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Exploring the relationship between production intensity and land use: A meta-analytic approach with shrimp aquaculture

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ABSTRACT

Shrimp are one of the fastest growing commodities in aquaculture and have a considerable land footprint. Here, we explored the impact of utilizing different production methods (extensive vs intensive) for expanding shrimp production on the cumulative land footprint of shrimp aquaculture. A meta-analytic approach was utilized to simultaneously estimate model coefficients to explore three relationships: production intensity and total land burden, production intensity and the proportion of land at the farm, and production intensity and the farmland burden. A literature review was conducted and a total of 7 datasets, 22 subsets, and 973 individual farms were included in this study. The global models were as follows: model 1 → ln (total land burden) = *0.1165–0.3863* * ln (production intensity), model 2 → proportion of direct (farm) land use:total land use = 0.7592–0.1737 * ln (production intensity), model 3 → ln (direct land use) = 0.1991–0.9674 * ln (production intensity). Production expansion was modeled under different scenarios. The most land intensive projections involved using only extensive systems to increase production when compared to a business-as-usual scenario. The least land intensive scenario involved utilizing intensive systems. A scenario where farmland was not expanded used 17% less land and 28% less land to produce 7.5 and 10 million tons of shrimp, respectively, when compared to business-as-usual scenarios. These estimates are limited by uncertainty in shrimp feed composition but demonstrate the effect of production intensity on the overall land footprint of shrimp production.

1. Introduction

Food production accounts for a substantial portion of humankind's land footprint. According to Food and Agricultural Organization (FAO) data, food production currently accounts for 38% of humankind's land footprint (FAO, 2016), and accounts for the highest percentage of land use by humans. In aquaculture, land use has been a source of controversy in the past. Early efforts in shrimp aquaculture were almost entirely in the tidal zone (Chamberlain, 2010), and ponds for shrimp aquaculture have been previously blamed for the decrease in mangrove stands around the world (Hutchison et al., 2014; Valiela et al., 2001). It is estimated that aquaculture is responsible for over 500,000 hectares (ha) of mangrove loss (Hamilton, 2013) in totality, with most of the losses occurring in Southeast Asia. This estimate is somewhat contested however, as Ahmed et al. (2018) showed that aquaculture is responsible for 1.89 million hectares of mangrove loss. Altogether, both of these studies show that land use is a point of contention in aquaculture and an environmental concern because of the impact shrimp and fish culture has had on the coastal areas in Southeast Asia and Latin America. A recent estimate by Boyd and McNevin (2018) showed that there is approximately 2.3 million hectares of shrimp ponds globally.

Aquaculture production exists on a continuum from "extensive" to "intensive" (see Joffre et al., 2018 for a thorough description). The definitions of "extensive", "intensive" and "semi-intensive" are somewhat malleable, though for the purpose of this study, semi-intensive production is regarded as beginning when pelleted feeds are used (Boyd and McNevin, 2015). In shrimp, extensive systems occur almost entirely in the tidal zones (Boyd and McNevin, 2018), and are prevalent in areas like the Mekong Delta in Vietnam (e.g., Ha et al., 2012; Joffre and Bosma, 2009). These systems rely on natural productivity and have limited to no feed use. From the perspective of the authors, systems can be described as intensive when the production relies on formulated feeds and aeration to increase production intensity (i.e., the amount produced per a given area). In terms of resource use, extensive systems are often

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thought to use less resources than intensive production due to the low input nature of the production methods. However, there is a great disparity between the land footprint of extensive systems and intensive systems and their output in terms of production. Extensive systems account for approximately 46% of the land footprint of shrimp ponds and only account for approximately 13% of the total annual production (Boyd and McNevin, 2018).

There are several factors beyond the production intensity that determine how land intensive shrimp farms are. Shrimp farms require more land than just the ponds, and this is a function of pond size to some extent (Jescovitch et al., 2016). Altogether, the land used at the farm for shrimp farming is considered "direct" land use. In intensive systems where pelleted feeds are used, the land footprint also includes embodied land, which is the land accounted for during the production of ingredients in the feed (Chatvijitkul et al., 2017). Therefore, the total land burden of shrimp farming is comprised of the farm area, and the land embodied in feeds. When considering efficiency on a per ton basis, these two values are modulated by the production intensity (metric ton (t)/hectare (ha) of pond area) and food conversion ratio (FCR), respectively. This means, for example, if the FCR of a farm is lowered, then the embodied land per metric ton of production is also lowered. The direct land use at the farm is a product of the farm:pond area ratio and then fluctuates with production intensity. Farms with high farm:pond surface area ratios have higher land burdens, and farms that have higher production intensities have lower land use burdens per ton raised compared to a farm with the same farm:pond surface area ratio.

