http://www.egejfas.org
Ege Journal of Fisheries and Aquatic Sciences, 42(1), 56-63 (2025)

Su Ürünleri Dergisi (2025)
DOI: 10.12714/egejfas.42.1.08

RESEARCH ARTICLE **ARAŞTIRMA MAKALESİ**

Fuel efficiency of trawlers per kilogram of landed catch: Insights for decarbonizing fisheries in Türkiye

Trol teknelerinin karaya çıkarılan bir kilogram av başına akaryakıt verimliliği: Türkiye'de balıkçılığın karbonsuzlaştırılmasına yönelik çıkarımlar

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Received date: 19.12.2024 *Accepted date: 20.02.2025*

How to cite this paper:
Fakıoğlu, Y.E. (2025). Fuel efficiency of trawlers per kilogram of landed catch: Insights for decarbonizing fisheries in Türkiye. *Ege Journal of Fisheries and Aquatic Sciences, 42*(1), 56-63. https://doi.org/10.12714/egejfas.42.1.08

Abstract: Demersal trawling is among the most energy-intensive fishing practices worldwide, primarily due to the drag and frictional force caused by their heavy components. This study aimed to estimate fuel use intensity (litres of fuel per kilogram of landed catch) and associated carbon dioxide emissions of Turkish trawl vessels, most of which still operate using traditional trawl nets equipped with heavy otter boards and lead ground gear, increasing towing resistance and consequently fuel consumption. Data from 129 commercial fishing trips conducted by 13 trawl vessels between 2021 and 2022 were analysed using Generalized Linear Models (GLMs). Overall, to catch one kg of landed marine product, the trawl vessels consumed approximately a median value of 1.22 litres of fuel and emitted 3.21 kg of CO_2 for the given period. Vessel length, engine power and the target species group were the main factors affecting the fuel use intensity. The results obtained from the study provide critical insights for implementing effective management measures to decarbonize fisheries, offering practical recommendations for decision makers. Expanding the dataset to encompass a broad range of vessels, regions, and fishing seasons would further enhance the generalizability and applicability across different fisheries.

Keywords: Energy use, low-impact-fuel-efficient fishery, carbon footprint

Öz: Dip trolleri, ağır bileşenlerinden kaynaklanan sürükleme direnci ve sürtünme kuvveti nedeniyle dünyanın en yoğun enerji tüketen balıkçılık yöntemlerinden biridir. Bu çalışma, çoğu hala çekme direncini ve yakıt tüketimini artıran ağır kapılar ve kurşun yakalarla donatılmış geleneksel trol ağlarıyla çalışan Türk trol teknelerinin yakıt kullanım yoğunluğunu (karaya çıkarılan bir kilogram av başına kullanılan yakıt) ve ilgili karbondioksit emisyonlarını tahmin etmeyi amaçlamıştır. 2021-2022 yıllarında 13 trol teknesiyle gerçekleştirilen 129 ticari balıkçılık seferinden elde edilen veriler Genelleştirilmiş Doğrusal Modeller kullanılarak analiz edilmiştir. Genel olarak, bir kilogram deniz ürünü avlamak için medyan değeri yaklaşık 1,22 litre yakıt tüketilmiş ve söz konusu dönemde 3,21 kg CO_2 salınmıştır. Tekne boyu, motor gücü ve hedeflenen tür grubu, yakıt kullanım yoğunluğunu etkileyen başlıca faktörler olarak belirlenmiştir. Mevcut çalışma, balıkçılık sektörünün karbonsuzlaştırılması için etkili yönetim önlemlerinin uygulanmasına yönelik kritik bilgiler sağlayarak karar alıcılar için pratik öneriler sunmaktadır. Daha geniş filo, farklı bölgeler ve balıkçılık sezonlarını kapsayacak şekilde veri setinin genişletilmesi, elde edilen sonuçların genellenebilirliğini ve farklı balıkçılıklarda uygulanabilirliğini daha da geliştirecektir.

Anahtar kelimeler: Enerji kullanımı, düşük-etkili-yakıt-tasarruflu balıkçılık, karbon ayak izi

INTRODUCTION

The environmental impact of fuel consumption in the fishing industry has become a critical concern due to increasing consumer awareness and efforts to combat climate change. Bottom trawling, a widely used fishing method, is particularly scrutinized for its high fuel use, greenhouse gas (GHG) emissions, and potential disturbance of seabed sediments, which may release additional carbon into the ocean (Sala et al., 2021; Hilborn et al., 2023). While bottom trawls contribute to approximately 26% of global marine catches and support millions of livelihoods (Steadman et al., 2021), they are also recognized as one of the most fuel-intensive fishing methods due to the drag and friction caused by heavy gear components (Tyedmers, 2001; Suuronen et al., 2012; Sala et al., 2022). Such fishing practices naturally result in remarkably higher GHG emission (Winther et al., 2020; Ziegler et al., 2021).

Previous research on fuel consumption per kilogram of landed marine product has been instrumental in assessing the carbon footprint of the fisheries sector and providing insights into energy efficiency and sustainability (Ziegler and Hansson, 2003; Thrane, 2004; Campos et al., 2011; Parker et al., 2017; Bastardie et al., 2022). According to those studies, fuel consumption in fisheries varies based on several factors, including vessel length, engine power, fishing gear type, target species, catch per unit effort, and operational characteristics such as distance travelled and towing speed (Davie et al., 2014; Parker et al., 2017; Kristofersson et al., 2021). Using different methods, global studies have found that the amount of fuel used in fisheries ranges from 0.44 to 1.7 $tFuel \cdot tCatch^{-1}$ (Tyedmers et al., 2005; Parker et al., 2018; Greer et al., 2019). Despite technological advancements aimed at improving energy efficiency—such as modifications to gear design and vessel operations—fuel consumption trends in some regions have increased over time(Hornborg et al., 2018).

