Economic Diversity of Maine's American Lobster Fishery

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Abstract

Maine's coastal communities critically depend on the American Lobster fishery, which is now exposed to ocean warming. There is uncertainty about the future robustness of the stock and the economic performance of the fleet appears vulnerable. This research characterizes economic heterogeneity in Maine's fishing fleet using latent class stochastic profit frontier analysis. We explore the diversity of business models and examine how they are associated with the economic performance of the fleet in the pre-warming period. The study uses unique firm-level data that captures the operational and economic information of the harvesters in the year 2010, the year before the reported environmental change in the Gulf of Maine. Our findings indicate economic efficiencies differ based on their choice of business models and found technical upgrades generally contribute to improved economic performance in the pre-warming period. Reported societal benefits associated with employment levels have characterized the lobster production environment over firm-level efficiency. This research establishes a critically important baseline for future comparison and quantification of policy reforms within the U.S. lobster fishery.

Keywords: lobster, *Homarus americanus*, profit efficiency, latent class stochastic frontier analysis, fisheries co-management.

Introduction

It has been argued that fisheries managed in congruence with the basic social and economic systems of the fishing community can generate effective co-management decisions designed to promote the health of the underlying resource and welfare of the fishing community (Acheson 1975a; Jentoft et al. 1998; Wilson 2006; Gutiérrez et al. 2011; Ishihara et al. 2021). However, most conventional models of economic systems of fisheries assume fleet homogeneity, despite observed heterogeneity (Acheson 1975b; Holland 2011a; Smith 2012; Lehuta et al. 2014). Consequently, fisheries management rules designed to be applied equally to everyone in a fair way, can fail to account for potential uneven and inequitable economic impacts of decision-making and result in resistance to proposed regulations. Prior studies have captured the socio-economics of the American lobster (*Homarus americanus*) fisheries qualitatively (Acheson 1975b; Anderson 1976; Wilson 1982; Steneck et al. 2011), but more quantitative economic research is needed. This study quantifies the economic diversity of Maine's lobster fleet and characterizes a variety of harvester business models according to their profit efficiencies. Analyzing the mean conditional profit efficiencies creates a bridge between anthropological and ecological studies of the fishery and can inform socio-ecological models in a measurable and repeatable way. `

We conduct a latent class stochastic frontier analysis developed by Orea and Kumbhakar (2004) using data obtained through a lobster industry survey undertaken in 2011. The survey characterizes the lobster fishery in the pre-warming period in the Gulf of Maine, where climate change impacts have started to become prominent in recent years. Since 2011, sea surface temperature in the Gulf of Maine has continued to exceed the long-term average, and marine heatwave events have become more frequent and prolonged, with 2012, 2016, 2021, and 2022 recording prolonged periods of marine heatwaves (Mills et al. 2013; Pershing et al. 2018; ASMFC 2020; GMRI 2022). Our analysis contributes to i) characterization of fleet heterogeneity in terms of harvester business models and related economic performance, ii) benchmarking of the economics of the fishery in the pre-warming period, and iii) novel repeatable quantitative socio-economic fisheries modeling approach, each of which is critical for understanding and evaluating impacts of policy changes and climate change-induced ecological changes. By applying latent class stochastic frontier analysis, our study aims to decouple and account for latent or unobservable features of a harvester business model in estimating profit efficiencies.

Background

The American lobster fishery, which dominates the Maine Coast, has seen steadily increasing landings since the 1990s, with harvest volume peaking in 2016 at 132 million pounds and an ex-vessel value of $540M (Maine Department of Marine Resources 2022). In the 6 years following this observed peak annual harvest level, Maine lobster landings have steadily declined with 108 million pounds landed in 2021 at the highest ever fishery ex-vessel value of USD 725 million (Maine Department of Marine Resources 2022). According to the most recent stock assessment, the fishery is “not overfished or experiencing overfishing (Atlantic States Marine Fisheries Commission 2020)”. Maine has a large number of communities that rely on the lobster fishery; lobster harvesters derive a median of 80% of their household income from lobstering, supporting the need for fisheries managers to incorporate economic impacts in the decision-making (Dayton and Sun 2012). Maine’s fleet has observed a change in the fishing practices over the years, actively engaging in fishery co-management through the establishment of the seven Maine lobster zones (Figure 1), which closely reflected traditional fishing territories (Acheson 1975b; Acheson and Gardner 2004), and a trap tag program in 1996 as a management input control

(Lobster Advisory Council 1999). A moratorium on the number of licenses and a limited entry licensing program went into effect in 1999, reflecting community concerns about excess effort and capitalization in the fishery and the associated risks to local economies associated with the non-malleability of fishing investments and labor (Lobster Advisory Council 1999; Steinback et al. 2008; Munro 2010; Steneck et al. 2011).

Decreases in licensing flexibility, and declines in the health of the New England groundfish stocks, have led to further concentration of effort in a single fishery (Stoll et al. 2017). Increased investment for some portions of Maine’s lobster fleet in vessels, new engines, and gear technologies seem to have improved the efficiency in some portions of the fleet (Lobster Advisory Council 1999). For instance, some harvesters invest upwards of $300,000 in a fishing vessel, and opt to fish year-round (Dayton and Sun 2012). Prior studies in other fisheries have attributed the variation in vessel performance to the skills of the operator, with certain individuals who seem to be able to earn substantially more than others with similar vessels (Pascoe and Coglan 2002; Sharp et al. 2004; Acheson and Acheson 2010). The observable physical attributes of the vessels in the fleet are also only one of the dimensions of the performance of a fishing operation (Squires 1987) and may not account for all of the variations in profit efficiency. Prior economic studies also explored the congestion effect of the fishery to investigate to what extent spatial and temporal concentration of effort inputs erode economic efficiency and suggest that trap reductions and changes in harvest timing can increase the fishery profits (Wilson et al. 2007; Holland 2011a, 2011b).