Farm surveys from Thailand, Vietnam, and India showed a negative relationship between the total land burden per ton of shrimp production and production intensity (Boyd et al., 2017, 2018) on the natural log (ln)-natural log (ln) scale. While these surveys were relatively limited in scope, they suggest there are relationships between production intensity and land burdens in shrimp aquaculture. Additionally, these surveys found that as the production intensity of a farm increases, the total land burden of a ton of shrimp is displaced into the feeds (Boyd et al., 2017). Due to the high rate of increase in annual production -whiteleg shrimp *Litopenaeus vannamei* (WLS) production increased at an average rate of 8.9% from 2006 to 2016 (FAO, 2020) - the land footprint of shrimp could grow drastically depending on how the expansion in production is realized.

Here, we explore different land use scenarios to understand the impact of production systems on land use in shrimp, with the aim of utilizing data in the published literature from major and minor shrimp producing countries. Meta analysis is the quantitative synthesis of literature that allows for researchers to compare across studies in a systematic process (Borenstein et al., 2011). A meta-analytic framework was used in the current work to obtain raw data from field studies related to shrimp farms in the published literature and other sources. Subsequently, the data were modeled using a meta-analytic technique for linear regression, and the regressions analyzed to explore scenarios under which the land burdens of future shrimp production could be examined. Three relationships were modeled in this work to calculate the necessary land use burdens in the scenarios presented: total land use and production intensity, direct land use and production intensity, and the production intensity and proportion of direct (farm) land use:total land use.

2. Methods

2.1. Data collection

A systemic search using Web of Science, the Aquatic Sciences and Fisheries Abstracts, and Google Scholar was performed to collect published studies related to resource use in shrimp aquaculture. Combinations of the terms shrimp farm, shrimp culture, production intensity, FCR, food conversion rate, LCA, life cycle assessment, resource use, and field surveys were used to search for articles in databases. An example of a search of Web of Science is as follows: the search terms used were: noft (shrimp culture OR shrimp farm*) AND noft (production intensity OR FCR OR food conversion rate OR LCA OR life cycle assessment OR resource use OR field survey). An information science professional was consulted in constructing the search terms for the database queries. Studies were included if they met the following criteria: (i) included the annual production, FCR, total farm area, and pond surface area in the dataset (ii) were a field survey with multiple farms included (iii) not a trial for experimental feeds (iv) published after 2003 (v) included farms that operate under intensive conditions (vi) the culture species was *Litopenaeus vannamei* or *Penaeus monodon* (BTS) (these two species currently account for 94% of penaeid shrimp aquaculture according to FAO (2020)) and (vii) was published in English. The year 2003 was used as a cutoff for studies because it is approximately the time when specific pathogen free larvae were introduced and production of whiteleg shrimp dramatically increased (Chamberlain, 2010). Studies related to extensive production were not included because in most cases, the only source of the land footprint is the farm, and therefore there is no need to model the relationship. For later calculations, the assumed average production of extensive farms, as reported in Boyd and McNevin (2018), was 0.667 t/ha. While this is likely an overestimate based on other figures in the published literature (e.g., Joffre et al., 2018) it is not unreasonable because it is still within the range of what could be expected from a system operated extensively. Three unpublished datasets were included in addition to sources identified during the systematic review. The Aquaculture Stewardship Council's farm audits were scraped for the variables of interest to generate a dataset (Accessed ASC website between August and September of 2020 https://www.asc-aqua.org/). A dataset including farms in Vietnam, Ecuador, and India using surveys similar to Boyd et al. (2018) collected in 2019–2020 by the World Wildlife Fund and a dataset from Indonesia collected by the Moore Foundation in 2017 was included. In later calculations, semi-intensive and intensive systems were categorized as "intensive" for the purpose of this study, as these systems have both direct and embodied land use. Once studies were identified for inclusion, the corresponding authors were contacted to acquire the raw data, of which the following statistics were used: i. Total farm area (ha), ii. Total pond area (ha), iii. Annual production (metric tons/yr), and iv. FCR.

2.2. Calculations

Total land use was calculated as follows with the variables described below:

Production intensity = annual production (t)/pond surface area (ha).

Embodied land in the feed (ha/t shrimp) = FCR * 0.202 for farms raising WLS and FCR*0.292 was used for farms raising BTS. For BTS, this is the average land use/t reported in Chatvijitkul et al. (2017), and subsequently used in Boyd et al. (2017) and Boyd et al. (2018). For WLS, the embodied land in Chatvijitkul et al. (2017) in shrimp feed was updated by Boyd and McNevin (*In press*), and the new average was used here. The land footprint of the feed is practically impossible to calculate in field surveys because feed companies consider their feed formulations proprietary and are unwilling to share them. Therefore, the feed coefficients used in this study represent a working average. Davis et al. (2021) shows that the ingredients in feeds are not very influential in determining the overall land use footprint of an individual farm, and therefore an average is sufficient. In most cases, FCR is self-reported by the farmer, but can also be calculated if the feed use in tons is reported.

Direct land use = farm area (ha)/annual production (t).

Total land use (ha/t shrimp) = direct land use + embodied land in feed.

