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Combining selection models and population structures to inform fisheries management: a case study on hake in the Mediterranean bottom trawl fishery

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A. Identification of high and low recruitment areas

The two sampling areas in Saronikos Gulf (off south Aegina and off south Salamina) were considered as high (HRA) and low recruitment (LRA) areas, respectively. Given that recruits are defined as the youngest fish entering the exploited component of the stock for the first time (GFCM, 2006), meaning the youngest of the juveniles, individuals with size <16 cm were considered as hake recruits.

This hypothesis is supported by biological and fisheries information from the literature. Bartolino *et al.* (2008) found that for hake age group 0, two length aggregations are discriminated by bathymetric distribution; the smaller sized group (<16 cm TL; the true recruits) concentrated in the nursery area over the upper slope (at depths between 170-220 m) and the larger sized group (especially individuals of 18-20 cm; the juveniles that are no longer true recruits) dispersed over the continental shelf (at depths between 70-100 m). Carpentieri *et al*. (2005) observed an important change in the hake trophic habits at 15-16 cm. Lombarte and Popper (1994) found a change in the inner ear of hake, related to the detection of objects and hearing at up to 15 cm TL. Several studies related to hake nurseries in the Mediterranean Sea use the length of 14-15 cm as threshold length for the hake recruits (e.g. Demestre & Sánchez, 1998; Fiorentino *et al*., 2003; Bartolino *et al*., 2008; Colloca *et al*., 2009; Druon *et al.*, 2015). Therefore, comparison and homogeneity purposes can also be mentioned here for the selection of this size. On the other hand, based on selectivity studies, the length at 50% gear selection was estimated at 13.75 and 10.32 cm and the length at 50% fisher selection was estimated at 15.39 and 15.12 cm for both 40S and 50D codends, respectively (Mytilineou *et al*., 2018). That means that individuals about 15 cm have high probability to be retained by the trawl codend and be sold by the fishers. As a result, hake recruits need to be protected since gear selectivity is not a sufficient tool. The case of a trawl prohibition in an area and period of high recruitment (HRA) would indirectly prevent fishers acting illegally, since no recruits will be included in their catches. If larger sized juvenile hake should also be protected, which would be ideal, a larger area and period of prohibition is needed. This is more difficult to achieve with compliance of fishers, and socio-economic issues should also be considered. The increase in the size-at-first capture for a stock, is a measure towards its sustainable exploitation (Armstrong *et al*., 1990). Therefore, any increase in this size as a first step, will be positive, even if the ideal size is not achieved.

The above information indicates that the size class of 15 cm could be considered as a critical size for hake from both a biological and fisheries point of view and therefore well selected as a threshold size to characterise hake recruits.

The estimation of the abundance (number/km^2) of hake recruits to the total number of individuals by sampling area and period, using the above-mentioned size threshold, revealed a very large amount of hake recruits in the area off south Aegina (HRA) during June and September (13411 n/km^2 & 757 n/km^2, respectively) compared to the values found off south Salamina (LRA) (2805 n/km^2 & 53 n/km^2, respectively) (Table S1). Descriptive statistics for the 75% percentile of the sizes in each area and period (Table S1) revealed smaller sizes off south Aegina (14.4 and 17.2 cm, respectively) than off south Salamina (20.5 and 26.2 cm, respectively). Finally, the depth range of each sampling area (off south Aegina: 170-265 m; off south Salamina: 85-100 m) (Table S1) coincided with the findings of Bartolino *et al*. (2008) and Druon *el al*. (2015) for the areas of new recruits occurring on the shelf break. The above information supported the hypothesis that the area off south Aegina is a HRA, whereas that off south Salamina is a LRA.

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Carpentieri, P., Colloca, F., Cardinale M., Belluscio A., Ardizzone, G.D., 2008. Daily ration and feeding activity of juvenile hake in the central Mediterranean Sea. *Journal of the Marine Biological Association of the UK*, 88, 1493-1501.

