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ORIGINAL ARTICLE

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# Improving the management of commercial giant mottled eel *Anguilla marmorata* aquaculture in Taiwan for improved productivity: a bioeconomic analysis

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**Abstract** A multivariate statistical analysis was conducted with the aim to identify the key factors affecting the profitability of commercial aquaculture of the giant mottled eel *Anguilla marmorata* on Taiwan. The results revealed significant differences between the different fish farming systems used on Taiwan in terms of sustainable and profitable commercial enterprise. In terms of production costs, the water circulation systems accounts for the highest costs in water production, and feed costs account for 82.3 % of the total production cost. However, the survival rate is low, about of 20–30 %. Eels were cultured for 2–3 years before a market profit was reached. The farming system in the eastern region of Taiwan had the lowest production cost. The benefit–cost ratio of the concrete pond in the central region of Taiwan and the soil pond in the eastern part of Taiwan was the highest, at about 2.6, and profitability was relatively good; however, the farming cycle is longer and the production risk is higher. These results also show that the survival rate is significantly correlated to production efficiency. Consequently, based on our analysis, we suggest that strengthening cultivation techniques, appropriately increasing stocking density and segmenting glass eels farming in terms of nursery rearing and grow-out will reduce the production risk and enhance the profitability of the industry.

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**Keywords** *Anguilla marmorata* · Giant mottled eel · Bioeconomic analysis · Multivariate analysis

## Introduction

There are 19 species of anguillid distributed throughout the coastal areas of the North Atlantic Ocean, Indian Ocean and West Pacific Ocean [1]. Of these, five species of freshwater eels, i.e., *Anguilla japonica*, Temminck & Schlegel 1846, *A. celebesensis*, Kaup 1856, *A. marmorata*, Quoy & Gaimard 1824, *A. bicolor pacifica*, Schmidt 1928 and *A. luzonensis*, Watanabe, Aoyama & Tsukamoto 2009, can be found in the waters around Taiwan [2–7]. *A. marmorata*, the giant mottled eel, is a tropical anguillid eel which is widely distributed throughout most of the tropical and subtropical West Pacific and Indian Oceans [8], as well as from East Africa through Indonesia to French Polynesia in the South Pacific Ocean where several different current systems exist [9–12]. Minegishi et al. [13] demonstrated that *A. marmorata* has four genetically different populations (North Pacific, South Pacific, Indian Ocean, Guam region). The hatching grounds of the North Pacific population extend from 12° N to 20° N and from 130° E to 142° E, west of the Mariana Islands of the North Equatorial Current region, with the spawning area overlapping with that of the Japanese eel *A. japonica* [8, 14]. In contrast to *A. japonica*, however, *A. marmorata* larvae transport into either the northward flow of Kuroshio Current or the southward flow of the Mindanao Current and recruit to Taiwan, Southern Japan, the Philippines and northern Indonesia, most predominantly in the spring and summer [14–19].

*Anguilla marmorata* is a highly valued aquatic product of major economic importance for the Chinese market. The main difference between it and *A. japonica* is the presence of black spots on the tail during the glass eel period and stripes along its back. In Taiwan, commercial eel aquaculture mainly focuses on the Japanese eel. However, due to overfishing, habitat destruction, climate change and other factors, the global catches of Japanese eels have plummeted in recent years [20–22]. The Japanese eel is now listed as an endangered species by International Union for Conservation of Nature [23–25]. This has led to a price increase for Japanese glass eel, with the result that commercial aquafarming of giant mottled glass eels and giant mottled eels has emerged in China, mostly concentrated in Hainan, Guangdong and Fujian provinces [26].

The lifting of the Enforcement Rules of the Wildlife Conservation Act on giant mottled eel cultivation by Taiwan in 2009 has led to the eel becoming a new target fish species for the aquaculture industry [27]. As the giant mottled eel is a tropical fish, the water temperature should be maintained above 18 °C [26], with the result that most of the commercial giant mottled eel ponds in Taiwan are located in central, southern and eastern Taiwan. The cultivation methods vary, with farming in outdoor soil ponds, concrete ponds and indoor ponds. Many studies have pointed out that geographic location and pond structure can affect the inputs and outputs of the production process [28–31].

The aim of this study was to evaluate the interaction effect of geographical location and pond structure on the costs and returns of commercial grow-out fish farming of the giant mottled eel in Taiwan. To this end, we studied a number of variables (measurements) at each farm. All of the variables were random and interrelated in such a way that their different effects cannot meaningfully be interpreted separately. Consequently, our statistical analysis was performed using multivariate techniques. The rationale underlying the use of a multivariate analysis is to consider several related random variables simultaneously, with each one being considered equally important at the start of the analysis. This analysis led to suggestions for improving farming management and, consequently, improved productivity.

## Materials and methods

Production and economic data were collected from giant mottled eel aqua-farmers in the central, southern and

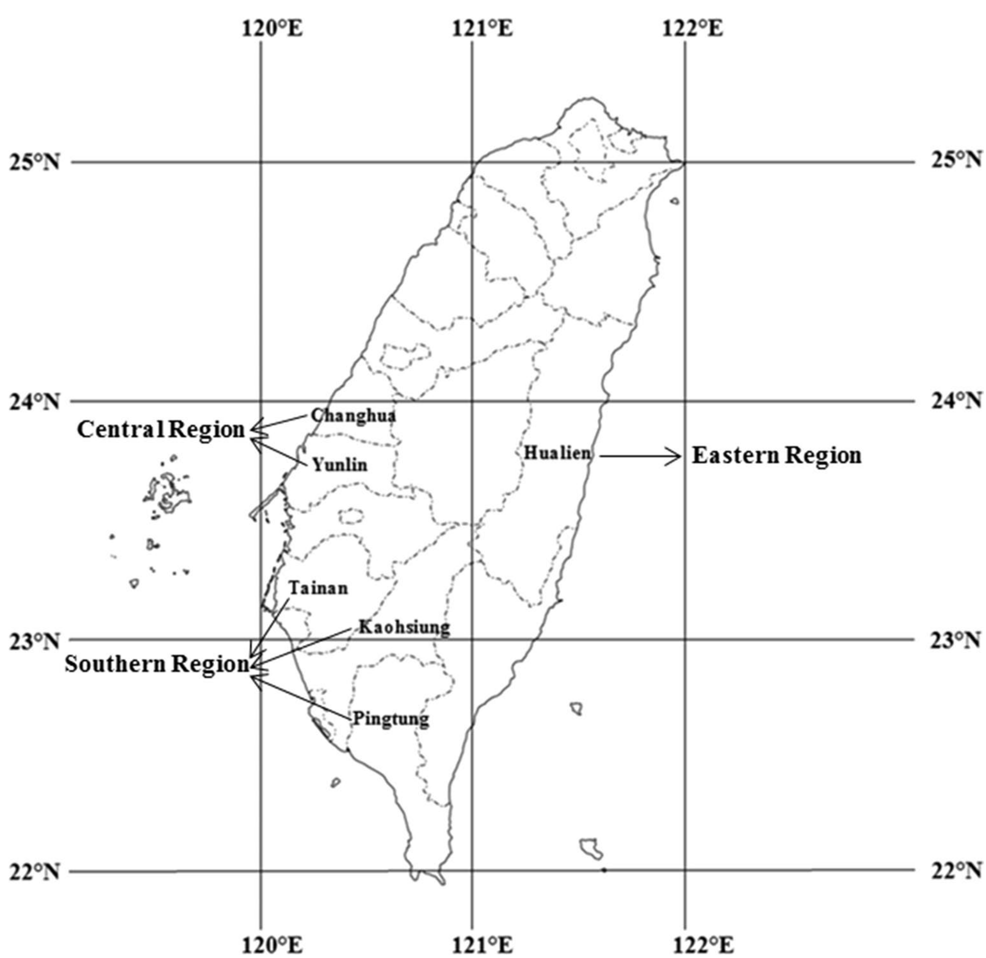


**Fig. 1** Geographical locations of giant mottled eel (*Anguilla marmorata*) aquafarms in Taiwan

eastern regions of Taiwan by means of an interview and questionnaire between March and July 2013 (Fig. 1) by stratified random sampling [32]. This survey was a one-to-one field investigation of eel aqua-farmers registered with the Taiwan Fisheries Agency. Those aqua-farmers for whom the questionnaire was incomplete were eliminated from the study, leaving 29 valid samples for further analysis. The findings showed that the total output of the farmers sampled was 2,085 tons and the area under aquaculture was 19.14 ha, accounting for about 80 % of Taiwan's giant mottled eel output in 2012. The data thus collected were divided into biological and economic categories, with the biological data relating to farming cycle, stocking density and survival rate, and the economic data including production costs and profits. The objective of our research was to evaluate the interaction effect of geographical location (central, southern and eastern regions; Fig. 1) and pond structure (soil, concrete and indoor pond) on the costs and returns of this grow-out industry in Taiwan. Aquaculture systems consisting of concrete and indoor ponds have higher construction costs but lower maintenance costs than those with soil ponds, and vice versa.