The American lobster fishery has benefited from favorable resource conditions in the Gulf of Maine for 50 years, where both inshore and offshore cold-rich waters have helped to bolster resource abundance. The stock is in healthy status (Atlantic States Marine Fisheries Commission

2020). But recent landings reports and recent studies indicate spatial and temporal changes in the availability of the resource over time (Wahle and Steneck 1991; Steneck and Wahle 2013). These changes may be associated with a variety of ecological factors such as depredation (McMahan et al. 2013), food availability (Tlusty et al. 2008; Grabowski et al. 2009), changes in habitat suitability (Chang et al. 2010; Tanaka and Chen 2015, 2016), ocean warming (Tlusty et al. 2008; Chang et al. 2010; Mills et al. 2013; Le Bris et al. 2018) or harvester related conservation measures designed to protect reproductive capacity of the stock (Le Bris et al. 2018). Variability in stock recruitment (Lehuta et al. 2014; Mazur et al. 2019), abundance and shifts in timing and spatial distribution of the resource (Oppenheim et al. 2019), prevailing winds and currents (Xue et al. 2008; Incze et al. 2010) all can have predictable and unpredictable effects, impacting economic return and the working communities that depend on the fishery (Cheng and Townsend 1993; Holland 2011a, 2011b; Mills et al. 2017). The choice of harvester business model may further be a reflection of the resource characteristic; productivity within a spatial area varies over time, with shifting of the spawning lobster stock observed and influenced by changing ocean conditions,

Previous studies note a socio-cultural element to the Maine lobster fishery, which appears to operate in a fashion that is not economically optimal, especially when compared to other crustacean trap fisheries such as New Zealand and Australia, each of which have undergone significant policy changes designed to maximize economic yield as a primary management objective (Norman-López and Pascoe 2011; Reid et al. 2013; Gardner et al. 2015). Changes in fleet investment as well as changing ecological conditions pose challenges to fisheries managers, and it has been proposed that effort reductions could ensure the socioeconomic and ecological health of the Maine lobster fishery (Lobster Advisory Council 1999; Fogarty and Gendron 2004; Steinback et al. 2008; Acheson and Acheson 2010), and improve fishing efficiency and economic yield to offset eroding profits resulting from increased production input prices (fuel, wage, bait) and ex-vessel price fluctuations. However, this is not a simplistic question and potentially resulting in uneven effects on harvesters in Maine's American Lobster fishery. Diversity of the fishing fleet, characterized by an understanding of the underlying harvester business models, a unique combination of technical and operational characteristics that influences their fishing style choices, therefore provides critical insight for fisheries managers to account for the socioeconomic dimensions of the fishery and an indicator of fleet resilience under changing ocean conditions in the Gulf of Maine.

Materials and Methods

This study uses latent class stochastic frontier analysis to investigate the economic performance of Maine's American lobster fishery. Farrell (1957) examined the firm's economic performance by examining production efficiency and by defining the output of the most efficient firm as the production frontier for all firms. Given that efficient firms with complete information should operate at "maximum" potential output levels (i.e., full profit efficiency), any deviation from the profit frontier measures profit inefficiency. This allows for the fact that firms may encounter various uncontrollable exogenous factors (random effects), such as performance of various machines, weather conditions, and uncertainty of input supplies. Battise and Coelli (1995) further developed this approach with stochastic frontier analysis, imposing allocative efficiency and removing the first-order profit-maximizing conditions. Our study follows an extension of stochastic frontier analysis developed by Orea and Kumbhakar (2004) to account for unobservable differences in harvester business models. We define a business model as a combination of technical and operational characteristics and investigate the profit efficiencies of different business models. Profit efficiency analysis assumes both input and output prices to be determined exogenously (Kumbhakar and Lovell 2004; Coelli et al. 2005). While technical efficiency analysis has been conducted for a number of fisheries (e.g., Sharma and Leung 1998; García del Hoyo et al. 2004; Tingley et al. 2005), there are few studies that have examined profit efficiencies in fisheries (Otumawu-Apreku and McWhinnie 2020). Maine's American lobster fishery consists of owner-operated small-scale fishing vessels[1]; as such, these vessels are more likely to be price takers in both input and output markets.

Characterization of fishing styles and associated economic performance

This paper characterizes a harvester business model, an unobservable or latent harvester characteristic, through a combination of observed technical and operational characteristics. Specifically, we chose vessel age, engine age, vessel length, and engine power as manifest variables of technical characteristics, and number of crew, steam time, soak time, gear configuration (number of traps per line), and number of per-trip trap hauls as manifest variables of operational characteristics.

Model specification

The ultimate objective of the stochastic profit frontier analysis is the estimation of inefficiency (i.e., $u_{i|c}$) for each latent class. To do so, we also need to estimate the parameters for input prices. We suppose that profit function for class $c = 1, \ldots, C$ for an individual $i = 1, \ldots, N$ can be expressed as

$$\Pi_{ic} = \pi(P_i, \beta_c) + v_{i|_c} - u_{i|_c} = \pi(P_i, \beta_c) + \epsilon_{i|c}$$

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[1] This is described in Maine State Statute §6341-E Vessel Limitation 1,2,3.

where p_i is the vector of input price faced by harvester i and β_c is the vector of parameters to be estimated for each latent class of fishing style *c*. Stochastic components are modeled for each class, where $v_{i\,|_c}$ is the two-sided random errors ($v_{i|_c} \sim \mathrm{N}(0, \sigma^2_{vc})$) and $u_{i|c}$ is the non-negative random variable associated with a harvester specific inefficiency component with a zero mean and variance $\sigma^2{}_{ic}$. Assuming half-normal distribution for $u_{i|c}$, conditional likelihood function can be expressed as

$$LF_{ij} = \frac{2}{\sqrt{\sigma^2_{u|c} + \sigma^2_{v|c}}}\phi\left(\frac{\varepsilon_{i|c}}{\sqrt{\sigma^2_{u|c} + \sigma^2_{v|c}}}\right)\Phi\left(\frac{\varepsilon_{i|c}\sigma^2_{u|c}/(\sigma^2_{u|c} + \sigma^2_{v|c})}{\sigma^2_{u|c}\sigma^2_{v|c}/(\sigma^2_{u|c} + \sigma^2_{v|c})}\right)$$

In the latent class stochastic frontier model, the profit frontier is estimated for each class. Class membership is estimated from a set of manifest variables (i.e., technical, and operational characteristics), which can be denoted as a vector z_i. The unconditional likelihood of a latent class is expressed as a weighted sum of the likelihood function such that

$$LF_i(\theta,\delta) = \sum_{c=1}^{C} LF_{ic}(\theta_c) \cdot P_{ic}(\delta_c) = \sum_{c=1}^{C} LF_{ic}(\theta_c)\frac{\exp(\delta_c{}'q_i)}{\sum_{c=1}^{C}\exp(\delta_c{}'q_i)}.$$

The translog model specification was used to measure the profit efficiency of Maine's lobster industry. Dropping subscripts for harvester i and latent class c, this can be expressed as

$$ln(\pi) = \alpha_0 + \sum_{j=1}^{3}\alpha_j ln(p_j) + \frac{1}{2}\sum_{j=1}^{3}\sum_{k=1}^{3}\tau_{jk} ln(p_j) ln(p_k) + \mathrm{v} - \mathrm{u}$$

We normalized profit π and input prices p_j by ex-vessel price of lobster. We considered three inputs: bait, fuel, and crew wage. Inefficiency term was defined as

$$\mathrm{u} = \delta_0 + \sum_{l=1}^{4}\delta_l W_l + \omega$$

We examined four inefficiency determinants W: resource index, household income dependency on the lobster fishery, and number of active calendar quarters in a year. Following Orea and Kumbhaker (2004) and Barros et al. (2013)[2] and the maximum likelihood estimation of latent class stochastic frontier model was implemented by using R (v. 4.1.2) by using sfaR package (v. 0.1.0, 2021) using Marquardt-Levenberg algorithm as optimization algorithm[3].

