Evaluation of policies for enhancing sustainable wheat production in Italy

ECOWHEATALY

Work Package 2: Model Development

Task report 2.1

Global Economic Model adaptation

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Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani

This project has received funding from the European Union's Next Generation EU fund under the Italiadomani plan with a call of the Italian Ministry of Education. Views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union or the other involved institutions. Neither the European Union nor the granting authorities can be held responsible for them.

Project information

Finanzing institutions:

EU Financing plan:	Next Generation EU
IT Financing plan:	Piano Nazionale di Ripresa e Resilienza (PNRR)
Thematic Priority:	Missione 4: istruzione e ricerca
IT Managing institution:	Ministero dell'Università e della Ricerca
Investment name:	Progetti di Ricerca di Significativo Interesse Nazionale (PRIN)
Call:	Bando 2022

Project details:

Title:	**Evaluation of Policies for Enhancing Sustainable Wheat Production in Italy**
Short name:	ECOWHEATALY
Contract No:	202288L9YN
Investment No:	Codice Unico Progetto (CUP): D53D23006260006
Start date:	28/09/2023
Duration:	24 months
Website:	www.ecowheataly.it
ERC field:	SH Social Sciences and Humanities
ERC subfields:	SH1_12 Environmental economics; resource and energy economics; agricultural economics SH7_6 Environmental and climate change, societal impact and policy
Consortium:	G. d'Annunzio University of Chieti-Pescara (coordinator) Consiglio per la ricerca in agricultura e l'analisi dell'economia agraria (sub-research unit) Italian National Research Council (research unit)

Document information

Document type:	Task report
Document ID:	2.1
Document title:	Global Economic Model adaptation
Work Package:	WP2 Model Development
Due date:	30/06/2024
Submission date:	30/06/2024
Authors:	Gianfranco Giulioni, Edmondo Di Giuseppe, Ilaria Zappitelli
Dissemination Level:	PU
No. pages:	34
Responsible person:	Gianfranco Giulioni
Status:	Plan/Draft/Working**Final**

Revision history:

Version	Date	Author	Comment
v.0.1	09/04/2024	Gianfranco Giulioni	First outline
v.1.0	15/06/2024	Edmondo Di Giuseppe	First complete version
v.2.0	30/06/2024	Gianfranco Giulioni	Final version after internal review

Quality Control:

	Who	Date
Checked by internal reviewer	Arianna Di Paola, Alessandro Ceccarelli	15/06/2024
Checked by WP Leader	Gianfranco Giulioni	25/06/2024
Checked by Project communication Managers	Massimiliano Pasqui	30/06/2024
Checked by Project Coordinator	Gianfranco Giulioni	30/06/2024

Dissemination Level:

PU	Public Use	✓
PP	Restricted to other programme participants	
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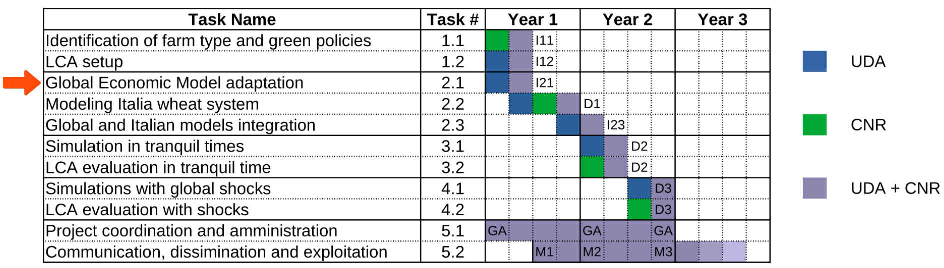
CO	Confidential, only for members of the consortium	

This document in the project:



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ACKNOWLEDGEMENTS

ECOWHEATALY is a project that has received funding from the European Union's Next Generation EU plan through the Piano Nazionale di Ripresa e Resilienza (PNRR), Missione 4: istruzione e ricerca. The funding is managed by Ministero dell'Università e della Ricerca with the investment named "Progetti di Ricerca di Significativo Interesse Nazionale (PRIN)", Bando 2022 under Grant Agreement No 202288L9YN. Please see www.ecowheataly.it for more information.

