly older fish are allowed to move to area 3 at specific periods of each year but return to their spawning ground to spawn. Under the movement scenario 1 (Fig. 4) the fish that move to area 3 are from the eastern stock, while the fish that occupy area 3 are from both populations under the other three movement scenarios (Figs. 5-7). Generally, young fish tend to stay close to their nursery grounds while older fish can also be found in areas that are further away from their spawning ground. As shown in the figures, the movement pattern of older fish differs considerably from the movement pattern of young fish, under these assumptions.

The number of fish in each age class in 1950 and 1997 and the depletion of fish of different ages, for both stocks, are shown in Figure 8. For the western stock, the depletion of the population of old fish is much greater than the depletion in the part of the population that consists of young fish. The depletion of the population of fish from the eastern stock varies less with age which is due to the fact that the fisheries that exploit the eastern stock target fish from almost all age classes while the fishery in the western part of the Atlantic mainly targets older fish.

The effects of fishing on the population size depend on the assumptions about fish mixing that we use (Figure 9). The population of the western stock is less depleted when fish from the eastern stock can move to area 2 (scenario 4) while the depletion of the eastern stock is less affected by the assumptions for stock mixing. The depletion of the spawning stock biomass (SSB) was always greater than the depletion in the total number of fish for both stocks, because the fishery affects older fish more than younger fish.

The total number of fish and SSB in 2015 under each assumption for the catches in the future are presented in Table 4. The depletion of the population in numbers is much less than the depletion of the population in biomass of mature fish, and the magnitude of the change in population between 1997 and 2015 is less in numbers than in mature fish biomass for the same reason. As with depletion, the future trend of the eastern stock is largely unaffected by the movement scenario assumed, because the eastern stock is much larger than the western stock and the catches in areas 3 and 2 are small relative to the size of the eastern stock. Therefore, an increase in the catches that are taken from the eastern stock which would be equal to the catches in area 3 or 2 could only cause very small changes in the size of the population of the stock. Even under the scenario with movement of eastern fish to area 2 (scenario 4), an increase in the catch in area 2 by 50% has almost no effect on the size of the population of the eastern stock. Reducing the catches of the eastern stock in areas 5 and 6 slowed the decline, but it did not matter whether the reduction was in small fish catch (purse seines) or large fish catch (traps).

The population trend in the western stock is sensitive to the movement scenario assumed. The western population is more sensitive to changes in the catch in area 3 when western fish are assumed to dominate area 3 (scenario 3). The status of the western stock is better when fish from the eastern stock can move to area 2 (scenario 4) since part of the catches in the west are sustained by fish from the eastern stock. This could lead to overestimation of the ability of the western stock to sustain catches if fish from the eastern stock move to area 2 but the mixing of the population has not been taken into account in the estimation of the stock status.

The calculations were repeated using age independent movement rates and the values we got for both the total number of fish and SSB were different from the predictions of the model when age-dependent movement rates were used. The predictions of the model for the number of fish and SSB in 2015 that we found when age-independent movement rates were used were between 4% and 13 % greater than the values predicted otherwise.

4. DISCUSSION

The results of our calculations show that the assumptions used about the level of mixing of the two stocks could affect considerably the predictions of the model regarding the current status and prospects for rebuilding the western stock. Catches in the mid-Atlantic can reduce the potential from rebuilding if the mid-Atlantic area is dominated by western fish, but have little effect if eastern and western fish are present in the mid-Atlantic. If many eastern fish are present in the western Atlantic, the western fishery can sustain a higher catch. However, a stock assessment that does not account for this movement could over-estimate the potential for rebuilding the western stock by limiting catches in the west while the eastern stock continues to decline.

The assumptions about the age at which movement occurs strongly influence the results. In addition, the non-uniform selectivity of the gears that are used for the fishing of tuna affects the level of depletion that characterises fish in different age groups. Therefore, it is important to take into account the changes in gear selectivity when the status of the population is assessed. Furthermore, the movement pattern of fish of different ages needs also to be considered since it could affect the predictions for the depletion of the population in each age group.

We considered only a few of the movement scenarios that are plausible with current tagging and other data about migration. Scenarios that include more movement of western stock into the east might have very different implications for the rebuilding of the western stock. Also, this model was not fit to data. Fitting the model to the CPUE, catch and tagging data by age might allow estimating the relative plausibility of various movement scenarios. A scenario based assessment strategy could also be used, in which the eastern and western stocks are assessed under several plausible movement scenarios, and the results are presented in a decision table.

ACKNOWLEDGEMENT

We would like to thank Dr. JM Fromentin for the information he provided about bluefin tuna biology. This work was supported by the David and Lucile Packard foundation. E. Babcock's work was supported by the Constantine S. Niarchos Fellowship in Marine Conservation.

REFERENCES

BARROWMAN, N. J. and R. A. Myers. 2000. Still more spawner-recruitment curves: the hockey stick and its generalizations. Can. J. Fish. Aquat. Sci. 57; pp. 665-676

BEVERTON, R. J. and S. J. Holt. 1957. On the dynamics of exploited fish populations. Her Majesty's Stationary Office, London.

BLOCK, B. A., Dewar, H., Blackwell, S. B., Williams, T. D., Prince, E. D., Farwell, C. J., Boustany, A., Teo, S. L. H., Seitz, A., Walli, A., and Fudge, D. 2001. Migratory Movements, Depth Preferences, and Thermal Biology of Atlantic Bluefin Tuna. *Science* **293**; pp. 1310-1314

COOKE, J. G. and Lankester, K. 1996. Examination of alternative stock distribution models for the interpretation of blufin tuna (Thunnus thynnus) tag-recovery data. ICCAT Coll. Vol. Cci. Pap. **45**(2); pp. 135-138 (SCRS/95/080)

DE LA SERNA, J. M., 2001. Research activities caried out in the Eastern Atlantic and the Mediterranean applicable to the study of stock structure, migratory patterns and bluefin tuna mixing rate. ICCAT working document SCRS/01/77

DE METRIO, G. Arnold, G. P., Block, B., de la Serna, J. M., Deflorio, M., Cataldo, M., Yannopoulos, C., Megalofonou, P., Beemer, S., Farwell, C. and Seitz, A. 2001. Behaviour of post-spawning Atlantic bluefin tuna tagged with pop-up satellite tags in the Mediterranean and Eastern Atlantic. ICCAT working document SCRS/01/78

HESTER, F., 2001. Atlantic bluefi tuna: Some considerations on mixing on the feeding grounds. ICCAT working document SCRS/01/59

ICCAT, 2001. Report of the ICCAT workshop on bluefin mixing. ICCAT working document SCRS/01/020. 36pp

ICCAT, 2000. Report of the ICCAT SCRS west Atlantic bluefin tuna stock assessment session. ICCAT working document SCRS/00/24

ICCAT, 1998. Report of the ICCAT SCRS bluefin tuna stock assessment session. ICCAT working document SCRS/98/22

ICCAT, 1994. Report for the biennial period 1992-1993. Part II (1993). 395 pp.

