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Spatial and temporal fishery management assessment using DEA: Case study of spanner crabs in Queensland, Australia

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ABSTRACT

The aim of this case study was to assess potential temporal and spatial differences in productivity measures of vessels operating in the Queensland spanner crab fishery. This fishery's logbook records of catch and effort data allowed analysis of the impact of fishery management changes on productivity measures. Data envelopment analysis (DEA) with a 'window analysis' approach was used to derive estimates for measures of technical efficiency, capacity utilisation and scale efficiency over time for five different spanner crab fishing regions. The results suggest that average technical efficiency and capacity utilisation were relatively low over time and across fishing regions, implying a high level of technical inefficiency and the existence of excess capacity in the fishery. Scale efficiency was found to be high historically but decreased slightly since 2006 for all regions. The results suggest that this decline is likely not caused by the fishery management changes, but instead is due to other factors. Additional data (e.g., revenue, profit, costs, skipper experience) and analysis is needed to assess the causes for the low technical efficiency and capacity utilisation and reasons for the decrease in scale efficiency as a baseline for specific fishery management recommendations. The study shows that temporal and spatial efficiency and productivity analysis of fisheries can help identify potential issues that are not otherwise apparent.

1. Introduction

The management of commercial fisheries is vital to ensure long-term fish stock resilience and maximum economic yields for fishing fleets. While environmental and economic management objectives may require trade-offs, information about the economic performance of fishing fleets is generally considered as equally important as information about fish stock status or health for informed fishery management decisions (Hilborn, 2007; Rindorf et al., 2017; Asche et al., 2018).

Efficiency and productivity analysis offers a range of measures to assess how economic performance of fishing fleets may be changing even when detailed financial information (e.g., economic value of catch, costs, and earnings from fishing) about fleets is unavailable. These include measures such as technical efficiency and capacity utilisation, which measure how a vessel's output per unit of inputs (either both fixed and variable inputs or just fixed inputs, respectively), compares to the most efficient vessel in the fleet.

While the literature is rich in applications of efficiency analysis in the fishery sector (Chávez Estrada et al., 2018; Guttormsen and Roll, 2011; Kirkley et al., 1995; Kirkley et al., 1998; Pascoe and Coglan, 2002; Rust et al., 2017; Nguyen et al., 2022; Kompas et al., 2004; Sharma and Leung, 1998; Tingley et al., 2005) limited attention has been paid to

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temporal and spatial considerations as part of these assessments. Such analyses can provide fishery managers with information about potential differences in input-output relationships depending on vessels' fishing locations and across time periods. This can be important for fishery managers to develop appropriate harvest strategies (e.g., input or output controls) with biological and economic objectives.

The present case study focusses on the efficiency performance of the spanner crab (*Ranina ranina*) fishery in Queensland (QLD), Australia. Spanner crabs have been commercially caught in Australia since the late 1970s. Weak fishery management and subsequent high fishing effort resulted in the over-exploitation of the spanner crab stock in the 1980s (Jones, 1982) and 1990s (Brown et al., 1999). Improved fishery management (e.g., introduction of gear restrictions, fishery closure periods and individually transferable quotas) have contributed to achieving a sustainable stock status in 2020 (FRDC, 2020), which is a fundamental condition for the economic sustainability of the fishery at present and in future. Yet, there is limited information available about economic aspects of the spanner crab fishery, such as the input-output efficiency performance of the fleet.

The aim of this case study was to address this gap by estimating various efficiency measures for the QLD spanner crab fishery using a temporal and spatial perspective. This included an analysis of the impact of fishery management changes on the efficiency performance of the fleet. Estimates of measures such as technical efficiency, capacity utilisation, and scale efficiency were derived using data envelopment analysis (DEA), applied to time series panel data made available by the Queensland Government, the managing and regulating authority of the spanner crab fishery. The scope of this study is limited to the QLD spanner crab fishery due to the accessibility of data, although it shares its stock with a fishery that operates in northern New South Wales (NSW) (Schilling et al., 2022).

2. The Queensland spanner crab fishery

Spanner crabs are marine decapod crustaceans found in the Indo-pacific region (Kennelly, 2019). In Australia, spanner crabs inhibit coastal waters along the east coast and typically populate in sandy habitats in depths of 10–60 m (Sumpton et al., 1995; Skinner and Hill, 1987; Brown et al., 1999). This crab species matures at about 4–6 years of age (State of Queensland, 2020b), spawns between October and February (with peak during late November to late December) and can reach an age up to 15 years (Brown et al., 1999). Males grow to about 150 mm rostral carapace length (RCL, i.e., rostrum is the front section, e.g., head, nose, and carapace is a dorsal section of the exoskeleton or shell of the crab), females to approximately 120 mm RCL and weigh approximately 900 g (Brown et al., 1999). Spanner crabs can be distinguished from other crab species by their red carapace and elongated round body.

Spanner crabs are commercially caught in waters ranging from Yeppoon in QLD to Yamba in northern NSW (Brown et al., 1999; Dichmont and Brown, 2010; State of Queensland, 2020b). While this crab species also occurs north of Perth, Western Australia, no commercial harvest of spanner crabs is taking place in this state. About 88 % of Australia's commercial spanner crab catch is caught in QLD waters

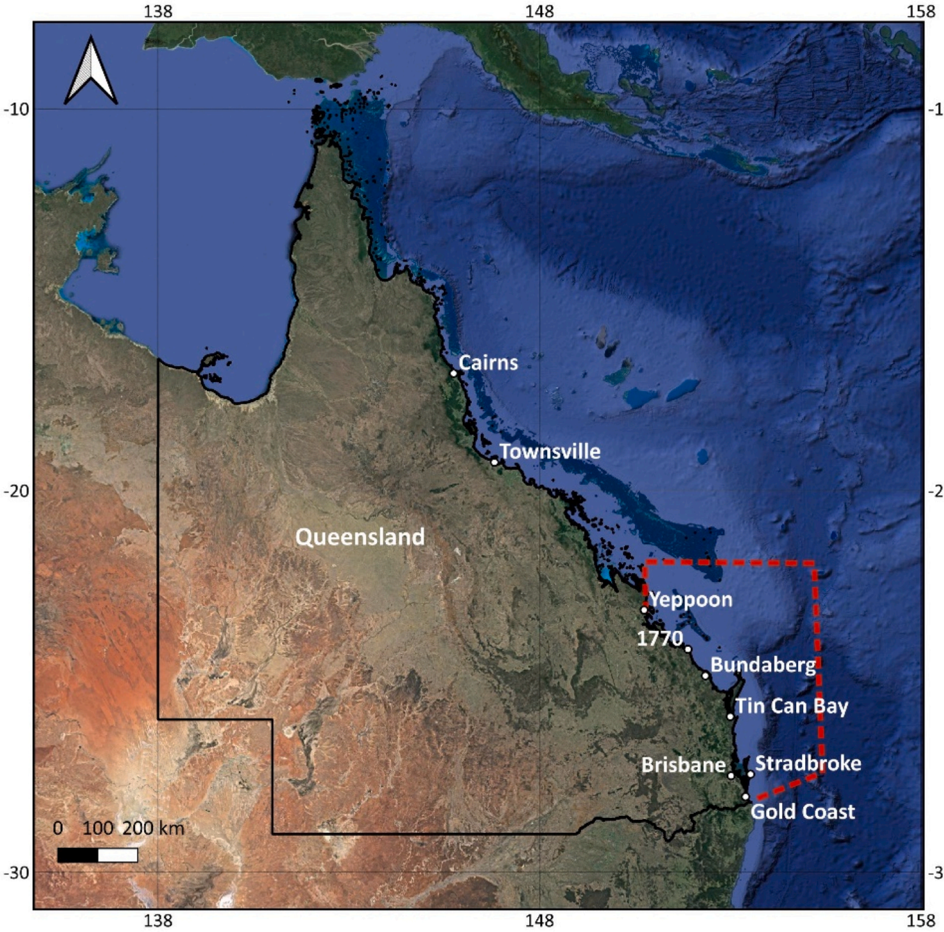

Fig. 1. Commercial spanner crab management area in Queensland.
Source: State of Queensland (2020a). Notes: The red dotted line identifies the commercial fishing area of spanner crabs in Queensland. 1770 denotes the Town of Seventeen Seventy.