In Türkiye, bottom otter trawling is a key component of the multispecies fishery, targeting high-value demersal species such as red mullet (*Mullus barbatus*), whiting (*Merlangius merlangus*), hake (*Merluccius merluccius*), and deep-water shrimps (*Parapenaeus longirostris, Aristaeomorpha foliacea, Aristeus antennatus*). However, studies on fuel consumption in the Turkish fishing fleet remain limited, despite the fleet's diverse fishing grounds and gear configurations. Most Turkish trawl vessels still operate using traditional Mediterranean trawl nets with heavy otter boards and lead ground gear, increasing towing resistance and fuel intensity. The impact of towing resistance created by such equipment during a fishing operation has significant implications for fuel use intensity, highlighting a significant knowledge gap. While some research has examined fuel use in purse seine and bottom trawl fisheries in specific regions (Demirci and Karaguzel, 2018; Sarica and Demir, 2021), a comprehensive assessment of fuel consumption and its determinants in Turkish bottom trawl fisheries is lacking. Nevertheless, recent studies have begun to shed light on different fishing gears, emphasizing their efficacy, such as utilizing artificial intelligence based models to predict the power of the main engine and the pollutants emitted by fishing vessels (Ozsari, 2023) or modifying beam trawls to improve fuel efficiency in the southern Black Sea sea snail (*Rapana venosa*) fishery (Kaykaç et al., 2017).

This study investigates the key determinants of fuel use intensity in Turkish trawl vessels, focusing on vessel length, engine power, and target species. By providing estimates of fuel consumption and associated CO_2 emissions, this research aims to contribute to the optimization of fishing operations and support a more sustainable and energy-efficient trawl fishery. Specifically, the research questions addressed are as follows:

- What are the key factors influencing fuel use intensity in Turkish bottom trawl fisheries?
- How do vessel characteristics, such as length and engine power, impact fuel consumption?
- What is the relationship between target species composition and fuel use efficiency in Turkish trawl fisheries?

MATERIALS AND METHODS

Collection of landed catch and fuel consumption data

The landed catch and fuel use (litre per hour) data during the fishing operations were obtained from otter trawl vessel owners and/or captains who record their catch data systematically and precisely. To ensure accuracy, the catch and fuel consumption values were cross-checked against available fuel logs and, when possible, compared with the standardized questionnaires conducted by fisheries observers under the discards monitoring program. This study was based on 13 trawl vessels that were regularly monitored through phone call interviews during 2021 and 2022. The sample size was determined by data availability, operational constraints, and the willingness of vessel owners to participate. While this sample provides valuable insights into fuel use intensity in Turkish trawl fisheries, a larger dataset would enhance the generalizability of the findings. The commercial fishing trips were conducted in three different sub-geographical areas (GSAs); GSA 22 (Aegean Sea), GSA 24 (Levant Sea) and GSA 29 (Black Sea).

Data analysis

Each fishing trip was classified as fish or shrimp targeted depending on the main target species that were composed of mainly shrimp or fish. The amount of fuel consumed per kg of landed catch (FUI) was estimated in two steps. First the average fuel consumption per hour data was multiplied by total tow duration in each fishing trip by using Eq. (1):

$$\mathrm{fTRIP} = hFUEL\,[\mathrm{l}] \times TD_j\,[\mathrm{h}] \qquad (1)$$

where *hFUEL* is the fuel use (litre) per hour, which was obtained from fishers and *TD* represents the total tow duration in a single fishing trip *j*.

Subsequently, the amount of fuel consumed for each fishing trip (*fTRIP*) that was obtained from Eq. (1) was divided by the total landed catch in each fishing trip by using Eq. (2):

$$\mathrm{FUI} = fTRIP_j\,[kg] \,/\, TW_j\,[\mathrm{h}] \qquad (2)$$

where TW_j is the total weight of landed catch in a single fishing trip *j*.

To calculate the carbon dioxide emission, the method applied by Sala et al. (2022) was employed, assuming that the total amount of CO_2 released when burning one litre of diesel was reported as 2640 g. However, in this study, only the fuel consumption during active fishing (tow time) was considered, excluding time spent before and after capture. Using the fuel consumed per one kg of marine product, which was calculated by Eq. (2), the catch related CO_2 emission was estimated by Eq. (3):

$$\mathrm{cGHG}\left[kg_{ghg}/kg_c\right] = \mathrm{FUI} \times 2640\,g/l \times 10^{-3} \quad (3)$$

Generalized linear model

A GLM was performed using the MASS package (Venables and Ripley, 2002). The goal of this analysis was to build a model that could explain the relationship between the fuel consumption per one kg of landed catch (response variable) and vessel length (explanatory variable), engine power (explanatory variable) and targeted group of species (explanatory variable), either fish or shrimp. Since there was no shrimp fishery in the Black Sea, the data obtained from GSA 29 was not included in the model. To assess multicollinearity among the explanatory variables, a Variance Inflation Factor (VIF) test was performed. Any explanatory variable with a VIF value exceeding a threshold would indicate problematic collinearity. In such cases, the variable was excluded from the model to ensure that the relationships between the remaining variables were not confounded. For the logistic regression model, family = Gamma distribution was employed as this distribution was suitable for variables having highly skewed positive values. The model with the lowest Akaike's information criterion (AICc) was chosen (Akaike, 1974). DHARMa package containing quantile–quantile plot, residual investigation, and dispersion test was performed to assess whether the chosen model fits (Hartig, 2020; Araya-Schmidt et al., 2022). All statistical analyses and visualizations were performed in R (R Core Team, 2018).