Data

An economic and fishing effort survey of the New England American lobster fishery industry conducted in partnership between Gulf of Maine Research Institute and Maine Lobsterman Association was used in this study. The survey was administered by telephone in 2011 and collected information related to lobster landings, revenue, fixed and variable production inputs and associated costs, and production technology used during the calendar year 2010 (Gulf of Maine Research Institute 2014). The survey participants consisted of active lobster harvesters in Massachusetts, New Hampshire, and Maine. The survey collected information from 1,001 commercial lobster harvesters, out of which 834 are Maine-based harvesters. For our study, we considered Maine-based harvesters who reported to have made at least one trip and earned the revenue of at least $1,000 from lobster fishery in 2010 (N=662). While the previous publication on this survey reported a high completion rate of 98%, the resulting panel dataset included many observations with missing information due to respondents not providing answers to some of the questions. For our study, we only included Maine-based harvesters who reported to have earned more than USD 1,000 (nominal value) in the year 2010. We further restricted observations to

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[2] Both of these studies examined cost efficiency. In cost efficiency model, the error components are modeled as v + u.

[3] The details of the computation can also be found in (Dakpo et al. 2021; "Stochastic Frontier Analysis using R" 2021)

those who reported to have at least one lobstering trip, one lb of harvest, and reported at least 1% dependence on lobstering for household income (N=545). Because we rely on self-reported data, we checked for outliers. We first dropped observations that had estimated mean ex-vessel that fell below or above 1th and 99th percentile. We further restricted our data by dropping observations that recorded daily wage of less than or equal to USD 10, engine built after 2011, bank fee greater than or equal to USD 10,000, mooring fee greater than or equal to USD 10,000, vessel maintenance cost greater than or equal to USD 100,000, number of crew greater than or equal to 4 (regulation restricts the number of crew members to be less than 3), bait price less than or equal to USD 0.01. We also dropped observations that did not report on any of the eight technical characteristic variables and/or missing fuel and bait cost information. Our final dataset consists of 232 observations. Most variables were obtained directly from the survey, but some variables required further derivation (See supplementary information for the detailed description of data cleaning process.). Wage variable, for instance, was calculated in multiple steps as crew renumeration system differ by operators. In the survey, respondents were first asked to indicate whether crew were paid flat wage rate or received revenue share. For those who answered that the crew were paid flat wage rate, the rate was derived by dividing the total crew labor cost (including both fishing and non-fishing payments) by the number of crew labor days. For those who answered that the crew were paid revenue share, we further asked whether they deduct fuel and/or bait cost before calculating the share. Based on this answer, we calculated the total crew labor cost. The wage-equivalent value was then calculated based on the calculated total crew labor cost. The resource index is a proxy for the relative productivity of the fishing ground each harvester operates in, and accounts for other harvesters operating within the same spatial zone to provide a fishing ground productivity measure per trap fished. This was calculated using the

2010 lobster resource abundance estimate of the American Lobster Settlement Index, which estimated resource abundance for each of Maine's lobster fishing zones (Oppenheim et al. 2019). We denote the estimated resource abundance in zone *j* as S_j. In order to estimate this relative productivity of fishing ground, we first calculated the reported number of traps set in each zone. While the majority of the harvesters reported that they have only harvested in one zone, there are some harvesters who set traps in multiple zones. We made an assumption that those who were active in two zones allocate 60% of their traps in the primary zone and 40% of their traps in the secondary zone, and those who were active in three zones allocate 60% of their traps in the primary zone, 25% of their traps in the secondary zone, and 15% of their traps in the tertiary zone. This assumption was informed by the regulation to allocate at least 60% of the traps in the primary zone and to limit the number of active zones to three. We further denote the number of total traps set in each zone by aggregating individual's allocation in each zone. We denote the total number of traps set in zone *j* as the following:

$$traps_j = \sum_i traps_{i \in j}.$$

Relative availability of the resource stock (s_j) was then calculated as follows:

$$s_j = \frac{S_j}{traps_j}$$

And, for each individual harvester, their relative resource availability can be expressed as:

$$s_i = \begin{cases} s_{primary} \ \ if\ active\ in\ one\ zone \\ 0.6 \cdot s_{primary} + 0.4 \cdot s_{secondary}\ if\ active\ in\ two\ zones \\ 0.6 \cdot s_{primary} + 0.25 \cdot s_{secondary} + 0.15 \cdot s_{tertiary}\ else \end{cases}$$

Table 1 reports the descriptive statistics of the data used in the analysis.

Results

Our choice of the number of latent classes was supported statistically through multiple criteria and results as shown in Table 2. Our choice was further informed by deep knowledge of the study system and validated through industry feedback. Both likelihood ratio tests and AIC suggest five classes while others suggest pooled model (i.e., 1 class). Thus, we report results of both pooled and five classes examine both models.

Our specification of the lobster fishery business model represents a combination of technical and operational characteristics. Figure 2 shows the estimated mean scaled values of manifest technical and operational characteristics and Table 3 shows the descriptive statistics for each latent class that represents a business model.

Technical characteristics for class 1 indicate a high degree of investment in a new and large vessel and engine power. Operational characteristics reveal a fishing strategy of more frequent trips, with less steam time, and hauling through a higher proportion of traps set with shorter soak times, which are configured with multiple traps attached to each vertical line in the water, i.e. trawling up. Business model represented by Class 3 is similar to the one for Class 1 with investment in a new boat and new engine and operating within a 40 min steam time area. Class 3 employs longer soak times than Class 1, and actively fishes all four quarters of the calendar year, where Class 1 focuses on peak seasons. Class 3 exhibits a tradeoff decision between investment in vessel or crew, and more active fishing year-round, resulting in lower mean conditional efficiency for Class 3, relative to Class 1.

Business models represented by Class 2 and 4 both operate mostly without crew, fishing gear configured as a single trap per line, and a longer soak time, which averages four days. Class 2 average vessel length is larger than Class 4, and vessels are equipped with smaller engines, which appears to be the primary difference in the operational characteristics between Class 2 and 4.

Business model represented by Class 5 displays many of the attributes originally described as the traditional Maine lobsterman by Acheson (Acheson 1975b, 1975a). Technical characteristics feature mid-size older vessels powered by older lower horsepower engines. Class 5 employs limited crew, traps configured as a single trap per line, or in pairs. Fishing effort is focused on prosecution of the fishery within a 50-minute steam time and soak times of seven days on average.

