UNIVERSIDADE ESTADUAL PAULISTA – UNESP

CENTRO DE AQUICULTURA DA UNESP

EFEITO DA INTENSIFICAÇÃO SOBRE A SUSTENTABILIDADE DO CULTIVO DO CAMARÃO BRANCO DO PACÍFICO

Carolina Mendes Costa

Jaboticabal, São Paulo
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Carolina Mendes Costa

Orientador: Dr. Wagner Cotroni Valenti
Coorientadora: Dra. Janaina Mitsue Kimpara

Tese apresentada ao Programa de Pós-graduação em Aquicultura do Centro de Aquicultura da UNESP-CAUNESP, como parte dos requisitos para obtenção do título de Doutor.

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Jaboticabal, 26 de fevereiro de 2019.

“Oguntê, Marabô
Caiala e Sobá
Oloxum, Ynaê
Janaina e Yemanjá
São rainhas do mar

Mar, misterioso mar
Que vem do horizonte
É o berço das sereias
Lendário e fascinante

Olha o canto da sereia
Ialaó, oquê, ialoá
Em noite de lua cheia
Ouço a sereia cantar
E o luar sorrindo
Então se encanta
Com as doces melodias
Os madrigais vão despertar

Ela mora no mar
Ela brinca na areia
No balanço das ondas
A paz, ela semeia
Ela mora no mar
Ela brinca na areia
No balanço das ondas
A paz, ela semeia...”

Lenda das Sereias, Clara Nunes

SUMÁRIO

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APRESENTAÇÃO DO TRABALHO

A presente tese de doutorado é um dos projetos que integra a Rede de Pesquisa Sustentabilidade na Aquicultura. Esta rede é formada por 38 pesquisadores de 15 instituições de pesquisa das cinco regiões do país e vem sendo coordenada pelo Prof. Wagner C. Valenti. A formação da rede de pesquisa surgiu a partir do Grupo de Trabalho em Sustentabilidade, constituído pelo Ministério da Pesca e Aquicultura em 2009 para estudar e propor um conjunto de indicadores adequados para avaliar a sustentabilidade da aquicultura brasileira. Por isso, a Rede tem como objetivo avaliar a sustentabilidade ambiental, econômica e social dos principais sistemas de cultivo aquícola existentes no país. A partir de dados obtidos em campo, foram determinados os indicadores de sustentabilidade econômica, social e ambiental que serão utilizados para acompanhar o desenvolvimento de ações para aumentar a sustentabilidade da aquicultura brasileira em políticas públicas.

Durante o projeto, foi construído o laboratório de Aquicultura Sustentável, pioneiro na área, com intuito de ser também uma central de análises. O laboratório (financiado pela Finep e Caunesp/Jaboticabal) possui equipamentos de ponta e está localizado no câmpus da Unesp do Litoral Paulista - CLP na cidade de São Vicente-SP. As amostras para as análises ambientais coletadas pelas equipes foram enviadas para a Central de análises para serem processadas e os dados obtidos retornaram para as respectivas equipes para serem analisados. Portanto, além do documento final produzido auxiliar ao governo brasileiro na implantação de políticas públicas, também vão gerar trabalhos científicos com padrão internacional e formação de pessoal capacitado para trabalhar com análises de sustentabilidade.

O presente trabalho juntamente com os outros diferentes sistemas avaliados irá compor um documento com os indicadores e respectivos métodos de obtenção, que será enviado a Secretaria de Aquicultura e Pesca. Esta se encarregará da incorporação nas políticas públicas para o Setor Aquícola brasileiro. Portanto, haverá o desenvolvimento de um produto que poderá ser usado em políticas públicas e formação de recursos humanos capacitados para trabalhar com análises de sustentabilidade no Brasil. A importância desta tese é o fato de que o monocultivo de camarões marinhos é a atividade de maricultura mais importante no Brasil, sendo a região nordeste do país o principal polo de produção. Apesar disso, é uma atividade que causa conflitos na questão ambiental, mas é responsável por gerar uma quantidade significativa de empregos. Estes dados servirão para mostrar os pontos positivos e negativos dos sistemas de produção da carcinicultura marinha para em breve alcançar a sustentabilidade.

RESUMO GERAL

O Brasil encontra-se entre os 10 maiores produtores mundiais da espécie *Litopenaeus vannamei* e segundo na América Latina. Na região Nordeste, existem muitas fazendas que operam em diferentes sistemas de produção e níveis de intensificação. Normalmente, a maioria das fazendas utiliza sistemas semi-intensivos (densidade de estocagem entre 10 e 30 camarões por m^{-2}), mas há uma tendência de intensificar a atividade, aumentando a densidade e diminuindo a área de cultivo. Sem controle efetivo, operações intensivas geralmente aumentam a carga de nutrientes e matéria orgânica para o ecossistema. Isso mostrou que uma gama maior de estudos é necessária para entender os possíveis benefícios ambientais-econômicos-sociais da intensificação. O objetivo deste estudo foi avaliar a sustentabilidade ambiental, social e econômica da carcinicultura marinha operando em diferentes níveis de intensificação no Nordeste do Brasil. Oito fazendas foram avaliadas em quatro níveis de intensificação: Nível 1 (10-15 camarão m^{-2}), Nível 2 (20 camarão m^{-2}), Nível 3 (35 camarão m^{-2}) e Nível 4 (51-100 camarão m m^{-2}). Amostras de água, sedimentos, gases de efeito estufa, camarões e dietas foram coletadas para determinar os indicadores ambientais. Para os indicadores sociais e econômicos, utilizamos questionários semi-estruturados. O Índice Geral de Sustentabilidade mostrou que as fazendas de Nível 4 apresentam maior sustentabilidade, seguidas pelos níveis 1, 2 e 3. O nível mais intensificado (Nível 4), apresentou maior índice de sustentabilidade ambiental por utilizar menos recursos, maior eficiência energética, menor potencial de eutrofização em áreas locais, poluição orgânica e assoreamento em comparação às fazendas nos demais níveis de intensificação. Na sustentabilidade econômica, este nível também se destacou na eficiência de recursos financeiros. Logo, temos o sistema menos intensificado (Nível 1), que apresentou uma forte resiliência econômica. O nível 2 apresentou valores intermediários em todos os aspectos. No aspecto social, o Nível 3 foi mais sustentável devido à inclusão social e apresentou melhor proporção em relação ao número de funcionários e produção. O conjunto de indicadores aplicados gerou um índice único que permitiu identificar e quantificar os principais aspectos da sustentabilidade geral dos sistemas de produção de camarões marinhos. Esses indicadores e o índice são ferramentas adequadas e eficazes para avaliar a sustentabilidade ambiental, social e econômica na carcinicultura marinha.

PALAVRAS-CHAVE: *Litopenaeus vannamei*, produção, intensificação, densidade de estocagem, manejo, sustentabilidade, conjunto de indicadores.

GENERAL ABSTRACT

Brazil was ranked among the 10 largest world producers of *Litopenaeus vannamei* and second in Latin America. In the Northeast region, there are many farms operating in different production systems and levels of intensification. Usually, most farms use semi-intensive systems, with densities varying between 10 to 30 shrimp m^2, but there is a trend to intensify the activity, increasing the stocking density and decreasing the culture area. Without effective control, intensive operations usually increase the nutrient and organic matter load to the ecosystem. This showed that a greater range of studies is needed to understand the possible environmental-economic-social benefits of the intensification. The aim of this study was to evaluate the environmental, social and economic sustainability of marine shrimp farming operating in different levels of intensification in Northeastern Brazil. Eight farms were evaluated in four levels of intensification: Level 1 (10-15 shrimp m^{-2}), Level 2 (20 shrimp m^{-2}), Level 3 (35 shrimp m^{-2}) and Level 4 (51-100 shrimp m^{-2}). Samples of water, sediments, greenhouse gases, shrimps and diets were taken to determine environmental indicators. For the social and economic indicators, we used a semi-structured questionnaire. The General Sustainability Index showed that Level 4 farms shows greater sustainability, followed by levels 1, 2 and 3. The most intensified level (Level 4), had the higher environmental sustainability index as it used less resources, has the higher energy efficiency, the lower potential of eutrophication in surrounding areas, organic pollution and siltation in comparison to the farms in the other intensification levels. In the economic sustainability, this level also highlighted in the efficiency of financial resources. Therefore, we have the least intensified system (Level 1), which showed strong economic resilience. Level 2 presented intermediate values in all aspects. In the social aspect, Level 3 was more sustainable due to social inclusion and it presented better proportion in relation to the number of employees and production. The set of indicators applied generated a unique index that made it possible to identify and quantify the main aspects of general sustainability of marine shrimp production systems. These indicators and the index are adequate and effective tools to evaluate the environmental, social and economic sustainability in marine shrimp farming.

KEY WORDS: *Litopenaeus vannamei*, production, intensification, stocking density, management, sustainability, set of indicators.

CAPÍTULO 1

INTRODUÇÃO GERAL

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Histórico da carcinicultura no Brasil

A produção de camarões marinhos iniciou-se no Brasil em meados do ano de 1970, quando pesquisadores da região Nordeste do Brasil iniciaram experimentos com a espécie exótica *Litopenaeus vannamei* (Kautsky *et al.* 2000). Na mesma época, o governo do Rio Grande do Norte e uma grande empresa salineira iniciaram a produção comercial de camarões da espécie *Penaeus japonicus*. O projeto foi rentável, mas alguns retrocessos (mudança das condições climáticas, furtos, má gestão do empreendimento) resultaram no fechamento da fazenda (Nunes e Rocha, 2015).

A década seguinte foi marcada pela transição de espécies de cultivo e financiamento de bancos, empresas e governo. Em primeiro lugar, os financiadores impuseram obrigações aos produtores como o uso do *P. japonicus* e a construção de seus próprios laboratórios. Esta espécie requer elevada quantidade de proteína na ração, apresenta baixa sobrevivência e as fazendas não tinham infraestrutura adequada ao cultivo comercial. Durante esse período, tentou-se utilizar a espécie nativa *Penaeus subtilis*, principalmente no Estado do Piauí, mas os resultados não foram economicamente viáveis. A produtividade do camarão variava entre 50 e 200 kg ha ciclo^{-1} e então a maioria das fazendas existentes faliu (Moles e Bunge, 2002).

A consolidação da produção de camarão começou com o primeiro laboratório de larvicultura comercial instalado na região Nordeste nos anos de 1990. Este laboratório foi responsável pelo fornecimento de pós-larvas de *P. vannamei* (inicialmente baseadas em modelos do Equador) e de camarões nativos (*Litopenaeus schmitti*, *Farfantepenaeus brasiliensis* e *Farfantepenaeus paulensis*). A partir disso, novas fazendas foram implementadas usando elevada densidade populacional na fase do crescimento final (Wasielesky Jr. *et al.* 2006). No cenário econômico, o Plano Real e a sobrevalorização da moeda obrigaram os produtores a vender o camarão no mercado interno. Em 1999, o mercado internacional foi o mais explorado devido à desvalorização da moeda e dos surtos de doenças que ocorreram nas fazendas da costa do Pacífico (Rocha, 2011).

Até 2003, a produção de *P. vannamei* cresceu exponencialmente, atingindo 90.000 toneladas neste ano. Em 2004, a mesma caiu drasticamente devido a surtos de doenças, *dumping* e inundações. A produção de camarões estabilizou-se de 2005 a 2013, com volumes variando de 60.000 a 70.000 toneladas (Sussel *et al*., 2010). Mesmo assim, o Brasil foi classificado dentre os 10 maiores produtores mundiais de camarão e o segundo na América Latina (FAO, 2014).

A região Nordeste é responsável por mais de 95% da produção nacional de camarões marinhos e o mercado interno consome a maior parte dessa *commodity* (Rocha e Mendonça, 2015). Atualmente, os produtores buscam aumentar a produção e a venda no mercado interno após surto de mancha branca que atingiu os Estados da região Nordeste em 2015. Um dos recursos adotados para controlar a doença e minimizar as perdas na produção foi a implantação do sistema de bioflocos, que tem como vantagem a troca mínima ou zero de água no sistema de produção (Zhou and Hanson, 2017). Outra estratégia é a Tecnologia Multitrófica Integrada (IMTA) que além de cultivar outras espécies alvo, como ostras e algas, tem a capacidade de aproveitar o máximo dos nutrientes durante o cultivo (Chopin *et al*., 2001; Pantjara *et al*., 2015). Também são comuns os cultivos realizados em regiões interiores que utilizam água do subsolo e de baixa salinidade (Nunes & Rocha, 2015). Quanto ao mercado internacional, ainda não há previsão para exportação.

O camarão do Pacifico – Litopenaeus vannamei

O camarão *Litopenaeus vannamei* é nativo da costa leste do Pacífico, desde Sonora no México, até o extremo sul de Tumbes no Peru, em áreas onde a temperatura da água é normalmente acima de 20 °C durante todo o ano. Esta espécie vive em habitats marinhos tropicais. Os adultos vivem e desovam em mar aberto, enquanto as pós larvas migram para a costa para passar seus estágios juvenis e sub-adultos em estuários costeiros, lagoas ou áreas de mangue. Os machos amadurecem a partir de 20 gramas, as fêmeas a partir de 28 g com a idade entre 6 a 7 meses. Eles podem gerar até 250 mil ovos. A eclosão ocorre cerca de 16 horas após a desova e fertilização. As larvas do primeiro estágio, chamadas náuplios, nadam intermitentemente, são positivamente fototáticas e não se alimentam. Os outros estágios larvares (protozoea, mísis e pós-larvas) permanecem planctônicos por algum tempo, se alimentam de fitoplâncton e zooplâncton, e são levados para a costa por correntes de maré. As pós-larvas (PL) mudam seu hábito planctônico cerca de 5 dias após a primeira muda, se deslocam para a costa e começam a se alimentar de detritos bentônicos, vermes, bivalves e crustáceos (FAO, 2014).

A produção no mundo e no Brasil

O camarão de cultivo contribui com mais de 50% do total do fornecimento mundial. A espécie mais cultivada mundialmente é o camarão *Litopenaeus vannamei* que possui fácil manejo durante o cultivo, menor custo de produção quando comparada às outras espécies e grande aceitação de mercado (FAO, 2009). Esta espécie é responsável pela maior parte desta produção (79,6%) seguido do camarão *Penaeus monodon* (14,63%), isto em 2015. Os maiores produtores mundiais são a China, Tailândia, Vietnã e Indonésia. A maior parte da produção da China é consumida domesticamente, enquanto os outros países exportam para os mercados dos Estados Unidos, Japão e União Europeia (FAO, 2014). Em resposta aos preços mais altos, o aumento da produção nestes países, juntamente com o Equador e México levaram a um aumento da produção mundial acima de 4 milhões de toneladas em 2014, mas caiu novamente em 2015 (FAO, 2016). Na América Latina, o crescimento mais significativo foi no Equador, chegando a quase 400 mil toneladas. (FAO, 2018). Em 2016, o Brasil produziu 60 mil toneladas, mas desde 2003 o país não tem alcançado os melhores números de produção (ABCC, 2017). O estado do Ceará é o maior produtor nacional de camarão cultivado, tendo uma produção total no ano de 2015 de 41 mil toneladas e 27 mil toneladas no ano seguinte. Esta redução ocasionada, principalmente pela incidência do vírus da mancha branca (ABCC/MAPA, 2017).

As fazendas de camarões marinhos

As fazendas de camarões marinhos no Brasil apresentam diversos tamanhos, e, na sua maioria, é composta por médios produtores que possuem áreas entre 10 à 50 hectares. Estes empreendimentos também se diferenciam pelos sistemas de produção utilizados, intensificação e manejo. A seguir, citamos alguns dos métodos de produção mais comuns utilizados em fazendas de camarões no país. Eles são considerados fundamentais nos processos ecológicos e econômicos dos sistemas.

Na região Nordeste existem muitas fazendas que operam em diferentes sistemas de produção e níveis de intensificação. De acordo com o tamanho dos viveiros, densidade de estocagem, uso de água, requisitos de insumos, rendimentos e capital, o cultivo de camarões pode ser classificado como produção extensiva, semi-intensiva ou intensiva. Normalmente, a maioria das fazendas utiliza sistemas semi-intensivos, com densidades de estocagem variando entre 10 a 30 camarões m^{-2} e produtividade em torno de 2,5 $t.ha^{-1}$ por ciclo. Mas há uma tendência de intensificar a atividade, aumentando a densidade e diminuindo a área de cultivo.

Um dos métodos de produção aplicados hoje em dia é a utilização de berçários nas fazendas. Os berçários são tanques menores onde as pós-larvas são mantidas por um determinado tempo antes de serem transferidas para os viveiros de engorda. Nestes berçários, as pós-larvas se desenvolvem rapidamente, favorecidas pela capacidade de crescimento compensatório do camarão marinho (Mishra *et al*., 2008). Com isso, a instalação desses tanques berçários, contribuiu para a diminuição do tempo de cultivo nos viveiros de engorda, elevando-se a taxa de sobrevivência, inclusive, nas regiões onde os agentes patogênicos já são endêmicos.

Já na fase de engorda, os produtores podem aplicar diversos tipos de manejos, sendo o arraçoamento um dos mais importantes devido ao manuseio da ração. Este é o item mais significativo da produção tanto no aspecto econômico como ambiental. Para isto, eles utilizam bandejas. Estas permitem observações diretas sobre o consumo de ração pelos camarões. Esse manejo reduz desperdícios, melhora a conversão alimentar e, em consequência, a qualidade do solo. Geralmente usa-se em média 30 bandejas por hectare.

O policultivo é um tipo de sistema que pode favorecer o produtor. Este ainda não é tão comum nas fazendas de camarões marinhos. Embora a porcentagem dos praticantes seja pequena, eles costumam cultivar peixes (tilápia, tambaqui), moluscos (ostras) e camarões (Martínez-Porchas *et al.*, 2010).

A presente preocupação com doenças fez os produtores aumentarem a biosseguranca das fazendas. As medidas aplicáveis são a instalação de pedilúvios, rodolúvios, cercas para animais (ovinos, caprinos, bovinos), cercas específicas para crustáceos invasores, higienização de equipamentos, exigência de pós-larvas *Specific Pathogen Free* (SPF) e reuso de água.

Por fim, para conhecimento da situação das fazendas no país, uma outra questão importante são as áreas de preservação permanente (APP) e licenças. Num relatório do governo brasileiro, 55,45% dos produtores entrevistados confirmaram áreas de preservação, com uma média de dimensão de 43 hectares. Outros confirmam que possuem Áreas de Reserva Legal (ARL) com média de 57 hectares. O relatório ainda indicou que a maior parte dos produtores estão licenciados por meio de órgãos ambientais (ABCC/MAPA, 2017).

A sustentabilidade na aquicultura

A definição de aquicultura sustentável é baseada na utilização racional dos recursos financeiros, naturais e humanos no processo de produção. Desse modo, é uma atividade economicamente viável, que propicia melhoria da qualidade de vida das comunidades locais, sem degradar os ecossistemas nos quais se insere (Arana, 1999; Valenti, 2008). Envolve três componentes: a produção lucrativa, a conservação do meio ambiente e o desenvolvimento social (Valenti, 2000). Estes são essenciais e indissociáveis para que a atividade seja perene.

Para alcançar uma aquicultura sustentável, é essencial medir a sustentabilidade dos sistemas de produção usados, das técnicas de manejo e das novas tecnologias que vão sendo geradas e adotadas. Os principais métodos usados para mensurar a sustentabilidade da aquicultura no mundo são: Análise Emergética (Garcia *et al*., 2014), Pegada Ecológica (Chang *et al.,* 2017), Análise do Ciclo de Vida (Medeiros *et al*., 2017), Resiliência (Troell *et al*., 2014) e Conjuntos de Indicadores (Kimpara *et al.*, 2012; Valenti *et al.,* 2018). Estes métodos variam na dificuldade de obtenção dos dados e interpretação dos resultados.

Os Conjuntos de Indicadores dão uma visão merística, possibilitando a análise de cada parte do sistema produtivo em separado. Isso permite localizar os pontos fracos para correção. Assim, os indicadores escolhidos devem ser diversificados o suficiente para cobrir todas as facetas da aquicultura. Além disso, devem possibilitar a consolidação em gráficos ou índices combinados que permitam uma interpretação geral. Os dados são de mais fácil obtenção e a interpretação dos resultados é simples e facilmente compreensível (Valenti *et al.*, 2011).