2.3. Statistical analysis

2.3.1. Regression analysis

Once studies were compiled and the raw data collected, the datasets were reformatted for statistical analysis. Several studies included data from multiple countries or multiple species. The studies were split into what will be called 'datasets" according to the country x species combinations for linear regression analysis (e.g., Boyd et al. (2017), would result in three useable datasets: Vietnamese WLS, Thai WLS, and Thai BTS). Studies were split according to country of production and species because there is evidence that BTS aren't as efficient at utilizing commercial feeds as WLS (Boyd et al., 2017, 2018), and production practices vary by country. Three linear models were fitted based on the datasets generated. The equations below were chosen to model each relationship based on finding linear relationships between the variables in preliminary investigations with the data from Boyd et al. (2017) and Boyd et al. (2018). This was to create suitable models for the following meta-analysis. They are as follows, where β_0 is the intercept of the resulting model and β_1 is the slope:

Model 1 (Land use):

ln (total land burden) $= \beta_0 + \beta_1$ * ln (production intensity).

Model 2 (Proportion of farm land in the total land burden): proportion direct (farm) land use:total land use $= \beta_0 + \beta_1$ * ln (production intensity)

Model 3 (Farm land use):

ln (direct land use) $= \beta_0 + \beta_1$ * ln (production intensity).

Log-Log transformations on the natural log scale were applied in each case to create linear relationships based on preliminary investigations with data from Boyd et al. (2018). With each equation, the slope and intercept from a fixed effects linear model were extracted along with the variance and covariance of the coefficients. The coefficients were then simultaneously calculated using the framework proposed in Becker and Wu (2007) to yield meta-analytic models, that is models that represent a weighted average of all the regression coefficients from individual data subsets. Like other meta-analytic techniques, the regression coefficients from each data set for the three models in this study were weighted based on the standard errors of the coefficients and synthesized to yield one set of coefficients for each model. Confidence intervals and a Q statistic for homogeneity were calculated from Becker and Wu (2007) as well. Henceforth, these three models will be referred to as "global models" for the purpose of this study.

2.3.2. Land use scenarios

Land use was considered at three production levels. The first level would be the 2016 totals consistent with the global production of farm shrimp in Boyd and McNevin (2018), which is about 4.875 million metric tons. Additionally, two future production levels, 7.5 million t and 10 million t, were considered. These levels represent roughly a 50% and 100% increase over the levels reported in Boyd and McNevin (2018). Four scenarios were considered at each production threshold. For all scenarios, the production intensity from extensive systems was assumed to be the same as calculated in Boyd and McNevin (2018), 0.667 t/ha. First, a business-as-usual (BAU) projection was constructed (Scenario I). Here, the ratio of production between extensive and intensive production was maintained (about 87% intensive and 13% extensive), and the production intensity of intensive production was maintained at the same level as presented in Boyd and McNevin (2018). The total land use/-metric ton was ascertained using model 1. Using the pond area and production from intensive farms calculated in Boyd and McNevin (2018), the farm area and embodied land were calculated using model 2. The farm area was considered the product of the result of model 1 and model 2 and the embodied land was considered to be the difference of the resulting product and the result of model 1. The next scenario (Scenario II) utilized only extensive production to expand production totals. The same amount of intensive production in the baseline scenario was maintained and the difference in production was met with extensive production. Thus, extensive land was increased to meet production goals. This scenario is not as likely as the BAU scenario or scenarios that follow but demonstrates well the impact of increasing the use of extensive production for meeting future demand in shrimp production. Scenario III estimated land use with the expansion in production with intensive production only, but at the same production intensity as the baseline scenario. This scenario was meant to explore to the increase in land while maintaining current industry practices while limiting the expansion of extensive production. The final scenario (Scenario IV) examined land use under a scenario where farmland for shrimp farms was not increased. The extensive production, and therefore land totals, was maintained at the baseline levels, and the farm area for shrimp ponds was not increased from the estimate in the baseline scenario. The production intensities needed to meet the production target (7.5 million t or 10 million t) was calculated using model 3 from the meta-analysis by calibrating the model based on the farmland/production ratio. Model 1 was then used to calculate the total land footprint and the embodied land was considered the difference. Once total land burdens were calculated, the net difference between each of the three scenarios and business as usual projections were calculated. A concise description of the scenarios is given in the supplemental information and the calculations are provided in the R code at the end supplemental information.

Error terms were developed for estimates in land use when possible and appropriate. In scenario 1,2, and 3, the error of model estimates was estimated using the delta method (Casella and Berger, 2002). The error of embodied land used estimates from both Model 1 and Model 2. Thus, the error model estimates were approximated using the multivariate delta method (Ver Hoef, 2012). The farmland estimate involved differences in total land estimate and the embodied land estimate. A conservative variance of the total farmland for scenario 1,2, and 3 is given by the sum of the variances of the total land use and embodied land use. In scenario IV, production intensity needed to be estimated for land use estimates at 7.5 and 10 million metric tons. The uncertainty in production intensity was incorporated in the estimation using a Monte Carlo simulation approach (Hammersly, 2013), where samples were drawn from the distribution of ln (production intensity). Details of the statistical methodology are provided in the Supplementary Documentation.

