NON-PARAMETRIC TESTS OF THE TRAGEDY OF THE COMMONS

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The Tragedy of the Commons

- Open Access Resources (non-excludable)
- Examples

  - Over-grazing, Overpopulation (Hardin Science 1968)

  - Over-fishing (Gordon JPE 1954)

  - Race to pump water or oil

  - Computer networks and clubs (average cost game)

- Literature
  - Large-N case: all rent dissipated (Gordon 1954)
  - Game-theoretic case (Sen RESTUD 1966, Wetzman JET, 1974)

Property Rights and Extraction

- Catch shares reduce the race to fish
  - Costello, Gaines, And Lynham (Science 2008)
  - Birkenbach, Kaczan and Smith (Nature 2017)

- Unitization reduces the race to pump oil
  - Balthrop and Schnier (REE 2016)

- Property rights-based management in fisheries remains controversial

Non-Parametric Approach: Test the Behavioral Model

- Derive revealed-preference-like conditions for consistency with the model.
- Test using Norwegian fisheries data.
- Comparative test for two property rights regimes.

Non-Parametric Approaches

- GARP and Afriat's (1967) Theorem

  - The data satisfies GARP $\equiv$ There exist numbers $u^t, \lambda^t \geq 0$ such that $u^{t'} \leq u^t + \lambda^t\left(P^t \cdot X^{t'} - Y^t\right)$ for all t, t'

- Varian (Ecta 1984)
  - Firm's cost-min and profit-max

- Carvajal et al. (Ecta 2013) on Cournot Model
  - Testable conditions derived from first-order conditions and convexity of cost functions.
  - Data is consistent with Cournot if and only if positive marginal costs meeting these conditions.

Tragedy of the Commons Model (Static Average Return Game)

$$\max_{q_{i,t}} \left\{ \frac{q_{i,t}}{Q_t} * p_t F_t(Q_t) - C_i(q_{i,t}) \right\}$$

- $q_{i,t}$ is effort (input) for firm *i* in period *t*
- $Q_t = \sum_i q_{i,t}$
- Group-level production: $Y_t = F_t(Q_t)$

  $F(0) = 0$, $F'(Q) > 0$, and F' non-increasing

- Firm-level cost of effort: $C_i(q_{i,t})$

  $C_i'(q_{i,t}) > 0, C_i'(q_{i,t})$ non-decreasing

- $q_{i,t}$ increases group output and firm's share

Tragedy of the Commons Model (Static Average Return Game)

$$\max_{q_{i,t}} \left\{ \frac{q_{i,t}}{Q_t} * p_t F_t(Q_t) - C_i(q_{i,t}) \right\}$$

First-order Condition:

$$\frac{q_{i,t}}{Q_t} * p_t F_t'(Q_t) + \left(1 - \frac{q_{i,t}}{Q_t}\right) * \frac{p_t F_t(Q_t)}{Q_t} = C_{i,t}'$$

Re-arrange:

$$\frac{p_t F_t(Q_t) - Q_t C_{i,t}'}{q_{i,t}} = \boxed{\frac{p_t F_t(Q_t)}{Q_t} - p_t F_t'(Q_t)}$$

Linear Program

Given data $\boldsymbol{p_t F_t}, \boldsymbol{q_{i,t}}$ and $\boldsymbol{Q_t}$, a set of observations is consistent with the Tragedy of the Commons Model if there exists numbers $C'_{i,t}$ satisfying:

i. Common-Ratio Property

$$\frac{p_t \mathrm{F}_t(Q_t) - Q_t C'_{i,t}}{q_{i,t}} = \frac{p_t \mathrm{F}_t(Q_t) - Q_t C'_{j,t}}{q_{j,t}} \geq 0 \ \ \forall\, i, j \in I, \forall\, t \in T;$$

ii. Co-Monotone Property

$$\left(q_{i,t} - q_{i,t'}\right)\left(C'_{i,t} - C'_{i,t'}\right) \geq 0 \ \ \forall\, i \in I, \forall\, t, t' \in T$$

iii. Non-Negativity Constraint

$$C'_{i,t} \geq 0 \ \ \forall\, i \in I, \forall\, t \in T.$$

What Is Tested?