Table 4 shows the estimated mean profit efficiencies for the model with five latent classes and pooled model. As expected, the pooled model yielded efficiency estimates lower than the model with five classes. Overall, we found mean profit efficiencies in the range between 0.69 and 0.96. In the model with five classes, Class 5 and 1 demonstrates the lowest and highest overall mean conditional efficiency, respectively. In general, we found that business models that employ a higher degree of vessel investment matched by more intense harvesting operations are associated with higher profit efficiency. Additional vessel investment as seen in business models represented by Class 1 and 3, which operate new boats with new and more powerful engines, showed the highest mean conditional profit efficiency. Class 1 couples vessel investments with crew investments, trawling up gear configuration, and short soak times to optimize profit efficiency. Mean overall efficiency for Class 2 and 4, which operate equally small or smaller vessels with newer engines showed similarities in operational characteristics, but Class 2 and 4 differ starkly in estimated profit efficiencies, ceteris paribus, suggesting another source of variation such as uneven underlying stock productivity.

Table 5 reports the parameter estimates from the latent class stochastic profit frontier analysis. The estimated coefficients show the relative contribution of each factor contributing towards profit efficiency. The signs of the estimated input price parameters found to be significant are the same for both pooled and latent class models. For the latent class model, the signs of the estimated input price parameters found to be significant are the same for all except for the half quadratic term for bait price for Class 5. The estimated parameters of inefficiency determinants found to be significant differed between the pooled and latent class models. We also found some variations across classes in the latent class model results In four out of the five business model classes, ‘Resource stock’ was found to be significant and positive (i.e., higher inefficiency) for the pooled model and for Class 3 of the latent class model. This is counterintuitive as we expect the higher resource abundance to be associated with higher profit efficiency. For Class 4, it was found to be significant and negative, which is aligned with our intuition. There are stark differences between Class 3 and 4 differ in terms of their vessel length, engine power, and soak time. Class 3 operates with a larger and more powerful vessel with traps soaked longer periods of time than Class 4. It is possible that in an environment where the resource is more abundant, long soak times are unnecessary and allow the lobsters to take advantage of the trap’s escape measures. This in turn results in lower efficiency. Dependence on the fishery was found to be significant and negative. This is indicative of a possible specialization effect. Quarters active variable was found to be significant and negative for Class 3, 4, and for the pooled model, but positive for Class 5. Class 5, as compared to Class 3 and 4, use the older engine and have a longer steam time. For this class, it is most likely not efficient to operate during the winter months. Experience variable was found to be significant and negative for Class 5 and for the pooled model, but positive for Class 3. Class 3 operates with newer, bigger, and more powerful vessels. It is possible that this group consists of relatively newer entrants to the fishery than Class 5. In sum, the latent class model allows us to explore the variable impacts of different fixed production factors (i.e., inefficiency determinants) across different business models that are masked in the pooled model estimation.

Further examination of latent class models on a zone-by-zone basis reveals notable differences in the mean profit efficiency for each class by zone (Figure 3 and 4), and variation in the proportion of harvester business models represented within each zone (Figure 5). The business model represented by Class 1 shows high mean profit efficiencies in all lobster management zones, and represents more than a quarter share of the fleet in zone B and F. Business model represented by Class 2 operates efficiently in zones E and G, whereas the business model represented by Class 4 shows a decrease in mean conditional efficiency in zones E and G. In general, comparing Class 4 and 5 across zones reveals decreases in its efficiency in the southwestern zones of the state, relative to eastern zones (Figure 5). Our results highlight the efficiency gains that can be achieved through intensification of technical and operational inputs, and these technical decisions may be moderated by zone-specific features such as abundance and geographical distribution of lobsters and lobster traps.

Discussion

Maine’s lobster fishery is one of the most sustainably managed fisheries in the world and a rare example of an owner-operator fishery supporting communities that live in rural and rugged environments (Acheson 2004). The lobster fishery’s conservation program has been integrated into successful business and fishing models that have achieved intergenerational longevity. An apprenticeship program and zone scale councils create a co-management system in which the harvesters are fully invested in the management of the resources that sustain them (Acheson et al. 2000; Brewer 2010). The tight controls on entry and exit, including non-transferability of licenses, and reductions in trap counts over 20 years, have maintained the sustainable balance of the fishery. The inshore fishing effort in the Maine lobster fishery is constrained by spatial management zones, which prevent migratory fishing practices and institutionalize the fishery's traditional territorial use rights schema that is honored within the fleet and by regulators (Acheson et al. 2000). The number of licenses per zone is constrained as well, and so the community accepts the natural fluctuations in the overall fishery return and shares in this together. Tight management has prevented over-fishing, and fishing licenses remain within the communities. These unique features bear significant conservation value that is rarely acknowledged.

Meanwhile, a previous study characterized this fishery as a 'gilded trap', where decades of success and resulting heavy dependence on this fishery make Maine's coastal communities more vulnerable to climate change impacts (Steneck et al. 2011). As the biomass of the lobster fishery shifts spatially over time, the fishing success may vary by the type of business model employed. We recognize a primary limitation of our research is that it characterizes differences in harvester business models for a single representative fishing year. We propose that this study nonetheless provides a unique insight into the connections between inputs and economic profit within differing explicit management boundaries and effectively captures the latent characteristics, which we further hypothesize to be enduring over time, and a question we recommend for future research.

Studies show that the lobster resource has seen changes in recruitment patterns, and landings are expected to also shift further eastward (Fogarty and Gendron 2004; Holland 2011b; Mills et al. 2013; Steneck and Wahle 2013; Oppenheim et al. 2019; Goode et al. 2019). Our research confirms that harvesters employ a variety of business models, amount of effort and producer inputs that meet their social and economic business objectives. Previous studies described the fishery and its harvester interactions as scramble competition, a race to productive fishing ground, and interference competition, trap cutting to obstruction of other harvesters' fishing efforts (Acheson 1975b; Wilson et al. 2007). Harvesters are able to pursue the resource, limited only by the spatial zone management area and maximum number of allowable trap tags (Tanaka et al. 2019). Harvester business models that vary in their frequency of trap tending and active monitoring of average catch per trap haul can prompt a relocation of traps and fishing effort in pursuit of more productive areas within the management zone and as allowed by the social territory. Further, we found a contrasting relationship between resource abundance and efficiency for Class 3 and 4, who differ in technical capacity and trap soak time, indicating that a certain business model may fare better under low resource abundance.

Mean conditional profit efficiency of individual classes within the different Maine lobster zones show variation in keeping with biological productivity estimates of the fishery and American Lobster Settlement Index (e.g., Chang et al. 2016; Oppenheim et al. 2019). Fleet composition by Class by zone supports the hypothesis of a pursuit fishery and correlates with habitat suitability and biological productivity models. Notably, Zone F which is situated in the Southern Gulf of Maine and characterized by islands and a fjord-like coastline, observed rapid changes in average water temperatures relative to the historic baseline (Oppenheim et al. 2019). This can explain our finding of decreases in abundance and unsustainable fishing efficiency for the business models represented by Classes 3 through 5 in our study. Zone F has incurred one of the highest fleet investment rates and provides compelling evidence of community-level adaptation to changing ocean conditions. Three of five harvester business models in other westward zones of the Gulf of Maine also demonstrate a mean conditional efficiency of less than .50, prompting questions of community sustainability in the face of change.