The partners in the project are:
G. d'Annunzio University of Chieti-Pescara (coordinator)
Consiglio per la ricerca in agricultura e l'analisi dell'economia agraria (sub-research unit)
Italian National Research Council (research unit).

The content of this document is the result of the worked developed by the partners in the context of the project.

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Global Economic Model adaptation

Contents

Executive Summary

This report presents the results of Task 2.1 of the ECOWHEATALY project, which focuses on the adaptation of the Global Economic Model (GEM) used to simulate the dynamics of the international wheat market. The purpose of this task is to develop a modelling framework capable of analysing the economic mechanisms governing global wheat production and trade, while preparing the model for its integration with the environmental and farm-level components developed in the previous tasks of the project.

The model employed in this task builds upon the CMS-Wheat model previously developed by members of the research team. This computational model has been successfully used in earlier studies to reproduce wheat price dynamics in major markets and to analyse the effects of large-scale shocks such as export bans and climate-related phenomena. The model represents the global wheat market as a system of interacting regions or countries, each acting as a producer, consumer, or trader of wheat.

Within the model, agents represent sovereign countries located at specific geographical coordinates. These spatial attributes are used to compute transportation costs between trading partners, which in turn influence international trade flows. The model operates in discrete time steps and simulates market interactions through repeated trading sessions in which supply and demand are matched across the global system.

Task 2.1 adapts this modelling framework to the objectives of the ECOWHEATALY project. In particular, the structure of the model is revised to allow the integration of detailed data on wheat production systems and agricultural practices derived from the Italian farm-level database developed in Task 1.1. This adaptation also prepares the model for the incorporation of environmental impact indicators derived from the Life Cycle Assessment framework implemented in Task 1.2.

The resulting model provides a flexible computational platform capable of linking global wheat market dynamics with farm-level production behaviour and environmental outcomes. This integration represents a key step toward the development of policy simulations aimed at evaluating the economic and environmental consequences of sustainable agricultural policies.

1 The Original CMS-Wheat Global Economic Model

The main goal of the Global Economic Model (GEM) is to simulate the international wheat market. To achieve this, we calculate the difference between production and consumption at the global level for each year from 2010 to 2023. When there is excess production, the area or country can supply wheat to others. Conversely, when production falls short, it indicates the need to source wheat from international markets to meet domestic demands.

The previous version of the GEM model is fully described in two papers authored by some of the researchers involved in Ecowheataly. This is a computational model, originally called the CMS-wheat model, designed to simulate the dynamics of the global wheat production system. The CMS-wheat model successfully reproduced monthly price dynamics at major US markets [Giulioni et al., 2019] and was employed to assess the impact of the 2010 Russian Federation wheat export ban. Additionally, the model was utilized to analyze the effect of El Niño Southern Oscillation on global wheat prices [Di Giuseppe et al., 2022].

In those studies, the reference was the sub-continental aggregation included in the FAOSTAT regions section. However, countries particularly relevant to the global wheat-producing system were highlighted individually, notably the US, India, Pakistan, the Russian Federation, and China.

We give hereafter some additional details on the original model.

1.1 General Architecture

The model describes the global wheat market as a multi-market system in which sovereign countries act either as producers, buyers, or both. Each agent is associated with a geographical location defined by latitude and longitude coordinates. These spatial coordinates are used to compute transportation costs and influence trade flows.

The model operates in discrete time steps. Within each time step, multiple market sessions are organized, corresponding to the different producers participating in international trade.

The CMS-Wheat model is a partial equilibrium framework in which:

- Supply is determined by producers' inventories and production cycles,
- Demand is represented by linear demand functions submitted by buyers,
- Market prices are endogenously determined by the intersection of aggregate demand and available supply,
- Trade flows emerge as the outcome of decentralized market interactions.

1.2 Producers

Producers represent wheat-producing countries. Each producer is characterized by:

- Geographic location,
- Initial production share,
- Target production level Y_p^T,
- Inventory level,

- Export policy (export allowed or export ban),
- Production cycle length.

Production follows a cyclical structure and is subject to stochastic fluctuations. Realized production is defined as:

$$Y_p = Y_p^T(1 + u), \tag{1}$$

where $u \sim U(-y, y)$ represents a stochastic shock.