The annual production costs of the 29 giant mottled eel farms included in the analysis were separated into two categories, i.e., fixed and variable costs. Fixed costs had already been depreciated and were excluded from the analysis. Variable costs related to production costs include feed costs, glass eel costs, labor costs, water and electricity costs, among others (maintenance, medicine, etc.). Calculation of cost inputs and profit variables was based on each farming cycle as the fundamental standard. Variables of costs were estimated using corresponding input intensities (Taiwanese dollars per fen, with '1 ha = 10.31 fen'). Profit variables consisted of total revenue, net revenue and benefit–cost ratio (B/C) [33–35]. The total revenue (for each individual aquafarm) was estimated by the unit price [Taiwan Dollar (TWD)/kg] offered by the large commercial buyers (directly exchanged at farms) multiplied by the total production (kg). The net revenue was obtained by subtracting the annual production cost from the total revenue.

One-way and two-way multivariate analyses of variance (MANOVA) [36] were applied to examine the effects of geographical location and pond structure on management performance. The Mahalanobis distance [37, 38] among each of the seven categories was calculated using the three sets of variables, respectively, to verify the differences in performance. In order to be able to make a clear statement that, for example, a difference (distance) between indoor ponds in the southern region and soil ponds in the central region was significant or not, "$P$ (probability)" was set at 0.05. Two categories were significantly 'distant' when compared to their corresponding means of biological original variables, input intensities variables and profitability variables as a whole; otherwise, they were 'close' (not different) by setting $P = 0.05$.

The analysis of canonical discriminant functions [39, 40] was further utilized to distinguish the seven category performances with visual aids. By computing the canonical discriminant functions, the corresponding canonical variables may indicate a group of quantified management indices and therefore provide farming systems with an improved space in the future. As a last step, canonical correlation analysis [36, 41] was used to investigate the relationships between two groups of variables, i.e., the biological and economic types. Determining which relationship exists between these two groups of variables is of considerably bioeconomic interest. Computer software developed by SAS Institute (Raleigh, NC) was used for the analyses at a significant level of $P = 0.05$.

## Results

The means and standard deviation of the original biological variables in the seven farming categories are listed in Table 1. The highest stocking density of giant mottled eel was found at an indoor fish farm in southern Taiwan. However, better survival rates were found for fish farms with soil and concrete ponds in southern Taiwan and those with concrete ponds in central Taiwan. The aquafarming cycle in the soil and concrete ponds in southern Taiwan was 2 years, and elsewhere it was 3 years (Table 1).

A two-way MANOVA indicated that geographical location, pond structure and their interaction had significant effects on their corresponding mean vectors with the biological original variables at $P < 0.01$, respectively (Table 2). In terms of input intensities, feed cost and glass eel cost were the highest among pond structures in all locations (Table 3). Taking into consideration the set of input intensities, a two-way MANOVA (Table 4) shows that the individual main effects of geographical location ($P < 0.0001$) and of pond structure ($P < 0.0286$) were each not only significantly different but their interaction was also significantly different at $P < 0.0001$. Table 5 shows that fish farms with concrete ponds located in the central region had the highest profitability, and in Table 6 a two-way MANOVA shows that the mean vectors with the profitability variables were significantly different not only between locations ($P < 0.0001$) and pond structures ($P < 0.0001$) but also between their respective combinations ($P < 0.0001$).

The Mahalanobis distances among the seven categories were calculated using the three sets of variables, respectively, to verify the differences in management performance. The southern region/indoor pond (SI) category and other six categories were found to be significantly 'distant' in terms of the original biological variables ($P < 0.05$)

**Table 1** Original biological variables of seven-category *Anguilla marmorata* aquafarms in Taiwan, 2012

| Geographical location | Pond structure | Number of farms ($n$) | Stocking density[a] (×1,000 pcs/fen) | Survival rate[b] (%) | Farming cycle (months) |
|---|---|---|---|---|---|
| Central Taiwan | Soil | 4 | 50.90 ± 33.43 a | 17.75 ± 10.01 a | 42 ± 8 a |
| | Concrete | 1 | 50.00 a | 30.00 a | 39 ab |
| | Indoor | 2 | 10.00 ± 0 a | 22.50 ± 10.61 a | 36 ± 0 ab |
| Southern Taiwan | Soil | 3 | 26.67 ± 7.64 a | 31.67 ± 17.56 a | 27 ± 12 ab |
| | Concrete | 14 | 40.35 ± 26.20 a | 30.64 ± 16.88 a | 23 ± 10 b |
| | Indoor | 2 | 170.00 ± 0 b | 22.50 ± 3.54 a | 38 ± 14 ab |
| Eastern Taiwan | Soil | 3 | 20.00 ±10.00 a | 16.67 ± 2.89 a | 44 ± 7 a |

Values are presented as the mean ± standard deviation (SD). Values followed by different lowercase letters in the same column are significantly different from each other ($P < 0.05$)

[a] Stocking density was measured by ×1,000 fish per fen, with 1 ha = 10.31 fen

[b] Survival rate (%) = 100 × (final adult eel number/initial glass eel number)

**Table 2** Two-way MANOVA of effects of geographical location and pond structure on original biological variables of *A. marmorata* aquafarms in Taiwan, 2012

| Number of factors | Statistical criteria | Value | $F$ value | Pr > $F$ |
|---|---|---|---|---|
| Location[a] | Wilks' lambda | 0.5521 | 2.31 | 0.0527 |
| | Pillai's trace | 0.4612 | 2.10 | 0.0737 |
| | Hotelling–Lawley trace | 0.7871 | 2.57 | 0.0447 |
| | Roy's greatest root | 0.7552 | 5.29 | 0.0071 |
| Pond structure[b] | Wilks' lambda | 0.5967 | 1.96 | 0.0939 |
| | Pillai's trace | 0.4175 | 1.85 | 0.1131 |
| | Hotelling–Lawley trace | 0.6523 | 2.13 | 0.0857 |
| | Roy's greatest root | 0.6137 | 4.30 | 0.0164 |
| Interaction of location and pond structure[c] | Wilks' lambda | 0.3195 | 5.13 | 0.0005 |
| | Pillai's trace | 0.6958 | 3.73 | 0.0046 |
| | Hotelling–Lawley trace | 2.0822 | 6.79 | 0.0002 |
| | Roy's greatest root | 2.0590 | 14.41 | <0.0001 |

*MANOVA* Multivariate analysis of variance

[a] This is a test of the null hypothesis, namely, that the means of the main effects (expressed in mean vectors) caused by the factor of geographical location are not statistically different. The test, namely, is $H_0$: $\mu_C = \mu_S = \mu_E$, where $\mu_C$, $\mu_S$ and $\mu_E$ are the mean vectors of the original biological variables obtained from the *A. marmorata* farms located in central region, southern region and eastern region, respectively

[b] This is a test of the null hypothesis, namely, that the means of the main effects (expressed in mean vectors) caused by the factor of pond structure are not statistically different. The test, namely, is $H_0$: $\mu_S = \mu_C = \mu_I$, where $\mu_S$, $\mu_C$ and $\mu_I$ are the mean vectors of the original biological variables obtained from the *A. marmorata* farms designed as soil, concrete, and indoor ponds, respectively

[c] This is a test of the null hypothesis, namely, that the combination of means (expressed in mean vectors) caused by two factors of geographical location and pond structure are not statistically different. The test, namely, is $H_0$: $\mu_{CS} = \mu_{CC} = \mu_{CI} = \mu_{SS} = \mu_{SC} = \mu_{SI} = \mu_{ES}$, where $\mu_{CS}$, $\mu_{CC}$, $\mu_{CI}$, $\mu_{SS}$, $\mu_{SC}$, $\mu_{SI}$ and $\mu_{ES}$ are the mean vectors of the original biological variables obtained from the *A. marmorata* aquafarms in the central region/soil pond, central region/concrete pond, central region/ indoor pond, southern region/soil pond, southern region/concrete pond, southern region/indoor pond and eastern region/soil pond categories (Table 1), respectively

(Table 7). The central region/concrete pond (CC) category was significantly 'distant' from the other six categories in terms of input intensity and profitability variables ($P < 0.05$), respectively (Tables 8, 9).

