Research paper

A stock assessment model for transit stock fisheries with explicit immigration and emigration dynamics: Application to upstream waves of glass eels

Yu-Jia Lin[a,*], Wang-Nian Tzeng[b,c], Yu-San Han[b], Ruben H. Roa-Ureta[a]

[a] Center of Environment and Water, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia
[b] Institute of Fisheries Science, College of Life Science, National Taiwan University, Taipei 10617, Taiwan
[c] Department of Environmental Biology and Fisheries Science, National Taiwan Ocean University, Keelung 20224, Taiwan

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ABSTRACT

Fisheries for catadromous fish migrating through the fishing grounds are conceptualized as transit stock fisheries, whose local population dynamics is completely controlled by immigration and emigration. We present an extension to generalized depletion models to estimate the abundance and natural mortality rate of transit stock fishes using detailed fishery catch and effort data. We apply the model to 13 annual seasons of the *Anguilla japonica* glass eel fishery in the Shuang River estuary, northeast Taiwan. Estimates of abundance and natural mortality compare well with estimates for other species obtained from experimental studies or from data-rich stock assessment models at similar spatial scales. Parameter estimates are generally robust to biases and imprecision in the fisheries catch and effort data. The size of migration waves arriving at the estuary support a splitting mechanism controlled by eddies during oceanic migration. This extension of generalized depletion model provides a useful tool for the assessment of glass eel fisheries in East Asia, South East Asia, Europe and North America when only fisheries-dependent data are available.

1. Introduction

Fisheries for catadromous fish migrating through the fishing grounds involve thousands of fishermen and substantial economic revenue. The fisheries for juvenile freshwater eels (glass eels) in North America, Europe, the Mediterranean basin, East Africa and South East Asia are the most important in terms of number of fishermen and economic importance (Aranburu et al., 2016: Beaulaton and Brian, 2007; Fenske et al., 2011; Shiraishi and Crook, 2015). From the point of view of stock assessment there is a basic difference between fisheries for demersal and pelagic stocks those for migrating stocks such as glass eel and salmon during upstream migration. The former are fisheries acting on resident stocks inhabiting or moving inside a given area whose exploitation includes several cohorts over the spatial distribution of the stock (King, 2013). In contrast, the latter are fisheries acting on transient stocks that are passing through localized fishing grounds during a specific period of their life history. Thus, we refer to fisheries on passing parts of migrating stocks, 'transit stock fisheries'.

Freshwater eels (genus *Anguilla*) have a complex catadromous life cycle. Adults spawn in the open sea and the leaf-like larvae, leptocephali, are transported passively via major ocean currents toward the continents. They metamorphose to transparent and eel-shaped early juveniles, glass eels, on the continental shelf and become pigmented in the estuaries where they are targeted by fishers. Juvenile eels live and grow in fresh- and saltwater habitats until the start of sexual maturation. Maturing eels migrate to the spawning ground in the sea to spawn, and die after spawning (Tesch, 2003). Three temperate eel species, European eel *Anguilla anguilla*, American eel *A. rostrata* and Japanese eel *A. japonica*, have suffered significant declines in recruitment over the past 30 years (Dekker, 2003a; Dekker and Casselman, 2014). They have been listed as endangered or critically endangered by the International Union for Conservation of Nature (IUCN, Jacoby et al., 2015). Possible causes are climate change (e.g., Kim et al., 2007), habitat loss and deterioration (e.g., Belpaire and Goemans, 2007; Chen et al., 2014), and overfishing (e.g., De Leo and Gatto, 1995; Dekker, 2003b; Lin et al., 2010; Fenske et al., 2011; Tanaka, 2014).

Glass eels are exploited in the estuaries during migration to juvenile habitats as the sole source of eel fries for eel aquaculture, which is the main source of eels for human consumption worldwide (FAO, 2015). *A. japonica* is the most valued species, especially in Japan (Kuroki et al., 2014). Due to its decline in abundance, new fisheries have emerged targeting other anguillid species in both temperate and tropical regions

(Shiraishi and Crook, 2015). Glass eel fisheries may have a large impact on the abundance of glass eels, with the potential to remove nearly all of the stock in specific locations in extreme cases (Tzeng, 1984a; Jessop, 2000a; Briand et al., 2003; Bru et al., 2009; Harrison et al., 2014; Aranburu et al., 2016).

Stock assessment of recruiting waves of glass eels into estuaries has advanced significantly in the 2000 s (Jessop, 2000a; Beaulaton and Briand, 2007; Bru et al., 2009; Fenske et al., 2011; Tanaka, 2014; Aranburu et al., 2016; Drouineau et al., 2016). This progress involves fishery-independent biological data from scientific surveys in addition to data from regular fishing operational data (fishing effort and catch). However, such complementary biological and fishery-independent data may be unavailable in both new and established fisheries for glass eels. Here we adapt generalized depletion models (Roa-Ureta, 2012) to the stock assessment of transit stock fisheries with the general purpose of allowing their management through the exploitation rate and/or escapement abundance when fisheries-dependent catch and effort data are the only available data. Our case study is the fishery for *Anguilla japonica* glass eels in the estuary of Shuang River, northeastern Taiwan.

