Agricultural Cold Chain Analysis and Prioritization (AgCAP)

Methodology Description

Disclaimer

ACKNOWLEDGEMENT

This methodology document presents the Agricultural Cold Chain Analysis and Prioritization (AgCAP) tool, situating it within the broader landscape of geospatial modelling for energy access planning. As a piece of methodological communication, the document has benefited enormously from a peer-review process that pushed us to be more precise about what AgCAP measures, where it sits relative to other tools in the productive-use-of-energy (PUE) ecosystem, and where its claims are best framed as proxies, hypotheses, or open limitations.

Peer review. We are particularly indebted to the institutions and individuals listed below – and other reviewers this work benefitted from –all of whom reviewed the methodology in detail and provided feedback that materially improved how the work is presented.

- **World Resources Institute (WRI).** Dimitris Mentis, Douglas Ronoh, and Akansha Saklani, whose perspective on the wider PUE mapping ecosystem pushed us to position AgCAP more clearly as complementary to, rather than overlapping with, existing tools in this space.
- **Carnegie Mellon University Africa.** Nathan Williams, Associate Professor, whose methodological scrutiny led us to disclose the limitations of equal-weighted averaging across sub-indices and to reposition the aggregated Cooling Potential Index as a heuristic rather than a planning input.
- **BASE Foundation.** Roberta Evangelista, Senior Digitalisation Specialist, and Rebecca Botello, Sustainable Finance Specialist, whose review improved terminology consistency, the linkage between methodological steps and document structure, and the accessibility of the document for non-technical audiences.
- **Giacomo Falchetta**, Scientist at the Euro-Mediterranean Center on Climate Change and the International Institute for Applied Systems Analysis, whose review sharpened the lexicon, grounded several framings in the relevant literature, and surfaced open research directions on sensitivity analysis and market proxies.

In addition, we would like to express our gratitude to the partners listed below.

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Pilot country partners. The methodology was tested and refined through pilot work in Madagascar, in collaboration with the Ministry of Energy and Hydrocarbons, the Ministry of Agriculture and Livestock, the Ministry of Fisheries and Blue Economy, the Ministry of Industry and Commerce, the Rural Electrification Development Agency, and the National Statistical Institute. The pilot was guided by a technical working group, which further included WWF, GIZ, FAO, and WFP, whose field experience on cooling interventions for fisheries in southern Madagascar directly shaped several of the modelling assumptions and use cases described here.

Data and open-source community. AgCAP relies on an extensive set of openly available geospatial datasets, without which a tool of this kind would not be possible at scale. We gratefully acknowledge the providers of the data sources listed in Table 4 of this document, and the maintainers of the libraries on which the tool is built.

We also thank the maintainers of the Python and geospatial open-source libraries on which the tool is built. As our own contribution back to this ecosystem, the AgCAP code and documentation are openly available at https://github.com/SEforALL-IEAP/AgCAP; we welcome feedback, contributions, and collaboration from the wider community.

Finally, we are grateful to all our colleagues at SEforALL, in particular the Integrated Energy Planning (IEP) and Sustainable Cooling teams, whose support and guidance shaped both the tool and this document at every stage.

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EXECUTIVE SUMMARY

In Sub-Saharan Africa, up to 40% of perishable harvested products are lost to spoilage before reaching markets, with significant consequences for rural livelihoods, food security, and the climate footprint of agriculture. Cold storage can reduce these losses substantially, but investments to date have produced mixed results: too many cold-chain projects in low- and middle-income countries have been deployed in the wrong place, at the wrong scale, or without the supporting market and energy infrastructure needed to sustain them. The challenge is not whether cold storage matters, but where, for whom, and in combination with which other interventions.

At the same time, national energy access planning – including Integrated Energy Plans (IEPs), Rural Electrification Plans, and Least-Cost Electrification Plans – has historically focused on residential demand. Productive Uses of Energy (PUE), including agricultural cooling, are rarely operationalized within these planning frameworks, leaving a significant blind spot in how electrification investments are designed, sized, and prioritized.

The **Agricultural Cold Chain Analysis and Prioritization** (AgCAP) tool is designed to help close this gap. Developed by SEforALL, AgCAP is an open-source, geospatial, multi-criteria prioritization tool that identifies communities most likely to benefit from cold storage interventions. It works at the settlement level – the same unit of analysis typically used in least-cost electrification planning – so that the results can be effectively integrated into national electrification and agricultural development strategies. The tool combines openly available datasets on agricultural production, climate, market connectivity, electrification status, food security, and socio-economic conditions into composite indicators that proxy the potential demand for cooling across export, national, and fresh-market value chains, for both crops and fisheries.

AgCAP is built for a range of users. **Government planners** can integrate its outputs into Integrated Energy Plans and value-chain development strategies. **Development partners** and **NGOs** can identify high-impact sites for humanitarian or climate-resilience interventions. **Mini-grid developers**, **solar contractors**, and **cold storage providers** can pre-screen candidate communities before committing to costly feasibility studies. Users access AgCAP through three pathways: the [AgCAP Insights Platform] (a browser-based interactive map for non-technical users), [Jupyter notebooks] (for modelers and analysts wishing to customize the analysis), and the [open-source code repository] hosted on GitHub.

The tool's outputs should be interpreted as a **first level prioritization to guide investments, not as final investment decisions**. AgCAP narrows the search space for cold-chain interventions; it does not replace the technical, market, and financial assessments required to confirm site-level viability. Its indices are relative proxies for cooling potential rather than quantitative measures of demand, and several limitations – particularly around market-side data and the dynamic nature of agricultural land use – are documented openly throughout the methodology. AgCAP is designed to evolve through use, peer review, and integration of higher-resolution country-specific data, and we welcome engagement from the broader community of practice in shaping its future development.

CHAPTER ONE

Introduction

1.1 Context

Cold chain investments are crucial in Sub-Saharan Africa, where up to **40% of perishable harvested products are estimated to be lost to spoilage**[1]. Furthermore, a lack of sustainable cold chains, including freezers and refrigeration, directly resulted in a global of food loss of 526 million tons in 2017, when looking solely from a technological perspective[2]. Food losses, being the decrease in edible food mass at production, postharvest, and processing stages in the food supply chain, account for 95% of total losses in Sub-Saharan Africa (as opposed to food waste, accounting for the other 5%)[3]. From an energy access perspective**, productive uses of energy** for agriculture, livestock, and fisheries, including cooling, have the potential to **enhance the effectiveness, increase the impact, and improve the economic viability of rural electrification**. Moreover, cold chains are also critical to supporting rural economies and value chain development in Sub-Saharan Africa, contributing to a **reduction of post-harvest losses, improving rural livelihoods, ensuring food security, food safety (especially for produce sensitive to spoilage like meat, fish, milk, etc.), contributing to the formalization of markets, and improving climate resilience.**

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[1] Davidson, I. (2025) *The cold chain in Africa*. Global Cold Chain Alliance (GCCA). Available at: https://www.gcca.org/magazine-article/the-cold-chain-in-africa/

[2] Sarr, J. et al. (2021) *The Carbon Footprint of the Cold Chain, 7th Informatory Note on Refrigeration and Food*. Paris: International Institute of Refrigeration (IIR). Available at: https://iifiir.org/en/fridoc/the-carbon-footprint-of-the-cold-chain-7-lt-sup-gt-th-lt-sup-gt-informatory-143457

[3] Gustavsson, J., Cederberg, C., Sonesson, U., van Otterdijk, R. and Meybeck, A. (2011) Global food losses and food waste: extent, causes and prevention. Rome: Food and Agriculture Organization of the United Nations. Available at: https://worldveg.tind.io/record/44378/files/eb0157.pdf

Challenges associated with a lack of agricultural cold chains in Sub-Saharan Africa are well-diagnosed, but a persistent lack of credible, spatially explicit, investment-ready data is a barrier that continues to hold back financing and implementation. This leads to a missed opportunity where access to energy and cold storage can foster local economic growth. We believe that the advent of geospatial science and the increasing availability of good Earth Observation (EO) data - indicating agricultural productivity, climatic conditions, existence of and access to markets, status of infrastructure, socio-economic conditions, and others - create an opportunity to improve the way candidate communities for agricultural cold storage interventions are identified and analyzed at scale.

1.2 Application

SEforALL aims to address this challenge through the development of the **Agricultural Cold Chain Analysis and Prioritization (AgCAP) tool**, a customizable multi-criteria cold chain prospecting tool. AgCAP complements the efforts of the Ministries of Agriculture, Fisheries, and Energy, as well as the National Statistics Institutes, to **identify communities most likely to benefit from cold storage solutions**, enabling data-driven site identification and guiding commercial viability assessments to inform investment opportunities at the pre-feasibility stages.

Users of the AgCAP tool can generate a **prioritized list of communities** ranked by an indicator of interest, such as **market potential for cold storage**. Customizable analysis allows users to prioritize sites according to their specific interests and needs: For example, for a humanitarian or climate resilience policy intervention, users may prioritize populations that are highly vulnerable to food insecurity, those facing the highest poverty rates, or who are more vulnerable to climate change-related hazards. For commercially oriented interventions, the tool could help identify relatively wealthy communities where cold storage facilities are more likely to be marketable and financially feasible, without necessarily focusing on the social benefits.

A fundamental concept driving the development of this model is that many Energy Access Plans, including **Integrated Energy Plans,** Rural Electrification Plans, and Least-Cost Electrification Plans, have traditionally placed greater emphasis on residential energy demand, while the systematic integration of Productive Uses of Energy (PUE) has received comparatively less attention.

Recent methodological advances in spatial PUE mapping and investment prospectuses (e.g., by WRI[4,5]; and Columbia University[6]), have made important contributions toward addressing this gap. AgCAP is intended to complement, rather than replace, these existing approaches by providing a more detailed demand-side assessment of specific productive-use potential, with a particular focus on agricultural and fisheries cold-chain needs.

AgCAP aims to assist decision makers, energy planners, developers, and donors in identifying communities with a high likelihood of generating income through **productive activities such as**

[4] Mentis, D., L. Odarno, D. Wood, F. Jendle, E. Mazur, A. Qehaja, and F. Gassert. 2019. Energy Access Explorer: Data and Methods. Technical Note. Washington, DC: World Resources Institute.

[5] World Resources Institute (WRI). 2025. Energy Access Explorer: Investment Prospectus. Washington, DC: World Resources Institute. [Accessed through https://wri-public-data.s3.amazonaws.com/EnergyAccess/website/uploads/Investment-Prospectus_2.pdf].

[6] Columbia University Quadrant Social Engineering Lab (QSEL). 2024. CWP-EPU Data Platform: Mapping Social and Productive Uses of Energy. New York: Columbia University. Available at: https://qsel.columbia.edu/cwp-epu-data-platform/.

post-harvest cooling. This enables them to carefully assess the most suitable electrification mode and the investment cost required for the implementation of energy access projects, such as **grid extensions or mini grids**. The results of the tool can complement broader geospatial energy-planning approaches, including least-cost electrification planning, by identifying settlements with a high PUE potential, including latent energy demand for cooling. This informs the commercial viability of electrification projects and is therefore a key consideration when operationalizing an Energy Access Plan.

In this way , AgCAP can support electrification planning by providing supplementary information on PUE potential, beyond household electricity needs . For example, if the demand assumptions are limited to considering residential demand, stand-alone solar kits are likely to be the most cost-effective solution for rural places with dispersed populations. However, if these areas have a high level of agricultural and/or fishing activity and are close to an airport and/or port, they may have additional commercial demand for cold storage and food processing. In this situation, deploying solar kits may not be the "optimal" solution, and there is a missing opportunity to **spur local economic development** through a mini-grid[7] or extension of the national grid[8]. Including these aspects in IEPs can strengthen the representation of non-residential energy demand and contribute to more **actionable national electrification plans**. The opportunities for various stakeholders include:

Table 1. AgCAP opportunities for various energy and agriculture actors.

Actor	AgCAP opportunity
Ministry of Energy (Rural Electrification Agencies/Authorities, Energy Planning & Coordination Units or similar)	Enhance Integrated Energy Access Planning through the **identification of Productive Use of Energy (PUE) for** cooling in Agriculture and Fisheries value chains.
Ministry of Agriculture (including Livestock)	Better inform agricultural policies, planning and implementation of **cold storage infrastructure to improve productivity and/or reduce food losses**. They will be able to make decisions and plan for investments based on a comprehensive high-resolution mapping of productive communities.
Ministry of Fisheries	
Ministry of Industry / Commerce	Ministries of industry and commerce are often responsible for the post-harvest processing and storage of agrifood produce. Therefore, they can similarly benefit from the analysis in planning and implementation of cold storage infrastructure according to their mandate.
Development partners	Identify suitable, **high-impact locations** for deploying projects aimed at improving livelihoods and reducing food insecurity through enhanced cold storage solutions for fisheries and agriculture, ensuring the highest likelihood of project success. The competitiveness of a cold storage solution needs to be evaluated compared to other interventions through a local assessment of the value chain characteristics and challenges.
Utilities	Identify potential anchor loads, like agricultural cold storage solutions. AgCAP can be useful in pre-selecting candidate communities before undertaking expensive feasibility studies.
Mini-grid developers	
Solar contractors	
Cold storage developers	Identify ideal locations for the implementation of grid-connected or solar-powered walk-in cold rooms

[7] This transition to mini-grid infrastructure involves complex considerations regarding willingness to pay and investment sustainability. For a practical case study on these dynamics in the context of agricultural PUE, see: https://nextbillion.net/minigrids-cold-storage-sustainable-development/.

[8] While here we focus on the 'least-cost' modeling perspective from a planning standpoint, it is recognized that 'true' optimality for beneficiaries and investors also depends on factors such as willingness and ability to pay, the financial sustainability of the delivery model, and long-term demand stability.

Throughout this document, terms such as "**cooling potential**" and the various "**Cooling Potential Indices**" are used to describe the outputs of the AgCAP tool. It is crucial to clarify that, given the high-level nature of the model, **these metrics do not represent a definitive, quantifiable demand for cooling services**, such as specific storage volumes, required system sizing, crates per year, or projected energy consumption (kWh/year). The AgCAP tool **does not replace the comprehensive technical, market, economic, and financial modeling required for a full site feasibility assessment.** Rather, these indices serve as relative, high-level indicators. They define the probability or potential of a site to be suitable for, and show interest in, a cooling intervention, based entirely on the multi-criteria parameters and use cases selected by the user. Therefore, **"cooling potential" in this context serves as a relative indicator of geographic potential rather than a technical or financial quantification of actual infrastructure requirements.**

1.3 Cold-chain planning nuances

While **cold storage implementations in developing economies** have increased, results have been mixed, and there are also numerous examples of **failed and underutilized investments**[9]. This is due to various factors, including the **lack of solid business cases**, the absence of electricity, a lack of market connectivity, the deployment of inappropriate technologies, technical knowledge gaps[10], and a lack of ownership, service provisions and spare parts. Agricultural cooling should not be seen as a silver bullet, and there is a clear need for differentiation between the various applications for cooling. There is a viability range for each type of cooling solutions depending not only on the product and cold chain type, but also on the **market and marketing sophistication in relation to the product and production sophistication**[11] as depicted in Figure 1.