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Lombarte, A., Popper, A., 1994. Quantitative Analyses of Postembryonic Hair Cell Addition in the Otolithic Endorgans of the Inner Ear of the European Hake, *Merluccius merluccius* (Gadiformes, Teleostei). *The Journal of Comparative Neurology*, 345, 419-428.

Table S1. Mean abundance (n/km^2) of hake new recruits, their proportion to the total number of individuals, 75% percentile of the sizes and depth range by sampling area (HRA/LRA) and time period. HRA: high hake recruitment area, LRA: low hake recruitment area.

Area/Period		**off south Aegina (HRA)**	**off south Salamina (LRA)**
June	mean abundance	13411 n/km^2	757 n/km^2
	proportion	81.07 %	33.06 %
	size 75% percentile	14.4 cm	17.2 cm
	depth range	170-265 m	85-100 m
September	mean abundance	2805 n/km^2	53 n/km^2
	proportion	55.10 %	4.30%
	size 75% percentile	20.5 cm	26.2 cm
	depth range	170-265 m	85-100 m

B. Estimation of the population entering the trawl codend size structure

The estimation of the hake population size structure *pop(l,a,t)* in an area *a* and period *t* over all hauls, based on equation (2) and considering the three compartments sampling design (the escapees, the discards, and the landings) as well as the sub-sampling in each compartment, is as follows:

$$pop(l,a,t) = 100 \times \frac{\sum_{h=1}^{H}\left\{\frac{nco_{hl}}{qco_h}+\frac{nd_{hl}}{qd_h}+\frac{ncm_{hl}}{qcm_h}\right\}}{\sum_{h=1}^{H}\sum_{l}\left\{\frac{nco_{hl}}{qco_h}+\frac{nd_{hl}}{qd_h}+\frac{ncm_{hl}}{qcm_h}\right\}}$$

where nco_{hl}: the number of measured fish in the cover in length class *l*; nd_{hl}: the number of measured fish in the codend in length class *l* being discarded; ncm_{hl}: the number of measured fish in the codend in length class *l* being landed; qco_h, qd_h, and qcm_h: the corresponding length-independent sub-sampling ratios for the cover, discarded and landed compartment in each haul, respectively, and calculated by dividing the weight of each sub-sample by the total weight of the catch of each component. The subscript *h* refers to the specific fishing haul. The summation in *l* is over all length classes in each haul *h* and the summation in *h* is over all hauls *H* of each area *a* during the period *t*. The area *a* here can be HRA or LRA and the time period *t* can be June or September.

Uncertainties (95% Efron confidence intervals; Efron, 1982) of the size structure of the population entering the trawl codend were obtained based on a double bootstrap method both considering the between haul variability in codend entry population structure and the uncertainty in numbers of each size class within each haul and compartment due to a limited number of fish entering the codend in that specific haul and as well the effect of the sub-sampling in each compartment. Specifically, the double bootstrap procedure followed accounts for between haul variability in the hake size-dependent codend entry by selecting hauls *H* with replacement from the number of hauls conducted in the area and the period. The number of hauls selected equaled the total number *H* conducted. The uncertainty in numbers of each size class of hake within each haul resampled was accounted for by within each compartment resampling with replacement of fish length measured followed by raising the numbers according to equation (3) with sub-sampling ratios. The number resampled for each compartment in this inner bootstrap loop equaled the total number of lengths measured in the respective compartment in the selected haul. Bootstrap repetitions (1000 in number) were conducted and used to calculate the Efron 95% (Efron, 1982) confidence limits for the population . The estimation procedure described above was implemented in the software tool SELNET that was used for this analysis (Herrmann *et al*., 2012).

