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Scenario analysis and land use change modelling reveal opportunities and challenges for sustainable expansion of aquaculture in Nigeria

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ABSTRACT

This study explores the critical factors of pond aquaculture development in Nigeria, and opportunities and challenges for sustainable expansion of the sector. Aquaculture's role in food security especially in developing countries has been recognized, including its growth potential. However, Nigeria's aquaculture development remains slow. Using Delphi technique, key factors influencing aquaculture were identified: availability/cost of aquafeed, land use change, government policy and climate change. Then scenario planning was used to develop four alternative but plausible pathways (scenarios) for Nigerian aquaculture development to 2035, depicting baseline, favourable, somewhat favourable, and unfavourable situations. For each scenario, future pond aquaculture production was estimated by modelling future changes in land use and pond yield potential. Government estimates suggest a potential of producing 2.5 million metric tonnes (t) of fish annually, but our results suggest Nigeria is unlikely to reach this estimate by 2035 without interventions. While the qualitative scenarios are useful to enhance discussions on potential interventions for improving aquaculture production and sustainability, the quantitative projections can be used for evaluating these interventions.

1. Introduction

The sustainable development of aquaculture needs a long term and comprehensive plan, which is often difficult to formulate due to uncertainties of the future (Gephart et al., 2020). Scenario analysis is one of the common methods for problem structuring (Marttunen et al., 2017) and strategic planning (Schoemaker, 1995). Scientists and planners use scenario analysis as a tool to generate plausible futures based on trends of events and uncertainties that support stakeholders in strategic decision-making (Vervoort et al., 2014). The definition of scenario varies with its purpose (Biggs et al., 2007). Popular proponents of scenario analysis in the 1990s such as Schoemaker (1991) and Van Der Heijden (1996) view scenarios as internally consistent and challenging set of narratives used to describe fundamentally different but possible futures. Scenario narratives may sometimes have a quantitative underpinning to help check the consistency of the narratives (Alcamo, 2008; Godet, 2000). In any case, scenario narratives or storylines that are relevant and credible help to stimulate creative thinking among stakeholders and decision makers on strategic issues (Bohensky et al., 2011; Malinga et al., 2013; Schoemaker, 1995).

Scenarios can take three forms—what-if (projection), what should (normative) or what could (exploratory)—happen in the future (Börjeson et al., 2006). In building scenarios, various flexible techniques are being used, such as matrices, Delphi, system dynamics and morphological analysis. Due to the wide range of methods available for conducting a scenario exercise, it is often difficult to decide what methodology to adopt (Bradfield et al., 2005). For this reason, it is suggested that a good understanding of the purpose which the intended scenario would serve, should be the topmost of the considerations for adopting a methodology (Biggs et al., 2007; Bradfield et al., 2005). Alcamo (2008) noted that scenarios tend to be qualitative when used in planning and quantitative for research. Adding that these can however be combined to achieve robustness.

Scenario analysis is sometimes referred to as scenario planning. According to Alcamo (2008), the term 'analysis' associates more with scientists being inquiry-driven, while 'planning' is often used to address stakeholders such as policymakers who are relatively strategy-driven. Robinson et al. (2015) emphasize that a scenario-based approach is often required for *ex ante* analysis of systems that are dynamic, including trends and nonlinear relationships that may deviate significantly in the future. This explains why several studies that explore how food systems could respond to future social and ecological changes have employed

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scenario analysis (Reilly and Willenbockel, 2010). However, in aquaculture planning, interest is just beginning to grow in the use of scenario analysis (Couture et al., 2021).

Scenarios of aquaculture development in relation to food security at global (Gephart et al., 2020) and regional (Chan et al., 2019) levels have been published. Using exploratory scenario narratives, Gephart et al. (2020) suggest that a globalised world in which economic policies are aligned with social equity and environmental concerns are necessary for the development of a nutrition-sensitive industry between 2030 and 2050. Chan et al. (2019) used the IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade) to generate a "business-as-usual" and three alternative scenarios of fish production, consumption, and trade in Africa by 2050. The alternative scenarios show how these outcome variables may respond if the trends in aquaculture investment and GDP per capita deviate from the current trends. However, it will be difficult to translate the insights of these larger scales directly to country-level applications to inform aquaculture policy and planning (Couture et al., 2021). The perspective of such top-down approach of assessing aquaculture development is different from that of bottom-up in that the former is broad, while the latter is more specific, as a result, the findings and recommendations are very likely to vary between global, regional, and national scales. For example, global aquaculture production and per capita fish consumption are expected to increase between 2018 and 2030 due to urbanization and income growth, but average consumption in Africa is expected to decrease by 0.2% per year, signifying different priorities for the African continent (FAO, 2020b). An optimistic scenario by Chan et al. (2019), which assumes a largely improved growth rate of aquaculture and GDP across the continent, portrays increasing per capita fish consumption up to 2050, yet it remains an open question as to how much effort and in what direction, different governments or agencies might invest to drive such development. Hence, the role of country-specific drivers of aquaculture development, including 'political will' needs to be considered (Stead, 2019).

Although the African continent is recognized as a region with high potential for aquaculture development (Aguilar-Manjarrez and Nath, 1998; Brummett et al., 2008), the absence of proper governance of the sector has been a critical factor in this potential remaining untapped (Chan et al., 2019; FAO, 2017). Nigeria is currently one of the top producers of farmed fish in Africa and is pivotal to supply and trade of the product in the sub-Saharan region (Adeleke et al., 2020; FAO, 2018). The country's aquaculture industry is characterized by African catfish (*Clarias gariepinus)*, providing a vital source of nutrition, income, and employment (Anetekhai, 2013). Production grew impressively from 25, 000 metric tonnes (t) in the early 2000s and peaked in 2015 at 317,000 t (FAO, 2020a). However, the goal of reaching self-sufficiency in fish supply in the mid-term according to the national aquaculture strategy (Abdullahi, 2011; FMARD, 2008) could not be met. Meanwhile, the Federal Department of Fisheries (FDF) estimates the national aquaculture potential at some 2.5 million t annual production (FDF, 2017). Hence, there is need for a better understanding of the constraints to aquaculture development in Nigeria, including options for addressing these.

Freshwater pond aquaculture is the most popular production system in Nigeria (Miller and Atanda, 2011) and its potential to expand in terms of availability of suitable land has long been established (Aguilar-Manjarrez and Nath, 1998). Unfortunately, access to land is obviously one of the important factors affecting aquaculture expansion in the country (Adedeji and Okocha, 2011). Worldbank (2020) show that arable land (ha per person) in Nigeria is on a downward trend, dropping from 3.0 to 1.7 between 1990 and 2018. The magnitude of impact of this trend on aquaculture across the country has not been studied. Although, the peri urban nature of aquaculture expansion (Miller and Atanda, 2011) suggests that any deliberate attempt to move towards rural areas may be met with challenges. One of such challenges is the rapid urbanization. The growth rate of urban population in Nigeria increased from 30% of the total population in 1990 to 50% in 2018 (UN, 2019). Given the poor knowledge on how much the accessibility to land, among other factors, is influencing the aquaculture industry in the country, an assessment of land use and land cover (LULC) change could offer some insights.

This study aims to use scenario analysis to develop and assess potential futures of freshwater pond aquaculture in Nigeria. Specifically, the assessment considers whether the Nigerian aquaculture sector could produce 2.5 million t of fish annually (FDF, 2017) by 2035. The objectives are: (i) To identify via a stakeholder consultation, the key factors that may affect the future of aquaculture in the country, (ii) To generate scenarios of Nigerian aquaculture development in 2035, (iii) To assess the trends in land use change and potential trajectories under the scenarios, and (iv) Evaluate the potential aquaculture production under each scenario and compare to the FDF (2017) estimate. The findings of this study will provide better understanding of the key issues affecting aquaculture production in Nigeria. More broadly, the study demonstrates an approach to support the development of national aquaculture strategies using scenario planning and LULC change assessment.

2. Methodology

2.1. Study area

Nigeria is a west African country with a total area of 923,768 km^2. It is divided into five topographic divisions, namely low coastal zone, low plateaus, Niger-Benue River valley, broad stepped plateaus, and mountainous zone. Nigeria shares its border with Niger, Gulf of Guinea and Benin in the north, south and west respectively and Cameroon and Chad to the east, where the Lake Chad is shared (Fig. 1). The country is highly diverse, which is evident in its large population and regional differences in natural resources and trade, as well as the many ethnolinguistic, religious and political groups (Metz, 1992).

