A game theoretic approach for management of the trans-boundary Pacific sardine fishery with environmental stochasticity.

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Pacific sardine fishery

- 1 fish stock - No trans-boundary agreement between stakeholders. (Canada, USA and Mexico)
- 87% of fish stock – USA + Canada
- 2 industry stakeholders/players (South (California) and PacNW (WA, OR and BC))

Pacific sardine stock assessment

US - coast wide – annual- single stock

Canada- Similar stock assessment as the US with a 3-year moving average to incorporate migration rates.

Both assessments use Sea Surface Temperatures as a reliable proxy to model abundance. Biomass closely follows the PDO cycle.

Model assumptions (Pacific sardine fish stock)

Age dependent availability to fishery

- Age 0 are considered as recruits
- Ages 1+ are fully mature and constitute the spawning stock.
- Additionally, it is assumed that ages classes 0, 1, 2 and 3 appear in Californian waters and ages 2+ are in the Pacific Northwest regions.

An age-structured model of a sardine population that can live to age 6+

Simulate fish population (Beverton-Holt); Added white noise

$$R(t+1)=\frac{1}{\alpha\kappa+\frac{\beta}{P(t)}}+\varepsilon$$

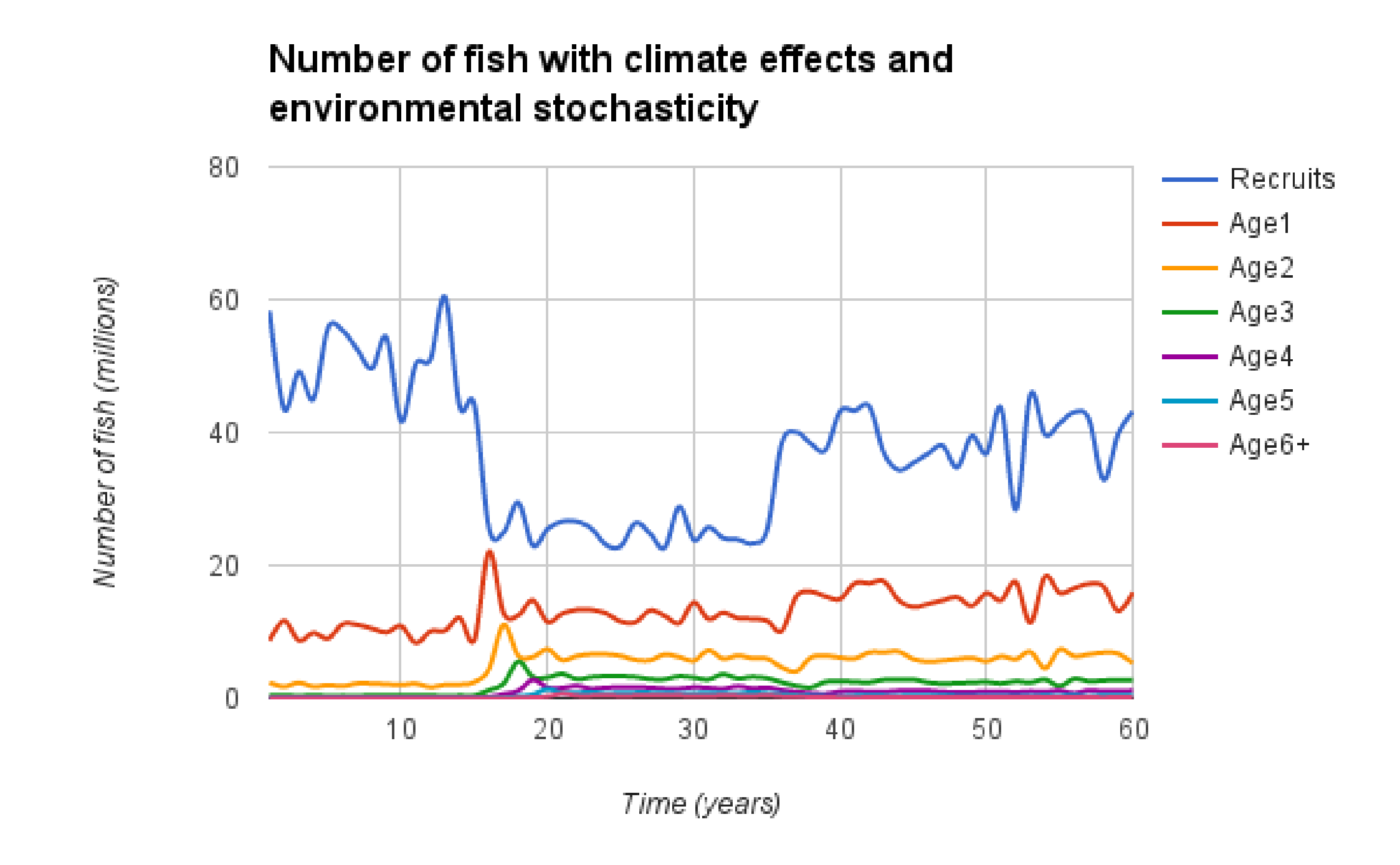
κ - a climate effect

