# FRESH WATER FISH FARMING SUITABILITY ASSESSMENT – CENTRAL AFRICAN REPUBLIC

## Draft version

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# Abstract

The aim of this report is to document Central African Republic fresh and warm-water fish farming suitability assessment, for the African Catfish and Nile Tilapia species. This aquaculture geographic information systems (GIS) multi-criteria decision analysis (MCDA) study was developed under the scope of the FAO Hand-in-Hand Initiative.

Sub-Saharan Africa fish farming context and background were assessed through literature review. The modelling methodology developed from Aguilar-Manjarez and Narh 1998 - A strategic reassessment of fish farming potential in Africa. The GIS-MCDA approach uses weighted factors including market demand, poverty, infrastructure, livestock and crop inputs, and biophysical (soil, slope, water availability), potential fish yield, and photovoltaic (PV) energy generation potential. Constraints or exclusive criteria were applied distinctly to different farming system models: protected areas, densely urbanized areas, large water bodies, flood areas, distance to major roads, and access to information technology and communications.

Results consist of a set of models, sub-models, and final mapping outputs which indicate the potential for high return on investment optimal sites, aimed at intensive fish farming for both closed catfish (tanks, raceways, ponds, recirculating aquaculture systems) and open tilapia ( cages in water bodies) systems, and zoning at regional and *Prefecture* scale directed at open non-intensive integrated pond systems, with potential impact on poverty alleviation, improving nutrition, and food security.

Results show intensive closed farming systems suitability spatial pattern centred around output markets, urban areas in the country western regions: Bocaranga, Bouar, Carnot, Berbérati, and Nola. In the Plateaux region southwest of Bangui. In the south: close to Bangassou and the Democratic Republic of the Congo border.

Tilapia open intensive systems in water bodies using open-net pens/ cage techniques, highest location score areas can be found in the more populated areas of the west and south regions Yadé, Equateur, Kagas, Plateaux, Bas-Oubangui. Top location sites are in:

- Yadé region, Bossangoa area the Ouham river tributary of the Chari River and Lake Chad major basin.

- Equateur - Near Carnot city, the Mambéré River, tributary of the sangha, in the Congo major basin.
- Bas-Oubangui – Bangui the Oubangui river tributary to the Congo River.

It should be mentioned that, while not showing in the final mapping, the major artificial waterbody in the country, Mbali River hydroelectric Boali Dam, northwest of Bangui, should also be evaluated for tilapia cage farming systems.

For the open non-intensive integrated fish/crop farming systems, highly suitable areas can be found the southern and western regions of the country closer to Cameroon, Congo and the Democratic Republic of the Congo borders. At *prefecture* average score the strongest candidates for interventions appear to be in:

- Southwestern Equateur Region: Mambéré-Kadei and Sangha-Mbaéré prefectures.
- Plateaux Region: Lobaye prefecture.
- South Haut-Oubangui Region: Basse-Kotto prefecture.

Caution is recommended over sustainability, for both environmental aspects, and health and disease management and monitoring. Interventions should also be outlined recognizing ethnic and cultural diversity and considering resource competition and regulatory issues. Security issues must also be considered.

**Keywords:** Aquaculture zoning; Aquaculture; Central African Republic; Aquaculture spatial analysis; Aquaculture zoning modelling; catfish tilapia zoning; catfish tilapia GIS

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# INTRODUCTION

This report documents a freshwater fish farming Geographical Information Systems - Multicriteria Decision Analysis (GIS-MCDA) suitability assessment, for aquaculture zoning and identification of potential sites in the Central African Republic.

Departure questions can be formulated as:

1. *What are the regions and prefectures where freshwater fish farming should be promoted for poverty alleviation, improving nutrition, and food security?*
2. *Where are the best sites for intensive commercial closed farming system investment?*
3. *Where are the best sites for intensive commercial Tilapia fish farming open systems?*

***Research methodology*** follows previous Hand-in-Hand initiative analysis for value chain infrastructure location. A brief literature review on sub-Saharan Africa and Central Africa Republic aquaculture fish-farming sector provides context, background, and perspectives. Modelling assumes a GIS-MCDA methodology applying weighted factors (AscoughII et al., 2019; Boroushaki & Malczewski, 2010; Malczewski, 2006).

Fish farming suitability/potential zoning modelling is based on specific sub-models, criteria, and spatial constraints. It builds from Aguilar-Manjarrez and Narth study on warm-water and temperate-water fish farming suitability in continental Africa ((Aguilar-Manjarrez & Narh, 1998)), a raster-based GIS-MCDA using fish-farm and land-quality factors, with sub-models and categories of criteria:

1. Constraints (urban areas, large water bodies, protected areas)
2. Water requirement
3. Soil and terrain suitability
4. Inputs – crops and livestock
5. Farm-gate sales - as a measure of population density classification.
6. Potential yields.
7. Urban market size and proximity.

Sector growth, data availability, and fish farming systems and technologies have considerably evolved since late 20$^{th}$ century. Some of the base data is updated, and sub-models, criteria weighting, and constraints reviewed.

Two distinct zoning efforts are presented. A first, at a broader scale, intends to identify states or regions where investment can positively impact poverty, hunger, malnutrition, and food security:

- Extensive to semi-intensive small-scale integrated farming systems.

The second pursues the location of high return on investment sites for intensive commercial aquaculture systems, for both:

- Catfish closed intensive farming systems.
- Tilapia open intensive farming systems using cages in water bodies.

Separate zoning efforts are developed for each farming systems or model, based on specific theory, distinct criteria combination, and weighting, and conditioned by a different set of constraints.

Three models were developed for:

1. Open non-intensive integrated fish/crop farming systems using ponds or small waterbodies.
2. Catfish closed Intensive systems – using closed/semi-closed-circulation technologies: recirculating tanks, raceways, flow-through systems, and ponds.
3. Tilapia open intensive systems in water bodies – using net pens/cage techniques.

The models use biophysical and socioeconomic input data, in the following criteria:

1. Physical geography
   a. Water requirement and seasonality
   b. Soil
   a. Terrain suitability (slope)
   b. Photovoltaic (PV) potential – Closed systems Intensification potential using alternative energy.
2. Supply
   a. Feed - crop production (Fischer et al., 2012) – crop by-products.
   b. Livestock – animal density (Robinson et al., 2014) – livestock by-products.
3. Demand - Human population density and large urban/metropolitan areas.
4. Infrastructure - Transportation network (accessibility).

The transportation network infrastructure is modelled as raster-based travel time/cost analysis ((Mulrooney et al., 2017) and accessibility/infrastructure travel time/cost to market is processed for large urban areas.

Applied constraints (depending on specificities of the farming system):

1. Urban Areas.
2. Protected Areas.
3. Flooding areas.

Final mapping exclusive criteria for intensive closed systems:

1. Distance to major roads.
2. Access to IT - mobile broadband coverage.

Due to lack of reliable data, access to finance – distance to bank agency – is not considered as an exclusive, final location, criteria.

The project is developed using open-source GIS software QGIS 3.22.16-Białowieża and mostly publicly available open-data sources[1].

This document is structured in 5 main sections: 1. CONTEXT AND BACKGROUND, 2. FISH FARMING ZONING MODELLING, 3. DATA PREPARATION; 4. CRITERIA SUBMODELLING - GEOPROCESSING; 5. SUITABILITY MODELLING, with INTRODUCTION and CONCLUSIONS presenting results, conclusion, closing remarks on assumptions and possible pitfalls, and recommendations.

## GIS Multicriteria Decision Analysis

Spatial decision problems involve a set of geographically defined alternatives and multiple and sometimes opposing assessment criteria. Alternatives are commonly assessed by many intervenient (decision-makers, stakeholders, interest groups).

GIS multicriteria decision analysis GIS-MCDA consists of a method to convert and combine spatial data/geographical information and decision-makers criteria to attain evidence for a decision-making process. GIS capabilities are enhanced by MCDA procedures, techniques, and algorithms for structuring decision problems, to design, evaluate and prioritize alternatives.

[1] Exceptions for AtlasAI (population density and asset wealth index) and Collins Bartholomew's Mobile Coverage Explorer data (from which a mobile broad band coverage data is derived).

Integration of GIS and MCDA provides a replicable model, improves communication between project participants or decision-makers, can offer a different perspective of problem and solution, helping to redefine initial specification and/or criteria.

GIS multicriteria analysis methods are usually presented in a three-stage hierarchy of: intelligence, design, and choice.

In the intelligence phase, data are acquired, processed, and exploratory data analysis is performed.

The design phase should entail the formal modelling/GIS interaction development of a solution set of spatial decision alternatives. The integration of decision analytical procedures and GIS functions is critical for supporting the design phase.

The choice phase involves selecting location alternatives from those available. Specific decision rules are used to evaluate and rank alternatives.

The three stages of decision making do not necessarily follow a linear path.

From a critical standpoint it can be stated that, while quantitative data analysis and evidence gathering through GIS modelling certainly contributes to attaining evidence for decision-making processes. It is a complex set of socio-economic, political, cultural, ethno-anthropological aspects, and power relations which shape processes and govern decision-making.

Modelling is as good as the input data. Its quality and reliability support the extent to which conclusions can be trusted, and these are just as sound as the analysis conducted. From that prism, specification and objectives define modelling assumptions and approximations and can always produce distinct answers ((Kitchin, 2014b).

Data are both social and material do not just represent the world but can actively produce it, are not mere raw material of information and knowledge, do not exist independently of ideas, techniques, technologies, people, and contexts that produce, process, manage, analyse, and store it. Positionality is always present even when "data speaks for itself" (Kitchin, 2014a).

# 1. CONTEXT AND BACKGROUND

According to OECD-FAO Agricultural Outlook 2021-2030 (OECD & FAO, 2021), fish production, trade and consumption all contracted in 2020 due to COVID19. But for the 2021–2030-decade, world fish production was projected to grow at 1.2% and aquaculture at 2.0% p.a., lower growth rates compared to the previous decade reflecting policy changes in China (sustainability and environmental protection), increased feed cost, reduced productivity gains, and competition for land. By 2030 aquaculture is anticipated to supply 57% of human fish consumption overtaking capture production by 2027.

## SUB-SAHARAN AFRICA

The population of the Sub-Saharan Africa (SSA) region was 1,211,170.18 in 2022, and with an annual growth rate of 2.5 % projected to reach between 1.5 and 2 billion by 2050. Unemployment rate was around 6.7% for the same year. Although poverty headcount ratios, in percentage of population, have fallen from over 60% in the 1990s to 35.4% in 2019, there are great disparities between countries and subregions (World Bank[2])

Per capita fish consumption in Africa is projected to decrease as the fast-growing population outpaces production growth.

Aquaculture production in SSA is predominantly inland and freshwater, with small-scale market-driven, and large industrial scale operations. According to FAO (Bartley, 2022),from 2000 to 2018 there was a 6.7 increase in production with a compound annual growth rate (CAGR) of 11.2%. Mainly of indigenous ubiquitous species of tilapia and catfishes. But In 2014, seven countries (the Federal Republic of Nigeria, the Republic of Uganda, the Republic of Ghana, the Republic of Kenya, the Republic of Zambia, the Republic of Madagascar, and the Republic of South Africa) concentrated 93% of production (Satia, 2017).

The sector as seen a steady growth based on indigenous species, genetic and feed improvement, government, and development agencies support and a large growing demand.

Some of the commonly identified constraints and risks miss supporting data and are poorly assessed in existing literature: environmental impacts and health/food safety related, social

[2] https://data.worldbank.org/indicator/SP.POP.TOTL?locations=ZG

impact, land and water competition, employment, value chain growth. Risks like climate change impacts or social and regional conflicts are also merely mentioned.

Recent fish farming growth has been driven by an increasing importance for improving food security, job creation, economic growth, and resource use. It is supported by external assistance from FAO and other development partners, donor organizations and investors, and with growing private sector participation.

## CENTRAL AFRICAN REPUBLIC

According to FAO Fishery and Aquaculture Country Profiles[3], the Central African Republic presents a varied and complex ecological environment in terms of aquatic resources. There is no accurate fisheries statistics production in the country, and there is insufficient knowledge of fish population dynamics. Fisheries is practiced in the ethnic and family context, in the off-season of agriculture, with estimated 85 000 people in related activities in 2018.

Available capture production data shows a decline from 2012 to 2018, from 32 000 to 29 000, justified by the civil war. The total fishery production is consumed domestically, and the country depends on imports to meet local demand, valued at USD 5.4 million USD in 2018. Per capita consumption was estimated at 7.9 kg in 2017.

Even tough aquaculture was introduced by colonial authorities in 1952, had the leadership of State Stations and support from international organizations (UNDP/FAO/USAID), production in 2021 was estimated at a mere 175 tonnes and in 2018 aquaculture employment was estimated in about 3 000 people.

[3] https://www.fao.org/fishery/en/facp/caf?lang=fr

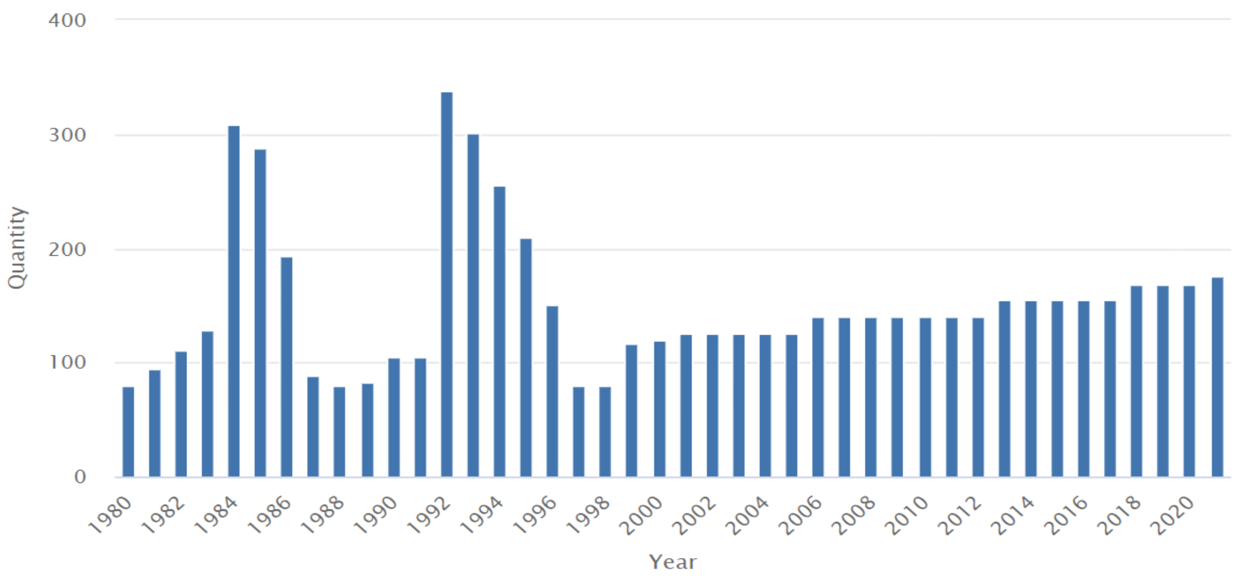


*Figure 1 – Graph - Global aquaculture production for species (tonnes)*

In 2015 there was a government effort, supported by the FAO, to produce an interim plan for the sustainable development of the aquaculture sector (MEFCP-RCA & FAO, 2015), the document follows 2009 government Strategic Development Framework for Aquaculture in the Central African Republic, preparing its implementation trough TCP/CAF/3401: Support for the implementation of a Sustainable Aquaculture Development Plan in the Central African Republic. The documents consisted of a preliminary draft of a future National Aquaculture Development Plan that has not been materialised to date.

Based on previous project's elements, pilot sites information and stakeholder consultations, the plan proposes 3 year activities around:

- capacity building of support services (public and private) to guide suitably producers.
- improvement in the efficiency of current production systems (fish production Tilapia nilotica and Clarias sp in earthen ponds and tanks) and seaweed farming; And
- improvement of the management of the aquaculture sector and introduction to professionalization.

The TCP/CAF/3401 technical support to the 2015 plan, mission report (MULONDA KALENDE, 2015), also details some of the opportunities and constraints to sector development:

As ***opportunities***, it cites a set of favourable biophysical and socio-economic conditions (temperature, rainfall, soil and arable land, relief, young population, strong market, availability of some ingredients, etc.); but also: the existence of previous fish or seaweed farming pilots, research, and training in agriculture in the country (ISDR, University of Bangui, fish farming stations, and processing units for agricultural products (feed for fish and livestock), political will, etc.