(FRDC, 2020). Recreational (including charter) and indigenous spanner crab fishing is also permitted in other coastal areas of QLD, however, 99 % of spanner crab harvest occurs by the commercial fishery (single-species fishery) (FRDC, 2020; State of Queensland, 2020b). Fishing methods include nets (mostly in NSW), traps, and dillies (which are framed nets) that are placed on the sea floor (Sumpton et al., 1995, FRDC, 2020, State of Queensland, 2020b).

The QLD spanner crab fishery is managed by the Queensland Government, which determines fishing areas, input, and output restrictions. The commercial fishery management area for spanner crabs is located in south-east QLD (State of Queensland (2020b), see Fig. 1). This fishery management area is divided into five fishing regions for the purpose of monitoring and assessment, and include (from north to south) the Town of Seventeen Seventy (identified as "1770" in the remainder of this study), Bundaberg, Tin Can Bay, Stradbroke and Gold Coast (State of Queensland, 2020a, see Fig. 1). These five fishing regions will be the focus of this study.

During the 1970–1990 s the QLD spanner crab fishery expanded significantly in regard to catch volume with its peak in 1994 when a total catch of approximately 3592 tonnes was recorded (Brown et al., 1999) (see Fig. 2). Since 1999, a range of management methods were gradually introduced to control fishing inputs and outputs, for example, gear restrictions (e.g., number of gear permitted), limiting fishing licenses, seasonal closures, and total allowable commercial catch (TACC, with latest reduction in TACC in 2018) managed through individually transferable quotas (ITQs) in commercial fishery management area (State of Queensland, 2020a; State of Queensland, 2022). The suite of management interventions has contributed to achieving a sustainable stock status in 2020 (FRDC, 2020).

Although there is a collaborative arrangement between NSW and QLD, each jurisdiction has separate management arrangements for their portion of the fishery (NSW DPI, 2020). A formal harvest strategy has more recently been implemented for the commercial spanner crab fishery in QLD which sets out decision rules to determine appropriate levels of harvest based on the status of spanner crab stocks (State of Queensland, 2020b). The aim of the harvest strategy is to set the catch at levels appropriate for achieving an economic-focused biomass target (i.e., a proxy for maximum economic yield), minimising the risk of a full fishery closure and maintaining catch shares amongst commercial and recreational sectors (State of Queensland, 2020b). Since no modelled stock assessment is available for spanner crabs, the stock is assessed on the basis for the performance of the fishery using commercial fisher catch per unit effort (CPUE) (annual standardised catch rate) (O'Neill et al., 2010) and fishery independent survey data (catch rate of legal-size crabs) to infer the status of the stock (State of Queensland, 2020b). Commercial logbooks, prior landing reports and buyers' logbooks are used to monitor the catch volume and compulsory vessel tracking units and to validate fishery operations (State of Queensland, 2020b).

By 2020 there were only 36 active businesses operating in the spanner crab fishery due to the decrease in fishing licenses over time. These generate a combined total production value of about AUD 8.0–9.3 million per annum (BDO EconSearch, 2020). This translates into an off-vessel average unit price of about AUD 9.30–9.40 per crab (BDO EconSearch, 2020). As such, the spanner crab fishery presently only contributes a relatively small economic value annually to QLD's economy compared to other fisheries such as the East Coast Trawl Fishery (AUD 109.8 million), Coral Reef Fin Fish Fishery (AUD 33.4 million) or the East Coast Mud Crab Fishery (AUD 26.0 million) (BDO EconSearch, 2020). However, it is estimated that the spanner crab fishery directly employs about 156 people in QLD (BDO EconSearch, 2020), hence, the fishery has socio-economic importance for fishing communities in south-east QLD.

As a seafood product, spanner crabs are caught for their meat, are sold mostly to the domestic market (BDO EconSearch, 2020) and are considered as a low-medium priced seafood product (SFM, 2021). At the domestic wholesale market, spanner crabs are sold at about AUD 25.00–29.50/kg (whole raw spanner crab) (GCFC, 2021, Scales Seafood, 2021). Only a small proportion of the catch is exported, generating a value of approximately AUD 0.3 million per annum (BDO EconSearch, 2020).

3. Data and methods

3.1. Data

Fishery logbook data for the analysis were made available from the Queensland Government, Department of Agriculture and Fisheries (QDAF). A total of 20622 observations were recorded after data cleaning (e.g., removal of observations with missing variables and extreme outliers) which includes monthly data ranging from January 1988 to

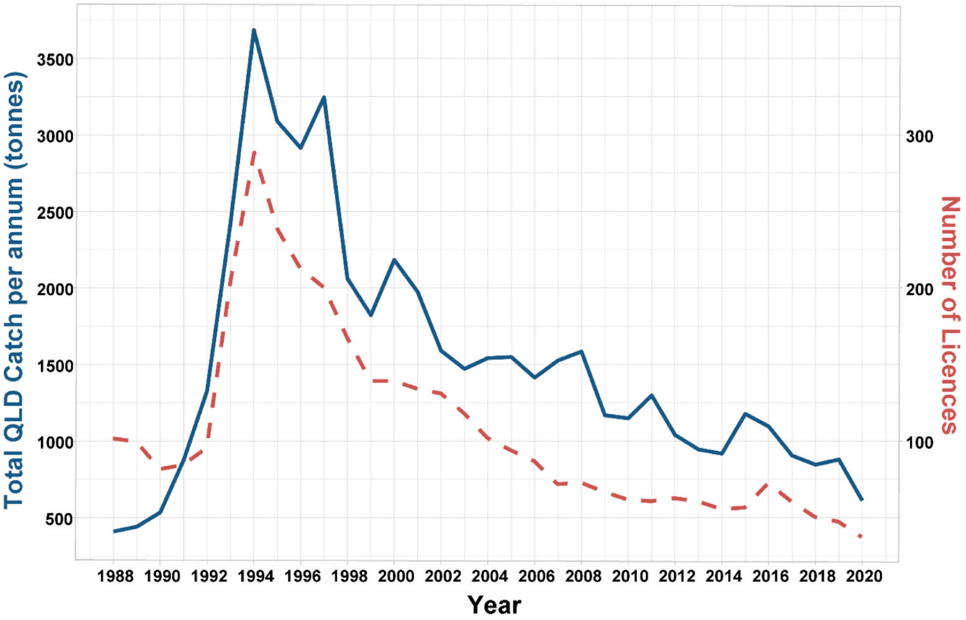

Fig. 2. Total QLD spanner crab catch per annum (in tonnes) and number of active licenses over time.
Source: State of Queensland (2020a).