Our study contributes to benchmarking the lobster fishery's economic efficiencies in pre-climate change. Harvester business model represented by Class 5, which most closely mirrors the 'traditional lobsterman', was found to be the least efficient business model across the fishery, suggesting vulnerability in the face of future changes. This has been historically viable where the Maine social fabric and job creation have been valued over efficiency of harvester business models and allows maximum participation in the fishery with low costs of entry. However, if climate change-induced ecological changes result in decreased fishing efficiency, there is a risk that this harvester business model may no longer be economically feasible and crowded out of this fishery. On the other end, the harvester business model represented by Class 1 benefits from additional investments in technical capacities to enable them to choose a more intensive fishing strategy, taking more frequent trips and operating during winter months to achieve high profit efficiency relative to the other vessel classes. At the same time, this business model may not be achievable for those who are financially constrained. Further, under declining resource conditions, this business model may be over capitalized, leading to an erosion of profit efficiency under constrained harvest levels. Our results indicate that bait quality contributes to improved profit efficiency for all business models. This supports the idea of underlying competition in the fishery. As the herring population has declined, harvesters are increasingly relying on imported bait, which we recommend as a topic for future studies.

Analyzing the changes in mean conditional profit efficiencies allows us to bridge between these ethnographic and anthropological studies of the fishery and inform ecological models in a measurable and repeatable way. Our study relied on unique cross-sectional data that was collected in 2011. The lack of socio-economic data in this fishery makes it challenging to examine causal relationships between environmental changes and the economic performance of the fishery. The approach employed in this study, combined with other latent class approaches such as latent transition analysis, can be useful for tracking changes in fleet heterogeneity and economic performance. Yet, scientists' ability to monitor such changes depends on data availability. The authors' personal communications with the industry stakeholders indicate that much has changed since this survey, indicating a critical need for longitudinal surveys.

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Data Availability

The data that support the findings of this study are available on request from the corresponding author, KT.

Competing Interests

The authors declare there are no competing interests.

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Table 1. Descriptive statistics (N=232)

Variable	Unit	Mean	Median	Std.Dev.	Min	Max
Profit	USD	86,507.44	71,316.00	71,482.46	1.00	471,126.00
Ex-vessel price	USD/lb	4.25	4.22	0.71	2.33	8.50
Fuel price	USD/gal	2.99	3.00	0.78	0.24	8.06
Bait price	USD/trap	0.42	0.36	0.25	0.06	2.07
Daily wage	USD/day	130.48	114.85	120.44	1.00	664.48
Resource stock	index	31.47	31.84	6.09	18.20	39.69
Dependence	%	75.34	80.00	26.51	2.00	100.00
Active months	months	9.22	9.00	2.27	3.00	12.00
Experience	years	29.42	30.00	14.83	1.00	63.00
Vessel age	years	19.30	17.00	11.91	1.00	61.00
Engine age	years	7.81	6.00	6.65	1.00	47.00
Vessel length	feet	34.18	35.00	6.26	14.00	56.00
Engine power	horsepower	332.45	317.50	166.76	50.00	997.00
Number of crew	number	0.82	1.00	0.54	0	2.00
Steam time	minutes	37.26	32.50	24.10	1.00	172.50
Soak days	days	4.37	4.00	1.73	1.13	18.67
Traps per line	number	2.98	2.00	3.22	1.00	20.50
Traps hauled per trip	number	241.91	250.01	89.50	30.56	500.00

Table 2. Selection statistics for latent classes

Number of classes	BIC	AIC	HQIC	LR test
5	720.14	306.53	473.33	
4	647.81	323.82	454.48	8.41e-06
3	575.82	341.45	435.97	7.51e-06
2	516.55	371.78	430.16	9.11e-08
1	452.37	397.22	419.46	5.17e-07

Table 3. Descriptive statistics by class (N=232)

		Class 1 (n=69)			Class 2 (n=58)			Class 3 (n=33)			Class 4 (n=44)			Class 5 (n=28)		
		Mean	Median	Std.Dev.	Mean	Median	Std.Dev.	Mean	Median	Std.Dev.	Mean	Median	Std.Dev.	Mean	Median	Std.Dev.
Profit	USD	129,190	120,251	69,558	67,950	62,856	36,718	124,247	101,046	92,402	35,508	31,326	25,994	55,430	30,046	71,507
Ex-vessel price	USD/lb	4.47	4.38	0.79	4.10	4.11	0.67	4.27	4.27	0.52	4.11	4.00	0.65	4.19	4.05	0.79
Fuel price	USD/gal	2.99	3.00	0.88	3.05	3.00	0.66	2.93	2.93	0.49	2.94	3.00	1.05	2.99	3.00	0.53
Bait price	USD/trap	0.43	0.42	0.21	0.42	0.35	0.33	0.51	0.46	0.24	0.35	0.30	0.22	0.37	0.29	0.21
Daily wage	USD/day	182.41	172.84	120.12	106.28	95.42	102.49	154.45	140.14	155.06	89.15	90.75	87.56	89.38	55.34	107.24
Resource stock	index	31.65	31.33	6.02	31.83	32.34	5.52	32.52	32.34	5.73	30.51	31.11	6.86	30.57	31.11	6.60
Dependence	%	81.43	90.00	20.97	70.91	75.00	26.79	85.94	90.00	17.47	62.09	63.50	32.09	77.79	95.00	28.70
Active months	months	9.65	9.00	2.23	9.00	9.00	2.10	10.18	12.00	2.11	8.18	9.00	2.18	9.11	9.00	2.38
Experience	years	30.70	30.00	13.73	28.72	30.00	15.21	30.36	33.00	13.40	25.80	25.00	14.91	32.32	36.00	17.77
Vessel age	years	13.42	11.00	9.90	23.43	22.50	12.22	14.85	14.00	9.42	22.77	23.00	11.16	25.00	24.50	12.08
Engine age	years	4.61	5.00	2.70	8.33	8.00	5.06	7.09	6.00	4.17	8.30	6.50	6.97	14.71	11.50	11.45
Vessel length	feet	36.33	37.00	4.65	33.60	35.00	4.59	38.39	38.00	3.04	29.14	31.00	6.92	33.04	35.00	8.50
Engine power	horsepower	408.42	375.00	168.59	236.83	225.00	80.03	477.88	435.00	152.65	247.27	225.00	116.81	305.79	280.00	175.15
Number of crew	number	1.16	1.00	0.49	0.66	1.00	0.47	0.74	1.00	0.52	0.68	1.00	0.47	0.63	1.00	0.59
Steam time	minutes	41.79	37.50	24.95	31.91	30.00	16.25	40.03	41.25	16.70	26.35	20.83	18.54	51.06	38.33	38.13
Soak days	days	4.01	4.00	1.19	4.48	4.29	1.33	5.88	5.00	2.91	4.06	3.58	1.42	3.77	3.71	1.24
Traps per line	number	4.74	2.00	4.38	1.71	2.00	0.65	2.55	2.00	1.86	1.90	2.00	1.48	3.52	2.00	4.27
Traps hauled per trip	number	305.36	296.05	70.87	217.79	230.64	73.74	234.53	241.54	63.99	213.25	216.67	96.94	189.25	190.73	93.65