Among the ***constraints*** or challenges listed are: Weak institutional capacity to manage the sector, limited access to inputs (feed and fry), difficult access to finance, low technical and organizational capacity of producers, insecurity in production areas, the destruction of state fish farming infrastructure and limited access to production sites.

Starting in 2012, the civil war, sets the security factor as a major issue framing aquaculture development in the country, to that challenge it sums poor low feed quality and availability, low quantity and quality of fingerlings, lack of trained personnel, lack of control over production technologies, difficulties in access to finance, and land.

A strong halieutic potential exists with a dense and abundant hydrographic network, rich and varied ichthyofauna, and there is a strong fish marketing system, due to the cultural habit/tradition of fish consumption (fish sausage with vegetables) with smoked, salted, or dried fish, and low losses on processes-transportation. Overall, the fishing potential is underexploited, according to FAO data with a possible estimated production between 20,500 and 100,000 tonnes per year.

## PRODUCTION SYSTEMS

Three major production systems are predominant in sub-Saharan Africa – earthen ponds, cages and concrete or earthen lined tanks (Satia, 2017). Open systems cage farming (tilapia and catfish) in large water bodies are the most profitable, with low capital investment per unit of fish production. The less-costly pond non-fed systems are undeveloped but have high potential impact on food security and nutrition. Closed systems, recycling, and land-based pump systems are still limited by lack, or unreliability, of energy supply.

Secondary Production Systems, dam, ponds, integrated systems, and aquaculture associated to rice still have a large growing potential.

The catfish *Clarias* species and their hybrids production are commonly divided in two major stages:

1. Fish hatchery—production of fingerlings and juveniles.
2. Pond culture—earthen/dug-out, concrete tanks, cage/pen culture, fibre tanks, intensive recirculation and FTSs (raceway).

Intensive catfish production in "Fish Farming Estate" model using Recirculatory Aquaculture Systems (RAS) is currently considered the most productive and successful in the region. (Obwanga et al., 2018). Nigerian cooperative, public/private, peri-urban aquaculture model using ponds or concrete tanks, is based on shared investment in management, security, development of hatcheries and high-quality fish feeds. (Miller & Atanda, 2011). The fish farm estates model cooperative management locates in peri-urban areas and has been fundamental in enabling access to credit. It results from both market factors and government intervention, farmers associations and government collaboration, also benefiting from international development agencies support.

Tank farming systems have been observed to have an increasing importance, these techniques have lower construction and maintenance cost, allow scalability, and can be located inside house compounds, limiting climatic constraints, and improving security.

Integrated aquaculture systems in small holder farming can have a direct impact on poverty alleviation, hunger, and malnutrition. In general, those are considered more sustainable and environmentally friendly, based in reusing and recycling of crop by-products, helping land/soil regeneration, pushing the reuse of idle land, and contributing to natural fertilization when in combination with irrigation small water bodies (SWB) (Musuka & Musonda, 2013; Mwayuli et al., 2010; Oribhabor & Ansa, 2006; Rasowo et al., 2010).

Rice-fish integration was found to bring benefits to subsistence farmers improving and diversifying nutrition and increasing income possibilities (Rasowo et al., 2010). Rice and fish are produced concurrently, enhancing crop productivity, and at the same time optimizing water, land, and labour resources. Small-scale decentralized hatchery, fingerlings production, in rice fields has been successfully tested. Since rice cultivars size and growth period are locally sensitive, its analysis implies field work in the identification of specific cultivars and the refining of potential areas.

Like with other small-holder and subsistence systems, rice and aquaculture integration interventions must consider socio-cultural or biophysical factors, like the educational status of farmers or the gender division of labour, and the rice paddy environment - temperatures, oxygen levels or water turbidity.

Investment in small water bodies and small holder fish farming must also be consistent with regional specificity, considering issues such as low productivity, high level of abandonment or seasonality, constraints in extension services, training, fish seeds fingerlings availability, feed cost, and poor marketing.

The lack of strong institutions, financial services, failing extension services, or seed, has forced development resources to change from targeting subsistence, non-intensive, to intensive commercial systems. But even though the investment in subsistence small-scale farming has failed in the past, at least for a visible fast production/productivity growth, the reasons are frequently not clearly identified.

# 2. FISH FARMING ZONING MODELLING

The analysis adapts Aguilar-Manjarrez and Narh approach to modelling warm-water and temperate-water fish farming potential in continental Africa. The 1998 technical paper follows Kapetski work - Strategic assessment of warm-water fish farming potential in Africa (Kapetsky, 1994), in adopting a raster based geographic information system approach, multi-criteria decision analysis, using fish-farm and land-quality factors.

The original study implied sub-modelling the following categories of criteria:

1. Constraints -urban areas, large water bodies, protected areas (exclusive criteria).
2. Water requirements – precipitation, evapotranspiration, seepage.
3. Soil and terrain suitability – soils, slope.
4. Input – crops and livestock (manure).
5. Farm-gate sales - population density classes.
6. Potential yields - number of degree days within optimal temperature range *(*air temperature, wind speed).
7. Commercial farming modelling adds urban market size and proximity.

Current data availability allows updating to higher spatial resolution and disaggregation, and farming systems evolution imposes a revision of some sub-models, criteria/factor weighting, and constraints.

Original sub-models and models were adapted considering most farmed species, the African catfish, and the Nile tilapia, for commercial (intensive) and small-scale (semi-intensive/extensive) farming systems.

Those systems present distinct objectives and business rules, modelling based on specific system criteria, criteria weighting, and different constraints or exclusive criteria.

**Small-scale, extensive to semi-intensive, pond integrated farming systems** directly targets poverty alleviation, hunger, malnutrition, and food security. The overall objective is the identification of potential regions or *départments*.

For **Commercial intensive systems**, using open or closed aquaculture techniques, the objective is the classification of top high return-on-investment sites:

- **Catfish intensive closed-systems** uses closed-circulation technologies like re-circulating tanks, raceways, flow-through systems, and inland ponds, essentially utilizing constructed or assembled manmade materials and using alternative solar power/photovoltaic (PV) potential.

- **Open intensive systems** consider tilapia pen/cage techniques in large water bodies (LWB). Where the main location factor is the existence of a reservoir or dam but are also dependent on high accessibility to input and output markets.

All modelling criteria, constraints, and steps is detailed on 4. CRITERIA SUB-MODELLING - GEOPROCESSING and 5. SUITABILITY MODELLING.

# 3. DATA PREPARATION

## 3.1 DATA GATHERING/SOURCES:

1. **Collins Bartholomew** - Mobile Coverage Explorer - raster data representation of the area covered by mobile cellular networks around the world.
2. **FAO**:
   - A strategic reassessment of fish farming potential in Africa (Aguilar-Manjarrez & Narh, 1998) data layers: Potential Yields and Soil Suitability.
   - Rivers of Africa.
   - Inland Waters of Africa.
   - Geo-referenced database of dams (Africa), Airports, Ports.
   - WaPOR water productivity precipitation an evapotranspiration timeseries (2009/20).
   - GAEZ Global Agro-Ecological Zoning version 4 (GAEZ v4).
3. **IFPRI Global Spatially-Disaggregated Crop Production Statistics Data for 2017 (MAPSPAM) -** https://data.apps.fao.org/map/catalog/srv/metadata/59f7a5ef-2be4-43ee-9600-a6a9e9ff562a
4. **GLW Gridded Livestock of the World** - GLW 4: https://data.apps.fao.org/catalog/iso/15f8c56c-5499-45d5-bd89-59ef6c026704
5. **HydroSHEDS (Hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scales)** – DEM- Void-filled elevation raster (30 sec) (Lehner et al., 2006) - https://www.hydrosheds.org/page/availability
6. **OpenStreetMap -** http://download.geofabrik.de/africa.html
7. **THE WORLD BANK - World - Photovoltaic Power Potential** (PVOUT) - Global Solar Atlas - https://datacatalog.worldbank.org/dataset/world-photovoltaic-power-potential-pvout-gisdata-global-solar-atlas
8. **UNEP-WCMC and IUCN (2021), Protected Planet: The World Database on Protected Areas (WDPA) and World Database on Other Effective Area-based Conservation Measures (WDOECM)** [Online], May 2021, Cambridge, UK: UNEP-WCMC and IUCN. Available at: www.protectedplanet.net.

9. **AtlasAI**

- Atlas AI Population Density (Africa, 2020)
- Atlas AI's Asset Wealth Index (AWI)

10. **Global Surface Water 1984-2021** (European Commission Joint Research Centre) https://global-surface-water.appspot.com/

## 3.2 EXTRACTION AND PRE-PROCESSING

Selection/edition by location and attribute, and creation of a country vector database *geopakage*[4].

1. ***OSM Road layer (gis_osm_roads_free_1.shp)*** – Selected by location and attribute to generate a major roads layer. A comprehensive description of the features can be found in (Ramm, 2019). Lack of data on road network conservation, quality, and speed limit for most of the network imposes a conservative approach.
   - Attributes fclass = ‘motorway’ OR ‘trunk’ OR ‘primary’.
2. OSM Railways (gis_osm_railways_free_1.shp) – Selected by location.
3. ***OSM Places Layer (gis_osm_places_free_1.shp)*** - Selected by attribute to generate major human settlements layer.
   - Attributes: ‘city’; ‘town’; ‘national_capital’.
4. ***FAO Data - Ports; Airports; Secondary Airports*** - csv file formats - FAO http://rkp.review.fao.org/geonetwork – selected by location for the country.
5. ***FAO Major rivers*** - Rivers of Africa derived from the World Wildlife Fund's (WWF).
6. ***FAO Inland Waters*** – Clipped by country boundaries.
7. **UNEP-WCMC and IUCN** (2021), Protected Planet: The World Database on Protected Areas (WDPA) and World Database on Other Effective Area-based Conservation Measures (WD-OECM): Datasets were Clipped for CMR, merged the several layers and overlapping polygons combined.

Data is edited extracted/clipped using official UN country borders.

[4] http://www.geopackage.org/

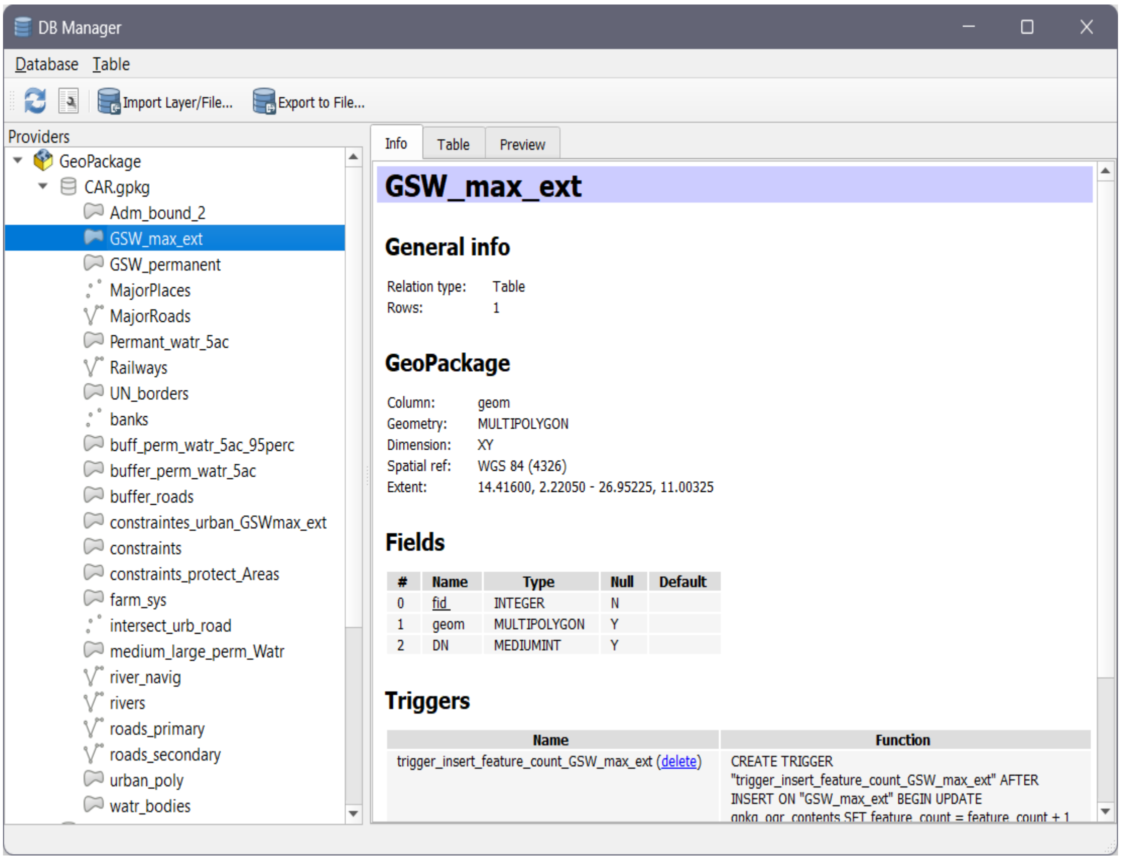


*Figure 2 – Geopackage*

# 4. CRITERIA SUBMODELLING - GEOPROCESSING

This section details modelling, editing and geoprocessing steps.

## 4.1 SUB MODELS: ACCESSIBILITY - INFRASTRUCTURE/MARKET

Accessibility data processing (travel time/cost surfaces) is based on the following assumptions:

1. Major urban areas: parameter was adapted to the country reality using population density above 1 200 habitants per square kilometre and a contiguous area larger than 5 km². Accessibility is calculated to major roads/major urban areas intersection points.
2. Lakes (inland waters) are represented by polygons; infrastructure network layers consist of linear features.
3. River navigation is extremely relevant in the country, again this parameter was changed from previous analysis to consider river segments with Strahler number > 4[5].
4. Road travel time/cost is modelled for primary/motorway/truck road classes; road network conditions are poor.
5. Lake and river navigation are treated as surface (polygons) not taking into consideration navigation infrastructure (points), it is assumed for small to medium cargo crafts (barges).
6. Bangui Port functions as the country seaport connecting to Brazzaville and Kinshasa.

The general steps to produce accessibility maps (travel time surfaces) are:

1. Rasterization vector layers.
2. Creation of cost friction surface.
3. Computation of a cumulative time/cost layer from/to points.

[5] https://www.jayconrod.com/posts/66/the-strahler-number

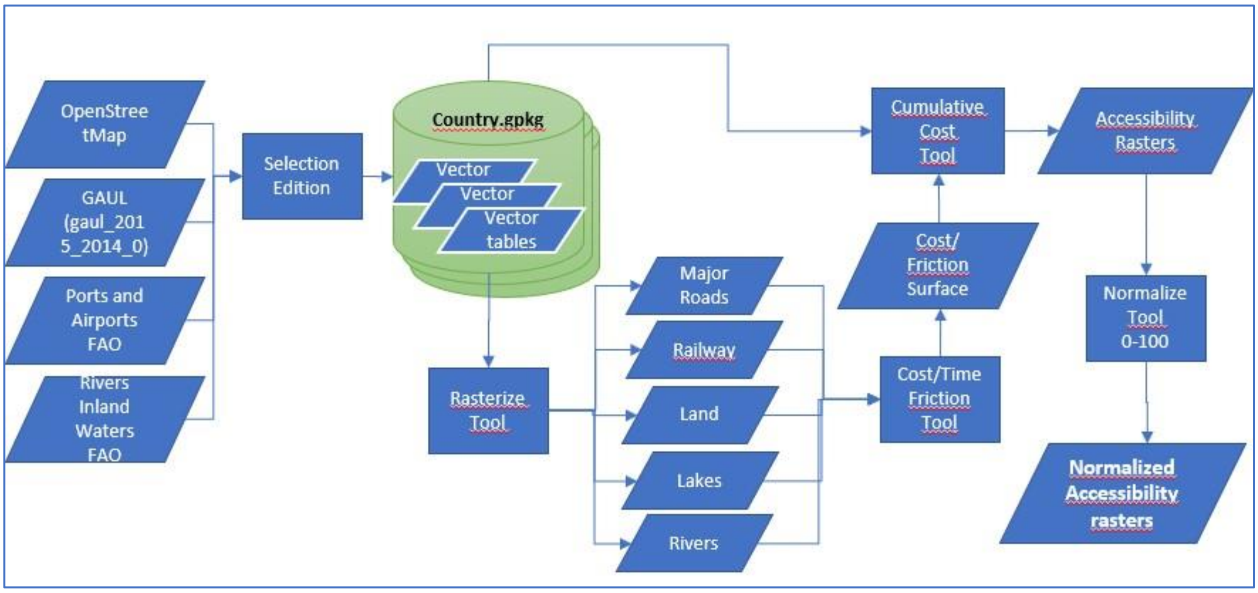


Figure 2 - Accessibility modelling flowchart

1. ***Rasterize* Tool** – Communication/transportation network and surfaces conversion from vector to raster, 1km cell grid burning a value for an average time (minutes) to cover a cell for the considered transportation mode ((a) land/walk, (b) major roads/vehicle, (c) railway/train, (d) navigation.
    - Modelling values:

| | |
|---|---|
| Land (a) | 20 |
| Primary roads (b) | 1 |
| Secondary roads (c) | 1.5 |
| Navigation (d) | 3 |

The rasterization outputs 1km raster grids with the modelling value per cell. Modelling value - speed - parameter can be changed/adapted to a different specification.