The upper section of Figure 1 shows that different types of produce have distinct cooling requirements: while some require an uninterrupted cold chain immediately after harvest, certain fruits can tolerate an initial ambient chain. The core matrix demonstrates that as target market distance and sophistication increase, so does the need for high-end technologies. Crucially, it highlights a viability threshold, indicating that smaller farmers lack direct access to advanced retail or export markets. To bridge this gap, they rely on the facilitation of intermediaries or service providers, which expands their viable market zone, albeit with increased dependency. As operations scale from low-tech domestic subsistence to high-tech export models, cooling interventions necessarily evolve from passive systems to active cooling, and ultimately to complex controlled atmospheres. Concurrently, the underlying incentives shift from combating local hunger to ensuring regional food security and driving national GDP.

9 Efficiency for Access Coalition (2023). *The Cold Truth: Uncovering the Secrets of (Un)successful Cold Chains*. In: *Keep it Cool: Harnessing Cold Storage to Reduce Food Loss & Support Sustainable Food Systems in Emerging Economies*, October 2023. Available at: https://www.foodcoldchain.org/wp-content/uploads/2024/04/Keep-it-Cool_Oct-2023_2023-10-21-110734_xzds.pdf.

10 GOGLA & WUR (2025). Beyond Silos: Strengthening Nexus Collaboration to Power Food Systems with Off-Grid Solar. Available at: https://gogla.org/wp-content/uploads/2025/04/Beyond-Silos_Strengthening-Nexus-Collaboration-to-Power-Food-Systems-with-Off-Grid-Solar-1.pdf/

11 Ibid

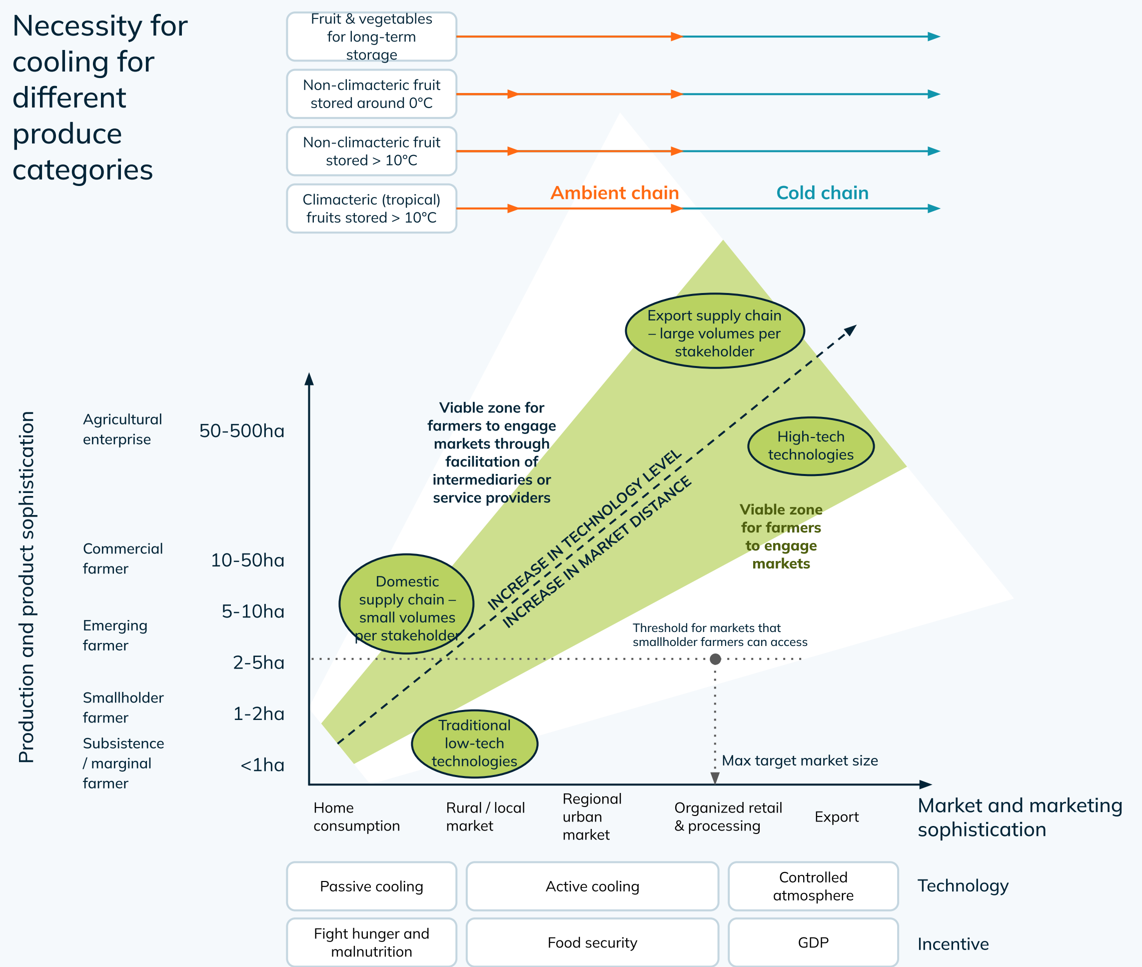

Figure 1. The image, adapted from[12], illustrates the complex interplay between product cooling needs, farm scale, and market sophistication.

For that reason, AgCAP does not solely focus on the production and type of crops that benefit from cold storage but also includes **parameters that contribute to the viability of a cold storage intervention,** where available, such as proxies for the market size, market connectivity, and farm sophistication through farm sizes. However, even with the inclusion of these parameters, **it is impossible to capture and assess all the nuances that affect the sustainable adoption of a cold storage**, also partially due to the lack of good-quality (content, spatial, and temporal resolution) input data and market dynamics.

Therefore, **AgCAP is designed as a settlement-level modelling framework to identify high-potential locations for cold storage interventions with high spatial granularity. While AgCAP prioritizes sites at the planning scale, specific site-level sizing and viability can be further refined using specialized tools**, such as the Postharvest Assessment Methodology, by Wageningen University and Research[13], or the cold storage suitability framework currently being

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[12] Defraeye, T., Vrba, J., Cloutier, J. et al. (2025) 'A Cooling Atlas for preserving fruit and vegetables in low- and middle-income countries', Journal of Agriculture and Food Research, 21. Available at: https://www.sciencedirect.com/science/article/pii/S2666154325001772

[13] Oostewechel, R.J.A. et al. (2022). *Postharvest Assessment Methodology*, Wageningen Food & Biobased Research. Available at: https://edepot.wur.nl/582556.

developed under the Efficiency for Access Coalition's Low-Energy Inclusive Appliances (LEIA) programme[14].

Finally, a cooling solution cannot be seen in isolation, and necessitates a wider value-chain approach, including the implementation of Good Agricultural Practices and establishing food safety regulations, like Hazard Analysis Critical Control Point (HACCP).

[14] https://efficiencyforaccess.org/program/low-energy-inclusive-appliances/

CHAPTER TWO

Methodology

2.1 Methodological Overview

The AgCAP methodology identifies and ranks sites with a high potential for sustainable cooling of specific perishable agricultural outputs, such as horticulture crops, fish, and dairy. The **suitability is based on a default mix of criteria and filters that the user can adjust**, making it a versatile tool for a wide range of applications and stakeholders in both the energy and agriculture sectors. In general, the methodology can be split into four steps:

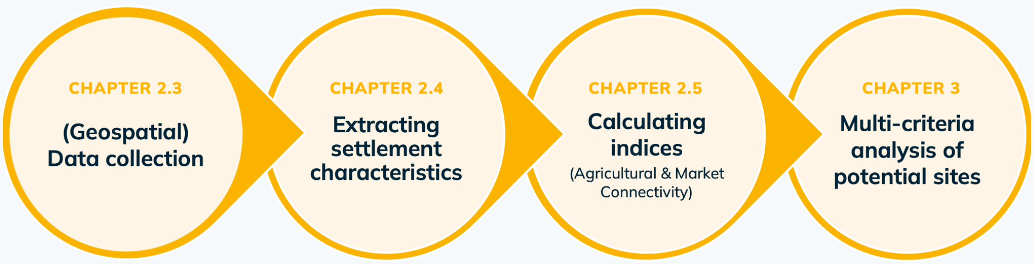

Figure 2. High-level overview of the AgCAP methodology.

The steps of this methodology are aligned with how the process is elaborated in this document, respectively following chapters 2.3, 2.4, 2.5, and 3. Some of the most important variables considered in the multi-criteria site analysis are the following:

Table 2. Variables included in the AgCAP analysis and their function.

Category	Variable	Function
(Agriculture and Fisheries) production	Production activity	Select sites with high **farming activity, fishing activity,** dairy, or a combination of those (if data is available).
	Cooling indices	Approximate cooling potential. Calculated from **production potential (cropland extent)** and **market connectivity.**
	Crop-specific production	Target sites with high output of specific perishable crops.
Energy	Electrification status/plan	Select electrified sites for **on-grid cold-chain solutions**, or unelectrified sites for **off-grid options**. Filter for sites with existing mini-grids to integrate cold rooms as **anchor loads**, creating mutual benefits. Alternatively, choose sites planned for **future mini-grid electrification**, where developers can incorporate cold storage to boost utilization rates and financial viability.
	Solar resources	Select sites with the highest solar PV productivity for **solar-powered cold-chain facilities.**
Socio-economic	Demographics	Exclude very small villages and large cities.
	Poverty (economic and food security)	Target **wealthier villages** to enhance the commercial viability of cold-chain facilities, or the poorest, most **food-insecure** ones.
	Security risks	Filter settlements by recorded violence in the last 2 years or cyclone hazard levels.
Geographic	Administrative areas	Focus on specific regions, districts, communes, or other administrative areas.
	Proximity to infrastructure	Prioritize sites with **strong sales potential** due to nearby populations, travel times to airports, ports, cities, and railway stations. NGOs may reverse this to target the **most remote sites for maximum intervention impact.**
	Physical geography	Filter by climate zone, elevation, temperature, humidity, precipitation, aridity, and similar factors to target **specific value chains** or identify sites suitable for **passive cooling solutions.**

The core functionality of the Agricultural Cold Chain Analysis and Prioritization (AgCAP) tool is built for both transparency and versatility. The implementation relies on **open-source scripts built in Python** to facilitate data handling, analysis, and visualization, and it is composed of **three distinct Jupyter Notebooks**[15]:

[15] An open-source interactive computational environment that supports versionable documents combining executable code (e.g., Python) with rich text and data visualizations, used for easier comprehension of the code and reproducibility.

Table 3. Model components.

Component	Primary Function	Key Output
Data Extraction Notebook	Handles **data extraction, cleaning, and preparation** from **multiple sources** (geospatial, socio-economic, etc.).	Clean, standardized input datasets.
Core Analysis Notebook	Contains the **AgCAP methodology** logic, including the calculation of **composite indices or indicators**.	Prioritized sites and analytical results.
AgCAP Insights Platform Launcher Notebook	Launches the **interactive map for the multi-criteria analysis** in a browser from within a notebook	Visualization platform (AgCAP Insights Platform)

The notebooks are equipped with step-by-step instructions and **interactive visualizations** to ensure user comprehension and analysis transparency. The resulting datasets are then visualized on an **interactive platform** where the user can perform the analysis and export results.

Note: Advanced users with Python skills (government officers, modelers, researchers) can build upon the standard notebooks provided to extract specific datasets that they might have access to, such as **country- or sector-specific data, including proprietary and government data**. They might also expand or modify the visualization platform to accommodate their needs.

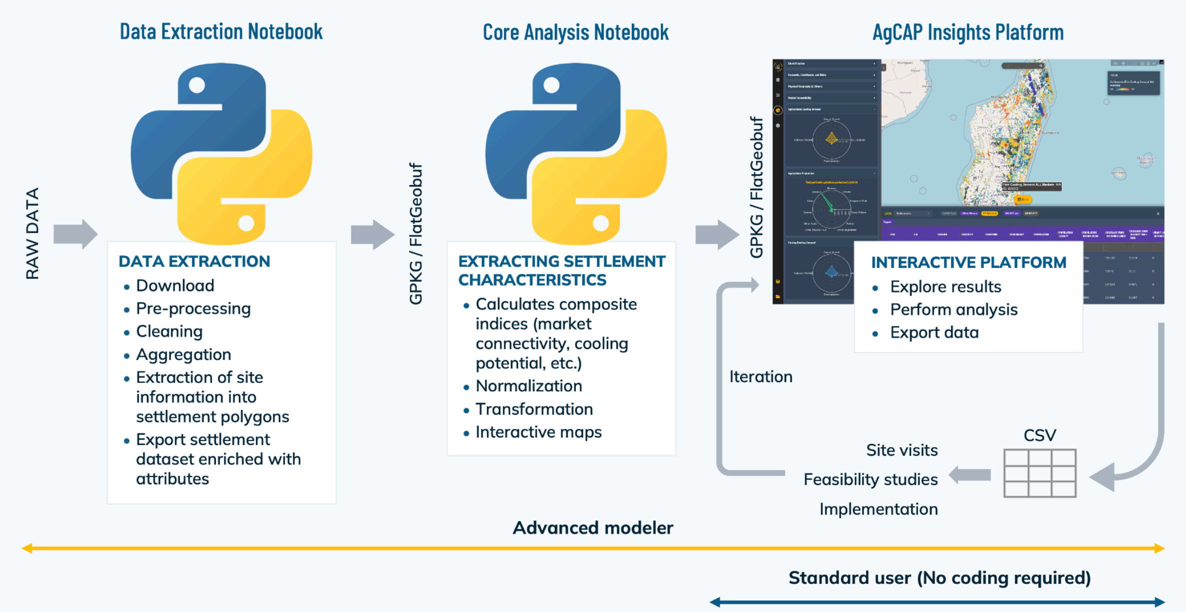

Figure 3. Detailed overview of the AgCAP methodology and technical tools used.

Users with no coding or GIS experience can interact solely with the modelling output - built on data/models run by SEforALL in targeted countries, to conduct multi-criteria site selection analyses, and export results via a user-friendly browser-run visualization platform. **Modelers with GIS knowledge and some programming experience** can run customized analyses or use the outputs for further processing using **Python or dedicated GIS software**.

2.2 Code and Documentation

The code and documentation are hosted on a GitHub repository[16]. The README explains the folder structure, the input data, the typical workflows, and the description of the different files.

2.3 Data Collection

The **data inputs** were selected keeping in mind replicability in other countries. For this reason, datasets with **global coverage** were prioritized over country-specific sources, even when this resulted in lower resolution or accuracy. This approach supports consistent applicability across different geographies. When global datasets were unavailable, alternative sources with regional availability were used, and only **in a few cases** were **country-specific datasets adopted**. For instance, **grid footprint data** and **mini-grid locations** must be obtained from the national utility. Table 4 presents the geospatial datasets used in AgCAP along with their source, link for download, format, and geographic coverage. All datasets will be addressed individually in the sections below Table 4.

Table 4. Main datasets used in the AgCAP workflow.