Along with the rural-urban dynamics in Nigeria, there is variation between the northern and southern regions in terms of demographics and food security, including fish demand and supply (Liverpool-Tasie et al., 2021). Although prices of fish are higher in southern Nigeria, consumption per capita for all fish forms in the region more than double that in the north and while the percentage of households consuming fish in the south increased between 2010 and 2015, the percentage remained unchanged in the north. There are several reasons for this disparity. First, over 40% of fish supply in Nigeria come from imports as frozen products arriving at seaports, all of which are in the southern area. While frozen fish are a common fish form in the south, the north is more inclined to smoked and dried fish, with the fresh fish form seen as a luxury option across the country (Liverpool-Tasie et al., 2021). Second, population density, which is one of the determinants of household consumption (Liu and Yamauchi, 2014), is higher in the south than north (Fig. 1). The northern region is relatively higher in total population and poverty, with lower educational attainment. Third, artisanal fishing and fish farming are higher in the southern region, with a declining artisanal fishing and less fish farming activities in the north. The Lake Chad area in northeast Nigeria is well known for its artisanal fisheries and contribution to dried fish supply across the country, however, this area is also under threat due to political conflict which is severely affecting fishing activities and trade in the area. These are clearly useful considerations for national aquaculture planning.

2.2. Identifying critical uncertainties and trends for aquaculture

In scenario analysis, critical uncertainties refer to factors that drive something of interest (in this case aquaculture development) and for which prediction of change is complex both in terms of magnitude and direction (Schoemaker, 1995). Accordingly, critical uncertainties in the present study were identified as factors that score very high in both importance and uncertainty.

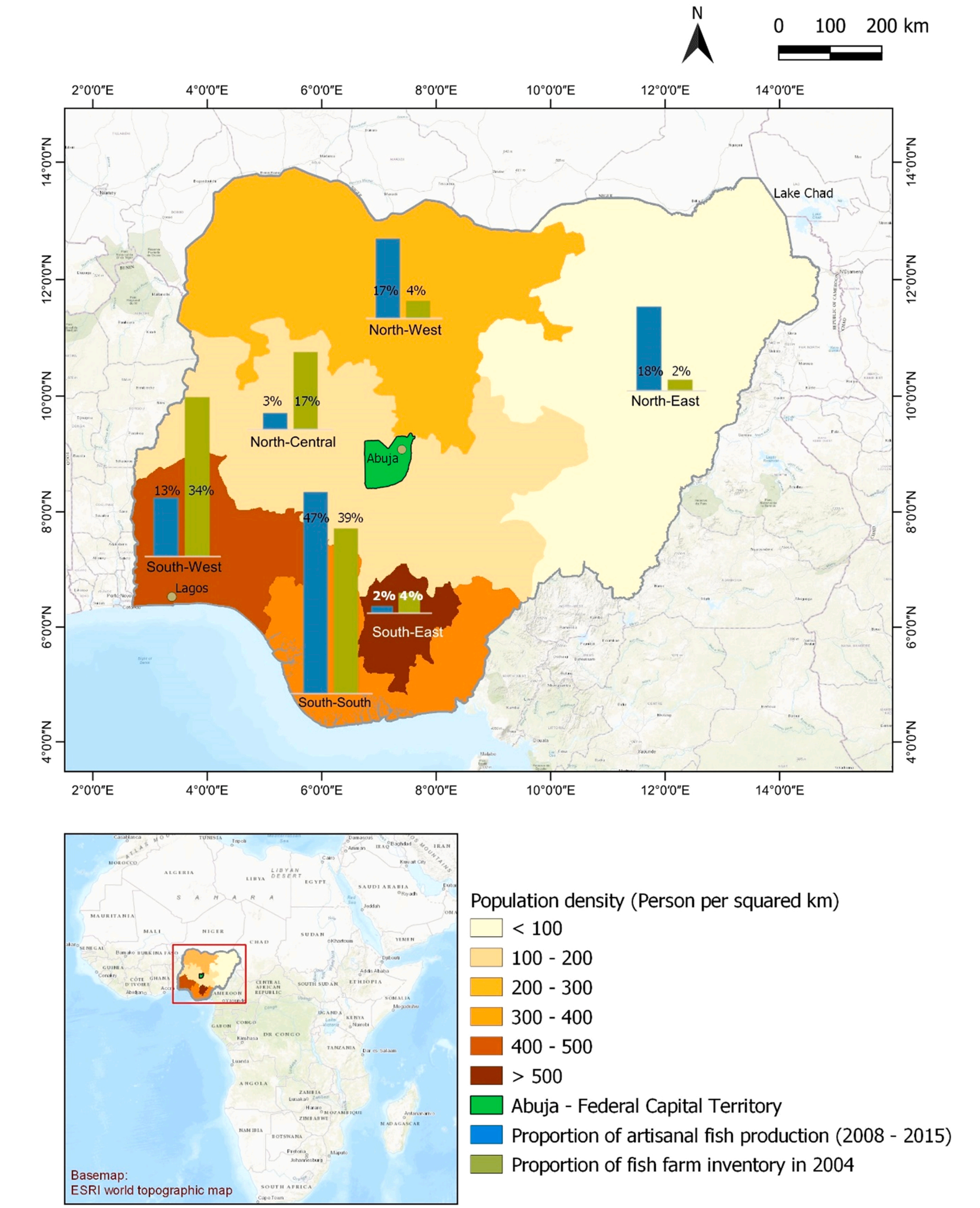

Fig. 1. Map of Nigeria showing population density and proportions of artisanal fish production (653,852 t) and fish farms (2658) by the six geopolitical regions. For each region, population density is 2015 estimate (NBS, 2021); Artisanal fish production is annual average (2008–2015) (FDF, 2017) and number of fish farms is the sum from the inventory report (FAO, 2007). Lagos is the commercial hub and Abuja the federal capital territory of Nigeria.

To populate these factors and assign scores, the Delphi method described by Okoli and Pawlowski (2004) was employed. The Delphi process involves establishing a structured group communication process where the opinions of individuals are elicited through a series of iterative questionnaires, to reach consensus. The advantages of this method over the face-to-face consultation include convenience, anonymity and ease of achieving agreement (Okoli and Pawlowski, 2004). In the present study, the process began with an overview of the literature (Table 1) to generate factors thought to be affecting aquaculture development in Nigeria. The summary as shown in Table 1 was also used to design the questionnaires (Appendix 1). The literature highlighted a lack of collaboration between research institutions and the aquaculture industry, which led to the decision to establish two groups of experts: academics (in aquaculture science) and practitioners (fish farmers, fish feed producers and extension officers). The groups each had nine individual experts, who had at least five years' experience in aquaculture.

The questionnaires were administered online to the two groups of experts. The first round of exercise treated all participants the same, regardless of their group. Each expert was asked to score the initial list of factors between 0 (not important) and 5 (highly important) based on their perceived importance of each factor to pond aquaculture development in Nigeria. The experts were also able to add more factors that they thought were important. The responses were collated, and a list of the top-ten factors was generated in order of descending average score.

In the second round, the list of top-ten factors from round one was used. Participants were asked to score each factor based on perceived importance (where 0 was not important and 10 was highly important) and level of uncertainty (where 0 was low uncertainty and 10 was high uncertainty) and suggest trends that may continue in the long-term. For each group, the Kendall's W (coefficient of concordance) was computed to measure the level of agreement in factor scorings using SPSS version 26 (IBM, 2019). The value of 'W′' ranges from 0 to 1, indicating no agreement to perfect agreement respectively within groups. According to Okoli and Pawlowski (2004), a value of $W \geq 0.7$ signifies strong agreement, meaning no further iteration of questionnaire is required. In the present study, W was less than 0.7 for the academic group, hence a third iteration of questionnaire was resent to the said group. Descriptive statistics of scores as well as notes on suggested trends from the previous round was enclosed to help revise their scoring, for participants who decide to do so. The Kendall's W was considered satisfactory after the third round. This produced a scored list of factors by each group in terms of importance and uncertainty and the mean scores of both groups were used to plot the chart of critical uncertainties (the factors that scored high in importance and uncertainty).

Table 1
A summary of factors identified in the literature[8], as important for aquaculture development in Nigeria.