December 2020. The data set comprised de-identified individual vessel time series panel data for production input variables such as the number of days per month fished, number of dillies set, number of dillies lifted, engine power in kilowatt, fishing region (i.e., 1770, Bundaberg, Tin Can Bay, Stradbroke, Gold Coast (see Fig. 2)), and production output (i.e., catch volume in kilogram). A previous study by O'Neill et al. (2010) described the spanner crab fleet characteristics using additional variables such as skipper experience, crew number, fuel use per day and some of these variables were collected for 2019 and 2020. However, such data were either not available for individual vessels and over time (1988–2018) or could not be made available for this analysis (2019–2020).

The descriptive statistics of the full sample and sub-samples (reasons for subsample splits are provided in Section 3.2) for input and output variables are presented in Table 1. The descriptive statistics show that observations for fishing areas in the northern regions (i.e., 1770, Bundaberg and Tin Can Bay) recorded a higher output over time and more input units compared to the southern fishing regions (i.e., Stradbroke, Gold Coast). Furthermore, there also appears to be large variation for specific variables (e.g., engine power, output) within each subsample.

Prior to conducting the detailed fleet performance assessment, the correlation between input and output variables were tested using the full sample (time period 1988–2020) to ensure monotonicity in outputs. The correlation between all variables was relatively small (see supplementary material).

The plotted mean values of input and output variables in Fig. 3 provide insight into their dynamics over time. While the average days fished decreased, the average number of dillies set increased from 45 to 75, reflecting further changes to the fishery management from 2008, which allowed individual spanner crab fishers to use more than the 45 dillies stipulated in the Fisheries Regulation 2008 (State of Queensland,

Table 1
Descriptive sample statistics (1988–2020).

Sample	Observations	Statistic	Inputs					Output
			Days Fished	Dillies set	Dillies lifted	Hull units	Engine power	
Full sample	20,622	Median	4.00	45.00	2.00	5.70	187.00	783.90
	[1988–2020]	Mean	5.25	47.86	2.83	8.06	199.40	1449.09
		St. dev.	4.44	19.81	2.08	8.46	100.92	1986.79
1770	2586	Median	4.00	45.00	2.00	6.90	231.00	994.60
	[1988–2020]	Mean	4.76	48.37	2.84	8.26	222.18	1541.56
		St. dev.	3.96	17.21	2.18	5.84	85.21	1587.16
	654	Median	4.00	30.00	2.00	6.00	179.00	1146.70
	[1988–1999]	Mean	5.56	30.60	3.31	8.18	201.57	1527.92
		St. dev.	4.42	7.09	2.72	5.95	87.40	1407.57
	1932	Median	3.00	45.00	2.00	6.90	238.00	950.00
	[2000–2020]	Mean	4.49	54.38	2.68	8.29	229.16	1546.18
		St. dev.	3.75	15.38	1.93	5.80	83.34	1643.83
Bundaberg	3410	Median	5.00	45.00	2.00	8.30	240.00	1200.00
	[1988–2020]	Mean	6.23	45.57	3.10	9.81	229.49	2038.11
		St. dev.	5.47	18.30	2.42	6.71	91.05	2370.57
	1084	Median	6.00	30.00	3.00	8.20	194.00	1490.00
	[1988–1999]	Mean	7.87	29.29	3.78	10.00	202.52	2409.13
		St. dev.	6.41	9.14	3.05	6.71	86.27	2776.44
	2326	Median	4.00	45.00	2.00	8.30	270.00	1062.50
	[2000–2020]	Mean	5.47	51.69	2.78	9.71	242.05	1832.41
		St. dev.	4.79	17.11	1.99	6.70	90.51	2037.38
Tin Can Bay	6831	Median	4.00	45.00	2.00	6.90	210.00	1015.00
	[1988–2020]	Mean	5.36	52.12	2.92	9.90	209.19	1818.29
		St. dev.	4.28	23.06	2.10	10.90	108.55	2543.81
	1223	Median	3.00	30.00	2.00	6.40	168.00	668.60
	[1988–1999]	Mean	4.51	27.84	2.73	7.07	194.47	1058.73
		St. dev.	3.73	9.03	2.02	6.68	106.56	1151.13
	5608	Median	4.00	45.00	2.00	6.90	210.00	1110.00
	[2000–2020]	Mean	5.54	57.41	2.96	10.52	212.40	1983.93
		St. dev.	4.37	21.76	2.12	11.53	108.72	2727.69
Stradbroke	4934	Median	3.00	45.00	2.00	3.70	150.00	470.00
	[1988–2020]	Mean	4.49	45.09	2.60	6.12	177.53	777.91
		St. dev.	3.76	17.47	1.89	7.05	96.07	842.09
	1225	Median	5.00	30.00	3.00	2.70	149.00	689.00
	[1988–1999]	Mean	5.68	30.24	3.14	4.72	151.27	987.41
		St. dev.	4.17	8.16	2.14	4.62	85.99	947.41
	3709	Median	3.00	45.00	2.00	3.80	168.00	420.00
	[2000–2020]	Mean	4.10	49.99	2.43	6.58	186.20	708.72
		St. dev.	3.53	16.95	1.77	7.62	97.65	792.35
Gold Coast	2861	Median	4.00	45.00	2.00	2.70	149.00	548.30
	[1988–2020]	Mean	5.55	46.94	2.70	4.73	157.31	966.11
		St. dev.	4.68	17.07	1.73	5.71	92.51	1183.84
	581	Median	4.00	30.00	3.00	2.30	149.00	560.00
	[1988–1999]	Mean	5.96	29.21	2.92	2.50	130.80	887.28
		St. dev.	1.07	7.11	1.84	1.87	59.36	943.67
	2280	Median	4.00	45.00	2.00	3.20	149.00	540.00
	[2000–2020]	Mean	5.45	50.20	2.65	5.30	164.07	986.20
		St. dev.	4.57	16.23	1.70	6.20	98.07	1236.99

Source: State of Queensland (2020a). Notes: Hull units (HU) were calculated based on HU = (L x B X D x 0.6) / 2.83, with L for length, B for beam, and D for depth of the vessel. The factor 0.6 represents a block coefficient to standardise variations in boat design and the factor of 2.83 represents a constant which converts cubic meters to units of 100 cubic feet.