#	Dataset Name	Source / Link	Format	Coverage
1	Admin Boundaries	OCHA	Shapefile (.shp)	38 low- and middle-income countries
2	Admin Boundaries (alternative)	GADM	GeoPackage (.gpkg)	Most countries
3	Airports location	Open Street Map Airports	GeoJSON (.geojson)	World
4	Aridity Index	Global Aridity Index and Potential Evapo-Transpiration (ET0) Database v3	GeoTIFF (.tif)	World
5	Climatic Classification	Köppen-Geiger Maps	GeoTIFF (.tif)	World
6	Conflict Events	ACLED	CSV (.csv)	World
7	Crop Production	MapSPAM	GeoTIFF (.tif)	World
8	Cropland Extent	Global cropland expansion in the 21st century (GLAD / Potapov)	GeoTIFF (.tif)	World
9	Cyclone Hazard	UNDRR Global Assessment Report (GAR)'s Global model of cyclone wind 50, 100, 250, 500, and 1000 years return period	GeoTIFF (.tif)	World
10	Diurnal Range (Temp)	WorldClim BIO Clim Variables	GeoTIFF (.tif)	World
11	Electrification Status (IEP)	Electrification Planning Studies (e.g., IEPs), from Government stakeholders	GeoPackage (.gpkg)	Country-specific
12	Elevation	Copernicus Digital Elevation Model (GLO-30 DEM)	GeoTIFF (.tif)	World
13	Food Security	Integrated Food Security Phase Classification (IPC)	GeoJSON (.geojson)	Selected food-insecure countries

[16] https://github.com/SEforALL-IEAP/AgCAP.git

14	Hot Days (hd30)	World Bank Group's Climate Change Knowledge Portal (WBG-CCKP)	GeoTIFF (.tif)	World
15	Livelihood Zones	FEWS Net Livelihood Zones	Shapefile (.shp)	54 low- and middle-income countries
16	Mini-Grids	Mini-grid location from Government stakeholders	Any vector format	Country-specific
17	MV Lines	Medium Voltage (MV) Electrical Lines from Government stakeholders	Any vector format	Country-specific
18	Satellite night-time lights	VIIRS/NPP Visible Infrared Imaging Radiometer Suite	GeoTIFF (.tif)	World
19	Population	WorldPop's constrained Individual Countries 2015-2030 100m resolution	GeoTIFF (.tif)	World
20	Port locations	Open Street Map Ports	GeoJSON (.geojson)	World
21	Precipitation	WorldClim BIO Variables	GeoTIFF (.tif)	World
22	PV Output (pvout)	Global Solar Atlas's Specific solar photovoltaic (PV) output	GeoTIFF (.tif)	World
23	Railway Stations location	Open Street Map Railway Stations	GeoJSON (.geojson)	World
24	Relative Humidity (hurs)	CIMIP6 from World Bank Climate Change Knowledge Portal (CCKP)	GeoTIFF (.tif)	World
25	Relative Wealth Index (RWI)	Meta's Relative Wealth Index Map	GeoTIFF (.tif)	93 low and middle-income countries
26	Settlements	GRID3 Settlement Extents	GeoPackage (.gpkg)	Sub-Saharan Africa
27	Shoreline	Global Self-consistent, Hierarchical, High-resolution Geography Database (GSHHG)	Shapefile (.shp)	World
28	Shoreline (alternative)	OpenStreetMap (OSM) Coastline	GeoPackage (.gpkg)	World
29	Temperature (Annual avg.)	Global Solar Atlas's Mean Temperature	GeoTIFF (.tif)	World
30	Travel Times	Travel times to Airports, Ports, Capital, Cities, Railways	GeoTIFF (.tif)	World
31	Water Occurrence	JRC Global Surface Water (GSW)	GeoTIFF (.tif)	World

The **Raw Input Data Table guides** the user on **data acquisition, local storage, and necessary pre-processing** to meet model format requirements.

Integrating country-specific microdata (e.g., census, surveys, production) is possible and recommended when available. Once converted to a geospatial format (points or polygons), these **contextual layers** can be overlaid with settlement data on the platform. Uploading contextual layers to the platform is as simple as dragging and dropping the file. However, data preparation might require some basic GIS skills. This allows users **to gain planning intelligence** and make informed decisions regarding cold chain infrastructure deployment.

2.4 Data Extraction & Preparation

The **following sections are a technical deep-dive** into the raw **input data** sources, their structure, and the extraction process logic.

2.4.1 Defining the study area

Although the analysis is designed for **national-level application** in any country, it can also be carried out at **sub-national scales**. The user may provide a vector polygon defining the area of interest – whether it represents an entire country or a specific administrative subdivision[17].

2.4.2 Defining settlements (population clusters)

Population clusters (also referred to as "settlements") serve as the **default spatial unit of analysis** in AgCAP. This choice ensures **compatibility with** the level of detail typically used in **least-cost electrification studies** (such as those conducted with the Global Electrification Platform[18] - GEP) and supports the generation of insights at a policy-relevant level of granularity for electrification planning.

The current version of the model utilizes the **GRID3 Settlement Extent v3.0 dataset**[19], an open-access dataset that provides settlement boundaries and building count for all countries in Sub-Saharan Africa. The latest available data depends on the country, consists of vector data, and follows no regular update schedule. Other comparable datasets – such as the GEP clusters[20] or the World Bank's DRE Atlas[21] – can also be used with slight adjustment of the script. The selection should be guided by the availability of Least-Cost Electrification Plans or Integrated Energy Plans[22] and the analytical unit used, to **ensure consistency across analyses and to maximize the added value of the results**.

GRID3 settlements[23] are downloaded as **vector polygons** and converted to the appropriate UTM Coordinate Reference System (CRS)[24]. The attributes that are needed in AgCAP include the following:

1. **id**: Unique identifier (used to align processing in different stages)
2. **Area**: indicating the area of the cluster (polygon) in m^2
3. **Type**: categorical settlement classification: Built-up area (BUA), Small Settlement Area (SSA), or Hamlet
4. **Building count**: estimate of building count in the cluster
5. **Geometry**: column indicating spatial characteristics of each cluster - needed as this is a spatial layer

Note that these columns may have different names if using alternative data sources, so users should ensure they are renamed as needed; the accompanying **Annex I – Data dictionary** can

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17 Working at sub-national level users should be cautious of market locations that fall outside of the defined administrative boundary, omitting those can give a distorted sense of market connectivity for settlements within the administrative boundary.

18 https://electrifynow.energydata.info/.

19 Center for International Earth Science Information Network (CIESIN), Columbia University and Novel-T. (2023) *GRID3 Settlement Extents, Version 02*. Palisades, NY: Geo-Referenced Infrastructure and Demographic Data for Development (GRID3). https://academiccommons.columbia.edu/search?f%5Bfeatured_search%5D%5B%5D=grid3&f%5Bsubject_ssim%5D%5B%5D=Human+settlements.

20 Based on 100m WorldPop population layer: https://hub.worldpop.org/geodata/listing?id=135.

21 https://dre.energydata.info/about.

22 https://sdg7energyplanning.org/.

23 https://data.grid3.org/search?sort=Date%20Created%7Ccreated%7Cdesc&tags=settlements.

24 Selected by the user for the area of interest based on https://epsg.io/.

serve as a reference. The settlement layer is converted into a *GeoDataFrame*, which serves as the foundation for all subsequent data extraction steps in the Python pipeline.

Settlements with fewer than 100 buildings are excluded, based on the assumption that communities of this size are generally **too small to support cold storage projects** (Figure 4). This assumption also helps reduce computational requirements by limiting the analysis to polygons with the highest potential. However, this is only a recommendation – the user **may adjust the threshold** to any value deemed appropriate or choose not to apply one at all.

The geometries are then **simplified to improve computational efficiency** using *gpd.simplify* (with a tolerance of 50 m and topology preserved). The resulting output is a cleaned *GeoDataFrame* with *MultiPolygon* geometries.

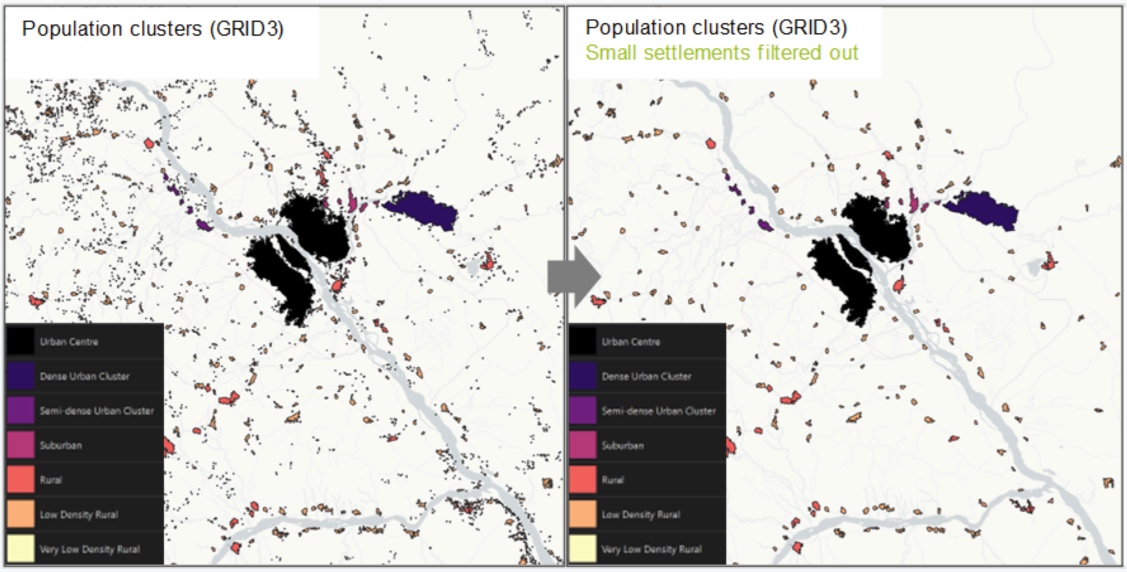

Figure 4. Population clusters before (left) and after (right) filtering out the ones with fewer than 100 buildings.

2.4.3 Extracting settlement characteristics

Population Count, Density & Projection

Population is a key characteristic of a settlement. In some cases, the settlement (population cluster) dataset already includes population estimates. When this is not the case, population distribution layers for the most recent available year can be downloaded from GRID3, **World Pop**[25], or any other reliable source. These datasets are typically provided as raster layers at 30 m, 100 m, or 1 km resolution. Users may choose any preferred source, but the source indicated in Table 4 (WorldPop) is useful because it provides projected population data for any year until 2030, and the user can pick **the current year of analysis**. The World Pop dataset follows no regular update schedule.

[25] https://wopr.worldpop.org/

Population values are **extracted for each cluster** using the extraction functions within the AgCAP model. **Population density** (ppl/km^2) is also estimated by dividing the population count to the settlement's area.

Population totals within a 20 km radius (measured from the polygon boundary) are also calculated to account for people who may travel into the area to sell and buy products.

Administrative division names

Administrative boundaries are downloaded from one of the two typical sources indicated in the input data table (Table 4), unless a more authoritative dataset is provided by the country government or obtained from other sources. This is the **basis for production data aggregation** and data validation at the sub-national level. Names of administrative divisions from 0 to 4 (or to the highest available level)[26] are extracted and assigned to each settlement using spatial analysis. Settlements spanning across multiple administrative divisions are assigned according to the largest overlap principle.

The latest available data depends on the country, consists of vector data, and follows no regular update schedule.

Average temperature

Average annual air temperature is obtained from SolarGIS[27] and assigned to the settlement dataset. This information is important for assessing the need for cold storage applications, as higher temperatures increase the amount of field heat that must be removed from the produce.

The latest available data is from the 1994-2024 period, has a resolution of 30 arc-seconds (1 km), and follows no regular update schedule.

Mean diurnal range

The mean diurnal range is defined as the mean of the **average difference between day-time and night-time temperatures**. This metric, available from the WorldClim BIO Variables V1 dataset[28] can help users select **sites** where a larger diurnal temperature range makes them **suitable for passive cooling solutions** that enhance the natural temperature cycle by maximizing heat loss during cool nights, thereby **reducing the need for mechanical cooling**.

The latest available data is from the 1970-2000 period, has a resolution of 30 arc-seconds (1 km), and follows no regular update schedule.

[26] The higher the number, the more granular the administrative segment. Typically, Level 0: National; Level 1: Major divisions (Provinces, Regions, States); Level 2: Intermediate divisions (Districts, Local Government Areas, Zones, Circles); Level 3: Sub-divisions (Administrative Posts, Communes, Woredas, Townships, Sub-counties); and Level 4: Community units (Localities, Villages, Kebeles, Hamlets, Wards).

[27] https://solargis.com/maps-and-gis-data/download or Global Solar Atlas.

[28] https://developers.google.com/earth-engine/datasets/catalog/WORLDCLIM_V1_BIO#bands.

Hot days

The **number of days in a year with daily maximum temperature >= 30°C**[29] is extracted from the World Bank Climate Change Knowledge Portal (CCKP)[30]. This data complements the average temperature in assessing the current need for cooling applications.

The latest available data is from 1995 to 2014, has a resolution of 0.25 degrees, and follows no regular update schedule.

Elevation

The Digital Elevation Model (DEM) is obtained from either the Copernicus Digital Elevation Model (GLO-30 DEM) through Google Earth Engine[31], or NASA's SRTM 1 Arc-Second Global dataset[32], which can easily be downloaded using the SRTM Downloader Plugin within QGIS[33] , Google Earth Engine[34] or the USGS EarthExplorer platform[35]. Settlements at **higher altitudes** benefit from **passive evaporative cooling systems** for storing agricultural products because such systems perform better in environments with low atmospheric pressure, cooler night-time temperatures, and drier air conditions, all common at high elevations[36].

The latest available data is from 2019, has a resolution of 30 arc-seconds (1 km), and follows no regular update schedule.

Climate Zones

Climate zones according to the **Köppen-Geiger classification** are extracted and assigned to each settlement. The current climate zone is represented by the latest available historical map (1991–2020)[37], which is based on high-resolution, observation-based climatology. Filtering settlements by climate zone can help planners target specific agricultural value chains and tailor cold storage interventions to the distinct environmental conditions of those regions. Moreover, this information helps anticipate regional spoilage patterns: in humid tropical zones, where high moisture triggers rapid mold and fungal rot within hours of harvest, while in dry hot areas, extreme heat causes shriveling and weight loss in vegetables due to rapid dehydration.

The latest available data is from the 1991–2020 period, has a resolution of 30 arc-seconds (1 km), and follows no regular update schedule.

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29 World Bank Group's Climate Change Knowledge Portal (WBG-CCKP) (n.d.) *Climatology HD30 Annual Mean (CMIP6 x0.25 Ensemble All Historical Median, 1995-2014)*. [Dataset]. Available at: https://wbg-cckp.s3.amazonaws.com/data/cmip6-x0.25/hd30/ensemble-all-historical/climatology-hd30-annual-mean_cmip6-x0.25_ensemble-all-historical_climatology_median_1995-2014.nc.

30 https://climateknowledgeportal.worldbank.org/download-data.

31 https://gee-community-catalog.org/projects/glo30/

32 https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-shuttle-radar-topography-mission-srtm-1.