Producers may adapt their target production level based on observed price signals. When average observed prices exceed an upper threshold, production targets are increased; conversely, when prices fall below a lower threshold, production targets are reduced. This introduces endogenous supply adjustment and dynamic feedback between prices and production.

1.3 Buyers

Buyers represent consuming countries and may or may not be associated with domestic production. Each buyer is characterized by:

- Geographic location,
- Demand share,
- Linear demand curve parameters,
- Import policy (imports allowed or forbidden),
- Minimum consumption threshold.

The demand of each nuyer in each market session m is represented by a linear function:

$$D_{b,m}(p) = \bar{D}_{b,m} - d_b p, \tag{2}$$

where $\bar{D}_{b,m}$ is the intercept and d_b is the slope parameter.

Buyers dynamically reallocate their demand across markets in order to minimize total acquisition cost, defined as the sum of market price and transportation cost. Demand adjustments occur when:

- Relative prices change,
- Export bans are imposed,
- New markets become available,
- Domestic consumption thresholds are not met.

This reallocation mechanism generates endogenous switching behavior in international trade flows.

1.4 Markets and Price Formation

Markets function as virtual clearing institutions. Producers organize market sessions in which buyers submit demand curves. Supply is represented as a vertical curve equal to the available inventory.

Aggregate demand is obtained by horizontal summation of individual demand curves. The equilibrium price p^* is determined by solving:

$$\sum_b D_{b,m}(p^*) = S_m, \tag{3}$$

where S_m is the available supply in market m.

Once the equilibrium price is computed, quantities are allocated proportionally to buyers' submitted demand at that price. Transactions are then executed and inventories updated.

1.5 Transportation Costs

Transportation costs are distance-based and depend on the geographical coordinates of producers and buyers. Buyers internalize transportation costs when deciding from which market to purchase. The effective unit cost faced by a buyer is therefore:

$$c_{b,m} = p_m + \tau_{b,s}, \tag{4}$$

where p_m is the market price and $\tau_{b,s}$ is the transport cost between buyer b and producer s.

This spatial structure introduces realistic trade frictions and allows the model to generate geographically consistent trade patterns.

1.6 Dynamic Sequence of Events

Each simulation time step follows a structured sequence:

1. Export policy updates,
2. Import policy updates,
3. Demand reallocation across markets,
4. Market sessions and price determination,
5. Consumption realization,
6. Production realization,
7. Adjustment of production targets.

/noindent This dynamic loop generates feedback between prices, inventories, production decisions, and trade flows, allowing the model to reproduce observed international price volatility and shock propagation.

1.7 Model Capabilities

The CMS-Wheat model has demonstrated the ability to:

- Reproduce historical price dynamics,
- Simulate export bans,
- Model climate-induced production shocks,
- Capture endogenous trade reallocation mechanisms.

The model therefore provides a structurally grounded computational representation of the global wheat market, suitable for policy and shock analysis.

As part of the Ecowheataly project, the original CMS-wheat model has undergone several enhancements to better meet project requirements, particularly its focus on the Italian market, and to incorporate updates from the FAOSTAT database.

1.8 A less technical description

The CMS-Wheat model (Commodity Market Simulator – Wheat) is a computational, agent-based, partial equilibrium framework developed to simulate the functioning of the international wheat market. Implemented within the Repast Simphony platform, the model represents the global wheat system as a decentralized multi-agent environment composed of producers, buyers, and markets. Each economic actor is geographically located by latitude and longitude coordinates, enabling the model to account for spatial trade frictions and transportation costs explicitly.

Conceptually, the CMS-Wheat model represents the global wheat economy as a network of interacting national markets coordinated through decentralized market sessions. Countries act either as producers, buyers, or both. Market interactions occur in discrete time steps, during which producers organize market sessions and buyers submit demand schedules. Prices are determined endogenously at each session through the intersection of aggregate demand and available supply. Trade flows emerge from these decentralized clearing mechanisms.