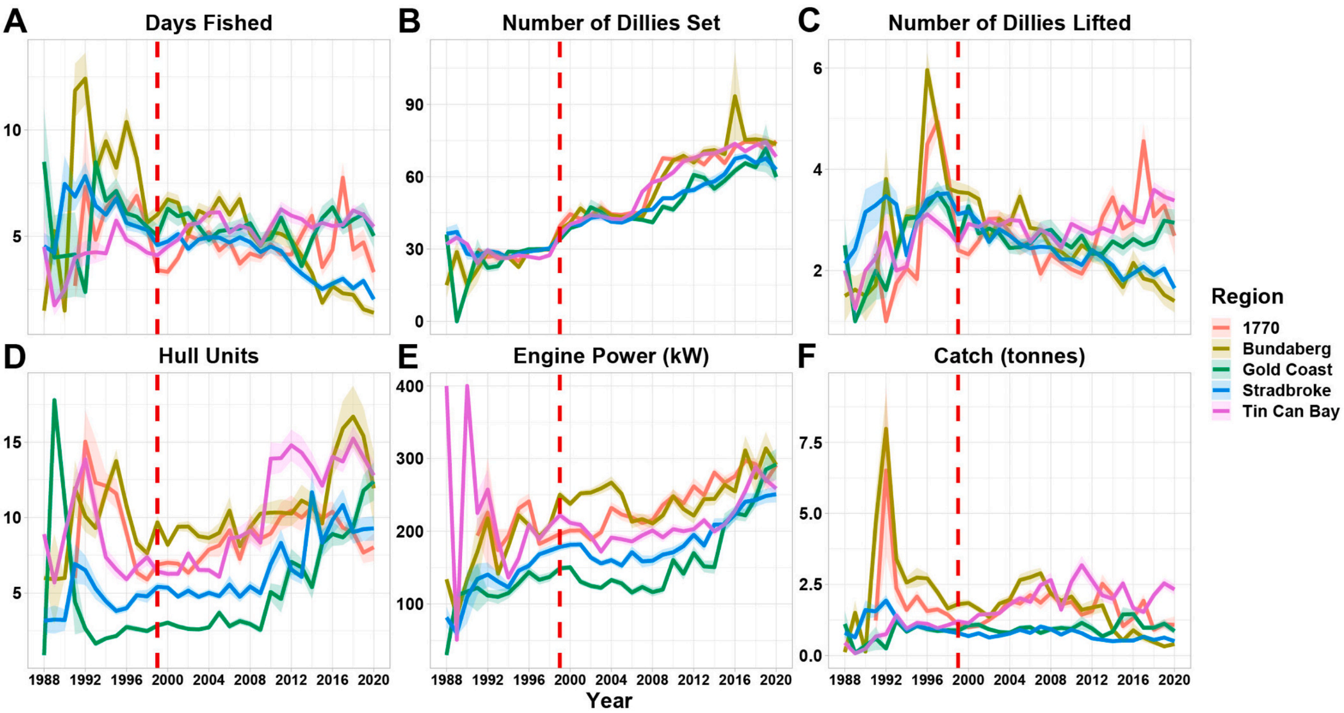

Fig. 3. Mean of input and output variables over time. Notes: Standard error of the mean shown as shaded area around mean for respective fishing regions. Red dotted line identifies the year 1999, when significant fishery management changes to inputs were introduced.

2008; Australian Government, 2012). Average hull units also increased with time (i.e., a shift to larger vessels), as did the engine power. The average number of dillies lifted increased in some regions while it decreased in others. The average catch decreased during the 2000 s compared to the 1990 s and remained approximately the same thereafter. The number of licenses for vessels operating in this fishery also reduced significantly over time (see Fig. 2).

3.2. Methods

3.2.1. Data envelopment analysis (DEA)

In this study, DEA was used to assess the relative performance of vessels operating within the five commercial spanner crab fishery regions in Queensland over time. DEA is a non-parametric, linear programming method proposed by Charnes et al. (1978) and based on work by Farrell (1957). DEA is widely applied in the field of economics (see within Boussofiane et al., 1991) and in the context of fisheries management (e.g., Maravelias and Tsitsika, 2008, Vázquez-Rowe and Tyedmers, 2013, Madau et al., 2018, Schrobback et al., 2015, Vestergaard et al., 2003, Rust et al., 2017) to measure the relative efficiency of individual vessels within a fleet, given a set of inputs and produced outputs. Hence, DEA can be considered as a benchmarking tool to assess the performance of individual vessels against all other vessels in a fleet, including the most efficient vessels which define the efficient or best-practice frontier (Coelli et al., 2005). Therefore, the best-practice production frontier 'envelopes' production practices that are less efficient.

DEA does not impose any assumption about the functional form of the production function and thus is less prone to misspecifications. However, as a non-parametric method, DEA cannot account for statistical noise and hence efficiency estimates may be biased if the production process is characterised by stochastic elements (Holland and Lee, 2002). While DEA also offers advantages over stochastic frontier analysis for the estimation for efficiency measures of multi-output fisheries, this is not a specific feature of DEA that is required here for the assessment of single-output fishery.

In this study, an output-orientated DEA model was considered given the assumption that fishers aim to catch the maximum output with their given inputs. It should be noted that input (e.g., maximum number of dillies that can be set per licenses and month was 45 in 1999) and output restrictions (e.g., TACC managed ITQ) have been introduced gradually for the spanner crab fleet over time (State of Queensland, 2020b; State of Queensland, 2020a). Yet, this does not affect the choice of model orientation as output restrictions equally apply to all vessels of the fleet. Inputs are allocated by individual vessels to derive the output as defined under their individual quota level. Furthermore, from a business perspective, vessel operators should aim for a high ratio of this input-output relationship, which would include taking their full allocation under prevailing restrictions. Given quota are transferable, it can be assumed that individuals will aim to adjust their quota holdings to maximise their ability to catch spanner crab given other constraints on their activities.

The assumption of the output-orientated DEA model is that the output vector of the jth vessel is expanded radially until the combination of inputs of the vessel reaches the efficient output frontier of production possibilities set for all other vessels in the fleet (Pascoe and Herrero, 2004). The model can be described as:

Maximise ϕ_1

$$\textit{Subject to} \quad \phi_1 y_{j,m,t} \leq \sum_j z_j y_{j,m,t} \quad m \in M \tag{1}$$

$$x_{1,n,t} \geq \sum_j z_j x_{j,n,t} \quad n \in N$$

where ϕ_1 is scalar indicating by how much output by vessels can be increased relative to the efficient frontier of the fleet; $y_{j,m,t}$ is the amount of output m by vessel j in year t; $x_{j,n,t}$ is the amount of input n used by vessel j in year t, and z_j represents weighting factors. The inputs are separated into variables (e.g., effort as days per month fished, number of dillies lifted) which allow values to change in the short-run and fixed inputs (e.g., dillies set, engine power, hull size) for which values can only change in the long-run. It should be noted that dillies set is here considered as a quasi-fixed input due to the restrictions on the maximum number of dillies that can be set by a license holder (State of Queensland, 2021).

To allow for changes in the relationship between fixed inputs and outputs, variable returns to scale (VRS) are imposed by adding the constraint $\sum_j z_j = 1$. This allows for increasing, constant, or decreasing returns within the production process. The use of VRS in DEA models is considered to account for circumstances such as changing government regulation and imperfect competition, which may cause vessel operators to be unable to operate at the optimal scale (Färe et al., 1983; Banker et al., 1984; Coelli et al., 2005). The alternative to the VRS assumption is the consideration of constant returns to scale (CRS), which is imposed by removing the above constraint.

Four productivity and efficiency measures are considered in this study: technical efficiency (TE), capacity utilisation (CU), unbiased capacity utilisation (UCU) and scale efficiency (SE). These measures have been previously used in fisheries analyses to assess productivity. For example, Rust et al. (2017), Madau et al. (2018) and Vázquez-Rowe and Tyedmers (2013) used DEA to assess the TE measure in their work in the context of fisheries. Previous studies that have applied CU and UCU include Lazkano (2008), Pascoe and Tingley (2007), Kerstens et al. (2006), and Vestergaard et al. (2003).

The TE measure describes the difference between output that is produced with a set of inputs (e.g., dillies set, engine power) and the production frontier, which is defined by the maximum output that could be produced with those inputs (output-oriented) (Farrell, 1957).