ICCAT, 1982. Recommendations by Panel 2 on bluefin management measures. ICCAT Report, for biennial period, 1980-81, Part II (1982), Vol.1.

LEGAULT, C. M., and Restrepo V. R. 1998. A flexible forward age-structured assessment program. ICCAT working document SCRS/98/58

LUTCAVAGE, M., and Luckhurst, B., 2001. Consensus document: Workshop on the biology of bluefin tuna in the mid-Atlantic 5-7 May 2000, Hamilton, Bermuda. Col. Vol. Sci. Pap. ICCAT, **52**; pp. 803-808

MABNUSON, J. J., Safina, C., and Sissenwine, M.P., 2001. Whose fish are they anyway? Science **293**; pp. 1267-68

MCALLISTER, M. K. and Ianelli, J. N. 1997. “Bayesian stock assessment using catch-age data and the sampling-importance resampling algorithm.” Canadian Journal of Fisheries and Aquatic Science **54**(2); pp. 284-300.

NEMERSON, D., Berkeley, S. and Safina C. 2000. Spawning site fidelity in Atlantic bluefin tuna, *Thunnus thynnus*: the use of size-frequency analysis to test for the presence of migrant east Atlantic bluefin tuna on Gulf of Mexico spawning grounds. Fish Bull. 98; pp. 118-126

NRC. 1994. Report of the National Research Council review of Atlantic bluefin tuna. National Academy Press. Washington, D. C. 148 pp.

ORTIZ DE ZARATE, V. and Rodriguez_Cabello, C. 1999. Bluefin baitboat fishery statistics in the Cantarian sea in 1998. ICCAT working document SCRS/99/114

ORTIZ DE ZARATE, V. and Rodriguez-Cabello C. 1999. Bluefin baitboat fishery statistics in the Cantabrian Sea in 1998. ICCAT working document SCRS/99/114

PORCH, C. E., Turner, S. C. and Powers J. E. 2001. Virtual population analysis of Atlantic bluefin tuna with alternative models of transatlantic migration: 1970-1997. Col. Vol. Sci. Pap. ICCAT **52**; pp. 1022-1045

PUNT, A. E. and T. I. Walker. 1998. Stock assessment and risk analysis for the school shark (*Galeorhinus galeus*) off southern Australia. Mar. Freshwater Res. 49; pp. 719-31

PUNT, A. E. and Hilborn, R., 1997. Fisheries stock assessment and decision analysis: the bayesian approach. Rev. of Fish Biol. And Fisheries 7; pp. 35-63

RAVIER, C. and Fromentin, J.M. 2001. Long-term fluctuations in the eastern Atlantic and Mediterranean bluefin tuna population. ICES Journal of Marine Science 58; pp.1299-1317

RAVIER, C, and Fromentin JM., 2001. Long-term fluctuations in the eastern Atlantic and Mediterranean bluefin tuna population. ICES journal of marine Science 58; pp. 1299-1317

Table 1. List of parameters

Symbol	Parameter
a	age
a_{max}	maximum age
a_{50}	50% of the fish at this age are mature
a_{95}	95% of the fish at this age are mature
s	stock
r	area
t	time
h	steepness
t_{rc}	age at recruitment
δ	time step
N	number of fish
$Z^{s}_{r,a,t}$	total mortality
F	fishing mortality
M	natural mortality
f	gear/fleet
v	vulnerability
u	exploitation rate
$T_{s,a,tr,r'}$	percentage of fish in area r' at time t that occupy area r at time t+1
$P^{s}_{r,r_{adj},a,t}$	probability of a fish to move from one area to an adjasted one (regardless of whether it remains in the latter or not)
Ω_a	proportion of fish at age a that are mature
k_m	constant
R	recruitment
R_o	recruitment under virgin conditions
α, β	constants of the Beverton-Holt stock recruitment function
B^{sp}	spawning biomass
B^{sp}_{o}	spawning biomass under virgin conditions
B^{expl}	exploited biomass
C	number of fish caught
w	fish weight
L	length
$\vartheta_{s,t}$	proportion of fish that spawn each year
$\lambda_{r,t}$	the maximum of the sigmoid equation
ρ	rate at which the maximum of the sigmoid equation is reached

Table 2. Calculation of $T_{s,a,t,r',r}$ for each stock and for fish of age, *a*, at time, *t* when probability that a fish moves from one area to an adjacent one, $P^{s}_{r,r_{adj},a,t}$, can be specified. The indeces for age, stock and time have been ommitted since they do not affect the way that $T_{s,a,t,r',r}$ is calculated. Therefore, only the area that fish depart from and the area they move to are shown below

Area r $\bar{r}$	**1**	**2**	**3**	**4**	**5**	**6**
1	$T_{1,1}=$ $1-P_{1,2}$	$T_{1,2}=$ $P_{1,2}(1-P_{2,3})$	$T_{1,3}=P_{1,2}T_{2,3}$	$T_{1,4}=$ $P_{1,2}T_{2,4}$	$T_{1,5}=$ $P_{1,2}T_{2,5}$	$T_{1,6}=0$
2	$P_{2,1}$ (=0, for mature fish unless t: sp. period, s: western stock)	$1-P_{2,1}-P_{2,3}$	$P_{2,3}(1-P_{3,4}-P_{3,5})$	$P_{2,3}P_{3,4}$	$P_{2,3}P_{3,5}(1-P_{5,6})$	$P_{2,3}P_{3,5}P_{5,6}$
3	$P_{3,2}P_{2,1}$	$P_{3,2}(1-P_{2,1})$	$1-P_{3,2}-P_{3,4}-P_{3,5}$	$P_{3,4}$	$P_{3,5}(1-P_{5,6})$	$P_{3,5}P_{5,6}$
4	$P_{4,3}T_{3,1}$	$P_{4,3}T_{3,2}$	$P_{4,3}(1-P_{3,2})$	$1-P_{4,3}-P_{4,5}$	$P_{4,5}(1-P_{5,6})$	$P_{4,5}P_{5,6}$
5	$P_{5,3}T_{3,1}$	$P_{5,3}T_{3,2}$	$P_{5,3}(1-P_{3,2})$	$P_{5,4}$	$1-P_{5,3}-P_{5,4}-P_{5,6}$	$P_{5,6}$
6	0	$P_{6,5}T_{5,2}$	$P_{6,5}T_{5,3}$	$P_{6,5}P_{5,4}$	$P_{6,5}(1-P_{5,4}-P_{5,3})$	$1-P_{6,5}$

Notes about movement:

- $P_{a,b}$ gives the proportion of fish from area *a* that leave the area moving in the direction of area *b* (*b* is an adjacent area)
- Fish that move from area 3 to area 4 are not allowed to move to area 5 at the same time step. Similarly, movement from 5 to 4 and then to 3 does not occur in one time step.
- The direction in which a fish is moving does not change in a time step. For example, a fish that moves from area 4 to 3 cannot end up in area 5 at the end of the time step.