In our case, there were three canonical variables which could be theoretically found each time no matter what group of variables was studied (Tables 10, 11, 12). When the analysis of canonical discriminant functions was performed by considering the original biological variables, these canonical variables were:

$$\mathrm{CAN1} = 0.9783\mathrm{SD} - 0.1713\mathrm{SR} + 0.2452\mathrm{FC} \quad (1)$$

$$\mathrm{CAN2} = -0.2269\mathrm{SD} - 0.3851\mathrm{SR} + 0.8964\mathrm{FC} \quad (2)$$

**Table 3** Input intensities of the seven-category *A. marmorata* aquafarms in Taiwan, 2012

| Geographical location | Pond structure | Number of farms ($n$) | Glass eel[a] | Feed[b] | Labor[c] | Water & electricity[d] | Other[e] | Total cost |
|---|---|---|---|---|---|---|---|---|
| Central Taiwan | Soil | 4 | 247.13 ± 236.86 a | 3281.41 ± 3953.58 ac | 116.97 ± 132.20 a | 45.83 ± 36.18 a | 3.12 ± 1.43 a | 3694.35 ± 4105.25 ac |
| | Concrete | 1 | 250.00 a | 25,974.00 b | 10.30 ab | 7.31 ab | 0.32 ab | 26,241.94 b |
| | Indoor | 2 | 448.57 ± 577.81 a | 12,089.83 ± 15,631.34 ab | 2668.83 ± 3498.82 b | 2,593.93 ± 3604.73 b | 652.23 ± 895.88 b | 18,453.38 ± 24,208.57 bc |
| Southern Taiwan | Soil | 3 | 115.00 ± 82.61 a | 1584.95 ± 1797.86 ac | 221.72 ± 276.19 a | 210.96 ± 285.50 a | 17.58 ± 17.88 a | 2150.20 ± 1695.16 ac |
| | Concrete | 14 | 132.23 ± 109.36 a | 1510.05 ± 1611.38 c | 38.67 ± 36.93 a | 21.55 ± 18.76 a | 5.54 ± 9.71 a | 1708.04 ± 1698.08 a |
| | Indoor | 2 | 523.60 ± 19.23 a | 10,710.00 ± 3,029.25 abc | 1,087.45 ± 1174.23 ab | 779.73 ± 705.38 ab | 67.80 ± 45.37 ab | 13,168.58 ± 4934.99 abc |
| Eastern Taiwan | Soil | 3 | 19.17 ± 3.82 a | 553.09 ± 295.93 ac | 31.20 ± 35.52 a | 8.48 ± 9.36 a | 1.23 ± 0.95 a | 613.16 ± 308.52 a |

Values are presented as the mean ± SD, where the unit is 1,000 Taiwan dollar (TWD) per 1 fen. One U.S. dollar = 30.0 TWD. One hectare = 10.31 fen. Values followed by different letters in the same column are significantly different from each other ($P < 0.05$)

[a] Glass eel (GE) input intensity (1,000 TWD)/fen) = glass eel cost (1,000TWD)/area (fen)

[b] Feed input (FD) intensity (1,000TWD/fen) = feed cost (1,000TWD)/area (fen)

[c] Labor input (LR) intensity (1,000TWD/fen) = labor cost (1,000TWD)/area (fen)

[d] Water & electricity (WE) input intensity (1,000TWD/fen) = Water& electricity (1,000TWD)/area (fen)

[e] Other (OR) input intensity (1,000TWD/fen) = other cost (1,000TWD)/area (fen)

**Table 4** Two-way MANOVA analysis of input intensities on geographical location and pond structure for *A. marmorata* aquafarms in Taiwan, 2012

| Number of factors | Statistical criteria | Value | $F$ value | Pr > F |
|---|---|---|---|---|
| Location[a] | Wilks' lambda | 0.1217 | 6.72 | <0.0001 |
| | Pillai's trace | 1.0200 | 3.96 | 0.0009 |
| | Hotelling–Lawley trace | 6.0513 | 10.55 | <0.0001 |
| | Roy's greatest root | 5.8523 | 22.24 | <0.0001 |
| Pond structure[b] | Wilks' lambda | 0.0553 | 11.71 | <0.0001 |
| | Pillai's trace | 1.3560 | 8.00 | <0.0001 |
| | Hotelling–Lawley trace | 9.6465 | 16.81 | <0.0001 |
| | Roy's greatest root | 8.8014 | 33.45 | <0.0001 |
| Interaction of location and pond structure[c] | Wilks' lambda | 0.0395 | 14.52 | <0.0001 |
| | Pillai's trace | 1.4857 | 10.98 | <0.0001 |
| | Hotelling–Lawley trace | 11.0295 | 19.22 | <0.0001 |
| | Roy's greatest root | 9.6511 | 36.67 | <0.0001 |

[a] This is a test of the null hypothesis that the means of the main effects (expressed in mean vectors) caused by the factor of geographical location are not statistically different. The test, namely, is $H_0$: $\mu_C = \mu_S = \mu_E$, where $\mu_C$, $\mu_S$ and $\mu_E$ are the mean vectors in terms of the input intensities variables obtained from the *A. marmorata* aquafarms located in the central region, southern region and eastern region, respectively

[b] This is a test of the null hypothesis that the means of the main effects (expressed in mean vectors) caused by the factor of pond structure are not statistically different. The test, namely, is $H_0$: $\mu_S = \mu_C = \mu_I$, where $\mu_S$, $\mu_C$ and $\mu_I$ are the mean vectors in terms of the input intensities obtained from the *A. marmorata* aquafarms designed as soil, concrete, and indoor ponds, respectively

[c] This is a test of the null hypothesis that the combination means (expressed in mean vectors) caused by two factors of geographical location and pond structure are not statistically different. The test, namely, is $H_0$: $\mu_{CS} = \mu_{CC} = \mu_{CI} = \mu_{SS} = \mu_{SC} = \mu_{SI} = \mu_{ES}$, where $\mu_{CS}$, $\mu_{CC}$, $\mu_{CI}$, $\mu_{SS}$, $\mu_{SC}$, $\mu_{SI}$ and $\mu_{ES}$ are the mean vectors in terms of the input intensities obtained from the *A. marmorata* aquafarms in the central region/soil pond, central region/concrete pond, central region/ indoor pond, southern region/soil pond, southern region/concrete pond, southern region/indoor pond and eastern region/soil pond categories (Table 3), respectively

**Table 5** Profitability variables of seven-category *A. marmorata* aquafarms in Taiwan, 2012

| Geographical location | Pond structure | Number of farms (*n*) | Total revenue[a] | Net revenue[b] | Benefit–cost ratio[c] |
|---|---|---|---|---|---|
| Central Taiwan | Soil | 4 | 12,677.54 ± 17,486.07 ac | 8983.19 ± 13,401.21 a | 2.68 ± 0.93 a |
| | Concrete | 1 | 129,870.00 b | 103,628.07 b | 4.95 a |
| | Indoor | 2 | 43,675.71 ± 56,421.06 a | 25,222.33 ± 32,212.49 a | 2.59 ± 0.34 a |
| Southern Taiwan | Soil | 3 | 7,355.00 ± 7,108.42 ac | 5204.81 ± 5417.24 a | 2.66 ± 1.51 a |
| | Concrete | 14 | 5,097.04 ± 5,751.3 c | 3388.99 ± 4603.73 a | 2.64 ± 1.40 a |
| | Indoor | 2 | 33,639.60 ± 10,068.64 ac | 20,471.02 ± 5133.64 a | 2.59 ± 0.21 a |
| Eastern Taiwan | Soil | 3 | 2,550.00 ± 1,360.89 ac | 1936.84 ± 1055.97 a | 4.07 ± 0.42 a |