2. ***Cost/Friction Tool*** *(GRASS r.series tool)* – A cost or friction surface is obtained overlaying (a), (b), (c), (d) grids, propagating the minimum cell value.
3. ***Cumulative Cost Tool (****GRASS r.cost tool)* – Service Area – The cumulative cost/accessibility maps are produced selecting a central point, or points, and defining service areas.

Accessibility to major urban areas/regions (urban>1 200 habitants/km², area>5km²) is defined to 10 urban regions in Central African Republic, calculated using roads layer (lines) intersection points with urban areas (polygons)  for a total of 50 access points.

Assuming the existing large fish production/consumption deficit, external demand (exports, cross border trade, accessibility to large regional cities) was not considered.

4. ***Normalization*** – Units are normalized/scaled (0 to 100) for score calculations (weighted sum). Low accessibility (time or cost) 0, high accessibility 100.

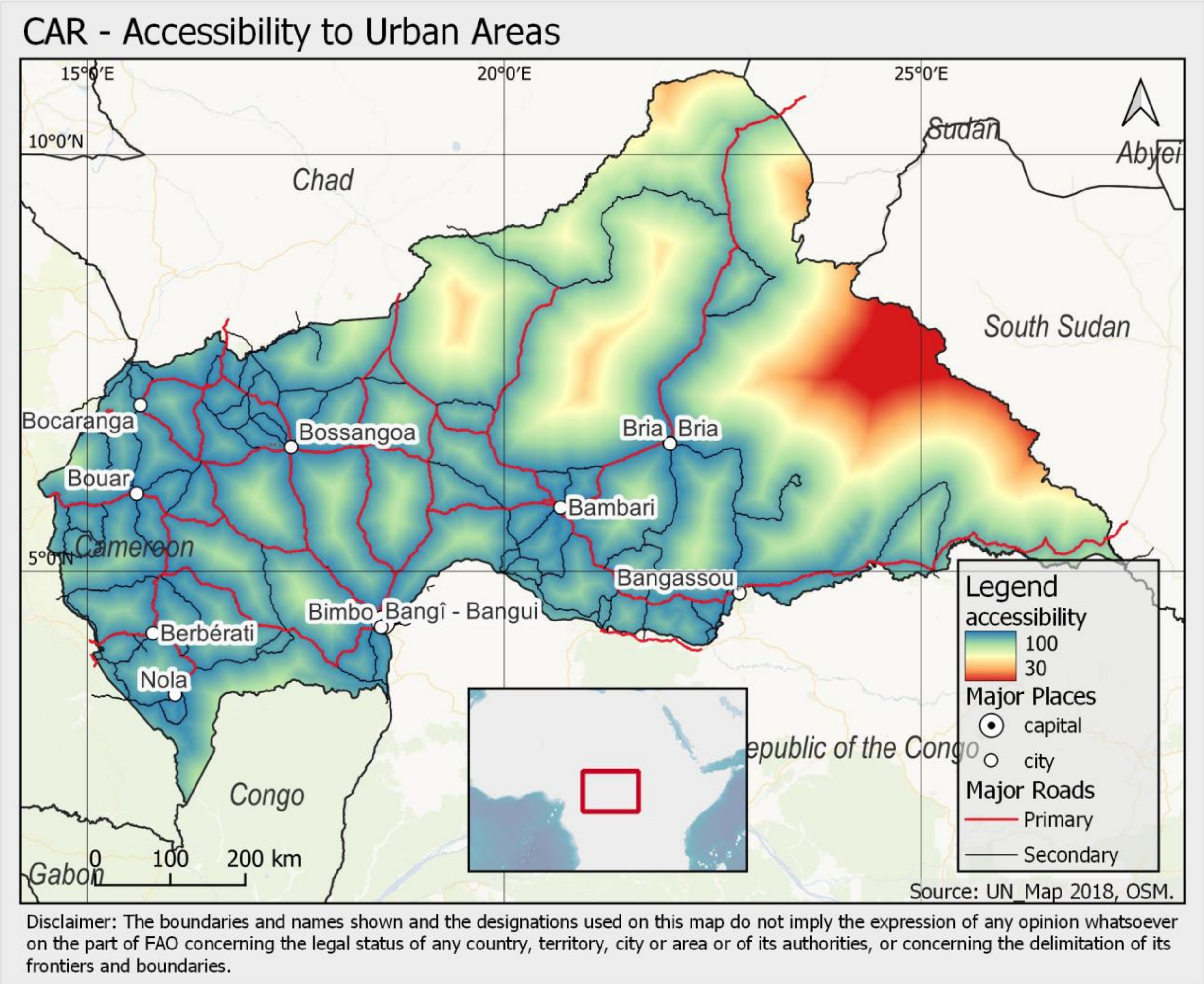


*Figure 3 – Map - Accessibility to urban areas*

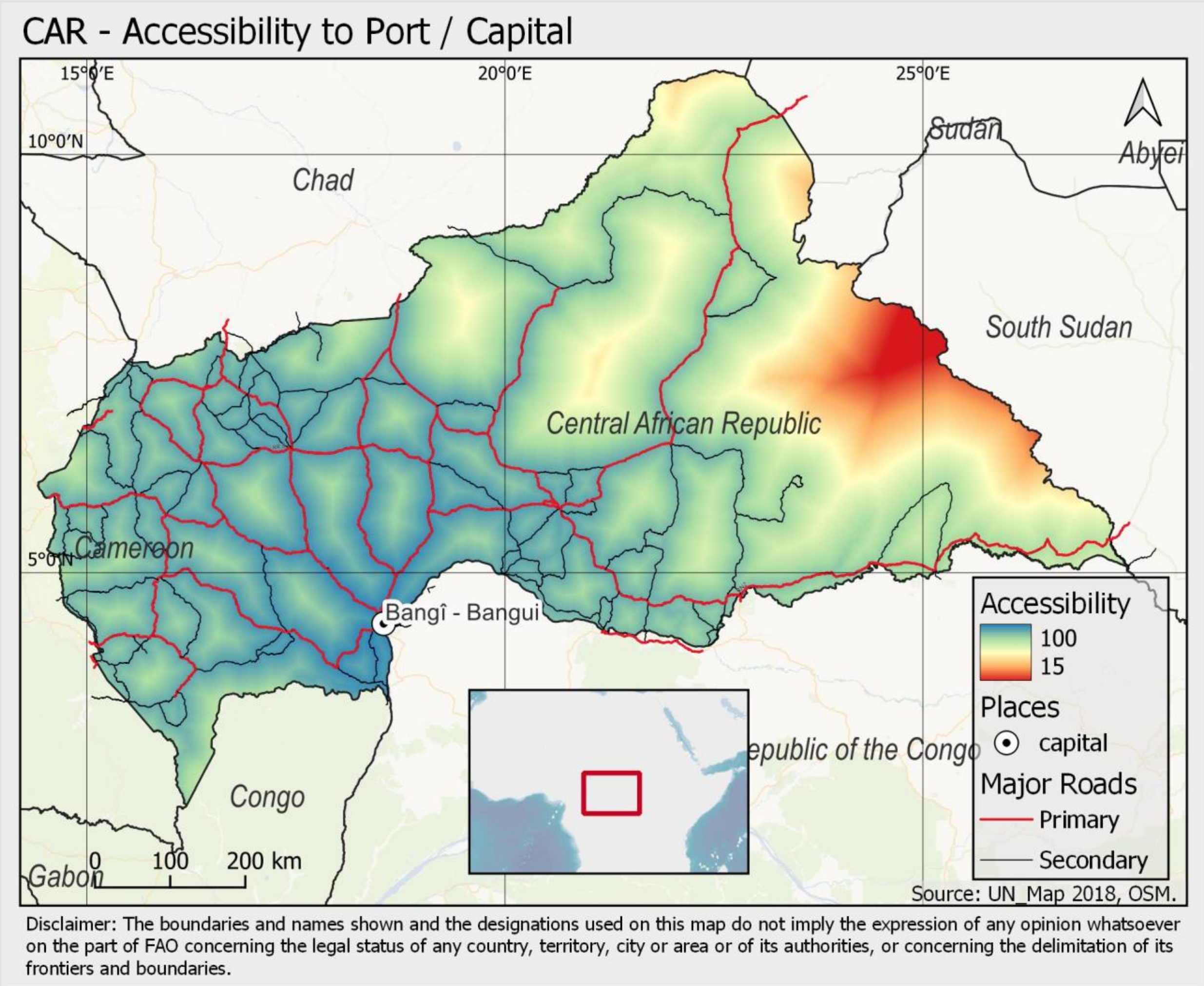


*Figure 4 – Map - Accessibility to ports*

## 4.2 SUB MODELS: MARKET/DEMAND

Market demand sub model utilizes population density and accessibility.

### 4.2.1 Cities/Urban areas

Urban areas are defined as having more than 1 200 habitants/km² and covering an area equal or larger than 5km² (total of 10). The following steps were applied:

1. ***Raster calculator tool: 1/0 layer where 1 = PopDens>1200***
2. ***Polygonise tool*** - converts the raster/grid cells to vector polygons.
3. ***Geometries (Check validity /fix geometries tools):*** Polygon geometries are checked for errors and validated.
4. ***Field calculator tool***: create a new field “Area” where *$area* (km²).
5. Export>save features as: UrbanAreas
6. ***Select by attributes***: * FROM UrbanAreas ” WHERE “Area”>5km².
7. Export>save selected features.

### 4.2.2 Farmgate sales

Criteria sub-modelling applies Aguilar-Manjarrez and Narh classification to population density:

- Class 4 - Very suitable: 150-300 [h/km²]
- Class 3 – Moderately suitable: 25-149 [h/km²]
- Class 2 – Marginally suitable: 1-24 [h/km²]
- Class 1 – Unsuitable: <1 and >300 [h/km²]

***Normalization*** – Units are normalized/scaled (0 to 100) for location score calculations (weighted sum).

## 4.3 SUB MODELS: PHYSICAL GEOGRAPHY

### 4.3.1 Water

Availability is estimated using an annual water balance and Global Surface Water Explorer (GSW) seasonality and maximum extent data.

The GSW maximum seasonality value is used to evaluate the persistence of surface water for cage systems. The GSW maximum extent, from the 32-year time-series, is used as a flood area constraint for non-intensive pond systems.

The **water balance sub-model** uses WaPOR precipitation and evapotranspiration monthly time-series from 2009 to 2020, calculating a mean water balance layer, through the following steps:

1. ***Clipping*** to country borders.
2. ***GRASS r.series tool*** – time-series mean value calculation for precipitation and evapotranspiration.
3. ***Raster calculator tool***: modelling values: (Precipitation * 1.1) - (evapotranspiration * 1.3).
4. ***Normalization – raster calculator*** – grid scaling normalizing (0-100)

**GSW data processing**

1. Extracted/downloaded in tiles 10°x10° degrees for *max_extent* and *seasonality.*
2. ***Clipped*** to UN borders and ***merged mosaic*** to single dataset***.***
3. *Max_Extent* (flood areas mask layer)***: polygonise > dissolve***
4. *Seasonality* (permanent waters)***:***
    - ***Raster calculator tool:*** *("Seasonality"=12) * "Seasonality"*
    - ***polygonise > dissolve***

## 4.3.2 Soil and terrain suitability for ponds

Assuming there is no substantial change in conditions, the soil suitability sub-model data is from Aguilar-Manjarrez and Narth study. The data represents limitations for fishpond construction, using FAO soil units: acid sulphate layer; organic layer; lime requirement; clay content; depth to water table; salinity/alkalinity; gypsum content; soil depths.

Slope is updated using higher resolution data (Watershed DEM 30s) with the following modelling steps:

1. ***Clipping*** – Digital elevation model (DEM) and Soil data to country borders.
2. ***GDAL Slope tool****:* DEM to slope transformation (in degrees).
3. ***GRASS r.reclass tool – reclassify values*** – Slope layer classification (4 classes)
    - Class 4 - Very suitable: <2

- Class 3 – Moderately suitable: 2 - 5
- Class 2 – Marginally suitable: 5 - 8
- Class 1 – Unsuitable: > 8

4. ***Raster Calculator tool***: Soil and terrain suitability for fishponds = (1.5X soils) + Slope
5. ***Normalization – raster calculator*** – grid scaling normalizing (0-100)

The SoilSlope sub-model values are applied to modelling small scale extensive to semi-intensive integrated pond farming systems.

Intensive commercial closed systems modelling use slope data separately.

### 4.3.3 Potential Yield

Potential Yield sub-modelling uses data from Aguilar-Manjarrez and Narh study. Fish growth is directly proportional to the number of days within an optimal temperature range. Water temperature is originally estimated using air temperature and wind velocity data for the considered species and the fish yield estimation presented as crops/y. The potential yield layer is clipped for the country and normalized/scaled (0, 100).

There are some gaps in the fish yield datasets that might have some impact on the final zoning exercise.

## 4.4 SUB-MODELS: INPUTS

### 4.4.1 Crops

Crop products and byproducts can be used directly as feed or as raw materials for feed mills. Local aquafeed production can be determinant for fish farming sustainability and competitiveness.

The crop input sub-model uses production aggregate from IFPRI MapSPAM 2017.

1. ***Clipping*** – To country borders.
2. ***Normalization – raster calculator*** – grid scaling normalizing (0-100)

### 4.4.2 Livestock

The livestock input can be considered for both, organic fertilization (manuring) or, the use of by-products (blood, bones etc.) for feed ingredients. Different production systems requirements imply distinct sub-models.

#### *4.4.2.1 Open non-intensive and integrated production systems*

Sub-model uses chicken and duck density grids from the Gridded Livestock of the World (GLW) database. Livestock is considered for manuring, feeding, and as natural aerators in the case of duck-fish integrated farming.

As feed, integrated systems benefit directly from chicken and duck nutritious rich faeces and direct feed wasting. (Oribhabor & Ansa, 2006). In the case of organic fertilizing (manuring) it contemplates that chicken are mostly farmed enclosed, employing cages and feeders, thus consisting of the best manure source.

Input sub-model uses GLW production spatial data:

1. ***Clipping*** – to country borders.
2. ***GRASS r.series tool*** – duck and chicken density aggregation (sum).
3. ***Normalization – raster calculator*** – grid scaling normalizing (0-100)

#### *4.4.2.2 Intensive production systems*

Most intensive production systems do not use organic fertilizing and are artificially fed. slaughterhouse waste by-products can consist low-cost alternatives ingredients for both industrial and small-scale feed mills.