O conjunto de indicadores são distribuídos nas dimensões ambiental, social e econômica. Os indicadores ambientais estão principalmente focados em aspectos relacionados com a poluição (ex. as concentrações de nutrientes no efluente) e o uso eficiente dos recursos (ex. a eficiência no uso do nitrogênio e fósforo). Os indicadores sociais são ligados a questões como a equitatividade na distribuição de renda, a geração de postos de trabalho (empregos e auto empregos) e a segurança alimentar. Os indicadores econômicos mais utilizados são a renda anual, a taxa interna de retorno, o período de retorno do capital e o valor presente líquido. Os custos referentes às externalidades, no entanto, devem ser incluídos nas equações matemáticas que geram esses indicadores tradicionais. As externalidades são efeitos secundários (positivos ou negativos) de uma atividade econômica. As externalidades negativas surgem quando alguma parte do custo de uma atividade não é assumida pelos produtores ou consumidores do bem ou serviço em questão.

No Brasil, o grupo de pesquisa do Setor de Carcinicultura do CAUNESP, vem trabalhando no desenvolvimento de indicadores há vários anos (Valenti *et al*., 2011). A partir da aplicação desses indicadores em fazendas de camarões marinhos pode-se avaliar a pertinência, eficácia e adequação da produção em cada nível de intensificação. Além disso, os indicadores irão mostrar um panorama da sustentabilidade de um segmento da aquicultura nacional.

OBJETIVO GERAL

Avaliar o efeito da intensificação sobre a sustentabilidade ambiental, social e econômica do sistema de cultivo de *Litopenaeus vannamei* em viveiros.

OBJETIVOS ESPECÍFICOS

1. Caracterizar a sustentabilidade das fazendas de camarões marinhos de acordo com os níveis de intensificação nos Estados do Ceará e Piauí;

2. Determinar indicadores de sustentabilidade ambiental, social, econômico destes sistemas de produção, mostrando os pontos fortes, fracos e apontar possíveis soluções;

3. Identificar qual sistema usa menos recursos naturais, é mais eficiente na conversão destes recursos em biomassa de valor econômico e libera menos poluentes para o ambiente;

4. Testar a hipótese de que os sistemas menos intensificados são mais adequados para evitar o aumento dos gases de efeito estufa;

5. Determinar os custos de produção e a viabilidade econômica de cada sistema de produção;

6. Determinar um índice geral de sustentabilidade para os sistemas de produção de camarões marinhos de acordo com o nível de intensificação.

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CAPÍTULO 2

EFFECT OF INTENSIFICATION ON THE SUSTAINABILITY OF PACIFIC WHITELEG SHRIMP FARMING

EFFECT OF INTENSIFICATION ON THE SUSTAINABILITY OF PACIFIC WHITELEG SHRIMP FARMING

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ABSTRACT

The aim of this study was to evaluate the environmental, social and economic sustainability of marine shrimp farming operating in different levels of intensification in Northeastern Brazil. Eight farms were evaluated in four levels of intensification: Level 1 (10-15 shrimp m^{-2}), Level 2 (20 shrimp m^{-2}), Level 3 (35 shrimp m^{-2}) and Level 4 (51-100 shrimp m^{-2}). Samples of water, sediments, greenhouse gases, shrimps and diets were taken to determine environmental indicators. For the social and economic indicators, we used a semi-structured questionnaire. The General Sustainability Index showed that Level 4 farms shows greater sustainability, followed by levels 1, 2 and 3. The most intensified level (Level 4), had the higher environmental sustainability index as it used less resources, has the higher energy efficiency, the lower potential of eutrophication in surrounding areas, organic pollution and siltation in comparison to the farms in the other intensification levels. In the economic sustainability, this level also highlighted in the efficiency of financial resources. Therefore, we have the least intensified system (Level 1), which showed strong economic resilience. Level 2 presented intermediate values in all aspects. In the social aspect, Level 3 was more sustainable due to social inclusion and it presented better proportion in relation to the number of employees and production. The set of indicators applied generated a unique index that made it possible to identify and quantify the main aspects of general sustainability of marine shrimp production systems. These indicators and the index are adequate and effective tools to evaluate the environmental, social and economic sustainability in marine shrimp farming.

KEY WORDS: marine shrimp, sustainability, intensification, social issues, economic viability, greenhouse gases.

INTRODUCTION

Brazil was ranked among the 10 largest world producers of *Litopenaeus vannamei* and second in Latin America (FAO, 2014). The Northeast region is responsible for more than 95% of national production and the domestic market consumes the majority part of this commodity (Rocha and Mendonça, 2015). The coast of Ceará and Piauí States represents an important area for marine shrimp farming in Brazil.

In the Northeast region, there are many farms operating in different production systems and levels of intensification. For example, according to size of the ponds, stocking density, water use, requirements of outside inputs, yields and capital, shrimp farming may be classified as extensive, semi-intensive or intensive production (Anh *et al*., 2010; FAO 2014). Usually, most farms use semi-intensive systems, with densities varying between 10 to 30 shrimp m^2 and productivity around 2.5 $t.ha^1$ per cycle (Pontes, 2006). But there is a trend to intensify the activity, increasing the stocking density and decreasing the culture area (Dung, 2016).

We may define intensification of aquaculture production as the improvement of the production system in order to increase productivity per unit area. Intensification can optimize natural and economic resources (Edwards, 2015). This includes the use of high stocking densities, improved breedstock, artificial food, management of water exchange, ecological dynamics, electricity and skilled labour (Smith *et al*., 2011; Henriksson *et al*., 2012; FAO, 2014).

Nevertheless, it is necessary to have prior knowledge about intensification and appropriate management practices. High profits in shrimp farming and increasing coastal land prices caused changes in the productive sector leading to the system intensification. Without effective control, intensive operations usually increase the nutrient and organic matter load to the ecosystem well beyond the carrying capacity of the environment causing coastal pollution (Swapan and Gavin, 2011). The destruction of mangroves (Hamilton, 2013), and water pollution (Hatje *et al*., 2016) were inevitable in Asia. Another problem is associated with disease occurrence. Although the onset of the disease is not well known (Santos *et al.,* 2013), an increase in population density can be a stressful factor for the animal and lead to unleashing diseases. For instance, the white spot syndrome virus (WSSV) is currently the most devastating pathogen in farmed shrimp worldwide, especially in Asia and Pacific (Subasinghe, 2017) causing 90–100% mortality in farmed *L. vannamei* (Sánchez-Martínez *et al*., 2007). Therefore, there have been production losses due to the contamination by shrimp pathogens and this consequently causes social and economic impacts, such as unemployment and difficulty in regulating enterprises (Abreu *et al*., 2011). Marine shrimp farming represents a major rural activity that generates employment and income in Brazil, though its development still finds difficulties and requires caution (Natori *et al*., 2011).

On the other side, few studies indicate that while a large number of individual farms may exceed environmental standards, intensive shrimp farming is not always associated with waste streams exceeding water quality standards (Anh *et al*., 2010; Silva *et al.* 2010a). This showed that a greater range of studies is needed to understand the possible environmental-economic-social benefits of the intensification (Waite *et al*., 2014; FAO, 2016).

Is it possible to intensify production systems in a sustainable manner? The sustainable intensification seeks not only maximize productivity but also minimize negative environmental impacts and contribute to human and environmental services (Pretty *et al*., 2011; Firbank *et al*., 2013). In short, sustainability can be defined as a profitable production that generates jobs for the local community, improving the quality of life and guaranteeing the ecosystem preservation. Engle and D'Abramo (2016), pointed out that a systematic approach based on data systems is necessary to identify more species or sustainable systems.

Several methods are used to assess sustainability in aquaculture, such as ecological footprint, life cycle assessment, emergy analysis, resilience and set of indicators (Valenti *et al*., 2018). These methods vary in difficulty from the obtaining of data to the interpretation of results. The set of indicators required data easy to access and can be applied to any segment of aquaculture worldwide (Valenti *et al*., 2018). By measuring sustainability, we may point out the weaknesses and strengths of production systems and thus apply technologies to improve the activity as a whole.

Some studies showed that intensification has been associated with increased environmental, social and economic impacts of marine shrimp farming. However, the results in the literature are controversial as cited above. Thus, more information is needed to understand this topic and studies must be conducted to confirm or refute this hypothesis and to determine the weaknesses of systems in order to introduce changes to increase the environmental sustainability of systems.

Thus, this study aims to evaluate the general sustainability of marine shrimp farms (grow -out ponds) located in Ceará and Piauí State that operate in different levels of intensification. The analyses aim to identify which levels of intensification use less resources, are more efficient in converting natural resources into biomass, release less pollutants to the environment per biomass produced and avoid the increase of the greenhouse effect. In addition, another specific objective was to determine the economic viability of production system in different levels of intensification and which of these levels promotes greater equity, social inclusion and job creation. With these answers, we may obtain the strengths and weaknesses of marine shrimp farming and point out solutions. To sum it up, another objective was to evaluate the adequacy of sustainability indicators to compare different systems of marine shrimp farming systems to choose among the most sustainable system.

MATERIALS AND METHODS

Study site

The study was conducted from May to November of 2015, during dry season, at eight marine shrimp farms located in Ceará (2°54'3.06"S; 40°7'52.62"W) and Piauí (2°54'36.49"S; 41°46'36.51"W) States, in Northeast Brazil. This region is in an equatorial zone, and has a tropical climate.

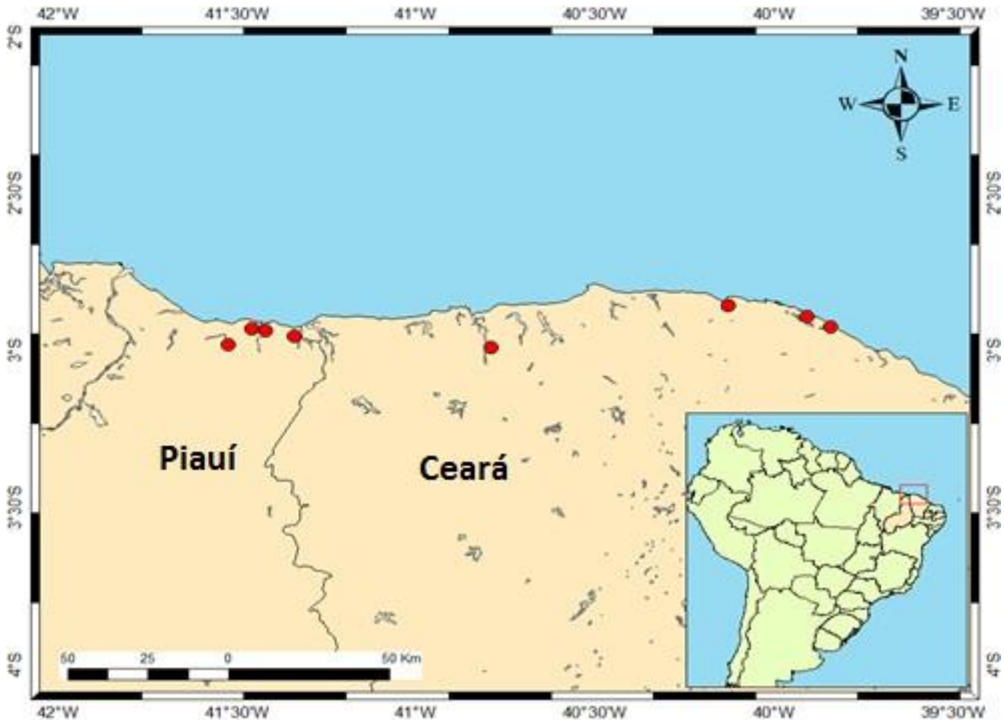


Figure 1. Study area with the points representing farms located in the State of Ceará (2°54'3.06"S; 40°7'52.62"W) and Piauí (2°54'36.49"S; 41°46'36.51"W).

Experimental design

Twelve earthen ponds from eight farms were studied and they were categorized into four levels according to stocking density management and technology: Level 1 (10-15 shrimp m^{-2}), Level 2 (20 shrimp m^{-2}), Level 3 (35 shrimp m^{-2}) and Level 4 (51-100 shrimp m^{-2}). Within these 4 stocking densities, 3 replicates were considered and they were named as L1a, L1b, L1c (Level 1); L2a, L2b, L2c (Level 2); L3a, L3b, L3c (Level 3) and L4a, L4b, L4c (Level 4). At the time of this study we observed that farms applied different production systems such as system intensification and polyculture. Therefore, the levels were determined according to the present conditions. We interviewed a total of 20 farms and selected eight farms to obtain the necessary data to calculate the indicators and determine the environmental, social and economic sustainability of the marine shrimp production systems. It should be clarified that the selection of these farms was complex. The distance between them to carry out the collection might have been impossible if we did not have the necessary financial resources. Another point was the communication with the farmers. All of them were accessible to our research and reported on some different procedure applied in culture. As it is real-scale production, significant changes in the farms could invalidate this study. The characteristics of management in the studied farms are shown in Table 1.

Table 1. Characterization of the management used in the studied farms.

Farm characteristics	Level 1 10-15 shrimp m^{-2}	Level 2 20 shrimp m^{-2}	Level 3 35 shrimp m^{-2}	Level 4 51-100 shrimp m^{-2}
Farm area (ha)	550	137	62	11
Pond size (ha)	12.5	6.1	3	1.8
Nursery	yes	yes	yes	No
Production cycle (days)	60 to 70	60 to 90	90 to 100	45 to 85
Crops (year)	5.5	3.5 to 6	3.5	3.5 to 5
Aeration use (hp ha^{-1})	No	No	6	10
Fertilization (F), Probiotic (P) use	F	F	F	F/P
Water exchange (% / day)	10	3	2	0
Soil management	No	Yes	Yes	Yes
Feed conversion rate (FCR)	1.05	1.4	1.3	1.1
Final shrimp weight (g)	7 to 8	7 to 8	7 to 8	7 to 8
Survival (%)	60	70	70	75
Productivity (t ha^{-1} $cycle^{-1}$)	0.93 ± 0.09	1.40 ± 0.08	2.3 ± 0.1	4.3 ± 1.2
Products	Shrimp, oysters, fish	Shrimp PL, harvested shrimp	Shrimp	Shrimp

Pond and farm management

In traditional systems, grow-out ponds usually measure over 1 hectare and they are called low-density and low-input systems. It should be considered that the less intensive farm in this study also produce fish (*Centropomus undecimalis*) extensively in water supply channels and native oysters (*Crassostrea rhizophorae*) in the drainage channels. By contrast, system intensification reduces the pond sizes and the culture period, increase stocking density and requires high-technology and high-cost facilities. The use of nurseries is an option in which the shrimp post larvae remain for a certain time period to increase the growth rate. We found that on all farms the ponds remain empty around 15 to 20 days between a harvest and the next crop. The days of the production cycle varies according to the stocking density and the final size of the shrimp. The use of mechanical aeration depends on the stocking density of the animals and fertilization and water renewal are managements that the farmer establishes according to culture needs. In the first two weeks of culture, the shrimps were fed three times a day with a species-specific commercial feed containing 40% crude protein. After that, farmers use commercial feed containing 38% crude protein until the end of rearing cycle. The feed was supplied in feeding trays to evaluate and correct the amount of food to be provided. We accompany some harvests and they start at night and performed slowly that demand organization, attention of workers and machines.

Environmental sustainability analysis

Environmental sustainability of farms was evaluated based on the Indicators of Sustainability developed by Valenti *et al*., (2018). The environmental indicators are grouped into four categories (Table 2).

Table 2. Environmental indicators used to assess the sustainability of intensification in the culture of Pacific white leg shrimp in Northeast Brazil.

A. Use of natural resources	**Formula**
Use of Space (S)	S= area used (ha)/production (t)
Dependence on Water (W)	W= consumed volume m^3/production (t)
Use of Energy (E)	E = energy applied (MJ)/production (t)
Use of Nitrogen (N)	N = mass of nitrogen applied (kg)/production (t)
Use of Phosphorus (P)	P = mass of phosphorus applied (kg)/production (t)
Use of Carbon (C)	C = mass of Carbon applied (kg)/production (t)
B. Efficiency in the use of resources	
Energy Efficiency Use (EE)	EE = energy recovered production (MJ)/energy applied (MJ) *100 (%)
Nitrogen Efficiency Use (NE)	NE = mass N recovered production (kg)/mass N applied (kg) *100 (%)
Phosphorus Efficiency Use (PE)	PE = mass P recovered production (kg)/mass P applied (kg) *100 (%)
Efficiency in the Use of Carbon (EC)	EC = mass C recovered production (kg)/mass C applied (kg) *100 (%)
C. Pollutants released to the environment	
Eutrophication Potential (Nitrogen, Phosphorus) (EP)	EP = mass (N, P) released in effluents/production (t)
Potential of Organic Pollution (POP)	POP = mass organic matter released in effluents/production (t)
Potential of Siltation (PS)	PS = mass total suspended solids released in effluents/production (t)
Accumulation of N sediment (AN)	AN = mass N accumulated in sediment/production (t)
Accumulation of P sediment (AP)	AP = mass P accumulated in sediment/production (t)
Accumulation of C sediment (AC)	AC = mass C accumulated in sediment/production (t)
Potential of Global Warming (PGW)	PGW = mass CO_2, CH_4, N_2O (CO_2 equivalent) released to atmosphere/production (t)
D. Conservation of genetics and biodiversity	
Risk of Farmed Species (RFS)	RFS = {1, 2, 3, 4, 5, 6 or 7}

The use of natural resources was evaluated by indicators that quantify area, volume of water, energy, nitrogen and phosphorus used to produce each ton of shrimp. The efficiency in the use resource was evaluated by indicators that show the amount of resources incorporated into production as energy, carbon, nitrogen and phosphorus. The release of pollutants to the environment includes the indicators for potential of eutrophication, organic pollution, siltation and the greenhouse gases in carbon dioxide equivalents (CO_2e.) released to the atmosphere per unit of production. The pollutants accumulated in ponds present the indicators that measure the mass of phosphorus, organic matter and particulate material in sediment. The value for conservation of genetic diversity and risk for farmed species was evaluated as: 1, 2, 3, 4, 5, 6 or 7, in which: 1=Local strain farmed in an open or closed system; 2=Species within the same basin (but not local strain) farmed in a closed system; 3=Species within the same basin farmed in an open system; 4=Allochthonous species, native species with reduced genetic variability, or hybrid (native or allochthonous species) farmed in a closed system; 5=Allochthonous species, native species with reduced genetic variability, or hybrid (native or allochthonous species) farmed in an open system; 6=Transgenic variety of any species farmed in a closed system; 7=Transgenic variety of any species farmed in an open system.

To calculate the environmental indicators, inlet water, water inside ponds during the culture, effluents, sediments, shrimps, gases and diet samples were taken. Sampling occurred in three stages: at the stocking (up to one week after stocking shrimp), in the middle and at the harvest (up to one week before harvesting shrimp) of the rearing cycle. All samples were transported and analyzed at the Sustainability Laboratory of the Biosciences Institute, Coastal Campus of São Paulo State University – Unesp, in São Vicente, São Paulo, Brazil. The analyses are described as follows:

Water analyses

Inlet, ponds and effluent water were sampled, stored in polyethylene bottles and frozen for later analysis of total nitrogen, total phosphorus, total carbon and total suspended solids. Nitrogen and total carbon were determined by catalytic combustion oxidation using a Vario TOC Select (Elementar®)

equipment. For the determination of total phosphorus, the persulfate digestion method (APHA, 2005, Method 4500-P B5) was applied. Later, the orthophosphate was measured by the method of starch chloride (APHA, 2005, Method 4500-P D), using a digital spectrophotometer (Shimadzu UV 1800®). Total suspended solids were measured according to APHA (2005, Method 2540 D).

Sediment analyses

The sediment generated in the ponds, supply and drainage channel during 24 hours was sampled using tripton samplers. These were made with six 1.876 L PVC tubes, 25.4 cm long, with 9.7 cm diameter that covers a 450 cm^2 area. Each sediment sample was weighed and the values of dry weight, total nitrogen, total phosphorus and carbon content were obtained. The dry matter was determined by drying at 95-100°C according to the methodology described in AOAC (1995, Method 934.01). Nitrogen and carbon contents were determined on a CHNS elemental analyzer (Vario Macro Cube, Elementar®) by high temperature combustion, with a conversion of the sample into gases and detection by a TCD (Thermal Conductivity Detector) sensor. Total phosphorus was determined according to the metavanadate colorimetry method applied on samples previously incinerated in the muffle for four hours at 550° C (Michelsen, 1957). The obtained values were extrapolated for the entire grow-out period.