Values are presented as the mean ± SD, where the unit is 1,000 Taiwan dollar (TWD) per 1 fen. One U.S. dollar = 30.0 TWD. One hectare = 10.31 fen.Values (expressed as mean ± SD) with different letters in the same column are significantly different from each other ($P < 0.05$), for example all ‘a’ there were insignificant differences ($P > 0.05$) in benefit–cost ratio

[a] Total revenue was multiplied by 1,000TWD (Taiwan dollar) per fen

[b] Net revenue was obtained by subtracting production costs from total revenue and was multiplied by 1,000TWD per fen

[c] Benefit–cost ratio of total revenue to total cost

**Table 6** Two-way MANOVA in profitability variables analysis of geographical location and pond structure for *A. marmorata* aquafarms in Taiwan, 2012

| Number of factors | Statistical criteria | Value | *F* value | Pr > F |
|---|---|---|---|---|
| Location[a] | Wilks’ lambda | 0.0892 | 15.66 | <0.0001 |
| | Pillai’s trace | 1.0304 | 7.44 | <0.0001 |
| | Hotelling–Lawley trace | 8.8730 | 28.94 | <0.0001 |
| | Roy’s greatest root | 8.7193 | 61.03 | <0.0001 |
| Pond structure[b] | Wilks’ lambda | 0.0404 | 26.52 | <0.0001 |
| | Pillai’s trace | 1.3254 | 13.75 | <0.0001 |
| | Hotelling–Lawley trace | 14.7168 | 48.00 | <0.0001 |
| | Roy’s greatest root | 14.0728 | 98.51 | <0.0001 |
| Interaction of location and pond structure[c] | Wilks’ lambda | 0.0597 | 20.62 | <0.0001 |
| | Pillai’s trace | 0.9628 | 6.50 | <0.0001 |
| | Hotelling–Lawley trace | 15.3719 | 50.13 | <0.0001 |
| | Roy’s greatest root | 15.3474 | 107.43 | <0.0001 |

[a] This is a test of the null hypothesis that the means of the main effects (expressed in mean vectors) caused by the factor of geographical location are not statistically different. The test, namely, is $H_0$: $\mu_C = \mu_S = \mu_E$, where $\mu_C$, $\mu_S$ and $\mu_E$ are the mean vectors in terms of the input intensities variables obtained from the *A. marmorata* aquafarms located in the central region, southern region and eastern region, respectively

[b] This is a test of the null hypothesis that the means of the main effects (expressed in mean vectors) caused by the factor of pond structure are not statistically different. The test, namely, is $H_0$: $\mu_S = \mu_C = \mu_I$, where $\mu_S$, $\mu_C$ and $\mu_I$ are the mean vectors in terms of the input intensities obtained from the *A. marmorata* aquafarms designed as soil, concrete, and indoor ponds, respectively

[c] This is a test of the null hypothesis that the combination means (expressed in mean vectors) caused by two factors of geographical location and pond structure are not statistically different. The test, namely, is $H_0$: $\mu_{CS} = \mu_{CC} = \mu_{CI} = \mu_{SS} = \mu_{SC} = \mu_{SI} = \mu_{ES}$, where $\mu_{CS}$, $\mu_{CC}$, $\mu_{CI}$, $\mu_{SS}$, $\mu_{SC}$, $\mu_{SI}$ and $\mu_{ES}$ are the mean vectors in terms of the input intensities obtained from the *A. marmorata* aquafarms in the central region/soil pond, central region/concrete pond, central region/ indoor pond, southern region/soil pond, southern region/concrete pond, southern region/indoor pond and eastern region/soil pond categories (Table 5), respectively

$$\mathrm{CAN3} = -0.0085\mathrm{SD} + 0.9121\mathrm{SR} + 0.3732\mathrm{FC} \tag{3}$$

where SD is the stocking density, SR is the survival rate and FC is the farming cycle.

The corresponding means of CAN1, CAN2 and CAN3 for the seven categories are listed in Table 10. The approximated *F* values for CAN1 and CAN2 were significant at the 0.05 % level; CAN3 was not significant at the 0.05 % level ($P = 0.9689$) (Table 10). This result reveals that the seven farming categories could be well separated based on the two canonical variables CAN1 and CAN2 (Fig. 1).

**Table 7** A matrix of Mahalanobis distances for the original biological variables between seven categories of *A. marmorata* aquafarms in Taiwan, 2012

| Categories | Central region/soil pond (CS) | Central region/indoor pond (CI) | Central region/concrete pond (CC) | Eastern region/soil pond (ES) | Southern region/soil pond (SS) | Southern region/indoor pond (SI) | Southern region/concrete pond(SC) |
|---|---|---|---|---|---|---|---|
| Central region/soil pond (CS) | 0 (1.0000) | 1.4463 (0.2592) | 0.1939 (0.8993) | 0.8937 (0.4615) | 2.4129 (0.0968) | 10.0307 (0.0003) | 5.0677 (0.009) |
| Central region/indoor pond (CI) | | 0 (1.0000) | 0.6169 (0.6121) | 0.4196 (0.7409) | 0.6100 (0.6163) | 13.7018 (<0.0001) | 2.0312 (0.1419) |
| Central region/concrete pond (CC) | | | 0 (1.0000) | 0.5685 (0.6422) | 0.6017 (0.6215) | 5.2599 (0.0077) | 0.9390 (0.4403) |
| Eastern region/soil pond (ES) | | | | 0 (1.0000) | 2.0008 (0.1463) | 14.3660 (<0.0001) | 5.1216 (0.0086) |
| Southern region/soil pond (SS) | | | | | 0 (1.0000) | 14.1997 (<0.0001) | 0.4337 (0.7312) |
| Southern region/indoor pond (SI) | | | | | | 0 (1.0000) | 0 (1.0000) |
| Southern region/concrete pond (SC) | | | | | | | 0 (0.0000) |

Mahalanobis distance was expressed taking into consideration the seven original biological variables, including stocking density, survival rate and farming cycle as a whole, and calculated as $D_{ij}^2 = (\bar{x}_i - \bar{x}_j)' C^{-1} (\bar{x}_i - \bar{x}_j)$, where $D_{ij}^2$ is the Mahalanobis distance between category $i$ and category $j$, $\bar{x}_i$ is a mean vector of the $i$th category with dimensions $3 \times 1$ (Table 1), $C^{-1}$ is a unique inverse of variance–covariance matrix $C$ with dimensions $3 \times 3$ (Table 1). For example, the Mahalanobis distance between southern region/indoor pond (SI) and central region/indoor pond (CI) is 13.7018 and the probability of distances > 13.7018 is 0.0001 (in parenthesis). This value implies that these two categories were significantly 'distant' (different) as compared to their corresponding means in stocking density, survival rate and farming cycle as a whole

**Table 8** A matrix of Mahalanobis distances in input intensity variables between seven categories of *A. marmorata* aquafarms in Taiwan, 2012

| Categories | Central region/soil pond (CS) | Central region/indoor pond (CI) | Central region/concrete pond (CC) | Eastern region/soil pond (ES) | Southern region/soil pond (SS) | Southern region/indoor pond (SI) | Southern region/concrete pond (SC) |
|---|---|---|---|---|---|---|---|
| Central region/soil pond (CS) | 0 (1.0000) | 4.0940 (0.0117) | 36.9799 (<0.0001) | 1.0961 (0.3964) | 1.4224 (0.2636) | 4.7419 (0.0061) | 0.6581 (0.6595) |
| Central region/indoor pond (CI) | | 0 (1.0000) | 31.7994 (<0.0001) | 3.1771 (0.0314) | 5.3243 (0.0036) | 9.1270 (0.0002) | 4.9589 (0.6595) |
| Central region/concrete pond (CC) | | | 0 (1.0000) | 34.1249 (<0.0001) | 36.7525 (<0.0001) | 29.8898 (<0.0001) | 43.8801 (<0.0001) |
| Eastern region/soil pond (ES) | | | | 0 (1.0000) | 1.0825 (0.4031) | 7.1545 (0.0008) | 0.3830 (0.8539) |
| Southern region/soil pond (SS) | | | | | 0 (1.0000) | 4.6587 (0.0067) | 1.2583 (0.3241) |
| Southern region/indoor pond (SI) | | | | | | 0 (1.0000) | 8.5119 (0.0003) |
| Southern region/concrete pond (SC) | | | | | | | 0 (1.0000) |