Table 4. Mean profit efficiencies by zone

	Class 1				Class 2				Class 3				Class 4				Class 5				Pooled			
	n	mean	sd	se	n	mean	sd	se	n	mean	sd	se	n	mean	sd	se	n	mean	sd	se	n	mean	sd	se
All	69	0.96	0.16	0.03	58	0.92	0.32	0.04	33	0.88	0.22	0.04	44	0.77	0.28	0.04	28	0.69	0.32	0.06	232	0.69	0.21	0.01
A	12	0.92	0.25	0.07	7	0.77	0.38	0.14	4	1.00	0.00	0.00	10	0.89	0.17	0.05	6	0.79	0.28	0.11	39	0.66	0.21	0.03
B	12	1.00	0.00	0.00	5	0.78	0.44	0.19	6	0.92	0.15	0.06	3	0.77	0.37	0.22	1	0.33	-	-	27	0.72	0.21	0.04
C	7	1.00	0.00	0.00	8	0.95	0.09	0.03	3	1.00	0.00	0.00	7	0.84	0.26	0.10	5	0.53	0.43	0.19	30	0.68	0.24	0.04
D	16	0.89	0.25	0.06	19	0.95	0.11	0.03	14	0.84	0.25	0.07	6	0.82	0.17	0.07	5	0.82	0.18	0.08	60	0.72	0.15	0.02
E	4	1.00	0.00	0.00	13	0.97	0.07	0.02	3	0.84	0.25	0.15	8	0.60	0.31	0.11	3	0.70	0.15	0.09	31	0.65	0.22	0.04
F	13	1.00	0.00	0.00	1	0.50	-	-	-	-	-	-	2	0.88	0.16	0.12	4	0.90	0.14	0.07	20	0.75	0.16	0.04
G	5	0.95	0.11	0.05	5	0.99	0.02	0.01	3	0.75	0.40	0.23	8	0.67	0.38	0.13	4	0.44	0.45	0.23	25	0.67	0.28	0.06

Table 5. Results of maximum likelihood estimation of latent class stochastic profit frontier

	Five classes					Pooled
	Class-1	Class-2	Class-3	Class-4	Class-5	
Intercept	20.543 ***	20.792 ***	12.38 **	12.947 ***	35.299 ***	14.454 ***
	(3.697)	(4.456)	(5.072)	(1.365)	(0.223)	(3.788)
$ln\ (p_{\text{bait}})$	11.831 ***	3.157 **	7.237 ***	2.389 ***	2.494 ***	5.08 ***
	(2.086)	(1.388)	(0.673)	(0.165)	(0.071)	(1.211)
$ln(p_{fuel})$	-1.063	-1.813	-1.091	0.361	-6.563 ***	-0.068
	(1.203)	(1.651)	(2.471)	(0.574)	(0.060)	(1.205)
$ln(p_{wage})$	-4.462 ***	-2.054 ***	-1.586 ***	-1.131 ***	-3.044 ***	-1.949 ***
	(0.461)	(0.191)	(0.183)	(0.096)	(0.005)	(0.317)
$0.5ln(p_{bait})^2$	-0.338 *	-0.086	-0.077 *	-0.091 ***	0.784 ***	-0.054
	(0.180)	(0.120)	(0.046)	(0.018)	(0.002)	(0.140)
$0.5ln\ (p_{fuel})^2$	-0.112	0.172	0.694	-0.056	0.465 ***	0.05
	(0.181)	(0.343)	(0.616)	(0.116)	(0.004)	(0.202)
$0.5ln(p_{wage})^2$	0.217 ***	0.256 ***	0.255 ***	0.311 ***	0.237 ***	0.273 ***
	(0.034)	(0.034)	(0.010)	(0.002)	(0.000)	(0.028)
$ln\ (p_{bait})\ \cdot ln\ (p_{fuel})$	-2.362 ***	-0.421	-1.315 ***	-0.113 ***	-0.108 ***	-0.847 ***
	(0.521)	(0.353)	(0.162)	(0.042)	(0.017)	(0.293)
$ln(p_{bait})\ \cdot ln\ (p_{wage})$	-0.122 ***	-0.162 ***	-0.192 ***	-0.219 ***	-0.361 ***	-0.166 ***
	(0.033)	(0.024)	(0.009)	(0.001)	(0.001)	(0.03)
$ln\ (p_{fuel})\ \cdot ln\ (p_{wage})$	0.811 ***	0.236 ***	0.155 ***	-0.031	0.576 ***	0.198 ***
	(0.116)	(0.044)	(0.038)	(0.025)	(0.001)	(0.066)
Inefficiency determinants						
Resource stock	0.422 *	0.239 *	0.224 **	-0.053 **	0.087	4.301 ***
	(0.219)	(0.130)	(0.105)	(0.025)	(0.065)	(1.084)
Dependence	0.433	-0.133 ***	-0.287 ***	-0.069 ***	-0.055 ***	0.028
	(0.265)	(0.040)	(0.093)	(0.008)	(0.017)	(0.041)
Quarters active	-6.607	-0.498	-0.499 ***	-0.363 ***	1.739 ***	-0.036 ***
	(6.940)	(0.351)	(0.090)	(0.103)	(0.507)	(0.012)
Experience	-0.475	-0.084	0.477 ***	-0.019	-0.138 ***	-0.287 **
	(0.340)	(0.056)	(0.149)	(0.015)	(0.041)	(0.128)
Intercept	-1.025	0.668	-2.153	6.299 ***	-12.308 ***	-0.049 ***
	(23.347)	(5.362)	(2.709)	(0.958)	(4.432)	(0.013)
$\sigma^2 = \ \sigma_u^2 + \sigma_v^2$	93090.269	1.134	417749226.2	0.296	24.093	1.002
$\gamma = \sigma/(\sigma_u + \sigma_v)$	1.000	0.980	1.000	1.000	1.000	0.841
Noise component						
Intercept	-2.569 ***	-3.807 ***	-5.835 ***	-25.075 ***	-23.492 ***	-1.838 ***
	(0.212)	(0.311)	(0.272)	(0.571)	(1.375)	(0.292)
Estimated prior probabilities for class membership						
Intercept	1.797	1.453	0.412	2.259 **		
	(1.132)	(1.196)	(1.167)	(1.022)		