- 1st 20 years = 1 (warmer waters, higher productivity coast-wide)
- 2nd 20 years = 2 (cooler waters, lower productivity coast-wide)
- Last 20 years = 1.3 (Moderate productivity, coastwide) = 1.3

Parameter values for the current modeling approach for the Pacific sardine

Age at 50% maturity	1
Annual mortality	0.4
Maximum size (kg)	0.3
α	0.00000017
β	0.02
Climate 1 effect, κ (Good productivity)	1
Climate 2 effect, κ (Low productivity)	2
Climate 3 effect, κ (Moderate productivity)	1.3

An example population



Modeling strategic interactions: Game constraint-stochasticity introduced in age-0 fish

Population dynamics (Beverton-Holt constraint)

$$n(0,t) = \frac{1}{\alpha\epsilon_i + \frac{\beta}{P_t}}$$
$$n_{a,t} + h_{a,t} \leq s_{a-1} n_{a-1,t-1}$$
$$0 \leq a \leq 3 (Player1)$$
$$2 \leq a \leq 7 (Player2)$$
$$n_{A,t} + h_{A,t} \leq s_A n_{A,t} + s_{A-1} n_{A-,1,t-1}$$
$$h_{a,t} = \Sigma_{j=1,2}\; q_{j,a} e_{j,t} n_{a,t} (\text{for cooperative})$$
$$i \neq j (\text{for non-cooperative})$$

Modeling strategic interactions: Game Objectives

- Maximize Profit

$$\pi i,t = \pi(n_t, e_{it}) = \Sigma_{a=0}^{A} p_a w_a q_{i,a} n_{a,t} e_{i,t} - C(e_{i,t})$$

- Two scenarios (Non-cooperative and Cooperative with bargaining and side payment)

$$M_i(n, e_i) = \Sigma_{t=1}^{T} \delta_i^t \pi_i n_t, e_{i,t}$$

(Non cooperative each player's objective)