Table 3. Input parameter values and assumptions used in the calculations

Parameter	**Western stock**		**Eastern stock**	
	Value	**Reference**	**Value**	**Reference**
Maximum age	20		20	
Age at maturity (50%)	8	(SCRS/00/24)	4	ICCAT 1998
Age at maturity (95%)	9		5	ICCAT 1998
First age class	2.5 –5.0 months		2.5-5.0 months	
Natural mortality **(y^{-1})**	0.14 , age ≥ 1 y 0.18, 1 y > age ≥ 0.75 y 0.25, 0.75 y > age ≥ 0.5 y 0.49 0.5 y > age ≥ 0.25 y	For age>=1 : ICCAT (2000), SCRS/00/24	0.15, age > 18 y 0.1, 18y ≥ age ≥10 y 0.125, age=9 y 0.15, age=8 y 0.175, age=7 y 0.2, age = 6 y 0.24, 6 > age ≥2 0.49 0.25 y ≤ age≤ 1	For age>=1: ICCAT 1998
Mature fish biomass (virgin cond.)	1.6E8 Kg	[1] ICCAT (2000), SCRS/00/24	1.4E9 Kg	[1] ICCAT 1998
Spawning season	April - June	Nemerson et al 2000	April -June	
% of mature fish that spawn/ year	0.5		0.5	
Length – Age relationship	L_{inf} =382 cm K = 0.079 t_0 = -0.707 y	ICCAT 1998 SCRS/98/22	L_{inf} = 318.85 cm K = 0.093 t_0 = -0.97 y	ICCAT 1998
Weight (Kg) - Length (cm) relationship	a = 0.0000152 b = 3.05305	ICCAT 1998 SCRS/98/22	a = 0.000019607 b =3.0092	JM. Fromentin pers. com.
Males/females ratio	1			
Stock- recruits relat.	Beverton – Holt			
Steepness	0.7		0.7	
Selectivity	See figure 3			
Gears	Purse seine, trap, longline, other, baitboat, Japanese longline, rod and reel			
Movement pattern	See figures 4-7. See figure 2 for the function used to describe the change in the movement rates with age			
Time step	3 months			
First year : 1950, Final year: 1997				

---

[1] A value which was much greater than the value for the spawning biomass in 1970 which was estimated during the last assessment for each stock was used.

Table 4. The % change in the total number of fish and SSB between 1997 and 2015 under different scenarios for future catches. Brackets: the value of the parameter in 2015 as a fraction of the corresponding virgin value.

Assumptions for future catches	**Western stock**		**Eastern stock**	
	Total numbers	**SSB**	**Total numbers**	**SSB**
Movement scenario 1: No trans-Atlantic movement				
Status quo	+9% (0.86)	+27% (0.68)	-21% (0.61)	-45% (0.31)
20 % increase in catches	+6% (0.84)	+20 (0.64)	-37% (0.48)	-65% (0.20)
50 % increase in catch in area 1 and 2	+2% (0.80)	+9 (0.58)	-21% (0.61)	-45% (0.31)
Decrease in catch with traps (area 5 and 6)	+9% (0.86)	+27% (0.68)	-14% (0.65)	-35% (0.37)
Decrease in catch from purse seines (area 6)	+9% (0.86)	+27 (0.68)	-15% (0.64)	-36% (0.36)
No fishing	21% (0.96)	64% (0.87)	25% (0.95)	51% (0.86)
Movement scenario 2: Similar number of fish from both stock in area 3				
Status quo	+9% (0.84)	+29% (0.64)	-20% (0.61)	-45% (0.31)
50% increase in catches in area 1 and 2	+1% (0.77)	+8% (0.53)	-20% (0.61)	-45% (0.31)
50% increase in catch in area1 and 2, catch in area 3 at high 1996 level	-3% (0.74)	-3% (0.48)	-21 (0.60)	-46% (0.31)
No fishing in areas 1 and 2	+22% (0.94)	+68% (0.83)	-20% (0.61)	-45% (0.31)
Movement scenario 3: Area 3 is mainly occupied by fish from the west stock				
Status quo	+10% (0.83)	+31% (0.61)	-20% (0.61)	-45% (0.32)
50% increase in catch in areas 1 and 2	+1% (0.76)	+8% (0.51)	-20% (0.61)	-45% (0.32)
50% increase in catch in area1 and 2, catch in area 3 at high1996 level	-6% (0.71)	-9% (0.43)	-20% (0.61)	-45% (0.32)
No fishing in areas 1 and 2	+24% (0.94)	+73% (0.82)	-20% (0.61)	-45% (0.32)
Movement scenario 4: probability to move to area 3 is the same for both stocks. Fish from the east stock also move to area 2				
Status quo	+6% (0.87)	+19% (0.71)	-20% (0.6)	-45% (0.31)
50% increase in catch in areas 1 and 2	-0.1% (0.82)	+4% (0.62)	-21% (0.60)	-45% (0.31)
50% increase in catch in area1 and 2, catch in area 3 at high 1996 level	-1% (0.81)	+2% (0.61)	-22 (0.59)	-47% (0.30)
No fishing in areas 1 and 2	+17% (0.96)	48% (0.89)	-21% (0.60)	-45% (0.31)