RESULTS

Engine power and size of the trawl vessels investigated in the study were 316.2 kw and 17.0 m in length on average (Table 1). According to data provided by the trawlers, the average fuel consumed during a fishing operation provided by vessel owners was 30.3 l h^{-1} on average (Table 1). No correlation was detected between vessel lengths and engine powers (0.13, Figure 1).

Table 1. Technical specifications and fuel consumption per hour of the investigated trawl vessels (Values in parentheses are the 95% CI)

No. Trawl Vessels	LOA (m) 17.0 [14.7-19.4]	Engine Power (kW) 316.2 [272.5-359.8]	Fuel Consumption (l h^{-1}) 30.3 [24.87-35.75]
1	16.8	320.8	45.0
2	14.9	447.8	40.0
3	17.3	368.9	40.0
4	19.7	373.1	38.0
5	20.8	335.8	35.0
6	19.9	313.3	35.0
7	14.9	298.5	25.0
8	14.0	212.7	25.0
9	12.2	186.5	22.0
10	14.3	335.8	20.0
11	18.2	335.8	20.0
12	12.6	223.9	19.0
13	26.2	358.1	30.0

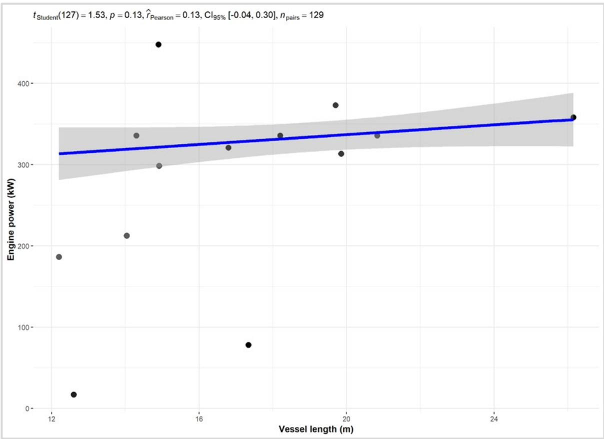

Figure 1. The relationship between vessel length and engine power

The number of commercial fishing trips analyzed was broken down as 28 for GSA 22 (22 %), 57 for GSA 24 (44 %) and 44 for GSA 29 (34 %) across the sub-geographic areas, totaling 129 (Table 2). The average catch per hour was 19.11, 24.12 and 45.77 kg for GSA 22, 24 and 29, respectively.

Table 2. Characteristics of fishing trips, median value of FUI and associated CO_2 emissions across the GSAs

Parameters	GSAs			
	22	24	29	Overall
No. of fishing trips	28	57	44	129
Avg. trip duration (h)*	9.36	8.04	7.65	8.19
FGSAFuel per trip (l)	374.29	205.05	282.31	268.14
FUI (l)	2.28	1.15	0.82	1.22
CO_2/kg of landed (kg)	6.01	3.03	2.16	3.21

*The average trip duration encompasses only the total time (hour) spent during the trawl operations.

The amount of fuel consumed for each fishing trip was estimated at 268.14 l (95% CI: 247.23, 289.04) (Table 2). Based on that calculation, for the investigated demersal trawl vessels, the FUI and the associated CO_2 emissions were estimated at a median amount of fuel of 1.22 l and 3.21 kg CO_2/kg landed, respectively (Table 2). Figure 2 illustrates the variation in estimated FUI across the 13 trawl vessels included in the study, which ranged between 0.42 and 2.49 l/kg landed catch. The results show considerable differences in fuel consumption between vessels, of which, some (Vessel 2 and 13) exhibits the highest variability and occasional extreme values. This suggests that operational factors such as engine power, vessel size, and fishing effort may significantly influence fuel consumption. Conversely, some of them (Vessel 4, 10 and 12) show relatively low and stable fuel consumption patterns, likely due to more consistent operational efficiency.

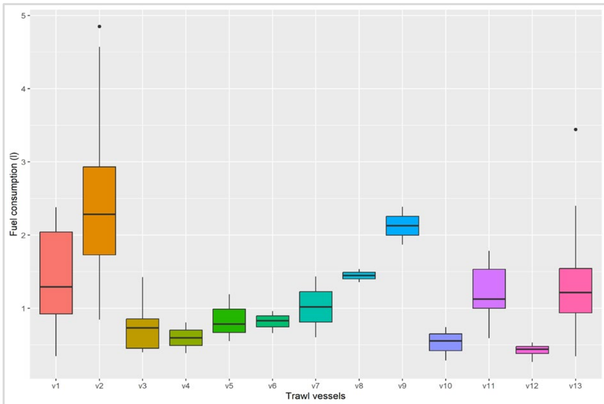

Figure 2. Box plot showing the fuel use intensity of each trawl vessel investigated

The Figure 3 presents the distribution of FUI across the three geographical sub-areas (GSAs): GSA 22 (Aegean Sea), GSA 24 (Levant Sea), and GSA 29 (Black Sea). The highest median FUI was observed in GSA 22, followed by GSA 24. In contrast, GSA 29 exhibited the lowest FUI, likely due to differences in target species and fishing practices in the Black Sea, where the shrimp fishery is absent, and fish-targeted trips typically use less fuel. (Table 2, Figure 3).Trawl vessels consumed a median amount of fuel of 1.69 l to catch one kg of landed catch during shrimp targeted fishing trips whereas fuel consumption was calculated 1.38 l for the fish targeted fishing trips (Figure 4, Table 3). According to the GLM results, the difference between these two types of fishing trips was also significant (Figure 4, Table 4).