2. Materials and methods

2.1. Data collection

The glass eel fishery in the Shuang River estuary, northeastern Taiwan, occurs during the northern hemisphere winter season. A questionnaire survey was conducted over 13 fishing seasons, from November 1981 to March 1994. The survey included approximately 70 fishermen who individually operated any of three types of fishing gear: set nets in the entrance of the river, lamp and dip nets in the inner river, and hand trawling nets along the coast nearby the river (Tzeng, 1984a,b; 1985). We simplified the issue of multiple gears by assuming a single fleet (Tzeng, 1985) whose effort was measured in hours of fishing because the common unit of effort of these three fishing methods was the time spent fishing in hours. A single intermediary who purchased 80–100% of the glass eel catch in each season was commissioned to fill out the questionnaire at the time of purchasing. The questionnaire included information on the name of the fisher, fishing date and site, effort in hours, gear type, catch in numbers, water temperature, weather conditions and unit price of the glass eel.

Fishing was usually conducted from October to March and separated by seven to nine months of inactivity. Seasons lasted 105 days on average (standard deviation: 32 days), with a range from 56 to 152 days, and the exerted total fishing effort ranged from a minimum of 200 h in season 1981–1982 to a maximum of 10,000 h in season 1984–1985. The glass eels caught were classified into white and black types, according to the caudal pigmentation patterns (Leander et al., 2012). The white-type glass eels are the target species, *A. japonica*, while the black-type glass eels are composed of three species of little commercial interest (Leander et al., 2012). In this study we focus on the catch of *A. japonica* exclusively. The catch of the *A. japonica* glass eels ranged from around 12,000 individuals in season 1981–1982, to nearly 300,000 in 1989–1990.

2.2. Model development

Generalized depletion models have been described from three different angles in Roa-Ureta (2012, 2015a) and Roa-Ureta et al. (2015). Here we briefly present the reasoning supporting them as they extend to the particulars of the glass eel fishery. The start is the axiom that two necessary conditions for a positive fishing yield C in numbers of fish captured by time step t is that both the fishing effort E and the fish abundance N take positive values at time t. From this it follows that,

$$C_t = f(E, N) = f_E(E_t) f_N(N_t) \qquad (1)$$

such that both f_E and f_N determine a zero catch whenever E and/or N

are zero. The power form for f_E and f_N is consistent with the axiom, and incidentally is equivalent to assuming that catchability (the process underlying f_N) varies with abundance (Roa-Ureta, 2012),

$$C_t = kE_t^{\alpha} N_t^{\beta}. \qquad (2)$$

The parameter k is a scaling constant similar to catchability q in the model CPUE=C/E=qN, α is the effort-response and β is the abundance response. When $\alpha < 1$ the response of catch to effort is saturable, when $\alpha > 1$ effort response is synergistic, and when $\alpha=1$ effort response is proportional (Bannerot and Austin, 1983). Similarly when $\beta < 1$ the response of catch to abundance is hyper-stable, when $\beta > 1$ abundance response is hyper-depleted, and when $\beta=1$ abundance response is proportional (Hilborn and Walters, 1992). In generalized depletion models it is assumed that effort is observed exactly whereas abundance is a latent variable. To make abundance manifest it is expanded with Pope's (1972) recursive equation which introduces two new parameters, initial abundance N_0 (number of glass eels in the fishing grounds before the start of the season) and natural mortality (M):

$$C_t = kE_t^{\alpha} \left(N_0 e^{-Mt} - e^{-M/2} \left(\sum_{i=1}^{i=t-1} C_i e^{-M(t-i-1)} \right) \right)^{\beta} e^{\frac{-M}{2}}. \qquad (3)$$

Note that the exponential term for survivorship up to mid time step is necessary because of the discrete time formulation.

Eq. (3) is a simple depletion model for a closed population with the innovations that effort is a nonlinear predictor (instead of being the standardizing denominator in the standardized response variable, *CPUE*, in the traditional model *CPUE*=qN) and that catchability q varies with abundance, $q=q(N)$. Introducing P additive migration pulses of abundance R_j ($j = 1, …, P$) into the fishing grounds at specific time steps τ_j makes the models appropriate for open populations. At the time step of each migration pulse, the depletion is reset and restarted creating a spike of catch from which the magnitude of the migration pulse can be estimated with the catch data, provided there are enough time steps and not too many migration pulses. Weak migration pulses are more difficult to estimate than stronger ones.

The crucial operational feature in generalized depletion models is the time step. When the time step is daily or weekly there might be many pulses in a single fishing season, driven by the implicit spatial dynamics, which can be of two types: incoming waves of recruits (Roa-Ureta, 2012) or expansion in the area of operation of the fleet (Roa-Ureta et al., 2015). When the time step is monthly there should be one wave per year in a multi-annual time series, representing the annual recruitment event (Roa-Ureta, 2015a; Maynou, 2015).

The extension to account for the transit stock nature of the glass eel fisheries is based on the rapid (daily) time step, many pulses interpretation (Fig. 1). The pulses (R_1 to R_3) are the incoming waves of glass eels occurring during the season. The specific extension is that the incoming waves (immigrants) that entered at time step τ become exiting waves (emigrants) at some later time step υ during the season. Thus the remaining abundance of emigrants from each specific wave needs to be removed from the catch model at a unique specific date. However, this remaining abundance of emigrated waves has to be kept on a separate accounting that decays due to natural mortality only, in order to correctly evaluate total escapement abundance, at season's end. Thus, the population model is split into (1) a vulnerable abundance on the fishing grounds, consisting of the addition of the numbers from all recruitment waves still on the fishing grounds, and (2) an escapement abundance corresponding to the addition of all recruitment waves that have already completed their transit time. These concepts translate into the following generalized depletion model for the true unobserved catch in a transit stock fishery,