C. Exploitation Indicators in weight

The exploitation indicators in weight for the average percentage of the retained catch below the MCRS (*wP_*), the average discard ratio in weight (*wdRatio*) of individuals below MCRS to the weight of the total catch and the average fisher discards ratio in weight of the discards to the total catch ($wdRatio_f$) were estimated as follows:

$$wP\_(a,t,g) = 100 \times \frac{\sum_{l<MCRL}\{w_l \times pop_{disc}(l,a,t,g) + w_l \times pop_{land}(l,a,t,g)\}}{\sum_{l<MCRL} w_l \times pop(l,a,t)}$$

$$wdRatio(a,t,g) = \frac{\sum_{l<MCRL}\{w_l \times pop_{disc}(l,a,t,g) + w_l \times pop_{land}(l,a,t,g)\}}{\sum_{l}\{w_l \times pop_{disc}(l,a,t,g) + w_l \times pop_{land}(l,a,t,g)\}}$$

$$wdRatio_f(a,t,g) = \frac{\sum_{l}\{w_l \times pop_{disc}(l,a,t,g)\}}{\sum_{l}\{w_l \times pop_{disc}(l,a,t,g) + w_l \times pop_{land}(l,a,t,g)\}}$$

The weight-length relationship of hake in the study area [$w_l = 0.0037652\, l^{3.1912401}$; calculated by IMASFISH (Kavadas *et al*., 2003) based on the DCF data 2014-2016, was used for the estimation of the weight w_l of each length class *l*.

References (not included in the main manuscript)

Kavadas, S., Damalas, D., Georgakarakos, S. Maravelias, C., Tserpes, G. *et al*. 2013. IMAS-Fish: Integrated MAnagement System to support the sustainability of Greek Fisheries resources. A multidisciplinary web-based database management system: implementation, capabilities, utilization and future prospects for fisheries stakeholde. Mediterranean Marine Science, 14 (1), 109-118.

D. Estimating the Exploitation Indicator in value

The indicator for the ratio in value ($vulRatio_f$), indicating the value of the undersized individuals (below MCRS) that are included by the fisher in the landings to the value of landings according to the rules (individuals above MCRS), was estimated as follows:

$$vulRatio_f(a,t,g) = 100 \times \frac{\sum_{l<MCRS}\{v_l \times pop_{land}(l,a,t,g)\}}{\sum_{l>MCRS}\{v_l \times pop_{land}(l,a,t,g)\}}$$

where v_l is the economic value of each length class given by the weight of this length class (according to the length-weight relationship mentioned above) and the value of hake by market category in euro/kg. The sorting of hake landings by market category has been done by the crew on board and the average annual economic value of each market category (euro/kg) for hake was reported according to the fisher's considerations. Since there is an overlap in the lower and upper sizes between market categories, a rough estimation of the size range of each category was based on the 95% percentile of the sizes for each category, used as the maximum size of this category or the minimum size of the next one. The derived size groups and their economic value are given in Table S2.

Table S2. Average market values of hake (Euro/kg) for each market category.