Diet and shrimp analyses

Samples of 20 g of shrimp and diet (the analyzed samples refer to the feed of 38% crude protein) were collected and weighed for determination of the initial shrimp mass, final average individual mass, nitrogen, phosphorus, carbon and energy contents. Samples were kept in a drying oven with forced circulation at 60° C for 48 h until the weight was constant. They were then weighed, grounded, transferred to plastic tubes and stored in a freezer until analysis. The total nitrogen and carbon content were evaluated according to the methodology described for sediment. For the analysis of phosphorus, the samples were submitted to reaction with magnesium nitrate, nitric acid, ammonium hydroxide, acidified molybdate solution, followed by filtration and titration with nitric acid (AOAC, 1995 - method 969.31 A) and spectrophotometer reading (Shimadzu UV 1800®). The energy contained in the shrimp and diet were evaluated by automatic calorimetric combustion (C-2000, IKA®) and the results are expressed as KJ/g DM (DS = dry mass).

Greenhouse gases analyses

The release of CO_2, CH_4 and N_2O into the atmosphere can occur by bubbling and emanation, i.e. diffusion gas exchanges at the water-air interface (Matvienko *et al.*, 2000). To capture the bubbles, funnels suspended by floats were installed on the surface of the pond. The funnel is 35 cm high and has 36 cm of diameter. In the top of the funnel, a 250 mL bottle was connected, and bubbles were retained over the course of 24 hours. After this period, the sample was conditioned in 12 mL gasometric borosilicate vials (LABCO) and send to the laboratory for chromatographic analysis. The diffusion at the water-air interface was evaluated by the equilibrium method, in which confined portions of air are allowed to partially equilibrate with the gas dissolved in water for periods of 0, 1, 2 and 4 minutes using diffusion chamber. This process was performed in two periods (day/night). Then, the samples containing these portions of air were conditioned in vials for later analysis by gas chromatography. The amount of CO_2, CH_4 and N_2O were determined by means of a gas chromatograph with TCD detector - Shimadzu GC-2014® and ECD-Electron Captor Detector. Global warming potential caused by shrimp farming was estimated by summing up greenhouse gases emissions, subtracting gases absorptions and multiplying the result by the conversion factor 21 (CH_4) and 310 (N_2O) to quantify total CO_2 equivalent emission (or absorption) (IPCC, 2007).

Social sustainability indicators

In this work, the social indicators of the production systems were analyzed, considering the grow-out phase, harvest and sale. The shrimp farm in the Level 1, farms fish extensively in supply channels and oysters in the drainage channel, but is still underdeveloped commercially. Only one farm in the Level 2 has the larviculture sector in which it supplies post larvae to local farmers. The shrimp farms of Levels 3 and 4 work uniquely with the nursery and grow-out phase.

The data needed to calculate the social and economic indicators (Table 13 and 14) were primary and secondary. The primary data were obtained from the farms through direct interviews with the owners, administrators, technicians and employees, using a semi-structured questionnaire. The secondary data were obtained through research carried out with public agencies, which maintains the records of the property and the region, such as the Brazilian Geography and Statistics Institute (IBGE), data files of the extinct Ministry of Fisheries and Aquaculture (MPA), State Secretariats of Aquaculture and / or Agrarian Development, Brazilian Agricultural Research Corporation (Embrapa), Prefectures among others.

The social sustainability was evaluated considering four aspects: the principle of equity and the income distribution, equality of opportunities, the generation of jobs and benefits for local communities. The principle of equity considered the individual remuneration of the labor, including the entrepreneur, percentage of the cost of production (or breakeven price) that corresponds to the labor remuneration, including family labor. The income distribution shows the relationship between the amount paid as wages + charges + social benefits (i.e. company health plan) and profit generated. The indicator shows for each US$ dollars of the entrepreneur's profit how many US$ dollars are distributed to the workers. The remuneration of labor can also be expressed in units of production, considering the mass of shrimp produced.

The equality of opportunities measures the social inclusion considering the five main ethnic groups in Brazil: White, Brown, Black, Yellow and Indigenous. We also considered the age groups as young (10 to 19 years), adults (20 to 39), middle age (40 to 59) and old (> 60). The data on the social composition of the local population (racial, age and gender) were obtained from the IBGE database (IBGE, 2016) and the number of jobs occupied by the local population in the farms. The generation of jobs measures the work required per unit production and area, proportion of self-employment jobs, direct and indirect jobs by total amount invested and permanence in the activity.

The benefits for local communities measured the relationship between production, workers, local market, community activities, health and education conditions, and the fixation of income. The proportion of jobs generated that allowed recruitment among the local population, considering their culture, level of education and skills. It also considered the purchases of inputs, products, equipment, etc., that were made in the local market, except for labor. The indicator Workplace Safety (WS) quantifies accident prevention procedures. We analyzed 15 items that represent equipment, actions and practices that give security to the worker, as the following: Use of life vest; Use of sun protection goggles; Use of protective goggles against mud, scales, etc.; Use of a pigmented glove; Use of waterproof and non-slip boots; Use of own clothes to stay in the sun or rain; Use of equipment that alleviates physical exertion; Use of adequate lighting in places; Use of appropriate electrical and hydraulic installation; Use of machines, equipment, implements, furniture and tools that provide good conditions for posture, visualization, movement and operation; Use of machines and equipment by a qualified professional; Use of protective apron when necessary; Guaranteed rest breaks for activities that are performed while (or necessitate) standing up; Well-equipped and easily accessible first-aid kit; Indication of any danger areas. In order to evaluate social sustainability, the indicators showed in Table 3 were used (Valenti *et al.,* 2018).

Table 3. Social sustainability indicators used to assess marine shrimp *Litopenaeus vannamei* production systems.

A. Principle of equity and Income distribution	**Formula**
Pay equality	PE = 1- (Standard deviation of salaries/mean of salaries)
Proportional cost work	PCW = cost of work/cost of production
Income distribution	ID = salaries + social fees + social benefits/profit
Remuneration production	RP = remuneration paid/unit produced
B. Equality of opportunities	
Racial inclusion	RI = racial jobs composition /racial local population composition
Gender inclusion	GI = generic jobs composition /generic local pop. composition
Age inclusion	AI = age jobs composition /age local population group

Table 3. (Continued)

C. Jobs generation	Formula
Investment direct empl.	ICDE = investment/numbers of jobs generated
Investment total empl.	ICTE = investment/number of jobs and self-employed jobs generated (direct + indirect)
Self-employment proportion	SE = number of self-employed/total number of jobs
Required work area	WA = person-hours per year/occupied area
Required work production	WP = person-hours per year/unit produced
Permanence in the activity	PA = average time spent by each worker in the aquaculture industry (in years)
D. Benefits for local communities	
Use of local workers	LW = jobs suitable for local population/total number of jobs
Development of local economy	LE = products and services from local markets ($)/total products and services used ($)
Local consumption of production	LC = mass of product sold in the local market/total production
Health-insurance programs	AHP = number of employees and owners with health insurance/total number of employees and owners
Schooling	Sc = number of employees study/total number of employees
Participation community activities	PCA = number of workers participating in community activities/number of total workers
Safety at work place	SW = equipment, actions and practices that give security to the worker present in the enterprise/total analyzed items

Economic sustainability indicators

We interviewed the farmers using a semi-structured questionnaire. The economic indicators were defined to reflect the aspects: The efficiency in the use of financial resources; the ability of resilience; that is, the ability to deal with future uncertainties and generate enough income to keep the producer on the business. All expenses were estimated, considering the initial investments in works and equipment and the annual operating costs defined for each marine shrimp production system. Gross revenues were determined considering the sale price per unit, according to size classes and productivity obtained in each system.

For the category “efficiency in the use of financial resources” we used the following indicators (Table 4): The Income-Investment Ratio measures the income generated per unit of capital invested. Ventures with lower initial investment and that generate the same net income are more sustainable, since they correspond to a more efficient use of capital resources. For this category, we also used traditional economic indicators such as the Internal Rate of Return (IRR), Pay-back Period (PBP), Benefit-cost ratio (B/C) and Net Present Value (NPV), Profit (P) (Shang, 1990) and Break-Even Point (BEP). The Internal Rate of Return takes into account the variation of capital over time. This indicator can be considered as the interest rate received for an investment over a given period within regular intervals where payments are made to cover all the costs of creating and proceeds from the sale of the product. When evaluating a project by Internal Rate of Return, it appears that it is economically viable only when the rate exceeds a specified hurdle rate.

The minimum annual hurdle rate of attractiveness considered in this study was 13%, equivalent to the interest received on cash investments based on the SELIC (Special System of Settlement and Custody), which is released by the Brazilian Monetary Policy Committee (COPOM). Demarcated by SELIC is that are set interest rates charged by financial market. Besides IRR, Net Present Value (NPV) is the present value of series of future revenues for a period, discounted using the interest rate, subtracted from net investment. The Pay-back Period (PP) is defined as the number of years required for the company to recover the initial capital invested in the project. The Benefit / Cost Ratio (B/C) consider the relationship between annual net benefit in year (gross revenue minus operating expenses) and the capital invested in year (initial investment plus reinvestments). This indicator also considers the project horizon fixed in 20 years and discount rate based on the hurdle rate of attractiveness. The Profit (P) corresponds to Gross Revenue (GR) minus Total Cost of Production (TC) (Fixed costs + variable costs); P = GR-TC. Annual Income (AI) corresponds to the Gross Revenue (GR), deducting the Operating Expenses of production (OE), Depreciation (D), and Taxes (T), that is, AI corresponds to Profit Plus the Cost of Opportunity, Taxes and Fees. The opportunity cost includes: owner's compensation, interest on fixed capital, and current, and land remuneration; AI = GR-OE-D-T. The Break-Even point (BEP) is the point at which revenue is exactly equal to costs and hence no profit is made and no losses are incurred. To understand the "resilience capacity" category, we used the indicators of Business Longevity (BL) that corresponds to the time (in years) that each farm is engaged in aquaculture, the average life expectancy of the farms. The Risk Rate (RR) measures the proportion of risk factors for marine shrimp production systems present in the farms. We considered 11 factors that raise the risks and negative impacts on marine shrimp production systems:

1. Lack of Business Plan in the installation planning phase;
2. The owner/manager lacks technical or administrative capacity;
3. Administrative deficiencies, especially in logistics and problem solving;
4. Lack of well-established trade flow for the product, i.e., needs to open the market;
5. Farm is installed at an inappropriate site, subject to floods, urban, rural and industrial pollution, etc;
6. Lack of responsible technician part-time or full-time;
7. Lack of nocturnal and weekend supervision and/or surveillance and security systems against theft;
8. Practice of intensive system, adding much material and energy and operating close to the carrying capacity of the system;
9. Institutional instability: continual changes in laws and regulations by funding, regulatory and enforcement agencies;
10. Agglomeration: close proximity to other farms producing the same organism, which use the same environmental services and produce the same type of pollution;
11. The farm faces conflicts with the local community and/or NGO.

RR=number of risk factors observed/number of risk factors analyzed

For the same category we also considered the diversification of products and markets. The Market Diversity (MD) measures the number of markets that absorb production like wholesalers, fishing hotels and restaurants, respectively. The Product Diversity (PD) indicator measure the number of products offered by the farms like other agricultural products and / or services.

Table 4. Economic sustainability indicators used to assess marine shrimp *Litopenaeus vannamei* production systems.

A. Efficiency in the use of financial resources	**Formula**
Net-income-Investment ratio	Annual income/Initial investment
Internal Rate of Return	Valenti *et al*. (2018)
Payback Period	Valenti *et al*. (2018)
Benefit Cost Ratio	Valenti *et al*. (2018)
Net Present Value	Valenti *et al*. (2018)
Profit	P= Gross revenue minus total production costs
Annual Income	AI= Profit plus the cost of opportunity, taxes and fees
Break-Even Point	BEP= (Break even (quantity) / production) *100
B. Resilience capacity	
Business Longevity	BL=Average life expectancy of companies
Risk Rate	RR=Risk factors observed/ total risk factor analyzed
Market Diversity	MD=Number of markets that absorb production
Product Diversity	PD=Number of products offered by the enterprise

General analysis of indicators

Indicators were calculated according to the formulas shown previously. Raw data indicators were analyzed using One-Way ANOVA followed by Tukey as the post-hoc test. Arcsine transformation was used for indicators showed in percentage. After that, each indicator was converted into a performance scale (Bellen, 2008, Valenti, 2008, Valenti *et al*., 2018), with scores ranging from 0 to 1. The intensification level with the best indicator value (more sustainable when compared to the others) was arbitrarily scored as 1, and the others were determined by proportion. Subsequently, a sub-index was determined for each dimension of sustainability assessed. The General Sustainability Index (GSI) was determined by the average of the sub-indices of environmental, social and economic sustainability in each production system and expressed in multidimensional diagrams. To investigate the patterns observed in the indicators, as well as the relative influence of each intensification level, Principal Components Analysis (PCA) (SIMCA 14.1) was used to explain the maximum variability in environmental, social and economic indicators across the samples.

RESULTS

Environmental sustainability

Water quality

The concentration of nutrients in water is shown in Table 5. The Level 2 showed higher dissolved organic carbon concentration compared to the beginning of the cycle.

Table 5. Variation of the nitrogen, phosphorus, dissolved organic carbon and suspended solids (mg L^{-1}) concentration in water at the stocking, middle and harvest of the production cycle in each intensification level (L1, L2, L3, L4). Values are presented in mean ± standard deviation. Capital letters are vertical comparison within a column, while lowercase letters are horizontal comparison. Different letters are significantly different by Tukey test (P<0.05).

	L1	**L2**	**L3**	**L4**
Nitrogen (mg L^{-1})				
Stocking	1.07 ± 0.16	0.99 ± 0.79	0.66 ± 0.59	1.77 ± 1.41
Middle	0.81 ± 0.20	0.91 ± 0.16	0.73 ± 0.38	1.13 ± 0.3
Harvest	0.68 ± 0.36	1.77 ± 2.21	0.90 ± 1.41	1.80 ± 0.46
Phosphorus (mg L^{-1})				
Stocking	0.03 ± 0.014	0.05 ± 0.12	0.06 ± 0.08	0.11 ± 0.07
Middle	0.04 ± 0.01	0.03 ± 0.03	0.02 ± 0.02	0.01 ± 0.00
Harvest	0.02 ± 0.00	0.02 ± 0.08	0.02 ± 0.02	0.11 ± 0.04
Dissolved organic carbon (mg L^{-1})				
Stocking	2.03 ± 0.63	2.95 ± 2.56^{B}	1.76 ± 1.92	5.54 ± 4.39
Middle	1.38 ± 0.87	6.59 ± 0.87^{AB}	4.84 ± 2.82	8.99 ± 1.47
Harvest	2.50 ± 2.08	8.68 ± 8.03^{A}	6.49 ± 6.35	11.79 ± 4.60

Table 5. (Continued)

Suspended solids (mg L^{-1})				
Stocking	15.28 ± 7.12	18.33 ± 36.94	101.70 ± 134.46	18.05 ± 54.42
Middle	74.89 ± 54.37	14.15 ± 111.06	70.60 ± 65.94	112.13 ± 51.76
Harvest	66.10 ± 70.96	15.22 ± 137.53	32.40 ± 210.12	144.00 ± 91.85

Sediment

The average values of sedimentation rate and nutrients concentration in sediments did not differ statistically at stocking and harvesting ponds or between levels of intensification (Table 6).

Table 6. Variation of sedimentation rate (g.m^{2}day^{-1}), total nitrogen (%), total phosphorus (mg L^{-1}) and organic carbon (%) concentrations in sediments at the stocking and in the harvest of the production cycle in each intensification level (L1, L2, L3, L4). Values are presented in mean ± standard deviation.

	L1	L2	L3	L4
Sedimentation rate g.m^{2}day^{-1}				
Stocking	47.19 ± 33.98	29.11 ±14.49	41.48 ±5.63	37.19 ± 14.78
Harvest	351.11 ± 269.78	198.22 ± 262.27	353.41 ± 293.61	502.78 ± 391.00
Total nitrogen (%)				
Stocking	0.45 ± 0.16	0.46 ± 0.10	0.25 ± 0.12	0.54 ± 0.35
Harvest	0.59 ± 0.27	0.44 ± 0.26	0.51 ± 0.27	0.85 ± 0.46
Total phosphorus (mg L^{-1})				
Stocking	0.02 ± 0.01	0.02 ± 0.02	0.01 ± 0.00	0.03 ± 0.01
Harvest	0.02 ± 0.01	0.01 ± 0.01	0.05 ± 0.03	0.05 ± 0.03
Organic carbon (%)				
Stocking	3.62 ± 0.87	1.70 ± 1.12	1.86 ± 0.62	3.72 ± 3.08
Harvest	4.44 ± 3.46	4.92 ± 3.00	4.08 ± 4.01	8.63 ± 3.50

Greenhouse gases

Greenhouse gases sampling was performed at day and at night as metabolism of ponds vary in these periods. These sampling periods are shown in Figure 2, 3 and 4. Considering diffusive emission of greenhouse gases, there was a low emission of methane in all levels of intensification comparing to the emission of CO_2 and N_2O. Level 4 presented significantly higher CO_2 emissions in the end of the rearing cycle, close to harvest, comparing to the beginning (stocking) of the cycle. The same level emitted more CO_2 in the end of the cycle than the other levels. On the other hand, Level 4 absorbed more N_2O than Levels 2 and 3. This absorption was higher at the end and in the middle of the cycle comparing to the beginning of the cycle.

The values of diffusive and ebulitive emissions from ponds are shown in Table 7. The ebulitive emission contributed to less than 1% of the greenhouse gases emitted by ponds: Level 1 showed higher carbon dioxide and nitrous oxide emission at the beginning (stocking) of the cycle and lower in the end (harvest) of it. Level 2 emitted the highest amount of nitrous oxide in the end of the culture comparing to the other levels of intensification.

Figures 2, 3 and 4 summarize the greenhouse gases budget in the beginning (stocking), middle and end (harvest) of shrimp rearing cycle in each intensification level (L1, L2, L3, L4). We can observe a high variability in the results.

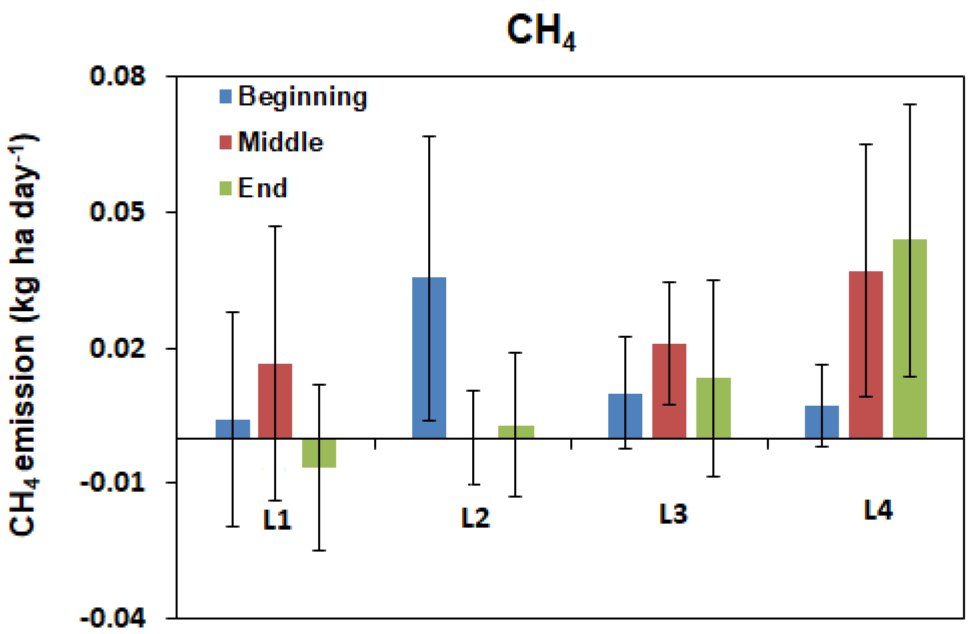


Figure 2. Mean values and standard deviation of the diffusive and ebulitive CH_4 flows (kg.ha.day^{-1}) during culture period in each intensification level. Absorption are negative values and emissions are positive values. Beginning = stocking; End = harvest.