33 https://plugins.qgis.org/plugins/SRTM-Downloader/.

34 https://gee-community-catalog.org/projects/glo30/.

35 https://earthexplorer.usgs.gov/.

36 lal Basediya, A., Samuel, D. V. K., & Beera, V. (2011). Evaporative cooling system for storage of fruits and vegetables - a review. Journal of Food Science and Technology, 50, 429–442. https://doi.org/10.1007/s13197-011-0311-6

37 Beck, H. E., McVicar, T. R., Vergopolan, N., Berg, A., Lutsko, N. J., Dufour, A., Zeng, Z., Jiang, X., van Dijk, A. I. J. M. and Miralles, D. G. (2023) 'High-resolution (1 km) Köppen–Geiger maps for 1901–2099 based on constrained CMIP6 projections', *Scientific Data*, 10 (1), p. 724. https://doi.org/10.1038/s41597-023–02549-6.

Aridity Index

The **Aridity Index (AI)** in Version 3 of the Global Aridity Index and Potential Evapo-Transpiration Database[38] is a unitless index that quantifies water availability by comparing incoming moisture (precipitation) to atmospheric water demand (evapotranspiration). Higher AI values indicate more humid conditions, while lower values reflect more arid climates. **Arid conditions limit rainfed agriculture and increase vulnerability to drought**, making crop yields more uncertain and often reduced. Because arid locations face water scarcity, they are **more likely to benefit from agricultural cooling and storage facilities** (like post-harvest cooling) to reduce food loss and **maintain food security**.

The latest available data is from the 1970-2000 period, has a resolution of 30 arc-seconds (1 km), and follows no regular update schedule.

Relative humidity

High humidity at a site can cause fresh food to rot and increase bacterial contamination on surfaces, while sites that are too dry can accelerate the perishability of fresh vegetables due to shriveling and weight loss, if the field heat is not removed immediately after harvest.

Average annual **humidity** is obtained from the World Bank's Climate Change Knowledge Portal (ERA5 data) and assigned to the settlement dataset[39].

The latest available historical data is from the 1991-2020 period, has a resolution of 0.25 degrees, and follows no regular update schedule.

Annual precipitation

Average annual **precipitation** is obtained from the ClimateAF v1.10 database[40], available for Africa. The latest available data is from the 1970-2000 period, has a resolution of 30 arc-seconds (1 km), and follows no regular update schedule. For countries outside Africa, a lower-resolution dataset (30 km) from the World Bank's Climate Change Knowledge Portal (ERA5 data) can be used[41]. Frequent heavy rains create mud-clogged roads that trap delivery trucks, meaning a crop can spoil while waiting for transport, which makes this data useful for identifying sites where produce is likely to be stranded without immediate cooling.

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[38] Zomer, R. J., Xu, J. and Trabucco, A. (2022) 'Version 3 of the Global Aridity Index and Potential Evapotranspiration Database', *Scientific Data*, 9 (1), p. 409. https://doi.org/10.1038/s41597-022-01493-1.

[39] World Bank Group's Climate Change Knowledge Portal (WBG-CCKP) (n.d.) *Climatology: Annual Mean Relative Humidity at Surface, 1991–2020 (ERA5)*. [Dataset]. Available at: https://wbg-cckp.s3.amazonaws.com/data/era5-x0.25/hurs/era5-x0.25-historical/climatology-hurs-annual-mean_era5-x0.25_era5-x0.25-historical_climatology_mean_1991-2020.nc.

[40] Namiiro, S., Hamann, A., Wang, T., Castellanos-Acuña, D. and Mahony, C. R. (2025) 'A high-resolution database of historical and future climate for Africa developed with deep neural networks', *Scientific Data*, 11, p. 1278. https://doi.org/10.1038/s41597-025-05575-8.

[41] World Bank Group's Climate Change Knowledge Portal (WBG-CCKP) (n.d.) *Climatology: Annual Mean Precipitation, 1991–2020 (ERA5)*. [Dataset]. At: https://wbg-cckp.s3.amazonaws.com/data/era5-x0.25/pr/era5-x0.25-historical/climatology-pr-annual-mean_era5-x0.25_era5-x0.25-historical_climatology_mean_1991-2020.nc.

Degree days for agricultural cold storage

The model calculates the **annual cooling degree days (CDD)[42] relative to a 4 °C cold-room setpoint for the settlement's climate.** It measures cooling requirements based on the difference between the air temperature and the cold room's desired internal temperature (4°C assumed, a trade-off for mixed product storage), and it can be used as an **input variable for system sizing**. A simplified formula is used, assuming that the average daily temperature at any given site is always positive:

$$CDD_{@4C} = (Temp_{year\_avg} - Temp_{base}) * 365$$

Where:

$$CDD_{@4C} = \ cooling\ degree\ days\ at\ a\ base\ temperature\ of\ 4°C\ for\ one\ year$$

$$Temp_{year\_avg} = \ air\ temperature,\ long - term\ daily\ average$$

$$Temp_{base} = \ base\ temperature,\ set\ at\ 4°C$$

This metric quantifies a site's thermal stress, and can therefore be used as proxy data for refrigeration energy needs and operational expenses. While it is true that demand for cooling is often seasonal, AgCAP adopts an annual metric as a pragmatic planning proxy due to the practical impossibility to consider site-specific crop calendars and to know which crops are grown, ensuring a consistent global analysis.

Specific PV output

Specific solar photovoltaic (PV) output is the **expected annual electricity generation per installed kW of PV capacity** at the settlement [kWh/year per kW]. Derived from the Global Solar Atlas[43], it is a useful indication of the **feasibility of solar-powered cold chain facilities**. It should be noted that this generation is aggregated over an entire year and might not always align with the energy demand for cooling over a year, especially with year-round cooling.

The latest available data is from the 1994-2024 period, has a resolution of 30 arc-seconds (1 km), and follows no regular update schedule.

Food insecurity

Sites identified as food-insecure are often plagued by conflict, extreme climate shocks, or geographic isolation, factors that break supply chains and spike the price of imported food. Establishing community-based cold storage in these areas might serve as a strategic buffer, extending the shelf life of local harvests so that high-quality, chilled produce remains available and affordable during off-seasons, directly outcompeting the expensive, low-quality imported commodities that low-income groups are otherwise forced to rely on.

The **percentage of people in food insecurity Phase 3 and above,** as per the IPC latest available monitoring analysis [%] in the belonging area. The data comes from the IPC Acute Food

[42] https://www.degreedays.net/introduction.

[43] https://globalsolaratlas.info/download.

Insecurity (IPC AFI) initiative[44], which monitors the different levels of severity of acute food insecurity at the sub-national level[45]:

(1) Minimal/None

(2) Stressed

(3) Crisis

(4) Emergency

(5) Catastrophe/Famine

Since the dataset **covers only the most food-insecure areas**, locations excluded from the analysis are assumed to have no critical food insecurity - a **limitation to consider** when interpreting results. The latest available data and its resolution depend on the country, but it is typically updated two to four times a year.

Livelihood zones

Livelihood zones, per USAID's FEWS NET[46], are geographic areas where communities share similar food/income sources and market access. This helps identify **key agricultural value chains** and characterize local economies.

The latest available data depends on the country, consists of vector data, and follows no regular update schedule.

Poverty indicator (Relative Wealth Index)

Demand for chilled food is driven primarily by the growth of the middle class; since granular data to quantify the middle-class share in each community is often unavailable, Meta's **Relative Wealth Index** (RWI)[47] serves as a critical proxy to identify where local purchasing power is sufficient to support the service fees and retail prices necessary to sustain a viable cold storage business. On the other hand, poverty relief programs might want to identify the poorest communities, although this requires high subsidization levels to make cold storage applications viable in these contexts.

This index is a standardized **score for local relative wealth** (0 → national mean, negative → poorer, positive → wealthier). The latest available data is from 2021, has a resolution of 2.4 km, and follows no regular update schedule. It is downloaded as point vector data from HDX[48] and transformed into raster using a standalone script before it gets ingested by the tool. If available, more precise poverty indicators derived from national census microdata can be used to replace the RWI.

[44] https://www.ipcinfo.org/ipcinfo-website/ipc-overview-and-classification-system/en/.

[45] https://www.ipcinfo.org/ipc-country-analysis/ipc-mapping-tool/.

[46] https://fews.net/data/livelihood-zones

[47] https://dataforgood.facebook.com/dfg/tools/relative-wealth-index.

[48] https://data.humdata.org/dataset/relative-wealth-index.

Security risk

Evaluating local conflict events might help ensure site safety to protect stored produce from theft and damage, while reducing development costs associated with project delays and uncertainties. The total **number of fatalities due to conflict events within 10 km** is calculated for the last year available. This index gives the user a measure of the security risk for each settlement. The data is retrieved from the **ACLED** (Armed Conflict Location & Event Data) database, which is constantly updated. The data can be retrieved either using its dedicated API or the Data Export Tool[49]. All event types are included, and the period range should be the last two years.

The latest available data is real-time, consists of point data, and is updated weekly.

Location of airports, main ports, and railway stations

Proximity to transport infrastructure is essential for evaluating market connectivity, ensuring the ease of delivery and distribution of perishable goods to high-value markets.

Location of airports, main ports, and railway stations is extracted from **Open Street Map** using OverPass-Turbo[50], QGIS's Quick OSM Plugin, or other sources. Table 4 provides the links to tailored OverPass-Turbo queries to download the data.

The latest available data is real-time, has a spatial resolution of point data, and is updated daily.

Location of the capital city and major cities

The **capital city** is considered a **major market and export hub** that can receive agricultural products.

Travel times for market connectivity indicators

Market connectivity **indicators** require the calculation of **travel times (in hours) from each settlement to the nearest airport, port, main cities, capital city, and railway stations**. In order to calculate travel times from each settlement to any facility of interest, the tool employs an adaptation of the Generic accessibility mapping script (R) from the Malaria Atlas's Accessibility to Healthcare[51] and Dr. Daniel Weiss' earlier research into travel time to cities[52]. The Jupyter Notebook used to create travel times is made available within the AgCAP package as an auxiliary tool.

Compute cyclone hazard indicator

Mapping extreme wind speeds allows planners to filter settlements by hazard levels, mitigating risks to the physical integrity of agricultural and cold chain infrastructure. This is particularly important in countries most exposed to tropical cyclones. A gridded dataset of cyclone wind

[49] https://acleddata.com/data-export-tool/.

[50] https://overpass-turbo.eu/.

[51] https://malariaatlas.org/project-resources/accessibility-to-healthcare/.

[52] Weiss, D., Nelson, A., Gibson, H. *et al.* A global map of travel time to cities to assess inequalities in accessibility in 2015. *Nature* **553**, 333–336 (2018). https://doi.org/10.1038/nature25181.

speeds with a 100-year return period is used to represent **cyclone hazard**[53]. This metric indicates the maximum wind speed that has a statistical probability of occurring once every 100 years on average, reflecting the intensity of extreme cyclone events expected at this frequency.

The latest available data is from 2015, has a resolution of 5 km, and follows no regular update schedule.

Compute refined electrification status indicators

Assessing grid availability allows developers to select electrified sites for on-grid cold-chain solutions, target off-grid options, or strategically integrate cold storage facilities as anchor loads for planned mini-grids.

Where a recent Integrated Energy Access Plan (IEP) or Least-Cost Electrification Plan/Analysis[54] (LCEP) is available, the **electrification status** of settlements should be extracted from that source. Ideally, the settlements (unit of analysis as defined in previous sections) used in AgCAP are the same as the existing IEP or LCEP in order to align the analysis with the existing plan. However, depending on the format of the IEP data, some preliminary analysis may be necessary to assign the electrification status accurately to the settlement polygons.

The recommended **least-cost electrification modality** should also be extracted, if available.

If there is no IEP/LCEP data available (or assessed not appropriate to use, e.g., no longer relevant), the model has an **optional function to infer electrification status based on proximity to medium voltage (MV) power lines and satellite night-time lights**, following the criteria listed below:

Table 5. Indicative criteria for electrification status based on MV line distance and night-time lights.

Electrified	Very close to existing MV power lines < 0.5 km **OR** high night-time light radiance values > 0.4 Watts/cm²·sr
Likely electrified	Not close to existing MV power lines > 0.5 km **AND** moderate night-time light radiance between 0.03 and 0.4 Watts/cm²·sr
Un-electrified	Not close to existing MV power lines > 0.5 km away **AND** low night-time light radiance < 0.03 Watts/cm²·sr

Satellite night-time lights latest data is from 2025, has a resolution of 15 arc-seconds (500 m), and is updated annually.

[53] https://data.humdata.org/dataset/cyclone-wind-100-years-return-period.

[54] https://sdg7energyplanning.org/.

Influence areas

Influence areas are the surroundings of a settlement where agricultural statistics are calculated. The primary method is **Voronoi tessellation**, which divides space into **continuous, non-overlapping zones** based on proximity to the settlement (see Figure 5). The territory partition involves dividing space into regions composed of all sites that are closer to one settlement than to any other. Cropland extent and crop production of a given settlement are calculated within its influence area.

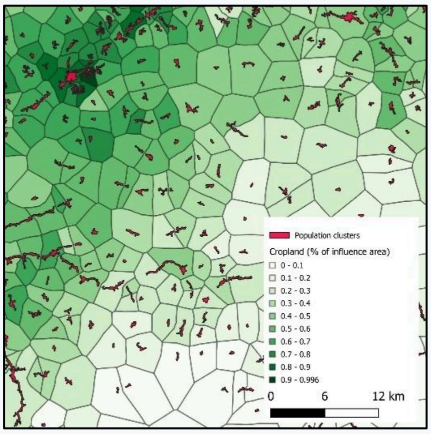

Figure 5. Example of influence areas

It is worth noting that this step is the most arbitrary part of the analysis. Voronoi tessellation is a standardized way of partitioning space, but it does simplify the attribution of agricultural production to solely the distance to the nearest settlement.

Utilizing existing boundaries for the influence areas, either low-level administrative boundaries or otherwise defined natural boundaries, can help delineate influence areas in a more “natural” way, as they are commonly based on on-ground activity or natural boundaries. This could be a preferred option when, e.g., highly accurate agricultural data is available from a national census at a low administrative level. However, these boundaries will not always align with the settlement locations and can therefore include multiple or no settlements. This approach can be pursued by slightly modifying the original script, although it is currently not included in the AgCAP source code.

Cropland extent

The model leverages **high-resolution cropland extent** data as a proxy for **local agricultural economic activity**. Two specific datasets are currently recognized as **industry standards**:

- The **Global cropland expansion in the 21st century**[55] is a globally consistent cropland extent time-series at 30-m spatial resolution based on processed Landsat satellite data archive from 2000 to 2019 (this study uses the most recent epoch from 2016 to 2019), and follows no regular update schedule. The claimed **overall accuracy** is **96.5 %,** with an f-score of 0.8 for Africa.
- **Digital Earth Africa's Cropland extents for Africa**[56], is a cropland extent dataset covering the entire African continent, based on Copernicus Sentinel-2 satellite images from 2019, with a resolution of 10 metres, and follows no regular update schedule. Cropland is defined as "a piece of land of a minimum of 0.01 ha (a single 10m x 10m pixel) that is sown/planted and harvestable at least once within the 12 months after the sowing/planting date". The claimed **overall accuracy** is **86.4 %,** with an f-score of 0.75 for Southern Africa.