Category	Size (cm)	Value (euro/kg)
C	< 23	5
B	24- 35	8
A	>35	12

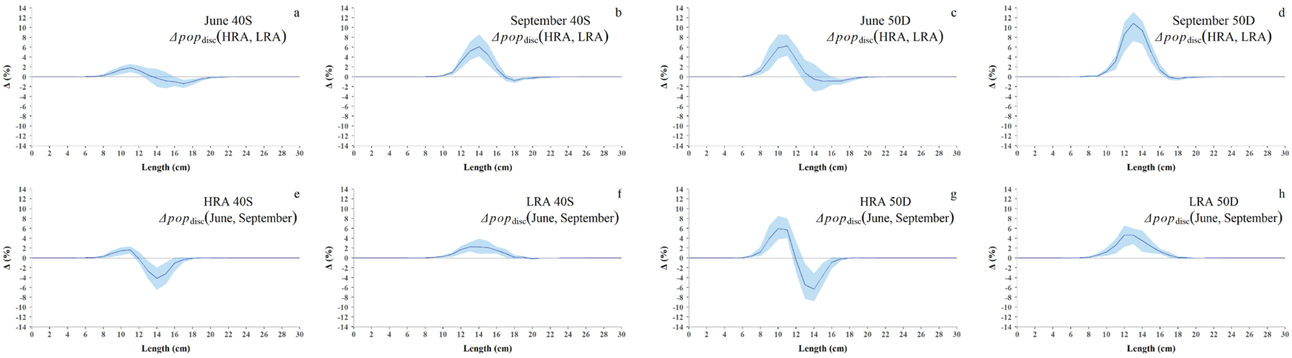

Fig. S1: Difference Δpop_{disc} *(l,a,t,g)* in the hake discards size structure between the two sampling areas (HRA, LRA) in June for 40S (a), September for 40S (b), June for 50D (c), and September for 50D (d) and between the two sampling periods (June, September) in HRA for 40S (e), LRA for 40S (f), HRA for 50D (g) and LRA for 50D (h). 95% Efron percentile confidence intervals are also given (coloured area around line). HRA: high recruitment area, LRA: low recruitment area, 40S: 40 mm square mesh in the trawl codend; 50D: 50 mm diamond mesh in the trawl codend; Δ (%): difference in percentage (%).

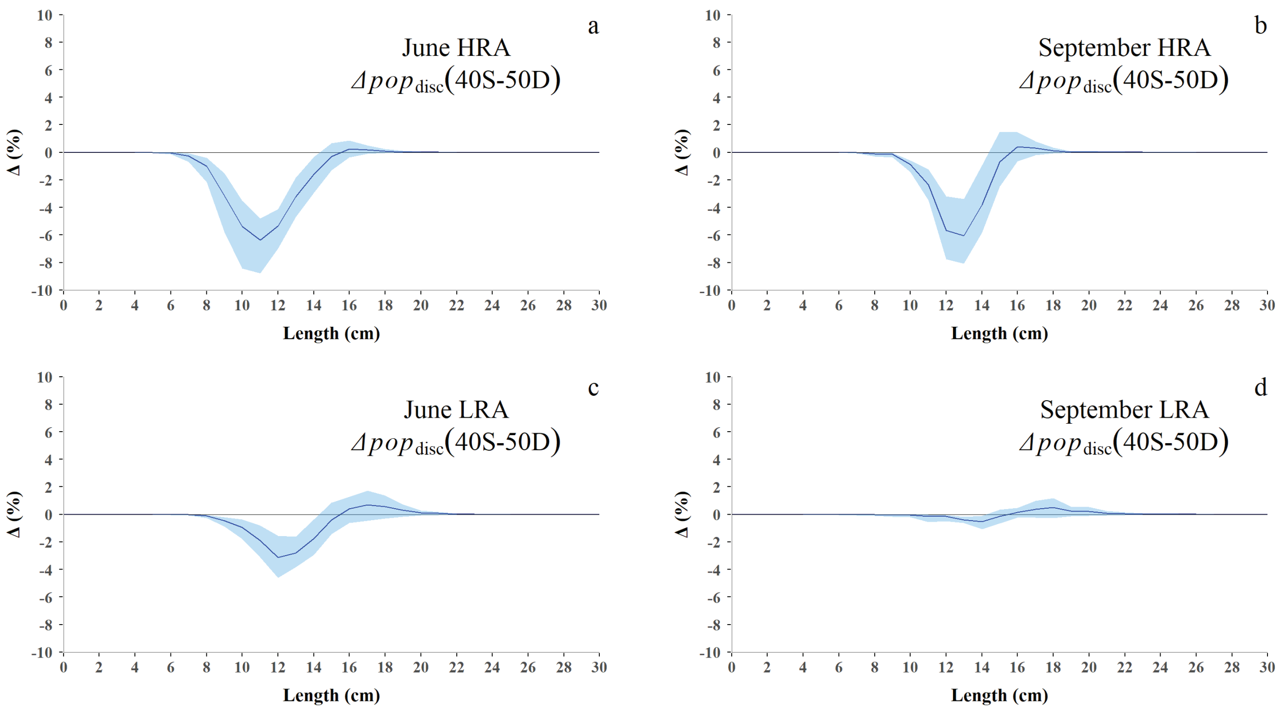

Fig. S2: Difference Δpop_{disc} *(l,a,t,g)* in the hake discards size structure between 40S and 50D codends in HRA in June (a), HRA in September (b), LRA in June (c) and LRA in September (d). 95% Efron percentile confidence intervales are also given (coloured area around line). 40S: 40 mm square mesh in the trawl codend; 50D: 50 mm diamond mesh in the trawl codend; HRA: high recruitment area, LRA: low recruitment area; ; Δ (%): difference in percentage (%).