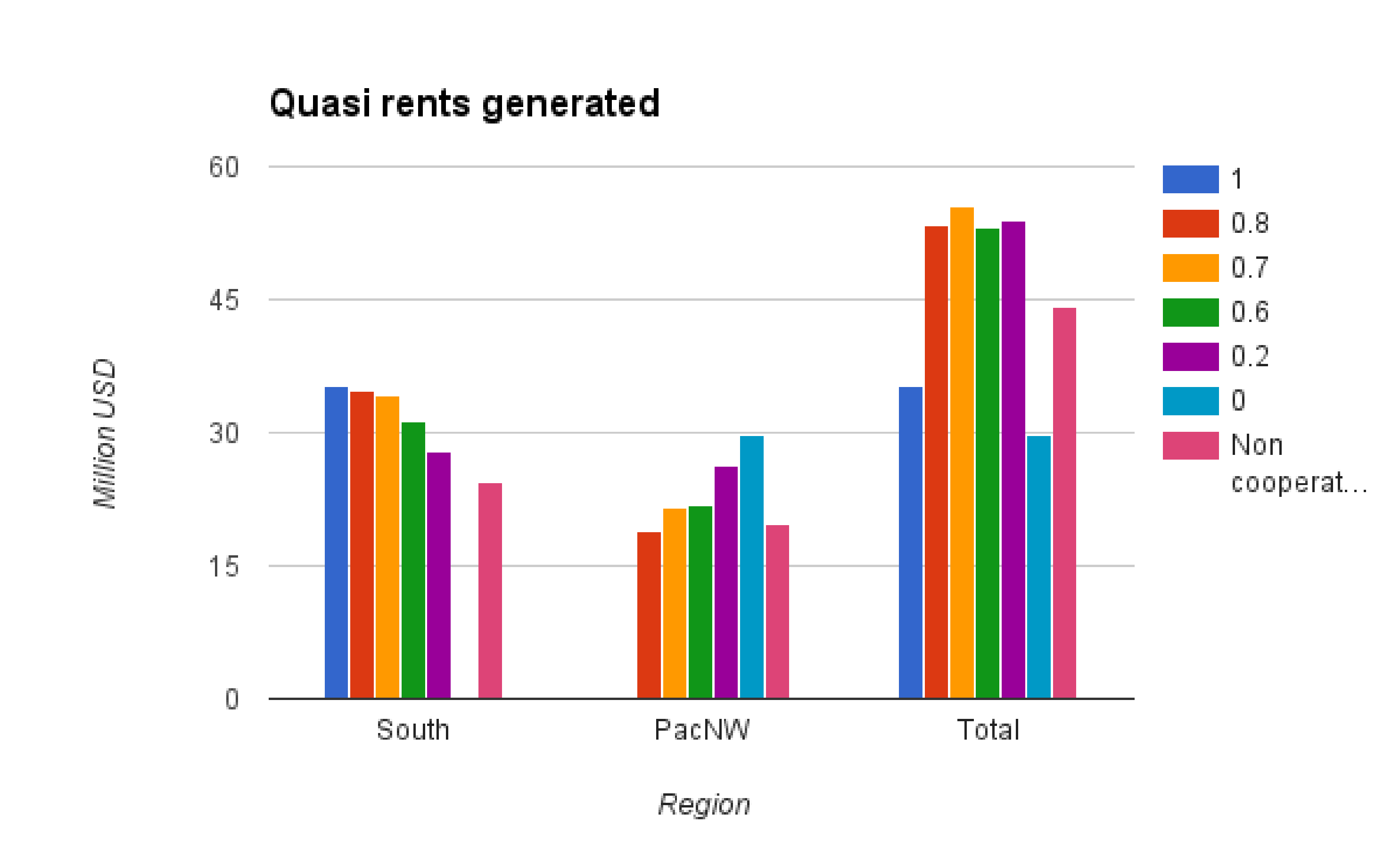
$$prof_{combined} = \beta M_1(n, e_1) + (1-\beta) M_2(n, e_2)$$

(Cooperative objective with bargaining power β and transferring payments)