Livestock is modelled aggregating Goat, Sheep, Pig, Cattle, animal density, weighted by the average live weight (LW), adopting Tacon 1989 and Vincke 1985 values, in (Aguilar-Manjarrez & Narh, 1998):

- Goat: 30kg
- Sheep: 30kg
- Cattle: 210kg
- Pig: 63kg
- Chicken/duck: 2.2kg

Modelling steps:

- ***Clipping*** – individual livestock layers to country borders.
- **GRASS r.series tool –** animal density aggregation (weighted sum ): (goat X 0.089) + (sheep X 0.089) + (cattle X 0.626) + (pig X 0.188) + (chicken+duck X 0.007).
- ***Normalization – raster calculator*** – grid scaling normalizing (0-100)

### 4.4.3 Photovoltaic energy generation potential

Closed faming systems intensification is constrained by poor energy supply. Considering that a large part of the territory has no grid access and that the existing network has stability and quality issues, modelling inputs an alternative energy source, photovoltaic power potential (PVOUT), average daily total in kWh/kWp, as a measure of intensification potential. Data processing involves:

- ***Clipping*** –to country borders.
- ***Normalization – raster calculator*** – grid scaling normalizing (0-100)
- Raster ***resampling/aligning***.

# 5. SUITABILITY MODELLING

Zoning targets Catfish and Tilapia farming systems technologies:

1. Extensive to semi-intensive open systems using ponds or small water bodies.
2. Peri-urban intensive/commercial catfish closed (semi-closed) systems using ponds, tanks, RAS, flow through or recirculation.
3. Intensive Tilapia farming systems using cages in large water bodies.

The following sections details selected criteria, weighting, and applied constraints.

## 5.1 EXTENSIVE/SEMI-INTENSIVE SYSTEMS (CATFISH AND TILAPIA)

Extensive/semi-intensive and integrated small-scale farming systems, for both Catfish and Tilapia, are the most dependent on natural and geographic factors or criteria. Feeding can be based on natural food supply, from integrated systems (crop/livestock waste), or additional complementary feeding resourcing to on farm or locally produced feed.

Assumptions:

1. Water availability is suitable or very suitable for most of the territory - criteria weighting could be lowered and weighting transferred to farmgate sales.

Considered criteria:

a) Farm-gate sales.
b) Water Balance.
c) Soil/Slope - (1.5X soils) + Slope.
d) By-products inputs (Crops/Livestock) (1.5X ChickenDuck) + CropAgg).

Constraints (used as clipping mask layers):

a) Urban areas.
b) Protected areas.
c) Dams and Large Water Bodies.
d) Flood areas - GSW max extent (polygonise/dissolve raster).

### 5.1.1 Location Score

The location score is obtained by way of a simple arithmetic weighted sum (*GRASS r.series tool*) of criteria normalized/scaled grids, theoretically varying from 0 to 100: *("WaterBalance" X 0.5) + ("Soil/Slope " X 0.25) + ("Byproducts" X 0.125) + ("FarmgateSales" X 0.125)*

The following ***constraints*** are applied:

a. Urban areas.
b. Protected areas.

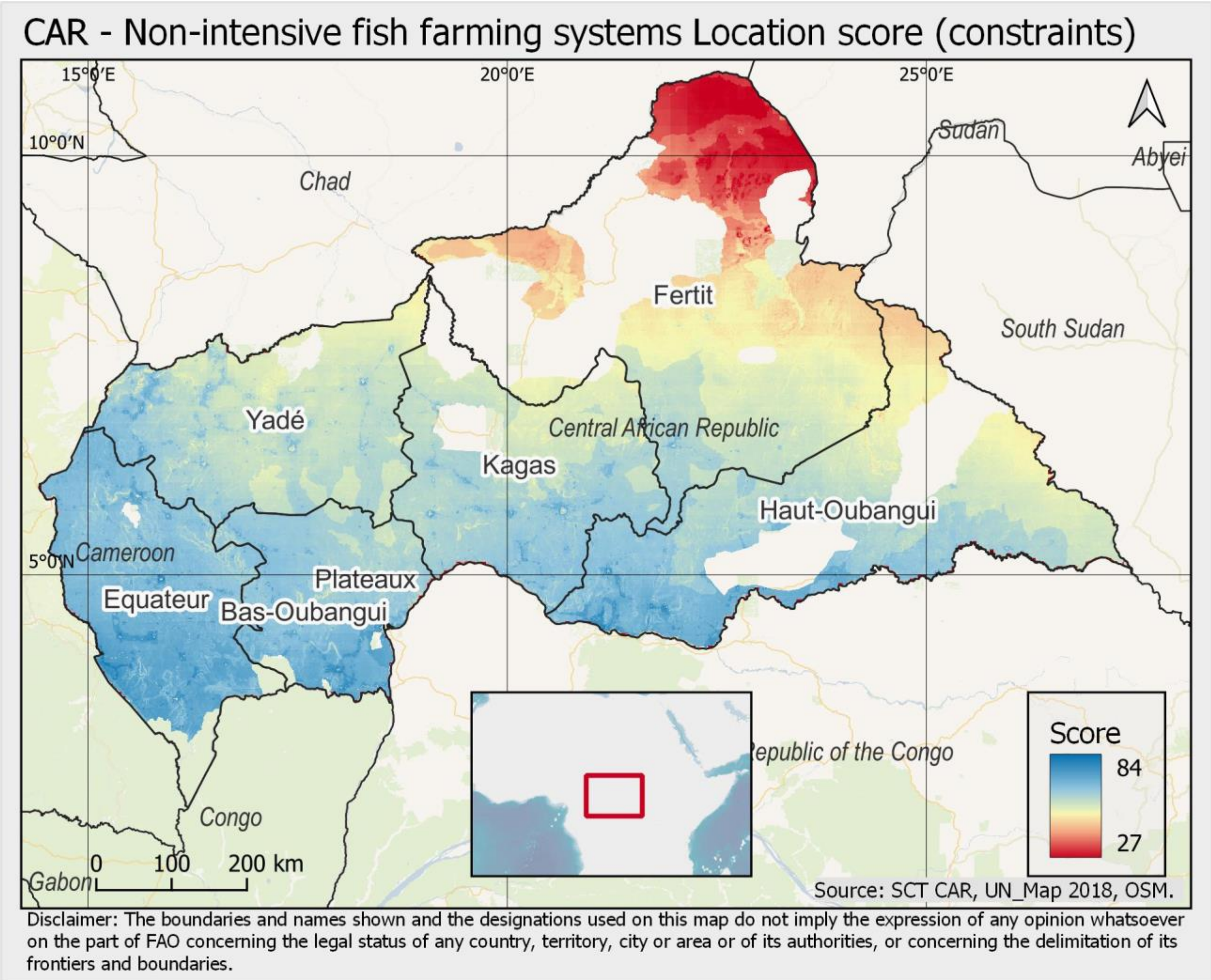


*Figure 5 – Map - Non-intensive and integrated systems suitability*

Highly suitable areas are found in the southern and western regions of the country closer to Cameroon, Congo, and the Democratic Republic of the Congo borders .

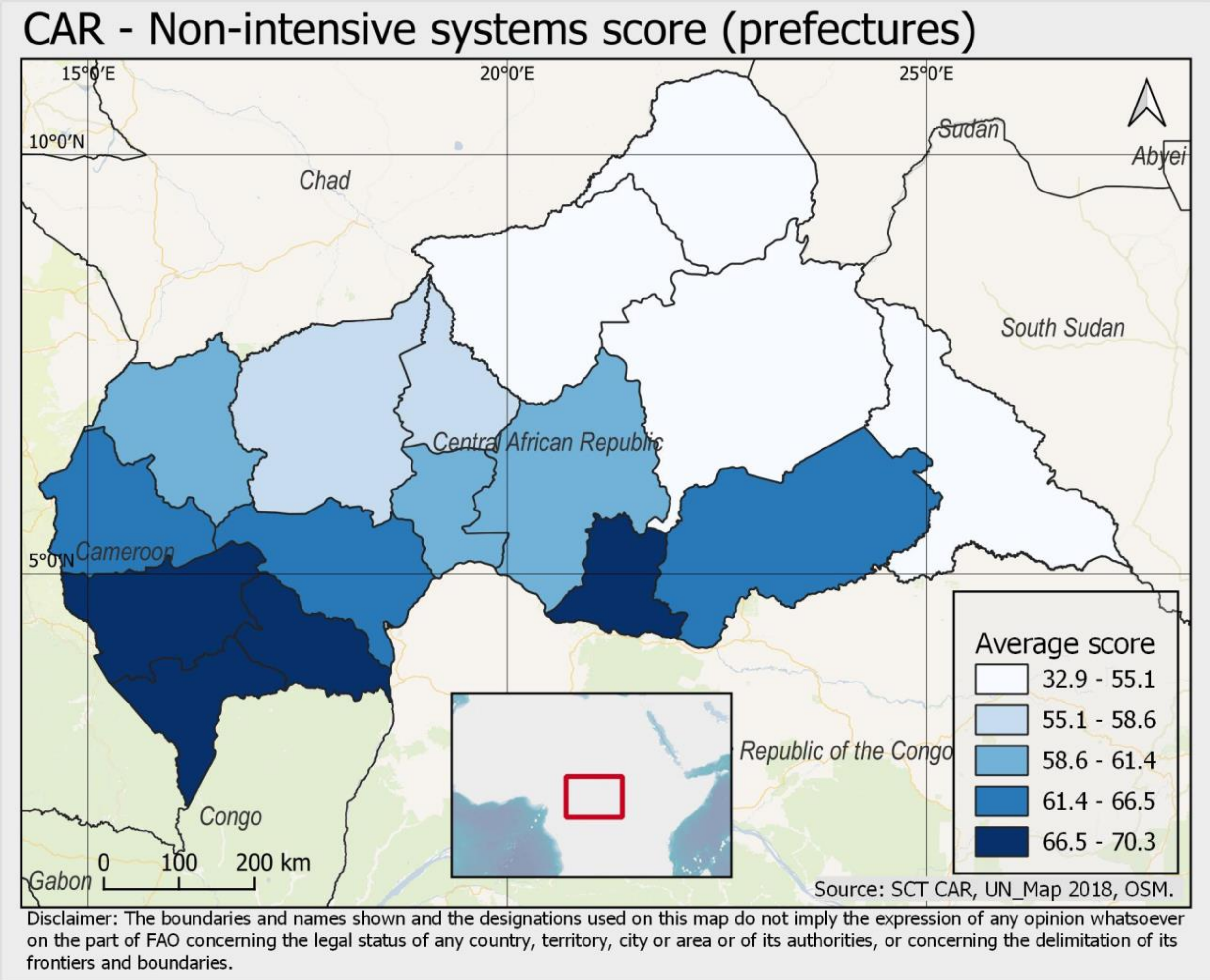


*Figure 6 – Map - "Prefecture" average, non-intensive systems suitability*

The *prefecture* average score permits individualizing and prioritizing administrative units for interventions. The strongest candidates appear to be the southwestern Mambéré-Kadei, Sangha-Mbaéré, Lobaye, and south Basse-Kotto prefectures.

## 5.2 PERI-URBAN INTENSIVE CATFISH CLOSED (SEMI-CLOSED) SYSTEMS

Intensive closed farming systems are limited by poor and unreliable energy distribution networks (Satia, 2017). Solar power/photovoltaic (PV) can supply operational needs[6] of closed systems pumps and aerators, to provide oxygen, to move water into and through the system, and to purify water. Suitability assessment modelling introduces PV as intensification potential.

It is assumed that closed systems techniques using ponds, tanks, RAS, flow through and recirculation are considerably less dependent on natural or physical geographical criteria, because:

- Require less water because are based in reuse/recirculation.
- Water balance can be even less significative considering that the modelling does not weight groundwater availability.
- Tank systems can be placed indoors or in compounds lowering climatic limitations.
- Land and soil requirements are minimal since tanks are produced with manmade materials - concrete, steel, fiberglass, or plastic.

Closed containment farming methods also pose smaller environmental risks due to controlled exchange between farm and environment. In recirculation methods, water is treated and recirculated, with minimal wastewater discharges[7], reducing pollution, fish escapes, negative wildlife interactions, parasite, and disease transfer.

Assumptions:

1. There is enough water availability in most of the territory (even without considering ground water).
2. Closed intensive systems are not dependent on soil characteristics.

Considered criteria:

a. Market accessibility (major urban areas).
b. Water Balance (water requirements).
c. Potential Yield.
d. Crop input (CropAgg) - availability of agricultural by-products.

[6] https://thefishsite.com/articles/photovoltaic-applications-in-aquaculture-a-primer

[7] https://www.seachoice.org/info-centre/aquaculture/aquaculture-methods/

e. Livestock input (weighted animal density aggregation) - availability of livestock by-products.
f. Slope - terrain suitability.
g. Photovoltaic (PV) energy potential.

Constraints:

a. Urban areas.
b. Protected areas.

Final maps exclusive criteria:

a. Mobile broadband coverage.
b. Maximum distance to major roads.

The exercise presents alternative outputs with and without PV.

### 5.2.1 Location score (without PV)

The location score is obtained by way of a simple arithmetic weighted sum (normalized/scaled grids), theoretically varying from 0 to 100, with the following weighting: *(“Accessibility MajorUrbanAreas” X 0.5) + ("WaterBalance" X 0.15) + ("potential Yield" X 0.15) + (“CropsInput” X 0.075) + (“LivestockInput” X 0.075) + ("Slope " X 0.05)*

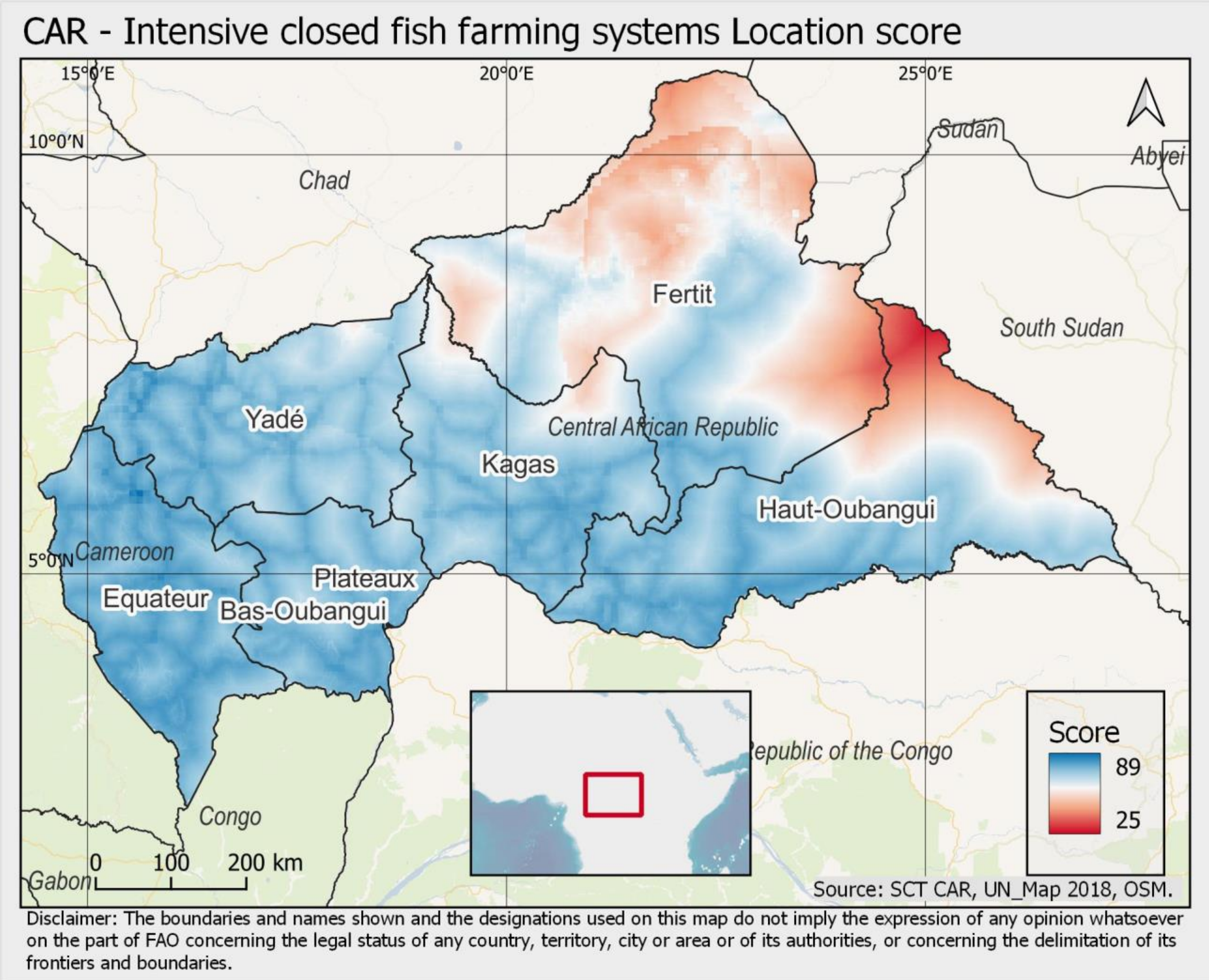


*Figure 7 – Map - Intensive closed catfish systems suitability*

Since the demand factor is of major importance, intensive closed commercial farming systems suitability spatial pattern follows output markets, urban areas.