[55] Potapov, P. et al. (2022) ‘Global Maps of Cropland Extent and Change Show Accelerated Cropland Expansion in the Twenty-First Century’, *Nature Food*, 3 (1), pp. 19–28. https://doi.org/10.1038/s43016-021-00429-z.

[56] Digital Earth Africa. (2022) *Digital Earth Africa’s Cropland Extents for Africa*. Digital Earth Africa. Available at: https://deafrica.africageoportal.com/datasets/bc6a9440f3cb41d6904b2c8831745903.

Limitations & Adjustments: Most standard datasets capture annual crops but often miss **perennial woody crops** (fruit trees) and include **cereals** (like rice/maize), irrelevant to cooling. To improve accuracy, it is recommended to **mask out cereal crop areas** using specific cereal crop distribution datasets[57] before analysis to focus on perishables requiring cold storage.

The model calculates two variables and adds them as new columns to the settlement dataset:

Table 6. Cropland parameters calculated for each settlement within AgCAP analysis

Cropland extent	Area occupied by cropland within each settlement's influence area (Voronoi polygons) in hectares. It gives an indication of the **magnitude of the agricultural activity**.
Cropland percentage of the influence area	Percentage of the defined influence area around the settlement classified as cropland [%]. This metric indicates **farming intensity** by controlling for the size of the influence area. This approach effectively distinguishes **smaller regions with concentrated cropland** near population centres from **larger regions with more dispersed croplands**.

These metrics feed into the agricultural activity index described below.

Crop production for selected crops

Crop production (in tons/year) within each settlement's influence area is obtained from the 2020 SPAM v2 (Spatial Production Allocation Model[58]) dataset, which contains gridded crop data for 46 crop types. While the benefits of cold storage apply across a wide spectrum of agricultural products, the economic viability varies significantly by crop type. For the purposes of this AgCAP analysis, we have selected a suite of food crops where temperature optimization is recommended as the primary focus of post-harvest storage in FAO literature. These include fruits, vegetables[59], roots and tubers[60]. Cereals[61], pulses[62], and oil crops[63] are not evaluated by default, as cooling would only come in for optimizing temperature after drying, except for fresh green beans[64]. However, the model is designed to be user-defined, allowing for the inclusion of any crop type based on the specific geographic scope or policy objectives of the study. An overview of all available crops in MAPSPAM can be found in Annex II.

57 https://zenodo.org/records/13729353.

58 International Food Policy Research Institute (IFPRI). (2024) *Global Spatially-Disaggregated Crop Production Statistics Data for 2020 Version 2.0.* [Geospatial Data]. https://doi.org/doi:10.7910/DVN/SWPENT.

59 https://www.fao.org/4/ae075e/ae075e00.htm.

60 https://www.fao.org/4/t0073e/T0073E00.htm.

61 https://www.fao.org/4/t0522e/T0522E00.htm.

62 https://www.icar-iipr.org.in/wp-content/themes/ICAR-wp/images/pdf/postbulletins2may13.pdf.

63 https://openknowledge.fao.org/server/api/core/bitstreams/b0ba48d4-6a9d-4721-b9d2-e3d6d94c1824/content.

64 https://www.fao.org/4/ae075e/ae075e00.htm.

Table 7. MAPSPAM crops are included by default in the AgCAP analysis.

Crop ID	SPAM name	Crop name
9	pota	Potato
10	swpo	Sweet Potato
11	yams	Yams
12	cass	Cassava
13	orts	Other Roots
14	bean	Bean
37	bana	Banana
38	plnt	Plantain
39	citr	Citrus
40	trof	Other Tropical Fruit
41	temf	Temperate Fruit
42	toma	Tomato
43	onio	Onion
44	vege	Other Vegetables

The SPAM raster data is extracted into each settlement's influence area and then assigned to the corresponding settlement. The latest available data is from 2020, has a resolution of 5 arc-minutes (10 km), and is updated every 5 years. The native spatial resolution, which is too coarse for direct extraction into settlement polygons (see Figure 6).

To ensure methodological compatibility with the settlement-level unit of analysis, we applied a **mass-preserving spatial disaggregation** (resampling the SPAM data down to a finer resolution of 100x100m). While this process does not enhance the underlying data quality, the finer spatial resolution enables a zonal statistics algorithm to more accurately distribute each pixel's production value among the intersecting settlement influence areas. This approach **improves the precision of linking crop production data with settlement-level geographic units,** and prevents the spatial 'aliasing' that occurs with coarse-resolution overlays.

It is important to note that SPAM data, while the best publicly available source of global crop distribution – to the best of our knowledge – should be interpreted with some caution. Because it is produced by downscaling national and sub-national crop statistics using satellite-derived cropland extents, **uncertainties are inherent in the dataset**. Furthermore, the values are static and do not fully reflect the **temporal dynamics** of agriculture, such as crop rotation or shifts in farmer incentives. Nonetheless, it remains **the most comprehensive and accessible option currently available; in our analysis, we used it as a complementary layer to physical cropland extent**. While not within the current scope, a nexus approach combining cropland extent with crop suitability modeling offers a promising avenue for future research into evolving cooling potential.

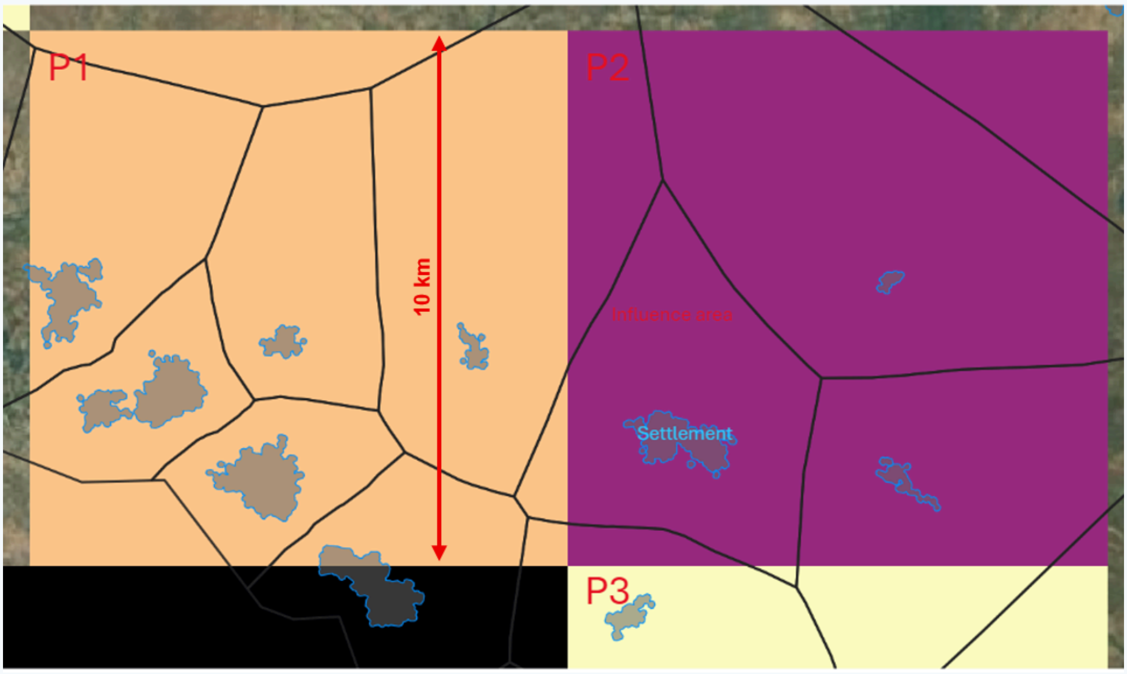

Figure 6. SPAM data resolution 10km x 10km, which is not suitable for direct extraction of production within influence areas. Data is resampled down to 100m x 100m.

Fish activity for marine and inland fisheries

Fishing activity is used as an approximation of the **fishing productivity at a settlement level**. Due to the unavailability of granular, open data on marine and inland fisheries production levels (either artisanal or formalized), it is at this point not possible to develop a generalized method for estimating fishing production at a settlement level. For that reason, the fishing activity is calculated with the assumption that fishing activity is related to the ease of accessing fishing waters. In order to calculate this index, the distance to permanent water bodies (either marine or inland) is used, combined with the size of inland water bodies to ensure they can sustain fishing activities. These distances are then inversely normalized, with a set cut-off value, in order to estimate a fishing activity index. The exact method is explained in the Fish Cooling Potential Index (FCPI) section under 2.5.2.

However, many countries invest in data collection through fishing censuses, and the results, especially microdata, can be used instead of the currently implemented approximation approach. In this approach, the fishing production would be normalized and assigned to each settlement to be used as a Fishing Activity Index as described in the Fish Cooling Potential Index (FCPI) section under 2.5.2. This implementation is currently not part of the code in the repository.

2.5 Development of Composite Indicators

2.5.1 Context

The AgCAP tool employs a **mixed approach** that **combines traditional geospatial analysis with bespoke composite indicators or indices.** The traditional geospatial analysis leverages measurable data from remote sensing and established geospatial vector data sources, including sub-national statistics and sectoral data that can be spatially referenced. Meanwhile, the **composite indicators** are constructed by **aggregating** a series of observed measurable data, applying **weights** that represent their relative importance.

These composite indicators are especially useful for **studying complex multi-dimensional phenomena,** such as, in our case, **market connectivity** and the **potential demand for cooling services** across different markets.

This approach has proven to be effective in selecting and scoring countries based on their economic performance, as well as in risk modelling and other applications[65]. In AgCAP, it supports analyzing and comparing the suitability and the potential demand for sustainable cooling solutions. Since these phenomena depend on multiple variables and site suitability is highly influenced by specific use cases and stakeholder interests, composite indicators provide, for each use case, a **holistic view by synthesizing multidimensional data into a few scores**.

However, they should be used only with a full awareness of their limitations and a thorough understanding of the primary measures and their respective weights involved in their calculation. According to the *OECD's Handbook on Constructing Composite Indicators*[66], the **limitations of this approach** include the following:

- Risk of **conveying incorrect messages** if indicators are misinterpreted
- **Simplistic conclusions** may arise if the construction process lacks transparency
- Sensitivity to indicators' selection and their assigned **weights**, which depend heavily on the specific use case
- No single composite indicator can fully capture the **complexity of market demand**
- Potential data quality issues, including **missing or unreliable data**, which can distort results
- **Correlations** among indicators can cause certain aspects to be overemphasized
- Difficulty in establishing a coherent theoretical framework for indicator selection and weighting

Therefore, planners and users of the AgCAP tool should use the aggregated composite indicators provided by the AgCAP tool with caution. **Advanced users/modelers are encouraged to develop their own customized composite indicators** by selecting relevant variables from those available for each settlement and weighting them **based on their sectoral expertise** and contextual understanding.

Note that users willing to create their own set of indicators using the AgCAP tool need to understand the role of **data normalization**. This is an essential step to **adjust values from different data sources**, measured in different scales and units, to a notionally common scale, **making them meaningfully comparable and suitable for aggregation**. The AgCAP model employs the min-max normalization, a data scaling technique that transforms the values of a feature so that they fit within a specified range, usually from 0 to 1. Note that min–max

[65] Market Accessibility Index (World Bank); Human Development Index (HDI) [UNDP]; Global Multidimensional Poverty Index (MPI) [UNDP]; FAO Food Price Index (FFPI) [FAO]; Human Capital Index (HCI) [World Bank]; Logistics Performance Index (LPI) [World Bank]; Women's Empowerment in Agriculture Index (WEAI) [IFPRI / FAO]; Agricultural Stress Index System (ASIS) [FAO]; Global Agro-Ecological Zoning (GAEZ) Suitability Scores [FAO]; Social Progress Index (SPI) [Social Progress Imperative]; The Malaria Atlas Project (MAP) [WHO].

[66] OECD/European Union/EC-JRC (2008), Handbook on Constructing Composite Indicators: Methodology and User Guide, OECD Publishing, Paris, https://doi.org/10.1787/9789264043466-en.

normalized scores are relative to the range of values observed within the study area and dataset. They are therefore suitable for comparing settlements within the same analysis, but should not be interpreted as absolute or directly comparable across different country studies. For example, a score of 0.8 in Mozambique may not represent the same underlying conditions or level of potential as a score of 0.8 in Madagascar, unless both analyses use the same input data, reference range, and normalization parameters.

2.5.2 Market connectivity & Cooling potential indices

The AgCAP data analysis notebook calculates **market connectivity and cooling potential indices** by taking a **weighted average of selected input data layers** (Figure 7, Figure 8, Figure 10). These normalized composite indices range from 0 (low potential) to 1 (high potential) and help users in a multi-criteria site selection process. These are created so that users can choose the indices relevant to their specific needs to filter and rank settlements along with other variables.

Weighted average is a common approach to **combine multiple normalized variables into a single composite index** by assigning each variable a weight that reflects its relative importance, and it works as follows:

1. **Define the composite indicator** and its purpose.
2. **Select variables** that are meaningful to its definition.
3. **Assign weights** to each variable to reflect their relative importance. To help reduce the subjective bias, the weights should be chosen or validated by sectoral experts or following stakeholder consultation, and their choice must be transparent.
4. Normalize the variables **using the min-max normalization** to make values comparable as per the formula:

$$x^{norm} = \frac{x_i - x_{min}}{x_{max} - x_{min}}$$

5. Analyze the **statistical distribution** of the variables.
6. **Adjust for skewness or outliers** by transforming data if necessary. Variables with highly skewed statistical distributions or with outliers need to be properly transformed before combining them together, in order to prevent domination of one over the other by extreme values.
7. **Aggregate** by multiplying each normalized variable by its weight and summing these to produce the composite index, as per the formula:

$$\underline{x} = \frac{\sum_{j=1}^{n} w_j x_j}{\sum_{j=1}^{n} w_j}$$

   where x_j are the variables to combine, and w_j are the respective weights.
8. **Normalize** the composite index to bring it back to a scale from **0 (low) to 1 (high)**.
9. **Test** how the variance of variables and weights can affect the index outcome.

The methods for creating spatial composite indicators were developed by SEforALL based on best practices available from literature, mainly the ***OECD's Handbook on Constructing Composite Indicators***, and *Creating Composite Indices Using ArcGIS: Best Practices*[67].

Figure 7 illustrates how AgCAP aggregates different Cooling Potential Indices across various applications and markets.