Essentially, TE measures a vessel's ability to produce more output with the same fixed and variable inputs. TE is estimated from the output of the model in Eq. 1 by:

$$TE = \phi_1^{-1} \tag{2}$$

Pascoe et al. (2004) define the capacity of a vessel as the maximum level of output that it could be expected to produce under normal working conditions. Hence, CU is the level at which a vessel is achieving its potential (capacity) output given its physical characteristics (i.e., fixed inputs such as engine power, hull size) (Pascoe et al., 2004; Pascoe and Tingley, 2007). CU is derived by solving Eq. 1 using fixed inputs only. The obtained measure, ϕ_2, is used to calculate the CU score by:

$$CU = \frac{y}{\phi_2 y} = \frac{1}{\phi_2} = \phi_2^{-1} \tag{3}$$

Färe et al. (1989) argued that the CU measure is biased downward since it considers both capacity utilisation (fixed inputs) and technical efficiency (fixed and variable inputs) and propose an adjustment to separate the CU component in order to correct for this bias. Hence, the UCU measure as suggested by Färe et al. (1989) can be described as:

$$UCU = \frac{\phi_{1y}}{\phi_{2y}} = \frac{\phi_1}{\phi_2} \tag{4}$$

A key advantage of estimating UCU is that the random error embodied in both the raw capacity utilisation and technical efficiency measures largely cancel out (Holland and Lee, 2002).

Lastly, SE is used to measure the difference between vessel's output and the output at the optimal production scale, that is, the output where returns to scale are constant (Frisch, 1964). The SE is estimated as the ratio of TE with CRS (TE(CRS)) to TE with VRS (TE(VRS)):

$$SE = \frac{TE(CRS)}{TE(VRS)} \tag{5}$$

In case the vessel's score for TE(CRS) and TE(VRS) differ, it can be concluded that the vessel operated at a scale that is less than efficient (i.e., either too big or too small). The result will offer insight into how close vessels perform to their technically optimal scale. As with UCU, SE is less impacted by random error due to the error in each component measure cancelling out.

For all four measures, an efficiency score of 1 indicates the vessel is operating on the production frontier, that is the best performing vessel against which other vessels in the fleet are compared. A score less than 1 suggests the presence of inefficiency for the respective efficiency measure.

3.2.2. *Window analysis*

Considering the available time series panel data (see Section 3.1) and the aim of this study to identify temporal and spatial efficiency performance of the spanner crab fleet, DEA was applied using a 'window analysis' approach (Bergendahl, 1998, Charnes et al., 1984, Paradi et al., 2004). In this approach, 'window' refers to the reference period selected for determining of the best-practice efficiency frontier (Bergendahl, 1998, Paradi et al., 2004, Petridis et al., 2016). It assumes that the performance of a vessel operating in a specific time window, here selected as one year, and fishing region is compared with its performance in other time windows, e.g., other years, in addition to the performance of the other vessels that operated in the same time window and fishing region (e.g., Paradi et al., 2004, Petridis et al., 2016). Hence, an individual vessel is treated as a 'different' or an independent vessel in each year and in each fishing region (e.g., Petridis, 2016). The mean value of vessels' efficiency performance estimated for each year and each fishing region is compared against the best-performing vessel in the same and the same fishing region. The comparison of the annual mean efficiency scores over time, here 1988–2020, provides information about the moving average of the respective efficiency measures in each fishing region (e.g., Paradi et al., 2004, Petridis et al., 2016).

A key reason for selecting the window analysis approach is because it accounts indirectly for changes in the broader environment in which the fleet is operating at each point in time. For example, natural changes to biological/ecological conditions (for which no data was available) may have affected vessels' input-output relationship over time (i.e., 1988–2020). By using the window benchmarking approach, the environmental conditions (e.g., changes to stock abundance and food net, extreme weather events) in a selected year are assumed to apply to all vessels, including the most efficient vessels, that operated within the same fishing region. Furthermore, technological change (e.g., upgraded fixed inputs such use of newer vessels and more powerful engines, use of other equipment for which no data is available) which likely occurred over the entire time period and is also indirectly accounted for when comparing the annual moving averages of the efficiency measures (e.g., Paradi et al., 2004). Hence, this method acknowledges that the system in which the fleet operates (e.g., including biological, technological, regulation, behavioral components, fleet composition) continuously evolves over time (Petridis, 2016). Not accounting for such conditions in the proximity of time at which vessels operate (e.g., selecting the efficiency benchmark from all observations over the 1988–2022 period) when determining the best-practice frontier would generate incoherent results (e.g., comparing recent fleet performance with past best-practice frontiers when the broader environment may have changed significantly).

3.2.3. *Treatment of inputs and outputs across time*

Input and output controls imposed by the management authority can influence the economic efficiency of vessels (Greenville et al., 2006). Two time periods are considered to assess potential differences in efficiency measures prior to and post the introduction of the *Fisheries (Spanner Crab) Management Plan 1999*, which resulted in gear restrictions such as number of dillies permitted to be used and net specifications, and the commencement of a TACC (State of Queensland, 2001). The first period includes production years ranging from 1988 to 1999 (subsequently denoted as "before 2000") while the second period includes the years 2000–2020 (subsequently denoted as "after 2000") (see Table 2).

An important assumption for the first period is that only the inputs

Table 2
Assumptions for different time periods.

Assumptions	Period 1: Before 2000	Period 2: After 2000
Time period focus	1988–1999	2000–2020
Fixed inputs	Engine power, hull size	Dillies set, engine power, hull size
Variable inputs	Dillies set, effort, dillies lifted	Effort, dillies lifted
Output	Output	Output
Fishing regions	All five regions	All five regions
Implicit considerations	Limited input and output controls implemented	Considerable input and output controls implemented

hull size and engine power are considered as fixed, while dillies set, effort and dillies lifted were considered as variable inputs to derive the output. For the second period (2000–2020), the variable number of dillies set was also treated as a fixed input to reflect the implementation of this restriction according to the *Fisheries (Spanner Crab) Management Plan 1999* (State of Queensland, 2001) (Table 2). Given the TACC and ITQs (introduced in 1999 (State of Queensland, 2020b; State of Queensland, 2020a)) are set based on regular CPUE assessments, which is assumed to provide an indicator of stock health, it was assumed for 2000–2020 that the fleet operated within sustainable yield limits, notwithstanding the need for a further significant reduction in TACC in 2018 in response to declining stock status (State of Queensland, 2022).

To assess differences between the mean scores of the periods before and after 2000, a Student’s t-test was undertaken assuming unequal variances and was further adjusted for multiple comparisons using the Benjamini and Hochberg correction method (Benjamini and Hochberg, 2000; Benjamini and Hochberg, 1995). To determine the effect of re-assigning dillies set from a variable input in the period before 2000 to a fixed input in the period after 2000, the analysis was also undertaken with these treated as variable inputs in all time periods, with the results compared to the base models through bivariate Pearson correlation analysis.

4. Results

4.1. Efficiency and productivity scores

The results for the four productivity measures in Fig. 4 represent the moving annual means of efficiency scores with standard errors for the five fishing regions which were derived using the DEA window analysis approach. The results in Fig. 5 compare the median of annual mean scores for all efficiency measures across the two time periods under review.