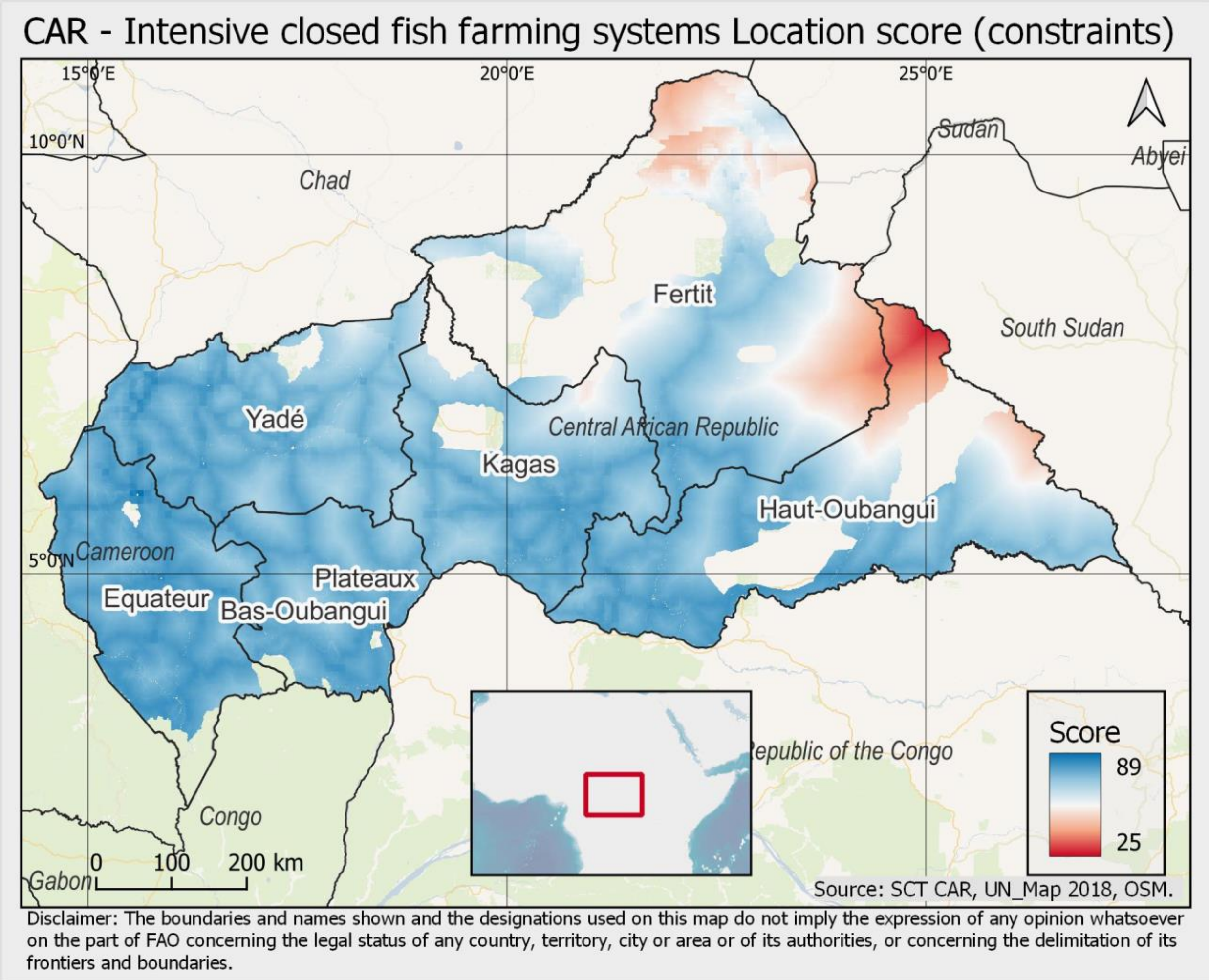


*Figure 8 – Map - Intensive closed systems suitability (constraints).*

### 5.2.2 Location score - with PV

The location score is obtained by way of a simple arithmetic weighted sum (normalized/scaled grids), theoretically varying from 0 to 100, with the following weighting: *(“Accessibility MajorUrbanAreas”x 0.4) + (PVOUT x 0.10) + ("potential Yield"x 0.15) + (“CropsInput” x 0.1) + (“LivestockInput” x 0.1) + (("WaterBalance" x 0.1) + ("Slope "x 0.05)*

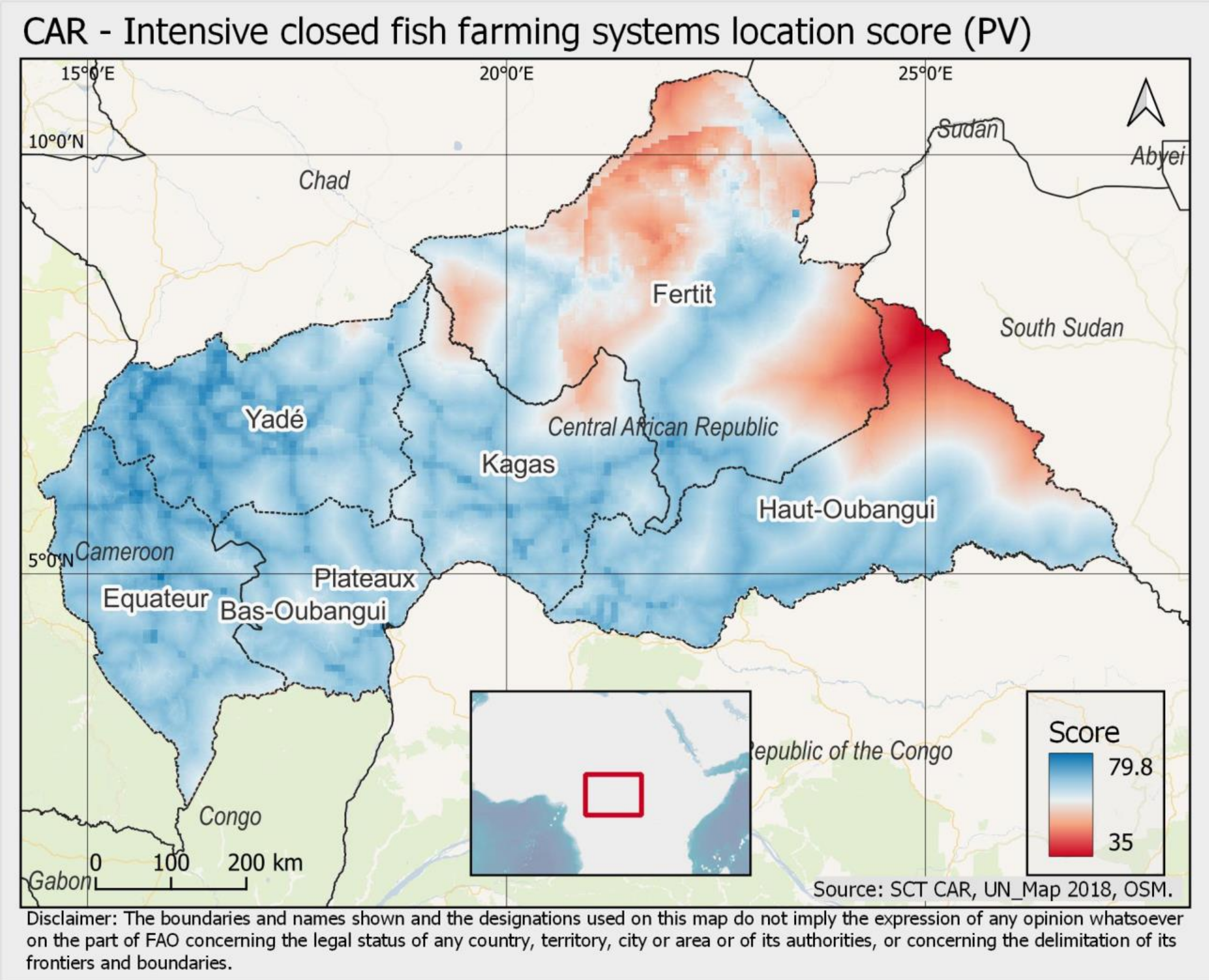


*Figure 9 – Map - Intensive closed systems intensification potential (PV)*

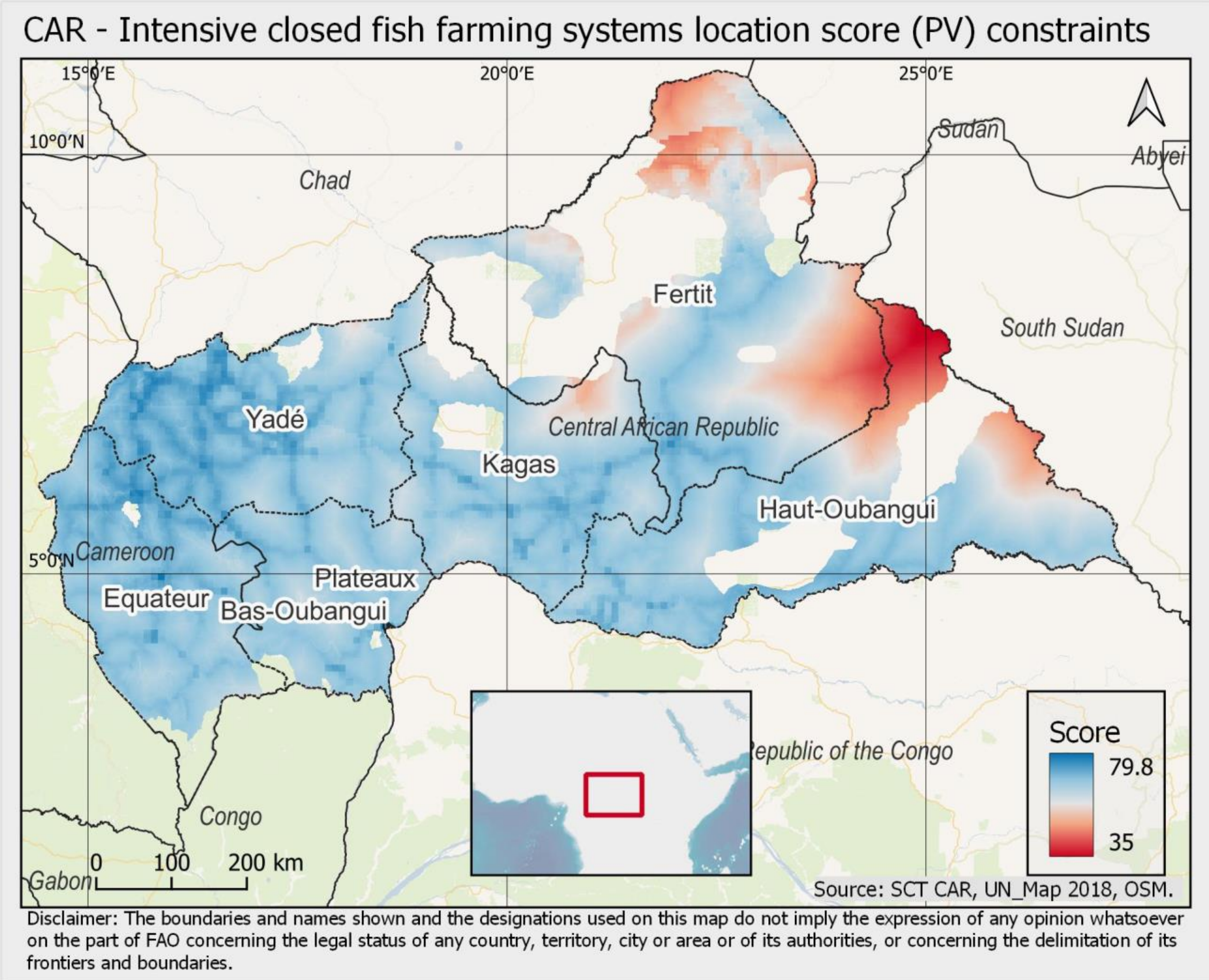


*Figure 10 – Map - Intensive closed systems intensification potential (PV) (constraints)*

The market/demand criteria using population density can also be misleading, urban population concentration *per se* does not guarantee market purchase power for intensive large-scale production.

### 5.2.3 Final Maps

Final maps identify areas suitable for investment, employing as final or exclusive criteria: distance to major roads and access to ITC (mobile broadband coverage).

ITC usage has a growing importance in marketing, helping to reduce information asymmetry between traders and producers, but also allows improved extension services, microcredit apps/tools, or innovative digital finance using, for example, blockchain technologies. Innovative applications can also be envisioned in fields like disease monitoring or management.

Final mapping follows the subsequent procedure:

- ***Buffering*** – A buffer area for all the features in an input layer using fixed or dynamic distance:
    - Major roads - 2km (0.018 degree) buffer radius.
- ***Intersection*** - extracts the overlapping portions of features in the Input and Overlay layers: *Roads_Buffer* and *Mobile_Broadband_coverage*.
- ***Dissolve*** - Takes the intersection vector layer and combines the features into a new feature, a single polygon.
- ***Clip Raster by Mask Layer*** – The grids are extracted using the polygon.
- ***Raster Calculator:***
    - Final recommended top score sites are selected using the 95$^{th}$ percentile and raster calculator: *“raster”>95th percentile X “raster”*
    - Setting the value 0 as no data: ((“raster” >0) X “raster”)/ (((“raster” >0) X 1) + (“raster” >0) X 0)))

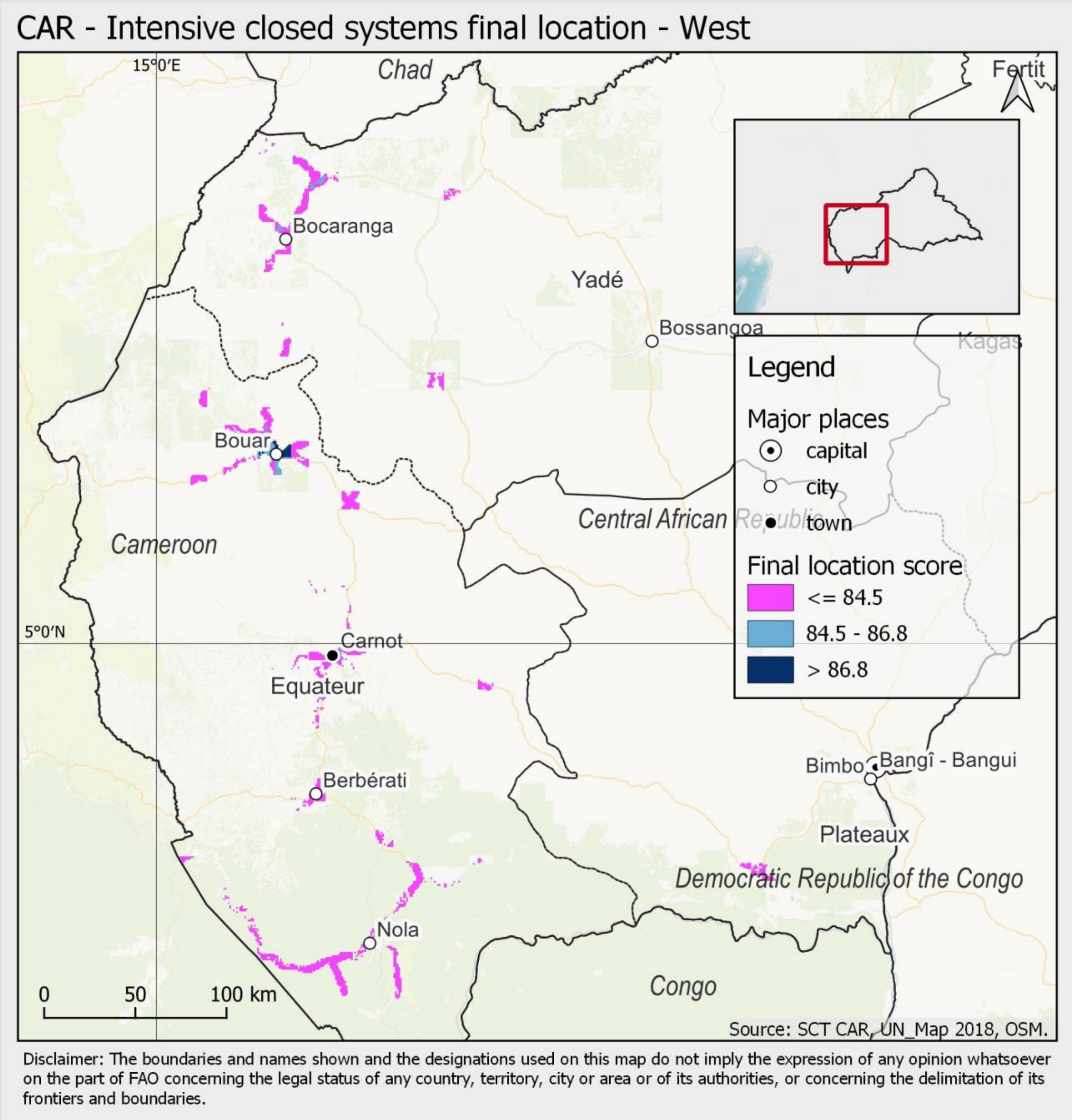


*Figure 11 – Map - Intensive closed systems final (west)*

Suitability appears to be higher in the country western regions, in proximity to urban areas: Bocaranga, Bouar, Carnot, Berbérati, and Nola, but also in some extent in the Plateaux region southwest of Bangui.