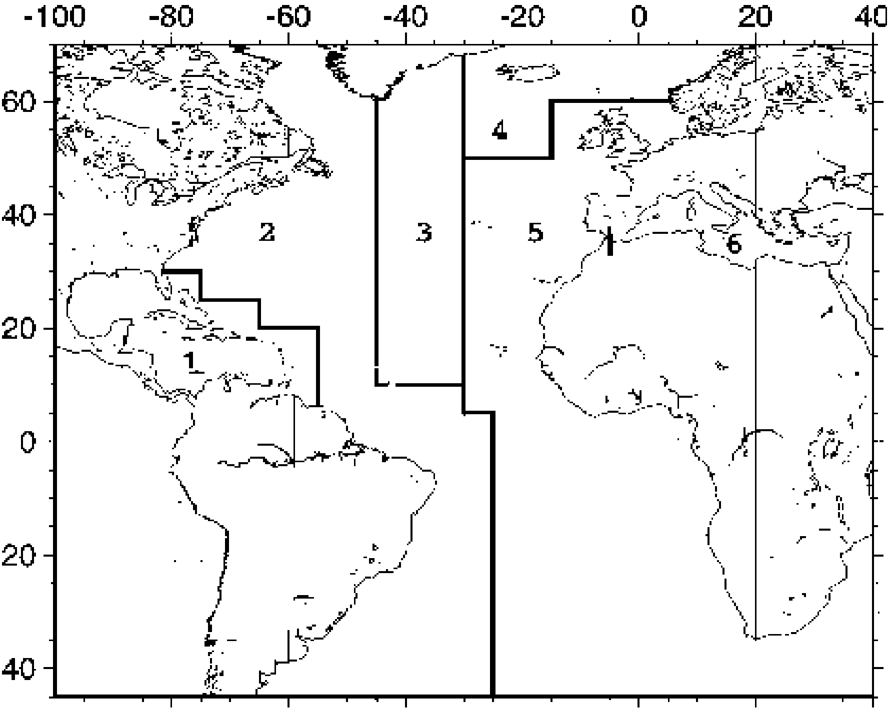


Figure 1. Graphical representation of the areas that are used for the model. (Spatial structure recommended by the scientists that attended the 2001 ICCAT workshop on bluefin tuna mixing. ICCAT, 2001)

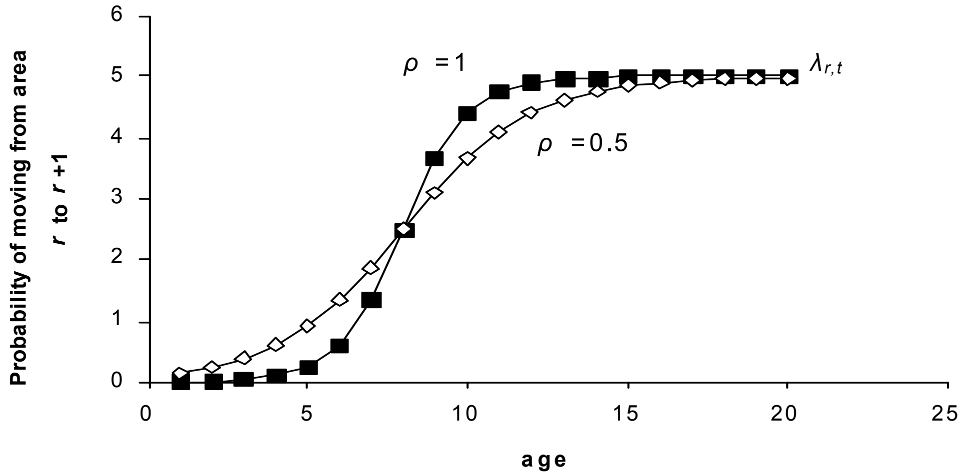


Figure 2. The general form of the function used to describe the relationship between probability of a fish to move from one area to an adjucent one, which is further away from its spawning ground, and fish age. ρ is a constant that changes the rate at which the maximum of the equation ($\lambda_{r,t}$) is reached

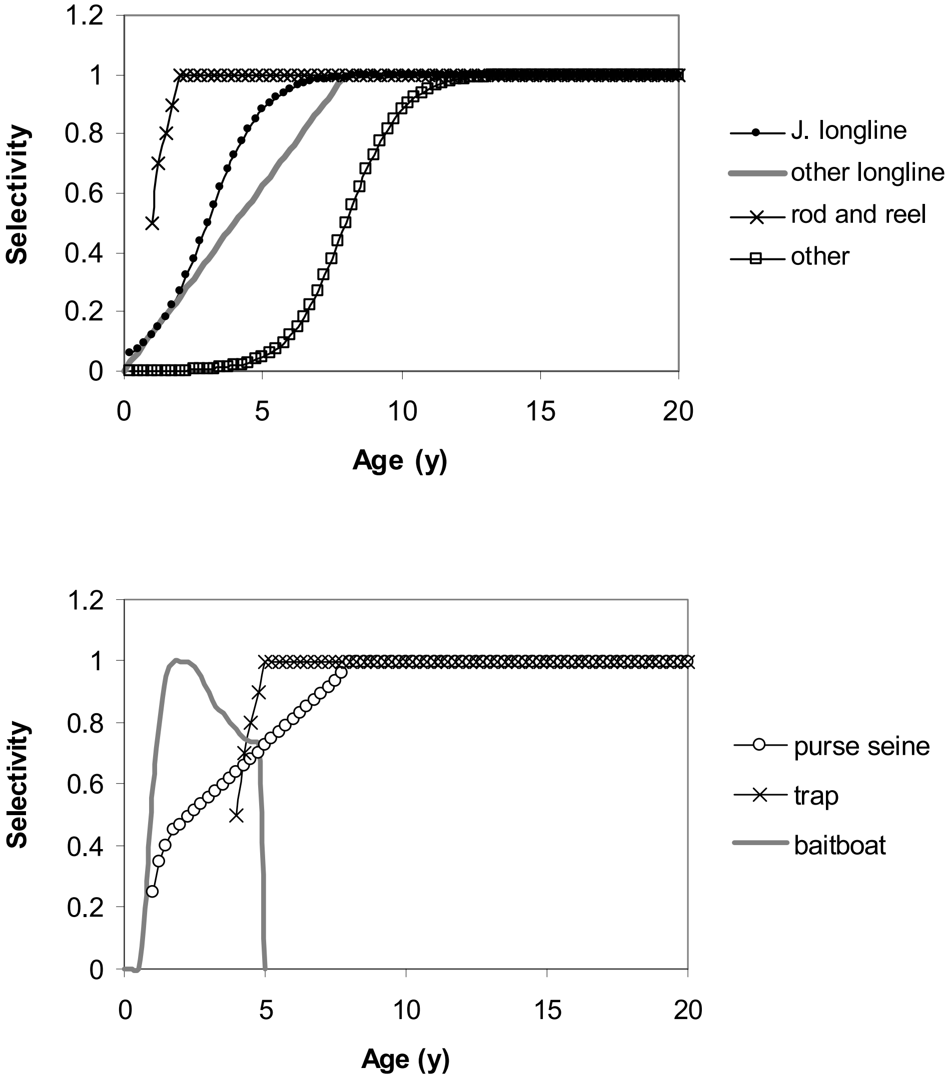


Figure 3. Selectivity for each of the gears used. Selectivity of gears in figure 3a: Legault and Restrepo 1998 (SCRS/98/58), figure 3b: purse seine: Legault and Restrepo 1998 (SCRS/98/58), trap: Ravier and Fromentin, 2001, baitboat: Ortiz de Zarate and Rodriguez-Cabello, 1999.