Factor	Description
Government policy	The inconsistency between governments results in unstable economic and other policies. A key aspect being the lack of coherent sector policy for aquaculture that can help to better manage production.
Land	Poorly regulated ownership and cost of purchase or rent of land affect land use. The impact of this will tend to be more on smallholder famers than big businesses that have got better access to resources.
Input supply	The low expertize and technology for fish seed and feed production creates excessive reliance on imported materials in Nigeria. This implies poor distribution and high cost of inputs, with subsidies left as a window (just as in crop production) to sustain increase in farmed fish production.
Disease	Despite the role of good disease management in sustainable production, there is less attention in this direction for aquaculture in Nigeria. This is because major outbreaks are rare, making such measures to be considered by farmers as additional cost.
State of the economy	Macroeconomic factors such as interest rate, unemployment, international trade, GDP affect businesses including aquaculture. These factors are big issues interacting with the fast population growth in Nigeria to influence the demand and supply of farmed fish.
Geopolitical change	This factor clearly impacts aquaculture in Nigeria, given the differences across geopolitical regions, in terms of changing patterns of infrastructural development, economic and cultural landscapes. Although farming intensity is seen to vary across the regions, it is not clear how this is changing over time.
Research and development	There is weak linkage between research institutions and the aquaculture industry in Nigeria. This affects the drive for innovation, which in turn stagnates productivity.
Climate change	The understanding of the effects of changing climate on different livelihood activities including aquaculture is largely based on theoretical/qualitative data in Nigeria. Despite the evidence from changing weather pattern, flood and drought occurrence, the impacts of their interaction on aquaculture production across space and time is unknown.

[8]References: (Adedeji and Okocha, 2011; Adeleke et al., 2020; Anetekhai, 2013; Atanda, 2007; Atanda and Fagbenro, 2017; Magawata and Ipinjolu, 2014)

2.3. Scenario construction

Four scenario themes that depict alternative developments of aquaculture were created using a morphological analysis (MA). MA is a technique used to create a scenario space in which alternative outcomes or perspectives can be explored by a team during problem structuring (Ritchey, 2006). Accordingly, the MA technique was used to form the scenario themes by combining the critical uncertainties that emerged from the previous section, based on a gradient of possible outcomes: low to high (Table 2). Every alternative combination represents one scenario theme. The internal consistency and plausibility of each combination was assessed considering the interdependence between the critical uncertainties, along with their current trends as described by Schoemaker (1995). Each theme was given a title and its narrative developed taking into account other factors and information that were gathered from the Delphi exercise.

2.4. Scenario simulation

Aquaculture development is dependent on the availability of suitable areas to establish farms. Thus, Land Use and Land Cover (LULC) change was used to estimate the potential expansion of pond area under each scenario. The potential pond area was then used to calculate the aquaculture production potential. Such quantitative projection is useful for better understanding of the scenario narratives and assessment of strategic options (Alcamo, 2008).

2.4.1. Land change data and modelling

Global land cover maps for 2000, 2010 and 2015 available at 300 m resolution were downloaded from the ESA-CCI (European Space Agency Climate Change Initiative) database version 2.07 (ESA, 2017). From these maps, the spatial extent of Nigeria was extracted using TerrSet geospatial software system version 18.31 [Clark Labs, Massachusetts, USA] to create the land cover data layers. These were projected onto the Clark Labs Hammer-Aitoff Grid for Africa (CLABSHA), since Nigeria spans across three UTM zones (30N, 31N and 32N) and does not have a

Table 2
Critical uncertainties and boundaries of possible outcome used in the morphological analysis (MA).

Scenario theme	Critical uncertainty I	Critical uncertainty II	Critical uncertainty III	Critical uncertainty IV
1	medium/high	medium	medium	low
2	medium/ medium	medium	medium	medium
3	high/low	high	high	medium
4	low/high	low	low	low

harmonized national grid for projection. The original land use classes were then reclassified into 12 thematic land use categories (Table 3) for use in the change analysis and projection. The land cover data layers for 2000 and 2010 were used to model LULC change and transition potential, and the layer for 2015 was used for validation.

The Land Change Modeler (LCM) in TerrSet was used to analyse LULC change. The LCM enables the user to model an empirical relationship of LULC change based on some explanatory variables to create transition potential maps (TPMs) for every specified transition sub-model. Two transition sub-models (all transitions to urban and to rainfed cropland categories) were considered in this study because aquaculture mostly associates with these two land use categories in the study area. Explanatory variables are drivers that would influence or contribute to a change in land use (e.g., distance to an urban area could be an explanatory variable for urbanisation). The explanatory variables used in the present study are given in Table 4. Given the large study area, common physical explanatory variables of land use change (e.g., slope) (Linard et al., 2013) was selected along with a key socioeconomic variable (population/wealth indicator) (Stehfest et al., 2019) for each sub-model. The TPMs indicate the potential of each pixel to transition from one LULC class to another, thereby helping to project future changes (Eastman, 2016a).

The spatial layers of the distance variables were created from the ESA-CCI extracted LULC map of the study area for year 2000. The elevation layer, resampled (bilinear) to 300 m, was derived from the 90-m hole-filled SRTM for the globe Version 4 (Jarvis et al., 2008). Slope was derived from the elevation layer. A map of state boundaries was obtained from DIVA-GIS (https://www.diva-gis.org/gdata), and used to create the poverty index data layer using data obtained from UNDP (2018) and the population density layer using data from NBS (2021). The population density layer was normalised to values between 0 and 1. The empirical likelihood variables were created using the variable transformation utility tool in the LCM. All the data layers were projected onto CLABSHA.

2.4.2. Land use change quantification and transition potential modelling

For the LULC change analysis, the reclassified LULC layer for year 2000 was used as the start date and LULC layer for year 2010 was used as the later date (Fig. 2). The loss and gain in area (hectares) were computed for each LULC class, with every change representing a transition. Focusing on the two transition sub-models specified above (all transitions to urban areas and to rainfed cropland categories), only transitions that were greater than five percent of the highest in each sub-model were considered in this study. The rationale was that those transitions less than the threshold may not be worth modelling relative to the highest transition that occurred between 2000 and 2010.

Table 3
Reclassified LULC values with their new label for the study area.

Original value	Original label	New value	New label
0	No data	1	No data
10, 11	Cropland, rainfed	2	Rainfed cropland
20	Cropland, irrigated or post-flooding	3	Irrigated cropland
30	Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover) (<50%)	4	Mosaic vegetation
40	Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland	4	
50	Tree cover, broadleaved, evergreen, closed to open (>15%)	5	Forest
60, 62	Tree cover, broadleaved, deciduous, closed to open (>15%)	5	
100	Mosaic tree and shrub (>50%) / herbaceous cover (<50%)	6	Mosaic forest
110	Mosaic herbaceous cover (>50%) / tree and shrub (<50%)	6	
120	Shrubland	7	Shrubland
130	Grassland	8	Grassland
150	Sparse vegetation (tree, shrub, herbaceous cover) (<15%)	8	
170	Tree cover, flooded, saline water	9	Marshy areas
180	Shrub or herbaceous cover, flooded, fresh/saline/brackish water	9	
190	Urban areas	10	Urban areas
200	Bare areas	11	Bare areas
210	Water bodies	12	Water bodies

Table 4
Explanatory variables for modelling transitions to urban areas (sub-model I) and to rainfed cropland (sub-model II) LULC.

Sub-model I	Sub-model II	Operation[§]
Distance[†] from urban areas	Distance[†] from rainfed cropland	Dynamic
Population density by state	Poverty index by state	Static
Elevation	Elevation	Static
Slope	Slope	Static
Empirical likelihood of change[‡] to urban area	Empirical likelihood of change[‡] to rainfed cropland	Static

[†] Distance refers to Euclidean distance between each pixel of urban areas/rainfed cropland to the nearest pixel of other LULC.
[‡]Empirical likelihood of change is the quantitative representation of a LULC based on its vulnerability to change to either of the two LULC classes being modelled.
[§]Operation: Dynamic means that the distance will be recalculated at the end of every interval during the land change prediction, whereas Static operation remains constant.

In creating the TPMs, the Multi-Layer Perceptron Neural Network (MLP-NN) option in the LCM was used since there was more than one transition in a sub-model. The MLP utilizes a back-propagation algorithm to train and test for each transition sub-model. The process starts from random selection of samples of the pixels that transitioned and those that did not (persisted). Thereafter, the MLP selects 50% of these sample pixels for training and keeps the remaining 50% to test the predictive power of a transition sub-model. The training/testing is then allowed to run on default parameters or modified. In the present study, some parameters were modified as shown in Table 5, following recommendations in Eastman (2016a).

The MLP trained on the sample pixels and developed a multivariate function for predicting the potential for transition (to urban areas and to rainfed cropland) based on the values at any location for the five explanatory variables provided for each sub-model. This means that the five variables specified for each of the two sub-models were used to explain their respective transitions which occurred between 2000 and 2010.