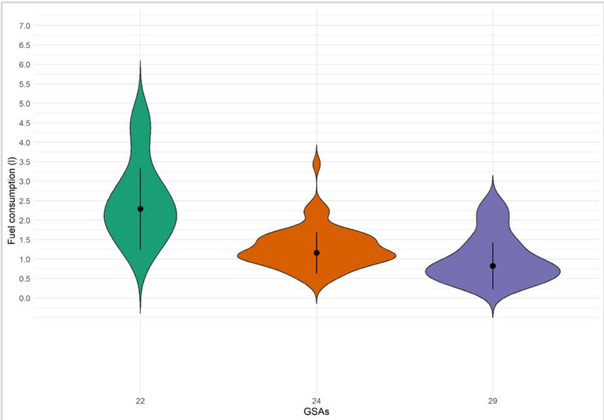

Figure 3. FUI across the GSAs

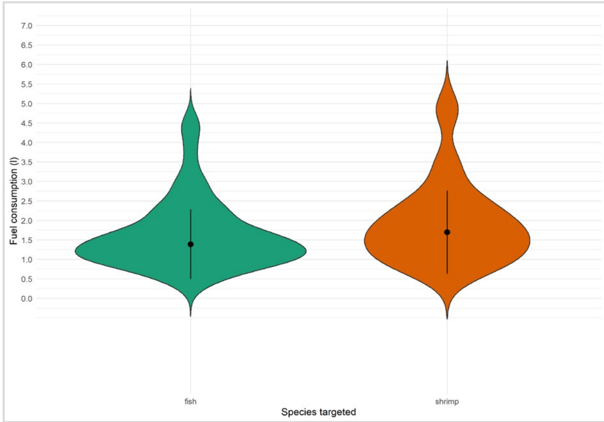

Figure 4. Violin plot showing the FUI for fish (green) and shrimp (orange) targeted fishing trips (GSA 29 region excluded)

Table 3. Comparison of published studies investigating FUI in different regions around the world

FUI (l/kg)	Differences in %	Fishery type	Region	References
3-5	77 %, 195 %	Shrimp	Skagerrak	(Ziegler et al., 2016)
2.6	88 %	Patagonian Toothfish (*Dissostichus eleginoides*)	Australia	(Hornborg et al., 2018)
0.2	-85 %	Demersal fish	Baltic and North Sea	(Thrane, 2004)
1.4	1 %	Atlantic cod (*Gadus morhua*)	Sweden	(Ziegler & Hansson, 2003)
4.2	185 %	Mixed demersal species	Strait of Sicily	(Sala et al., 2022)
11.4	568 %	Shrimp	Strait of Sicily	(Sala et al., 2022)
3.8	211 %	Mixed demersal species	Levant Sea	(Demirci & Karaguzel, 2018)
1.16	-31 %	Nephrops	Northern Ireland	(Cappell et al., 2022)
1.39	13 %	Mixed demersal species	Levant Sea	(Sarica & Demir, 2021)
1.22	-	Mixed demersal species	Turkish waters	The present study
1.69	-	Shrimp targeted	Turkish waters	The present study
1.38	-	Fish targeted	Turkish waters	The present study

GLM results indicated a significant relationship between fuel consumption, engine power, vessel length and the targeted group of species (Table 4). Table 4 shows the numerical output of the model that corresponds to the log-odds. The model with the lowest AIC included vessel length, engine power and targeted species as explanatory variables (Table 4). The GSA was removed from the predicters as there was no shrimp targeted fishery. Besides, its inclusion emerged higher AIC and caused multicollinearity during the analysis.

Table 4. Estimated regression parameters

Predictors	Estimate	SE	t-value	*p*(>t)
Intercept	-0.987	0.617	-1.600	0.113
Vessel length (m)	-0.028	0.011	-2.415	<0.05*
Engine power (kw)	0.005	0.001	4.458	<0.001*
Shrimp targeted fishing trips	0.412	0.117	3.519	<0.001*

Standard errors (SE), t-values and *p*-values for the GLM with the lowest AIC (Akaike's Information Criterion) model. *Statistically significant

The GLM results suggest that engine power is the strongest predictor of fuel consumption intensity, with each 1 kW increase in engine power resulting in a 0.5% increase in fuel use intensity, holding other variables constant. The coefficient of the engine power variable indicates that the log-odds of fuel consumption to catch one kg of landed catch increases by a constant 0.005. This means for every kW increase in engine power the odds ratio of fuel consumption to catch one kg of landed catch increases on average by a constant factor of 1.005, assuming that fishing trip type and vessel length are held constant.

Vessel length had a negative relationship with fuel consumption, where each meter increase in vessel length was associated with a 3% decrease in fuel use intensity. The coefficient of the vessel length variable has a numerical value of -0.028, which indicates that for every unit increase in vessel length, the log-odds of fuel consumption to catch one kg of landed catch decrease by -0.028. When exponentiated, for every meter increase in vessel length, the odds ratio of fuel consumption to catch one kg of landed catch decreases on average by a constant factor of 0.971 (or -3 %).

Finally, shrimp-targeted fishing trips had significantly higher fuel consumption compared to fish-targeted fishing trips, with shrimp-targeted trips having approximately 1.5 times the fuel consumption odds of fish-targeted trips. The difference in the log-odds of fuel consumption between shrimp and fish targeted fishing trips was 0.412, indicating that the fuel consumption in shrimp targeted fishing trips is significantly higher than that of the fish targeted fishing trips.