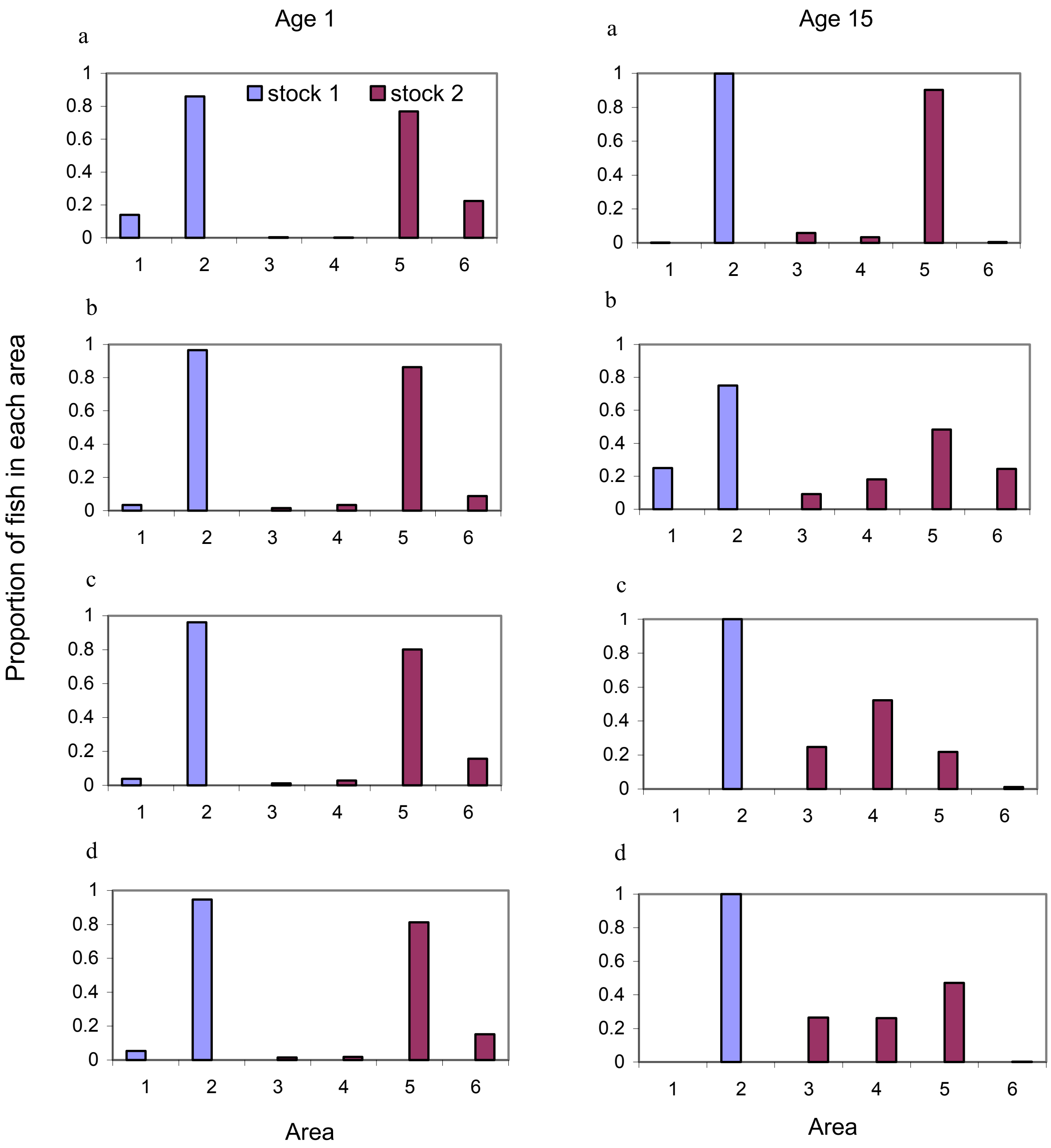


Figure 4 Fish distribution, in each season when there is no mixing of the two stocks (movement scenario 1). a. Jun-March, b. April- June, c. July- Sept., d. Oct. –Dec.