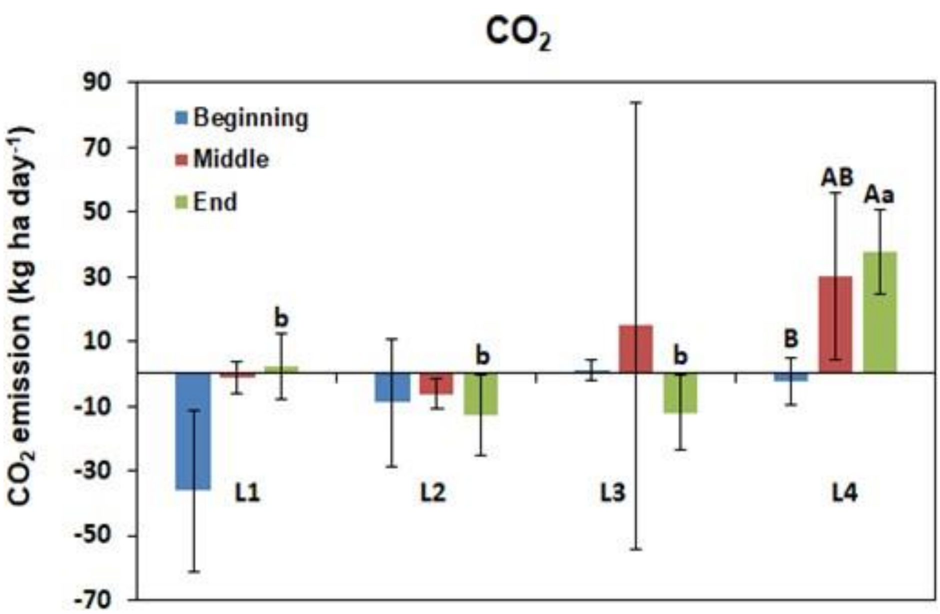


Figure 3. Mean values and standard deviation of the diffusive and ebulitive CO_2 flows (kg.ha.day^{-1}) during culture period in each intensification level. Absorption are negative values and emission are positive values. Capital letters indicate significant differences within the same level. Lowercase letters indicate

significant differences at distinct levels and periods (Beginning, middle, end). Different letters are significantly different by Tukey test (P<0.05). Beginning = stocking; End = harvest.

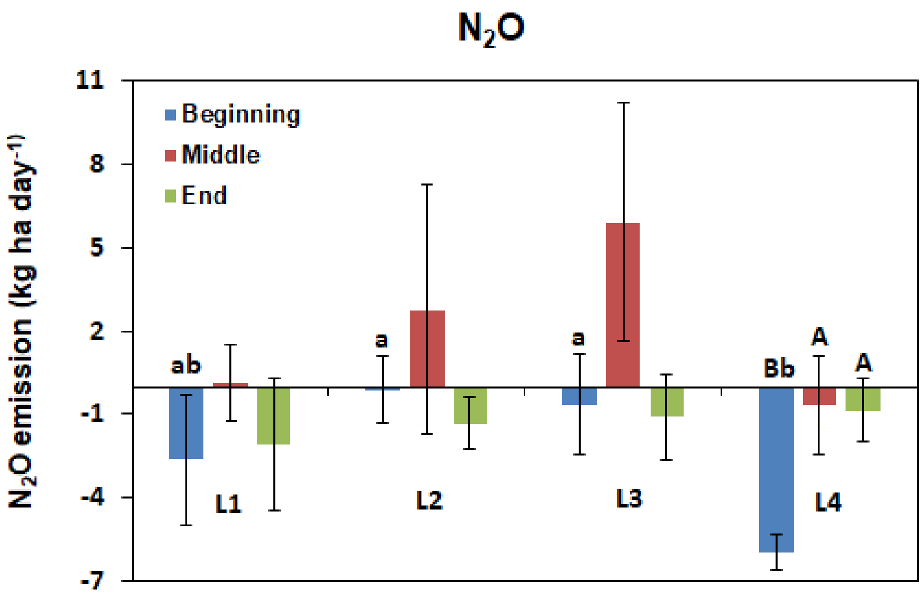


Figure 4. Mean values and standard deviation of the diffusive and ebullitive N_2O flows (kg.ha.day^{-1}) during culture period in each intensification level. Absorption are negative values and emission are positive values. Capital letters indicate significant differences within the same level. Lowercase letters indicate significant differences at distinct levels and periods (Beginning, middle, end). Different letters are significantly different by Tukey test (P<0.05). Beginning = stocking; End = harvest.

Table 7. Total diffusive and ebulitive emissions of greenhouse effect gases (kg.ha. day^{-1}) for the following systems: Level 1 (L1), Level 2 (L2), Level 3 (L3) and Level 4 (L4). Carbon dioxide equivalent (CO_2e) represents the sum of the gases and negative values represent absorption. Values are presented in mean ± standard deviation. Different letters in the same line indicate significant differences between levels by Tukey test (P<0.05).

	Gases	L1	L2	L3	L4
Diffusive emission	**CH_4**	0.00 ± 0.02	0.01 ±0.01	0.00 ± 0.00	0.02 ± 0.02
	CO_2	-11.98 ± 4.21	-9.03 ± 10.25	1.18 ± 26.80	21.90 ± 8.33
	N_2O	-1.58 ± 1.33^{ab}	0.28 ± 0.93^{ab}	1.32 ± 2.01^{a}	-2.90 ± 0.71^{b}
	CO_2e	-501.79^{ab}	77.72^{ab}	411.27^{a}	-876.36^{b}

Table 7. (Continued)

	Gases	L1	L2	L3	L4
Ebulitive emission	**CH_4**	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
	CO_2	0.01 ± 0.01	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.01
	N_2O	0.00 ± 0.00^{b}	0.01 ± 0.00^{a}	0.00 ± 0.00^{b}	0.00 ± 0.00^{ab}
	CO_2e	0.88^{b}	2.45^{a}	0.90^{b}	1.04^{ab}
Total GEE emissions	**CO_2e**	-500.91^{ab}	80.17^{ab}	412.17^{a}	-875.32^{b}

Considering diffusive emissions, L4 absorbed more N_2O than L3. There was no significant difference in diffusive emission among L1, L2 and L3. Ebulitive emissions of N_2O and CO_2e were higher in L2 than in L1 and L3. (Table 7).

Shrimps

The contents of nitrogen, phosphorus, carbon and energy in the biomass of shrimps are showed in Table 8. The nitrogen content increased in the final sampling in Level 2. The most intensified level, differed from Level 3 in phosphorus content presenting higher proportion of this nutrient. Levels 1, 2 and 4 showed higher amount of carbon in the final sampling when compared to the beginning of the culture. For energy contend, the same trend for carbon was observed in the Levels 1, 2 and 3.

Table 8. Nitrogen (%), phosphorus (%), carbon (%) and energy ($MJ.kg^{-1}$) contents in animal biomass at the stocking and in the harvest of the cycle of marine shrimp farming according to intensification levels: Level 1 (L1), Level 2 (L2), Level 3 (L3) and Level 4 (L4). Values are presented in mean ± standard deviation. Capital letters show vertical comparison within a column, while lowercase letters are horizontal comparison. Different letters are significantly different by Test t and Tukey, respectively ($P<0.05$).

Rearing cycle phase	L1	L2	L3	L4
		Nitrogen content (%)		
Stocking	10.16 ± 1.40	6.65 ± 2.30^{B}	7.52 ± 3.06	10.22 ± 0.69
Harvest	11.03 ± 0.71	10.87 ± 1.17^{A}	10.97 ± 1.42	10.75 ± 1.08
		Phosphorus content (%)		
Stocking	3.10 ± 0.19^{ab}	2.84 ± 0.21^{ab}	2.76 ± 0.28^{b}	3.41 ± 0.27^{a}
Harvest	2.97 ± 0.50	3.14 ± 0.50	3.37 ± 0.43	3.43 ± 0.25
		Carbon content (%)		
Stocking	41.78 ± 0.10^{B}	25.96 ± 9.40^{B}	27.81 ± 10.99	37.50 ± 2.75^{B}
Harvest	45.21 ± 0.51^{A}	43.68 ± 1.36^{A}	44.99 ± 1.71	44.56 ± 2.92^{A}
		Energy content ($MJ.kg^{-1}$)		
Stocking	19.60 ± 0.00^{B}	16.35 ± 1.25^{B}	17.77 ± 0.79^{B}	18.15 ± 1.82
Harvest	20.41 ± 0.37^{A}	20.09 ± 0.19^{A}	20.02 ± 0.24^{A}	20.03 ± 0.46

Diet

Phosphorus concentration was significantly higher in L4 than in L1 (Table 9). The results below are from the 38% CP feed.

Table 9. Nitrogen (%), phosphorus (%), carbon (%) and energy ($MJ.kg^{-1}$) concentrations in the diet provided during culture at different intensification levels: Level 1 (L1), Level 2 (L2), Level 3 (L3) and Level 4 (L4). Values are presented in mean ± standard deviation. Different letters in the same line indicate significant differences between levels by Tukey test (*P*<0.05).

Variable	L1	L2	L3	L4
Nitrogen (%)	6.30 ± 0.00	6.48 ± 0.53	6.58 ± 0.40	6.07 ± 0.42
Phosphorus (%)	3.65 ± 0.16^{b}	4.76 ± 0.64^{ab}	4.44 ± 0.33^{ab}	4.99 ± 0.53^{a}
Carbon (%)	40.90 ± 0.00	41.53 ± 1.19	41.30 ± 1.38	40.07 ± 1.77
Energy ($MJ.kg^{-1}$)	18.53 ± 0.00	17.20 ± 1.75	18.01 ± 2.42	18.03 ± 0.36

Ecological indicators

The annual values of the variables to calculate the ecological indicators were calculated per area and are shown in Table 10. The less intensified Level (Level 1) uses more area, L4 yields more productivity and energy recovery and presented more N, P and C in shrimp biomass than the other levels. Organic C release in effluents was lower in L1 comparing to L2.

Table 10. Total values of the variables used to calculate the indicators of environmental sustainability. Values are presented in mean ± standard deviation. Different letters in the same line indicate significant differences between levels by Tukey test (P<0.05).

Variable	L1	L2	L3	L4
Pond area (ha)	11.3 ± 1.52^{a}	6.17 ± 2.75^{b}	2.5 ± 0.86^{b}	1.79 ± 1.16^{b}
Energy applied ($MJ. year. ha^{-1}$)	157850 ±13567	183911 ±35065	238243 ±38461	506631 ± 186077
Total production (ton ha^{-1}cycle)	0.93 ± 0.09^{b}	1.44 ± 0.08^{b}	2.34 ± 0.09^{b}	4.34 ± 1.20^{a}
Energy recovered ($MJ.year.ha^{-1}$)	31001 ± 2428^{b}	37289 ± 11255^{b}	48842 ± 2347^{b}	126622 ± 57896^{a}
N-water (kg ha^{-1})	25.7 ± 3.7	41.2 ± 29.5	27.9 ± 10.4	34.6 ± 4.6

Table 10. (Continued)

Variable	L1	L2	L3	L4
P-water (kg ha^{-1})	1.00 ± 0.20	1.60 ± 0.99	1.17 ± 0.96	1.46 ± 0.31
Organic C-water (kg ha^{-1})	59.07 ± 20.80[b]	181.50 ± 89.63[a]	164.80 ± 62.05[ab]	179.47 ± 45.98[ab]
N-sediment (kg ha^{-1})	747 ±542	382 ±532	831 ±567	1565 ± 1707
P-sediment (kg ha^{-1})	0.44 ± 0.43	0.40 ± 0.64	1.42 ± 1.01	1.40 ± 0.98
Organic C-sediment (kg ha^{-1})	5423 ± 4064	2518 ± 2522	6797 ± 5944	4823 ± 2982
Greenhouse gases CO_2e (t ha^{-1})	-31.56 ± 25.85	10.84 ± 22.37	39.09 ± 59.85	-31.48 ± 48.39
N-shrimp (kg ha^{-1})	25.78 ± 3.39[b]	39.42 ± 5.94[b]	64.10 ± 7.81[b]	115.21 ± 26.94[a]
P-shrimp (kg ha^{-1})	6.99 ± 1.64[b]	11.41 ± 2.45[b]	19.68 ± 2.12[b]	37.74 ± 13.08[a]
Organic C-shrimp (t ha^{-1})	105 ± 9[b]	158 ± 12[b]	263 ± 7.67[b]	477 ± 101[a]

The environmental sustainability indicators were divided into categories and were calculated by total production (Table 11). Significant differences among intensification levels were only observed for use of natural resources category. The most intensified Level (Level 4) showed better use of space and water. In contrast, that level used higher amounts of phosphorus compared to the least intensified level (Level 1). The value for conservation of genetic diversity and risk of farmed species was 4, which corresponds to allochthonous species, *L. vannamei*, farmed in a closed system.

Table 11. Environmental sustainability indicators for the intensification levels: L1 (10-15 shrimp m^{-2}), L2 (20 shrimp m^{-2}), L3 (35 shrimp m^{-2}) and L4 (51-100 shrimp m^{-2}). Values are presented in mean ± standard deviation. Different letters in the same line indicate significant differences between levels by Tukey test (P<0.05).

Indicators	**L1**	**L2**	**L3**	**L4**
A. Use of natural resources				
Space (ha t^{-1})	1.08± 0.10^{a}	0.69 ± 0.04^{b}	0.43 ± 0.02^{c}	0.24 ± 0.07^{d}
Water (m^3 t^{-1})	21127 ± 2074^{a}	15391± 3620^{ab}	9696± 1509^{b}	3365 ± 1002^{c}
Energy (MJ t^{-1})	30916 ± 2622	30847 ± 9118	29047 ± 3729	25996 ± 711
N (kg t^{-1})	73.96 ± 5.64	77.74 ± 4.14	83.07 ± 7.60	77.84 ± 11.29
P (kg t^{-1})	42.82 ± 4.50^{b}	57.04 ± 7.39^{ab}	55.87 ± 3.51^{ab}	64.00 ± 12.40^{a}
C (kg t^{-1})	479 ± 36	498 ± 20	520 ± 40	510 ± 43
B. Efficiency in the use of resources				
E. Energy (%)	19.64 ± 1.54	20.46 ± 5.33	20.74 ± 2.50	24.42 ± 2.06
E. N (%)	37.02 ± 2.13	34.85 ± 3.65	33.16 ± 6.26	36.36 ± 1.23
E. P (%)	17.49 ± 4.69	13.75 ± 2.04	14.98 ± 1.24	14.28 ± 1.80
E. C (%)	23.45 ± 1.90	21.85 ± 1.16	21.63 ± 2.31	22.95 ± 1.54
C. Pollutants released to the environment				
Eutrophication N (kg t^{-1})	27.65 ± 4.70	27.97 ± 19.35	11.90 ± 4.25	8.19 ± 1.23
Eutrophication P (kg t^{-1})	1.08 ± 0.22	1.11 ± 0.70	0.50 ± 0.40	0.35 ± 0.10
Organic pollution (kg t^{-1})	64.78 ± 28.71	124.71 ± 60.69	70.86 ± 28.16	44.23 ± 17.12
Siltation (kg t^{-1})	548 ± 201	605 ± 195	584 ± 215	202 ± 51
N sediment (kg t^{-1})	800 ± 565	251 ± 343	358 ± 249	452 ± 559
P sediment (kg t^{-1})	0.46 ± 0.40	0.26 ± 0.41	0.62 ± 0.45	0.36 ± 0.25

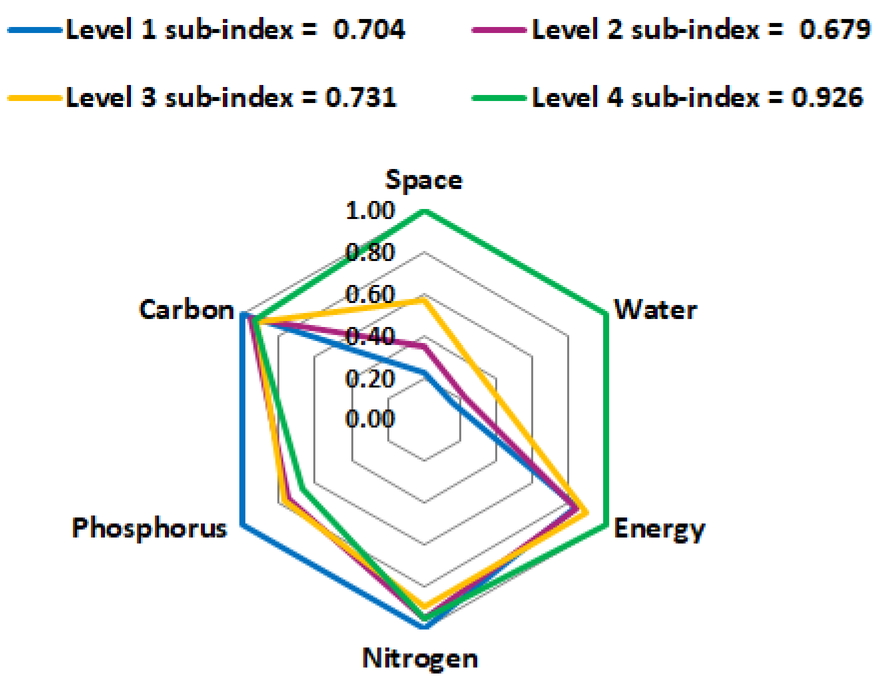
Table 11. (Continued)

Indicators	L1	L2	L3	L4
Organic carbon sediment (kg t^{-1})	5,970 ± 4,809	1,682 ± 1,604	2,959 ± 2,669	1,233 ± 807
Global warming potential (kg t^{-1})	-34240 ± 28503	7370 ± 15828	16702 ±25056	-8790 ± 14659
D. Conservation of genetic and biodiversity				
Risk farmed species	0.25	0.25	0.25	0.25

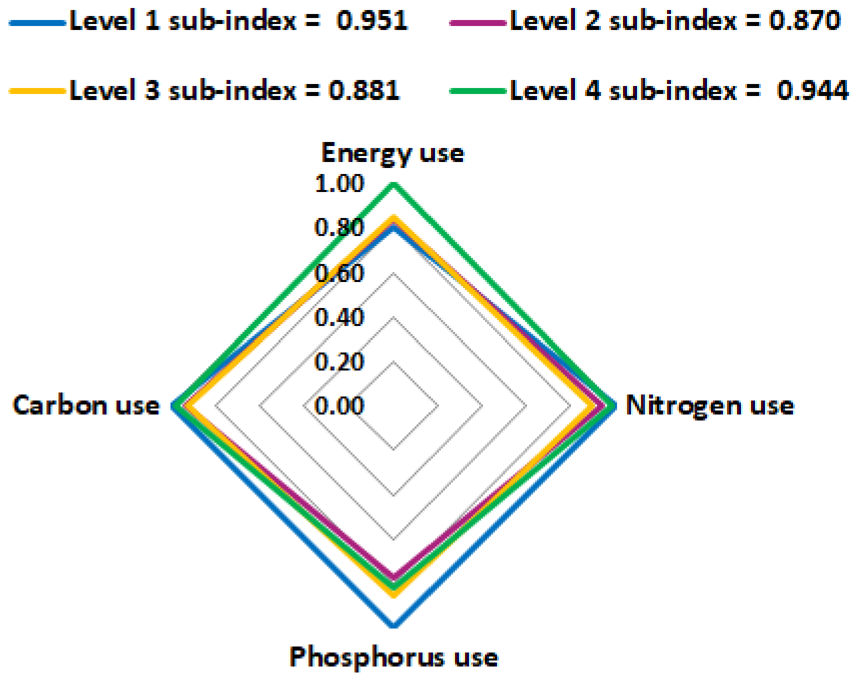
Environmental sustainability index

Level 4 had a better performance in the categories: Use of natural resources (Figure. 5a), Efficiency in the use of resources (Figure. 5b) and Water pollutants (Figure. 5c). For the category of Sediment pollutant (Figure. 5d), the Level 2 had the better score.