DISCUSSION

The results obtained from this study provides important insights into the fuel use intensity of Turkish bottom trawl vessels. However, it is acknowledged that the data collection is based on data from 13 vessels. Although these vessels represent a range of operational characteristics, a larger sample size would enhance the ability to generalize findings across the entire Turkish trawl fleet. Similar studies in other fisheries have also stressed the limited sample sizes (Parker et al., 2017), highlighting the challenge of obtaining comprehensive fuel consumption data.

When converting the FUI value of 1.22, to catch one ton landed, demersal trawl vessels consume roughly between 1 000 and 1 037 t fuel, considering that the diesel weighs between 0.82 and 0.85 kg per litre. The findings in this paper were comparable with an earlier study in which the average FUI for bottom trawlers were estimated at 1.39 (Sarica & Demir, 2021). Fisheries that are mainly characterized by active fishing gears such as demersal trawls have been known to consume remarkable quantities of fuel (Park et al., 2015; Bastardie et al., 2022). Tyedmers et al. (2005) quantified the global average fuel use intensity for all types of fishing practices by applying an average diesel fuel intensity of 0.85, which was 1.7 times lower than the results for the demersal trawls under investigation in this study.

A comparison of Fuel Use Intensity (FUI) across different fisheries worldwide (Table 3) reveals substantial variation, ranging from -85% to 568%, depending on the fishery type. Variability in reported FUI values may arise from differences in data collection methods (Coello et al., 2015) and whether estimates include fuel use associated with illegal, unreported, and unregulated (IUU) fishing (FAO, 2014; Dağtekin et al., 2022). Additionally, factors such as catch per unit effort (CPUE), vessel characteristics (engine power and vessel length) (Parker et al., 2017) and post-fishing processing and transport activities (Sala et al., 2022) can result in regional variations in fuel use intensity (Parker et al., 2015). Compared to other regions, the FUI in Turkish trawl fisheries falls within the mid-range of reported values. The shrimp-targeted trawl fishery in Türkiye (1.69 l/kg) shows more energy efficiency than some other shrimp fisheries (e.g., Strait of Sicily, 11.4 l/kg), likely due lower towing speed and hourly fuel consumption of the main engine measured or reported by skippers. Additionally, estimation of Sala et al. (2022) was higher than what is found in this study due to the energy audit applied to calculate FUI as well as inclusion of post-fishing processing.

The present study is based on self-reported fuel consumption data from fishers, which may introduce reporting biases. However, despite having shortcomings, questionnaires and surveys are one of the most used methodologies in data collection on fuel consumption (Ziegler et al., 2016; Parker et al., 2017; Cappell et al., 2022). The reason for variations in individual vessel fuel use could be explained by operational and technological factors as some of them continue to operate decades old engines, which may adversely affect the engine efficiency over time (Greer et al., 2019). It must be noted that future research should incorporate direct fuel monitoring for validation.

Using real-world emission data from fishing vessels, CO_2 emission for the year 2000 was calculated as approximately 134 million t with an average rate of 1.7 t of CO_2 per ton of live weight landed marine product (Tyedmers et al., 2005). Based on that and the other two global GHG estimations reported by Parker et al. (2018) (179 million tons of CO_2) and Greer et al. (2019) (207 million tons), the average CO_2 amount generated by the Turkish demersal trawl fleet represented about 0.04 % (see Conclusion). Sala et al. (2022) demonstrated how GHG emissions might differ even between the typical Mediterranean trawl fisheries. The authors remarked that the Italian bottom otter trawls were substantially more fuel-intensive than most fisheries around the world, with an emission of 10.7 kg CO_2/kg, which was more than twice what was found in this paper (3.21 kg CO_2/kg).

The results also indicated that the fishery occurring in GSA 29 was the most efficient one in terms of FUI. The main target species of the Black Sea bottom trawling is whiting, which is the most abundantly landed demersal fish in Turkish waters (TURKSTAT, 2022). Another reason for this variation could be due to the lower discard ratio in the region (G. Gökçe, personal communication, March 15, 2024), leading to a cleaner catch composition (Emecan et al., 2023) and yielding a higher profit margin relative to fuel utilized. In other words, as catch increases, emissions per unit decrease, which was also demonstrated for the Icelandic demersal fishery by Kristofersson et al. (2021). Besides, overall trawl designs based on what Black Sea trawlers target could make remarkable differences in terms of frictional force and associated fuel consumption in comparison with the trawl fisheries performed in other regions (McHugh et al., 2015; Grimaldo et al., 2015). The highest median fuel consumption was recorded in GSA 22, exhibiting a broader range of values than the other regions. This variation is likely influenced by differences in vessel size and fishing operations within the Aegean Sea. In contrast, GSA 24 displayed a more consistent fuel consumption pattern, suggesting greater standardization in deep-water shrimp-targeted fishing activities, which generally require higher fuel use due to extended towing durations.

Higher fuel consumption in shrimp targeted fishing trips compared to the fish targeted fishing trips is also worth discussing from operational point of view. The deep-water rose shrimp, giant red shrimp, and blue and red shrimp are the main three component of the shrimp targeted fisheries in GSA 22 and GSA 24 where the depth ranged between 400 and 700 m (Deval, 2020). One possible explanation could be that the fish targeted fishery occurs in shallower waters while shrimp targeted mostly takes place in deep waters, which requires relatively better equipped larger vessels, much more effort and considerable time during the steel warp releasing, hauling and settlement of the trawl net. Another possible reason could be that such species with relatively lower abundance encourages trawlers to tow longer periods and use heavier gear components to catch (Ziegler and Hansson, 2003). In the northeast Atlantic demersal trawl fishery, fishing trips targeting shrimps were shown to be significantly more fuel intensive than those targeting fish (Groen et al., 2013). Our results were also consistent with the findings of Ziegler and Hornborg, (2014), Parker et al. (2015) and Bastardie et al. (2022) but not with of Thrane (2004). Fuel consumption was also quantified and categorized as high for the northern shrimp (*Pandalus borealis* L.) stock shared by Sweden, Norway, and Denmark in the Skagerrak (Ziegler et al., 2016).