Vessel length	0.922	3.007 ***	3.459 ***	-0.459	
	(0.801)	(1.066)	(1.059)	(0.808)	
Engine power	-1.782 **	-4.275 ***	0.011	-1.39 *	
	(0.755)	(1.019)	(0.732)	(0.795)	
Vessel age	-1.235 **	-0.129	-0.604	0.288	
	(0.601)	(0.486)	(0.561)	(0.391)	
Engine age	-4.704 ***	-1.924 ***	-1.674 **	-1.765 ***	
	(1.157)	(0.652)	(0.756)	(0.533)	
Steam time	-3.187 ***	-3.392 ***	-4.03 ***	-3.197 ***	
	(0.831)	(1.030)	(1.014)	(0.860)	
Soak days	1.111	3.048 ***	3.821 ***	1.878 **	
	(0.819)	(0.828)	(0.935)	(0.793)	
Number of crew	1.279 *	-0.464	-1.59 ***	0.844 *	
	(0.725)	(0.701)	(0.576)	(0.506)	
Traps per line	0.536	-3.891 ***	-0.909	-1.462 **	
	(0.376)	(1.459)	(0.600)	(0.721)	
Traps hauled per trip	2.387 ***	2.241 **	1.929 **	2.615 ***	
	(0.682)	(0.910)	(0.870)	(0.782)	
Number of observations = 232					232
Log likelihood value = -33.26					-182.61

*p<0.1, **p<0.05, ***p<0.01

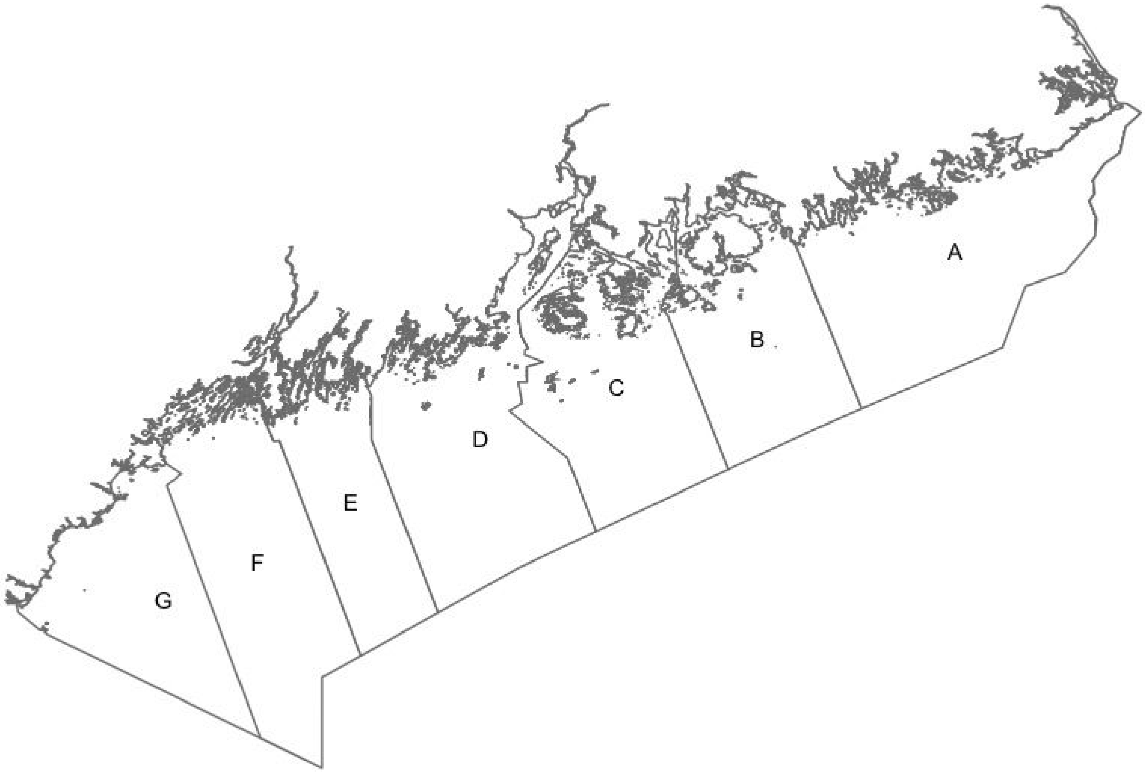

Figure 1: Maine lobster management zones (Shapefile source: Maine Department of Marine Resources)

Figure 2: Manifest technical and operational characteristics of each class (Axes show the scaled mean values of the manifest technical and operational characteristics for each latent class identified. The values were scaled with a mean zero.)