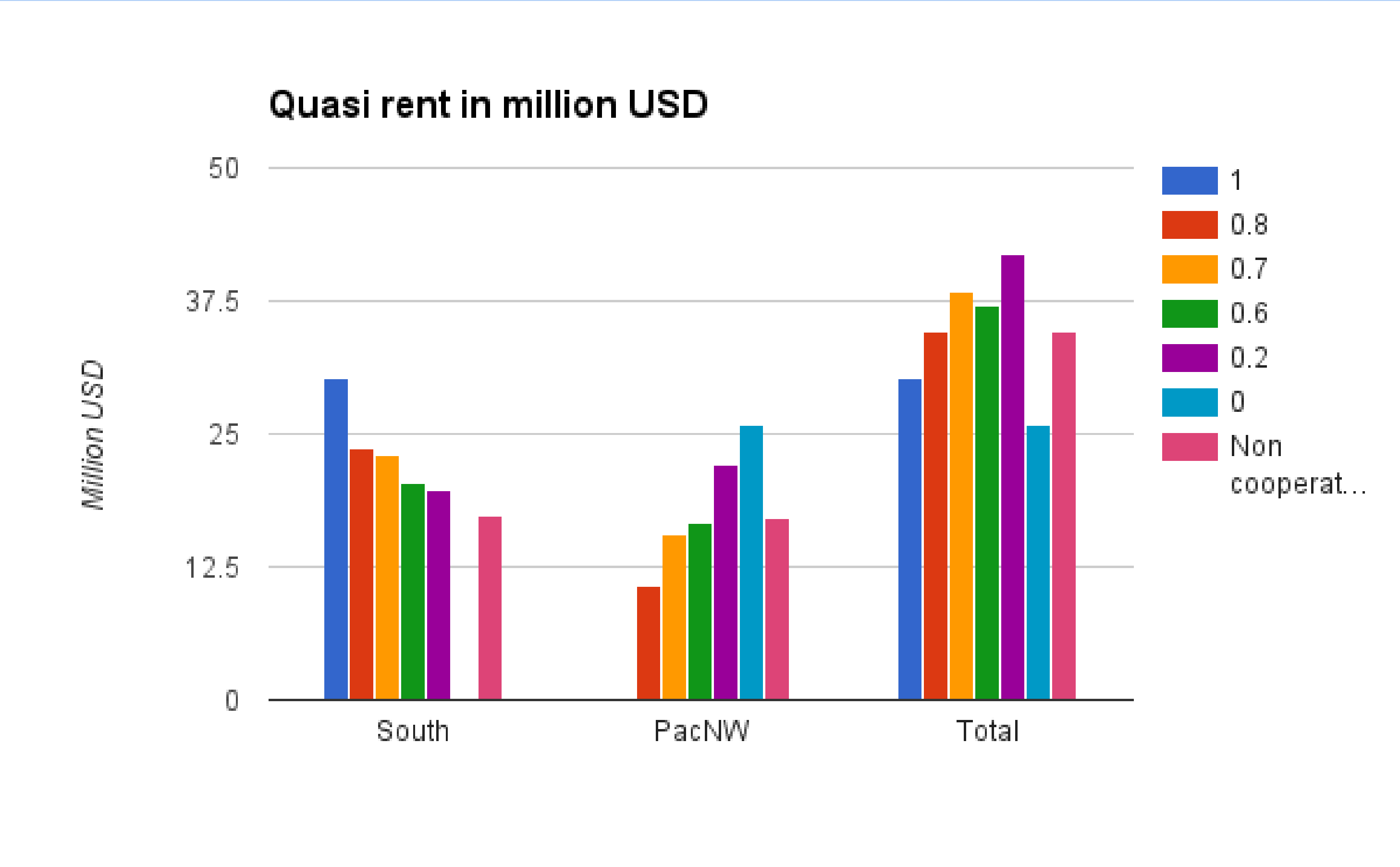
Computational details

- Models written in VBA and optimization was performed using CPLEX (IBM inc).
- The threat point was used to find individual player quasi-rents in the cooperative with bargaining situation and derive side payments.