The GLM output indicated that the trawl vessels with lower power engines were more fuel efficient which confirmed earlier studies (Davie et al., 2014). However, fuel use intensity was negatively correlated with the vessel size. Ziegler et al. (2016) found the same tendency in Denmark fisheries, with larger vessels being more fuel efficient than smaller ones, unlike Sweden and Norway fisheries. This could be attributable to what earlier studies (Ziegler and Hornborg, 2014; Parker et al., 2017) have pointed out; rather than technical capacity of the vessels, target species and gear type might have influenced much more fuel consumption. Indeed, the larger vessels could be more efficient due to the fact that they are capable of utilizing on their greater dimensions, thereby obtaining higher catch rates from a wider variety of locations over extended durations.

With the present study, engine power was identified as the strongest predictor of fuel consumption, with higher engine power leading to increased fuel use intensity. Additionally, vessel length and the type of targeted species (shrimp vs. fish) were significant factors. These results have direct implications for fisheries management and policy, suggesting the following practical recommendations:

- Given the significant impact of engine power on fuel consumption, modifying vessels with more efficient engines or implementing engine efficiency upgrades could substantially reduce fuel use and associated greenhouse gas emissions.
- The inverse correlation between vessel length and fuel consumption suggests that design alterations—such as optimizing vessel dimensions and enhancing gear configurations to minimize towing resistance—may improve fuel efficiency.
- The adoption of gear with reduced drag characteristics may decrease the overall energy required during fishing operations, particularly in shrimp-targeted fisheries where fuel consumption is higher.
- Targeted policies and incentives aimed at promoting technological improvements and operational modifications can encourage the adoption of fuel-efficient practices and innovative gear designs, thereby supporting sustainable fisheries management and reducing the sector's environmental footprint.

CONCLUSION

For the years 2021 and 2022, Turkish demersal trawl fisheries achieved a total landing of approximately 17 667 tons (G. Gökçe, personal communication, March 15, 2024). Based on product-specific calculations, the entire trawl fleet's fuel use was estimated at around 18 million tons, resulting in roughly 56 711 tons of CO_2 emissions. Notably, these capture-related CO_2 emissions accounted for only 0.08 % of the total emissions from Turkey's agriculture sector in 2021 (TURKSTAT, 2022). Although this study examines fuel use and emissions from 129 fishing trips conducted by 13 trawl vessels, these estimates provide valuable insights into the environmental impact of the Mediterranean trawl fleet.

However, future research should expand the dataset to include a broader range of vessels across different regions and fishing seasons to improve the robustness and generalizability of the findings. Additionally, incorporating emissions from the entire fishing process—including post-landing activities, cruising time, and transportation—would better guide fisheries managers in transitioning toward more fuel-efficient and environmentally sustainable fishing practices. Furthermore, considering climate change is a fundamental concern in the General Fisheries Commission for the Mediterranean (GFCM) 2030 Strategy, fisheries policymakers must take a proactive approach by prioritizing fuel-saving technologies and lowering emissions associated with fishing operations in alignment with the goals outlined in the Paris Agreement.

ACKNOWLEDGEMENTS AND FUNDING

I extend my gratitude to the captains and crew of the 13 trawl vessels for their dedication to this study in terms of data collection. Without their hospitality and patience, this work would not have been accomplished. I would like to acknowledge two fisheries observers on board, Yaşar İşitmez and Murat Uzun for their support and effort in collecting the data essential for this research. I would like to express my sincere gratitude to Gökhan Gökçe and Hüseyin Özbilgin for their invaluable guidance, insightful feedback, and unwavering support throughout the course of this research. Their expertise and encouragement have been instrumental in shaping this work.

AUTHORSHIP CONTRIBUTIONS

Yunus Emre Fakıoğlu: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization.

CONFLICT OF INTEREST

The author declares no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

ETHICS APPROVAL

No specific ethical approval was necessary for this study.

DATA AVAILABILITY

Data will be made available on request.

REFERENCES

Akaike, H. (1974). A new look at the statistical model identification. IEEE Transactions on *Automatic Control, 19*(6), 716–723. https://doi.org/10.1109/TAC.1974.1100705

Araya-Schmidt, T., Bayse, S.M., Winger, P.D., & Santos, M.R. (2022). Juvenile redfish (*Sebastes* spp.) behavior in response to Nordmøre grid systems in the offshore northern shrimp (*Pandalus borealis*) fishery of Eastern Canada. *Frontiers in Marine Science, 9*, 1-14. https://doi.org/10.3389/fmars.2022.920429

Bastardie, F., Hornborg, S., Ziegler, F., Gislason, H., & Eigaard, O.R. (2022). Reducing the fuel use intensity of fisheries: Through efficient fishing techniques and recovered fish stocks. *Frontiers in Marine Science, 9*, 1-22. https://doi.org/10.3389/fmars.2022.817335