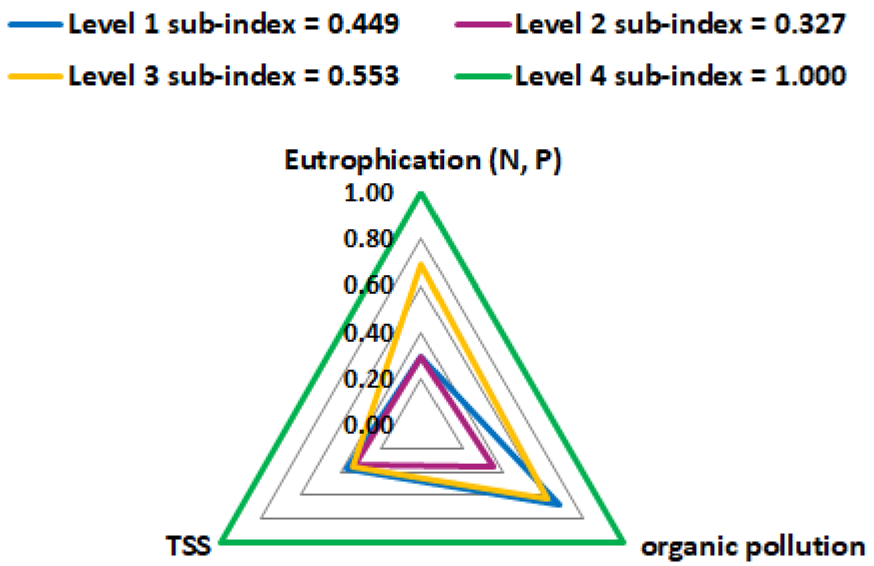
a) Use of natural resources



b) Efficiency in the use of resources



c) Water pollutants



d) Sediment pollutants

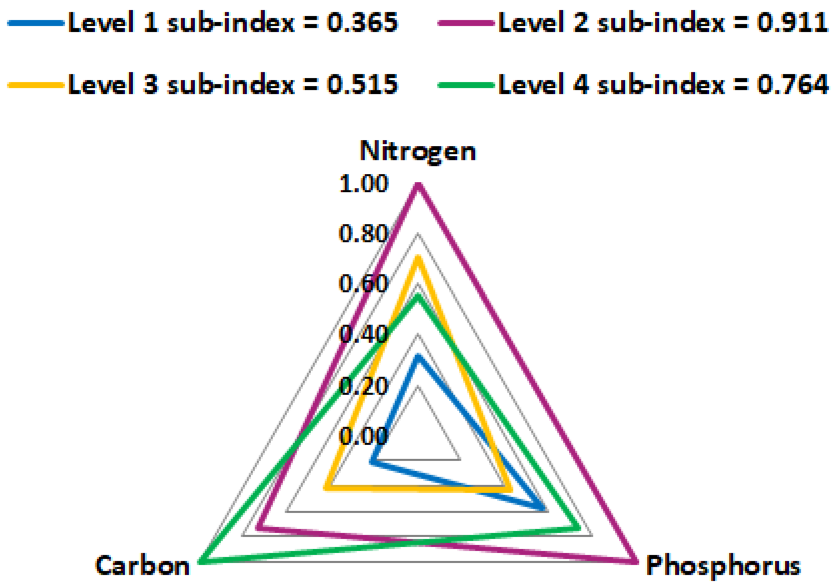


Figure 5. Indicators of environmental sustainability obtained for each category: (a) Use of natural resources, (b) Efficiency in the use of resources, (c) Water pollutants and (d) Sediment pollutants with their respective sub-index for each intensification level. Sub-index corresponds to the average of the values of the indicators obtained for each system.

Table 12 shows the Environmental Sustainability Index (ESI) for the four levels of intensification studied. The index is the mean of sub-indexes of environmental indicators obtained. We can observe the positive and negative aspects of shrimp production intensification (Figure 6). The release of pollutants into water and sediment was the weak point of Level 1. However, the category GHG emissions showed the best value among the levels. Level 2 showed less efficient in the amount of resources used in relation to production, efficiency in energy and nutrient use and the release of pollutants in water when compared to other levels.

Table 12. Environmental Sustainability Index (ESI) for each intensification level. The final score is the average of all sub-indexes.

Sub-index	Level 1	Level 2	Level 3	Level 4
Use of resources	0.704	0.679	0.731	0.926
Efficiency	0.951	0.870	0.881	0.944
Water pollutants	0.449	0.327	0.553	1.000
Sediment pollutants	0.365	0.911	0.515	0.764
GHG emissions	1.000	0.934	0.908	0.966
Biodiversity	0.250	0.250	0.250	0.250
ESI	0.620	0.662	0.640	0.808

All categories of environmental sustainability indicators are represented in figure 6. The Environmental Sustainability Index for the marine shrimp production systems presented the final score to be classified as more sustainable for the Level 4 followed by Level 2, Level 3 and Level 1.

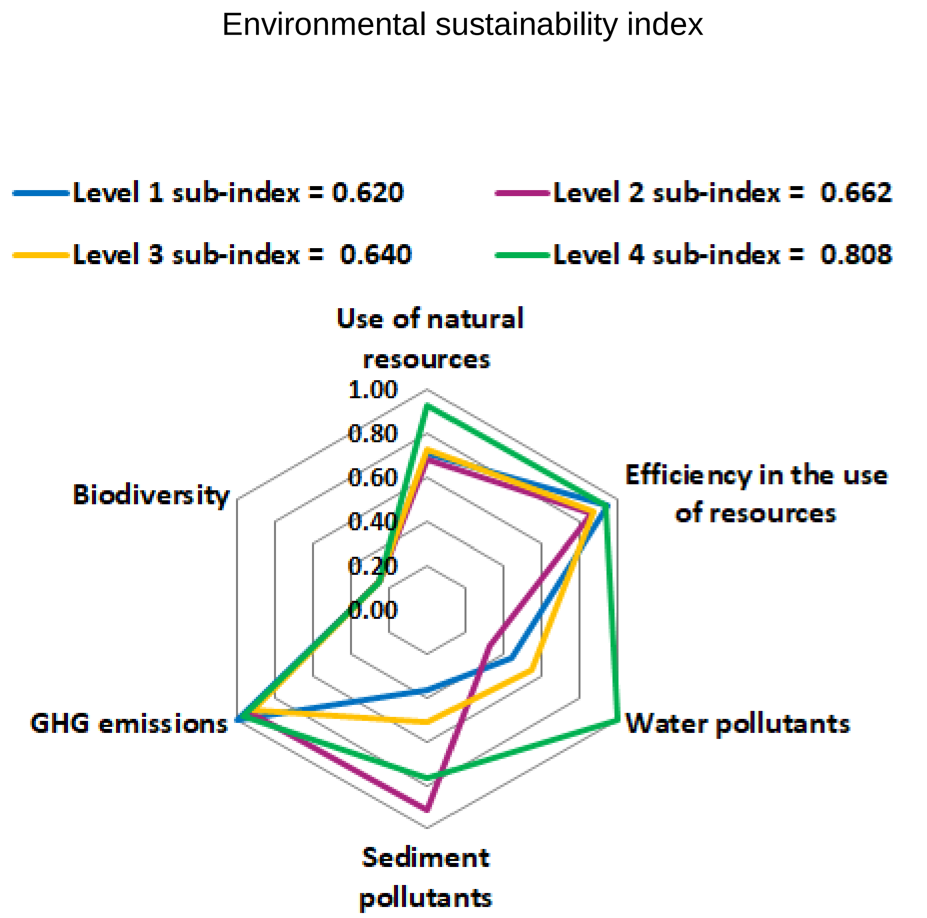


Figure 6. Environmental Sustainability Index. Sub-index corresponds to the average of the values of the indicators obtained for each system.

Social indicators

The items used to calculate social indicators and the cost of goods per production cycle for each system are described in Table 13 and 14.

Table 13. Items used as a basis for the calculation of social sustainability indicators in the intensification of production systems at different intensification levels: Level 1 (L1), Level 2 (L2), Level 3 (L3) and Level 4 (L4).

	L1	L2	L3	L4
Occupied area (ha)	400	135	63	11,4
Profit (US$ million)	2,658	1,177	0,406	0,360
Total production (unit/million)	180,180	81,527	39,046	27,180

Table 13. (Continued)

	L1	L2	L3	L4
Total production cost (US$ million)	3,188	1,520	0,977	0,509
Total investment (US$ million)	3,262	1,100	0,644	0,236
Employment (annual US$ million)	0,335	0,157	0,103	0,19
Eventual labor (annual US$)	768	1,440	800	373
Manager (annual US$)	27,200	14,933	12,800	12,800
Self-employment (annual US$)	128,000	96,000	96,000	96,000
Employment (unit)	110	50	30	6
Eventual labor (unit)	6	9	5	2
Manager (unit)	1	1	1	1
Self-employment (unit)	2	2	2	2
Employment* (hour/year)	352	469	528	352
Eventual labor (hour/year)	16	13	4	8
Manager (hour/year)	352	469	528	352
Employment (men-hour/year)	38,720	23,466	17,952	2,170
Eventual labor (men-hour/year)	96	117	40	18
Manager (men-hour/year)	352	469	528	352

Table 13. (Continued)

	L1	L2	L3	L4
Costs paid in the local market (US$)	341	209	148	112
Total cost of goods (US$)	10,407.00	9,605.00	8,680.00	11,270.00

*Annual hours = 176 hour/month x "n" months (cycle). Others details in Table 1. Commercial dollar value: 1 USD = 3.75 BRL.

Table 14. Cost of goods paid in the local market and in the interstate market (US$) per production cycle.

	L1	L2	L3	L4
Transport	240	35.46	32	183
Post-larvae	3,813	2,746	2,823	4,180
Feed	6,128	6,310	5,530	6,355
Lime	69	32.8	14	10
Chemical fertilizer	156	168	-	-
Molasses	-	310	280	149
Probiotics	-	-	-	391
Fuel*	106	19	16.9	48.5
employer meal*	234	190	132	63
Local market*	341	209	148	112
Interstate market	10,407.00	9,605.00	8,680.00	11,270.00
TOTAL	10,748.00	9,815.00	8,829.00	11,382.00

*All farms buy only fuel and employer meals in the local market.

The social indicators of the marine shrimp productions systems are presented in Table 15. Level 3 showed the best indicators of social sustainability in relation to the other production systems (Table 15; Figure 7 and 8). Level 1 showed the highest values in the indicators: Permanence in the activity, Development of local economy, Local consumption of production and Schooling. For the rest of the indicators it was equal to or less than the other levels. Level 2 presented intermediate values. The most intensified level (Level 4) was higher in the category Principle of equity and income distribution. Indicators of social sustainability obtained for each category and Social Sustainability Index are presented in Figures 7 and 8.

Table 15. Social sustainability indicators for the intensification levels: L1 (10-15 shrimp m^{-2}), L2 (20 shrimp m^{-2}), L3 (35 shrimp m^{-2}) and L4 (51-100 shrimp m^{-2}).

Indicators	**L1**	**L2**	**L3**	**L4**
A. Principle of equity and Income distribution				
Pay equality (%)	-1.2	-1.53	-1.35	-1.06
Proportional cost work (%)	14.80	19.22	22.13	29.58
Income distribution (US$)	0.03	0.08	0.13	0.12
Remuneration per production (US$/kg)	2.07	4.00	5.32	5.64
B. Equality of opportunities				
Racial inclusion (%)	76.94	79.58	78.89	70.42
Gender inclusion (%)	58.57	57.00	60.69	61.76
Age inclusion (%)	42.67	46.76	50.08	48.52

Table 15. (Continued)

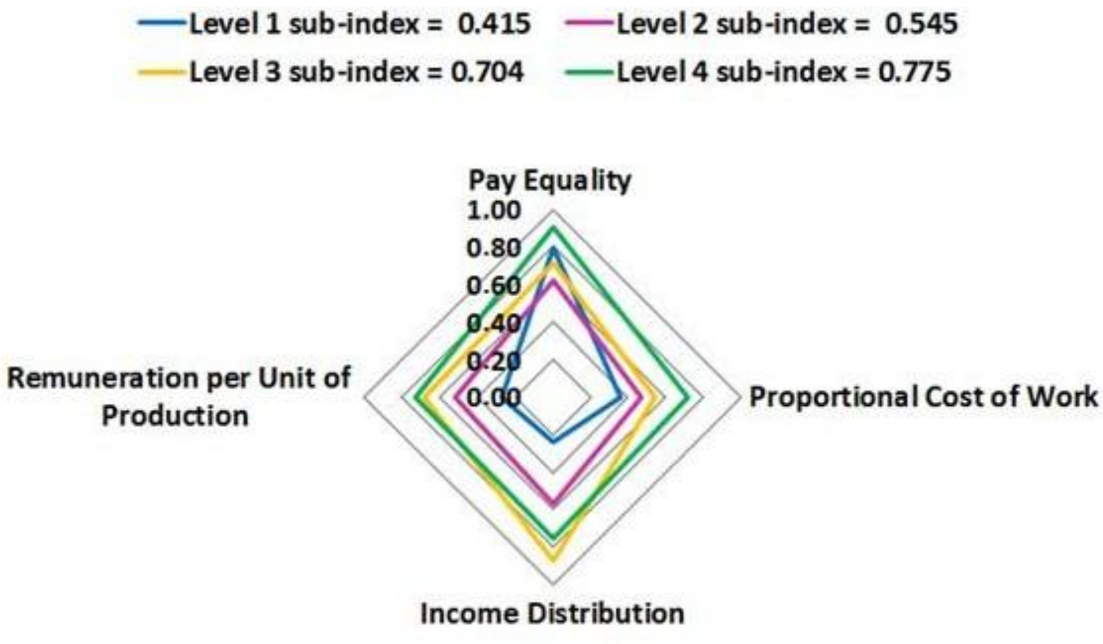
Indicators	**L1**	**L2**	**L3**	**L4**
		C. Jobs generation		
Required work per unit production (US$/1000)	0.05	0.10	0.12	0.04
Required work per unit area (man-hour/ha)	100	211.48	266.20	273.90
Self-employment proportion (%)	1.77	4.06	10.68	18.56
Investment to create direct employment ($x10^{-5}$)	9	12	12	8
Investment to create total employment ($x10^{-5}$)	9	13	13	10
Permanence in the activity (years)	30	22	18	20
		D. Benefits for local communities		
Use of local workers (%)	97.3	100	100	100
Development of local economy (%)	3.28	2.21	1.68	1.22
Local consumption of production (%)	10	10	10	0
Access to health-insurance (programs (%)	0.03	0.06	0.14	0.33

Table 15. (Continued)

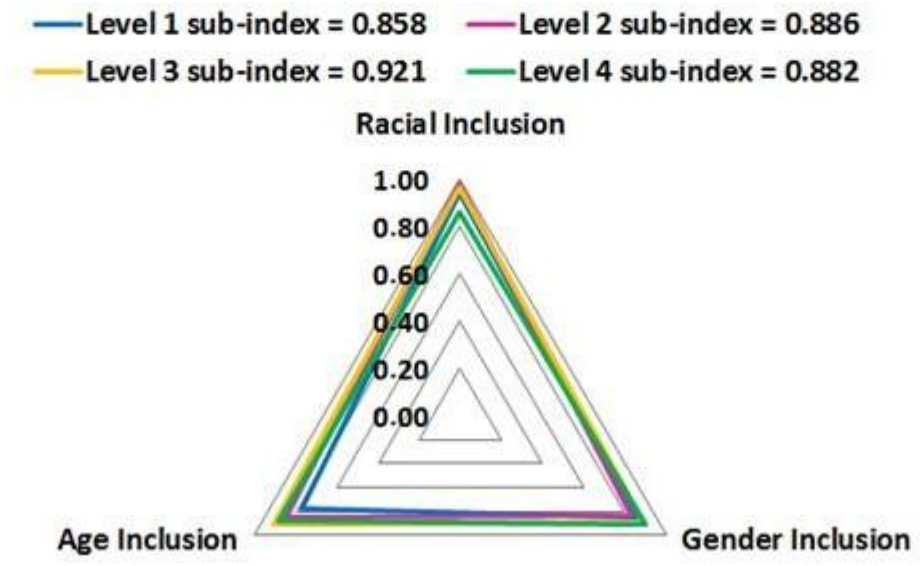
Indicators	L1	L2	L3	L4
Schooling (%)	11	3.33	0	0
Community participation (%)	0	0	0	0
Safety at work place (%)	100	100	100	100

Social sustainability index

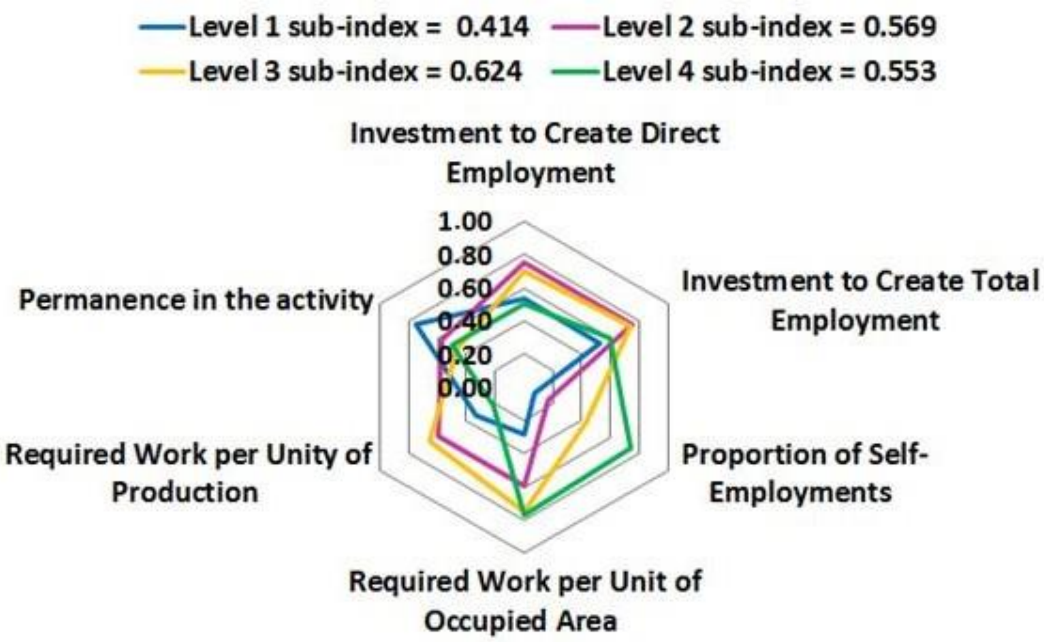
a) Principle of equity and income distribution



b) Equality of opportunities



c) Jobs generation



d) Benefits for local communities

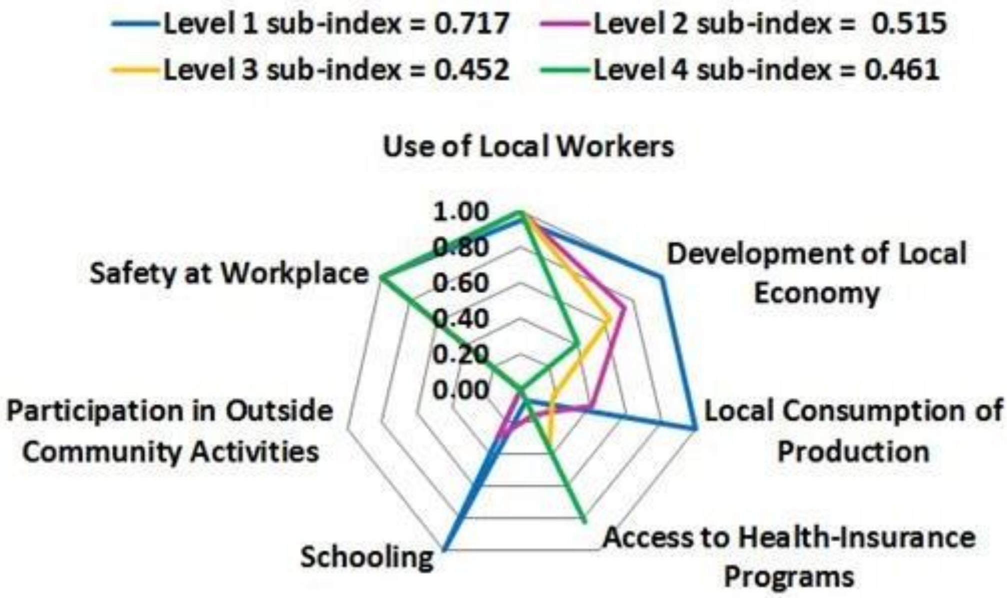


Figure 7. Indicators of social sustainability obtained for each category: (a) Principle of equity and income distribution; (b) Equality of opportunities (c) Jobs generation and d) Benefits for local communities with their respective sub-index for each intensification level.