3. Results

3.1. Literature search

The results of the literature search can be seen in Fig. 1. The total number of records screened by title and abstract was 1682, of which 62 were accessed for via full text. There were 29 records assessed via full text that were found to be suitable for inclusion in this study. Once the studies were identified, corresponding authors were contacted to obtain the raw data used in the studies. In the current study, 19 authors did not respond to queries regarding their work. Additionally, 5 authors lost the data for a published study and therefore did not make it available. A summary table of the studies included in this analysis are presented in Table 1.

3.2. Summary data of farms included in study

In total, 973 farms that were split into 22 datasets were included in this study representing 7 countries ranging in years from 2007 to 2020. The summary data for select farm characteristics can be seen in Table 2. The largest farms were found in the Americas, with the average farm size in Ecuador being 300 ha and the average farm size in Honduras being 1156 ha. The smallest farms were in China ($\bar{x} = 2.2$ ha). The mean production intensities observed in the data varied greatly, however lowest values for vannamei were in Ecuador and Honduras, while Indian monodon had the lowest value overall ($\bar{x} = 4.17$ t/ha/yr).

3.3. Regression analysis

The results of the individual regression lines for each country x

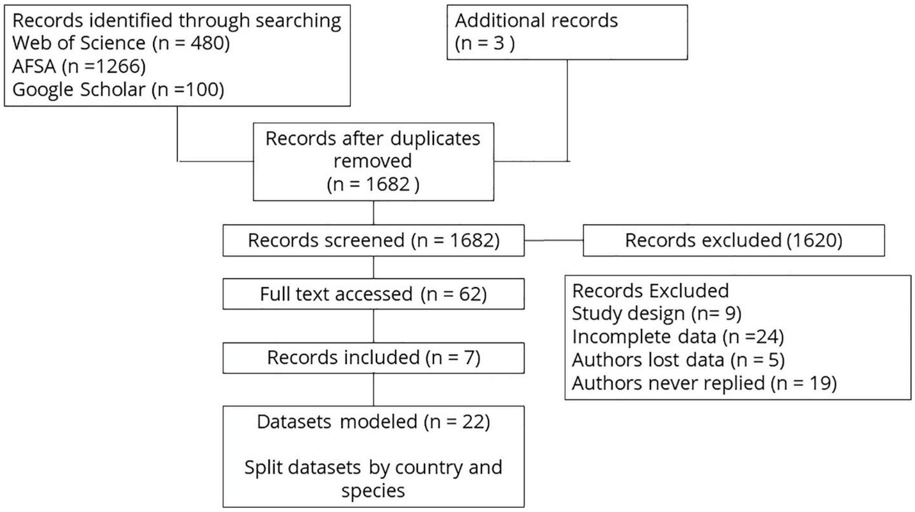

Fig. 1. Prisma flowchart for this study.

Table 1
A general description of the data used in this study.

Dataset	Year	n	Countries	Species	Number of Subsets
ASC	2019	71	Ecuador, Honduras, India, Indonesia, Thailand, Venezuela, Vietnam	vannamei	7
Boyd et al.	2017	82	Thailand, Vietnam	monodon, vannamei	3
Boyd et al.	2018	96	India	monodon, vannamei	2
Henriksson et al.	2015	256	China, Vietnam	monodon, vannamei	3
Joffre and Bosma	2009	59	Vietnam	monodon	1
Moore Foundation Surveys	2017	129	Indonesia	vannamei	1
WWF Field Surveys	2019	280	Ecuador, India, Vietnam	monodon, vannamei	5

species combination from the studies are included in the supplementary information in Tables S1–S3. The meta-analytic regressions, referred to as the 'global models', resulting from the meta-analysis are presented in Table 3. Model one is on a ln-ln scale, which lends to an easy understanding of the slope. In this case, a 10% increase in production intensity will decrease the total land burden by 3.8%. The relationship between land use and production intensity is modeled in Fig. 2. Model 2 shows that there is a decrease of land burden at the farm site proportionally as the production intensity increases. In each case, the Q statistic for heterogeneity was significant, which suggests there is variation across studies as well as within studies. Model 3 was used to calibrate the average production intensities needed to obtain production targets in Scenario IV of future land use.

3.4. Land use calculations

Utilizing Boyd and McNevin's (2018) estimate of extensive production as a baseline, the current land use (embodied and direct) in shrimp aquaculture is estimated with the models generated herein to be about 3.9 million ha. The results of scenarios to meet future production demands are found in Table 4. The business as usual (BAU) scenario

Table 3
The models resulting from meta-analyses. Coefficients and 95% confidence intervals are reported. The Q test for Homogeneity described in Becker and Wu (2007) and its p value is reported as well.