Mahalanobis distance was expressed considering the seven input intensity variables including glass eel cost, feed cost, labor cost, water & electricity cost and other cost as a whole, and calculated as $D_{ij}^2 = (\bar{x}_i - \bar{x}_j)' C^{-1} (\bar{x}_i - \bar{x}_j)$, where $D_{ij}^2$ is the Mahalanobis distance between category $i$ and category $j$, $\bar{x}_i$ is a mean vector of the $i$th category with dimensions $5 \times 1$ (Table 3), $C^{-1}$ is a unique inverse of variance–covariance matrix $C$ with dimensions $5 \times 5$ (Table 3). For instance, the Mahalanobis distance between central region concrete (CC) and central region soil (CS) is 36.9799 and the probability of distances > 36.9799 is 0.0001 in parenthesis. Therefore, this implies that these two categories were significantly 'distant' (different) as compared to their corresponding means in glass eel cost, feed cost, labor cost, water & electricity cost and other cost as a whole

**Table 9** A matrix of Mahalanobis distances in profitability variables between seven categories of *A. marmorata* aquafarms in Taiwan, 2012

| Categories | Central region/soil pond (CS) | Central region/ indoor pond (CI) | Central region/ concrete pond (CC) | Eastern region/ soil pond (ES) | Southern region/ soil pond (SS) | Southern region/ indoor pond (SI) | Southern region/con-crete pond (SC) |
|---|---|---|---|---|---|---|---|
| Central region/ soil pond (CS) | 0 (1.0000) | 3.9509 (0.0230) | 107.5442 (<0.0001) | 3.5758 (0.0322) | 0.2016 (0.8941) | 1.3384 (0.2901) | 0.9989 (0.4137) |
| Central region/indoor pond (CI) | | 0 (1.0000) | 101.6991 (<0.0001) | 4.5835 (0.0134) | 3.5295 (0.0336) | 0.5818 (0.6338) | 4.9828 (0.0096) |
| Central region/ concrete pond (CC) | | | 0 (1.0000) | 123.8964 (<0.0001) | 106.6435 (<0.0001) | 93.34618 (<0.0001) | 137.8487 (<0.0001) |
| Eastern region/soil pond (ES) | | | | 0 (1.0000) | 1.9964 (0.147) | 3.46172 (0.0357) | 2.3623 (0.1018) |
| Southern region/soil pond (SS) | | | | | 0 (1.0000) | 1.4065 (0.2701) | 0.1293 (0.9416) |
| Southern region/indoor pond (SI) | | | | | | 0 (1.0000) | 2.2515 (0.1137) |
| Southern region/con-crete pond (SC) | | | | | | | 0 (1.0000) |

Mahalanobis distance was expressed considering the seven profitability variables including total revenue, net revenue and benefit–cost ratio as a whole, and calculated as $D_{ij}^2 = (\bar{x}_i - \bar{x}_j)' C^{-1} (\bar{x}_i - \bar{x}_j)$, where $D_{ij}^2$ is the Mahalanobis distance between category $i$ and category $j$, $\bar{x}_i$ is a mean vector of the $i$th category with dimensions $3 \times 1$ (Table 5), $C^{-1}$ is a unique inverse of variance–covariance matrix $C$ with dimensions $3 \times 3$ (Table 5). For instance, the Mahalanobis distance between central region/concrete pond (CC) and central region/soil pond (CS) is 107.5442 and the probability of distances > 107.5442 is 0.0001 (in parenthesis). Therefore, this implies that these two categories were significantly 'distant' (different) as compared to their corresponding means in profitability variables including total revenue, net revenue and benefit–cost ratio as a whole

**Table 10** Canonical discriminant function analysis of seven categories based on the original biological variables

| Canonical discriminant function analysis | Canonical variables theoretically always present[a] | | |
|---|---|---|---|
| | CAN1 | CAN2 | CAN3 |
| Canonical variables and related coefficients | | | |
| Biological original variables | | | |
| Stocking density (SD) | 0.9783 | −0.2269 | −0.0085 |
| Survival rate (SR) | −0.1713 | −0.3851 | 0.9121 |
| Farming cycle (FC) | 0.2452 | 0.8964 | 0.3732 |
| Eigenvalue | 3.1001 | 1.2697 | 0.0240 |
| Approximated *F* | 3.86 | 2.20 | 0.13 |
| Pr > *F* | <0.0001 | 0.0366 | 0.9689 |
| Means on canonical variables | | | |
| Categories | | | |
| Central region/soil pond (CS) | 0.6123 | 1.2340 | −0.0956 |
| Central region/indoor pond (CI) | −1.2590 | 0.9700 | −0.0063 |
| Central region/concrete pond (CC) | 0.3674 | 0.6822 | 0.5642 |
| Eastern region/soil pond (ES) | −0.5725 | 1.7950 | −0.0520 |
| Southern region/soil pond (SS) | −0.9118 | −0.2588 | 0.2100 |
| Southern region/indoor pond (SI) | 5.3334 | −0.3548 | 0.0170 |
| Southern region/concrete pond (SC) | −0.4652 | −0.8184 | −0.0484 |

[a] See text for explanation of the three canonical variables which could be theoretically found each time no matter what group of variables was studied

Two significant canonical variables relating to the input intensities variables were also determined at $P < 0.05$, which are

$$\begin{aligned} \mathrm{CAN4} = & -1.5041\mathrm{GE} + 2.8850\mathrm{FD} - 1.6314\mathrm{LR} \\ & - 0.5310\mathrm{WE} + 0.7118\mathrm{OR} \end{aligned} \tag{4}$$

$$\begin{aligned} \mathrm{CAN5} = & -1.0830\mathrm{GE} + 0.1780\mathrm{FD} - 10.2947\mathrm{LR} \\ & + 3.3760\mathrm{WE} + 7.7577\mathrm{OR} \end{aligned} \tag{5}$$

where GE is the glass eel cost, FD is the feed cost, LR is the labor cost, WE is the cost of water and electricity and OR is other costs.

The corresponding means of CAN4 and CAN5 were also determined for the seven categories listed in Table 11. A plot of CAN4 against CAN5 would help in the recognition of differences in input intensities among the seven categories through visual aids (Fig. 2). Likewise, it was possible to distinguish the differences in profitability based on two significant canonical discriminant functions determined at $P < 0.05$, which are, as shown in Table 12,

$$\mathrm{CAN9} = -7.0619\mathrm{TR} + 7.8832\mathrm{NR} - 1.0853\mathrm{BC} \tag{6}$$

$$\mathrm{CAN10} = -3.8326\mathrm{TR} + 3.0248\mathrm{NR} + 0.0163\mathrm{BC} \tag{7}$$

**Table 11** Canonical discriminant function analysis of seven categories based on input intensities

| Canonical discriminant function analysis | CAN4 | CAN5 | CAN6 | CAN7 | CAN8 |
|---|---|---|---|---|---|
| Canonical variables and related coefficients | | | | | |
| Input intensity variables | | | | | |
| Glass eel (GE) | −1.5041 | −1.0830 | 0.3764 | −0.7789 | −0.7132 |
| Feed (FD) | 2.8850 | 0.1780 | −0.0182 | 0.0916 | 0.0948 |
| Labor (LR) | −1.6314 | −10.2947 | −8.3286 | 12.5287 | −7.4539 |
| Water & electricity (WE) | −0.5310 | 3.3760 | 6.1939 | −6.4560 | 6.2765 |
| Other (OR) | 0.7118 | 7.7577 | 2.7861 | −5.2499 | 1.3425 |
| Eigenvalue | 12.5540 | 2.8697 | 1.2741 | 0.3353 | 0.0376 |
| Approximated *F* | 6.38 | 3.6 | 2.41 | 1.24 | 0.41 |
| Pr > *F* | <0.0001 | <0.0001 | 0.0142 | 0.3059 | 0.6663 |
| Means on canonical variables | | | | | |
| Categories | | | | | |
| Central region/soil pond (CS) | −0.5323 | −0.3942 | 0.1854 | −0.8098 | −0.0871 |
| Central region/indoor pond (CI) | −0.3795 | 2.6300 | 3.0194 | 0.4403 | −0.0561 |
| Central region/concrete pond (CC) | 16.2175 | 0.5506 | −0.3792 | 0.0372 | −0.0507 |
| Eastern region/soil pond (ES) | −0.4423 | 0.9421 | −0.5946 | 0.2980 | 0.4399 |
| Southern region/soil pond (SS) | −0.9967 | −0.7770 | −0.8074 | 1.1151 | −0.2195 |
| Southern region/indoor pond (SI) | 0.6045 | −4.6077 | 1.5096 | 0.1260 | 0.1544 |
| Southern region/concrete pond (SC) | −0.7301 | 0.3204 | −0.3725 | −0.1550 | −0.0328 |