Table 16 shows the Social Sustainability Index (SSI) for the four levels of intensification studied. We can observe the positive and negative aspects of shrimp production intensification (Figure.8). The Equity- Income distribution and Jobs generation were the weak point of Level 1. However, the category Benefits for local communities showed the best value for Level 1. Level 2 was not expressive in any category. Although Levels 3 and 4 presented the lowest values for the category Benefits for local communities, although they presented the highest values of SSI. The Social Sustainability Index for the marine shrimp production systems presented the final score to be classified as more sustainable for the Level 3 followed by Level 4, Level 2 and Level 1.

Table 16. Social Sustainability Index (SSI) for each intensification level. The final score is the average of all sub-indexes.

Sub-index	Level 1	Level 2	Level 3	Level 4
Equity- Income distribution	0.415	0.545	0.704	0.775

Equality opportunities	0.858	0.886	0.921	0.882
Jobs generation	0.414	0.569	0.624	0.553
Benefits communities	0.717	0.515	0.452	0.461
ESI	0.601	0.629	0.675	0.668

Social sustainability index

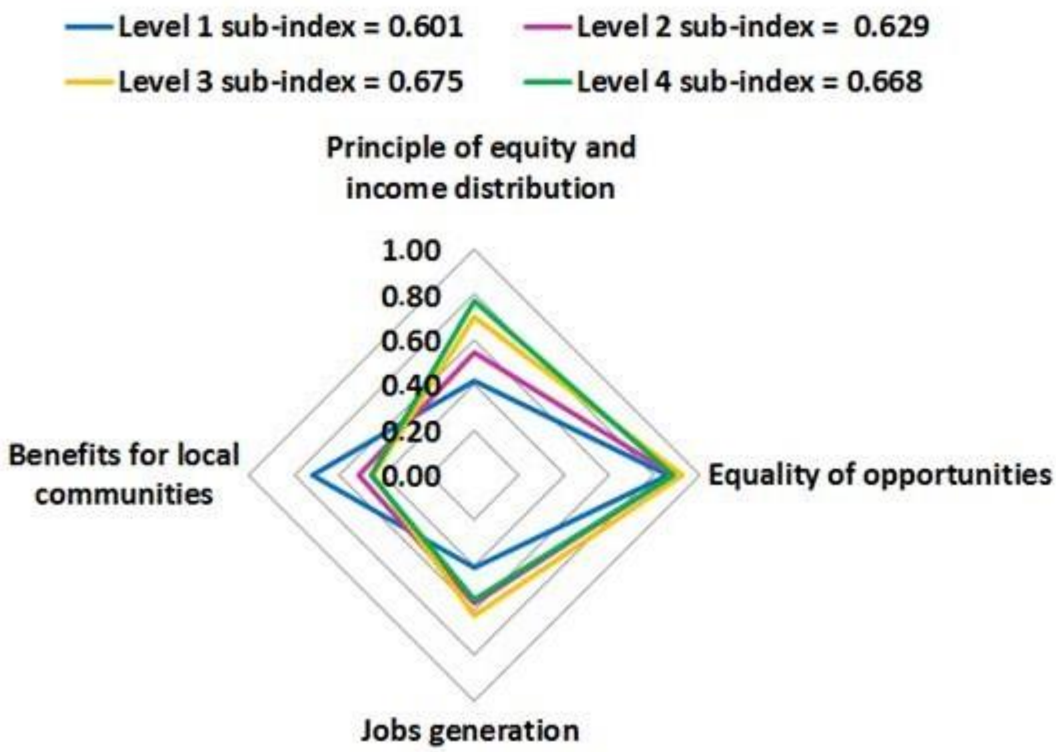


Figure 8. Social Sustainability Index. Sub-index corresponds to the average of the values of the indicators obtained for each system.

Economic indicators

Expenses were estimated by initial investments in works and equipment purchases and project cost (Tables 17 and 18). The total production cost was defined as the sum of variable costs and fixed costs (including depreciation and opportunity costs) (Figure. 9). Net revenue was obtained by subtracting the total operating cost from gross revenue and it was determined taking into account the shrimp sales price (Table 18).

Table 17. Investments according to intensification of marine shrimp culture (Levels 1 and 2).

Investment	**Unit cost (US$)**	**Total (US$)**			
		L1	**L2**	**L3**	**L4**
1-Equipaments					
Scale (1-10 kg)	6.6	13.2	6.6	6.6	6.6
Scale (100-150 kg)	80	160	80	80	80
Wheelbarrow	18.6	148	112	74.4	55.8
Trawl net (50 m)	106.6	530	320	212	212
Cast net	13	65	40	26	26
Boxes	5	1,000	530	500	250
Boxes (500 L)	45	450	220	135	135
Buckets	5	300	160	100	150
Secchi disk	3.2	16	6.4	6.4	3.2
Multi-parameter equipment	533	1,599	1,060	533	533
Tools	16	16	16	16	16

Table 17. (Continued)

Investment	**Unit cost (US$)**	**Total (US$)**

Aerators	660	0	0	6,600	1,920
Monk screens (1mm)	2.13	64	61	63	6.39
Trays	1.3	4,225	3,900	975	156
2-Instalations/vehicles					
Shed (m^2)	40	12,000	8,000	10,000	6,000
Ponds (ha)	8,000	3,600,000	1,600,000	240,000	96,000
Ponds house	40	600	600	0	0
Pumps	21,300	90,000	42,600	21,300	21,300
Pump house (m)	53	795	700	800	795
Generator	13,000	13,000	13,000	13,000	13,000
Electrical installation (m)	5	1,500	1,000	1,600	1,500
Office	250	7,600	10,000	3,800	5,000
Kitchen	250	6,300	5,000	3,800	3,000
Residence	250	0	0	38,000	37,500
Kayak	130	1,950	1,300	780	520
Motorcycles	1,300	6,500	6,500	3,900	1,300
Small truck	1,300	1,300	1,300	1,300	0
Cars	16,000	37,300	21,300	16,000	16,000

Table 17. (Continued)

Investment	**Unit cost (US$)**	**Total (US$)**

3- Project cost	114,656	35,255	17,743. 00	4,528.00
Total	3,946,618	1,252,800	666,958 .00	194,592.00

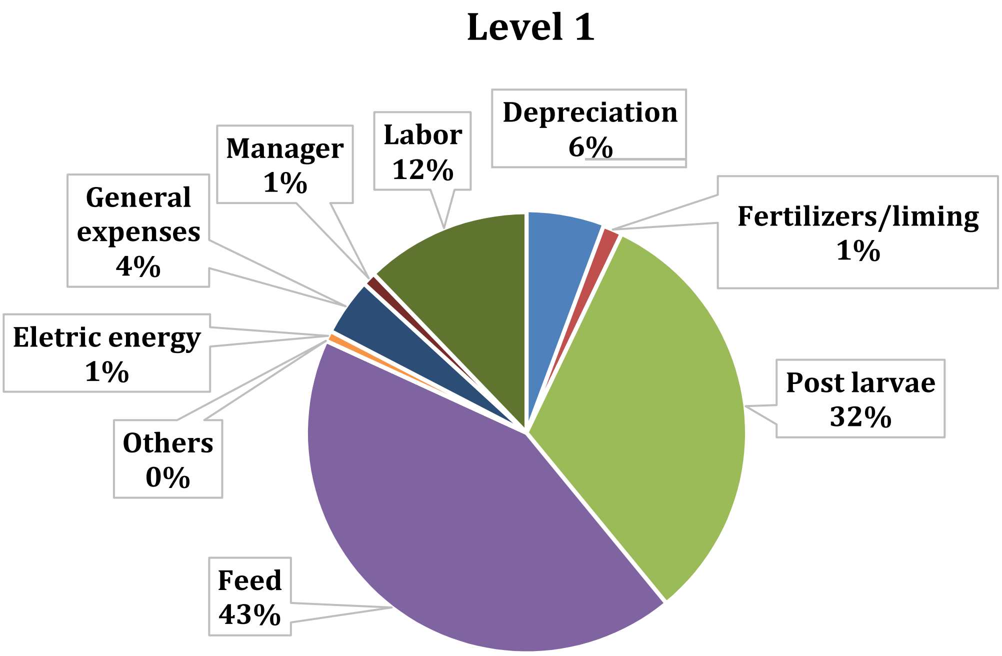
Table 18. Variables cost, fixed and total production cost according to the intensification levels.

	Value per year (US$)			
	L1	**L2**	**L3**	**L4**
Variable cost	2,298,978.00	1,038,653.10	618,136.96	290,810.63
Fixed cost	888,992.28	467,212.85	333,086.84	220,115.52
Total production costs	3,187,970.93	1,505,865.95	951,223.80	510,926.15
Sale price (US$ kg)	4.8	3.7	4.8	4.8

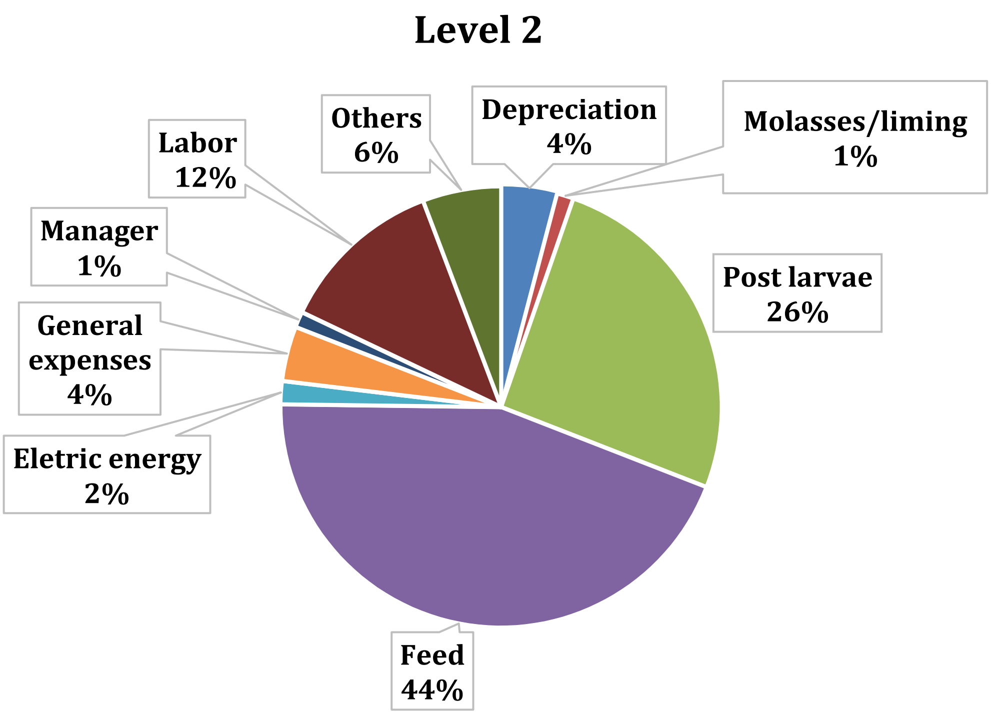
*Costs are specified in the Table 14 and 17.

The Total Operational Cost (TOC) for all levels is shown in Figure 9 (a, b, c, d). We observed that the most representative items were feed, post larvae and labor, in that order. Only for the most intensified level (Level 4), the third item with the highest cost was "Others", which includes taxes, meal and maintenance.

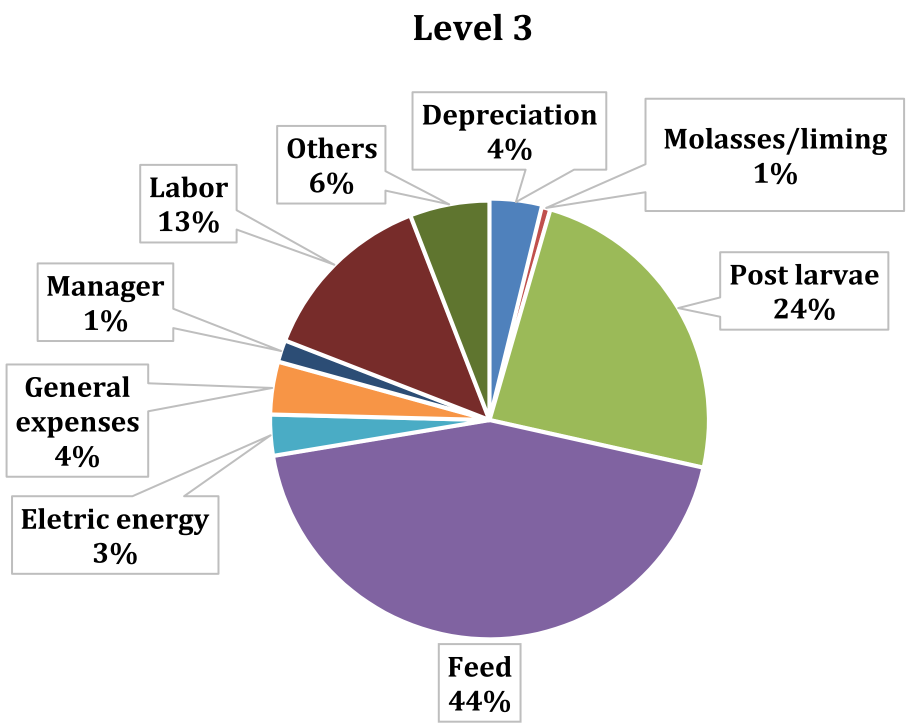
a)


Level 1
Depreciation 6%
Fertilizers/liming 1%
Post larvae 32%
Feed 43%
Others 0%
Eletric energy 1%
General expenses 4%
Manager 1%
Labor 12%

b)


Level 2
Depreciation 4%
Molasses/liming 1%
Post larvae 26%
Feed 44%
Eletric energy 2%
General expenses 4%
Manager 1%
Labor 12%
Others 6%

c)



d)

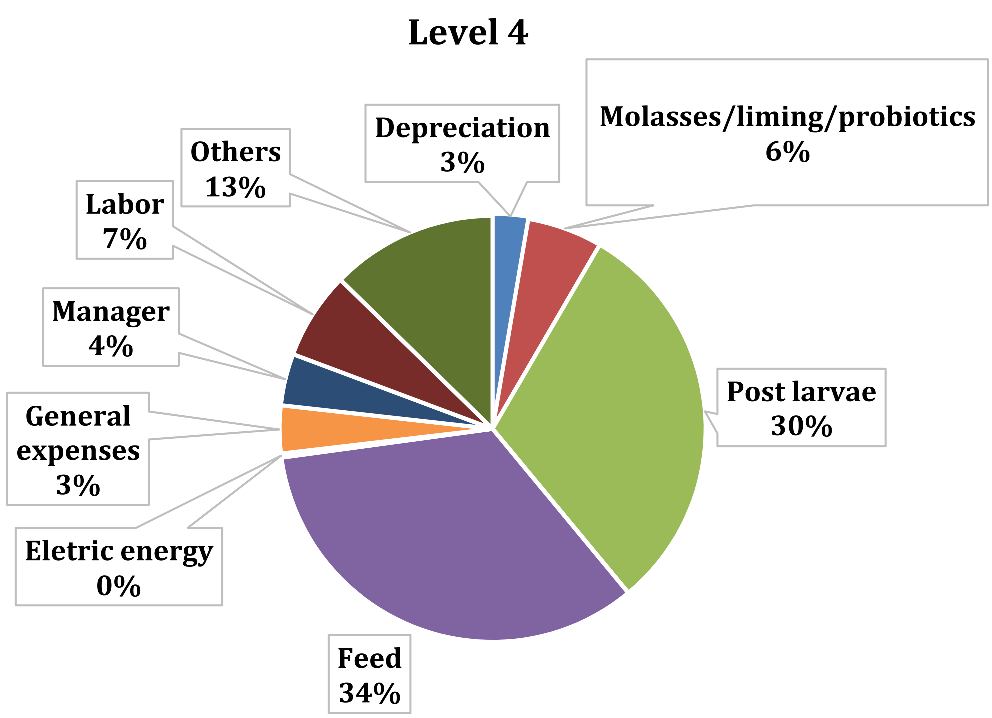


Figure 9. Participation of the items in the Total Operational Cost (TOC) for the different levels of intensification of marine shrimp farm (Levels 1, 2, 3 and 4).

The indicators of economic sustainability are presents divided in two categories (Table 19). We can observe that the values of the indicators Net Income, Internal Rate of Return, Payback Period and Benefit Cost Ratio are higher at the most intensified level. The Level 1 showed the lower values of Net Present Value, Profit and Annual Income. These indicators were directly proportional to the intensification. This level had the best score for the Break-Even Point indicator. The values for IRR were at least three times higher than the established attractiveness rate (13%) in all levels. At the most intensified level, the investment can be recovered in up to 1.5 years and for every US$ 1,00 invested, the producer can receive at least US$ 5,00 with the sale of the animals. The farmers of the Level 3 have been working in the business for less time than the farmers from the others production systems. This Level was lower than the other levels analyzed (Figure 10). Only Level 4 presented lower value for risk rate due to the factor: Practice of intensive system. Levels 1 and 2 present a diversification of products. Level 4 presented the best values for the indicators and the best sub-index for economic sustainability when compared to the other levels (Table 19; Table 20; Figure 10).

Table 19. Economic sustainability indicators for the intensification levels: L1 (10-15 shrimp m^{-2}), L2 (20 shrimp m^{-2}), L3 (35 shrimp m^{-2}) and L4 (51-100 shrimp m^{-2}).

Indicators	**L1**	**L2**	**L3**	**L4**
A. Efficiency in the use of financial resources				
Net-income-Investment ratio (%)	73.4	103.7	98.8	255.0
Internal rate of return (%)	46.1	55.8	48.1	105.2
Payback Period (years)	2.6	2.4	2.7	1.4
Benefit Cost Ratio (US$)	1.33	1.95	1.79	5.11

Table 19. (Continued)

Indicators	L1	L2	L3	L4
Net Present Value (US$) (US$/ha)	47,269.62	75,085.67	86,680.39	369,942.23
Profit (US$) (US$/ha)	5,665.47	8,156.66	8,245.62	31,310.87
Annual income (US$) (US$/ha)	6,362.51	9,876.67	11,718.98	45,234.46
Break even (%)	25.64	33	43	39
B. Resilience capacity				
Business longevity (years)	30	22.67	18.5	20
Risk Rate	1	1	1	0.91
Market Diversity	6	4.33	4	3
Product diversity	3	1.33	1	1

Economic sustainability index

Table 20. Economic Sustainability Index (ESI) for each intensification level. The final score is the average of all sub-indexes.

Sub-index	Level 1	Level 2	Level 3	Level 4
Efficiency in the use of financial resources	0.282	0.328	0.288	0.693
Resilience capacity	0.938	0.638	0.616	0.561
ESI	0.610	0.506	0.452	0.627

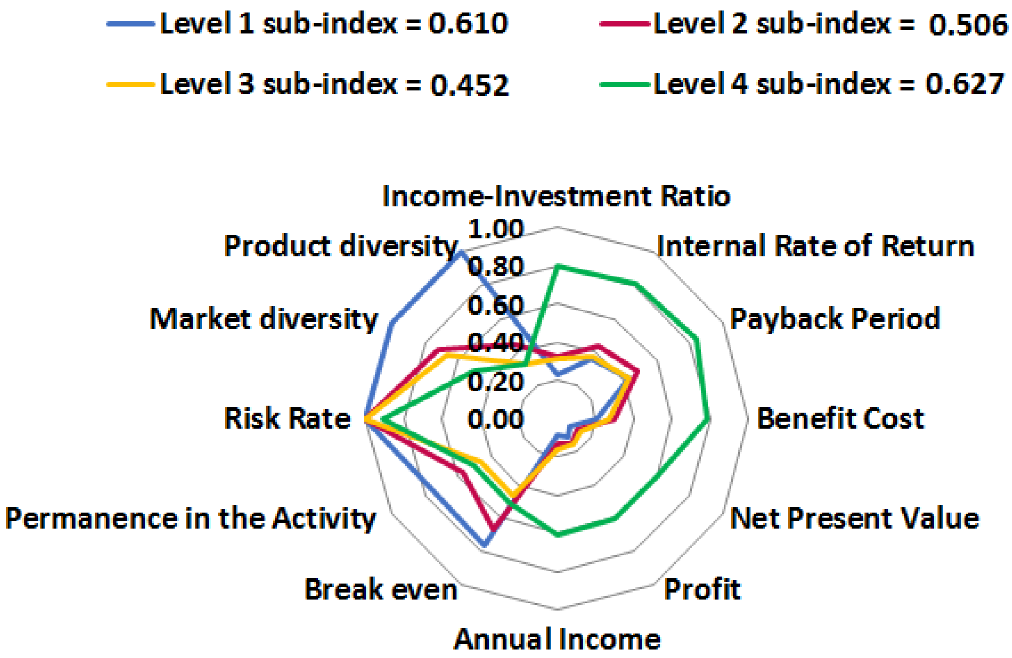


Figure 10. Economic Sustainability Index. Sub-index corresponds to the average of the values of the indicators obtained for each system.