Campos, A., Pilar-Fonseca, T., Parente, J., Fonseca, P., & Afonso-Dias, M. (2011). Fuel efficiency in trawlers under different fishing tactics using a consumption model and VMS data: A case-study for the Portuguese fleet. In E. Rizzuto, C.G. Soares (Eds.), *Sustainable Maritime Transportation and Exploitation of Sea Resources,* 1162 p. Published by CRC Press

Cappell, R., MacNab, S., & Holland, A. (2022). *Assessment of NI Fleet Emissions. Report for ANIFPO/NIFPO.*

Coello, J., Williams, I., Hudson, D.A., & Kemp, S. (2015). An AIS-based approach to calculate atmospheric emissions from the UK fishing fleet. *Atmospheric Environment, 114,* 1-7. https://doi.org/10.1016/j.atmosenv.2015.05.011

Dağtekin, M., Gücü, A.C., & Genç, Y. (2022). Concerns about illegal, unreported and unregulated fishing, carbon footprint, and the impact of fuel subsidy - An economic analysis of the Black Sea anchovy fishery. *Marine Policy, 140,* 105067. https://doi.org/10.1016/j.marpol.2022.105067

Davie, S., Minto, C., Officer, R., Lordan, C., & Jackson, E. (2014). Modelling fuel consumption of fishing vessels for predictive use. ICES *Journal of Marine Science, 72*(2), 708-719. https://doi.org/10.1093/icesjms/fsu084

Demirci, A., & Karaguzel, M. (2018). The evaluation of fishing vessels fuel consumption and pollutions emissions in the Iskenderun Bay. *Fresenius Environmental Bulletin, 27*(1), 508-514.

Deval, M.C. (2020). Population dynamics and biological patterns of commercial crustacean species in the Antalya Bay, Eastern mediterranean sea: III. The giant red shrimp aristaeomorpha foliacea risso, 1827. *Turkish Journal of Fisheries and Aquatic Sciences, 20*(4), 311-323. https://doi.org/10.4194/1303-2712-v20_4_07

Emecan, İ.T., Yıldız, T., Uzer, U., Çatal, A., Moussa, H., Aydın, C., & Karakulak, F.S. (2023). Catch composition of different bottom trawl cod-ends in the Western Black Sea. *Aquatic Sciences and Engineering*, *38*(1), 53-61. https://doi.org/10.26650/ASE20221187355

FAO. (2014). *General Fisheries Commission for the Mediterranean*. Report of the thirty-seventh session. Split, Croatia, 13–17 May 2013. GFCM Report. No. 37. Rome.104 pp

Greer, K., Zeller, D., Woroniak, J., Coulter, A., Winchester, M., Palomares, M. L.D., & Pauly, D. (2019). Global trends in carbon dioxide (CO2) emissions from fuel combustion in marine fisheries from 1950 to 2016. *Marine Policy*, *107*, 103491. https://doi.org/10.1016/j.marpol.2018.12.001

Grimaldo, E., Pedersen, R., & Sistiaga, M. (2015). Energy consumption of three different trawl configurations used in the Barents Sea demersal trawl fishery. *Fisheries Research, 165*, 71-73. https://doi.org/10.1016/j.fishres.2014.12.021

Groen, E.A., Ziegler, F., & Bokkers, E. A. M., Veldhuizen, L.J.L., de Boer, I.J. M., Donnelly, K., Sund, V., & Krewer, C. (2013). Variability in fuel efficiency of a northeast Atlantic demersal trawl fishery. *The 6th International Conference on Life Cycle Management.*

Hartig, F. (2020). *DHARMa: Residual diagnostics for hierarchical (multi-level/mixed) regression models*. R package version 0.2.0. *https://cran.r-project.org/web/packages/DHARMa/vignettes/DHARMa.html*

Hilborn, R., Amoroso, R., Collie, J., Hiddink, J.G.J., Kaiser, M.J., Mazor, T., Mcconnaughey, R.A., Parma, A.M., Pitcher, C.R., Sciberras, M., & Suuronen, P. (2023). Evaluating the sustainability and environmental impacts of trawling compared to other food production systems. *ICES Journal of Marine Science, 80*(6), *1567–1579.* https://doi.org/10.1093/icesjms/fsad115

Hornborg, S., Hobday, A.J., Ziegler, F., Smith, A.D.M., & Green, B.S. (2018). Shaping sustainability of seafood from capture fisheries integrating the perspectives of supply chain stakeholders through combining systems analysis tools. *ICES Journal of Marine Science, 75*(6), 1965–1974. https://doi.org/10.1093/icesjms/fsy081

Kaykaç, M.H., Düzbastılar, F.O., Zengin, M., Süer, S., & Rüzgar, M. (2017). Measurements of fuel consumption and towing resistance in sea snail beam trawl fisheries: Preliminary results. *Turkish Journal of Fisheries and Aquatic Sciences, 17*(5), *901–909.* https://doi.org/10.4194/1303-2712-v17_5_06

Kristofersson, D., Gunnlaugsson, S., & Valtysson, H. (2021). Factors affecting greenhouse gas emissions in fisheries: Evidence from Iceland's demersal fisheries. *ICES Journal of Marine Science, 78*(7), 2385–2394. https://doi.org/10.1093/icesjms/fsab109

McHugh, M.J., Broadhurst, M.K., Sterling, D.J., & Millar, R.B. (2015). Comparing three conventional penaeid-trawl otter boards and the new batwing design. *Fisheries Research, 167*, 180-189. https://doi.org/10.1016/j.fishres.2015.02.013

Ozsari, I. (2023). Calculating the main engine power of fishing vessels with artificial neural networks analysis. In *Proceeding Book of 2nd International Conference on Scientific and Academic Research, 1, 515–520.* https://as-proceeding.com/index.php/icsar/article/view/355