The transition potential maps (TPMs) were then created for each sub-model following a satisfactory accuracy and skill measures output from the MLP training/testing. The skill measure (Eq. 1) of the sub-model increases with increase in its accuracy rate as the MLP continued to run (see Eastman, 2016a for further information on the MLP-NN process). The skill measure varies from − 1 (worse than chance) to + 1 (Perfect prediction) with a skill of 0 indicating random chance.

$$\text{Skill measure} = (A - E(A)) / (1 - E(A)) \quad (1)$$

where A = measured accuracy.
E(A) = expected accuracy. E(A) = 1/(T + P).
T = the number of transitions in the sub-model.
P = the number of persistent classes.

2.4.3. Model validation

The final model is made up of the two transition sub-models, each containing a set of TPMs. To validate the model, LULC map of 2015 was predicted and compared with the actual 2015 LULC map.

In predicting change, the LCM used the Markov module to quantify the pixels or area that would change by the specified prediction date.

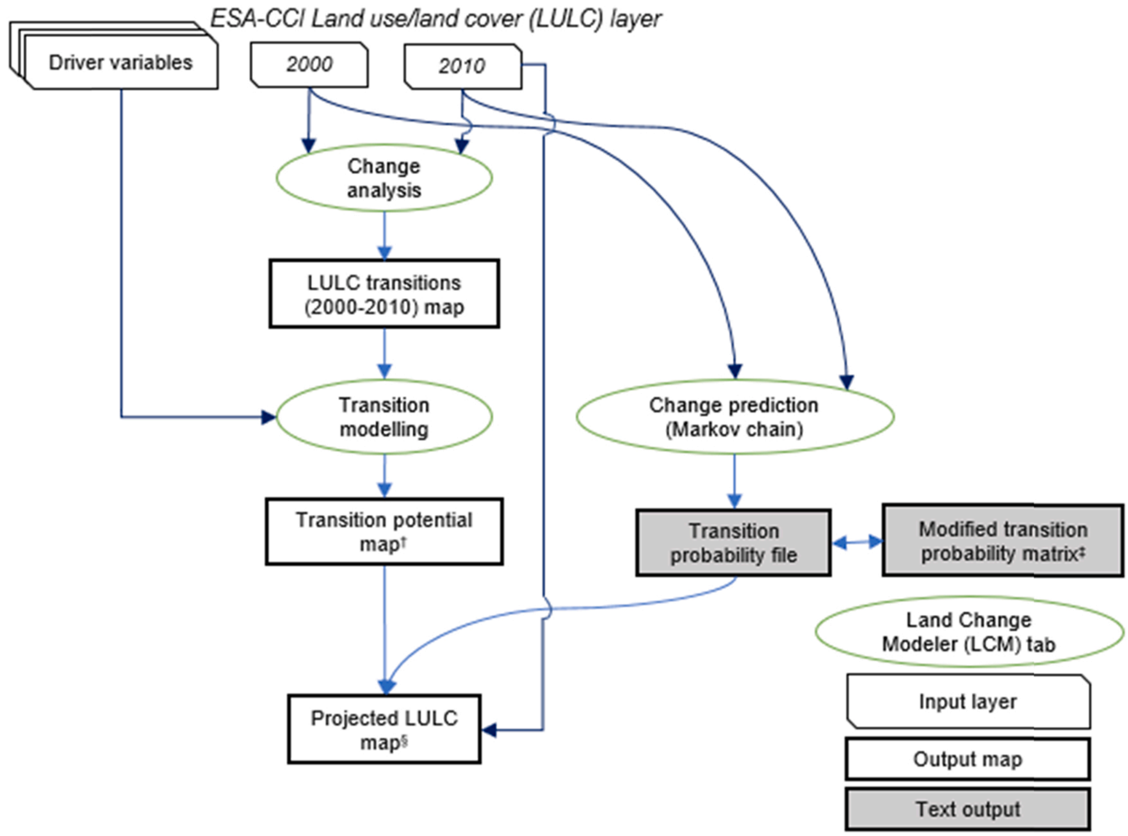

Fig. 2. Flowchart of the land change modelling procedure. Note: †Transition potential maps are regenerated at every interval of prediction (5 intervals from 2010 to 2035) as the distance variables are recalculated. ‡Four different transition probability files, each representing one scenario projection. §One LULC map produced at the end of each stage of prediction per scenario.

Table 5
Values of the parameters, default (*modified*) for running the MLP neural network.

Parameter	Value
Sample size per LULC class	Sub-model I = 849 Sub-model II = 10,000
Training	
Learning rate	0.01 (***0.00238***)
Momentum factor	0.5
Sigmoid constant	1.0 (***3.0***)
Hidden layer node	3 (***9***)
Stopping criteria	
RMS error	0.01
Iteration	10,000
Accuracy rate	100%

The module then outputs a transition probability matrix, calculated as the ratio of the number of pixels that are expected to change or persist per LULC class to the total number of pixels across rows. The probability matrix can be modified to portray different scenarios of future land change (Eastman, 2016b). Finally, the LCM spatially allocates the expected change according to the TPM of each transition. The allocation starts from the pixels with the highest potential to change and continues in that order until the change demand was met for each transition. The predictive power of the model was tested using Eq. 2 (Eastman, 2016b).

$$S_r = [h/\Sigma\ (h, f)]\ x\ 100 \quad (2)$$

Where S_r is success rate (%); h (number of hits) = areas correctly predicted to change and f (number of false alarms) = areas predicted to change but did not.

2.4.4. Land use change and aquaculture projection under each scenario

Quantitative simulation of pond aquaculture production under each scenario was achieved using Eq. 3. This was based on adaptation of the original concept of FAO (1984) which determines how a country could be designated as aquaculturally developed. The FAO (1984) concept involve setting a target production, indicated as per unit (of current population and areas of rainfed and irrigated croplands), then comparing these values with the situation in a designated aquaculturally developed country (ADC) to assess feasibility. In the present study, projected population and land use change were used rather than a comparison with supposed ADC. The change in pond area was modelled relative to change in the areas of urban and rainfed cropland LULC following the narrative of each scenario. This assumption was necessary because land use maps containing fishpond as a land use class was unavailable for the study area.

$$A_p = P_t\ x\ Y_t \quad (3)$$

Where A_p is aquaculture production in pond (Kg); P_t is pond area (ha) and Y_t potential yield (Kg/ha) each year.

LULC change to urban areas and rainfed cropland from 2010 to 2035 was projected under each scenario at 5-year intervals. For the baseline scenario in which past to present trend of events is expected to continue, simulation was achieved as follows: (1) The LCM was allowed to use the Markov projected quantities of change (transition probability) per modelled LULC to 2035. (2) The TPMs changed automatically after every 5-year interval because they were recalculated by the MLP at the end of each period, based on the dynamic operation specified for the distance to urban areas/rainfed cropland variables.

For the alternative scenarios, the projected quantities of change originally determined by the Markov module was modified (Table 6) by altering the probability matrix. Based on the detected change in LULC (between 2000 and 2010 & 2010 and 2015), a plausible range of deviation from a baseline projection up to 2035 was assumed to be 1–5%.

Table 6
Values[8] used to modify the transition probability matrix and pond yield for each scenario.

Scenario	Transitions to		Potential yield (%)
	urban areas (%)	rainfed cropland (%)	
1 (Baseline)	0	0	0
2	+ 1	-1	0
3	-1	+ 1	+ 30
4	+ 0.5	+ 0.5	+ 15

[8]Values show cumulative change within the projection period (i.e., between 2010 and 2035). A change of − 1% means a loss of 0.01 in the probabilities of expected transitions (indicated in the original matrix) to urban areas or rainfed cropland and a gain of 0.01 by the other LULC. Every row must equate to 1 (i.e., the sum of probabilities of expected transitions and persistence). In scenario 4, the + 0.5% change for the two LULC refers to a gain of 0.005 each from the probabilities of expected persistence. Change in potential yield was assumed to start from 2025.

However, 1% deviation was used here because not all transitions were modelled. Whereas the signs show the direction of deviation considering each scenario narrative. The LCM then allocated the projected quantities according to the recalculated TPMs in each scenario. On the other hand, change in fishpond yield was assumed to be a function of the relevant factors described by each scenario narrative. Hence, a plausible percent change in yield was specified for each scenario (Table 6).

Each scenario simulation produced five maps (5-year interval), from which the areas in hectares of urban and rainfed cropland LULC were computed. The proportion of urban and rainfed cropland area in the actual LULC map 2015 that equated to 150,000 ha (available data on existing pond area as at 2015 according to FDF, 2017) was used to model past and future change in pond area.

The average annual yield from fishponds in the baseline scenario was 1500 Kg/ha, i.e., the lower limit for commercial pond yield (1500 – 3500 Kg/ha) as reported by FDF (2017). The results of pond aquaculture production were then generated by applying Eq. 3 under each scenario. Production per capita were also computed using the UN (2015) projected population of Nigeria.