The mean annual TE scores for the vessels operating in the five different fishing regions were relatively variable across years and regions in the period before 2000 (1988–1999) compared to the mean scores derived for the period after 2000 (2000–2020) (Fig. 4A). This result is likely an effect of the limited annual observations during 1988–1993 (e.g., 17–132). High interannual fluctuation in the mean scores including their standard errors before 2000 can be seen in other productivity measures (Fig. 4). The outcomes in Fig. 5A show that the aggregated mean annual TE scores for both time periods were relatively low, ranging between 0.30 and 0.51. In comparison, vessels on the production frontier have a technical efficiency score of 1.00. The aggregated mean TE scores have slightly decreased in the period after 2000 compared to before 2000 (Fig. 5A). The decrease in TE scores across both periods was statistically significant as indicated by the p-value of the Student’s t-test for all five fishing regions (presented on top of the respective boxplots in Fig. 5A).

The boxplot for the Stradbroke region in Fig. 5A, supported by the blue line graph in Fig. 4A, suggests that vessels operating this region were the least technical efficient on average during 2000–2020, although the average TE scores in the region improved in recent years. In contrast, vessels catching spanner crabs in Tin Can Bay appeared to have had slightly higher TE scores in the period after 1999 compared to

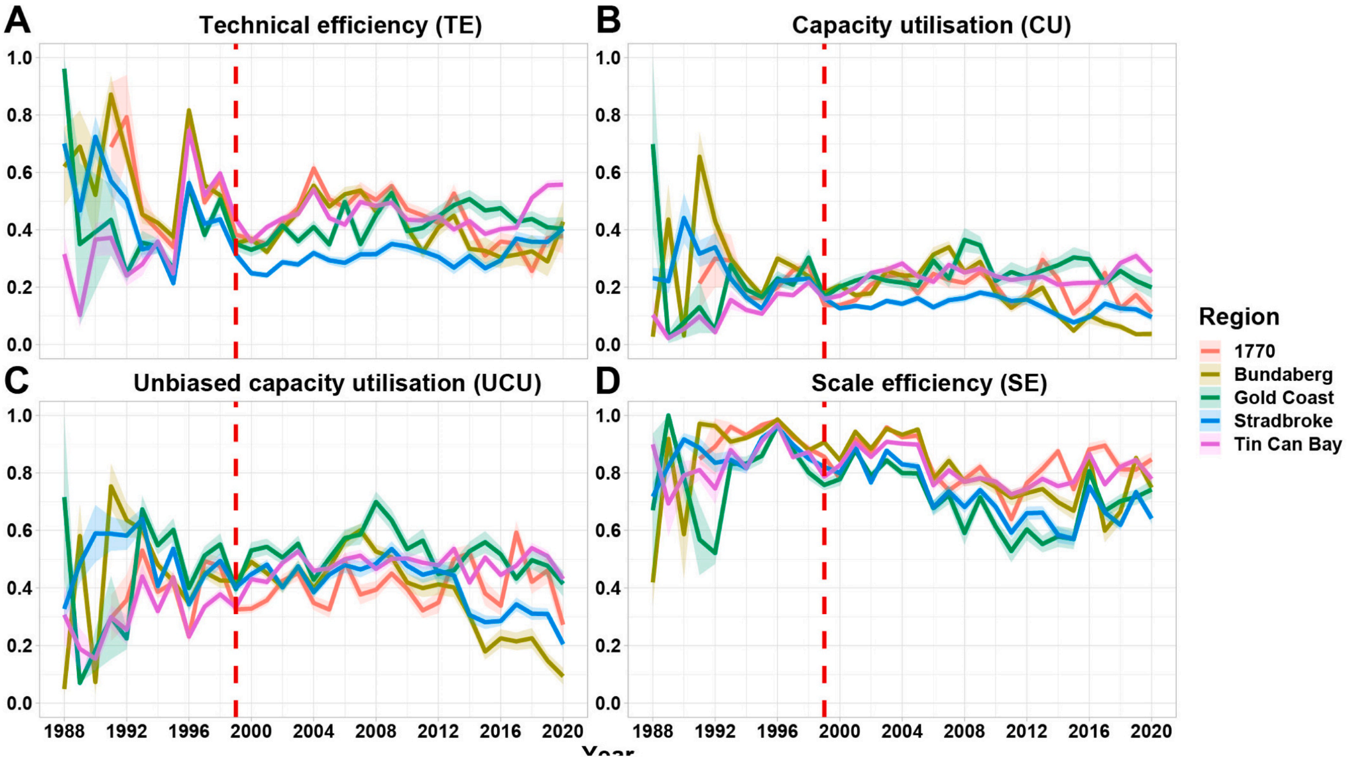

Fig. 4. Mean annual scores (with shaded standard errors) over time for key efficiency measures of the Queensland spanner crab fishery. Notes: Standard error of the mean score is shown as shaded area around the mean score line for respective fishing regions. The red dotted line identifies the year 1999, at which significant fishery management changes were introduced.

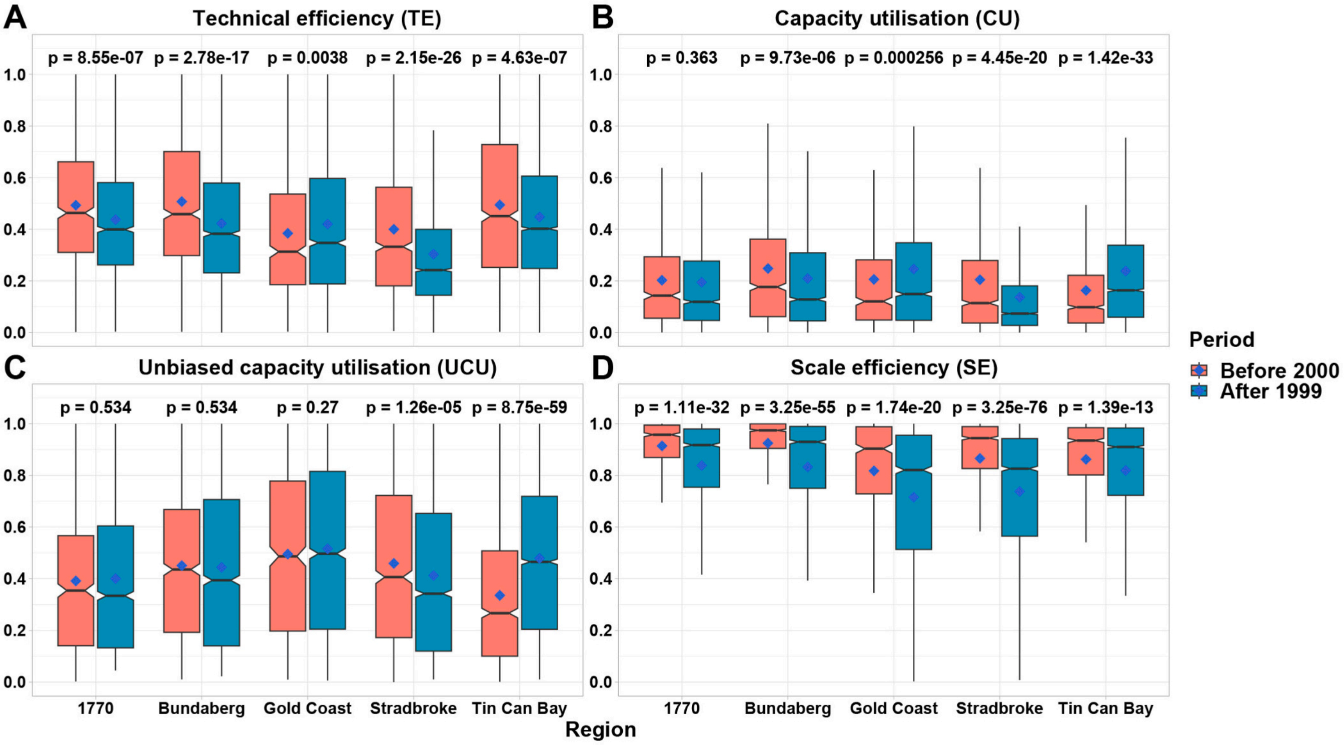

Fig. 5. Comparison of aggregated annual mean scores for various efficiency measures across both periods and across fishing regions. Notes: The height of the box indicates interquartile, the midline indicates 50th percentile (median). Whiskers of the boxplot signify the minimum and maximum scores. Whiskers of the boxplot signify 1.5 *Interquartile range. A blue diamond indicates the aggregated group (i.e., observations before 2000 and observations after 2000) mean score for the respective fishing regions. Notches in the boxplots allow to visually compare the significance of the median between groups. If the notches do not overlap, there is evidence that the medians are different. The p-value was calculated using a Student's t-test assuming unequal variance and compares the group mean scores for respective fishing regions across both periods.