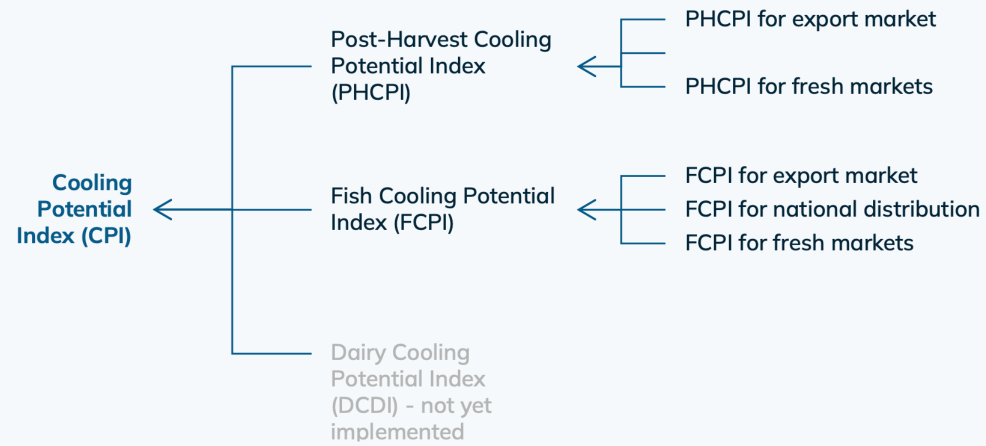

Figure 7. Diagram showcasing the formulation of the Cooling Potential Index (CPI).

Cooling Potential Index (CPI)

The **Cooling Potential Index (CPI)** is calculated as an arithmetic mean of the following sub-indices: a) **Post-Harvest Cooling Potential Index (PHCPI)**, b) **Fish Cooling Potential Index (FCPI)**, and **Dairy Cooling Potential Index (DCPI)**. Note that the Dairy Cooling Potential Index (DCPI) is not included in the current beta release of AgCAP due to the lack of standardized sector data. However, given its significant potential for cold-chain applications, it is presented here as a preview of features planned for future tool releases.

Post-Harvest Cooling Potential Index (PHCPI)

The PHCPI is the arithmetic mean of three sub-indices (see Figure 8): *PHCPI for the **export** market*, *PHCPI for the **national** market*, and *PHCPI for the **fresh market.***

[67] Esri (2024) *Creating Composite Indices Using ArcGIS: Best Practices*. [Technical Paper]. Redlands, CA: Esri. Available at: https://www.esri.com/content/dam/esrisites/en-us/media/technical-papers/creating-composite-indices-using-arcgis.pdf.

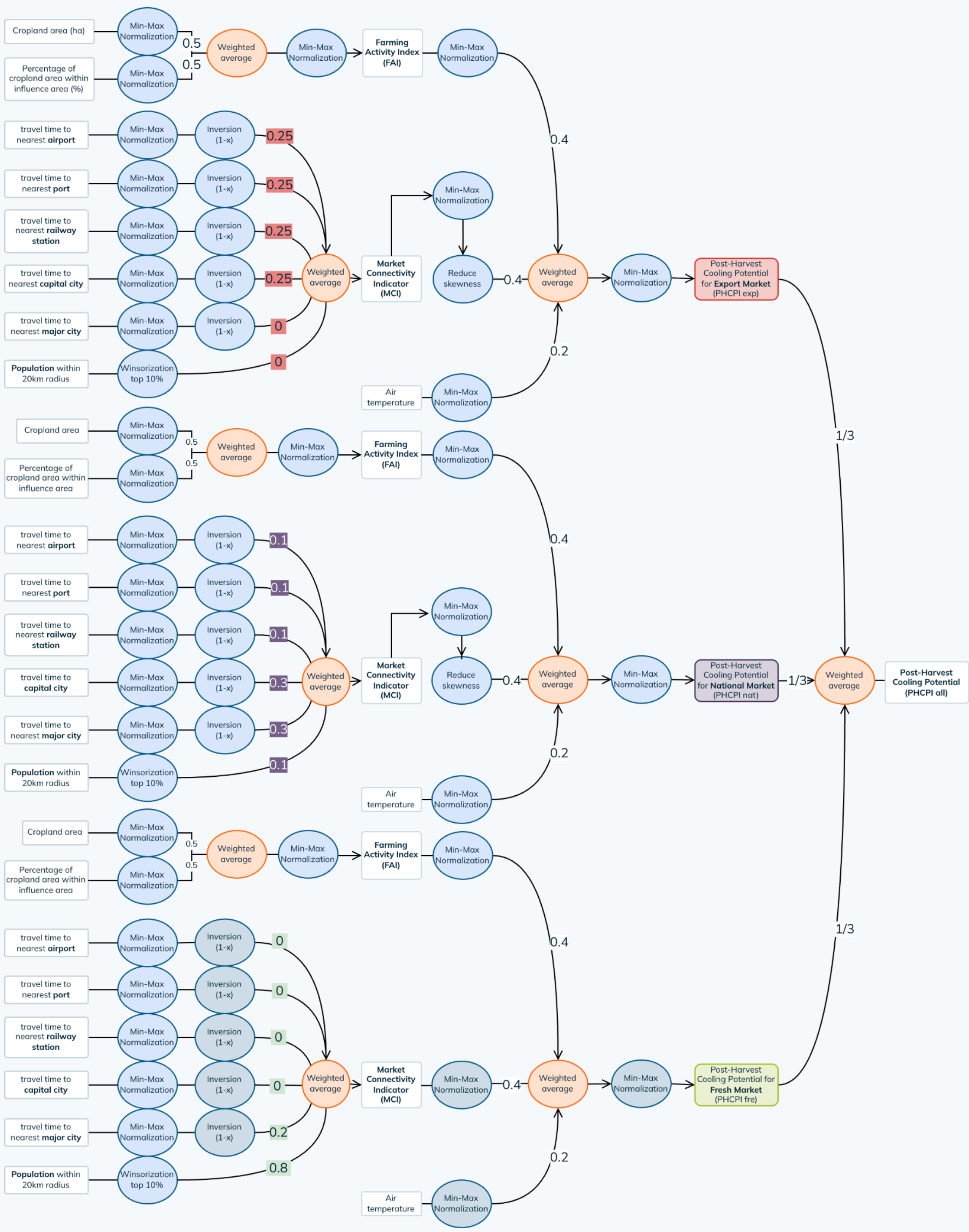

Figure 8. Construction of the Post-Harvest Cooling Potential Index (PHCPI)

Fish Cooling Potential Index (FCPI)

The **fishing-related indices** are derived based on each cluster's **proximity to either the coastline or inland permanent water bodies**, such as large rivers and lakes. These indices are computed according to the methodology illustrated in Figure 9, which relies on two geospatial proxy variables for potential fishing activity - one for inland waters and one for marine environments.

- **Marine fishing.** Only settlements within 10 km aerial distance from the coastline are given a fishing activity index, which is scaled based on their normalized distance, while the rest are given an index of 0. The justification for this metric is derived from empirical evidence gathered from the WFP Innovation Accelerator, according to which **fishermen are willing to travel distances of up to 7 to 10 km to sell their products in larger marketplaces**.

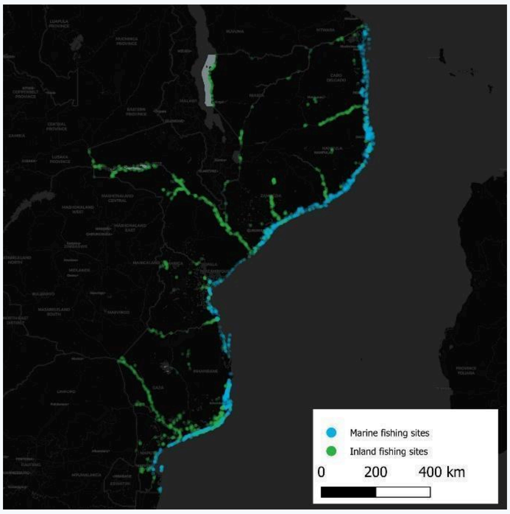

Figure 9. Population clusters with cold storage potential (marine and inland fishing).

For each settlement *i*, the Normalized Marine Fishing Activity Index $\left(FishAI^{norm}_{marine}\right)_i$ is calculated as follows:

$$(FishAI^{norm}_{marine})_i = \begin{cases} (10-(D_{coast})_i)^{norm} & if\ distance\ from\ coastline\ (D_{coast}) \leq 10\ km \\ 0 & if\ distance\ from\ coastline\ (D_{coast}) > 10\ km \end{cases}$$

where:

$\left(10-\left(D_{coast}\right)_i\right)^{norm}$ indicates the normalised proximity to shorelines, which decreases linearly from 1 (close to shoreline) to 0 (10 km or further). A min-max normalisation is used to rescale the index to a 0 to 1 range.

- **Inland fishing.** The **presence of nearby permanent inland water bodies** is analyzed by looking at the surface water observations from Landsat data from 1984 to 2021. A permanent water body is defined as any **surface that is covered by water for at least 85% of the time**, thus excluding seasonal rivers, lakes, and flooded rice fields. The model performs the following geospatial calculations to calculate the Inland Fishing Activity Index.
  - Calculation of the water body surface area within a 10 km radius from the settlement's centroid (A_{wb}), in hectares.
  - For any settlement where the surrounding available water area A_{wb} is less than one hectare, the Inland Fishing Activity Index is set to zero. This zeroing process is essential to eliminate false positives caused by noise in remote sensing data and to exclude locations with minimal fishing potential from the analysis.

- Normalization of A_{wb} using a min-max scaler to preserve the relative distances between data points while bounding all values within the fixed range (0 to 1).
- The resulting index ranges from 0 for settlements with a water area of 1 hectare or less, up to 1 for the settlement with the largest water area among all.

$$\textit{Inland Fishing Activity Index}\,(FishAI_{inland})_i = \begin{cases} A_{wb}^{norm} & if\ (A_{wb})_i \geq 1\ ha \\ 0 & if\ (A_{wb})_i < 1\ ha \end{cases}$$

The FCPI is the arithmetic mean of three sub-indices (see Figure 10): *FCPI for **export** markets*, *FCPI for **national** distribution*, and *FCPI for **fresh markets.***

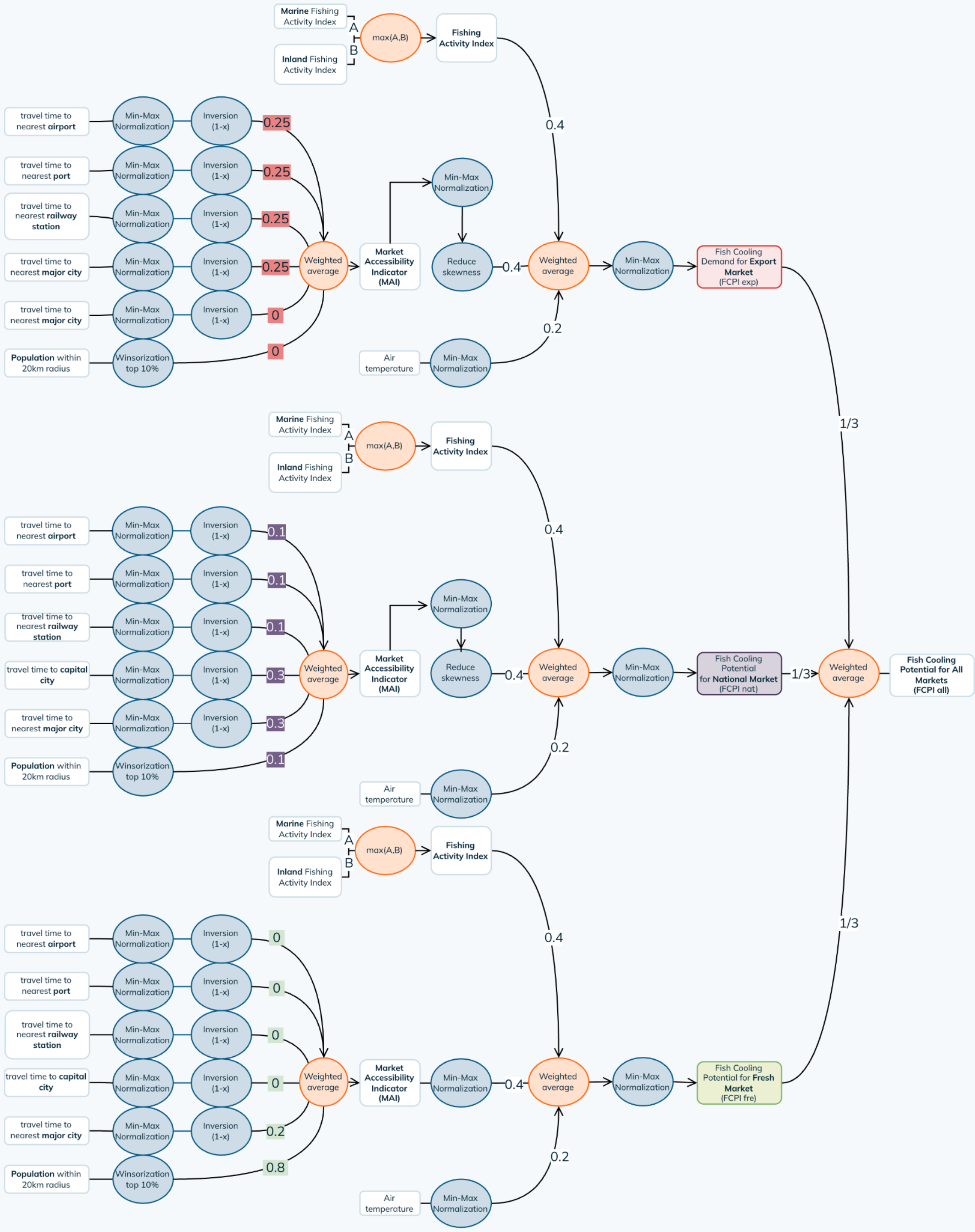

Figure 10. Construction of the Fish Cooling Potential Index (FCPI).

Advanced modelers can use the model to **add any additional country-specific data** that the government and other key stakeholders can provide to better characterize fisheries. For example, microdata from fisheries censuses often includes **information on the number of fishing households**, which may offer a more precise measure of fishing activity than the general methodology outlined above. However, a key **limitation of such microdata** is that it often stems from **sampling** rather than a full census and therefore may not be available for every settlement.

Consequently, this data becomes most **meaningful when aggregated at higher administrative levels** – such as regions, districts, or provinces – where sample sizes are sufficient to provide representative estimates.

Dairy Cooling Potential Index (DCPI)

Dairy value chains have a **very high potential to benefit from cooling**, even in off-grid settings, given the spoiling characteristics of fresh milk and year-round production[68]. However, due to data availability constraints, especially open data, there is currently no standardized implementation in the AgCAP analysis. The main reason is that, given the **challenges of obtaining** standardized and comprehensive **data on milk production sites** across multiple countries, there is no universal method to estimate potential cooling demand for milk chilling. **Each analysis must be tailored to the specific data available for the case at hand**. Population and economic censuses may provide valuable information, such as the **number of households engaged in milk production** or the **number of dairy cows owned**. Although this data can be aggregated to meaningful administrative levels – depending on sample sizes – it typically **does not offer sufficient detail to perform accurate assessments at the settlement level**. Nonetheless, when aggregated properly at regional, district, or provincial levels, such data can help identify administrative units with significant potential for milk cooling applications.