Principal Components Analysis

The Principal Components Analysis (PCA) showed that the first two components account for 92.0% of the total variance in the dataset (Figure 11; Table 21 and 22).

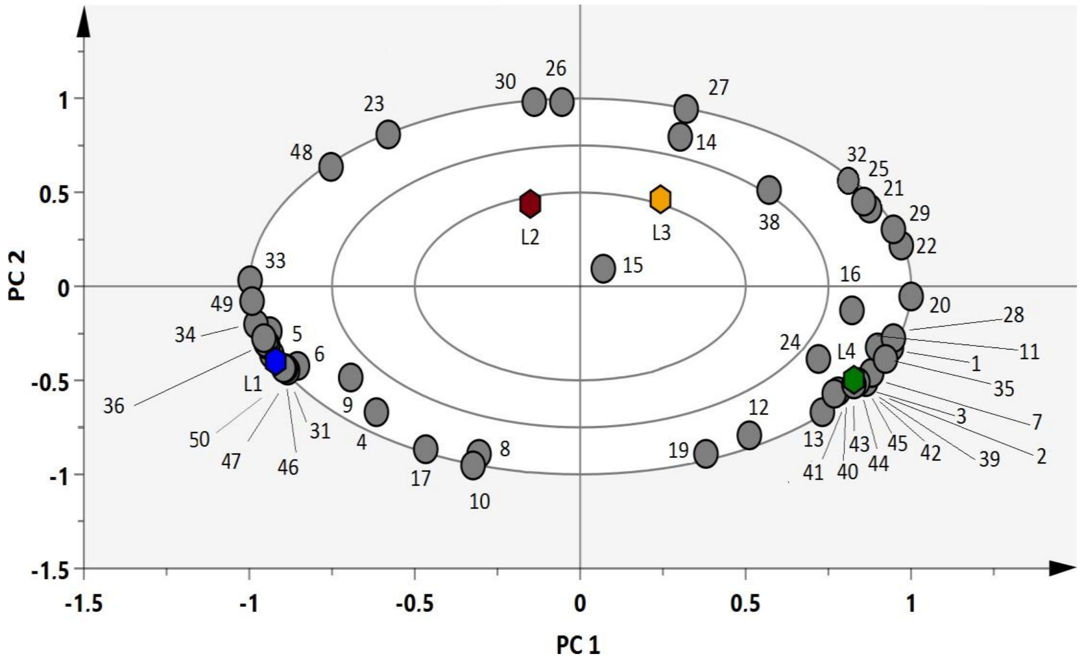


Figure 11. Biplot graph showing variability for intensification level and sustainability indicators. Farms were grouped by levels, with colors representing the intensification level (L1, L2, L3, L4). The indicators are represented by the color gray.

Intensification level (Farms colored according to level)	
Level 1 (10-15 shrimp m^{-2})	**Level 3 (35 shrimp m^{-2})**
Level 2 (20 shrimp m^{-2})	**Level 4 (51-100 shrimp m^{-2})**

The first component (61.0%) explains the greatest amount of the variance, and is characterized by highly positive loadings in Space (1), Water (2), Energy (3), E. Energy (7), Eutrophication (11), Siltation (13), S. Carbon (16), Proportional cost work (20), Income distribution (21), Remuneration per production (22), Gender inclusion (24), Age inclusion (25), Proportion of self-employment (28), Required work per area (29), Use of local workers (32), Access to health-insurance (35), Net income (39), Internal rate of return (40), Payback period (41), Benefit cost ratio (42), Net present value (43), Profit (44) and Annual income (45). The second component (31.0%) is characterized by highly positively loadings in S. Nitrogen (14), Racial inclusion (23), Investment Direct Employment (26), Investment Total Employment (27) and Required work per production (30). Most of the indicators are negatively correlated with Factor 2, mainly the environmental and economic indicators.

Table 21. Eigenvectors obtained for each factor for environmental indicators of shrimp farming according to the levels of intensification.

	Factor 1	**Factor 2**
ENVIRONMENTAL		
Use of natural resources		
1. Space	**0.98**	-0.20
2. Water	**0.92**	-0.39
3. Energy	**0.93**	-0.33
4. Nitrogen	-0.52	-0.76
5. Phosphorus	**-0.90**	-0.34
6. Carbon	**-0.79**	-0.55
Efficiency in the use of resources		
7. E. Energy	**0.93**	-0.34
8. E. Nitrogen	-0.18	**-0.94**
9. E. Phosphorus	**-0.62**	-0.55
10. E. Carbon	-0.19	**-0.98**
Pollutants released to the environment		
11. Eutrophication (N, P)	**0.94**	-0.19
12. Organic pollution	0.61	**-0.71**
13. Siltation	**0.81**	-0.58
14. Sediment Nitrogen	0.20	**0.81**
15. Sediment phosphorus	0.06	0.06
16. Sediment Carbon	**0.83**	-0.04
17. Global warming potential	-0.34	**-0.93**
Conservation of genetics and biodiversity		
18. Biodiversity*	-	-

Table 21. (Continued)

	Factor 1	**Factor 2**
SOCIAL		
Principle of equity and Income distribution		
19. Pay equality	0.49	**-0.82**
20. Proportional cost work	**1.00**	0.08
21. Income distribution	**0.81**	0.54
22. Remuneration per production	**0.93**	0.35
Equality of opportunities		
23. Racial inclusion	-0.69	**0.73**
24. Gender inclusion	**0.76**	-0.26
25. Age inclusion	**0.78**	0.58
Jobs generation		
26. Investment Direct Employment	-0.19	**0.96**
27. Investment Total Employment	0.19	**0.97**
28. Proportion of self-employment	**0.97**	-0.14
29. Required work per area	**0.90**	0.43
30. Required work per production	-0.27	**0.96**
31. Permanence in the activity	**-0.82**	-0.57
Benefits for local communities		
32. Use of local workers	**0.76**	0.61
33. Development of local economy	**-0.99**	-0.10
34. Local consumption of production	**-0.94**	-0.33
35. Access to health-insurance	**0.96**	-0.26
36. Schooling	**-0.87**	-0.49
37. Community activities*	-	-
38. Safety at workplace*	-	-

Table 21. (Continued)

	Factor 1	Factor 2
ECONOMIC		
Efficiency in the use of financial resources		
39. Net Income-investment ratio	**0.90**	-0.40
40. Internal rate of return	**0.85**	-0.46
41. Payback period	**0.84**	-0.48
42. Benefit Cost Ratio	**0.89**	-0.42
43. Net present value	**0.89**	-0.45
44. Profit	**0.88**	-0.45
45. Annual income	**0.89**	-0.44
46. Break even	**-0.84**	-0.37
Resilience capacity		
47. Business longevity	**-0.82**	-0.56
48. Risk rate	**-0.83**	0.54
49. Market diversity	**-0.97**	-0.21
50. Product diversity	**-0.83**	-0.55

*****Null value

The Level 1 presented a negative correlation with both factors. Level 2 was positively correlated to Factor 2. The Level 3 presented a positive correlation with both factors and Level 4 showed a positive correlation with Factor 1 (Table 22).

Table 22. Eigenvalues obtained for factors 1 and 2 for each level of intensification.

Intensification level	Factor 1	Factor 2
Level 1	-0.83	-0.47
Level 2	-0.22	0.39
Level 3	0.15	0.50
Level 4	0.91	-0.42

Sustainability of marine shrimp production systems

Table 23. General Sustainability Index (GSI) for each intensification level. The final score is the average of all sub-indexes.

Sub-index	Level 1	Level 2	Level 3	Level 4
Environmental	0.620	0.662	0.640	0.808
Social	0.601	0.629	0.675	0.668
Economic	0.610	0.506	0.452	0.627
GSI	0.610	0.599	0.589	0.701

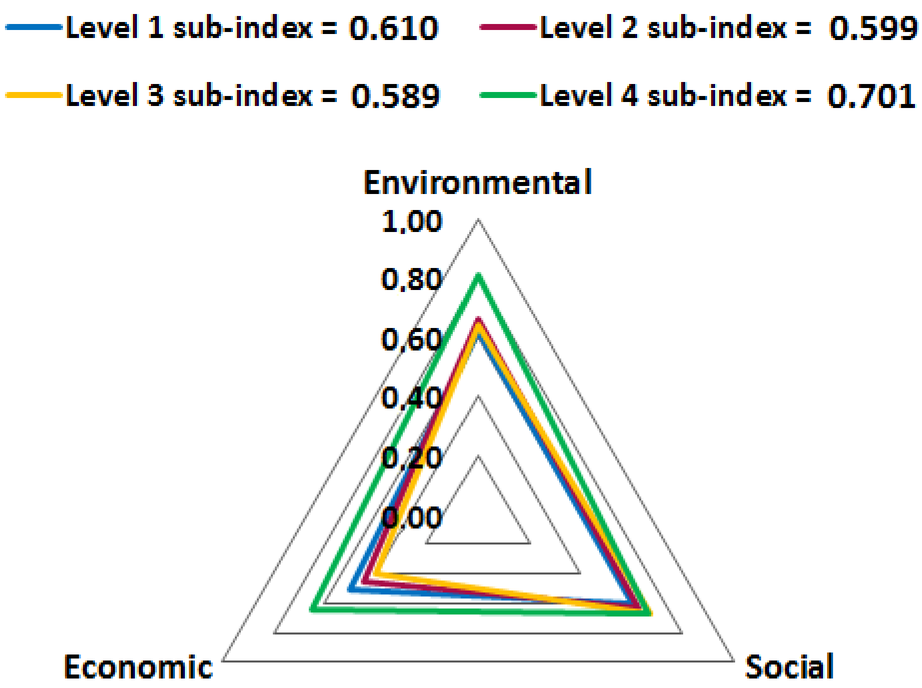


Figure 12. General Sustainability Index. The index corresponds to a mean between the indexes of environmental, social and economic sustainability of each level.

DISCUSSION

The present study resulted of samples and observations obtained on-farm to describe the environmental, social and economic conditions of marine shrimp production in Brazil. Therefore, this study showed the real conditions of the marine shrimp farms in activity. The discussion was organized into three topics. In the first one, we discussed about the environmental sustainability of farms according to intensification levels with focus on ponds. In the other two, we discussed about the social and economic sustainability of farms, because data were obtained for the farm and not specific for each pond.

Environmental sustainability

Level 1 had the lowest value in the Environmental Sustainability Index (ESI). We can observe a trend of decreasing the indicators use of Space (1) and Water (2) according to intensification of production systems. In addition, the productivity in this level was lower than the most intensified levels. This affects the value of the indicators because they are calculated considering the final biomass production. The higher quantity of pollutants released in the water and sediment per biomass produced were the weakness of this level in the environmental dimension. The Level 1 had less water and soil management in the ponds, which left a larger amount of suspended solids in the water at the end of the cycle, thereby, increasing the siltation potential. The sediment is the compartment that differ Level 1 from the other levels. The greatest amount of nutrients in the sediment of Level 1 is due the accumulation of sediment at the pond bottom caused by the non-removal of organic matter at the end of the rearing cycle, or because no probiotics is used, which promotes organic matter recycling (Ramu *et al*., 2017).

The strength of Level 1 is probably the efficiency in the use of natural resources, especially in the use of nutrients as nitrogen, phosphorus and carbon**.** Phosphorus was significantly lower than the most intensified level. In this case, the lowest stocking density and feed intake, and fish and oysters farming in the supply and drainage channel were responsible for the use of nutrients. The oyster seeds are introduced naturally into the channels by pumping. The use of mollusks in the drainage channel is indicated as a biofilter (Nunes, 2002; Viji *et al.,* 2014). This is an efficient mitigation action to remove nutrients from the environment and minimizes harmful microalgal blooms (Chopin *et al.*, 2008 Kim *et al*., 2013).

Level 1 had the best GHG emissions sub-index score. Methane emissions occurred during the culture. It is expected in aquaculture systems, in which organic matter from non-consumed feed and faeces accumulate in the bottom of ponds enhancing carbon stocks inside ponds, which will be deteriorated and released in part as methane. We can observe a trend of decreasing N_2O ebulitive emission during the culture. Level 1 absorbed CO_2 and N_2O. It may be due to high primary production in ponds, which increases in time. Lastly, L1 showed the most absorption of CO_2 equivalent. Despite the accumulation of sediment, other factors as lower stocking density, lower feed intake, fish in the supply channel and oysters in the drainage channel may have contributed to the CO_2e sequestration.

Despite farms with densities of 20 to 35 shrimp m^2 being categorized at different levels, which are 2 and 3, respectively, they presented high similarities. The majority of marine shrimp farms in Brazil are conducted according to the characteristics of these 2 levels. Levels 2 and 3 presented similar values of indicators and performances of environmental sustainability. Level 2 had the worst water pollutants sub-index score. The indicators Eutrophication (11), Organic pollution (12) and Siltation (13) presented the worst values among all levels.

In an individual investigation, the pond L2c presented the lowest value for Eutrophication (11) among all studied ponds. This pond was fertilized with silicate to favor diatom occurrence. The other two ponds in this level were fertilized with molasses to stimulate primary production. However, alike the common protocol in marine shrimp farms, water from ponds were renewed after fertilization and no mechanical aeration was used. It seems that despite organic fertilization and water renewal, primary production was enhanced and consumed nutrients added to ponds, resulting in low eutrophication potential of effluents in relation to the other levels and the produced biomass.

The category Pollutants released in the sediment was the strength of the Level 2. Unlike Level 1, farmers removed organic matter after harvest, which could have contributed to lower pollutants release via sediment. In the category Use of natural resources, the indicators Space (1) and Water (2) were low in Level 2 and Level 3. Methane emissions occurred during the culture of shrimps in these levels. This trend is common because CH_4 has low solubility (Tokida *et al*., 2013) and feed input and faeces accumulate during the rearing cycle. Concerning total ebulitive emission, Level 2 emitted a significantly larger amount of N_2O than the other levels. It could be a result of a higher denitrification in ponds due to unbalanced budget of nitrogen, added to ponds via feed and fertilization, and not metabolized by organisms inside the ponds.

However, ponds from this level presented lower values of nutrients in water than in sediments, which may have hampered the absorption of them inside the system and released part of these nutrients, especially in the form of N_2O. The efflux of nutrients from the sediments to the water column could have occurred, and it might be high due to the rapid cycling of nutrients (Holmer, 1992). Although the ebulitive emission contributes less than 1% of the gases released to the atmosphere**,** attention must be driven to the N_2O ebulitive emission values, as N_2O is 310 times more aggressive to global warming than CO2 (IPCC, 2007).

The categories Pollutants released in the water and sediment were the weakness of Level 3. There was a high accumulation of waste in the sediment, mainly. It affects the entire production system (Avnimelech and Ritvo, 2003). We observed that two ponds (L3a, L3b) that integrate this level were responsible for the lowest values in these categories. The farms use mechanical aeration only at night, renew water, add molasses and remove organic matter. Although this management favors the system, these practices may have been inappropriately applied. For example, daily water renewal may inhibit the development of a microbiota that was intended by molasses fertilization. Thus, there is accumulation of organic matter that is not recycled by the system (Han and Boyd, 2018).

Traditional shrimp culture is characterized by a wide variation of nutrients and low production control (Hargreaves, 2006). It is important to mention that a pond of this group (L3c) that showed the best result in this category also used the management above, except for water renovation. In this case, a relevant information is the pond age. During the study period, the pond L3c had one year aged and the other ponds (L3a, L3b) had above 15 years old. The old ponds remained in continuous production. This may explain the greater amount of nutrients and organic matter in the sediment in ponds that do not practice water renewal. Siddique *et al.* (2013) found that ponds over 10 years old accumulate significantly higher amount of organic matter in the sediment.

Generally, semi-intensive systems have superior nutrient efficiency use than more intensified systems (Boyd *et al.,* 2007). Level 3 had the lowest GHG emissions sub-index score, probably due to the high amount of organic matter input throughout the rearing cycle. Methane emissions occurred during the whole culture, like in the other levels. The high variation of CO_2 emission in the ponds of this level was a result of differences between ponds L3b and L3c. As discussed previously, these ponds have age difference (15 years in ponds L3a and L3b vs 1 year in the third studied pond), which may result in different metabolism due to diverse composition of microbiota in ponds. Considering the total diffusive emission, Level 3 ponds emitted a significantly larger amount of N_2O than Level 4, which in fact absorbed this gas. Therefore, Level 3 emitted the largest amount of CO_2 equivalent among the studied levels.

In ponds from the most intensified level (Level 4), we can highlight the highest stocking density (51-100 shrimp m^{-2}) with the highest productivity when compared to other levels. In addition to stocking density, the lowest land use, water reuse, possible higher stabilization of the microbiota and high technification are the relevant factors of this level. Level 4 was the more sustainable than others levels.

In the category Use of resources, use of Space (1) and Water (2) showed a declining trend with increased intensification. Generally, intensive shrimp ponds are smaller in area, use less water and presents higher productivity (Hai *et al*., 2015; Boyd, McNevin *et al.,* 2017). Hence, these factors benefited the indicators Use energy (3) and Efficiency energy (7), since the applied energy is offset by production (Boyd *et al.,* 2007). However, this level had a significant higher amount of Phosphorus in water. The higher stocking density requires higher feed input. Feed is responsible for the largest input of P in aquaculture systems (David *et al*., 2017). In this case, the more intensified level used 21 times more phosphorus to produce one ton of shrimp when compared to Level 1.

In the Level 4, the lowest value was found in the category pollutants released in the sediment. Even so, it is not a critical value, but their prior identification can improve the system conditions. Nitrogen (14) and Phosphorus (15) in the sediment had lowest value in this category. N in the sediment indicates a process of nitrification and denitrification. Less amount of N in sediment indicates higher denitrification process (Hargreaves, 1998). This study presumes a slow denitrification process due to higher amount of N, indicating an oxygenated sediment. Phosphorus accumulates in the pond over time. In the sediment the accumulation of this nutrient is around 60% and 10% retained in the animal biomass (David *et al*., 2017). However, Carbon in the sediment presented the best performance, or was accumulated in the lowest quantity in this compartment. Probably, the organic matter was recycled by microbial activity. Xinglong and Boyd (2006) demonstrated the intensity of microbial activity through respiration of soil organic carbon. The high productivity of this level improves its performance in sustainability indicators and category scores.

The category Pollutants released in the water was the strength of this level. The farmers use organic fertilization such as molasses and probiotics, which was a particularity of this level, as well as reused crop water. These factors supported the development of a microbiota able to cycle high amount of nutrients. This is observed in the values of indicators Eutrophication (11) and Organic pollution (12).

The carbohydrate present in molasses stimulates the growth of heterotrophic bacteria that absorbs nitrogen and produces microbial protein (Hu *et al*., 2012). Probiotics benefit the host and improve water quality (Verschuere *et al.,* 2000). In particular, the pond L4c (100 shrimp m^2) was filled with well water and reused the crop water for 3 years. Reuse provides better water quality because allows natural residual assimilation (Boyd *et al.,* 2007). The use of water rich in nutrients is used to increase primary productivity and is an alternative to aquaculture (Kimpara *et al.,* 2011), as well as the use of well water (Costa *et al.,* 2018). Furthermore, higher stocking densities improve the stabilization of the microbial community (Hargreaves, 2013). The ecosystem developed mainly in this pond influenced most of the indicators related to this level.

We can observe a strong positive relation between Siltation (13) and intensification. Higher feed intake, excretion, stocking density and mechanical aeration contributes to the increase in suspended solids (Boyd, 2003; Boyd, McNevin, *et al.,* 2017). In this level, we observed an opposite process. Depending on the composition of these solids, it is possible that most of them have been mineralized by bacteria present in the system. Overnell *et al.,* (1995) confirmed that this occur in the water column during resuspension than in the sediment.

Methane emissions occurred during the culture. Close to harvest, Level 4 emitted a significant amount of CO_2 comparing to the other levels. We observed a trend to increase the emission of this gas during the whole cycle in the diffusive emission. Considering the total diffusive emission, Level 4 absorbed N_2O compared to Level 3 emission, which emitted this gas. Level 4 ponds emitted mainly CO_2 and absorbed N_2O, and emitted a significant amount of CO_2 at the end of the cycle, probably due to feeding, which is one of the main sources of GHG emissions in aquaculture ponds (Robb *et al*., 2017).