Producers in the model correspond to sovereign wheat-producing countries. Each producer is characterized by a target production level, inventory levels, and an export policy that may permit or restrict participation in international trade. Production follows a cyclical structure reflecting agricultural harvest patterns and is subject to stochastic fluctuations. Realized production is modeled as a deviation from a target level through a multiplicative random shock. In addition to stochastic variation, producers adapt their target production over time in response to observed market prices. When average prices exceed an upper threshold, production targets are increased; when prices fall below a lower threshold, targets are reduced. This adaptive mechanism introduces endogenous supply adjustment and allows price signals to influence future production dynamics.

Buyers represent consuming countries and are modeled as price-responsive agents submitting linear demand functions to producer markets. Demand is defined through market-specific intercepts and slopes, which determine the quantity demanded at any given price. Buyers may be associated with domestic production or may rely entirely on imports. A central behavioral feature of the model is the dynamic reallocation of demand across markets. Buyers observe prices and transportation costs and adjust their purchasing strategies to minimize total acquisition cost. When relative prices change, when export bans are introduced, or when new trading opportunities arise, buyers shift their demand accordingly. This mechanism generates endogenous switching behavior and allows the model to reproduce realistic patterns of trade diversion and market substitution.

Markets function as virtual clearing institutions. Producers organize market sessions during which buyers submit demand curves. Supply is represented by the available inventory and is modeled as perfectly inelastic within each market session. The equilibrium price is determined analytically by equating aggregate demand to available supply. Once the equilibrium price is identified, quantities are allocated among buyers according to their submitted demand at that price, and inventories are updated accordingly. Because demand curves are linear and supply is vertical within each session, price determination is transparent and computationally efficient.

Transportation costs are explicitly incorporated through the agents' geographical positioning. The cost faced by buyers equals the market price plus a distance-dependent transport component. By internalizing transportation costs, buyers naturally favor geographically closer or cheaper suppliers, thereby generating spatially coherent trade flows. This spatial structure is essential for capturing trade frictions and for simulating the propagation of regional shocks through international markets.

Each simulation time step proceeds through a structured sequence of events: export and import policies are updated first, followed by the reallocation of demand across markets. Market sessions are then executed and prices are determined. After transactions are completed, consumption is realized, production shocks are applied, inventories are updated, and production targets may be adjusted. This dynamic loop creates feedback between prices, inventories, production decisions, and trade flows, enabling the model to reproduce price volatility and shock transmission mechanisms observed in real-world commodity markets.

Theoretical Classification. From a theoretical perspective, the CMS-Wheat model can be classified as a dynamic, spatially explicit, multi-market partial equilibrium model with adaptive supply behavior and decentralized demand switching. It belongs to the family of computational economic models in which equilibrium prices are determined within each market session. At the same time, quantities, inventories, and production targets evolve according to behavioral rules and stochastic shocks. The model does not attempt to solve a global general equilibrium problem; instead, it focuses on commodity-level market clearing under heterogeneous agents interacting through geographically differentiated trade costs. Supply is vertically fixed within each period but adjusts intertemporally through adaptive production rules, while demand is price-responsive and reallocated across markets to minimize effective acquisition costs. This structure situates the CMS-Wheat framework at the intersection of agent-based computational economics and partial-equilibrium commodity modeling.

To clarify the internal architecture of the CMS-Wheat model, Figure 1 presents a schematic of the interactions among producers, buyers, and markets. The diagram highlights the decentralized market sessions, the endogenous price formation mechanism, and the role of transportation costs in shaping trade flows.

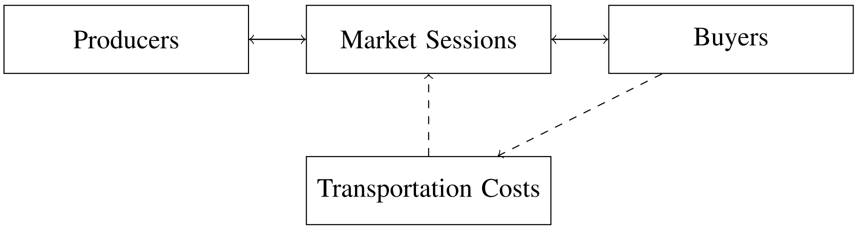

Figure 1: Conceptual representation of the CMS-Wheat model. Producers supply wheat to decentralized market sessions. Buyers submit linear demand functions. The intersection of supply and demand determines market prices. Transportation costs influence buyers' effective acquisition costs. Price signals feed back into producers' future production targets.