**Table 12** Canonical discriminant functions analysis of seven categories based on profitability variables

| Canonical discriminant function analysis | CAN9 | CAN10 | CAN11 |
|---|---|---|---|
| Canonical variables and related coefficients | | | |
| Profitability variables | | | |
| Total revenue (TR) | −7.0619 | −3.8326 | 0.9192 |
| Net revenue (NR) | 7.8832 | 3.0248 | −0.8854 |
| Benefit–cost ratio (BC) | −1.0853 | 0.0163 | 1.0820 |
| Eigenvalue | 21.6692 | 1.0364 | 0.1887 |
| Approximated *F* | 9.89 | 2.33 | 1.04 |
| Pr > *F* | <0.0001 | 0.0272 | 0.4102 |
| Means on canonical variables | | | |
| Categories | | | |
| Central region/soil pond (CS) | 0.1688 | 0.1790 | −0.1877 |
| Central region/indoor pond (CI) | −1.0373 | −2.6868 | 0.1456 |
| Central region/concrete pond (CC) | 21.2267 | 0.0914 | 0.2310 |
| Eastern region/soil pond (ES) | −2.1017 | 0.5725 | 1.0668 |
| Southern region/soil pond (SS) | −0.4296 | 0.3517 | −0.1773 |
| Southern region/indoor pond (SI) | −0.2010 | −1.5961 | −0.0306 |
| Southern region/concrete pond (SC) | −0.8451 | 0.3561 | −0.1699 |

where TR is the total revenue, NR is the net revenue and BC is the benefit–cost ratio. The differences among the seven categories are visualized in Fig. 3.

Table 13 shows the correlations within and between two types of variables, namely, the profitability variables and selected original variables. The highest correlation coefficient of 0.9125 ($P < 0.0001$) was noted between total revenue and total cost. The survival rate in our case study had a positive effect on the benefit–cost ratio ($r = 0.4339$ with $P = 0.0131$) but very little effect on the total revenue ($r = 0.1572$ with $P = 0.3902$) (Table 13).

The canonical correlation between $P_1$ (the first profitability index) and $M_1$ (the first manageability index) was 0.4993, which indicates that this mutual relationship was proportional and extremely significant at $P = 0.1251$ (Table 14) [28, 42, 43]. $P_1$ and $M_1$ are, respectively, linear combinations of the profitability variables and the selected original variables as follows (Table 14):

$$P_1 = -1.2139\text{TC} + 0.9463\text{TR} + 0.7227\text{BC} \quad (8)$$

$$M_1 = -0.3750\text{SD} + 0.9200\text{SR} \quad (9)$$

where TC, TR, BC, SD and SR are defined earlier in text. Nevertheless, the correlation between the second pair of canonical variates ($P_2$, $M_2$) was statistically insignificant with $r = 0.2608$ at $P = 0.3731$ (Table 14).

Table 15 shows the correlations between the two types of original variables and the computed canonical variates. Examining the first pair of canonical variables instead of the second one due to its insignificance, the signs (plus or minus) of correlations listed in Table 15 correspondingly match those coefficients listed in Table 14, but there are a few exceptions: the coefficient of SR in $M_1$'s function was 0.9200 (Table 14), which indicates that increasing the survival rate (SR) might increase the first profitability index ($P_1$). This relationship of inverse ratio agreed with a positive correlation, $r = 0.4629$, between SR and $P_1$ shown in Table 15.

## Discussion

In such an analysis as the one reported here, to distinguish the differences in management performance among categories—in this case, seven categories—varied sets of variables may be chosen by researchers depending not only on their own interests but also on their background knowledge. In our study, we failed to obtain clear distinctions

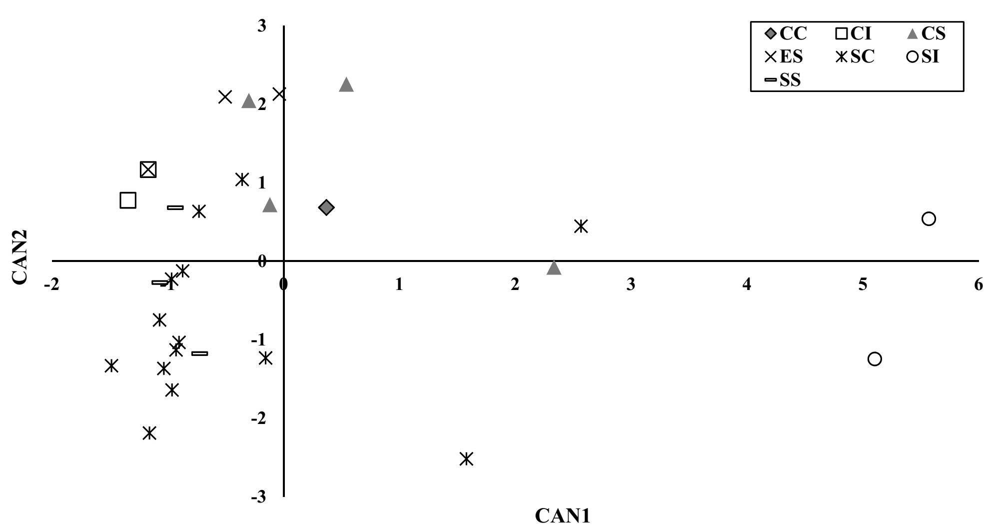


**Fig. 2** Distribution of seven-category farming based on two canonical variables (CAN1 and CAN2) computed using original biological variables. *CS* Central region/soil pond, *CI* central region/indoor pond, *CC* central region/concrete pond, *ES* eastern region/soil pond, *SS* southern region/soil pond, *SI* southern region/indoor pond, *SC* southern region/concrete pond. For definition of canonical variables, see text

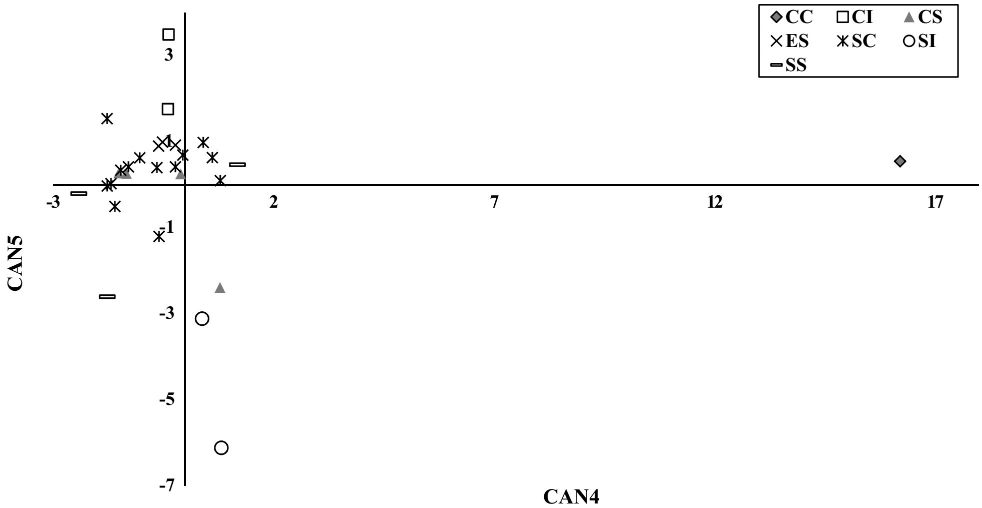


**Fig. 3** Distribution of seven-category farming based on two canonical variables (CAN4 and CAN5) computed using input intensity variables. *CS* Central region/soil pond, *CI* central region/indoor pond, *CC* central region/concrete pond, *ES* eastern region/soil pond, *SS* southern region/soil pond, *SI* southern region/indoor pond, *SC* southern region/concrete pond. For definition of canonical variables, see text

in the management performance among the seven categories using the original biological set of variables (Tables 1, 7). However, distinctions began to appear when the input intensities variable set (Tables 3, 8) and the profitability variable set (Tables 5, 9) were subsequently selected to analyze the management performance. Various statistical tools based on a particular set of variables could also be applied.