vessels fishing in the other regions (Fig. 4A, Fig. 5A). The findings about TE scores for Stradbroke and Tin Can Bay align well with both region's trends in variable inputs (i.e., days fishes, dillies lifted) as shown in Fig. 3.

The results for the bias-adjusted UCU measure were slightly higher than the CU scores across time and for all regions as expected, ranging between 0.34 and 0.52 (Fig. 5B, Fig. 5C). The p-values for the t-test suggest that the aggregated scores across the two time periods were not significantly different for the regions 1770, Bundaberg and Gold Coast. Notable in Fig. 4. B and Fig. 4C is that the CU and UCU scores for the Bundaberg region have more recently fallen (2000–2020) below the scores of other regions, which is not observable from the results in Fig. 5B and Fig. 5C due to the aggregation of mean scores across time periods. Overall, the derived results for UC and UCU suggest that fixed inputs such as hull units, engine power and dillies set (only during 2000–2021) remain relatively poorly utilised by vessels operating in this fishery.

Given a value of UCU, the potential catch (i.e., full capacity output) can be estimated from catch/UCU. From the results, the fishing fleet, if fully utilised, could have increased catch by between 92 % (corresponding to the UCU=0.52) and 194 % (corresponding to the UCU=0.34). Conversely, the same catch could have been taken by a smaller fleet, the exact size determined by the relative distribution of UCU scores (Tingley and Pascoe, 2005; Pascoe et al., 2013).

The outcome of the analysis also shows that the mean scores for SE were very high during 1988–1999 in all fishing regions ranging from 0.82 to 0.93 (Fig. 5D). The SE scores slightly decreased during 2000–2020 across all regions fluctuating between 0.72 and 0.84 (Fig. 5D). Fig. 4 shows that the decrease in SE scores specifically occurred from 2006. This suggests that the fleet on average has moved further away from its optimal production scale (determined at the scale at which SE=1).

Although only relatively small differences in scores of efficiency measures between the two periods were found in our analysis (Section 4.1), we tested if these differences were an artefact arising from the treatment of dillies set in different time periods (see Table 2) or from other influences.

The analysis was conducted using two scenarios. Scenario A involved estimating all productivity measures with dillies set as variable inputs across the entire time series, 1988–2020, and all fishing regions. Scenario B (the default analysis described above) involved estimation of the productivity measures with dillies set as fixed input). The results are shown in Fig. 6, which also includes the correlation between the results given the different scenarios. Estimates of TE and SE were identical under both scenarios ($r = 1$), and highly correlated for CU and UCU ($r = 0.92$) (Fig. 6). This result suggests that there are only negligible differences in the estimated productivity scores on average based on the treatment of dillies set as variable or fixed input.

5. Discussion

The results of this study suggest that TE, UCU, and CU within the spanner crab fleet have been fluctuating but remained relatively low over time in all five fishing regions, while SE appears to have only recently declined.

The low TE scores imply that the use of inputs across most of the fleet has been relatively inefficient over time and space compared to the most technical efficient vessels that operate on the production frontier. Similar results were found for CU and UCU, which indicates that there is a large proportion of excess capacity present within the fishery. This may imply potential overinvestment in fixed inputs, e.g., boat size (hull units), engine power, and the overall number of boats being too high

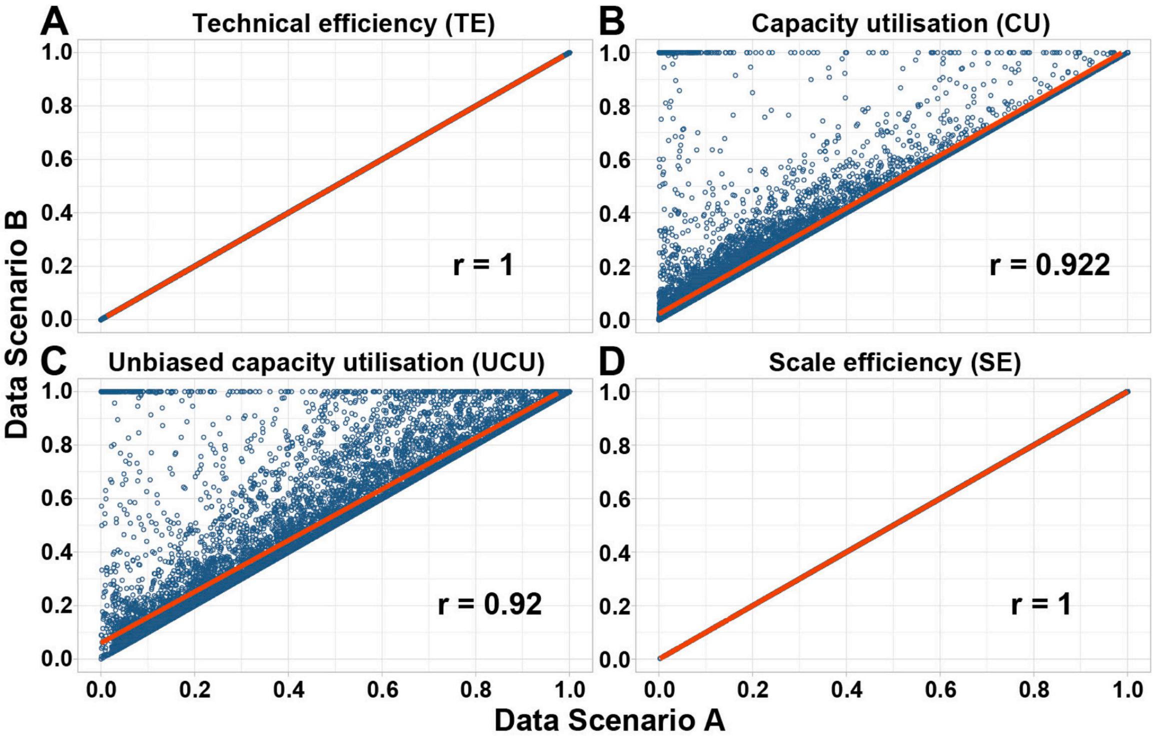

Fig. 6. Pearson' s correlation coefficient for comparison of scenarios. Notes: r is the Pearson correlation coefficient.

given the allowable available catch. Overall, these results suggest that the economic performance of the fleet was substantially lower than it could have been.