The above-described Post-Harvest, Fishing and Dairy Cooling Potential Indices (the latter depending on whether sufficient data can be gathered), are averaged together to calculate a **general Cooling Potential Index** which takes into account all the major productive applications of cold storage. This final composite index, as well as the intermediate indices, can be used **to identify at a high-level the settlements with high potential for cold storage applications** based on a standardized methodology using publicly available geospatial data. Please note that this general Cooling Potential Index is an oversimplification of the total cooling potential that should only be used as a quick analysis. It assumes that the level of potential from each individual market is similar. Therefore, this index should not be used directly for planning activities, but rather for the cooling potential for individual market types. The best solution is to develop customized cooling potential indices through the Multi-Criteria Analysis based on the agricultural expertise of the country stakeholders.

However, users should **not rely solely on these indices**, as their construction and the assigned weights inherently introduce **subjectivity**. Instead, **users are encouraged to leverage the interactive application to combine these indices with primary settlement attributes, which are generally more objective.** This approach enables greater precision by allowing users to select attributes tailored to specific use cases, apply custom filters to screen settlements, perform customized suitability analyses using weighted averages with user-defined weights, and rank shortlisted sites based on any chosen attribute or index.

[68] GOGLA (2025) *Beyond Silos: Powering Food Systems with Off-Grid Solar*. [White Paper]. GOGLA. Available at: https://gogla.org/whitepaper/beyond-silos/.

CHAPTER THREE

Analysis & visualization

The team has developed a **Multi-Criteria Analysis tool** within the **AgCAP Insights Platform** in which the user can perform **custom aggregation of attributes with custom weights**, picking among the composite indices described above, and any of the other attributes available.

The general approach for the multi-criteria analysis is to normalize the attributes to be used in the same way the composite indicators are normalized, through a min-max normalization.

The user will then define weights for each of the attributes to be included in the multi-criteria analysis, and the tool will **combine all the weights to end up with a final score for each site.** The sum of all the weights should be equal to 1, corresponding to 100%, and the attributes are aggregated as described in the previous section.

3.1 AgCAP Insights Platform

The multi-criteria analysis and visualization are done in the **AgCAP Insights Platform** (see Figure 11), which can be launched both **from a local environment** (for data privacy, full control, and custom analyses) or accessed via the **public platform made available by SEforALL for selected countries:**

- Public AgCAP Insights Platform for available countries - ideal for general users without modelling needs.
- Local Jupyter notebooks or app launcher - for full control over data, assumptions, and privacy.

The platform allows:

1. **Visualize settlement** data using **color scales** based on attributes like cooling potential indices to spot patterns and differences intuitively.
2. **Filter** the map using multiple attributes. Apply filters to display only sites that meet the user's specified conditions for the particular use case under analysis. Combined with custom color scales, this helps identify the most suitable sites for specific applications. Common filters include:
    a. **Production activities** in the village: Select sites with high **farming** activity, **fishing** activity, or a combination of both.
    b. Potential **cooling potential** indices: Based on production volumes and market connectivity.
    c. **Specific crop production**: Target sites with high output of specific **perishable crops.**
    d. **Demographics**: Exclude very small villages or those with low population density; also exclude large cities.
    e. **Geography**: Focus on specific regions, districts, communes, or other administrative areas.
    f. **Market connectivity**: Prioritize sites with strong sales potential due to nearby populations, travel times to airports, ports, cities, and railway stations. NGOs may reverse this to target the most remote sites for maximum intervention impact.
    g. **Socio-economic data**: Target wealthier villages to enhance the commercial viability of cold-chain facilities, or the poorest, most food-insecure ones.
    h. **Electrification status**: Select electrified sites for **on-grid cold-chain solutions**, or unelectrified sites for **off-grid** options. Filter for sites with existing mini-grids to **integrate cold rooms as anchor loads**, creating mutual benefits. Alternatively, choose sites planned for future **mini-grid** electrification, where developers can incorporate cold storage to boost utilization rates and financial viability.
    i. **Risks**: Filter settlements by recorded violence in the last 2 years or cyclone hazard levels.
    j. **Physical geography and climate**: Filter by climate zone, elevation, temperature, humidity, precipitation, aridity, and similar factors to target specific value chains or identify sites suitable for **passive cooling.**
    k. **Solar resources**: Select sites with the highest solar PV productivity for **solar-powered cold-chain facilities.**
3. Create **custom aggregated indicators** by utilizing any available attributes and assigning weights according to the specific use case users intend to analyze.
4. Optionally **import contextual geospatial datasets** - like census data, value chain production, roads, facilities, site assessments, or potential sites - to aid agricultural cold chain planning decisions.
5. **Add country- or sector-specific data, including proprietary data in the private user session**: users can export the settlements dataset, enrich it further using available data (e.g., using desktop GIS, spreadsheet software, Python, etc.), and import it back into the platform to continue the analysis.
6. **Rank** the settlements by the composite indicator that best defines the suitability under the chosen case study, typically one of the cooling potential indices.

7. Use the **interactive table** to see the attributes of the filtered settlements, and use the **dedicated columns to assign a score for shortlisting and annotations**. These files could then also be re-imported into the platform as additional layers (see point 4).
8. **Export the shortlisted sites** or the full dataset in **CSV** format. The table provides **valuable information for pre-feasibility analyses, preparation of site assessments, and general knowledge** in cold-chain planning and rural electrification planning. Users can perform further analysis in Excel and then re-import the updated file.
9. **Save the session and load previous sessions.** The session files can be shared with others or used as templates for different use cases.

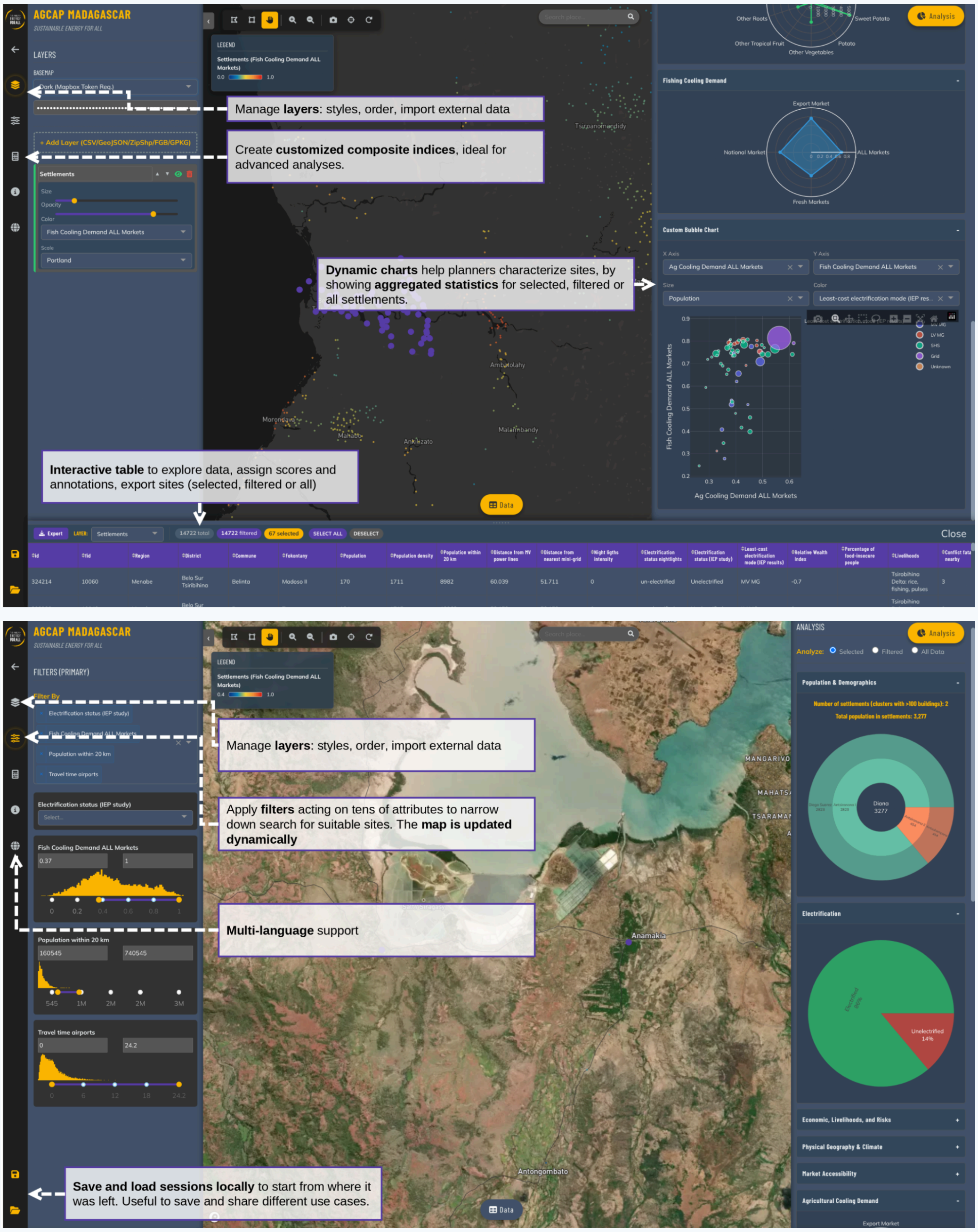

Figure 11. Snapshot of possible actions with the AgCAP Insights Platform.

3.2 Potential multi-criteria case studies

Studies on the viability and adoption of cold storage solutions in low- and middle-income countries have shown that there are various use cases in which sustainable adoption is more likely. Some of the factors that have a strong influence on the viability of cold chain investments are the level of production and market sophistication[69]. Furthermore, there are several value chains that are more suitable for cold storage interventions than others[70]. This section explores how multi-criteria analysis can support potential use cases. When implementing AgCAP, users will always need to collaborate with local agricultural stakeholders to ensure that use cases relevant to the country context are evaluated. Agricultural stakeholders are also key in identifying which of the additional settlement-level attributes need to be considered for the multi-criteria analysis.

3.2.1 High-potential sites for community-based cold storage of vegetables and non-climacteric fruits

The AgCAP tool enables government agencies, implementing partners, and the private sector to identify priority locations for solar-powered community-based walk-in cold rooms, with the objective of reducing post-harvest losses, enhancing livelihoods, and alleviating food insecurity.

The table below presents the criteria used in the multi-criteria site selection analysis, along with instructions on applying attribute filters based on specific thresholds. These thresholds vary by country and should be selected or validated by sector experts. Users can adjust these filters interactively and observe how settlements are dynamically removed from the contextual map, gaining sensibility on how each attribute affects the site selection.

Table 8. Example criteria for identification of high-potential sites for community-based cold storage of vegetables and non-climacteric fruits with the AgCAP model

Criteria	Attribute filters
Production of perishable products. Settlements surrounded by cropland are more likely to be engaged in agricultural activity (including production of perishable products) and therefore to show potential for cold storage. Census data on farming households, if available.	- Farming Activity Index > threshold - Number of farming households in the administrative unit to which they belong > threshold
Market potential, to ensure storage aligns with consumption or distribution needs. Sites with high connectivity to one or more markets (export, national distribution, local fresh markets) are likely to show interest in post-harvest cooling.	- Post-Harvest Cooling Potential (Export Market) > threshold - Post-Harvest Cooling Potential (National Market) > threshold - Post-Harvest Cooling Potential (Fresh Market) > threshold
More controlled criteria for market potential (alternative to the previous point): Connectivity by road or transport infrastructure for ease of delivery and distribution, ideally close to markets/logistic infrastructure.	- Population within a 20km radius > threshold - Travel time to nearest airport < threshold - Travel time to nearest port < threshold - Travel time to nearest major city < threshold - Travel time to capital city < threshold - Travel time to nearest railway station < threshold

[69] Defraeye, T., Vrba, J., Cloutier, J. et al. (2025) 'A Cooling Atlas for preserving fruit and vegetables in low- and middle-income countries', *Journal of Agriculture and Food Research*, 21. Available at: https://www.sciencedirect.com/science/article/pii/S2666154325001772.

[70] GOGLA (2025) *Beyond Silos: Powering Food Systems with Off-Grid Solar*. [White Paper]. GOGLA. Available at: https://gogla.org/whitepaper/beyond-silos/.

Food-insecure areas are to be prioritized	- Percentage of food-insecure people in the admin unit to which the settlements belong > threshold
Availability and reliability of power supply, preferably renewable or solar-powered solutions, to cope with the limited grid capacity typical in rural areas. Availability of solar resources.	- Electrification status: unelectrified - Night-time lights intensity < threshold - Specific solar photovoltaic (PV) output > threshold
Site safety and security to protect stored produce from theft and damage, and to reduce development costs associated with delays and uncertainties.	- Number of fatalities due to conflicts < threshold
Environmental factors such as temperature and humidity impact the needs and the efficacy of cold storage. Sites in warmer climates have higher post-harvest cooling potential. Food spoilage in dry and arid sites is accelerated.	- Annual air temperature > threshold - Number of hot days (above 30°C) > threshold - Average humidity < threshold - Aridity Index > threshold
Selection of one or more value chains of interest, narrowing down the search to sites with high production of specific agricultural products.	- Annual production of a specific crop > threshold - Livelihood zones of interest
Larger or denser settlements tend to have higher local potential for stored produce, making facilities economically viable by serving more users or buyers in nearby markets. It also helps avoid underutilization and ensures sufficient throughput to justify investment and operational costs.	- Population/population density > threshold

3.2.2 High-potential sites for community-based cold storage as mini-grid anchor loads

A further criterion can be added to the previous case study to identify sites where cold rooms can be used in synergy with planned rural electrification interventions. Unelectrified sites where mini-grids represent the least-cost mode of electrification (based on results from a separate least-cost electrification plan) would greatly benefit from the co-development of a community-based walk-in cold storage facility as an anchor load for the mini-grid. This synergy improves the financial viability and technical efficiency of both projects. The cold room provides a stable, predictable electrical load that supports mini-grid revenue and helps optimize energy system design and operations.

Conversely, the mini-grid ensures a reliable, renewable energy supply critical for cold storage performance, reducing dependence on fossil fuels or transient solutions. This integrated approach is especially promising in rural developing contexts where grid extension is costly or unavailable, and electrification plus cold storage are jointly needed to reduce post-harvest losses and improve livelihoods.

Table 9. Example criteria for identification of high-potential sites for community-based cold storage as mini-grid anchor loads with the AgCAP model

Criteria	Attribute filters
...Criteria from previous case study	*...Attributes from the previous case study*
Unelectrified sites where mini-grids represent the least-cost mode of electrification would benefit from the co-development of a community-based walk-in cold storage facility as an anchor load.	- Least-cost electrification mode = Mini-grid

3.2.3 High-potential sites for community-based, solar-powered ice makers and cold storage for fish

The AgCAP tool facilitates the identification of priority sites for solar-powered community-based ice makers and cold storage facilities, including chest freezers, tailored to fisheries, focusing on reducing post-harvest losses, enhancing livelihoods, and improving food security in fishing communities that are unelectrified but have a high solar-power potential.

The following table outlines specific criteria used in the multi-criteria site selection analysis for this sector; subject matter experts should set the defined thresholds based on local conditions and field knowledge. Through interactive filter adjustments, users can visualize how these criteria influence site suitability on the map, optimizing selection for fisheries-specific cold chain needs.