3. Results

3.1. Critical uncertainties and trends

From the Delphi exercise, the Kendall's 'W′ for the scores of factor importance was 0.771 (Chi -Square = 62.564) in the 'academic' group and 0.834 (Chi-Square = 67.564) in the 'practitioner' group. For the scores of factor uncertainty, 'W′ was 0.775 (Chi -Square = 62.735) in the 'academic' group and 0.824 (Chi-Square = 66.728) in the 'practitioner' group. A value of $W \geq 0.7$ signifies strong agreement. Fig. 3 shows the critical uncertainties (factors with high score in importance and uncertainty) of aquaculture development in Nigeria identified in this study. Availability/cost of input was the highest scoring critical uncertainty. However, LULC, climate change and government policy appeared in the same quadrant of the plot, hence, were all considered as critical uncertainties.

3.2. Scenario themes

The themes of the four scenarios are given in Table 7. Scenario S1 portrays a baseline situation in which past to present trends of aquaculture-related events are thought to continue up to 2035. As Availability/cost of inputs was the highest scoring critical uncertainty, it was a key focus and differentiator in the themes. In S1, there is a medium availability and high cost of inputs like fish feeds and fingerlings which is a somewhat preferred outcome. In S2, the medium availability and cost of inputs also portray a somewhat preferred outcome, while in S3, high availability of low-cost inputs show the most preferred (positive) outcome. S4 is the least preferred (negative) outcome with low availability of high-cost inputs. Also, evidence-based government policies, effective regulation of land use and fair understanding of climate change impact on aquaculture as in S3, are favourable outcomes for aquaculture development, which contrasts with the situation in S4 scenario.

3.3. Scenario narratives

The four scenario narratives are presented as follows.

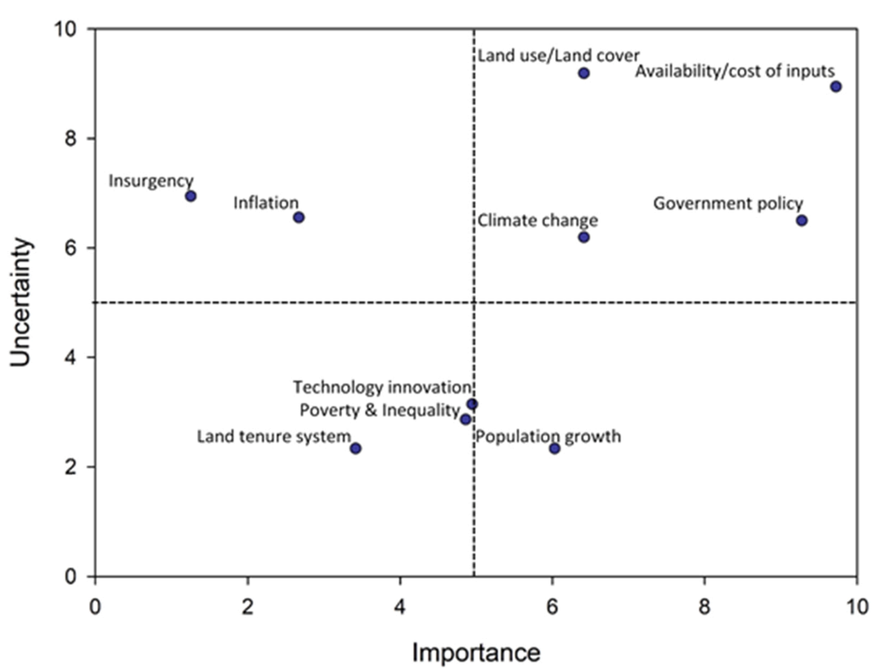

Fig. 3. Two-dimensional plot of factors with all four critical uncertainties in the top-right quadrant.

Table 7
Possible outcomes defining the critical uncertainties under each scenario.

Scenario	Availability/cost of inputs	Government policies	Land use & land cover change Regulation:	Climate change Understanding of impact/adaptation:
S1: A familiar route	Medium/high	Politically motivated	Ineffective	Poor
S2: Vicious cycle	Medium/medium	Politically motivated	Ineffective	Fair
S3: Nipped in the bud	High/low	Evidence-based	Effective	Fair
S4: Autopilot	Low/high	Largely absent	None	Poor

3.3.1. A familiar route (S1)

This is the baseline scenario. Nigeria follows a path in which past-to-present social and economic trends remain largely unchanged. Aquaculture is receiving the same kind of attention by the relevant authorities as it used to since the activity became popular in the early 2000s. Fisheries supply is almost flattened across the country. The costs of animal feed, raw materials and energy are rising without a corresponding rise in farmed fish price. The effects are seen in small to medium scale fish farmers gradually crashing out of business. Support schemes by relevant government agencies and NGOs providing soft loans and incentivized training, are increasingly available to existing and prospective fish farmers. Wealthy individuals and companies are taking advantage of the schemes to establish farms with arrays of water recirculating fish tanks with few earthen ponds. Land use regulation and tax regimes are weak, such that extensive land around peri urban areas is easily converted from one use to another. It is not clear how much progress has been achieved in the use of local feed materials and brood stock development due to lack of reliable data for evaluation. The impacts of changes in temperature, rainfall pattern and desertification on pond farms across geographical regions are not understood.

3.3.2. Vicious cycle (S2)

Human population in Nigeria grows as expected with significant rise in urbanization than baseline projection. Alleviating poverty and inequality remain a big challenge. The government is offering subsidies on imported animal feed including raw materials, causing significant rise in imports. More erratic rainfall and reduced stream flow is being experienced, even in the southern region. The water use legislation is in force, so measures are becoming stricter for conserving ground & surface waters along with aquatic resources. The expected decrease in the rate of expansion of fish farms, is however counteracted by the low-interest loan packages available for prospective and existing fish farmers. Other challenges include the growing competition for land between large-scale pond and rice farmers in some states. Allocation decision requires local knowledge, but there is insufficient data on both resource use efficiency and household economies. Since urban dwellers have better access to the government incentives, many are establishing fish farms in rural areas which are managed mostly by rural inhabitants.

3.3.3. Nipped in the bud (S3)

Following a strategy road map to implementing a comprehensive long-term aquaculture development plan, Nigeria sees light at the end of the tunnel. The country's urban population is growing at a significantly lower rate than expected. This may have resulted from the increasing number of manufacturing industries being established around rural areas. Road networks are rapidly improving with rail lines increasingly functional. In a bid for protectionism, the government aggressively regulates import and cost of inputs, while recording some progress in the development of local feed resources. Food systems research is being strategized, helping to create links with industries. The effort to develop tilapia and shellfish production is being intensified, while major private and government owned fish hatcheries are setting up promising breeding programs for *Clarias gariepinus*. The federal department of fisheries (FDF) have identified highly suitable land areas away from urban areas for large scale catfish production. Although, the process for obtaining license and the requirements to meet regulatory standards are yet to be established. Short-term droughts are more frequent in the Sudan-Sahel agroecological zone resulting in reduced water availability for fish farming.

3.3.4. Autopilot (S4)

Because the contribution of aquaculture to Nigeria's GDP is deemed negligible, no deliberate plan targets its development at the national level since the short-term national plan of 2011. Urban population and GDP growth rates are slightly more than the baseline projections. Only few states are attempting to provide guidelines for increasing cage fish farming to boost production. Built-up areas are more compact in the supposed peri urban areas as population density increases. Due to widening inequality, the proportion of the population living in extreme poverty increases proportionally to changes in population size. Many local authorities do not have legal restrictions on land conversion, and aquaculture widely remains a peri urban affair. Prices of most commodities including fish are unregulated. To stay in business, many small-scale fish farmers are cutting down on production cost by using waste food materials, including from slaughterhouses to feed their fish. Some have resorted to seasonal farming following the availability of these materials. Others do so in response to seasonal variation in temperature and rainfall.

3.4. Quantitative projection

3.4.1. Land use change

The results of LULC change analysis is shown in Fig. 4. Every LULC class lost land to others between 2000 and 2010; only the urban area did not. In year 2000, urban area was approximately 284,000 ha and rainfed cropland was 41,110,000 ha. From 2000–2010, a total of 233,000 ha was gained by urban area from the other ten LULC classes, while rainfed cropland gained 1,680,000 ha from eight classes (Fig. 4. a and b respectively). However, the transitions to urban area between 2000 and 2010 that were above the set threshold (5% of highest transition or 4600 ha) were from marshy area, forest, grassland, shrubland, mosaic vegetation, and rainfed cropland. In the case of transition to rainfed cropland, only forest, grassland, shrubland met the 5% or 64,000 ha threshold.