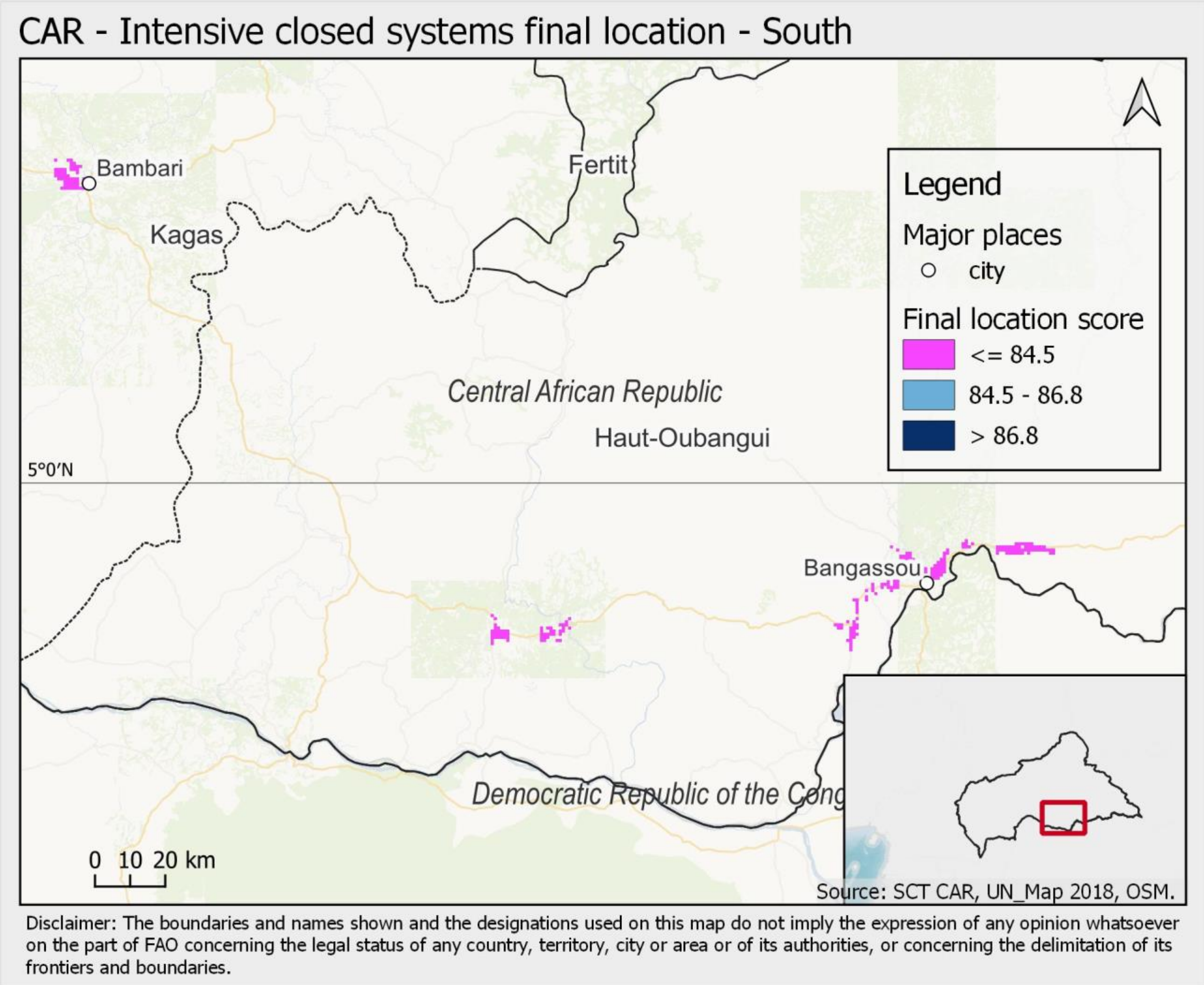


*Figure 12 – Map - Intensive closed systems final (south)*

Other suitable areas can be found in the south close to Bangassou and the Democratic Republic of the Congo border.

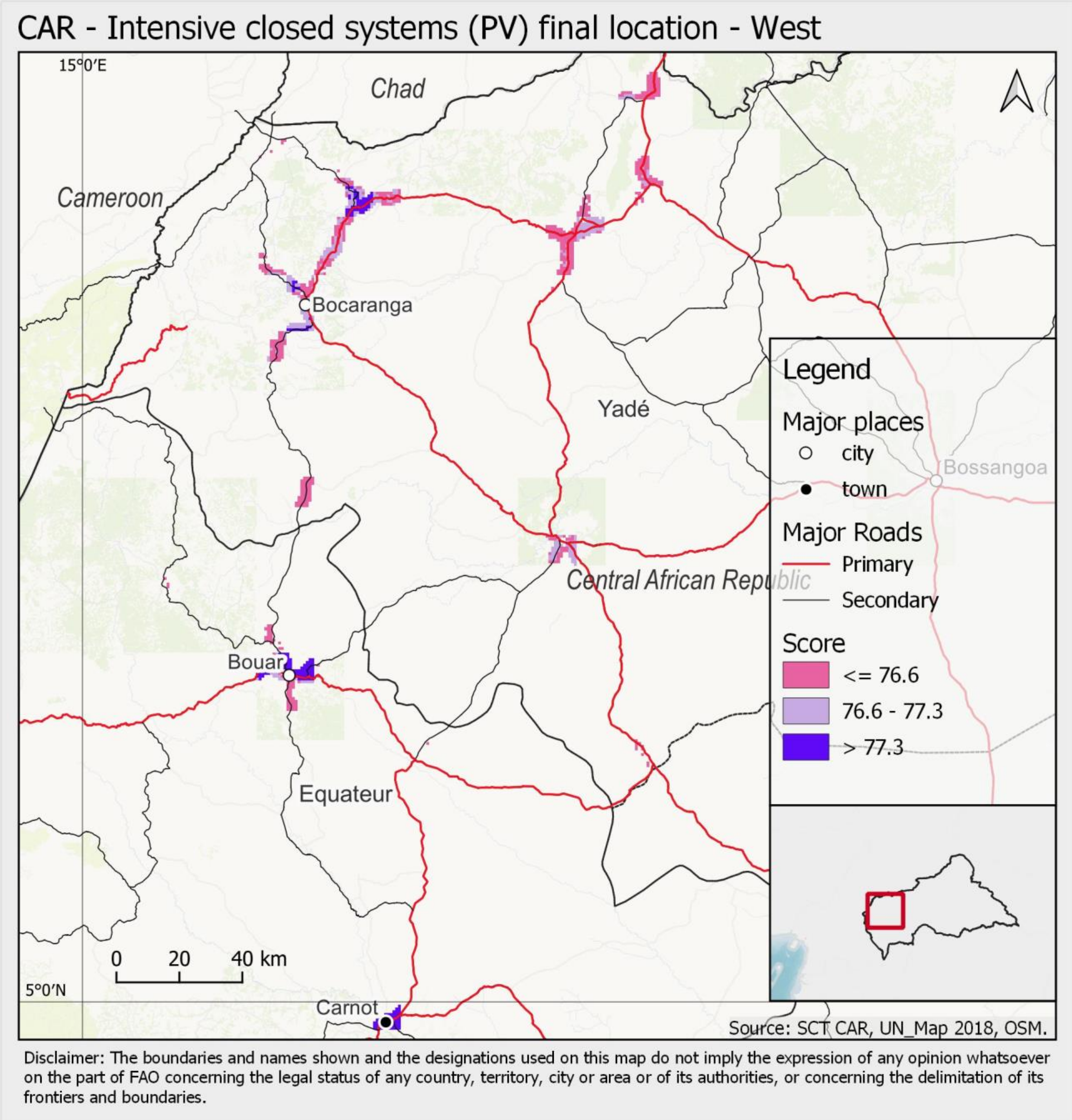


*Figure 13 – Map - Intensive closed systems final (PV) (west)*

Again, two main suitable areas can be visualized, in the western areas of the country close to Cameroon border, Bocaranga, Bouar and Carnot present the highest score.

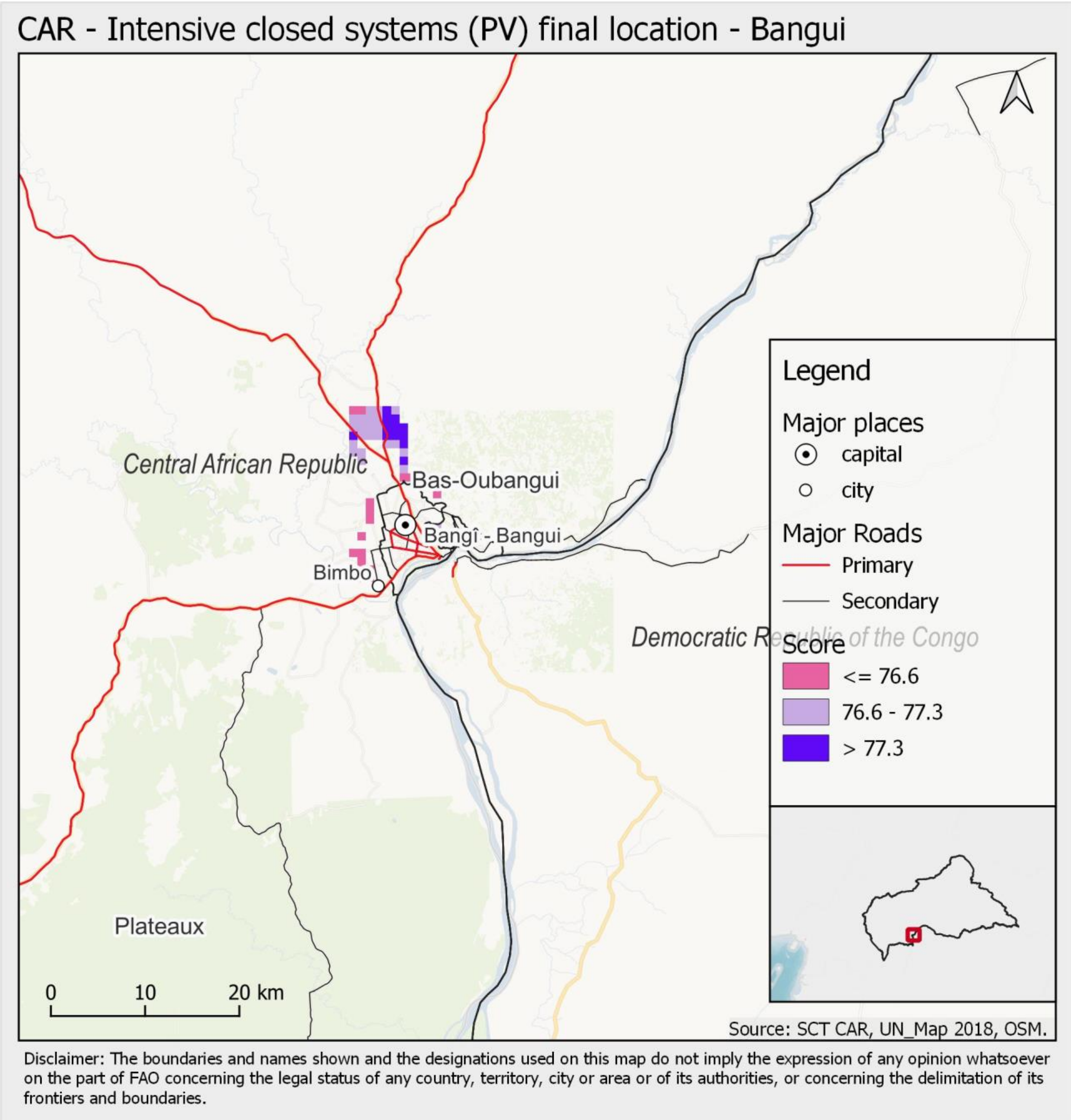


*Figure 14 – Map - Intensive closed systems final (PV) (Bangui)*

In the south, Bangui shows some potential peri-urban areas for intensive closed systems fish farming production.

## 5.3 OPEN INTENSIVE TILAPIA CAGE SYSTEMS

Intensive tilapia farming using cages in waterbodies are one of the most profitable fish farming systems. They require low initial investment, are usually located in public waters, and have low construction and energy requirements. Additionally, the tilapia breeding cycle is interrupted in cages, simplifying seeding management, and augmenting productivity, with harvesting also at low cost.

The disadvantages of open aquaculture systems result from exchanges with surrounding environment, transferring waste, chemicals, parasites, and disease, and with a high potential for fish escape. These systems are also more vulnerable to predation and poaching, farming in public waters face competing interests, and legal status sometimes is not well defined. Not all LWB offer appropriate conditions.

Tilapia post-harvest value chain is more demanding compared with the, mostly marketed alive, resistant catfish. Large scale distribution requiring cold chain/storage is obstructed by incipient infrastructure deployment - rural electrification, alternative energy sources and road infrastructure.

The Central African Republic analysis doesn't have many significative LWB, dams and reservoirs but possesses a large river network. GSW layer, seasonality, where seasonality is 12 months (maximum) is used to identify permanent waterbodies (> 5 acres) considered as minimum conditions for tilapia cage farming (Mcginty & Rakocy, n.d.).

The modelling methodology differs from the previous analyses since the defining location factor is the presence of permanent water with an area surface of more than 5 ac.

Criteria (score):

a. Market accessibility (large urban areas).
b. Crop input (CropAggGAEZ) availability of agricultural by-products.
c. Livestock input (weighted animal density aggregation) availability of livestock byproducts.
d. Accessibility to ports - considers that high quality/performance tilapia feed is imported.
e. Tilapia potential yield.

Constraints:

a. Protected areas.