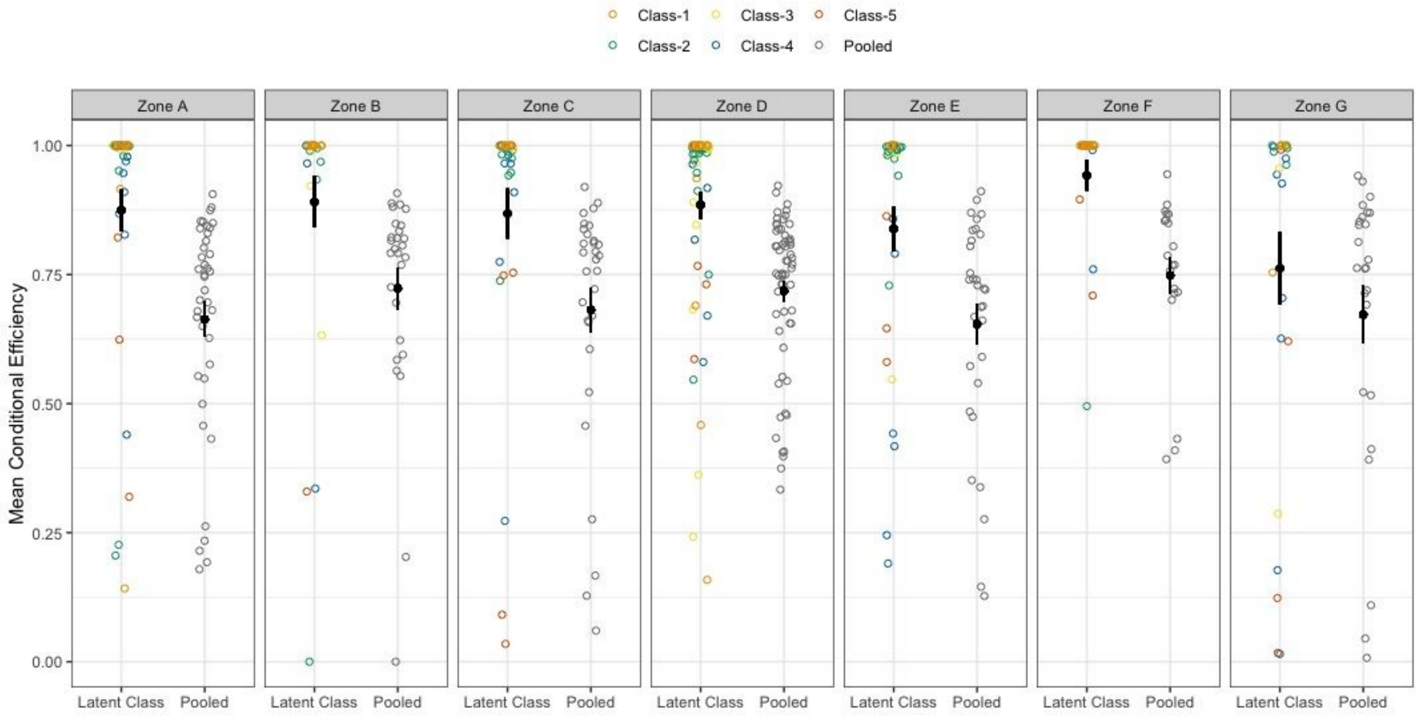

Figure 3: Mean conditional efficiency by zone estimated by the pooled and latent class models (Black solid dots in the figure indicate mean conditional efficiency. Black bars are standard error bars. Colored open circles indicate the estimated efficiencies of all harvesters.)

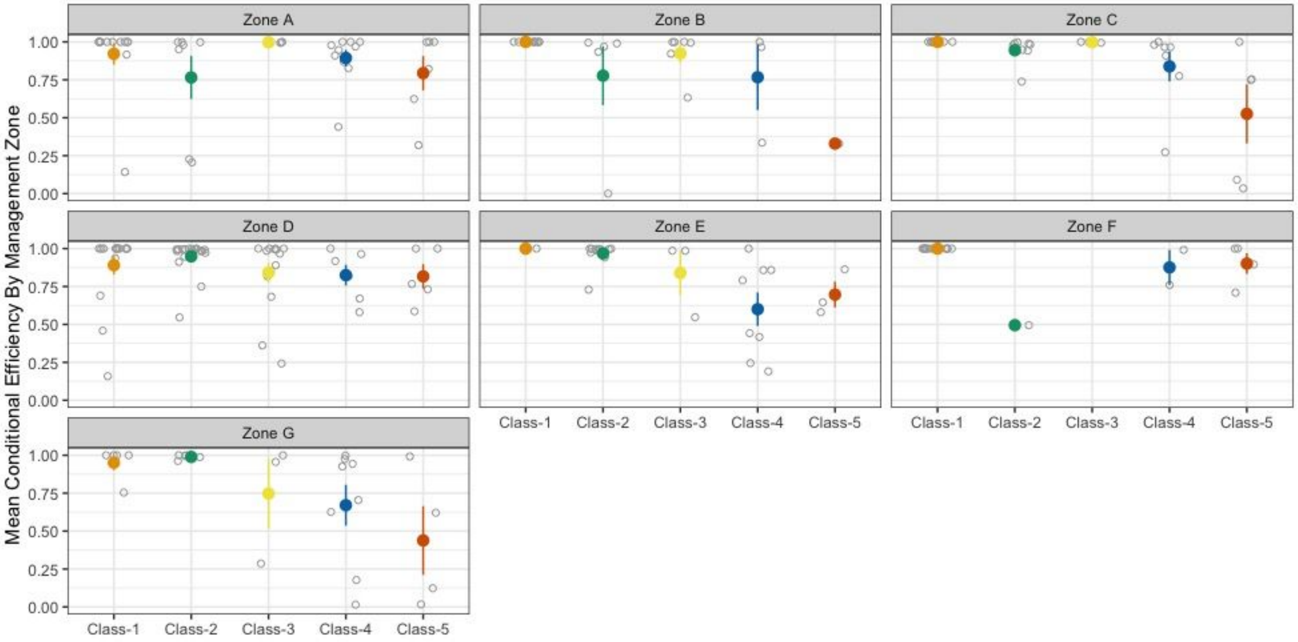

Figure 4: Mean conditional efficiency by zone (Colored solid dots in the figure indicate mean conditional efficiency. Colored bars are standard error bars. Gray open circles indicate the estimated efficiencies of all harvesters.)

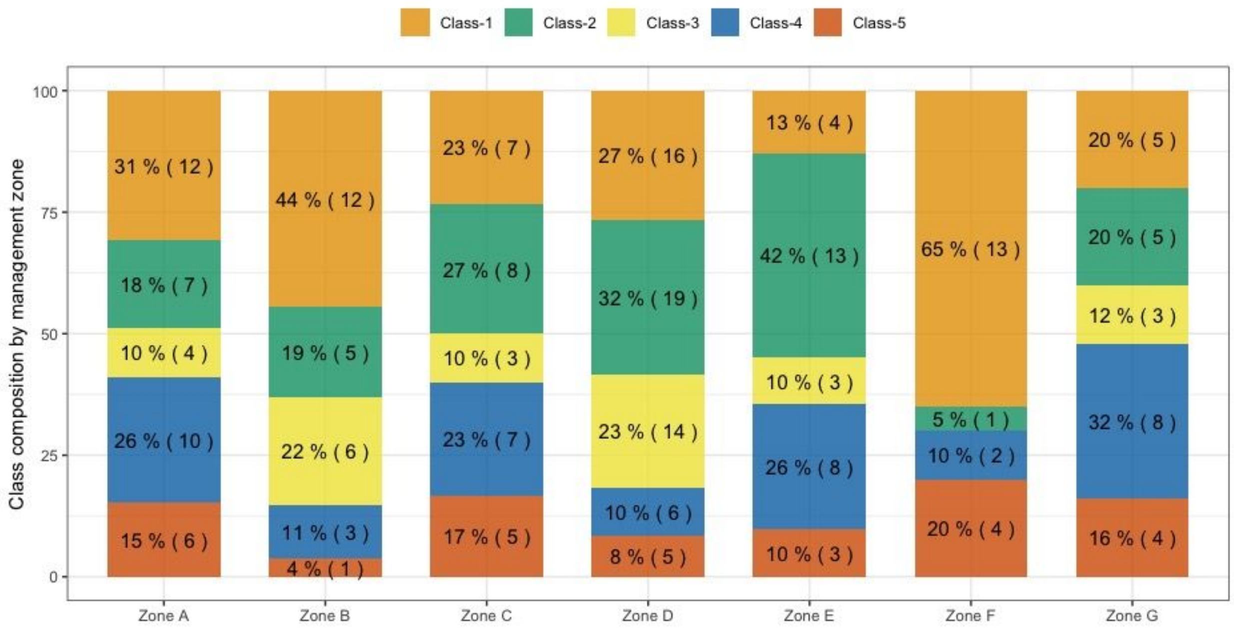

Figure 5: Business model composition by zone (Numbers in the parentheses indicate the number of observations in each class and zone combination.)