Park, J.A., Gardner, C., Chang, M.I., Kim, D.H., & Jang, Y.S. (2015). Fuel use and greenhouse gas emissions from offshore fisheries of the Republic of Korea. *PLoS ONE, 10*(8), e0133778. https://doi.org/10.1371/journal.pone.0133778

Parker, R.W.R., Blanchard, J.L., Gardner, C., Green, B.S., Hartmann, K., Tyedmers, P.H., & Watson, R.A. (2018). Fuel use and greenhouse gas emissions of world fisheries. *Nature Climate Change, 8*(4), 333-337. https://doi.org/10.1038/s41558-018-0117-x

Parker, R.W.R., Gardner, C., Green, B.S., Hartmann, K., & Watson, R.A. (2017). Drivers of fuel use in rock lobster fisheries. *ICES Journal of Marine Science, 74*(6), 1681–1689. https://doi.org/10.1093/icesjms/fsx024

Parker, R.W.R., & Tyedmers, P.H. (2015). Fuel consumption of global fishing fleets: Current understanding and knowledge gaps. *Fish and Fisheries, 16*(4), 684-696. https://doi.org/10.1111/faf.12087

R Core Team (2018) *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria.

Sala, A., Damalas, D., Labanchi, L., Martinsohn, J., Moro, F., Sabatella, R., & Notti, E. (2022). Energy audit and carbon footprint in trawl fisheries. *Scientific Data, 9*(1), 428. https://doi.org/10.1038/s41597-022-01478-0

Sala, E., Mayorga, J., Bradley, D., Cabral, R.B., Atwood, T.B., Auber, A., Cheung, W., Costello, C., Ferretti, F., Friedlander, A.M., Gaines, S.D., Garilao, C., Goodell, W., Halpern, B.S., Hinson, A., Kaschner, K., Kesner-Reyes, K., Leprieur, F., McGowan, J., … Lubchenco, J. (2021). Protecting the global ocean for biodiversity, food and climate. *Nature, 592*(7854), *397–402.* https://doi.org/10.1038/s41586-021-03371-z

Sarica, A., & Demir, O. (2021). Calculations about fuel and catch of trawl vessels, purse seines and small-scale vessels at Mersin Bay. *Fresenius Environmental Bulletin, 30(2 A)*, 1873-1884.

Steadman, D., Thomas, J.B., Rivas Villanueva, V., Lewis, F., Pauly, D., Deng Palomares, M.L., Bailly, N., Levine, M., Virdin, J., Rocliffe, S., & Collinson, T. (2021). New perspectives on an old fishing practice: Scale, context and impacts of bottom trawling. *Blue Ventures Report, Report 2021,* 1–44, Bristol, UK.

Suuronen, P., Chopin, F., Glass, C., Løkkeborg, S., Matsushita, Y., Queirolo, D., & Rihan, D. (2012). Low impact and fuel efficient fishing-Looking beyond the horizon. *Fisheries Research, 119–120*, 135-146. https://doi.org/10.1016/j.fishres.2011.12.009

Thrane, M. (2004). Energy consumption in the Danish fishery: Identification of key factors. *Journal of Industrial Ecology, 8*(1–2), 223-239. https://doi.org/10.1162/1088198041269427

TURKSTAT. (2022) Fisheries Statistics for 2021. Online. Avaliable at: https://data.tuik.gov.tr/Bulten/Index?p=Fishery-Products-2021-45745&dil=2 (Last access 15 May 2023)

Tyedmers, P.H. (2001). Energy consumed by North Atlantic Fisheries. In D. Zeller, R. Watson, D. Pauly, (Eds.), Fisheries impacts on North Atlantic ecosystems: Catch, effort and national/regional datasets. *Fisheries Centre Research Reports, 9*(3), 12–34.

Tyedmers, P.H., Watson, R., & Pauly, D. (2005). Fueling global fishing fleets. *Ambio*, *34*(8), 635-638. https://doi.org/10.1579/0044-7447-34.8.635

Venables, W.N., & Ripley, B.D. (2002). *Satistics and computing. Modern Applied Statistics with S*. Fourth edition, Publisher: Springer-Verlag.

Winther, U., Hognes, E.S., Jafarzadeh, S., & Ziegler, F. (2020). *Greenhouse gas emissions of Norwegian seafood products in 2017*. SINTEF Ocean AS Seafood Technology, *Report No. 2019:01505.*

Ziegler, F., & Hansson, P.A. (2003). Emissions from fuel combustion in Swedish cod fishery. *Journal of Cleaner Production, 11*(3), *303–314.* https://doi.org/10.1016/S0959-6526(02)00050-1

Ziegler, F., & Hornborg, S. (2014). Stock size matters more than vessel size: The fuel efficiency of Swedish demersal trawl fisheries 2002-2010. *Marine Policy, 44,* 72-81. https://doi.org/10.1016/j.marpol.2013.06.015

Ziegler, F., Hornborg, S., Valentinsson, D., Skontorp Hognes, E., Søvik, G., & Ritzau Eigaard, O. (2016). Same stock, different management: Quantifying the sustainability of three shrimp fisheries in the Skagerrak from a product perspective. *ICES Journal of Marine Science, 73*(7), 1806-1814. https://doi.org/10.1093/icesjms/fsw035

Ziegler, F., Jafarzadeh, S., Skontorp Hognes, E., & Winther, U. (2021). Greenhouse gas emissions of Norwegian seafoods: From comprehensive to simplified assessment. *Journal of Industrial Ecology*, *26*(6), 1908-1919. https://doi.org/10.1111/jiec.13150