2 From CMS-Wheat to the ECOWHEATALY GEM: Key Modifications

This section documents the main modifications introduced in the ECOWHEATALY Global Economic Model (GEM) relative to the original CMS-Wheat model. The objective is to clarify how the previous framework—designed as a general-purpose computational model of the global wheat market—has been adapted to meet the ECOWHEATALY project requirements, namely: (i) alignment with the updated FAOSTAT Food Balance Sheets (FBS) methodology, (ii) explicit treatment of Italy as an independent market entity, and (iii) a modular and scalable structure suitable for systematic policy and shock analysis at the global level. The original CMS-Wheat baseline architecture is described in the official manual Giulioni [2018], while the present modifications follow the ECOWHEATALY technical development notes ECOWHEATALY Research Team [2026].

2.1 Computational Implementation: From Java (Repast Simphony) to Python

The original CMS-Wheat model was implemented in Java within the Repast Simphony agent-based modeling framework Giulioni [2018]. Repast provides a structured scheduling environment in which agents interact through explicitly defined market sessions and simulation ticks. While this architecture ensured robustness and flexibility for standalone commodity simulations, it was designed primarily for general-purpose agent-based experimentation.

In ECOWHEATALY, the Global Economic Model has been fully reimplemented in Python. This transition was motivated by several considerations. First, Python allows seamless integration with the broader ECOWHEATALY modeling environment, including data processing, statistical calibration, and distributed simulation components. Second, the Python implementation enables modular design and easier interoperability with high-performance computing tools and MPI-based parallel execution strategies adopted in the project. Third, the use of Python improves transparency and reproducibility by leveraging widely used scientific libraries and open-source ecosystems.

The transition from Java/Repast to Python does not alter the model's fundamental economic structure ? namely, a dynamic, multi-market partial-equilibrium system ? but it significantly enhances modularity, scalability, and integration readiness. In particular, the market-clearing component is now implemented as a modular global-market function managed by a master process, consistent with the computational architecture adopted in ECOWHEATALY. This redesign facilitates systematic scenario analysis, controlled experimentation, and interaction with other model components developed within the project.

2.2 Data and Accounting Framework: FAOSTAT FBS Update (2010–2023)

A central modification concerns the data backbone. The original CMS-Wheat model relied on FAOSTAT inputs available at the time of its development, and its global balances were constructed accordingly. For ECOWHEATALY, the GEM has been updated to adopt the revised FAOSTAT Food Balance Sheets methodology, which has been applied since 2010. In particular, ECOWHEATALY uses the "Wheat and products" commodity time series over 2010–2023 corresponding to the FAOSTAT update released by the Statistics Division on 28 October 2025 ECOWHEATALY Research Team [2026]. This revision introduces a dedicated *Residuals* item to close the balance and implies changes in the naming and coding of geographic areas. As a result, the algorithms that compute FBS variables for both sub-regions and individual countries have been revised to ensure internal consistency under the new accounting definitions.

2.3 Geographic Resolution and the Explicit Treatment of Italy

In the original CMS-Wheat implementation, countries and macro-areas could be represented at different geographic scales, and aggregation choices were largely driven by the intended application Giulioni [2018]. In prior global wheat applications, the reference geographic partition typically relied on subcontinental FAOSTAT regions, whereas individual major wheat producers were highlighted. In ECOWHEATALY, the geographic representation has been adapted to emphasize the Italian market. Italy is treated as an explicit, standalone entity rather than being embedded within its macro-area (Southern Europe) ECOWHEATALY Research Team [2026]. This change is necessary to enable national-level analyses of market exposure and external vulnerability under global shocks, while retaining the global context for price formation and trade reallocation. It should be noted that the current FAOSTAT "Wheat and products" aggregate includes both hard and soft wheat, whereas ECOWHEATALY focuses on hard wheat; this motivates careful interpretation of global aggregates when the analysis is specialized to Italian production types ECOWHEATALY Research Team [2026].