The absence of data for additional variables limits our ability to explain reasons for the low TE, CU, and UCU scores across time and fishing regions. Yet, understanding the drivers for the low efficiency scores will assist to better inform recommendations for fishery management. For example, the low efficiency scores could be due to the presence of part-time or "hobby" fishers operating in the commercial spanner crab fleet, although this would require a substantial proportion of these to reduce the overall mean efficiency levels by this degree. Such findings were also reported for the Sydney rock oyster fishery in Queensland (Schrobback et al., 2015). Economic data such as input costs, profits, revenue and data on skipper demographics (e.g., age, experience, education) are needed to verify reasons for the identified low efficiency scores such as shown in similar studies (e.g., Mkuna and Baiyegunhi, 2021, Squires and Kirkley, 1999, Schrobback et al., 2015).

Although the study indirectly considered the impact of potential environmental, technological, or other external drivers on the vessel's efficiency performance using the window analysis approach, it is unclear which specific conditions may have affected the input-output relationship within the fleet. For example, Spencer et al. (2019) found that environmental drivers had a substantial impact on spanner catch rates, e.g., strength and direction of current, region-specific physical oceanographic processes such as bottom temperatures and upwellings. The impact of these drivers was also found to affect stock conditions in different parts of the fishery, reflecting the distinct oceanographic features of the respective fishing areas (Filar et al., 2021). Such drivers may explain some differences in TE between regions. Potentially, those fishers with the high TE scores in each region (who are defining the frontier) may be better skilled in terms of understanding the effects of these drivers on productivity and avoiding fishing regions or times when conditions are adverse (e.g., Jin et al., 2002). However, there is no information available to test this.

Additional data could also further explain why the Stradbroke region returned consistently low scores for TE and CU (Fig. 3), which appears to be due to a lower use of inputs (e.g., fewer days fished, low hull units and engine power, see Fig. 3) and potentially lower relative abundance of spanner crabs compared with other regions. Lower catch rates may result in less effort being applied (as the marginal revenue is lower).

Based on our results the change in fishery management, represented by the treatment of dillies set as an input of our analysis, appears unlikely to have substantially impacted the efficiency and productivity of the spanner crab fleet (Fig. 5). Furthermore, the significant TACC reduction in 2018 (State of Queensland, 2022) may not have provided a large incentive for inefficient vessels to leave the fleet. This can be seen from the TE scores in Fig. 5 which remain about the same compared to before 2018, while CU and UCU scores appear to have decreased further after 2018. This may change over time, as adjustments in fixed inputs depend on fishers' ability to reduce their overinvestment in capital (e.g., access to financial capital to invest in smaller vessels). With limited alternative use of these vessels, the opportunity cost of remaining in the fishery may be low.

While the results suggest that the reduction of TE and SE since 2000 (see Fig. 4A, Fig. 4C) may not be attributed to changes in management as considered in this study, it is likely that other management changes (e.g., subsequent fishery input regulations (State of Queensland, 2019; State of Queensland, 2008)) may have influenced the decreasing trend in these scores. For example, the average number of dillies set within the fishery sharply increased in 2008 (see Fig. 3). This is likely due to general fishing permits allowing individual fishers in the spanner crab fishery to use more than the 45 dillies stipulated in the Fisheries Regulation 2008 (State of Queensland, 2008; Australian Government, 2012).

Furthermore, the changes to permit-issuing policies may have caused the increase in hull size and engine power of vessels (fixed inputs), while the average output decreased slightly (likely due to decrease in TAC and licenses) (Fig. 3). Such dynamics could be an explanation for the decrease in TE and specifically for SE which commenced around the same time.

The overall results from this study are similar to findings in other Australian crustacean-based fisheries. For example, Kompas et al. (2004) and Greenville et al. (2006) identified a gap between actual and optimal economic performance levels of Australia's northern prawn fishery and the New South Wales prawn trawl fishery respectively, while Pascoe et al. (2013) and Rust et al. (2017) found excess capacity in the Torres Straits and Tasmanian rock lobster fisheries, respectively. A challenge that these authors identified as contributing to this situation includes insufficient prioritisation of economic objectives in the management of these fisheries.

While the spanner crab fishery is already tightly managed through a range of output and input controls with a focus on the ecological sustainability of the fleet, the management of its economic performance appears to be limited until recently when a formal harvest strategy with an economic-focused biomass target was introduced. As a result, the identified inefficiencies that occurred over time (i.e., TE, UCU) have not been addressed earlier by the fishery management. Hence, the development of specific economic objectives (e.g., technical efficient use of inputs, economic profitability of the fleet, continued employment (e.g., Hilborn, 2007) may be needed as a basis to increase the economic efficiency of the fleet, which in turn requires vessels to be both efficient and fully utilised. However, the development of the economic objectives needs to be made in consideration of the complete set of biological, ecological, social and governance objectives for the fishery (Ogier et al., 2020). Eliciting and prioritising these multi-objectives will require further research, including stakeholder engagements.

A program of regular collection of economic information such as annual vessel revenues, profits, operation costs, labor use, and fisher socio-demographic characteristics (e.g., skipper experience, education, age, fishing strategy) has been instigated recently as part of the Queensland Sustainable Fisheries Strategy (State of Queensland, 2017). Such data could be used to refine future analyses as a basis for fishery management decisions that focus on the improvement of the economic performance of the fleet. Understanding the level, distribution, and drivers of efficiency in a fishery on an ongoing basis is fundamental for achieving maximum economic yield.

Although the dataset used for this analysis only offers a limited number of variables (see Table 1), the relatively long time series and spatial data about vessel movements provide scope for further assessment. For example, closer examination of individual vessel dynamics could help understand whether there are any behavioral aspects that may explain the economic performance of the fleet.

6. Conclusion

The aim of this case study was to assess potential temporal and spatial differences in productivity measures of vessels operating in the Queensland spanner crab fishery. This included an analysis of the impact of fishery management changes on productivity measures.

The results showed that the fleet has been operating at a relatively low average level of technical efficiency and with an underutilised capacity over time and across all five fishing regions. SE was high historically but decreased slightly since 2006 for all regions. Changes in the management of the fishery did likely not substantially impact the economic performance of the fleet. The lack of data for additional variables (e.g., revenue, profit, costs, skipper demographics) limited an analysis of potential causes for the identified low productivity scores. While such data have been collected in 2019 and 2020, continued collection of such information and its assessment should be considered by the fishery's management.

Furthermore, clear and coherent economic fishery management objectives (e.g., viability and efficient of commercial fishers, maximising net economic returns) need to be developed, which align with the fishery's biological, ecological, governance, and social objectives (Ogier et al., 2020; Hilborn, 2007). Such objectives can guide managers to improve the fishery performance of the fleet.

Moreover, the management authority should consider the development of clear economic objectives and the monitoring of the fleet's economic performance to ensure a balance between maximum economic yield and ecological sustainability of the spanner crab fishery.

The study shows that efficiency and productivity analysis of fisheries can provide considerable information on the economic status of a fishery and can identify potential problems that are not otherwise apparent. Hence, efficiency and productivity analysis should be a method that is widely applied by fishery management.

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CRediT authorship contribution statement

Peggy Schrobback: Conceptualisation, Methodology, Software, Formal analysis, Data curation, Writing - original draft, Visualization, Project administration; **Karsten Schrobback:** Software, Data curation, Visualization; **Sean Pascoe:** Conceptualisation, Methodology, Writing - review & editing; **Stephanie McWhinnie:** Project administration, Funding acquisition, Writing - review & editing; **Eriko Hoshino:** Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The authors do not have permission to share data.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2023.106789.

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