- Entire data sets

  - Not individual observations or individual firms

  - The behavioral of participants

  - Explore sensitivity by taking repeated sub-sets of sample and look at rejection rates (*T*=3,6,8,10; *I* =5,10,50,100,150)

- Strength

  - Eliminates any type I error

  - Can compare rejection rates across different property regimes

- Weakness

  - Allows type II error, e.g. can never reject perfect cooperation

Rejection Rates
(Input - Days at Sea)

Years / Number of Vessels	3	6	8	10
5	0.00	0.02	0.15	0.21
10	0.01	0.02	0.28	0.55
50	0.37	0.54	1.00	1.00
100	0.65	0.90	1.00	1.00
150	0.88	0.98	1.00	1.00

Questions

- The test is nothing or all.
- What if a rejection is due to measurement errors or trembling hands?
- What can we conclude from the rejection table?

Test with Measurement Error

- Allow measurement error in total revenue and total input

$$p_t \mathrm{F}_t(Q_t) * \alpha_t \text{ and } Q_t * \beta_t$$

and Let $\lambda_t = \alpha_t \,/\, \beta_t$.

- Construct a linear program

(i) $\frac{\lambda_t p_t \mathrm{F}_t(Q_t) - Q_t(C'_{i,t})}{q_{i,t}} = \frac{\lambda_t p_t \mathrm{F}_t(Q_t) - Q_t(C'_{j,t})}{q_{j,t}} > 0, \forall\, i, j \in I, \forall\, t \in T;$

(ii) $(q_{i,t} - q_{i,t'})(C'_{i,t} - C'_{i,t'}) \geq 0 \;\; \forall\, i \in I, \forall\, t, t' \in T$

(iii) $C'_{i,t} \;\geq\; 0, \; \forall\, i \in I, \forall\, t \in T,$

(iv) $\lambda_t > 0, \forall\, t \in T.$

Rejection Rates (Input - Days at Sea)

λ_t - [0.95, 1.05]

Years / Number of Vessels	3	6	8	10
5	0.00	0.01	0.15	0.20
10	0.00	0.00	0.25	0.51
50	0.00	0.33	0.99	1.00
100	0.00	0.70	1.00	1.00
150	0.00	0.87	1.00	1.00

Statistical Test of Rejections

- Diewert (1973) and Varian (1985)

  - minimal perturbation of the budget constraints to make observed choices data be satisfied with GARP.

- Minimal adjustment needed in MC to turn a rejection to acceptance.

Statistical Test of Rejections

- A Chi-squared Test

  - Marginal costs of firms in consistent with the ToC model $\{\widetilde{mc}_{i,t}\}_{i\,\epsilon\, I, \forall\, t\,\epsilon\, T}$ ~ Truncated Normal $N(\mu, \sigma^2)$

  - Recovered marginal costs $\{\widehat{mc}_{i,t}\}_{i\,\epsilon\, I, \forall\, t\,\epsilon\, T}$

  - Null – recovered marginal costs conforms to the ToC model

  - $z_{i,t} = \frac{\log(\widehat{mc}_{i,t}) - \log(\widetilde{mc}_{i,t})}{\sigma}$ ~ Standard Normal

  - $T = \sum_{t=1}^{T} \sum_{i=1}^{I} {z_{i,t}}^2 / \sigma^2$ ~ Chi-squared

Statistical Test of Rejections
The linear program

$$\min_{mc_{i,t},\delta_{i,t}} \sum_{t} \sum_{i} |\delta_{i,t}|$$

Subject to

(i) $$\frac{\mathrm{p_t F_t(Q_t) - Q_t(C'_{i,t} + \boldsymbol{\delta}_{i,t})}}{\mathrm{q_{i,t}}} = \frac{\mathrm{p_t F_t(Q_t) - Q_t(C'_{j,t} + \boldsymbol{\delta}_{j,t})}}{\mathrm{q_{j,t}}} > 0, \forall\ \mathrm{i, j \in I}, \forall\ \mathrm{t \in T};$$

(ii) $$\left(\mathrm{q_{i,t} - q_{i,t'}}\right)\left(\mathrm{C'_{i,t} - C'_{i,t'}}\right) \geq 0 \ \ \forall\ \mathrm{i \in I}, \forall\ \mathrm{t, t' \in T};$$