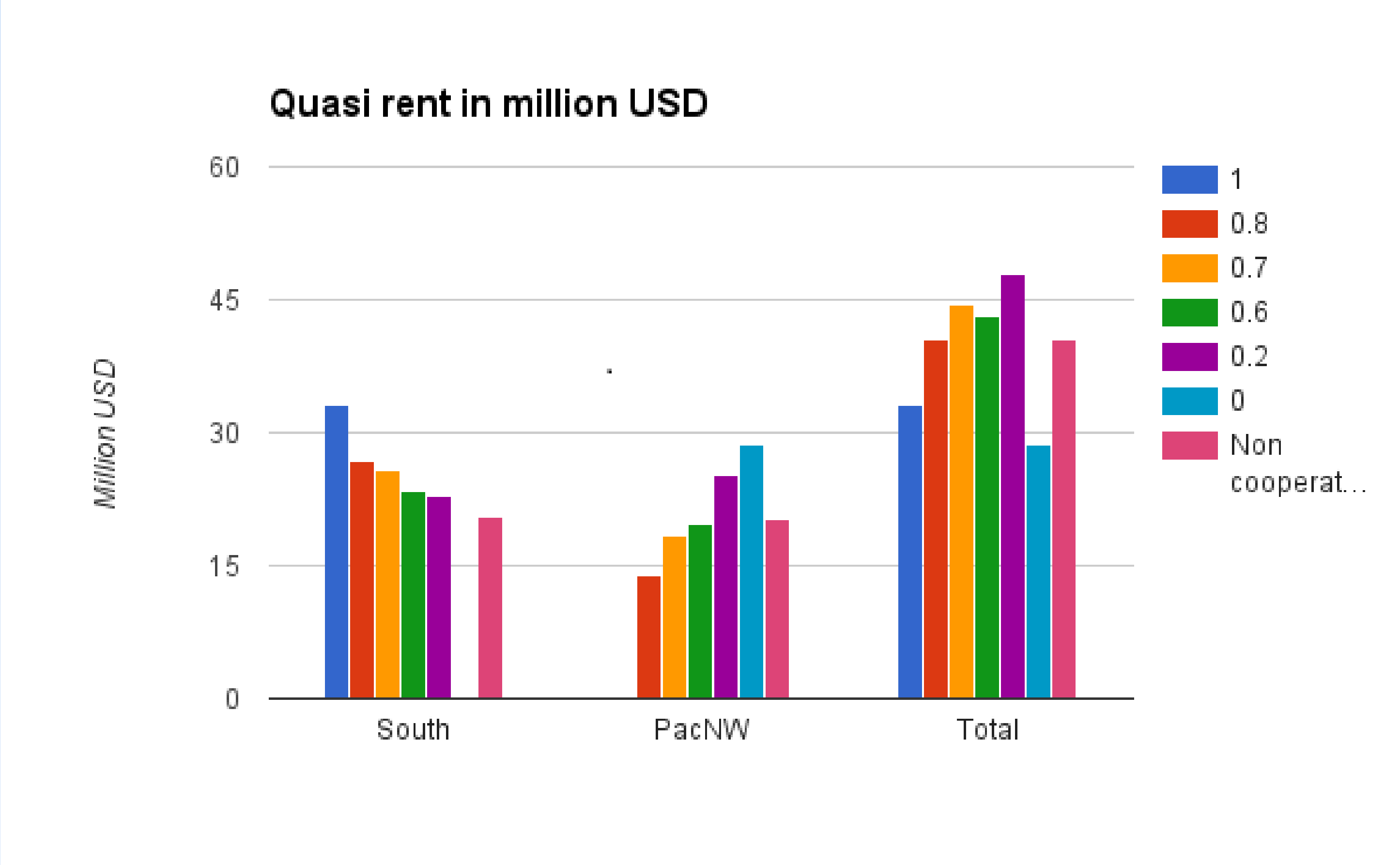
Results from the bio-economic model (first 20 years: high productivity)



Results from the bio-economic model (second 20 years: low productivity)



Results from the bio-economic model (last 20 years: moderate productivity)



Lessons from the numerical simulation: Stochastic Optimal control (2 player: South and Pacific NW)

- The south always gains in engaging in cooperative harvesting.
- PacNW would be interested in cooperation if it has bargaining (>0.3) during high productivity.
- PacNW would not be interested in cooperation unless it has a much higher bargaining (>0.7) during periods of low productivity.
- PacNW would not be interested in cooperation unless it has a moderate bargaining (>0.5) during periods of low productivity.
- To force cooperation, a side payment= 3.7 mil. USD (across the first 20 years) and 4.6 million (across the second 20 years) must be made from South to the Pac NW for both the South and Pac NW to sufficiently profit.
- Increasing the environmental stochasticity (increasing variance of white noise by a factor of 10) lowered the bargaining region for cooperation to >0.2 during periods of high productivity and did not have any significant effect during periods of low productivity.

Comparison to deterministic optimal control output for similar parameter values

- Cooperation happens in the current approach at a much lower level of bargaining during periods of high productivity.
- For deterministic, discrete time model (open loop NE) with similar parameter specifications, PacNW would not be interested in cooperation for a much higher bargaining level (>0.7), and productivity does not play an important role.

Conclusion and final comments

- Current work a much better representation of the Pacific sardine fish and fishery than the deterministic version of the model.
- Cooperation becomes a much more critical consideration for the Californian fishing industry especially when the fish stock status varies drastically (boom/bust cycle).
- The level of criticality plays an important role depending on the climactic conditions. During periods of high productivity, cooperation would be easier to attain (low bargaining) and during periods of low productivity, cooperation is much harder to attain (high bargaining).
- States involved in the southern part of the Pacific sardine fishery should always be interested in cooperation (no matter the level of productivity)
- The bio-economic model presented is consistent with the stock assessment of sardines. (Ref: The model framework is based on the Trawl/ Coastal cod game (Russia/Norway))

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