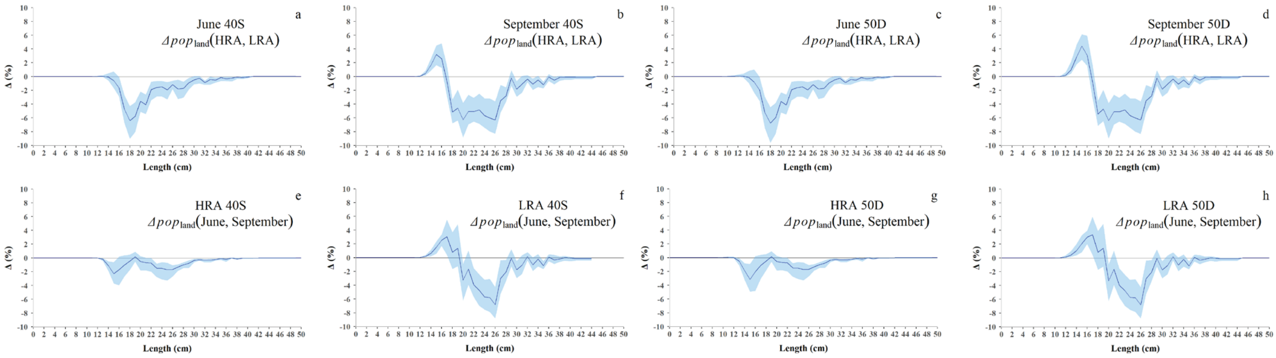

Fig. S3: Difference *Δpop$_{land}$ (l,a,t,g)* in the hake landings size structure between the two sampling areas (HRA, LRA) in June for 40S (a), September for 40S (b), June for 50D (c), and September for 50D (d) and between the two sampling periods (June, September) in HRA for 40S (e), LRA for 40S (f), HRA for 50D (g) and LRA for 50D (h). 95% Efron percentile confidence intervals are also given (coloured area around line). HRA: high recruitment area, LRA: low recruitment area, 40S: 40 mm square mesh in the trawl codend; 50D: 50 mm diamond mesh in the trawl codend; ; Δ (%): difference in percentage (%).