Regarding the profitability set of variables, Tables 5 and 9 show the corresponding multivariate statistics and a matrix of Mahalanobis distances for each of the seven categories. The computed canonical discriminant functions (Table 12) further provide a way to recognize the differences among the seven management groups through visual aids (Fig. 4). We therefore conclude that our strategy of combining various sets of variables with different analytical tools to observe differences in management performance was efficient and successful.

We used separation functions to analyze the differences in the biological data, production cost and profitability of the randomly sampled farmers. Analysis of the results allowed us to selected the canonical variables CAN1 and CAN2 based on their high significance; the original data of the randomly sampled farmers were put into the separation functional equation. The differences among all of the sampled farmers could then be displayed on a coordinate graph. As shown in Fig. 1, the larger the CAN1, the higher the stocking density of the farmer. A larger CAN2 value represented a longer culture cycle of the respective aqua-farmer. Our comprehensive analysis showed that the southern region/indoor pond (SI) category had the highest stocking density in terms of biological variables. Culture cycle and stocking density of the central region/soil pond (CS) category were higher than those of other aquaculture types. The southern region/concrete pond (SC) and southern region/soil pond (SS) categories had similar culture management activities (Fig. 2; Tables 7, 10). The southern region/indoor pond (SI), /soil pond (SS) and /concrete pond (CC) categories were very different from the other types of aquafarms sampled in terms of production cost

**Table 13** A correlation matrix of profitability variables and selected original variables

| | Profitability variables | | | Selected original variables | |
|---|---|---|---|---|---|
| | Total cost (TC) | Total revenue (TR) | Benefit–cost ratio (BC) | Stocking density (SD) | Survival rate (SR) |
| Total cost (TC) | 1 (0.0000) | 0.9125 (<0.0001) | 0.1996 (0.2735) | 0.2734 (0.1300) | −0.0005 (0.9981) |
| Total revenue (TR) | | 1 (0.0000) | 0.4059 (0.0212) | 0.2098 (0.2490) | 0.1572 (0.3902) |
| Benefit–cost ratio (BC) | | | 1 (0.0000) | −0.0867 (0.6372) | 0.4339 (0.0131) |
| Stocking density (SD) | | | | 1 (0.0000) | −0.0190 (0.9178) |
| Survival rate (SR) | | | | | 1 (0.0000) |

Each correlation coefficient is followed by a probability of *P* shown in parenthesis

**Table 14** Analysis of canonical correlations between profitability and manageability

| 1st profitability index | Coefficients of profitability variables | | | Canonical correlation between $P_1$ and $M_1$ | Approximated $F$ | Pr > $F$ |
|---|---|---|---|---|---|---|
| | Total cost (TC) | Total revenue (TR) | Benefit–cost ratio (BC) | | | |
| $P_1$ | −1.2139 | 0.9463 | 0.7227 | 0.4993 | 1.76 | 0.1251 |
| 1st manageability index | Coefficients of selected original variables | | | | | |
| | Stocking density (SD) | Survival rate (SR) | | | | |
| $M_1$ | −0.3750 | 0.9200 | | | | |
| 2nd profitability index | Coefficients of profitability variables | | | Canonical correlation between $P_2$ and $M_2$ | Approximated $F$ | Pr > $F$ |
| | Total cost (TC) | Total revenue (TR) | Benefit–cost ratio (BC) | | | |
| $P_2$ | 0.4811 | 0.5300 | 0.0338 | 0.2608 | 1.02 | 0.3731 |
| 2nd manageability index | Coefficients of selected original variable | | | | | |
| | Stocking density (SD) | Survival rate (SR) | | | | |
| $M_2$ | 0.9272 | 0.3925 | | | | |

Both indices of profitability and manageability are linear combinations with corresponding variables. For example, $P_1 = -1.2139\text{TC} + 0.9463\text{TR} + 0.7227\text{BC}$. All variables, including the indices, are in a standardized form with means of zero and SD of unity

**Table 15** Correlations between studied variables and canonical variates

| Study variables | Canonical variates | | | |
|---|---|---|---|---|
| | 1st Profitability index ($P_1$) | 1st Manageability index ($M_1$) | 2nd Profitability index ($P_2$) | 2nd Manageability index ($M_2$) |
| Total cost (TC) | −0.2061 | −0.1029 | 0.9715 | 0.2533 |
| Total revenue (TR) | 0.1321 | 0.0659 | 0.9828 | 0.2563 |
| Benefit–cost ratio (BC) | 0.8645 | 0.4316 | 0.3449 | 0.0899 |
| Stocking density (SD) | −0.1959 | −0.3924 | 0.2398 | 0.9198 |
| Survival rate (SR) | 0.4629 | 0.9271 | 0.0978 | 0.3749 |

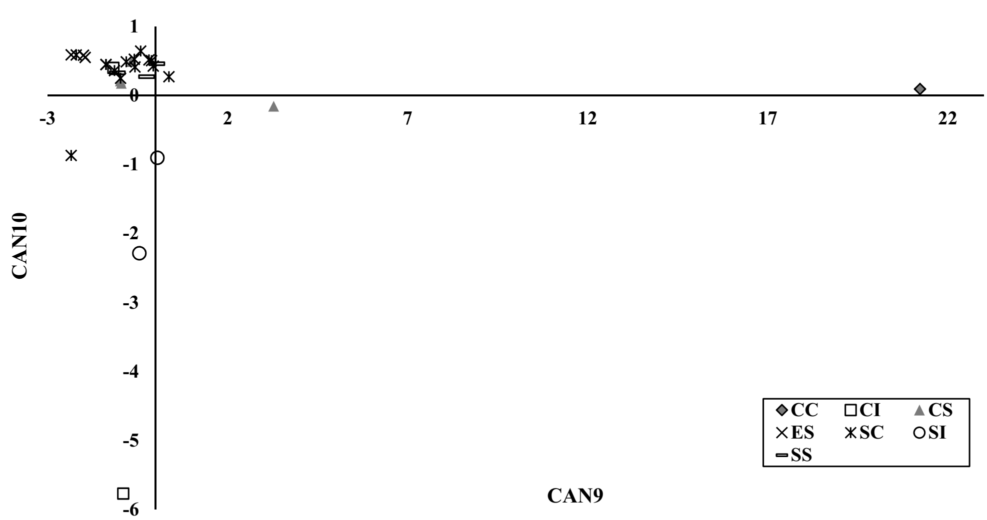


**Fig. 4** Distribution of seven-category aquafarming based on two canonical variables (CAN9 and CAN10) computed by profitability variables. *CS* Central region/soil pond, *CI* central region/indoor pond, *CC* central region/concrete pond, *ES* eastern region/soil pond, *SS* southern region/soil pond, *SI* southern region/indoor pond, *SC* southern region/concrete pond. For definition of canonical variables, see text

(Table 8). The central region/concrete pond (CC) category had the highest feed cost, and the southern region/indoor pond (SI) category had the highest labor cost. The other four types had similar production costs (Fig. 3). The categories central region/indoor pond (CI), central region/concrete pond (CC) and southern region/indoor pond (SI) differed most in terms of profitability from the other aquaculture types (Table 9). The main difference of between category CC was related to net income, while that between SI and other types was due to high gross income (Fig. 4).

Japanese eel has been cultivated in Taiwan for several decades. However, in recent years, due to reduced Japanese eel resources, the price of Japanese glass eel has increased gradually. In 2012, the price of giant mottled glass eel was New Taiwanese Dollar (NTD) 4–4.5 on average for fry of a size 5,000 pcs/kg (data obtained in this study. provided by giant mottled eel aquafarms). In 2013 the price had risen to NTD 150 per Japanese glass eel of the same size (data obtained in this study, provided by the Taiwan Eel Farming Industry Development Foundation). Giant mottled eel has a large commercial market in China and Taiwan. It is very expensive and regarded as a high-quality food item. As a result, with the lifting of the ban on commercial cultivation of the giant mottled eel in 2009, many farmers have started fish farms to breed this eel. However, production of the giant mottled eel in Taiwan is still insufficient, and the glass eel are largely imported from the Philippines (data obtained in this study by giant mottled eel aquafarms).