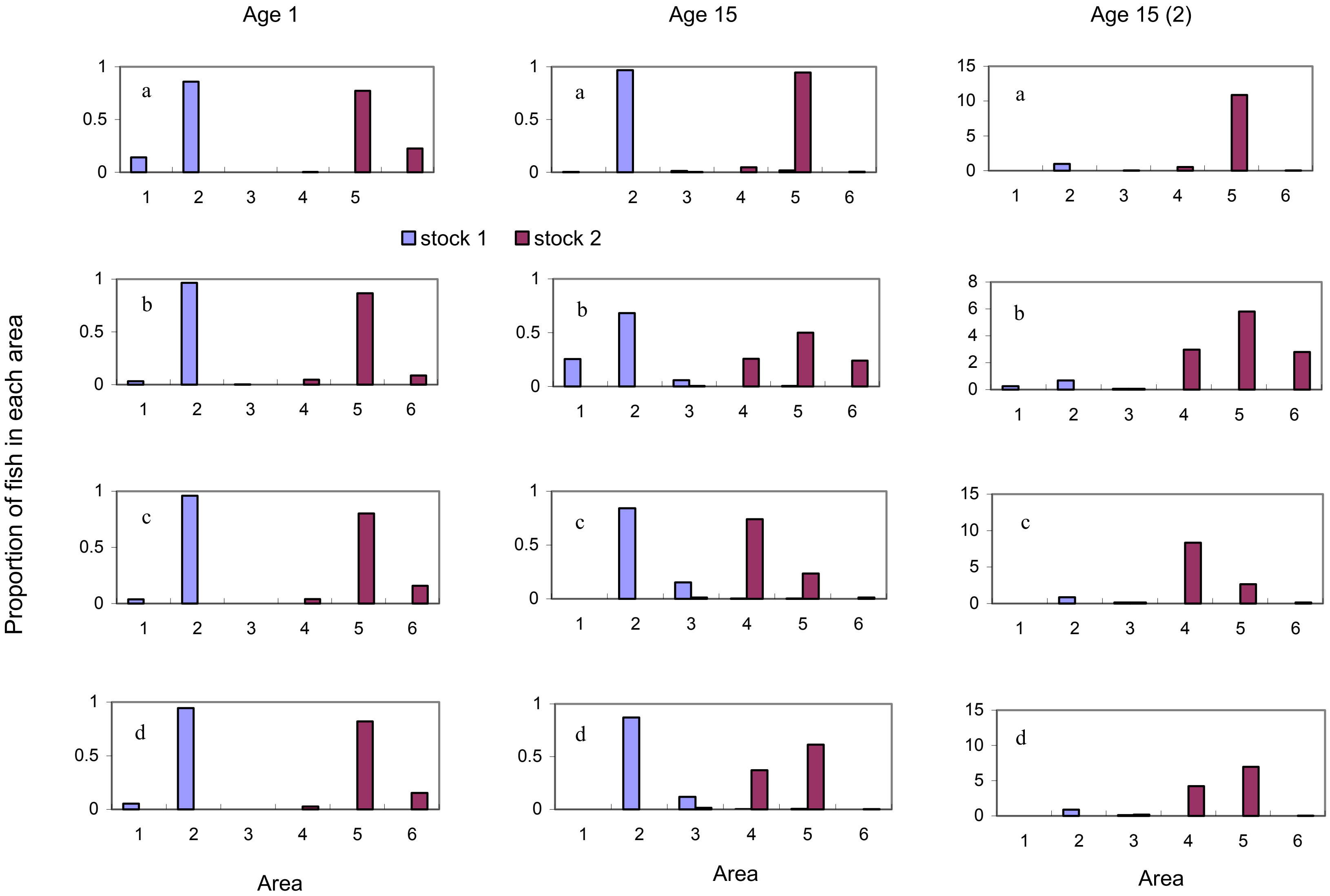


Figure 5 Fish distribution, in each season when there is mixing of the two stocks (movement scenario 2). a. Jun-March, b. April- June, c. July- Sept., d. Oct. -Dec. The third column (15(2)) is the same as the second one but the virgin number of fish of age 15 from the west stock has been used to normalise both the values for the eastern as well as the west stock. Thus, it is easy to notice that the number of fish that move to area 3 from each stock is similar.

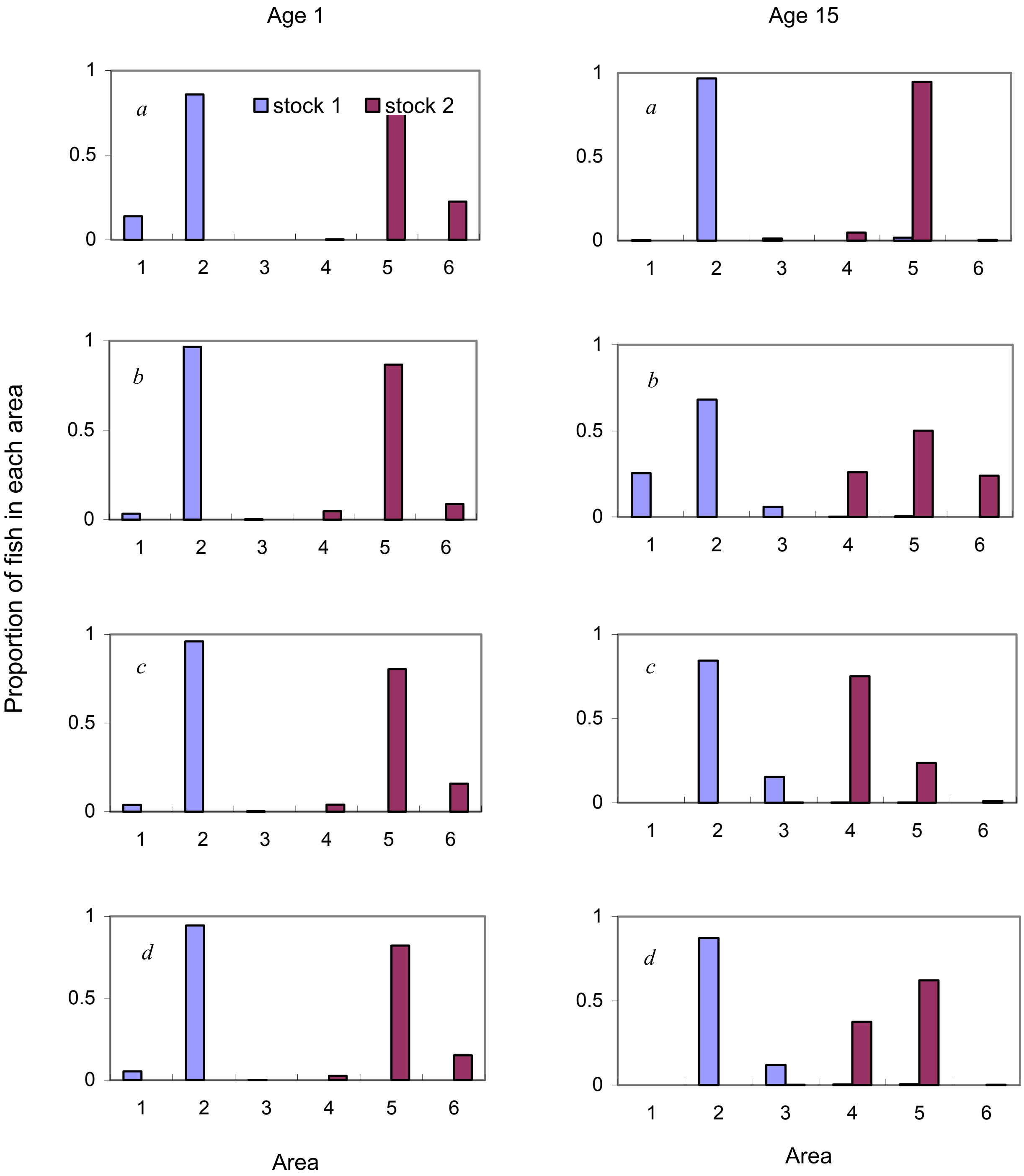


Figure 6. Fish distribution, in each season when there is mixing of the two stocks (movement scenario 3). a. Jun-March, b. April- June, c. July- Sept., d. Oct. –Dec.