3.4.2. Transition model and validation

The model comprises a set of transition potential maps for each of the selected transitions to urban areas and rainfed cropland LULC (sub-model I and II respectively). The skill measure of urban sub-model is 0.69, and 0.65 for the rainfed cropland sub-model. This suggests that the transitions to urban areas and rainfed cropland LULC in the training dataset (2000–2010) were adequately predicted. For predicted transitions between 2010 and 2015, the overall model shows a success rate of 24.3% (Fig. 5). Whereas the difference in quantity of change between actual and predicted LULC in 2015 (S1, baseline) is shown in Fig. 6. The model underestimates urban areas in 2015 by 2.52% and overestimates rainfed cropland by 0.95%, when the actual quantities were 0.647 million ha and 42.881 million ha, respectively.

3.4.3. Projection of land use change under the four scenarios

The change projected for urban and rainfed cropland areas under each scenario are given in Fig. 6. Between 2010 and 2035, the baseline

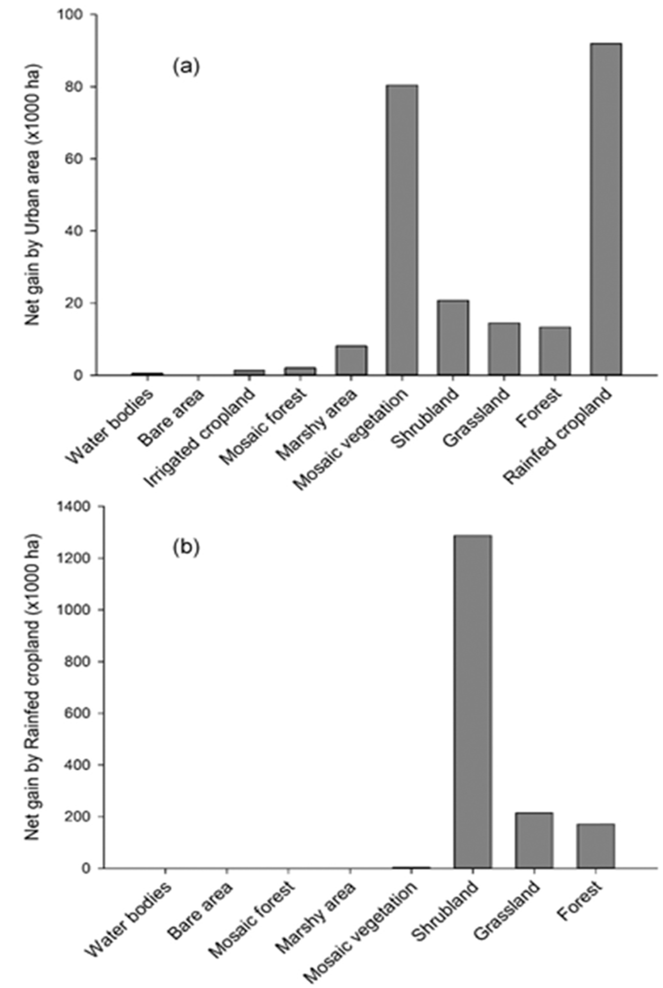

Fig. 4. Contributions to net gain experienced by Urban areas and Rainfed cropland between 2000 and 2010.

projection (S1) shows a 110% increase in urban areas. In the same period, rainfed cropland experienced an increase of only 6.9%. The three alternative scenario projections show the effects of at least 1% change respectively, in LULC transitions to urban areas (a) and rainfed cropland (b). In S2 (Vicious cycle), urban areas increase significantly, while rainfed cropland experiences slow growth rate as describe in the scenario narrative. In the S3 scenario (Nipped in the bud), where a greater control of urban sprawl is portrayed, urban area is projected to increase by 90% between 2010 and 2035, while rainfed cropland increased by 7.2%. The S4 (Autopilot) projections show higher increase for urban areas than those of S1 and S3 but less than S2 projection. For rainfed cropland, S2 projection is least and shows a marked deviation from others.

3.4.4. *Projection of pond aquaculture production under the four scenarios*

Based on the actual LULC map and the estimated area of aquaculture pond in Nigeria as of 2015, this study shows that aquaculture pond area was only 0.35% of the area of rainfed cropland and 23% of urban area. As seen in the land use change results in Fig. 6, the rate of increase in urban areas (a) is significantly higher than rainfed cropland (b). Therefore, the estimate of pond area projected by 2035 relative to change in urban area almost double the projections based on rainfed cropland in all scenarios. As a result, in Fig. 7, the projected aquaculture pond production across scenarios varies more in (a) than (b). In the baseline (S1) scenario, the estimate is 376,000 t and 240,000 t respectively by 2035. On a per capita basis, the projections of aquaculture production show a steadily increasing upward trend in the S3 scenario in (a) compared to others. Also, the trajectory of S3 in (b) is less steep than others. Thus, signifying the role of improved yield per hectare of pond area. However, the results show the range of possible per capita production to be between 0.7 and 2 kg/person/year by 2035.

4. Discussion

This study evaluates the potential future of aquaculture development in Nigeria using a scenario approach. Scenarios are useful to help stimulate creative thinking among stakeholders in designing interventions for development. The four scenarios described in this study represent four alternative, but plausible trajectories of aquaculture development based on a range of critical uncertainties and other factors identified in this study. The S1 scenario (a familiar route) considers the past and present situation of the Nigerian aquaculture sector and projects this to 2035. By so doing, it presents a comprehensive picture of the nature of opportunities and threats, to inform development planning. For example, as the availability/cost of fish feed is the priority constraint found in this study, stakeholders could use the scenario narratives around this constraint to develop interventions. Because aquaculture production cost has been increasing across the country without reasonable returns, the chances to make change also increase. However, if intervention(s) fail to consider options for aggressively developing local feed and seed resources and improve yield, their benefits may be short-lived. As noted by Chan et al. (2019), the African continent is likely to remain a huge net importer of fish up to 2050, and this indicates opportunities for businesses to develop if the needed policies are put in place. These suggestions reiterate the fact that scenarios are not meant as forecasts or predictions, but plausible descriptions of how the future might play out, based on a coherent and internally consistent set of assumptions about driving forces (Badjeck et al., 2011).

Land use change is another important factor identified for aquaculture development. The S1 scenario describes a situation where the pattern of land use change continues for most of the categories including inland fishpond expansion. If the average yield from pond is maintained at the same rate of 1500 kg/ha, then production (according to Fig. 7) will range between 240,000 t in (b) and 376,000 t (a) by 2035. This means that, on a per person basis, total production in ponds will not exceed 1.2 kg. However, If the 2.5 million t potential annual production were to be realised by 2035, this would mean a per capita production of 8 Kg/person/year based on the UN projection of Nigeria's population. Thus, looking at the scenarios presented in this study, there will be a gap of over 6 kg per capita that can be met by other production systems such as flow-through and cage by 2035. On the contrary, using the FAO (1984) ADC concept may imply that the 8 Kg/person/year would be feasible in ponds, just by considering China's achievement for example, as a reference point. In China, pond area had reached 2 million hectares with average yield of 7500 kg/ha since 2010 (Wang et al., 2015), implying about 15 kg of pond aquaculture production per capita (given a population of 1 billion).

The S2 (Vicious cycle) is a slightly different pathway from that of S1. It shows some positive results but unsustainable. S2 describes some policy actions that may be politically motivated rather than based on evidence. For example, subsidizing the cost of imports at the detriment of local feed resource development for animal production will rarely do the aquaculture sector any good. The importance of regulating the aquaculture value chain in a manner that encourages both smallholder farmers as well as low-income consumers have been discussed by Chan et al. (2019) and Kaminski et al. (2020). Providing loan packages to farmers where the business environment is hostile, especially to resource poor farmers will not yield expected outcome. Inequality will continue to spread across communities, along with rural-urban migration.