(iii) $$\mathrm{C'_{i,t}} \geq 0 \ \ \forall\ \mathrm{i \in I}, \forall\ \mathrm{t \in T}.$$

Statistical Test of Rejections

$N \in \{5, 10, 50\}$ and $T \in \{3, 6\}$

$$T_{chi} = \sum_{t=1}^{T} \sum_{i=1}^{I} {z_{i,t}}^2 / \hat{\sigma}^2 = 12365.8$$

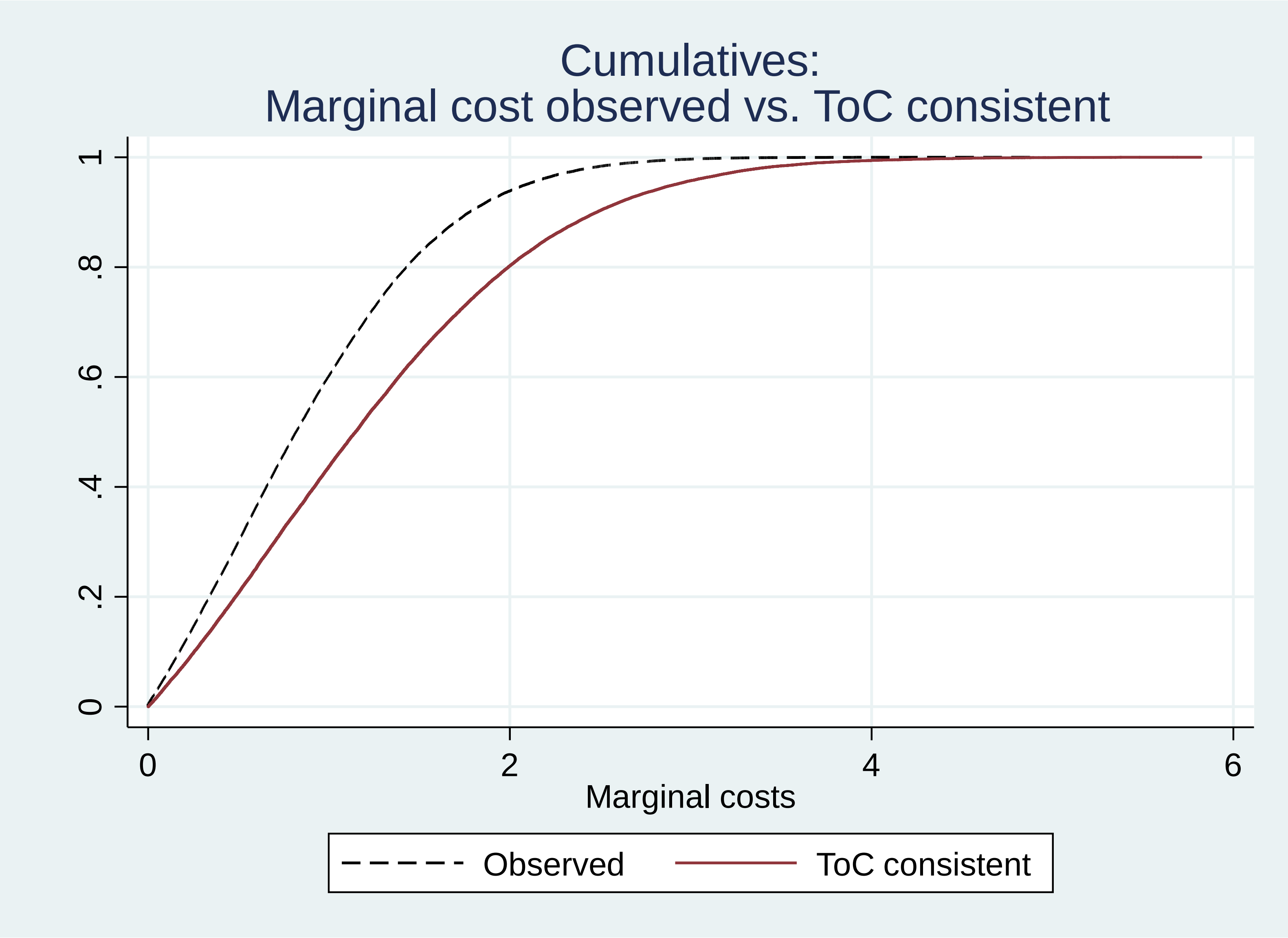
The chi-squared critical value $C_{0.05,58500} = 59064$