Model	Coefficient (95% CI)	Q	P Value
Land Use			
Intercept	0.1165 (0.0817, 0.1512)	680.9	<0.0001
Slope	−0.3863 (−0.3690–0.3982)		
Farm:Feed Ratio			
Intercept	0.7592 (0.7475, 0.7710)	16163.67	<0.0001
Slope	−0.1737 (−0.1786, −0.1687)		
Farm Land Use			
Intercept	0.1991 (0.1660, 0.2323)	794.1	<0.0001
Slope	−0.9674 (−0.9818, −0.9593)		

Table 2
Summary characteristics of key production parameters within the dataset by country x species combinations. Values presented are means, and SD represents the standard deviation.

Country	Species	n	Annual Production (t)	SD	Production Intensity (t/ha/yr)	SD	FCR	SD	Farm Area (ha)	SD	Pond Area (ha)	SD
China	Vannamei	125	23.2	37.2	15.94	13.66	1.70	3.11	2.2	4.2	1.8	2.9
Ecuador	Vannamei	110	1400.6	2833.8	6.86	9.03	1.36	0.35	300.3	588.4	228.7	447.4
Honduras	Vannamei	9	2992.8	3437.1	3.21	1.17	1.88	0.84	1156.2	1132.5	915.4	989.9
India	Monodon	28	14.4	16.0	4.17	1.54	1.36	0.06	5.6	5.9	3.7	4.0
India	Vannamei	208	104.9	183.4	12.64	8.86	1.38	0.31	11.0	16.1	8.8	13.5
Indonesia	Vannamei	132	48.8	72.2	22.85	25.97	1.40	0.30	5.4	9.1	2.9	4.8
Thailand	Vannamei	39	380.2	1510.9	18.80	17.94	1.46	0.24	23.1	35.8	13.0	22.7
Venezuela	Vannamei	3	4266.0	6460.5	3.89	2.51	1.95	0.30	1215.7	1110.2	721.6	878.8
Vietnam	Monodon	197	8.4	22.6	5.26	11.33	1.88	1.58	3.7	8.8	2.1	4.9
Vietnam	Vannamei	122	155.7	565.5	34.66	53.69	1.35	0.94	17.5	52.8	7.4	25.1

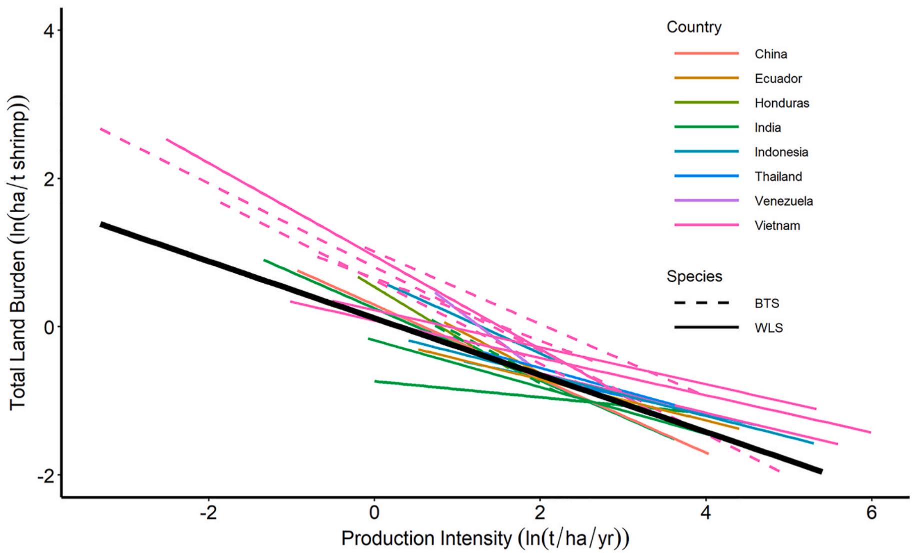

Fig. 2. The meta-analysis results of model 1: total land use and production intensity. The global model is y = 0.1165–0.3863(x) where y is the natural log of total land burden of shrimp production and the x is production intensity of a farm on the natural log scale. Colored lines represent individual regressions (country x species combinations), while the black line represents the overall relationship. "BTS" is an abbreviation for black tiger shrimp and "WLS" is for whiteleg shrimp.

(scenario I) resulted in a ~2.1 million ha increase in land footprint when the production increased to 7.5 million t, and ~4.0 million ha when production is increased to 10 million t. The extensive production (Scenario II) resulted in net increases in land use (~1.9 and 3.7 million ha, respectively) when compared to the BAU scenario, and intensive expansions resulted in net land savings in both the "intensive only" and "no farm expansion" scenario (Scenario III and Scenario IV, respectively) (see Fig. 3). In the "no farm expansion" scenario (Scenario IV), production intensities increased from 3.67 t/ha pond area as the baseline to 5.76 t/ha pond area at 7.5 million t and 7.94 t/ha pond area at 10 million t of production.