The giant mottled eel is a tropical fish, and the suitable temperature for cultivation is around 28–30 °C [26, 44, 45]. Eels die at a water temperature of <11 °C [26, 46]. Hence, giant mottled eel ponds in Taiwan are mainly located in the southern and eastern regions of the island. The cultivation methods include soil pond, concrete pond and indoor circulation culture. The marketable size of giant mottled eel is 1.8 kg (data obtained in this study, provided by mottled eel farms), with the price increasing with increasing size. It takes more than 3 years to breed giant mottled eels (Table 1). In addition, the commerical cultivation of giant mottled eel in Taiwan is an emerging industry in Taiwan, and improvements in farming technology and management are needed. Our research shows that the average survival rate was only 20–30 % (Table 1) and that the soil and concrete ponds in southern Taiwan had the highest survival rate. The average monthly temperature in southern Taiwan can be higher than 20 °C, while the average temperature in central Taiwan can be as low as 10 °C due to cold fronts [47]. This difference in average temperatures led to a lower survival rate of giant mottled eel in central Taiwan. Moreover, if the giant mottled eel is cultured in a low-temperature environment for a long time, it will have a lower intake rate and growth rate and, consequently, the farming cycle will be prolonged [46, 48].

The initial data collected from the randomly sampled aqua-farmers suggested that a stocking density of 10,000 to 170,000 eels per fen was suitable (Table 1), with the large difference in stocking density associated to the cultivation method and the sophistication of the farming technology applied. As giant mottled eel aquafarming is an emerging industry in Taiwan, some farmers relied on their previous experience with Japanese eel farming, while other farmers had no experience at all in aquaculture. Hence, the differences in stocking density. The aquaculture system of indoor pond/southern Taiwan had the highest stocking density: the circulatory water system was adopted for intensive farming in order to improve production capacity per unit through high density (Table 10; Fig. 1).

In terms of production costs, the average production cost of the giant mottled eel farming was 4,705,721 NTD/fen or 66.67 $m^2$. The feed cost was the highest component of the total production costs, accounting for 82.3 %, followed by labor cost (6.8 %), water and electricity cost (5.8 %), glass eel cost (4.0 %), and other costs (1.1 %).

In terms of the farming categories, the concrete ponds and indoor ponds in central Taiwan and the indoor ponds in southern Taiwan were associated with relatively higher feed costs. In terms of nutritional needs for the eels during the farming process, the protein and fish oil demands of the eels raised the feed price [44, 45, 49]. The indoor pond aquafarming system required more professional labor, resulting in relatively higher labor costs (Table 3), in addition a water circulatory system was applied in the production process, and thus water and electricity costs were relatively higher (Table 3; Fig. 2). The total product cost of the soil pond in eastern Taiwan was the lowest among the seven categories due to low stocking density and low glass eel costs (Table 1).

Hualien and Taitung counties in eastern Taiwan are the major fish farming areas of giant mottled glass eel on the island. Fishermen sell the glass eel to local farming farmers; imported glass eel are more expensive due to transportation and intermediary costs (data obtained in this study, provided by the Taiwan Eel Farming Industry Development Foundation). Moreover, the water supply in eastern Taiwan is abundant, allowing the farmers to use the flowing water system to reduce the expenses of water pumps. The feed costs of fish farms in this region were also the lowest of the seven categories. Fish farming using concrete ponds has mostly been adopted for giant mottled eel cultivation in southern Taiwan. The glass eel are mainly imported from the Philippines, and most farmers in this region have experience in farming Japanese eels, which is similar to farming giant mottled eels (information obtained in this study, provided by the Fisheries Agency, Council of Agriculture, Executive Yuan). As seen with CAN4 and CAN5 of Fig. 2, the production cost structure in southern Taiwan was similar and, therefore, the coordinates fell in the same block. The input intensities of the soil and concrete ponds in southern Taiwan were higher than those of soil ponds in eastern Taiwan due to a better control of feed and shorter farming cycles.

In terms of, profits, Hsueh reported that the average benefit–cost ratio of giant mottled eel farming was 1.3 in the period 2010–2012 [50]. In the present study, we found that the benefit–cost ratio was about 2.59–4.95, which indicates that the marketable price and profit in giant mottled eel aquafarming had gradually increased since 2009. According to Table 3, the B/C ratio of concrete ponds in central Taiwan and soil ponds in eastern Taiwan was >4 while that of the other five categories was about 2.59–2.68, suggesting that economic returns of giant mottled eel farming industry were good. The marketable size of giant mottled eel was around 1 kg/fish or >1.8 kg/fish. In general, it took about 2 years to raise glass eel to fish of the size of 1 kg, while it took more than 3 years to raise the eels to a size of >1.8 kg. However, eel size was a significant determinant of price, with the price increasing with increasing fish size. Moreover, the Chinese market prefers larger fish of >1.8 kg (Tables 1, 3). The profitability of pond culture for more than 3 years decreased. As it takes a farming cycle of >3 years to produce fish weighing >1.8 kg, the risks during the production process can increase accordingly. Using the soil pond in eastern Taiwan as an example, the B/C ratio was 4.07 for a farming cycle of 44 months, while the B/C ratio for farming cycle of 12 months was only 1.36 (Tables 1, 5). However, it takes only 7–8 months to raise Japanese eels in Taiwan, for which the B/C ratio is about 1 [50]. This suggests that the profitability in farming giant mottled eel is only slightly lower than that of farming Japanese eels.

The results of the canonical correlation analysis of the biological data and profitability data suggest that the survival rate of the giant mottled eel was very significantly correlated to profitability. When the survival rate increased, net revenue and the B/C ratio also increased (Table 13); however, we found that the survival rate was only 17–32 % (Table 1). Therefore, more efforts should be made in the research and development of farming management to improve the survival rate in Taiwan.

In order to address the problem of Japanese glass eel shortage, the Taiwanese government has provided easier access to land and water resources. Government universities are also providing help in the form of research on basic biological data [2, 3, 51–53], feed and nutrients [54–56], disease prevention [57] and business management [7, 18, 19, 44, 45, 58, 59]. These attempts are being made in the hope to promote the development of giant mottled eel farming to satisfy the market demand for eels.

To summarize, due to giant mottled eel cultivation being an emerging industry in Taiwan, the industry is characterized by many inadequacies in terms of farming technology and management. First, we determined that the average stocking density was 67,370 pcs/fen, but Cheng [44] pointed out that the suitable stocking density should be 100–120 thousand pcs/fen. Hence, there is space for improvement in terms of stocking density. Second, the temperature has a significant impact on growth, and the water temperature of the giant mottled eel should be maintained around 28 °C that the eels can grow faster and have relatively better economic value [26]. However, as the water temperature in central Taiwan is relatively low in winter, research institutes have tried to raise eels in the greenhouse in order to reduce the effects of cold weather. Third, we found that feed cost accounted for 82.3 % of production cost of giant mottled eel farming, with many farmers relying on their previous experience with Japanese eel farming. However, the digestion systems of these two kinds of eels differ, and thus the farming method used for Japanese eels may easily lead to diseases in the digestion system of giant mottled eel, thus increasing the mortality rate [57, 60]. Fourth, in terms of feed management of the giant mottled eel, in the early period the feed weight should be about 8–10 % of the fish body weight, following which it should be increased by 1–2 % every day. Later, the feed weight should be kept around 22–28 % of the fish body weight [61]. Feeds specifically for the giant mottled eel should be developed in order to reduce feed costs. Fifth, the glass eels which were bred in Taiwan were mainly of 7,000–3,000 pcs/kg (data obtained in this study, provided by the giant mottled eel farms). In the farming process, farmers were able to raise glass eel in inside ponds or in fiberglass reinforced plastic ponds before moving them to outside ponds. The size of the giant mottled eel varies greatly during the farming process, and it is possible that regular separation of eels may increase survival rate. Finally, in a long farming cycle, the eel farming process can be divided into difficult farming periods, such as nursery rearing, and growout farming to reduce the risk of farming cycle that is too long and thereby increase the economic benefits.

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