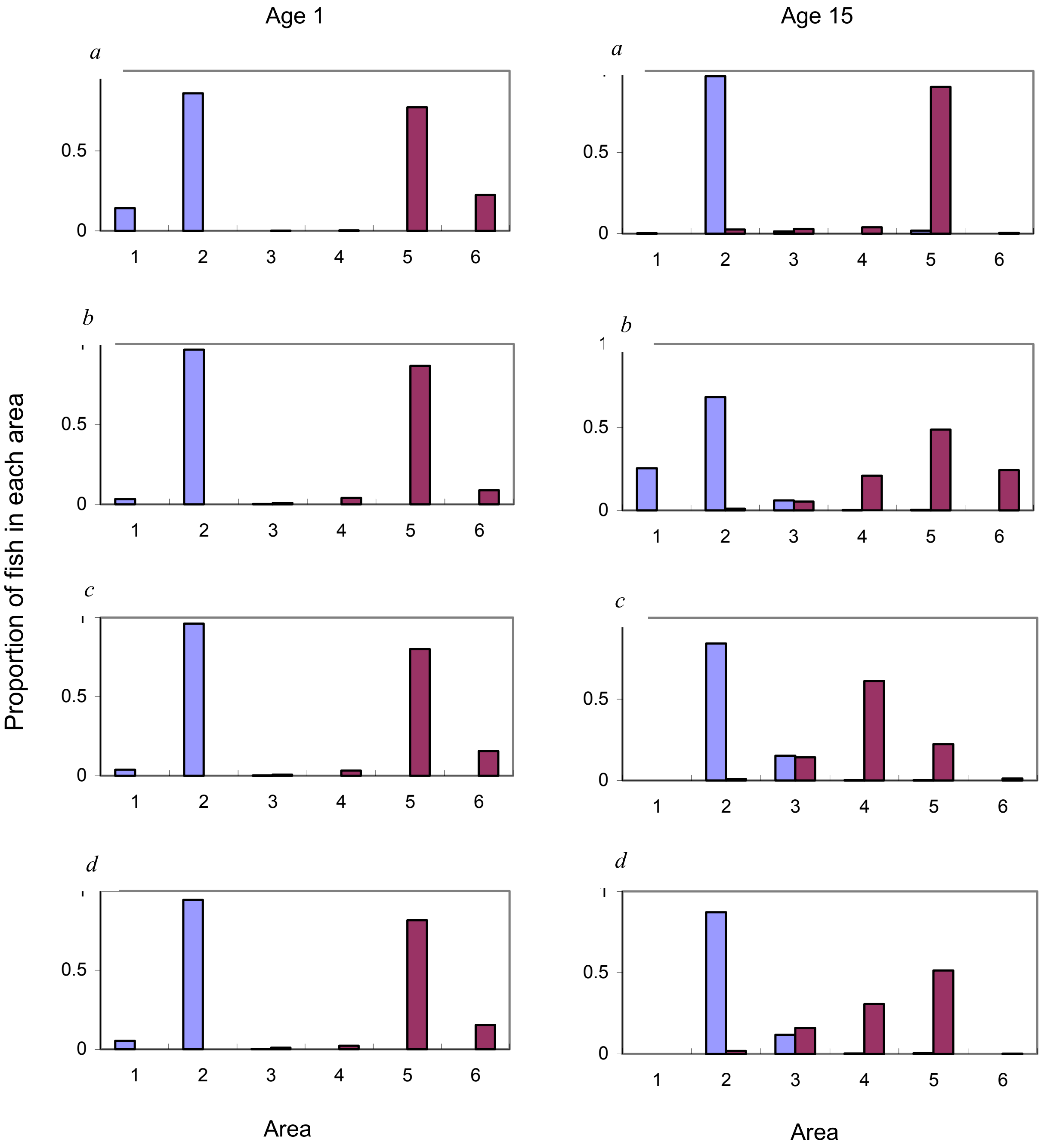
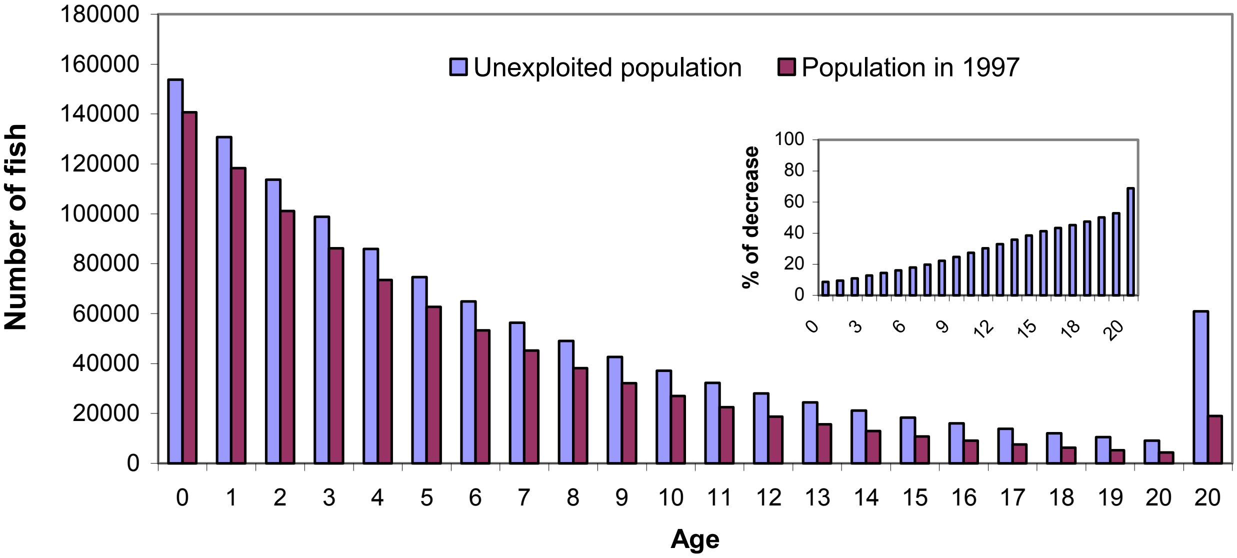


Figure 7. Fish distribution, in each season when there is mixing of the two stocks (movement scenario 4). a. Jun-March, b. April- June, c. July- Sept., d. Oct. –Dec.