4. Discussion

The use of land in shrimp aquaculture has been widely debated. Shrimp aquaculture has been rightly blamed for the conversion of

Table 4
The projected land use under different scenario using the models generated in meta-analysis. The baseline business as usual (BAU) scenario is based the ratio of production found in Boyd and McNevin (2018). SE represents the standard error of the estimate.

Scenario		Business as Usual (Scenario I)	SE[a]	Extensive Expansion Only (Scenario II)	SE[a]	Intensive Expansion Only (Scenario III)	SE[a]	No Aquaculture Farmland Expansion (Scenario IV)	SE[b]
2015 Baseline ~ 4.875 Million Tonnes	Extensive (Farm Only)	983100	–						
	Intensive	2882398	27909						
	Farm	1537687	42105						
	Embodied	1344912	50514						
	Total Land Use	3865698	27909						
7.5 Million Tonnes									
	Extensive (Farm Only)	1511364	–	4962121	–	983100		938100	
	Intensive	4436472	42953	2882398	27909	4674349	45256	4023621	430634
	Farm	2366582	64801	1537687	42105	2493474	68275	1537687	42105[a]
	Embodied	2069890	77744	1344912	50514	2180875	81913	2485934	430671
	Total Land Use	5947836	42953	7844720	27909	5657449	45256	4961721	430634
Net Difference From BAU		–		1896883		−290387		−986116	
10 Million Tonnes									
	Extensive (Farm Only)	2015152		8750000	–	983100		983100	
	Intensive	5915296	57271	2882398	27909	6380029	61770	4742154	519048
	Farm	3155443	86401	1537687	42105	3403348	93189	1537687	47717[a]
	Embodied	2759854	103659	1344912	50514	2976680	111803	3204467	519045
	Total Land Use	7930448	57271	11632598	27909	7363129	61770	5725254	519048
Net Difference From BAU				3702150		−567320		−2205195	

[a] Denotes standard errors that were estimated using the delta method.
[b] Denotes standard errors that were estimated with Monte Carlo Simulation.

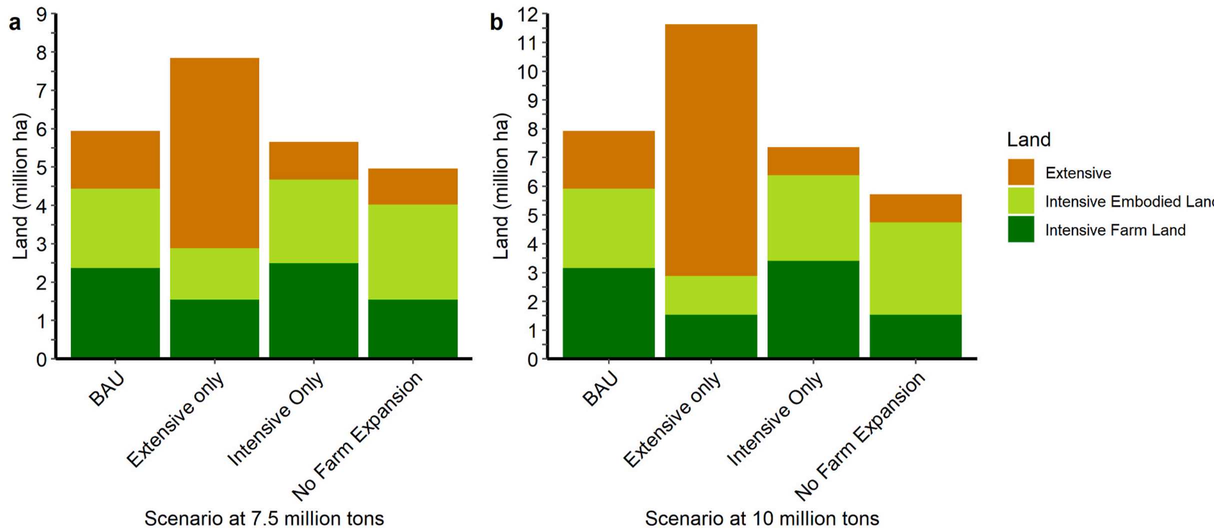

Fig. 3. The land use of different scenarios of shrimp production at a) 7.5 million t and b) 10 million t. The four scenarios at each threshold represent land use in a "business as usual" scenario, an extensive production increase scenario, an intensive production increase scenario, and a scenario where no farm expansion occurs.

mangroves in coastal areas and criticized for reckless expansion (Bailey, 1988; Hamilton, 2013). The model results from the meta-analysis showed that on average, total land use decreases 3.8% for every 10% increase in production intensity. This is the first attempt to report land burdens in this fashion, although Boyd et al. (2017) and Boyd et al. (2018) performed similar calculations. The ln-ln scale provides a relatively straight forward interpretation of the slope of the relationship (see Fig. 2). In studies that examine resource use over a given range of production intensities (e.g., Boyd et al., 2018; Boyd et al., 2017), this ln-ln scale provides a meaningful understanding of the relationship between the two variables over curvilinear responses which can be more difficult to interpret.