Statistical Test of Rejections

- Two-sample Kolmogorov-Smirnov test

  - equality of distribution functions between $\{\widetilde{mc}_{i,t}\}_{i \in I, \forall t \in T}$ and $\{\widehat{mc}_{i,t}\}_{i \in I, \forall t \in T}$

Smaller group	D	P-value
0	0.2417	0.000
1	-0.1336	0.000
Combined K-S	0.2417	0.000


Cumulatives:
Marginal cost observed vs. ToC consistent
0
.2
.4
.6
.8
1
0
2
4
6
Marginal costs
Observed
ToC consistent

Norwegian Ground Fishery Regime Revolution

- Change in property rights regime

  - 1998-2002: Open-access with restriction on capital

  - 2003 and on: Total allowable catch specified for each group by length

- Hypotheses

  - Expected higher rejection rates for vessels after 2002

Data

- Micro-level panel data on individual vessels
  - Many years of non-participation (zeros)
- Output
  - Annual catch and revenue by species and vessel
  - Sum over all species and vessels to obtain $\boldsymbol{p_t F_t}$ for the test
- Input
  - Observe vessel length, crew (man-days), fuel use, days at sea, operating days.
  - Need to obtain scalar-valued "effort", $\boldsymbol{q_{i,t}}$

Estimate Scalar-valued Effort

- Estimate production by regressing catch on inputs

  - $\ln(Catch_{i,t}) = a + b * lnE_{i,t} + \lambda_t + e_{i,t}$.

  - $\ln(E_{i,t}) = \alpha_1 \ln(man\ days_{i,t}) + \alpha_2 \ln(fuel\ use_{i,t}) + \alpha_3 \ln(labor\ compensation_{i,t}) + vesselid_i$.

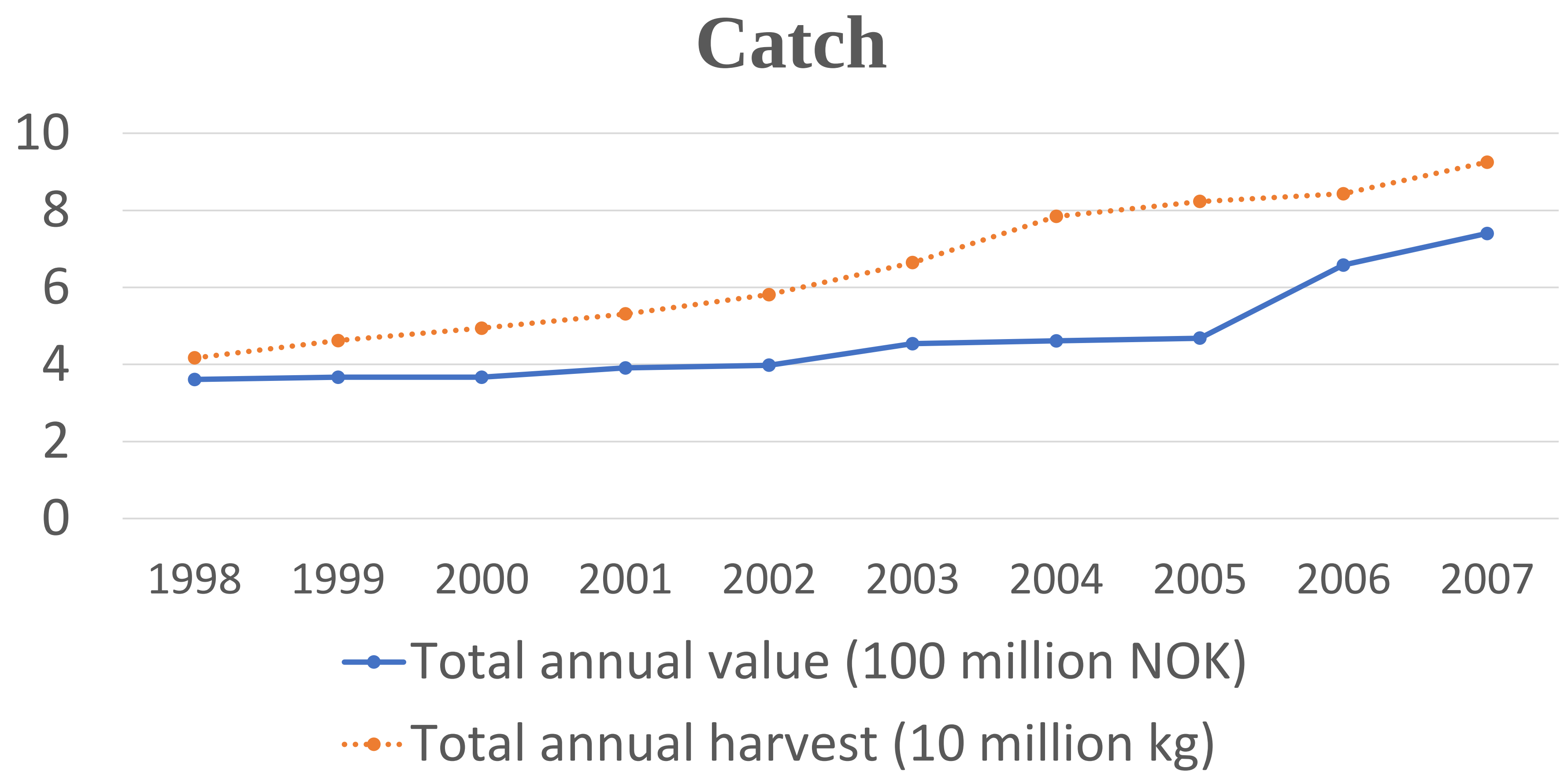
- Use fitted $\hat{E}$ as measure of effort
- Consider three other alternatives