Table 10. Example criteria for identification of high-potential sites for community-based, solar-powered ice makers and cold storage for fish with the AgCAP model

Criteria	Attribute filters
Fishing activity. Settlements near the coastline or surrounded by permanent water bodies (lakes and rivers) are more likely to be engaged in fishing activity and therefore to show potential for cold storage and ice production. Census data on fishing households, if available.	- Marine Fishing Activity Index > threshold - Inland Fishing Activity Index > threshold - Number of fishing households in the administrative unit to which they belong > threshold
Market potential, to ensure storage aligns with consumption or distribution needs. Sites with high connectivity to one or more markets (export, national distribution, local fresh markets) are likely to show interest in post-harvest cooling.	- Post-Harvest Cooling Potential (Export Market) > threshold - Post-Harvest Cooling Potential (National Market) > threshold - Post-Harvest Cooling Potential (Fresh Market) > threshold
More controlled criteria for market potential (alternative to the previous point): Connectivity by road or transport infrastructure for ease of delivery and distribution, ideally close to markets/logistic infrastructure.	- Population within a 20km radius > threshold - Travel time to nearest airport < threshold - Travel time to nearest port < threshold - Travel time to nearest major city < threshold - Travel time to capital city < threshold - Travel time to nearest railway station < threshold
Food-insecure areas are to be prioritized	- Percentage of food-insecure people in the admin unit to which the settlements belong > threshold
Availability and reliability of power supply, preferably renewable or solar-powered solutions to cope with the limited grid capacity typical in rural areas. Availability of solar resources.	- Electrification status: unelectrified - Night-time lights intensity < threshold - Specific solar photovoltaic (PV) output > threshold

Site safety and security to protect stored produce from theft and damage, and to reduce development costs associated with delays and uncertainties.	- Number of fatalities due to conflicts < threshold
Environmental factors such as temperature and humidity impact the needs and the efficacy of cold storage. Higher temperatures accelerate the growth of spoilage bacteria and microorganisms, leading to faster degradation of fish quality.	- Annual air temperature > threshold - Number of hot days (above 30°C) > threshold - Average humidity < threshold - Aridity Index > threshold
Larger or denser settlements tend to have higher local demand for stored fish, making facilities economically viable by serving more users or buyers in nearby markets. It also helps avoid underutilization and ensures sufficient throughput to justify investment and operational costs.	- Population/population density > threshold

3.2.4 Sites with potential for passive evaporative cooling chambers (ECCs)

A further criterion can be added to the previous case study to identify sites suitable for the implementation of low-cost, passive cooling technologies such as evaporative cooling chambers (ECCs), considering that these technologies are particularly effective in hot arid climates. These are suitable in lower-income communities, where active cooling services cannot be afforded by smallholder farmers. This solution can, for example, be used for long-term potato storage[71]. The AgCAP tool can be used to select sites with low relative humidity (<40% RH) and higher temperatures (>25°C), especially where the production is mostly based on smallholder farmers that sell to local markets or aggregators. Low-income farmers producing fruits and vegetables would presumably benefit the most from this technology, since it allows them to extend the shelf life of produce by several days at a reasonable cost, until it can be collected by an aggregator or sold in local markets.

Similarly, users can use altitude as a filter to select suitable sites for cooling systems that take advantage of cooling by night ventilation or radiative cooling during the night.

[71] Gitua, C. and Parker, M. (2020) *Social-economic feasibility of potato postharvest storage using differing storage units*. Lima, Peru: International Potato Center. Available at: https://doi.org/10.4160/9789290605652

CHAPTER FOUR

Final Thoughts & Recommendations

When the multi-criteria analysis has been performed in the **AgCAP Insights Platform**, **users can save and distribute the session file** and **export the CSV** data files, which contain all attributes listed in Annex I plus any additional attributes created in the user session, such as notes, scores, or custom aggregated indices created by the user. These can then be **shared with the relevant stakeholders** to interactively explore the most high-potential sites for their specific cold storage application. CSV files can be used for spreadsheet-style analysis, but users can also import them into GIS software or integration in existing (geospatial) energy access planning platforms, allowing for a high degree of compatibility.

Potential end-users for the suitability analysis range from **governmental actors in the Energy, Agriculture, Fisheries, Industrial, or Development planning sectors**, to **development partners**, **NGOs**, and **private sector** players that are looking to develop cold storage or energy access projects based on productive uses of energy.

Government stakeholders can use the results of the multi-criteria analysis for site prioritization within energy access or electrification planning projects, like during the development of an Integrated Energy Plan. However, the results can also easily be tailored to and **integrated into existing rural electrification plans** or national electrification strategies. Moreover, government **stakeholders in end-use sectors** can use the results to **ensure integration of energy aspects** into their value-chain development projects, specifically in value chains like **fish, dairy, and high-value horticulture products**, and especially in more sophisticated value chains. These results can then be integrated into existing sector-specific data platforms.

In a similar way, **development partners, NGOs, and private sector** players in **both the energy and agriculture sectors** can use AgCAP to identify sites according to their specific project needs, like value chain characteristics or geographical scope. They can use the national level results and refine and filter them to come up with a project-specific list of high-potential sites. This list can either be viewed and utilized in the online web interface or can be exported to develop project descriptions or reports.

AgCAP can thus be used to identify high-potential sites for agricultural cold storage **tailored to specific use-cases**. However, as discussed in Chapter 1.3, there are **numerous nuances when developing cold storage projects** in rural development settings, and not all of these can be fully covered in an analytical model. The results can therefore be used to **inform the prioritization of cold storage deployments**, or **identify high-potential energy access project sites**, but it is required to **complement them with a viability analysis** (like the Post-Harvest Assessment Method by WUR[72]) based on the specific value chain dynamics to confirm the specific cold storage needs and viability of interventions.

It is worth mentioning that geospatial multi-criteria analysis inevitably carries the risk of error propagation. Many underlying datasets contain their own uncertainties, spatial inconsistencies, and methodological limitations. When combined within a single modelling framework, these uncertainties may compound. **The outputs of AgCAP should therefore be interpreted as indicative screening results rather than definitive investment decisions**, and used as a starting point for deeper technical and field-level assessments.

The robustness of the analysis ultimately depends on the quality of the underlying data. **Users - particularly governmental institutions - are strongly encouraged to integrate higher-resolution, up-to-date, and locally validated datasets wherever available.** A key advantage of the AgCAP methodology is that layers can easily be customized by adapting the open-source Python code in the Jupyter notebooks. Investing in data collection, cleaning, harmonization, and conversion into appropriate spatial formats can significantly enhance the accuracy and policy relevance of such tools. **Strengthening national geospatial data ecosystems is therefore essential for evidence-based planning beyond AgCAP itself.**

Finally, AgCAP should be understood as a tool that is evolving. **It is designed as an open and collaborative tool that develops through engagement with a broader community of practice committed to transparency and methodological rigor.** Continuous adaptation, peer review, and collective improvement will be essential to further refine the analytical framework and push the boundaries of data-driven planning in the cold chain and productive use of energy sectors.

[72] https://edepot.wur.nl/582556.

ANNEX I - Data dictionary

Category	Column name	Description
Administrative & Location	id	Settlement unique identifier
	Region	Administrative level 1 of belonging
	District	Administrative level 2 of belonging
	Commune	Administrative level 3 of belonging
	Fokontany	Administrative level 4 of belonging
Population & Demographics	Population	Number of people living within the settlement boundary
	Population density	Population density in people [pp/km²]
	Population within 20 km	Number of people living within a 20 km radius
Electrification	Distance from MV power lines	Distance from the nearest Medium-Voltage power lines [km]
	Distance from nearest mini-grid	Distance from the nearest mini-grid [km]
	Night lights intensity	Median annual VIIRS nighttime lights radiance observed over the last full calendar year [W/cm²·sr]
	Electrification status (nightlights)	Electrification status inferred from distance to MV lines and nighttime lights
	Electrification status (IEP study)	Electrification status as per the latest national electrification plan (SEforALL IEP, 2024)
	Least-cost electrification mode (IEP results)	Recommended least-cost electrification modality as per the latest national electrification plan (SEforALL IEP, 2024)
Economic, Livelihoods, and Risks	Relative Wealth Index	Meta Relative Wealth Index standardized score for local relative wealth (0=national mean, negative=poorer, positive=wealthier)
	Percentage of food-insecure people	Percentage of people above Phase 3 food insecurity as per the IPC latest available monitoring analysis [%]
	Livelihoods	Dominant livelihood categories for households in the area
	Conflict fatalities nearby	The number of fatalities due to conflict events within 10 km is calculated for the last year available
	Cyclone hazard (1 in 100 years wind speed)	Maximum 1-in-100-year cyclone wind speed affecting the settlement area [km/h]
Physical Geography & Climate	Elevation	Mean ground elevation of the settlement above sea level [m]
	Mean temperature	Mean annual near-surface air temperature for the settlement area [°C]
	Mean diurnal temperature range	Average difference between daily maximum and minimum temperatures [°C]
	Cooling Degree Days Cold Room at 4C	Annual cooling degree days relative to a 4 °C cold-room setpoint for the settlement's climate [°C·days]
	Hot days (>30C) in a year	Average number of days per year with daily maximum temperature above 30 °C
	Relative humidity	Mean annual near-surface relative humidity for the settlement area [%]
	Precipitation	Mean annual total precipitation over the settlement area [mm/year]

Category	Column name	Description
	Aridity Index	Climatic aridity index (ratio of precipitation to potential evapotranspiration) for the settlement
	Climate class	Köppen climate classification category
	Solar PV Output (kWh/year per installed kW)	Expected annual electricity generation per installed kW of PV capacity at the settlement [kWh/year per kW]
Water & Cropland	Cropland percentage of the influence area	Percentage of the defined influence area around the settlement classified as cropland [%]
	Permanent water area (ha) within 10 km	Total area of permanent surface water within 10 km of the settlement [ha]
	Distance from coastlines	Distance from the settlement to the nearest coastline [km]
Market Connectivity	Travel time to airports	Estimated travel time from the settlement to the nearest airport [hours]
	Travel time to ports	Estimated travel time from the settlement to the nearest port [hours]
	Travel time to cities	Estimated travel time from the settlement to the nearest main city [hours]
	Travel time to the capital	Estimated travel time from the settlement to the capital city [hours]
	Travel time to railway stations	Estimated travel time from the settlement to the nearest railway station [hours]
	Export market connectivity	Composite indicator of market connectivity to export markets. Weighted average of travel times to airports, ports, railway stations and capital city (0=lowest, 1=highest)
	National market connectivity	Composite indicator of market connectivity to export markets. Weighted average of travel times to capital city, nearest cities, airports, ports, railway stations, and nearby population (0=lowest, 1=highest)
	Fresh Markets Connectivity	Composite indicator of market connectivity to export markets. Weighted average of travel times to capital city, nearest cities, airports, ports, railway stations (0=lowest, 1=highest)
Agricultural Cooling Potential	Farming Activity	Composite indicator of market connectivity to export markets. Weighted average of nearby population, travel times to capital city, nearest cities, airports, ports, railway stations (0=lowest, 1=highest)
	Ag Cooling Potential Export Market	Composite indicator of cooling potential for fish products destined for export markets (0=lowest, 1=highest)
	Ag Cooling Potential National Market	Composite indicator of cooling potential for fish products destined for national distribution (0=lowest, 1=highest)
	Ag Cooling Potential Fresh Markets	Composite indicator of cooling potential for fish products destined for local fresh markets (0=lowest, 1=highest)
	Ag Cooling Potential ALL Markets	Composite indicator of cooling potential for fish products across all destination markets (0=lowest, 1=highest)
Agriculture Production	Banana production	Banana production associated with the settlement influence area [tonnes/year]
	Cassava production	Cassava production associated with the settlement influence area [tonnes/year]
	Citrus production	Citrus production associated with the settlement influence area [tonnes/year]
	Cowpea production	Cowpea production associated with the settlement influence area [tonnes/year]

Category	Column name	Description
	Other Roots production	Other roots production associated with the settlement influence area [tonnes/year]
	Other Tropical Fruit Production	Other tropical fruit production associated with the settlement influence area [tonnes/year]
	Other Vegetables production	Other vegetables production associated with the settlement influence area [tonnes/year]
	Potato production	Potato production associated with the settlement influence area [tonnes/year]
	Sweet Potato production	Sweet potato production associated with the settlement influence area [tonnes/year]
	Temperate Fruit Production	Temperate fruit production associated with the settlement influence area [tonnes/year]
	Tomato production	Tomato production associated with the settlement influence area [tonnes/year]
Fishing Cooling Potential	Fishing Activity (marine + inland)	Composite indicator of fishing activity (both marine and inland) based on water resources available (e.g., distance from shorelines and availability of permanent inland water nearby (0=lowest, 1=highest)
	Fishing type	Fishing modality (marine or inland)
	Fish Cooling Potential Export Market	Composite indicator of cooling/ice making potential for fish products destined for export markets (0=lowest, 1=highest)
	Fish Cooling Potential National Market	Composite indicator of cooling/ice making potential for fish products destined for national distribution (0=lowest, 1=highest)
	Fish Cooling Potential Fresh Markets	Composite indicator of cooling/ice making potential for fish products destined for local fresh markets (0=lowest, 1=highest)
	Fish Cooling Potential ALL Markets	Composite indicator of cooling/ice making potential for fish products across all destination markets (0=lowest, 1=highest)
Geometry	geometry	Geometric representation of the settlement boundaries

ANNEX II - MAPSPAM crops

Crop ID	SPAM name	Crop name	Included by default
1	whea	Wheat	No
2	rice	Rice	No
3	maiz	Maize	No
4	barl	Barley	No
5	pmil	Pearl Millet	No
6	smil	Small Millet	No
7	sorg	Sorghum	No
8	ocer	Other Cereals	No
9	pota	Potato	Yes
10	swpo	Sweet Potato	Yes
11	yams	Yams	Yes
12	cass	Cassava	Yes
13	orts	Other Roots	Yes
14	bean	Bean	Yes
15	chic	Chickpea	No
16	cowp	Cowpea	No
17	pige	Pigeonpea	No
18	lent	Lentil	No
19	opul	Other Pulses	No
20	soyb	Soybean	No
21	grou	Groundnut	No
22	cnut	Coconut	No
23	oilp	Oil Palm	No
24	sunf	Sunflower	No
25	rape	Rapeseed	No
26	sesa	Sesame Seed	No
27	ooil	Other Oil Crops	No
28	sugc	Sugarcane	No
29	sugb	Sugarbeet	No
30	cott	Cotton	No
31	ofib	Other Fibre Crops	No
32	acof	Arabica Coffee	No
33	rcof	Robusta Coffee	No
34	coco	Cocoa	No
35	teas	Tea	No
36	toba	Tobacco	No
37	bana	Banana	Yes
38	plnt	Plantain	Yes
39	citr	Citrus	Yes
40	trof	Other Tropical Fruit	Yes
41	temf	Temperate Fruit	Yes
42	toma	Tomato	Yes
43	onio	Onion	Yes
44	vege	Other Vegetables	Yes

About SEforALL

Sustainable Energy for All has a global mandate to accelerate progress on the energy transition in emerging and developing countries. Hosted by UNOPS, we work at the intersection of energy, climate and development, partnering with governments and organizations worldwide to end energy poverty, double energy efficiency, significantly expand renewable energy and combat climate change.

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