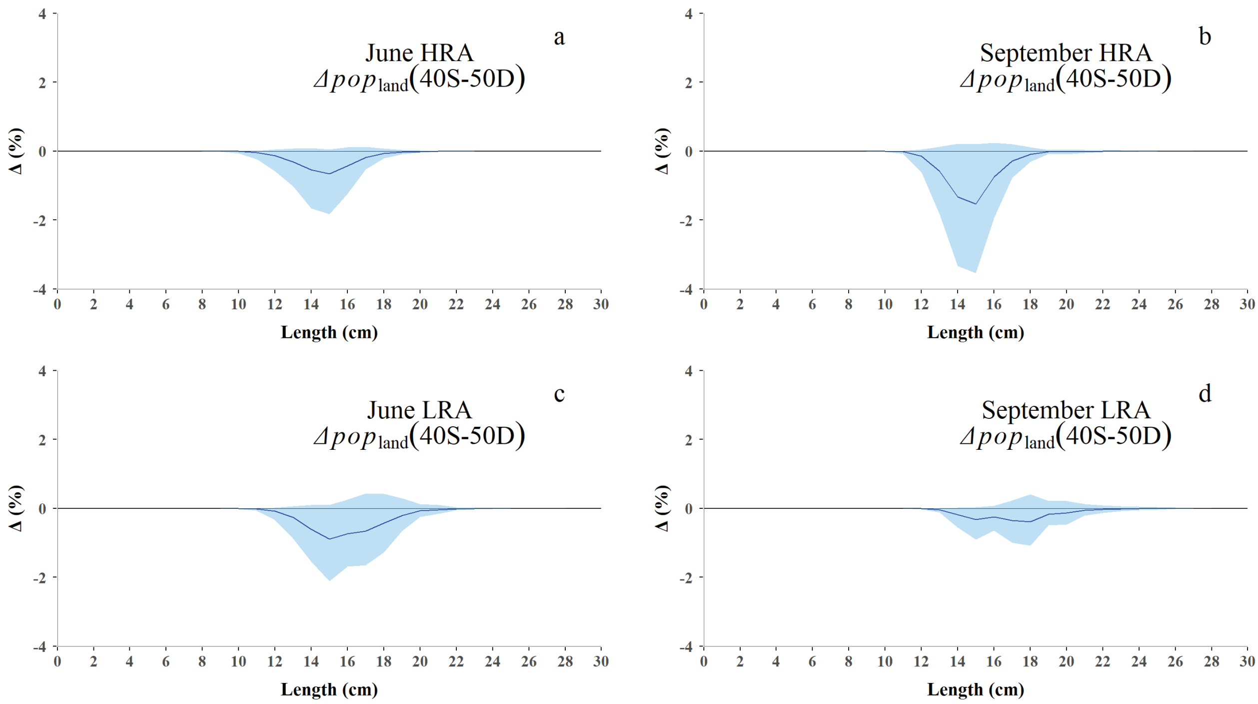

Fig. S4: Difference *Δpop$_{land}$ (l,a,t,g)* in the hake landings size structure between 40S and 50D codends in HRA in June (a), HRA in September (b), LRA in June (c) and LRA in September (d). 95% Efron percentile confidence intervals are also given (coloured area around line). 40S: 40 mm square mesh in the trawl codend; 50D: 50 mm diamond mesh in the trawl codend; HRA: high recruitment area, LRA: low recruitment area; ; Δ (%): difference in percentage (%).

Table S3. Difference in hake exploitation indicators between the two areas (HRA, LRA) or the two periods (June, September) using two different trawl codends (40S, 50D). 95% CI are also presented entre parenthesis below the difference value. Expl. Indicat.: Exploitation Indicator; HRA: high hake recruitment area; LRA: low hake recruitment area; 40S: 40 mm square mesh, 50D: 50 mm diamond mesh.

Area/ Period		HRA, LRA June	HRA, LRA September	HRA June, September	LRA June, September
Expl. Indicat.	**Codend**				
nP_ (%)	**40S**	-34.80 * (-47.83, -23.60)	-32.95 * (-41.02, -20.26)	-21.86 * (-35.72, -10.61)	-20.02 * (-28.03, -7.51)
	50D	-23.78 * (-32.84, -13.77)	-10.88 * (-16.94, -2.43)	-20.86 * (-29.28, -11.08)	-7.96 (-13.63, 0.52)
wP_ (%)	**40S**	-31.31 * (-44.43, -20.68)	-29.93 * (-36.91, -19.06)	-12.79 * (-28.87, -2.05)	-11.42 * (-16.25, -5.20)
	50D	-15.92 * (-24.22, -9.01)	-9.95 * (-13.13, -5.42)	-10.29 * (-18.51, -3.87)	-4.32 * (-6.31, -1.93)
ndRatio (%)	**40S**	24.88 * (13.09, 36.43)	44.79 * (30.90, 54.98)	17.11 * (6.31, 31.37)	37.02 * (24.38, 47.94)
	50D	25.14 * (15.71, 37.19)	51.83 * (39.51, 60.25)	14.72 * (7.69, 26.36)	41.41 * (28.07, 51.70)
wdRatio (%)	**40S**	21.56 * (0.83, 40.71)	16.27 * (6.91, 24.17)	25.03 * (6.04, 44.05)	19.75 * (11.13, 28.70)
	50D	29.28 * (11.14, 47.21)	22.26 * (11.27, 30.98)	28.97 * (12.31, 47.03)	21.94 * (12.91, 31.54)
$ndRatio_f$ (%)	**40S**	35.03 * (24.64, 44.14)	37.30 * (25.86, 46.62)	15.66 * (4.37, 28.28)	17.92 * (1.05, 25.31)
	50D	43.02* (31.81, 55.18)	47.67 * (35.22, 55.92)	20.54* (10.23, 34.61)	25.19 * (15.07, 33.41)
$wdRatio_f$ (%)	**40S**	17.86 * (9.22, 26.77)	11.26 * (5.82, 16.83)	24.16 * (15.16, 32.93)	6.30 * (3.48, 9.65)
	50D	28.04 * (19.19, 36.05)	16.29 * (9.30, -22.40)	19.35 * (9.59, 30.72)	7.60 * (4.24, 11.14)