### 5.3.1 Location Score

The location score is obtained by way of a simple arithmetic weighted sum (normalized/scaled grids). Varying from 0 to 100, with the following weighting: *("Accessibility MajorUrbanAreas" X 0.40) + ("CropsInput" X 0.15) + ("LivestockInput" X 0.15) + ("Accessibility Ports" X 0.15) + (Tilapia Yield x 0.15)*

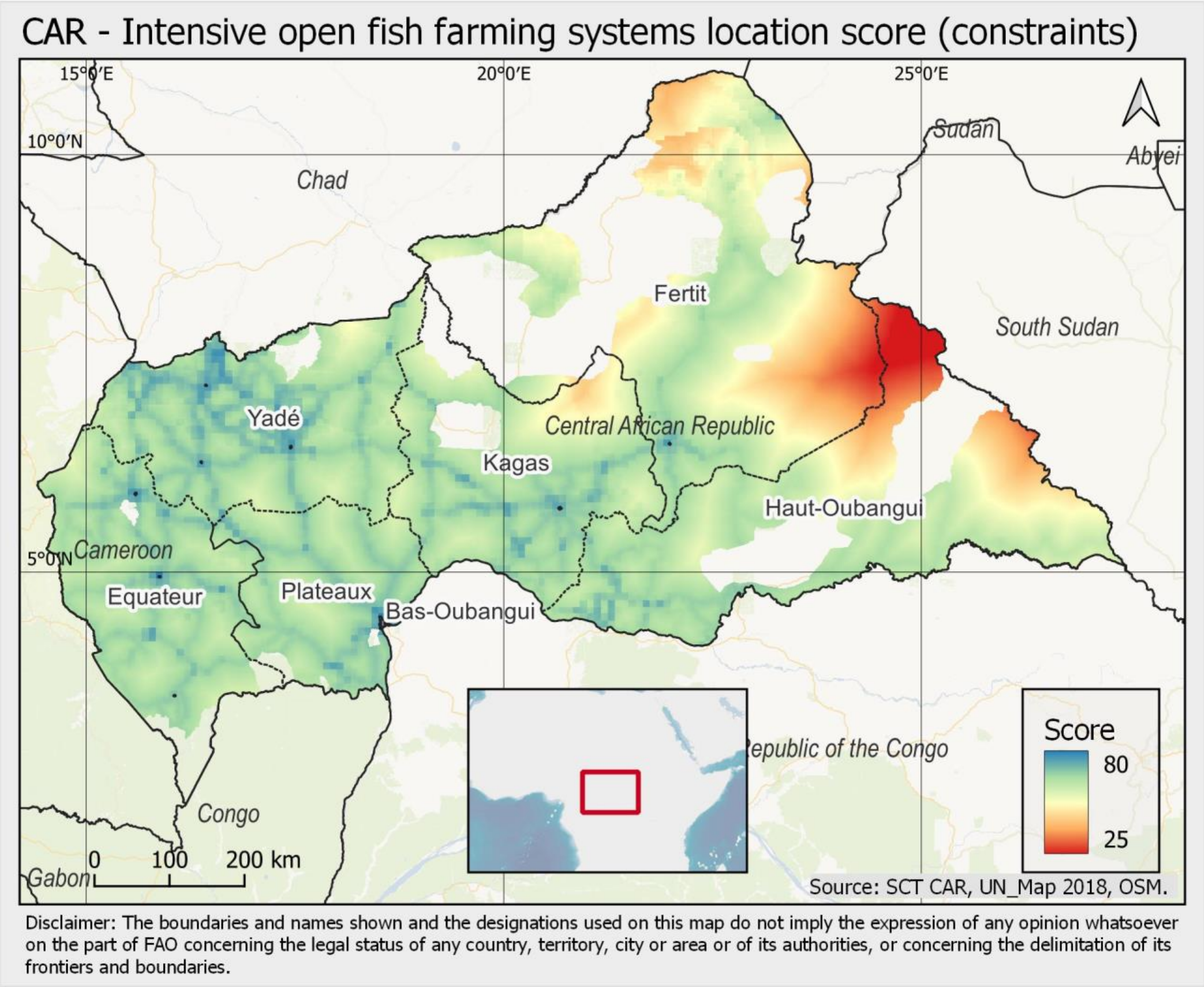


*Figure 15 – Map – Tilapia cage suitability*

Highest location score areas can be found in the most urbanised regions of the country in the south and west: Yadé, Equateur, Kagas, Plateaux, Bas-Oubangui.

### 5.3.2 Constraints and Final Mapping

Recommended locations require the presence of permanent waters with a surface area larger than 5 acres, final mapping follows the approach:

1. ***Clipping*** - Location score mapping is clipped using a 1km buffer from permanent waters (>5ac area) polygon layer.
2. ***Zonal statistics tool*** - Extract the maximum (max) score value from the grid layer to the buffer layer polygons.
3. Select/display of the top 95$^{th}$ percentile.

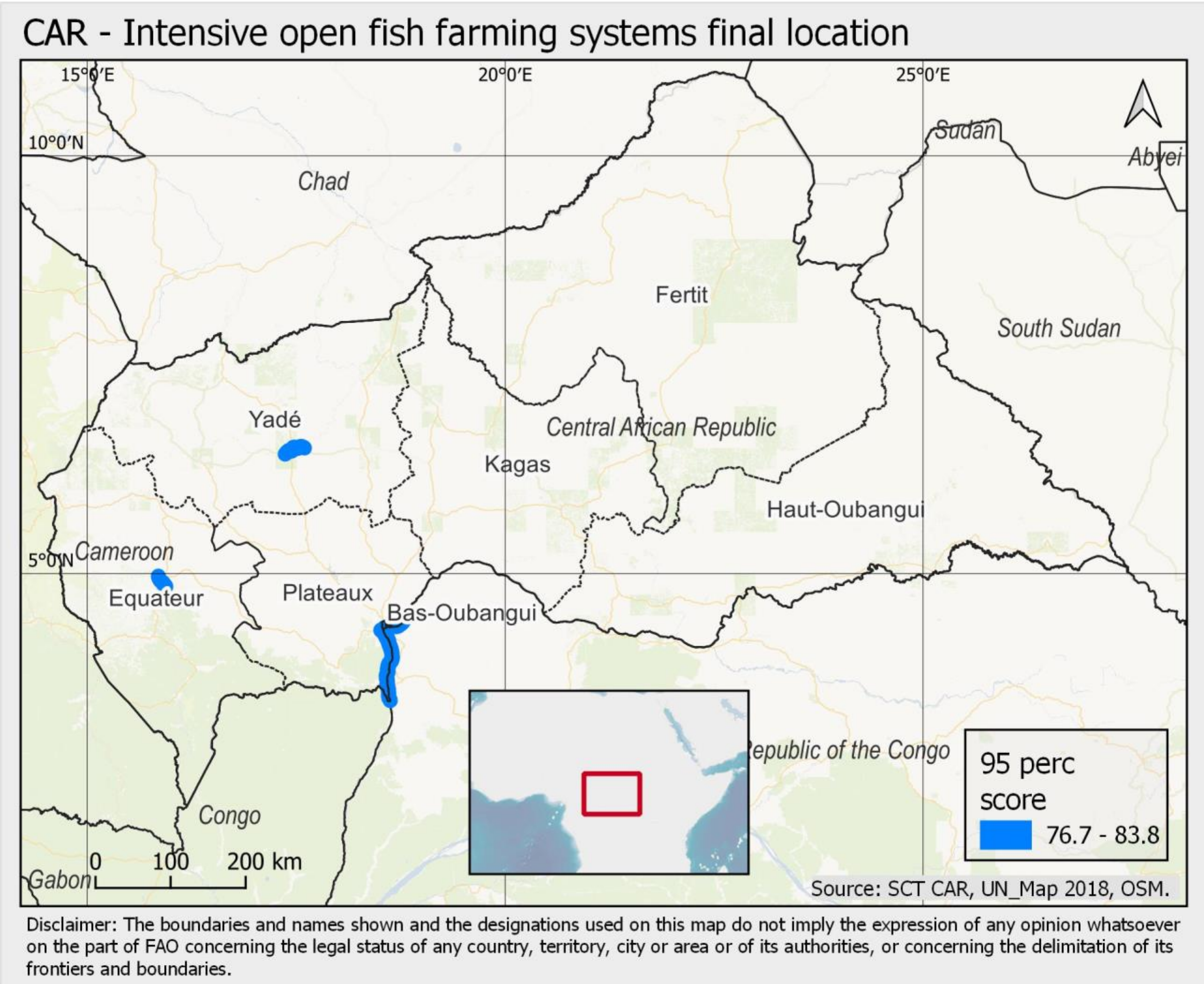


*Figure 16 – Map - Tilapia cage suitability (95th percentile)*

Three major areas are identified using the selection criteria and constraints, in Yadé, Equateur and Bas-Oubangui regions. Further large scale mapping presents more detail on those locations.

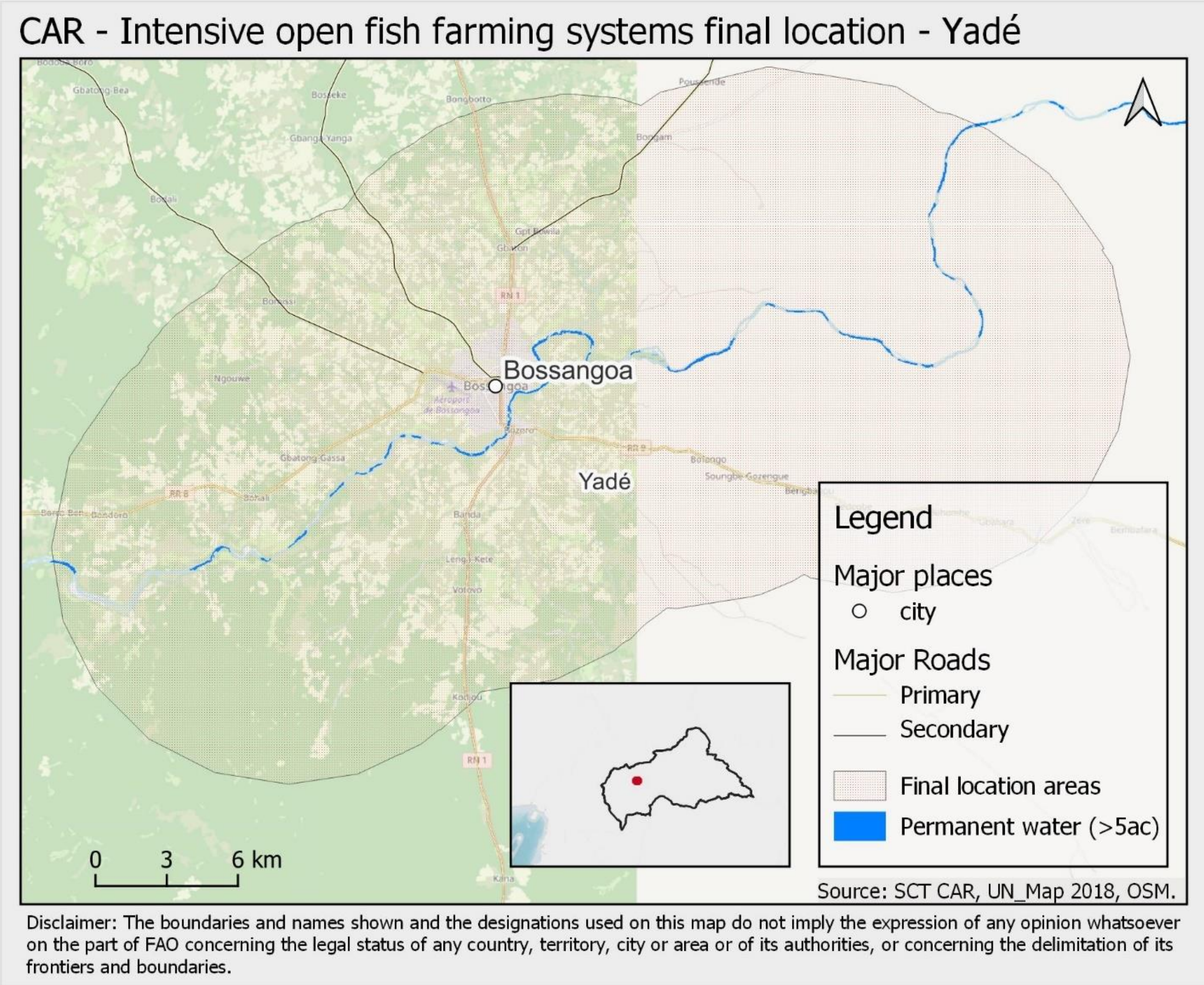


*Figure 17 – Map - Yadé/Bossangoa - tilapia cage final*

In the Yadé region, Bossangoa area, the Ouham river might have potential conditions for intensive open cage farming systems.

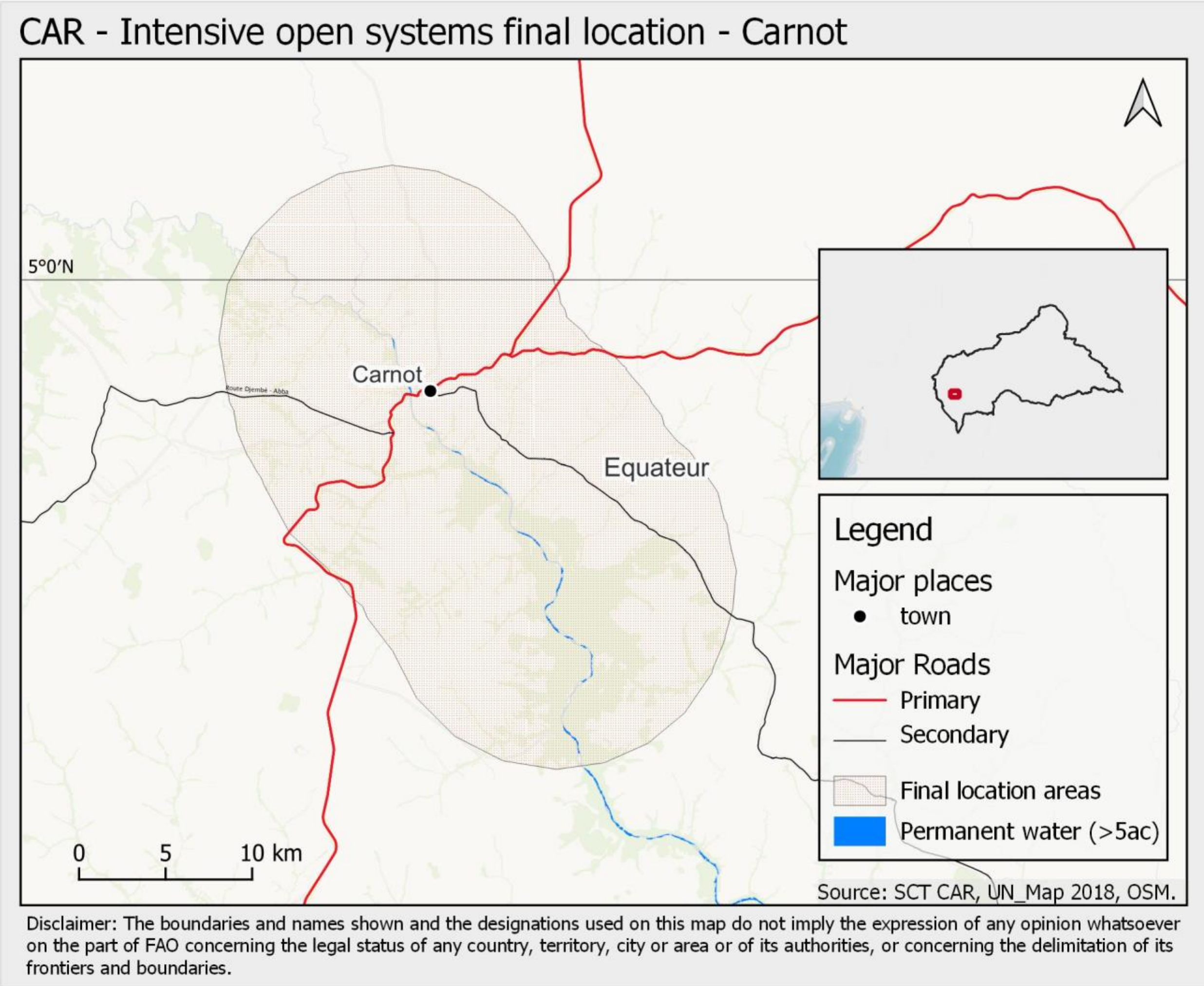


*Figure 18 – Map - Equateur/Carnot - tilapia cage final*

In the area of Carnot city, the Mambéré River, tributary of the Sangha, and the Congo River major basin, could also show prospective conditions for tilapia cage farming systems.