2.4 International Market Setup: Producer Summary and Export Policy Handling

While CMS-Wheat already allows producers to impose export bans via an export policy flag Giulioni [2018], the ECOWHEATALY GEM introduces a more structured procedure for constructing the international market environment based on recent observed balances. Specifically, ECOWHEATALY computes an "international producers summary" that characterizes each producer's recent excess production (production minus domestic demand) using the last three observations ECOWHEATALY Research Team [2026]. The summary includes (i) the latest recorded excess production, (ii) the number of positive excesses within the last three years, (iii) the mean excess, (iv) the coefficient of variation, and (v) a supply share proxy based on non-negative mean excesses.

Export bans are explicitly incorporated by setting an export indicator that determines whether a producer's supply contributes to the open international market in a given period ECOWHEATALY Research Team [2026]. This design makes the availability of supply in global markets a transparent, data-driven object, facilitating scenario construction and shock experiments.

2.5 Buyer Construction and Monthly Demand Allocation Consistent with FAOSTAT

A key operational difference between CMS-Wheat and the ECOWHEATALY GEM concerns how buyer demand schedules are initialized from yearly data and mapped into the monthly trading environment. CMS-Wheat models buyers as agents submitting linear demand curves, with intercepts evolving dynamically under a set of heuristic rules to minimize total unit costs, respond to trade restrictions, and maintain minimum consumption [Giulioni, 2018]. In the ECOWHEATALY GEM, the buyer creation procedure is re-centered on FAOSTAT yearly balances: for each buyer, the quantity to be imported is computed as domestic demand minus domestic production, and when positive it is distributed across producers according to the producers' supply share proxy [ECOWHEATALY Research Team, 2026]. When some producers impose export bans, supply shares are rescaled over the subset of open markets so that they sum to one ("open market share rescaled") [ECOWHEATALY Research Team, 2026]. The yearly demand quantities are then converted into monthly demands by dividing by 12, with special handling of "buyer-producer" entities (areas that both produce and import). This procedure ensures that monthly market participation is coherent with annual accounting identities and that the baseline allocation reacts mechanically to market closures in a transparent manner.

2.6 Demand System Parameterization via Elasticities

CMS-Wheat uses linear demand curves whose intercepts are strategically updated by buyers over time [Giulioni, 2018]. In ECOWHEATALY, linearity is retained for transparency and aggregation convenience, but demand curves are parameterized so that demands directed to different producers share a common elasticity at the average price while allowing for very different demand scales across trading relationships. Given demand at the average price and a target elasticity, ECOWHEATALY derives the slope and intercept of each bilateral demand function analytically. This retains computational simplicity (linear aggregation implies linear aggregate demand) and ensures scale consistency across markets [ECOWHEATALY Research Team, 2026].

2.7 Market Organization and Clearing

The ECOWHEATALY GEM preserves the core logic of market clearing at the level of producer markets: each producer collects bilateral demands, aggregates them, and clears the market by equating aggregate demand to a monthly supply level. Compared to the original CMS-Wheat implementation—which organizes exchanges through explicit market sessions in Repast Simphony [Giulioni, 2018]—the ECOWHEATALY version is implemented as a modular global-market component managed by a master process (rank 0), consistent with the project's broader computational strategy. The fundamental economic mechanism remains a partial equilibrium clearing rule with endogenous prices and quantities; the main changes lie in how buyer demands are initialized from updated data and how producer availability is conditioned on recent excess production and export policy [ECOWHEATALY Research Team, 2026].

2.8 Transportation Costs: Ports, Gateways, and Land–Sea Differentiation

A major extension in ECOWHEATALY is the explicit transport layer based on centroids and representative ports. In CMS-Wheat, transportation costs are distance-based and affect buyers' effective unit costs [Giulioni, 2018]. ECOWHEATALY formalizes this component by assigning to each geographic area both a centroid and a closest maritime port, with explicit handling of landlocked regions via gateway ports [ECOWHEATALY Research Team, 2026]. Trade routes are then classified as domestic (land), land transport between neighboring areas (centroid-to-centroid), or maritime shipping (port-to-port, including gateways). Transport costs are simplified using a linear function of distance, with different unit costs for sea and land transport [ECOWHEATALY Research Team, 2026]. This structure is designed to preserve geographic realism while keeping the model computationally tractable for large-scale scenario analysis.