* : denotes statistically significant difference

Table S4. Difference in hake exploitation indicators between the two studied trawl codends (40S, 50D) in each area (HRA or LRA) during each period (June or September). 95% CI are also presented entre parenthesis below the difference value. 40S: 40 mm square mesh, 50D: 50 mm diamond mesh, HRA: high hake recruitment area, LRA: low hake recruitment area.

	Area / Period/ Codend			
Exploitation Indicator	**HRA June (40S, 50D)**	**HRA September (40S, 50D)**	**LRA June (40S, 50D)**	**LRA September (40S, 50D)**
nP_ **(%)**	-29.80 * (-40.64, -22.46)	-28.80 * (-39.77, -16.24)	-18.78 * (-27.88, -9.88)	-6.72 * (-14.42, -0.54)
wP_ **(%)**	-25.38 * (-35.88, -16.05)	-22.88 * (-34.40, -9.81)	-10.00 * (-17.70, -2.59)	-2.90 (-8.75, 1.87)
ndRatio **(%)**	-6.17 * (-11.32, -3.50)	-8.56 * (-12.93, -4.24)	-5.91* (-9.82, -3.10)	-1.52 * (-3.30, -0.19)
wdRatio **(%)**	-10.17 * (-0.40, -0.09)	-6.23 * (-9.94, -2.30)	-2.44 * (-4.42, -0.65)	-0.25 (-0.77, 0.12)
$ndRatio_f$ **(%)**	-14.89* (-24.42, -6.57)	-10.01* (-17.45, -0.87)	-6.90* (-14.17, -0.24)	0.01×10^{-1} (-0.04, 0.03)
$wdRatio_f$ **(%)**	-10.93* (-18.10, -4.07)	-4.47* (-8.24, -0.27)	-0.75 (-4.28, 2.35)	0.55 (-0.72, 1.75)

* : denotes statistically significant difference

Table S5. Difference in hake discard *Ratio* between that estimated based on the MCRL (*dRatio*) and that based on the fisher behaviour (*$dRatio_f$*) in each area (HRA or LRA) during each period (June or September) using different trawl codends (40S or 50D). 95% CI are also presented entre parenthesis below the difference value. HRA: high hake recruitment area, LRA: low hake recruitment area, 40S: 40 mm square mesh, 50D: 50 mm diamond mesh.

		Area/Period			
Difference in Exploitation Indicators	**Codend**	**HRA June**	**HRA September**	**LRA June**	**LRA September**
ndRatio, $ndRatio_f$ **(%)**	**40S**	27.13 * (16.46, 37.72)	25.68 * (19.00, 32.07)	37.27 * (29.42, 44.96)	18.18 * (14.37, 22.39)
	50D	18.41 * (10.00, 27.88)	24.22 * (18.67, 32.84)	36.29 * (29.65, 42.56)	20.06 * (15.97, 24.24)
wdRatio, $wdRatio_f$ **(%)**	**40S**	23.57 * (12.38, 33,87)	11.43 * (6.89, 15.02)	19.87 * (13.58, 26.54)	6.42 * (4.79, 8.36)
	50D	22.80 * (12.12, 32,64)	13.19 * (8.35, 17.79)	21.56 * (14.88, 28.21)	7.22 * (5.54, 9.16)

* : denotes statistically significant difference