a



b

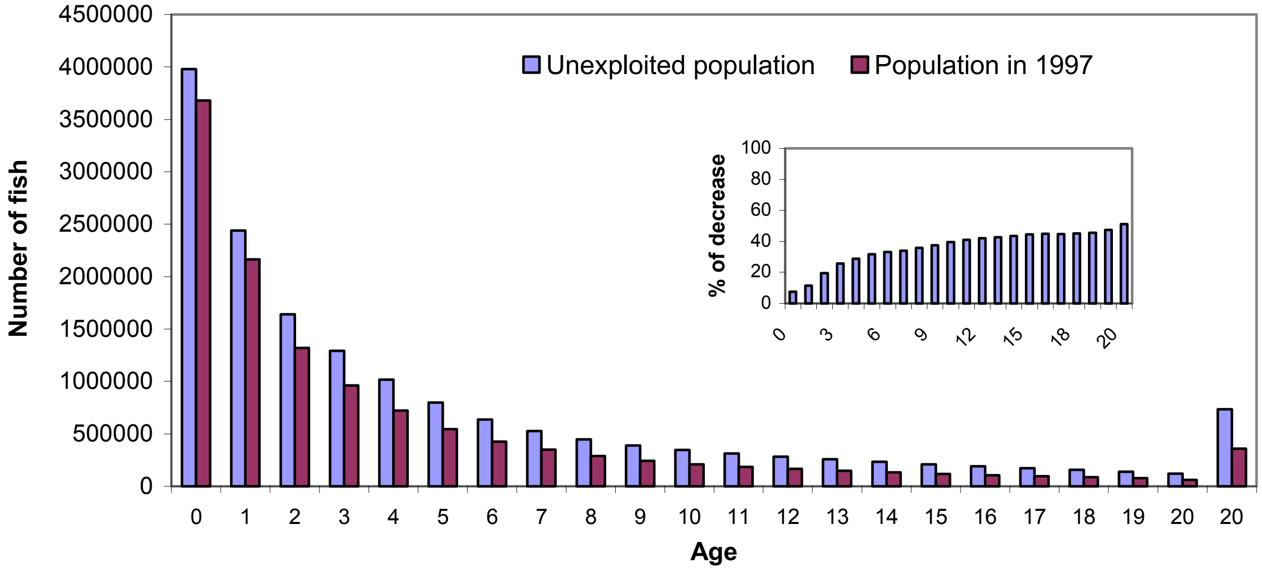


Figure 8. Total number of fish in each age in 1950 and 1997 for the first movement scenario. Inside figure: Depletion of the population in each age. a. western stock , b. eastern stock .

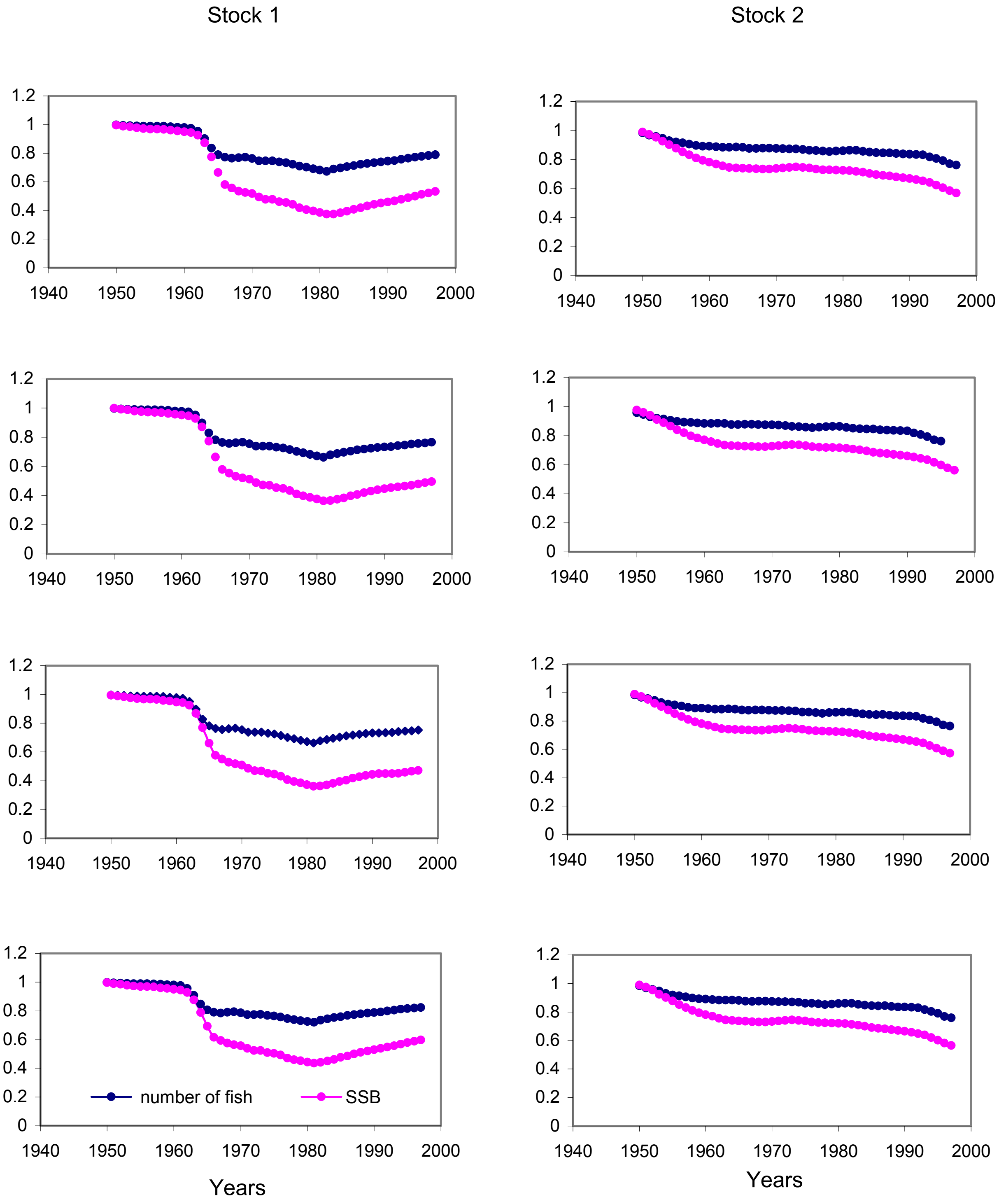


Figure 9. The total number of fish and spawning stock biomass (SSB) as a fraction of the corresponding virgin value for the years from 1950 to 1997. First row: movement scenario 1, Second row: movement scenario 2, Third row: movement scenario 3, Fourth row: movement scenario 4. Stock 1 is the western stock and stock 2 is the eastern stock.