While this study aims to assess land use in shrimp aquaculture; it is important to recognize the limitations of the data presented. To begin, land conversion is not the only environmental impact of shrimp aquaculture. For example, shrimp farms can use a considerable amount of fresh water (e.g., Henriksson et al., 2018; Verdegem and Bosma, 2009), can pollute surrounding waterways with effluents from production ponds (Anh et al., 2011; Naylor et al., 1998), generate greenhouse gas emissions (Aime et al., 2018; Soares and Henry-Silva, 2019; Yang et al., 2018), cause salinization of soils and water (Cardoso-Mohedano et al., 2018; Paez-Osuna, 2001), and pollute surrounding waterways with antibiotic residues (Binh et al., 2018; Holmstrom et al., 2003). These cannot be ignored when discussing expansions in intensive production systems. This assessment of land use favors the expansion or intensification of intensive aquaculture operations in terms of saving land, which could be subsequently conserved. The production intensities reached in the "no farm conversion" scenario (Scenario IV), 5.76 and 7.94 t/ha pond area for 7.5 million metric tons of production and 10 million metric tons respectively, are not unreasonably high levels such that they are unattainable by farmers in a practical sense. In the recent surveys of India, Thailand, and Vietnam, 62% and 47% of farms from the three countries are already operating at 5.76 and 7.94 t/ha (Boyd et al., 2017, 2018). Additionally, these values represent the average intensity to meet these targets, and therefore not all farmers would need to operate at these levels, as many are likely technically or practically limited below these thresholds. It is also important to recognize that the land use calculations in Table 4 are estimates and meant to demonstrate the effect of increasing intensities on the land footprint of shrimp globally. It is difficult to know the actual global land footprint of shrimp farms because the exact formulations of commercial feeds are unknown and not all aquaculture ponds are typically accounted for in official government records.

Perhaps the greatest challenge here in estimating the land footprint of shrimp aquaculture is estimating the land footprint in the feed. This study uses average values from Chatvijitkul et al. (2017) and (Boyd and McNevin, *In press*) that have been previously used in similar work (e.g., Boyd et al., 2018). These estimates serve as an attempt to calculate the land use, not a definitive value. Factors like average crop yield that vary greatly by region and country (Balmford et al., 2005), affect the land burden of agricultural crops and not all shrimp feeds will include the same levels of land-based ingredients. However, because feed companies are not willing to share their feed formulations for traceability and resource use assessments, an industry-wide average based on published diets is the closest approximation available. The average land footprint of shrimp feeds could be reduced using secondary products like distillers' grains (Qiu et al., 2017) or alternative feed ingredients like insect larvae proteins (De Leon-Ramirez et al., 2018), but this is not yet common in the commercial setting. Increasing fish meal as a protein source in shrimp feeds would be another way to decrease the land footprint, but this is unlikely and unadvisable given the diminishing supply of fish meal, environmental concerns about fisheries harvests (Boyd and McNevin, 2015), and the increasingly high prices (Tacon and Metian, 2008).

Joffre et al. (2015) demonstrated that there are financial and knowledge barriers for small shareholders to make changes in mode of production from extensive to intensive. Additionally, the adoption of new technology and intensification can increase risk and therefore volatility of monetary returns (Joffre et al., 2018; Rego et al., 2017). However in all scenarios present, no conversion of extensive to intensive farms is considered. This is intentional, as the land where many extensive farms are located is likely not suitable for conversion to intensive farms (Tho et al., 2011), and therefore this is not necessarily an appropriate pathway for increasing production. The extensive farms are in mostly inter-tidal areas where water exchange occurs via the tide, which is not suitable for intensive management, and have acidic soils which are poor for intensively managed shrimp ponds. Previous attempts to intensify the intertidal zones and the subsequent failures are well documented (Chamberlain, 2010). However, reducing the area of extensive farms would, at current levels, have a great impact on land conversion in shrimp aquaculture. As an example, Vietnam was estimated to have 43,222 ha of IMA shrimp ponds in the Ca Mau province alone that yielded between 9815 and 15,776 t of shrimp, annually (sensu Joffre et al., 2015). If these ponds were replaced with intensive methods assuming an average production of 5 t/ha, the same amount of shrimp could be produced with between about 2000 and 3200 ha of land, relieving about 40,000 ha of land in the intertidal zone for mangrove restoration. This type of intensive for extensive trade-off is unlikely to occur because of socio-political factors (nor are the authors explicitly recommending this) in practice, but it demonstrates the hidden resource cost of extensive production in the farmland. As global shrimp production increases however, the land from extensive production will become a smaller proportion of the overall land footprint if new extensive ponds are not created. The majority of the land footprint of shrimp farming will be embodied in the feeds, not in farm area in the coastal areas. This is especially true if intensive farms or increased intensification are the means used to increase production.