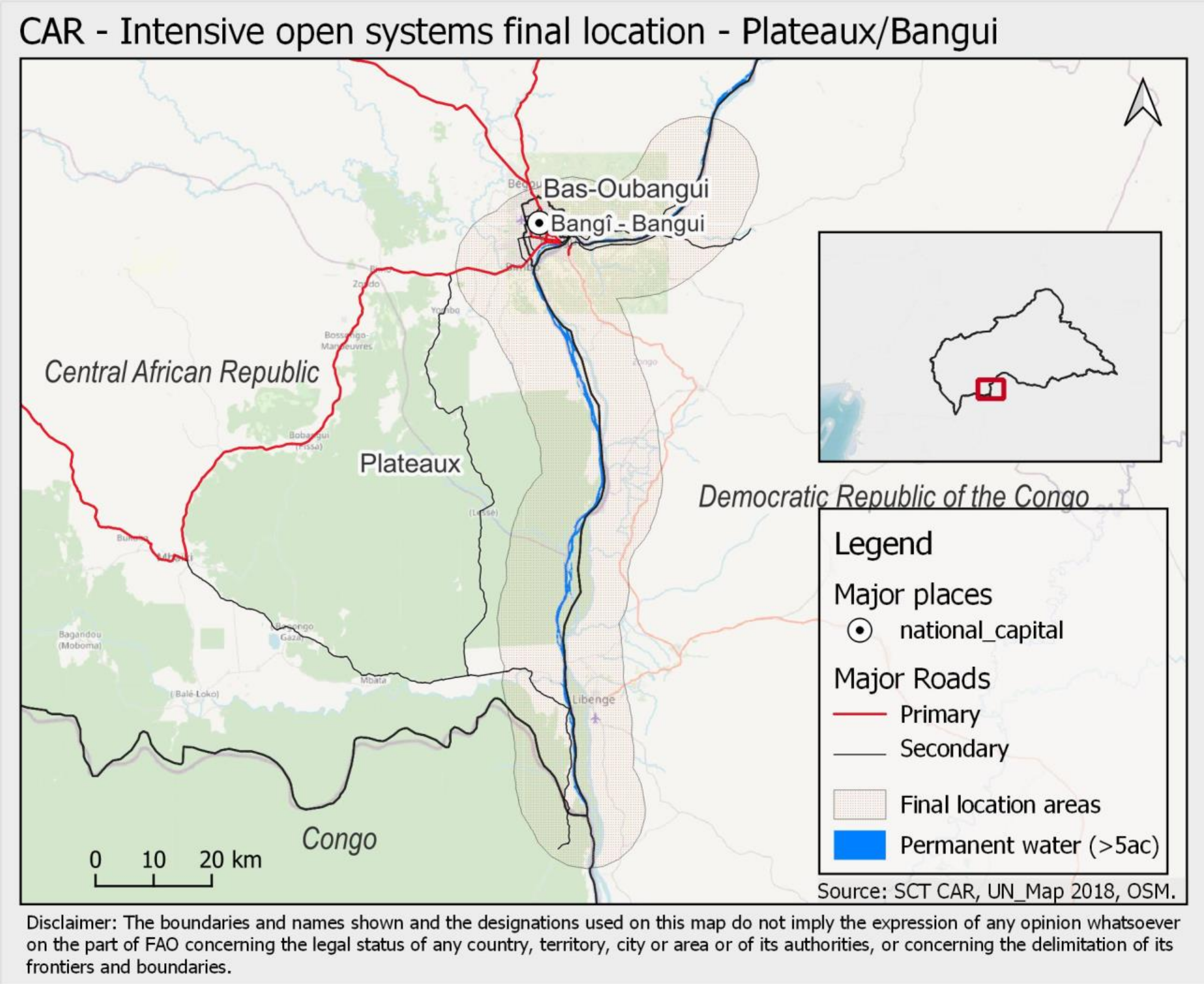


*Figure 19 – Map - Plateax/Bangui - tilapia cage final*

In the proximity of the country capital, Bangui, the Oubangui river, one of the major Congo River tributaries, might also offer conditions for tilapia cage farming. Other waterbodies not featured in the final mapping using the current criteria and constraints, should be explored as potential sites, it is the case of the Mbali River dam, northwest of Bangui.

 

# CONCLUSIONS

This section includes results, conclusions and closing remarks.

## RESULTS

Mapping is provided at distinct scales for the different fish farming systems.

***Open non-intensive integrated* small-scale farming systems, *using ponds or small waterbodies* (Catfish and Tilapia).**

Highly suitable areas are found in the southern and western regions of the country closer to Cameroon, the Republic of the Congo, and the Democratic Republic of the Congo borders. At prefecture average score the strongest candidates for interventions appear to be:

- Southwestern Equateur Region: Mambéré-Kadei and Sangha-Mbaéré prefectures.
- Plateaux Region: Lobaye prefecture.
- South Haut-Oubangui Region: Basse-Kotto prefecture.

**Intensive closed peri-urban catfish farming systems** - adoption is limited by poor electricity distribution networks. Closed/semi-closed-circulation technologies (re-circulating tanks, raceways, flow-through systems, and ponds) are less dependent on natural or biophysical criteria and pose smaller environmental risks due to controlled exchange between farm and environment.

Final location mapping, optimal theoretical investment sites, are within exclusive criteria of distance to major roads and access to IT (mobile broadband coverage).

Spatial pattern follows output markets, urban areas. The market/demand criteria using population density can be misleading since urban population concentration per se does not guarantee market purchase power. Suitability appears higher in the country western regions, in proximity to the urban areas of Bocaranga, Bouar, Carnot, Berbérati, and Nola, but also to some extent in the Plateaux region southwest of Bangui. Other suitable areas can be found in the south close to Bangassou and the Democratic Republic of the Congo border.

**Using the PV potential as an intensification measure** two main suitable areas can be identified, in the western regions of the country, close to Cameroon border, Bocaranga, Bouar and Carnot present the highest score. In the south, Bangui shows some potential areas.

***The tilapia open intensive cage farming systems in waterbodies*** are considered one of the most profitable despites of its downsides from exchanges with the surrounding environment.

Highest location score areas are around the urbanised regions in the south and west: Yadé, Equateur, Kagas, Plateaux, Bas-Oubangui. Final mapping reveals three major areas, in Yadé, Equateur and Bas-Oubangui regions where permanent waters can be found.

- Yadé region, Bossangoa area the Ouham river tributary of the Chari River and Lake Chad major basin.
- Equateur - Near Carnot city, the Mambéré River, tributary of the sangha, in the Congo major basin.
- Bas-Oubangui – Bangui the Oubangui river tributary to the Congo River.

It should be mentioned that while not showing in the final mapping the major artificial waterbody in the country Mbali River hydroelectric Boali Dam, northwest of Bangui, should also be evaluated for tilapia cage farming systems.

## CONCLUSIONS

Spatial decisions involve a set of alternatives and multiple assessment criteria. GIS-MCDA proposes a method to convert and combine spatial data, and decision-makers criteria to attain evidence for an informed decision. More importantly, it provides an auditable and replicable model, improves communication, offers diverse problem and solution standpoints, and helps refining specification and/or criteria.

From a critical standpoint, we can state that while data analysis and evidence gathering through GIS modelling does contribute to support decision-making processes, a more complex set of socioeconomic, political, cultural, ethno-anthropological aspects, and power relations, shape and govern most spatial decision-making.

Modelling is also as good as the input data. Its quality and reliability support the extent to which conclusions can be trusted, and these are just as sound as the analysis conducted. From that prism, specification and objectives define assumptions and approximations, and can always produce distinct answers.

The Central African Republic is a landlocked country with an area of 623 000 km2 and a population of 4.7 million inhabitants, i.e. a density of 7.47 inhabitants/km2. It possesses a varied and complex ecological environment in terms of aquatic resources.

Accurate statistics production is missing in the country, and there is insufficient knowledge of fish population dynamics. Even tough aquaculture was introduced more than 70 years ago ( 1952), has been supported by both state and development agencies, and finds favourable biophysical and socioeconomic conditions, production in 2021 was estimated at a mere 175 tonnes. Reasons for this are common to many sub-Saharan Africa, lack of feed, seed, difficult access to finance, low technical capacity, and organization. Adding to that there is strong security threats resulting from the ongoing civil war.

At the institutional and normative level progress is also slow, and the country lacks a national aquaculture development plan, with preliminary proposals pointing to activities around:

- Support services (public and private) capacity building.
- Improving production systems efficiency (Tilapia nilotica and Clarias sp in earthen ponds and tanks) and seaweed farming; And
- Improving aquaculture sector management and professionalization.

There are examples in the sub-Saharan African region that can frame sector development proposals. It is the case of Nigeria's African catfish farming success, a species highly adapted to local environment, resistant to hi-densities and hard conditions, that can be marketed alive, with a cooperative, public/private peri-urban farming model.

***Departure research questions*** were formulated as:

1. *What are the regions and prefectures where fish farming should be promoted for poverty alleviation, improving nutrition, and food security?*
2. *Where are the best sites for intensive commercial closed farming system investment?*
3. *Where are the best sites for intensive commercial Tilapia fish farming open systems?*

***Research methodology*** followed previous Geographic Information Systems (GIS) fish farming suitability assessment analysis. A brief literature review on aquaculture fish-farming sector context, background, and perspectives. A GIS Multi-Criteria Decision Analysis (GIS-MCDA) modelling applying weighted factors, constraints, and exclusive criteria.

Fish farming suitability/potential zoning develops from Aguilar-Manjarrez and Nath study on warm and temperate freshwater fish farming suitability in continental Africa, raster-based GIS-MCDA using fish-farm and land-quality factors, with sub-models and categories of criteria:

1. Constraints (urban areas, large water bodies, protected areas).
2. Water requirement.
3. Soil and terrain suitability.
4. Inputs – crops and livestock.
5. Farm-gate sales - as a measure of population density classification.
6. Potential yields.
7. Urban market size and proximity.

Sector growth, fish farming systems, and data availability, all substantially evolved since late 20$^{th}$ century, thus imposing updating and reassessment of data, criteria, weighting, and constraints.

Two distinct zoning efforts were defined:

1. To ***define and suggest regions and prefectures where investment can positively impact poverty, hunger, malnutrition, and food security*** - Extensive to semi-intensive small-scale integrated farming systems.
2. ***To select the best possible sites (high return on investment) for intensive commercial systems***, for both:
    a. Catfish closed intensive farming systems using re-circulating tanks, raceways flow-through systems, and ponds.
    b. Tilapia open intensive cage farming systems.

Distinct **farming systems modelling** are developed based on specific theory, thus defining criteria combinations, weighting, and applying separate constraints:

1. Open non-intensive and integrated fish/crop farming systems – using ponds or small waterbodies.

2. Catfish closed Intensive systems –closed/semi-closed-circulation technologies: recirculating tanks, raceways, flow-through systems, and ponds.
3. Tilapia open intensive systems – using open-net pens/ cage techniques in public waters.

***Modelling criteria*** cover: physical geography conditions, supply, demand, infrastructure and accessibility, and intensification potential (PV):

*1.* Physical geography conditions:
    a. Water requirement.
    b. Soil.
    c. Terrain suitability (slope).
    d. Potential yield (temperature).
*2.* Supply
    a. Crop production– feed.
    b. Livestock – animal density – feed and organic fertilizing.
*3.* *Demand* - Human population density – farmgate sales and markets (urban/metropolitan areas).
*4.* *Infrastructure* - Transportation network (accessibility ports and urban/metropolitan areas).
*5.* *Energy* - Photovoltaic (PV) potential – Intensification potential.

Infrastructure and demand (market) sub-models involve raster-based travel time/cost analysis and is processed for large urban/metropolitan areas and ports.

Applied **constraints** (according to farming system specificities):

1. Urban Areas.
2. Protected Areas.
3. Large water bodies.
4. Flood areas.

Final mapping **exclusive criteria** for intensive closed systems:

1. Distance to major roads.
2. Access to IT - mobile broadband coverage.

## CLOSING REMARKS

Closing remarks discuss assumptions and pitfalls, findings limitations, and future developments.

The exercise focuses on warm-temperate freshwater fish farming suitability modelling for African Catfish and Nile Tilapia species.

### General Assumptions

1. Water availability is suitable or very suitable for most of the territory.
2. Natural and physical geography criteria are considerably more relevant to open, non-intensive integrated fish/crop farming systems.
3. Intensive systems depend on accessibility to input (feed/seed) and output markets (large urban areas demand).
4. Production intensification, that can take place using closed-circulation technologies - re-circulating tanks, raceways, flow-through systems, and inland ponds - are reliant on energy supply.

### Sub-Models Assumptions

1. Accessibility infrastructure sub-model
    a. Inland water navigation is processed as polygons, infrastructure network as lines.
    b. Considered navigable river segments have *Strahler* number[8] > 4.
    c. Navigation is assumed for small to medium cargo crafts.
    d. Road travel time/cost is modelled for cargo freight, tertiary and local traffic roads are not included; country road network conditions are poor.
2. Demand/market sub-models
    a. Accessibility to large regional cities (markets) - Cross border trade is not considered due to the large fish production consumption deficit.
    b. Urban areas - Population density above 1 200 h/k² and area larger than 5 km². Accessibility calculated to major roads (polylines) intersection points with urban areas (polygons). Small or less dense urban fabrics might not be accounted as substantial markets.

[8] https://www.jayconrod.com/posts/66/the-strahler-number

3. Demand/Farmgate sales sub-model:
    a. Uses population density classes and does not account for purchasing or acquisitive power.
4. Physical Geography:
    a. Fish yield (temperature) and soil data are from original study (1997).
    b. Soil/slope sub-model is used for small scale extensive, semi-intensive, pond systems.
    c. Slope data is used individually for intensive commercial closed systems.
5. Inputs sub-models' assumptions:
    a. Crop – products/by-products can be used as feed or as raw materials for feed mills.
    b. Livestock - considered for organic fertilization and/or feed ingredients.

## Suitability/Potential Modelling Assumptions

1. Non-intensive open farming systems:
    c. biophysical criteria weight the most on low input systems.
2. Intensive closed Catfish farming systems:
    a. Are limited by absent or unreliable energy distribution networks.
    b. Are not dependent on soil characteristics.
    c. Have low dependency on water resources (reuse).
3. Open intensive tilapia farming systems:
    a. The defining location factor is the presence of a permanent water body with a surface area > 5 acres.
    b. High quality/performance feed is imported (accessibility to port).

### CONSTRAINTS

- Protected area constraints can be disputed. The type and level of restriction in place is not considered, and socio-economic benefits can outweigh protection concerns.
- The definition of thresholds and classification (value judgement) for buffer distance to/from roads might lead to missing potential areas.

- A set of assumptions are inherited in IT access from mobile broadband coverage maps estimations.
- Security considerations are not used as constraints but data from MINUSCA could be added to limit and model accessibility.

## RECOMMENDATIONS

Caution and examination should be considered over intensification and growth within aquaculture development, as well as sustainability and possible impacts. Environment, health and disease, and land and water competition challenges must be assessed, and objective assessment of ethnic, cultural, religious, socio-political diversity, and conflict issues must frame interventions.

Environmental issues are missing from the equation for most of the industry literature. Integrated farming systems can positively impact sustainability and recirculation techniques have low water requirement and output effluents. Fish farming can also reduce fishing pressure. Still, little research and data are available on impact issues like eutrophication, reduction in dissolved oxygen, production of toxic microorganisms, toxicity on aquatic ecosystems, and disruption of fish assemblage in the wild or genetic pool impact.

In other sub-Saharan countries where fish farming has had some development, there is evidence of an increase in harmful organic and chemical effluents, and direct discharge of untreated waste waters in river streams (Albine et al., 2021; Bouelet Ntsama et al., 2018). Open systems exchange with the surrounding environment, transferring waste, chemicals, parasites, disease and have a high potential for fish escapes.

Health and disease monitoring and management must also be considered, putting in place surveys, monitoring, diagnostic, and guidelines on biosecurity.

Activity expansion and impacts additionally increase land and water competition that are already prone to conflict problems, and open systems in public waters commonly face conflicting interests.

This set of long-term impacting issues must be balanced with the immediate socio-economic objectives and improving productivity should promote environmentally sustainable production and extension technologies.

Besides considering physical geographical conditions, supply, demand, infrastructure, accessibility, and alternative energy (photovoltaic potential), awareness of social-cultural, ethnic, and political context and factors must guide proposed interventions. A holistic approach can result in successful and sustainable adapted proposals, targeting systems and models which can positively impact poverty, hunger, malnutrition, food security, and/or can lead to high return on investment on commercial aquaculture systems and job creation.

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