Scenario S3 (nipped in the bud) highlights an alternative future development that offers better prospect for aquaculture growth. The scenario indicates a potential for the aquaculture sector to achieve a

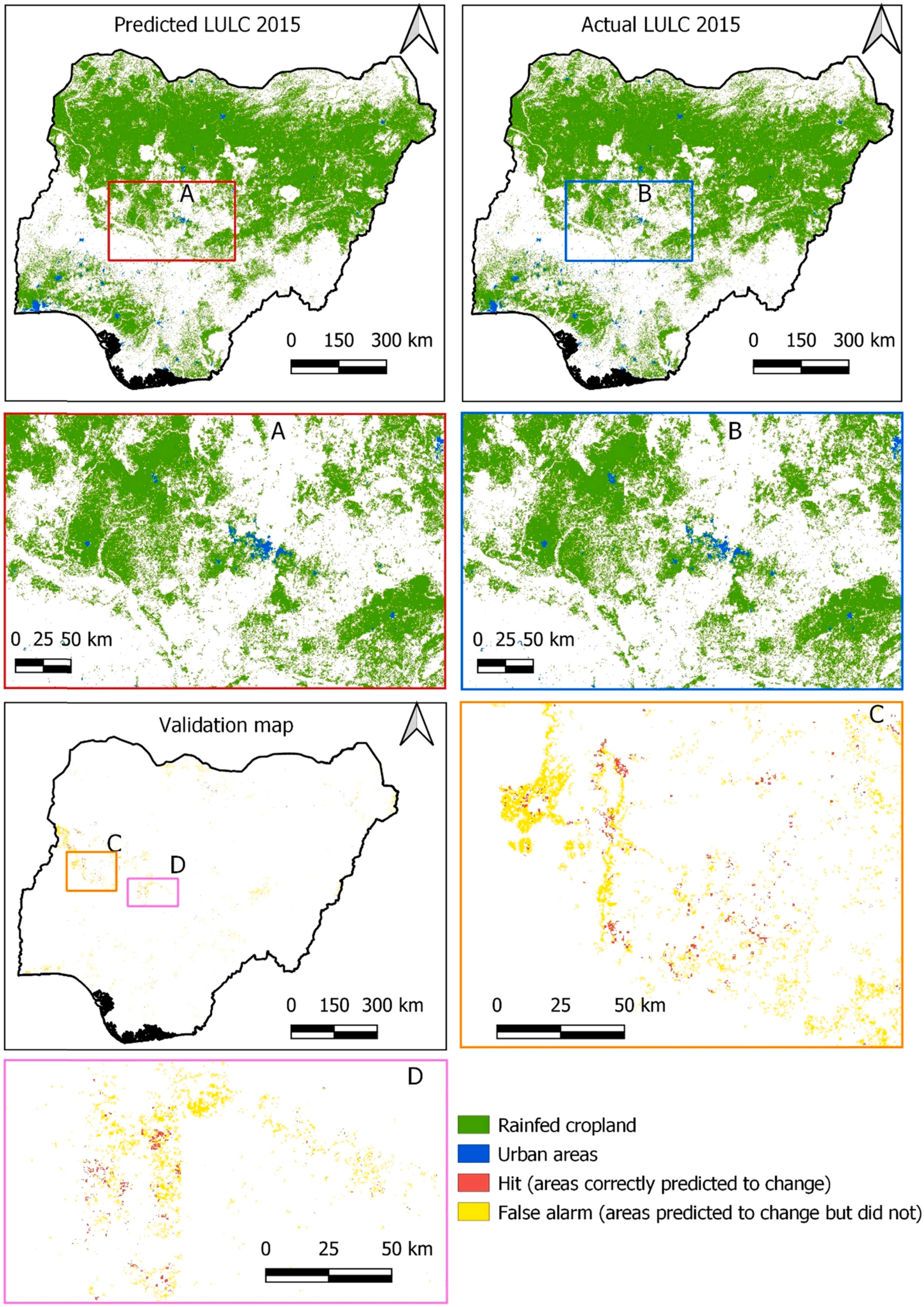

Fig. 5. Predicted, actual and validation maps for Urban areas and Rainfed cropland LULC (Land use/land cover) between 2010 and 2015.

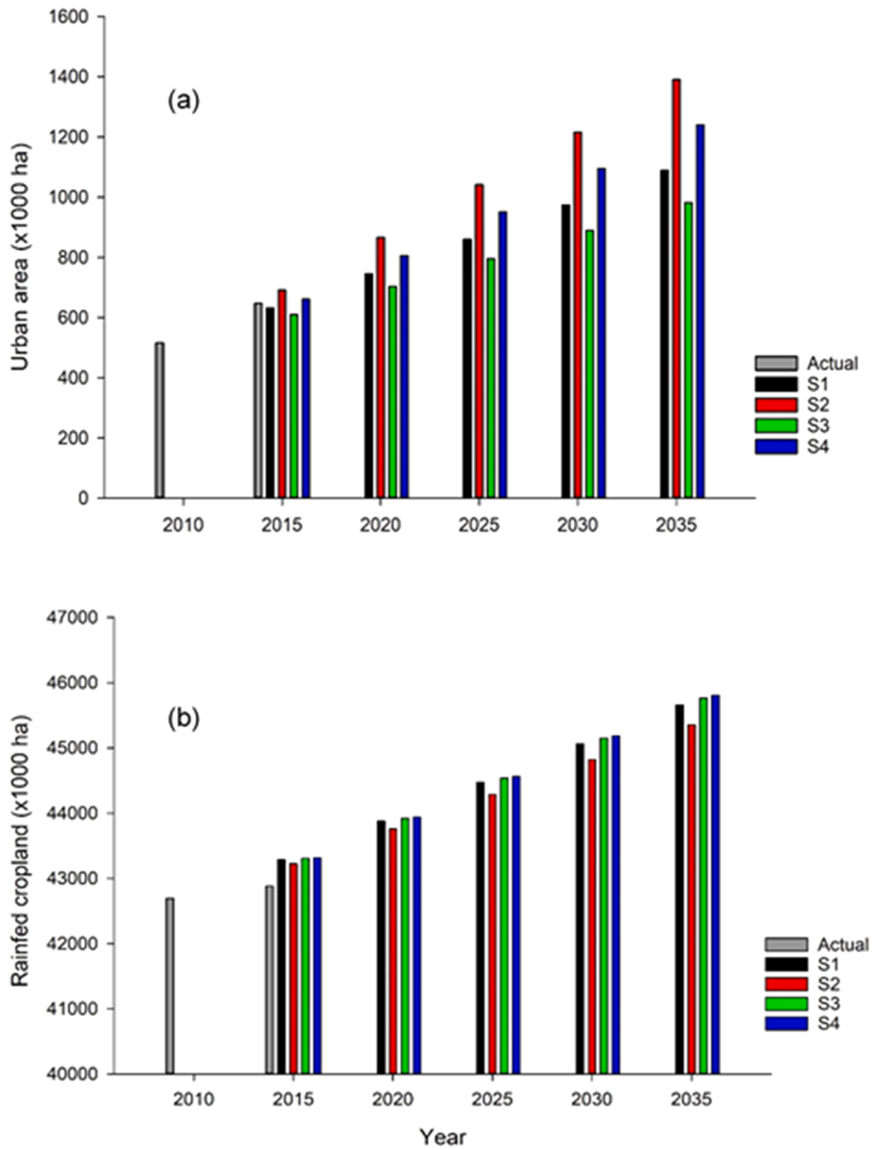

Fig. 6. Projected change in Urban areas (a) and Rainfed cropland (b) across the different scenarios.

significant and sustainable transformation, resulting from the implementation of evidence-based policies. This includes aquaculture not being treated in isolation, such that exogenous aspects to the industry are considered alongside the internal ones. For example, while improving farming practices and development of less popular aquaculture species, land use zoning and international trade for aquaculture must consider the sector as part of a whole. The ecosystem approach to aquaculture (FAO, 2008) is a framework that links the internal and external parts of aquaculture development.

The knowledge of climate change impact on aquaculture is important for planning. In scenario S2 and S3, the situation was termed 'fair' to portray a sector which has begun to benefit from a robust research investment. In scenarios for fisheries and aquaculture development in west Africa by 2050, Badjeck et al. (2011) described the role of climate change. It is also important to note that some plans like establishing breeding programme and developing raw materials for feed are a long-term investment. Hence, the trajectory of aquaculture production in S3 would be less steep if pond yield were assumed to improve later than 2025. Gephart et al. (2020) suggests the possibility of reduced production efficiency and protein intake across middle and low-income countries, if nationalism is upheld as global aquaculture evolves. Some reasons being that technology transfer will be limited, regulatory systems will be underdeveloped and import barriers will affect feed prices. National authorities must however uphold the role of governance (FAO, 2017) during interventions for sustainable aquaculture development.

On the other hand, scenario S4 describes a situation in which the national government trivializes the role of aquaculture in its food security and economic plans. Farmers and other actors along the value chain are then forced to take absolute responsibility for aquaculture activities around the country. In this case, production may continue to rise with increasing urbanization and average income. But increasing average income does not translate proportionally into betterment of the livelihoods of more numbers of poor farmers or consumers due to widening inequality. Market forces could favour fish prices, hence sustaining the upward trend in production in the mid to long-term, given a steady consumer preference. However, the public health concern from excessively improvising farming methods by smallholders may harm the industry's food safety reputation. Resorting to uncontrolled usage of slaughterhouse wastes for instance, to feed pond fish directly, increases the risk of transmitting parasites (Glencross et al., 2020).