In general, all studied levels presented a low score for the indicator Biodiversity. This is because *Litopenaeus vannamei* is an exotic species and even when farmed in a closed system, it is considered risky. White leg shrimp presents high yields, low feed conversion rates and high adaptability to diverse environmental parameters (Moss *et al.,* 2010). These are the reasons why this is the most farmed shrimp species in Brazil. Despite this fact, the escape of these animals can lead to ecological risks such as reducing aquatic biodiversity or spreading pathogens and may undermine the aquaculture sustainability (De Silva *et al*., 2006).

Social sustainability

In the social aspect, although Level 3 showed a better result in only three indicators, it did not present the lowest score in the remainder and opposite to it, we find Level 1. For example, Income distribution (ID) is directly related to the profit and the salary of the employees. In the less intensified farm (Level 1), there is an imbalance between these elements. This level has the highest number of workers and the highest wage payment, but it is still disproportionate to the profit it earns. Its income distribution is up to 4 times lower than Level 3.

Level 3 showed the best value in the category Equality of opportunities, mainly for Age Inclusion (AI). This level seems to reflect the demographic structure of the local population, unlike Level 1. The adult age group prevails on all farms. In Required Work per Production (WP), Level 3 was more proportional in the relation men / hour / year and the production than all levels. Already Level 4, presented a production similar to Level 3, but the factor men / hour / year was inferior to the all farms. It´s important to elucidate that in the indicators Required Work per Production (WP), Required Work per Area (WA) and Remuneration per Production (RP) was considered the annual labor, because the farms remain constantly with culture in progress. On all farms, the ponds remain empty for about 15 to 20 days between harvest and the next crop. The WA and RP indicators are taken up during the discussion.

Level 1 had a positive highlight in the category Benefits for local communities for the indicators Development of local economy (LE), Local consumption of production (LC) and Schooling (Sc), whereas the indicators LE and LC were inversely proportional to the intensification. Total expenditure on goods is similar to that of other farms, but this one consumes most in the local market, mainly fuel (this farm has the longest distance to the nearest town) and food for employees (all farms provide breakfast, lunch, and dinner). In addition, all farms sell on average 10% of their production to the local market, this means that Level 1 contributes more.

For Sc indicator, Latruffe *et al.* (2005) demonstrated that low schooling influences the inefficiency of management practices in agriculture. Chiang *et al.* (2004) related that the higher level of owner experience and greater amount of labor used are related to the technical inefficiency of production. The authors suggest that less experienced owners are more motivated and adapt better to changes. In the case of the less intensified farm (Level 1), this does not seem to be related, because in Sc indicator the workers have the highest education level and the company also offers literacy and technical courses. Besides that, the farm present greater economic sustainability and the owner implemented another system, such as oysters culture. For Rego *et al*. (2018), they detected management inefficiency in both conventional and Biofloc systems. Following the classification in Sc indicator, there is a farm from Level 2 that also offers technical courses. These courses are directed to the larviculture sector, in which greater experience and responsibility are fundamental. The other two levels did not score in Sc indicator. Usually, all owners have a higher level of education in these farms.

Finally, to Permanence in the activity (PA), the owner (Level 1) has more time in the activity, but this is not related to the size of the farm, because we identified a shorter time in Level 3. Indeed, this is related to the nature of the marine shrimp activity. It presents risks as any kind of enterprise, but Goodwin and Mishra (2000) warned that aquaculture is a risky venture and deserves attention. Some of the risks are the market conditions, diseases and natural disasters (Oosterveer, 2006). High vulnerability does not necessarily lead to low resilience (Akter & Mallick, 2013). The resilience of shrimp culture systems is the ability to maintain in response to external changes (Folke, 2006). After the interviews with the farmers, and considering the time in the activity, we understand that everyone has experienced at some point both the difficulties and the benefits of this business. As mentioned in the background, these recent changes and challenges have been occurring since 2003.

In Use of local workers (LW), all farms use 100% local labor, with the exception of Level 1, in which the owner and his family are of Ecuadorian origin but they live in Brazil. All these farms are located in underdeveloped regions which have low Human Development Index (HDI) of the country (IBGE, 2017). But we can highlight the positive social-economic impact in these regions. For example, large farms generate jobs and income, promote business facilities that provide inputs to the farms and contribute considerably to direct municipal budget (Rocha and Mendonça, 2015). In 2002, they generated 50,000 direct jobs, i.e. 3.7 jobs per hectare, but because of the market failure, it generated only 1.86 jobs per hectare in 2009 (ABCC, 2011). In the regions where the farms are located, the activity offered 2,088 jobs in 2016, corresponding to 42.7% of all formal agricultural jobs in these municipalities (ABCC/MAPA, 2017). The marine shrimp monoculture is not the most sustainable system in aquaculture, but it generates a large number of jobs.

The indicators Required Work per Area (WA), Proportional Cost Work (PCW), Remuneration per Production (RP), Proportional of self-employment (SE), and Access to Health Insurance (AHP) are better as the system intensifies. For WA indicator, this is because more intensified systems use smaller areas, and they presented lower total production cost. That is, the amount of manpower / labor used is proportional to the production. Most of these owners invest in other ventures, as will be discussed in the economic indicator Product Diversity. Thus, the farmers do not depend financially only on these farms. The reason for SE indicator to be better in the intensified system is because Level 4 has the lowest number of hired employees and this increases the proportion of self-employment. In the case of AHP, it is best in Level 4 because the number of workers decreases with intensification system. Since only the owner and manager have access to private health insurance.

The indicators Pay Equality (PE), Gender Inclusion (GI), were better at Level 4 and lower at Level 2. In general, employees earn a minimum wage, which when compared to the salary of the manager / owner, becomes disharmonious. One way of improving this situation would be to offer incentives to workers. For example, there are large-scale farms in Rio Grande do Norte State that use a reward plan for employees. Each worker is responsible for a certain amount of ponds and they have productive goals. When these are achieved or exceeded, they can earn up to seven times their wages (Pimentel, 2018). This commission strategy can improve pay equity and encourage employees socially and economically.

In GI indicator, most women work directly with management, but different from Level 2, in which women work in the administrative and larviculture sectors. It is clear that aquaculture is still a predominantly male activity. Racial inclusion (RI), presented an opposite result to the previous one, showing that Level 2 had greater inclusion. In these cities, the majority of the population is brown-skinned (IBGE, 2017). Equality of opportunities is an important aspect, because the weakness in these items (age, gender and racial inclusion) can lead to rural unemployment, marginalization of local residents and food insecurity as discussed by Hossain *et al.* (2013). All owners are males, between 40-60 years and have over 15 years of farming experience. This seems to agree with Mansaray *et al.* (2018) who explains that this age group is productive and economically active. The indicators Investment to Create Direct Employment (ITDE) and Investment to Create Total Employment (ITCE) were also higher on Level 2 and lower in levels 4 and 1, respectively. The generation of direct jobs considers the amount invested in the farms.

All levels had the same score for the indicators Participation in outside community activities (PCA) and Safety at work place (SW). Although there are some associations, they do not provide the necessary assistance to the farmers and community. During the interviews, we verified that the environmental license and the lack of incentive fishery production continue being the obstacle of the sector. The farmers themselves exchange experience and information on the activity. Abreu *et al*. (2011) pointed out the factors that limit the growth of activity in the Rio Grande do Norte State: absence of public policies, high tax and delays in the environmental license process. So, they suggest that environmental, social and economic incentives are key factors for successful production. It is important to inform that at the national level there is the organization Associação Brasileira de Criadores de Camarão (ABCC), created in 1984, which is responsible for political, technological and financial support. (Schwab Weber, Lehmann, 2002). For SW indicator, all farms maintain a well-established pattern of workplace safety. This did not prove to be dependent on the intensity level or the system applied.

Economic sustainability

In the analysis of economic sustainability, we observed that the indicators had the highest score at Level 4, followed by Levels 1, 2 and 3. Level 4 presented the highest score in most economic indicators and it had the highest value in the Economic Sustainability Index (ESI). The indicators Net Present Value (NPV), Profit (P) and Annual Income (AI) were inversely proportional according to the farm size.

The indicators mentioned above and the Net Income-Investment Ratio (RII), Internal rate of return (IRR), Payback Period (PP), and Benefit Cost Ratio (B/C) were the strengths of Level 4. For RII indicator, the relationship between annual income and investment in the Level 4 was more efficient in capital use than Level 1. The difference between these levels can be explained by the amount of initial investment for construction of the ponds, the supply and drainage systems. These are the most representative items of the investment in all the farms studied. Especially in Level 1, it accounted for 95% because it has the largest area and grow-out ponds. For Level 4, the percentage is up to 51%. So, this level uses the infrastructure better and has a low cost (Bjornsson *et al.*,

2012) compared to others levels. It is necessary to clarify that intensified farms can be more costly, but these costs are compensated by high productivity.

As for the IRR indicator, it was better at most intensified level and it showed the best NPV in which it is the main indicator analyzed in the long-term investments (Brealey, Myers, & Allen, 2013). Silva *et al.* (2012) in 2009, evaluated traditional farms in the Rio Grande do Norte State and found results of NPV and IRR of US$ 86,322.86 and 60%, respectively. These farms had a maximum of 2.5 cycles per year and the shrimp price was US$ 3.13/kg. In farms of Level 4, the minimum is 3.5 cycles per year, shrimp price of US$ 4.80/kg and the IRR above 100%. In other example, a high IRR was 103.65%, stocking density of 50 shrimp m^{-2}, on a farm of only 10 hectares and 10 years of cash flow in the Ceará State (Silva and Bezerra, 2004). The authors reported that the activity was attractive, but there were risks such as disease outbreaks and climatic factors such as flooding. The latter happened severely in 2008/2009 in the Rio Grande do Norte State and destroyed 2700 hectares of nurseries shrimp farming (Abreu *et al*., 2011). Rego *et al*. (2017a, b) evaluated both traditional and BFT systems and noted that IRRs were feasible as the investments available in the market, similar to this study. Overall, all systems studied are economically viable because they present IRR higher than the minimum annual hurdle rate of attractiveness stipulated to 13%.

In the Payback Period (PP), the most intensified farms recovered their initial investment faster than traditional ones, mainly as Level 3. Engle (2010), comment that the preferred investments in aquaculture are those of shorter paybacks period. Level 4 presented the Benefit cost ratio almost four times higher than Level 1. Even so, all levels showed B/C higher than one, this indicates that they can pay for both fixed and operational costs. Olagunju *et al.* (2007) comments that B/C greater than one, equal to one or less than one, shows profit, break-even or less profit, respectively. Generally, marine shrimp farms are well-organized and well-structured companies. The most of the farms did not present a risk factor, except the intensive farms (Level 4).

Profit is related to gross revenue and total production cost. That is, to be profitable, the farm must have a higher revenue than the total production cost. Level 1 showed the highest total production cost among all farms. Bastola and

Engle (2012) reported that to increase enterprise revenue is necessary to increase the gross yield without increasing costs. Comparing the farms studied per hectare, the Level 4 presented the highest productivity which in turn presented the highest profit. We observe that the profit was inversely proportional to the farm size. Level 4 was six times greater than the less intensified level. Mansaray *et al*. (2018) revealed on economic analysis of shrimp farms in China, that the farms revenue was significantly influenced by the cost of inputs and the size of the farm. It is important to report that the discrepant size of these farms influenced the results of the indicators, even with higher productivity at the most intensified level.

In all farms, except Level 4, the most representative items of the total cost were feed, post larvae and labor (in that order). Gammanpila (2015) verified that feed costs generally account for most variable costs (55%) and total operational costs (44%) in marine shrimp culture. For Level 4, the item labor was not expressive because they employ fewer workers. The farmers reported that price instability and poor management of the feed and post larvae lead to negative consequences for production, as well as observed by Andrade *et al.* (2005) in Brazil. In the environmental analyses we discuss that farms use different management for water quality such as fertilization, application of molasses or probiotics. But these items represent a maximum of 6% of variable costs. In addition, if large-scale farms use probiotics, this can reduce costs because it improves survival. (Peterson *et al.,* 2012; Hossain *et al.*, 2013).

At the least intensified level (Level 1), if we increase one unit on the average shrimp price, we would have a 16% increase in revenue. It means that the sale price is one of the most significant variables in shrimp production (Quagrainie *et al*., 2015). An interesting point is that for this level to reach similar values of Profit and NPV in a smaller area, it would have to intensify only 10% of its production area and use at least 100 shrimp m^{-2} as at Level 4. It is interesting to know that even though the different production scales, all farmers have a high purchasing power.

The stocking density is an important factor, because besides influencing the water quality, it also has an influence on the economic aspect. Costa *et al*. (2016) point out that, the increase in stocking density favored the economic indicators such as profit and total production cost in tambaqui farming. In our study, the intensive farms showed a high profit compared to the other levels which have lower stocking densities.

The Annual Income (AI) is the sum of profit and opportunity costs. The Level 4 had the highest profit and this is more advantageous when we consider the owner remuneration by area and production cycle. In addition, in the opportunity cost we consider land leasing for renewable energy use. Currently, wind energy is a good investment in Northeastern Brazil and can reduce the pressure of energy use in aquaculture (Nookuea *et al*., 2016). By the way, this is becoming so popular that one farm from Level 2 has already installed wind turbines on its property.

The break-even point is the point at which revenue is exactly equal to costs and hence no profit is made and no losses are incurred. The low break-even point obtained in the Level 1 demonstrated that the farm is able to operate at a lower capacity than those in this study and to pay costs. This is a positive factor, since the activity presents risks such as the occurrence of diseases (Murwantoko *et al*., 2016). On the other hand, Level 3 had the highest break-even point, even though it did not have the greatest technological potential among the levels, which could lead to increased costs.

Despite considered better at the less intensified level, the Market Diversity (MD) is not related to production volume. In general, the farms sell the production to markets of other states. The main buyers of Level 1 production are from the Southeastern region of Brazil. Business longevity (BL) followed the same understanding of the social indicator Permanence Activity (PA). For the conservation of the business, it is also important the decision-making by the farmer in the face of changes and the influence of the interested organs, stakeholders, among others (Lebel *et al*., 2006). Although the time difference in the activity, all these farmers seek to maintain it and make it perennial. For example, we can observe in this study that the shrimp price is similar on all farms. This is one of the strategies agreed between them to improve marketing or the exchange of management information when the outbreak of the white spot virus occurred in 2015.

Level 1 farm has the higher Product Diversity (PD) indicator because it cultivates fish and native oysters in the supply and drainage channels. Until the present moment, oyster culture is still a beginning trade for the farmer. This farm has commercial interest in oyster culture, since the world production is growing including in Brazil (Gallardi, 2014; Brasil, 2013). The use of physical structure of the marine shrimp farm, the low cost of material to construction pillows, easy management and jobs generation are incentives for the marketing of this product. By personal communication, this farm has the potential to produce more than 1,000,000 dozens / oysters / year. This activity is economic attractive and its adoption improves sustainability. Soon, they intend to expand the project to multitrophic with algae, oyster, shrimp and fish (Reid *et al*., 2018). Another particularity of this venture is that it has a tourist area of sport fishing. It is practiced in the supply channels and in the nearest river. They also offer tours by kayaking in the mangrove for environmental awareness.

It is important to note that a farm from Level 2 also stands out in the PD indicator. The farm has an aquaculture sector and is responsible for the supply of post larvae in the region. The remaining farms of levels 2 and 3 maintained other types of activity at the site, such as coconut plantation. Level 4 farms maintain the primary goal of intensifying farms and using other resources such as greenhouses. This diversity of products and the markets increase resilience in aquaculture (Valenti *et al*., 2018). In the present analyses, we consider only the shrimp grow-out phase.

CONCLUSIONS

In summary, the general sustainability index, Level 4 was the most sustainable, followed by Level 1, 2 and 3. The intensified system (Level 4) was the most environmentally sustainable and it is not necessarily associated with the largest amount of waste, as generally considered (Trai *et al.,* 2007; Anh *et al.* 2010). We can highlight the use of resources and water quality as the strength of this level. This is because Level 4 uses smaller areas, reuses crop water and it focus on strengthening the microbiota through the use of organic fertilization such as molasses and probiotics. These farms were also efficient in the absorption of greenhouse gases.

Socially, Level 4 was evident in category Principle of equity and income distribution. It presented a number of workers more proportional to the total production cost and total production. In the economic aspect, the category Resilience capacity was the weakness of these farms. Firstly, because of the intensive system is considered a risk factor. Another peculiarity is that this level is more specialized in a product and access fewer markets, decreasing resilience (Valenti *et al*., 2018). However, the production of oysters or fish in Level 4 farms is feasible and would increase the number of products and markets, increasing resilience.

We can cite Net Present Value, Profit and Annual Income values as key indicators that raised the economic sustainability of this level. Mainly because NPV is heavily used by large enterprises (Graham and Harvey, 2001). Others indicators as Net income-investment ratio, Internal rate of return, Payback Period and Benefit Cost Ratio contributed positively to this level due to higher productivity. The Payback period is widely used by smaller companies (Graham and Harvey, 2001) and these indicators are among the most appropriate to analyze the economic viability (Ross *et al*., 2010). Furthermore, the ability to increase stocking density and productivity are factors that attract investors (Browdy and Moss, 2005).

Following the most intensified level in general sustainability, we found Level 1. Although it presented the lowest score in Environmental sustainability, this level presented high efficiency on use of the resources. The farm carries out a low stocking density combined with the use of fish and oysters in the supply and drainage channel, respectively, providing positive aspects of nutrient absorption, especially phosphorus. This level also absorbed greenhouse gases. This fact may be considered a positive externality and may support the payment for ecosystem services to farmers in the carbon credit market. In addition to greenhouse gas, this system can also be offset by sequestration of nutrients (Chopin, 2014). Another positive point was the planting of 600 carnauba seedlings in the legal reserve. Level 1 has the potential to increase its environmental sustainability.

Socially, Level 1 provided more benefits to local communities than others levels. This farm purchased more inputs and sold a greater amount of production in the local market. In addition, it raised the education level of its employees. The highlight on the economic issue was due to the break-even point that demonstrates the robustness of system, as well as the Business Longevity, Risk Rate, Market and Product Diversity.

The traditional cultures, Level 2 and 3, presented intermediate values in the indicators. Although they use a lower stocking density than the most intensified level, it is necessary to reevaluate the farms management to improve environmental sustainability. Particularly with regard to water quality and pollutants release such as greenhouse gases. Socially, Level 3 was more sustainable due to social inclusion and it showed better proportion in relation to the number of employees and production. Technical support is strongly recommended, especially for these levels, for improvement in the use of environmental and financial resources.

In this study, the extreme levels (Level 1 and 4) showed to be more relevant in the sustainability indicators compared to traditional systems (Level 2 and 3). However, it should be noted that in addition to the stocking density, the farms studied have different management that influenced the degree of sustainability. Monoculture of marine shrimp is not the most sustainable aquaculture activity, but it can be improved if shared with other aquaculture species, as in multitrophic systems.

In contrast to Silva Filho *et al*. (2008), despite the difficulties encountered in the activity, marine shrimp farms have improved their relationships with environmental and social issues. Evidence about this was the most ecological management, especially on intensified farms. In Level 1, there is also a concern to develop environmental education. In general, in the social aspect, farms prioritized local workers and they showed interest in the professional development of employees. Another important point is the use of Net present value in this work, because as seen by Ruiz Campo & Zuniga-Jaras (2017), it is still not usually used in the aquaculture literature. Economic indicators revealed that all levels were economically viable and they represent important investment alternatives for the Brazilian rural sector.

Our study indicated that not only stocking density but also management have produced changes in environmental, social and economic indicators. The set of indicators are an adequate and effective tool to evaluate the environmental, social and economic sustainability in marine shrimp farming. It was possible to identify the strengths and weaknesses of the production systems. We demonstrated that intensified marine shrimp systems may be sustainable, if managed with efficiency in the use of resources, reduced pollutants discharge and control to avoid animal escapes. Finally, this work shows that it is possible to mitigate negative impacts such as implementing better practices and technology in the farms and establish standards to promote the development of sustainability in marine shrimp farming in the country. Our findings also provide an accurate picture of the environmental, social and economic conditions for Brazilian production of Pacific whiteleg shrimp. The farms in this study are a good, full-scale sample of the most common production systems currently in operation in the country. More precisely in the State of Ceará and Piauí that are one of the main poles of production.

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