  - Days at sea (imputing zeros)

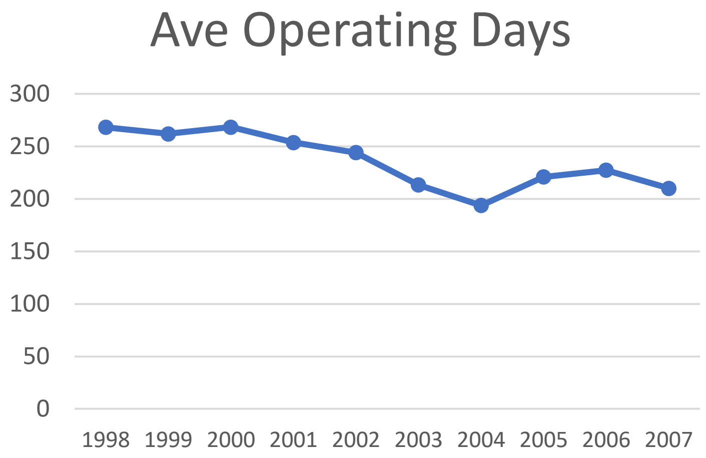
  - Imputed days at sea times vessel length

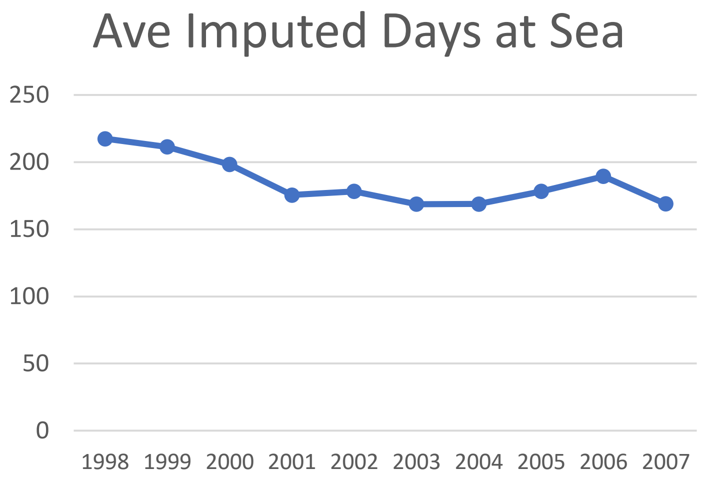
  - Operating days

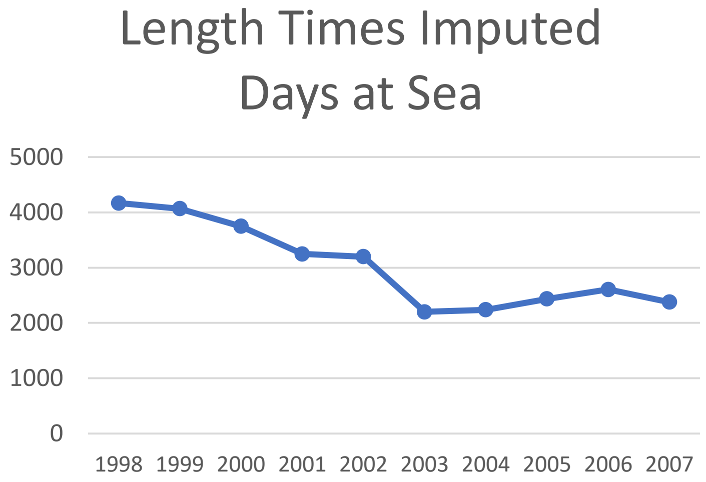
Output Trend

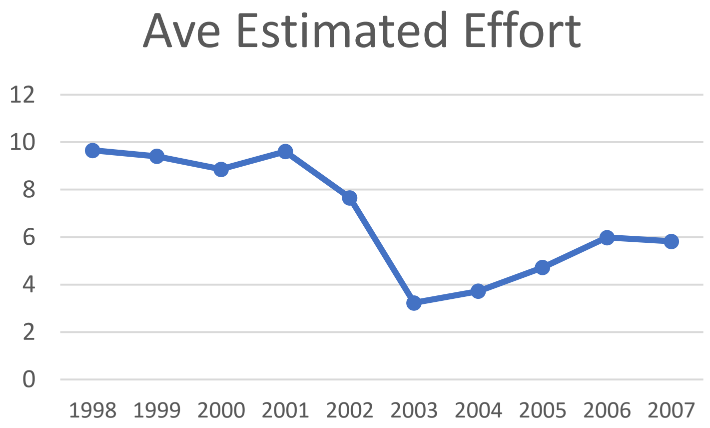


Input


Ave Operating Days
300
250
200
150
100
50
0
1998 1999 2000 2001 2002 2003 2004 2005 2006 2007


Ave Imputed Days at Sea
250
200
150
100
50
0
1998 1999 2000 2001 2002 2003 2004 2005 2006 2007


Length Times Imputed Days at Sea
5000
4000
3000
2000
1000
0
1998 1999 2000 2001 2002 2003 2004 2005 2006 2007


Ave Estimated Effort
12
10
8
6
4
2
0
1998 1999 2000 2001 2002 2003 2004 2005 2006 2007

Rejection Rates
(Input - Days at Sea)

Years / Number of Vessels	3	6	8	10
5	0.00	0.02	0.15	0.21
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50	0.37	0.54	1.00	1.00
100	0.65	0.90	1.00	1.00
150	0.88	0.98	1.00	1.00

Rejection Rates (Estimated Effort)

Years / Number of Vessels	3	6	8	10
5	0.01	0.00	0.09	0.19
10	0.01	0.02	0.24	0.35
50	0.22	0.49	0.98	1.00
100	0.57	0.80	1.00	1.00
150	0.77	0.95	1.00	1.00

Rejection Rates by Groups (Input - Days at Sea)

Years	Vessels	>=2002	<2002	Diff
3	5	0.11	0.08	0.03
3	10	0.29	0.27	0.02
3	50	0.96	1	-0.04
5	5	0.22	0.13	0.09
5	10	0.6	0.4	0.2
5	50	1	0.98	0.02

Conclusion

- Behavior of vessel/fishermen of the Norwegian ground fishery cannot be explained by the Tragedy of the Commons model.

- Help to answer which regulatory regime help to address the first-order problem of the commons

Get In Touch

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