The methodology adopted in the present study combined recommendations from both business and environmental scenario literatures. Nowack et al. (2011) suggested the integration of Delphi technique in

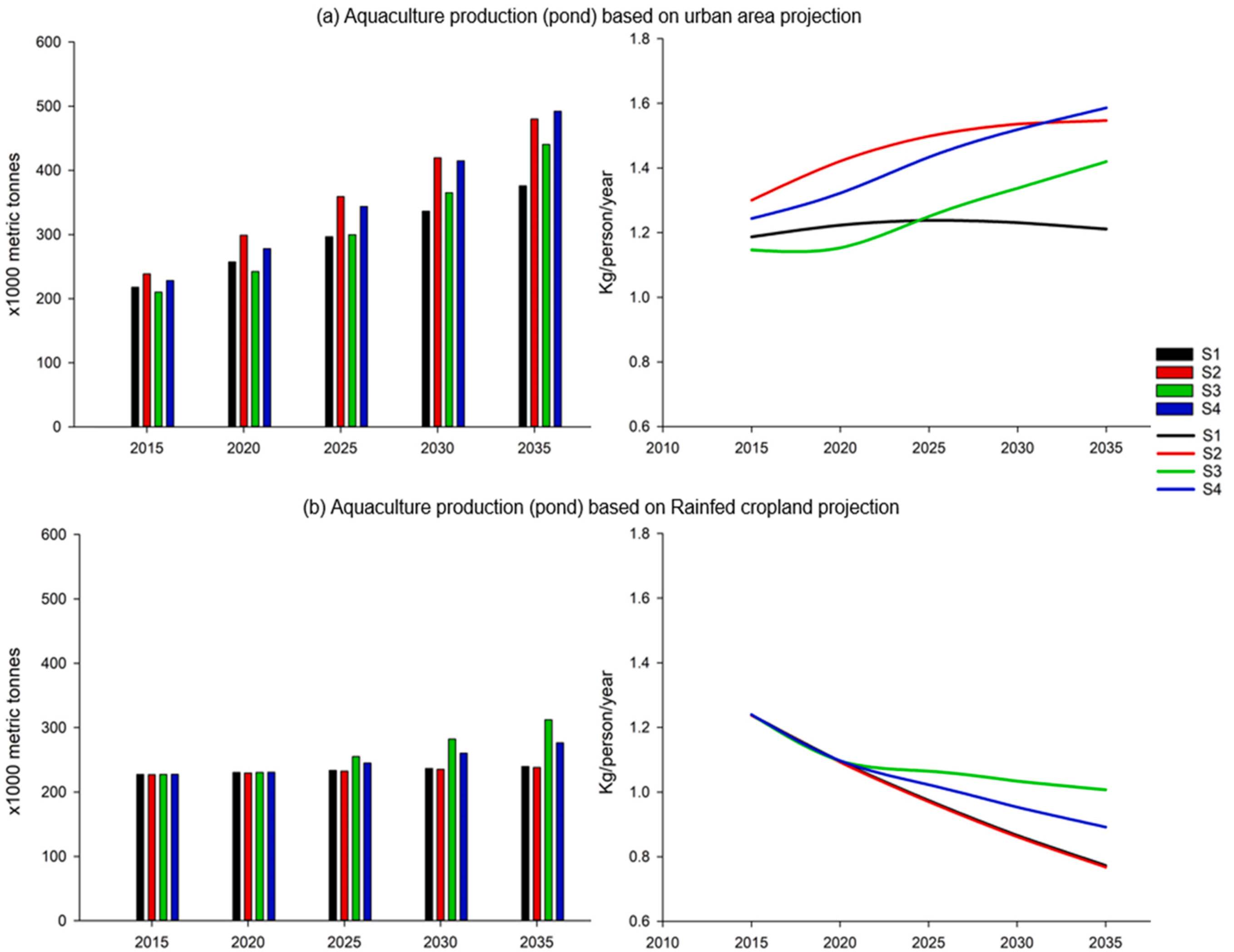

Fig. 7. Projected aquaculture production (t) in pond, as total and per capita, across the different scenarios.

scenario building process when expert knowledge is required to boost credibility and objectivity. The Delphi method was used here to support the ideas generated previously from the literature. Qualitative and quantitative scenarios were combined to promote transparency and reproducibility of the narratives and complement model assumptions. Ideally, scenarios should be interrogated by a guidance team through which iterations are necessitated (Alcamo, 2008). But the supposed users in the study area were assumed not to be familiar with the scenario approach, as its application has only just begun in aquaculture. Hence, the present study used expert opinions from the Delphi exercise instead, as well as the literature regarding aquaculture in Nigeria, to shape the narratives and simulation. While acknowledging that certain assumptions may be limited by the availability and quality of data, they are sometimes necessary. For example, modelling rainfed cropland and urban area as proxies for cultivated pond area was thought reasonable, since estimates of change in pond area can better inform strategic options for aquaculture development compared to the use of common indicators like fish demand.

Importantly, models such as the land use model used here, are inherently sources of uncertainty since they attempt to simplify complex systems. Although, the scenario narratives often serve to manage such uncertainties (Reilly and Willenbockel, 2010), different combinations of the driver variables and/or incorporation of the error maps from the validation results may help improve the simulation outputs. Also, future studies may reflect on the nuances of aquaculture. Firstly, aquaculture can be characterised by species, system, production scale, geographic scale, etc., and each of these can uniquely define the topic of a scenario analysis. Secondly, the interdependence of aquaculture and fisheries is considerable (Kristofersson and Anderson, 2006) yet, it seems difficult to associate them with the same set of drivers (Ravagnan et al., 2016). Despite these, global food models used for simulating aquaculture production treat aquaculture products as commodities often from an econometric point of view. Therefore, more specialised tools that includes environmental and technological interactions for foresight modelling in fisheries and aquaculture will be useful. For Nigeria in particular, improved regulatory and data collection protocols are required and further studies should address options for improving farming practices, sustainable land use and potential impacts of change in consumer preference.

In conclusion, the Nigerian aquaculture sector is unlikely to realize its estimated potential of 2.5 million t annual production (FDF, 2017) by 2035, if the current trend of change in price of fish feed, land use change and research investment continue. For this estimate to be reached, aquaculture must grow by at least 21% from 2025 to 2035. This requires interventions to both expand aquaculture production areas and improve yield through efficient resource use. In terms of expansion, the findings in this study point to the need to integrate aquaculture pond in land use plans. This will help to identify and establish highly suitable sites for the sustainable development of aquaculture and encourage clustering of farms. Cluster farming may be a way to improve farmers access to financial and technical supports as well as strengthen aquaculture value chain in Nigeria. Scenario planning shows the potential effects of action and inaction on a long-term basis. With the rapid growth of total and urban population in Nigeria, fish demand will increase and land use pattern may change across geographic locations. The country's aquaculture development strategy and plans must respond accordingly to ensure a sustainable future for the sector.

CRediT authorship contribution statement

Suleiman O. Yakubu: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, **Lynne Falconer**: Conceptualization, Methodology, Writing – review & editing, **Trevor C. Telfer**: Conceptualization, Writing – review & editing, Supervision.

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 1. Questionnaires

1. Name

2. Email:

3. Affiliation:

Delphi 1: Factor identification questionnaire

1. In your opinion, what are the requisites for Nigeria to realize its estimated potential of 2.5 million metric tonnes (t) of aquaculture fish production? *Please type in the box below*

2. On a scale of 0 - 5 (0=not at all, 5=high), to what extent do you agree with each factor in the list below as an important driver of change for pond aquaculture in Nigeria?

ID	Factor	Scale
1	Population growth	
2	Poverty and Inequality	
3	Climate change	
4	Availability/cost of inputs	
5	Land use & land cover change	
6	Inflation rate	
7	Unemployment rate	
8	Geopolitical change	
9	Research-Industry relationship	
10	Land tenure system	
11	State of technology	

3. Please state additional factors that you feel are missing from the above list. *Please type in the box below*

Delphi 2: Factor uncertainties and trends questionnaire

1. Below is a shortlist of factors suggested by all the experts; in your judgement, please rank in order of importance and uncertainty for pond aquaculture development in Nigeria.

Factor ID	Factor	Rank	
		Importance	Uncertainty*
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			

**Uncertainty refers to the extent to which a factor is out of the industry's control and the likelihood that any change in the factor will impact aquaculture.*

2. Looking at the current state of factors, what trends do you expect to continue in the long term (10 – 20yrs)? *Please type in the box below*

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