The issue of land use is extensively studied in protein production. On a per ton basis, the average land use for shrimp estimated in this study (calculated from the data presented in Table 4) ranged from 0.57 to 1.16 ha/t, based on the various scenarios presented. The land use for intensive shrimp farms in the various scenarios was less than the overall averages in the scenarios and ranged from 0.51 to 0.68 t/ha. Nijdam et al. (2012) summarized land use estimates across the literature for milk, beef, pork, chicken, and eggs. Based on the ranges presented in Nijdam et al. (2012), the authors recalculated the ranges on an equivalent basis to this study as ha/t of live production with edible portion factors from Flachowsky et al. (2018), which reproduced the summary data from Nijdam et al. (2012). Therefore, the ranges are as follows; 0.95–1.90 ha/t for milk, 0.35–2.10 ha/t for beef, 0.48–0.90 ha/t for pork, 0.30–0.48 ha/t for chickens, and 0.36–0.63 ha/t for eggs. Based on these ranges, shrimp are better on a land usage basis than milk, and comparable to pork, chicken, and eggs. Although the range of land usage for intensive shrimp production is within the range of beef, it is likely that many beef production systems use considerably more land, which has been shown in studies previously (e.g., Ridoutt et al., 2014). Land use studies are more limited in aquaculture, but a study on tilapia in Mexico showed that tilapia had a higher land use as production intensity increased (Guzman-Luna et al., 2021), which is contrary to this study. However, several differences exist in the way land use was measured in that study compared to this study. Guzman-Luna et al. (2021) attempted to account for mortality in their study and included a more holistic accounting of the tilapia production system by including hatcheries and processors. While this study was limited by the data available, there are shrimp farms that operate processing plants within the grounds, especially in Latin America. Hatcheries and processing facilities often have relatively small land footprints compared to ponds, and it is likely that this would be relatively inconsequential to the analysis of this study. Henriksson et al. (2018) calculated the land use of 14 different aquaculture systems in Bangladesh. The range of land use was between 0.27 and 0.91 ha/t fish or shellfish product produced, which shows that shrimp, especially from intensively (and semi-intensively) managed systems have a relatively small land footprint for aquaculture systems.

Ultimately, this study can be understood in the context of the land sharing vs land sparing framework (Green et al., 2005; Phalan, 2018). The results here support land sparing, especially if the goal is to protect high value areas like mangroves and coastal land, which will be important in both stymieing the impacts of climate change (Atwood et al., 2017; Donato et al., 2011; Macreadie et al., 2017) and protecting coastal communities from its impacts, such as severe storms (Danielsen et al., 2005). While several other studies have reached similar conclusions (Balmford et al., 2005; Hodgson et al., 2010; Hulme et al., 2013), it should be noted that land sparing is only effective when policies are in place to ensure the land is converted back to natural space (Fischer et al., 2011). In aquaculture, systems exist that operate under a principle of land-sharing, and these are referred to as "silvofisheries" or "integrated mangrove aquaculture". These systems are often seen as environmentally conscious alternatives to intensive shrimp production (Primavera, 2000, 2006), although the ecological benefits of these systems have not been quantified in any meaningful way, and silvofisheries have recently been shown to contribute to the fragmentation of mangroves (Liu et al., 2020). Land use is a result of government policy, especially in mangroves, and therefore any changes to current patterns in land sparing and land sharing are likely going to results in shifts from governmental focus and not individual shrimp farmers changing practices.

The move towards a more intensive shrimp production supply chain would allow for flexibility in retailers and producers that are aiming to improve their "sustainability". When a majority of the land footprint is in the feed ingredients as is the case in intensive production, buyers could actively choose where their land footprint is. Almost the entire land footprint of extensive farming is in the coastal area, and therefore mitigation is not possible or feasible without ceasing operations in those areas, which is less flexible. Additionally, future growth in shrimp aquaculture could come at the expense of mangrove areas in places like Africa where there is relatively little aquaculture, but growth is expected (Ottinger et al., 2016). This study shows that minimizing the expansion of extensive production could mitigate losses to mangroves in those areas.

5. Conclusions

In conclusion, the results of this assessment of land use utilizing meta-analysis demonstrates that land use at set production targets is decreased by increasing production intensity, and the land footprint of shrimp farming is displaced from the farms to the embodied land used captured in feed ingredients to produce the feeds as production intensity increases. This study only examined shrimp aquaculture; however the principles of this study could be applied to any species grown under what would be described as intensive conditions, especially in ponds where the culture system is similar to shrimp, and enough data likely exists in the published literature to compare across species in this framework (e.g., tilapia or catfish). Similarly, a meta-analtyic framework could be utilized to examine the relationship between production intensity and land use in agricultural protein production such as chicken, pork, or beef.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.113719.

Credit author statement

Robert Davis – Conceptualization, Methodology, Formal analysis, Data Curration, Writing- Original Draft, Visualization, Ash Abebe - Formal Analysis, Writing - Reviewing and Editing Claude Boyd - Conceptualization, Writing- Original Draft, Writing - Reviewing and Editing, Supervision, Funding acquisition, Aaron McNevin - Conceptualization, Funding acquisition, Writing – Reviewing and Editing.

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