2.9 Summary Comparison

Table 1 summarizes the main differences between the original CMS-Wheat model and the ECOWHEATALY GEM.

Table 1: Summary of key modifications from CMS-Wheat to the ECOWHEATALY GEM.

Component	**CMS-Wheat (baseline)**	**ECOWHEATALY GEM (current)**
Data backbone	FAOSTAT-based setup as available at model development time; generic configuration-driven initialization Giulioni [2018]	Updated FAOSTAT FBS methodology for 2010–2023; revised codes/names; explicit handling of *Residuals* ECOWHEATALY Research Team [2026]
Geographic treatment	Flexible scale (countries/macro-areas); aggregation driven by application Giulioni [2018]	Italy treated as standalone entity separated from Southern Europe; tailored to Italian focus ECOWHEATALY Research Team [2026]
Export restrictions	Producer export policy flag; policy switching modeled within simulation loop Giulioni [2018]	Export bans incorporated into producer availability and share rescaling in baseline demand allocation ECOWHEATALY Research Team [2026]
Buyer demand initialization	Buyer intercepts and strategy updated heuristically to minimize unit cost and satisfy minimum consumption Giulioni [2018]	Buyer demand levels derived from FAOSTAT annual balances; mapped to monthly quantities; allocation across producers based on recent excess-production shares ECOWHEATALY Research Team [2026]
Demand system	Linear demand curves; intercepts dynamically updated by buyers Giulioni [2018]	Linear bilateral demand curves parameterized to enforce common elasticity at average price across heterogeneous flow sizes ECOWHEATALY Research Team [2026]
Market clearing	Explicit market-session clearing within Repast Simphony Giulioni [2018]	Producer-market clearing with modular global-market component managed by master rank (rank 0) ECOWHEATALY Research Team [2026]
Transport costs	Distance-based transport costs affecting effective unit costs Giulioni [2018]	Explicit centroid and port assignment; land/sea route classification; gateway ports; linear cost-by-distance with different unit costs ECOWHEATALY Research Team [2026]

3 FAOSTAT data update

The Food Balance Sheets (FBS) are a structured representation of a country's food availability, presented as an accounting of the supply and use of resources and food during a specified reference period. For each geographic area, the following balance holds:

`production + imports = food + feed + seed + processed + losses + other uses + stock variation + residual`

Recently, FAOSTAT adopted a new imputation methodology for the FBS. However, this new methodology was applied only from 2010 onward; for the preceding period, the old methodology was retained. For the Ecowheataly project, we adopted a new methodology, selecting the *Wheat and products* commodity for the period 2010 to 2023. This corresponds to the time series made available by the Statistics Division following the update on 28 October 2025.

As a consequence of adopting the new methodology, a new variable, the *Residuals*, was introduced to close the balance. Furthermore, some geographic area names and codes have been modified since the first version of the CMS-wheat model. The algorithms used to compute the quantities of each variable included in the FBS, for both sub-regions and countries, were updated accordingly. In addition, the variables for Italy were treated separately from its region, *Southern Europe*. This implementation enables us to examine the Italian wheat market in relation to global trade, the project's main objective. Nevertheless, it is worth noting that Ecowheataly focuses on **durum(hard) wheat**, whereas the *Wheat and products* commodity reported in the FAOSTAT database includes both durum(hard) and soft wheat.

4 The ECOWHEATALY GEM

4.1 Setting up the international market

The international market is managed by the master rank (rank 0). The data for producer creation are read from the `producers_fao_1993_2016.csv`, which contains the data shown in Figure 2.

Area	ISO3.Code	LAT	LON	markets	commodities	GatherMonth	Value.1993	Value.1993	Value.1994	Value.1995	Value.1996	Value.1997	Value.1998	Value.1999	Value.2000	Value.2001	Value
Northern America	CAN	57.7487	-101.56	market	wheat	8	27234492	27234492	29255619	24886059	24860420	26338670	25871814	24644277	26433866	25161492	205
South America	ARG	-35.220	-65.149	market	wheat	12	15647253	15647253	12890470	19089838	5973752	22073602	23354361	15620771	19198296	22128251	228
Central Asia	KAZ	48.1916	67.2846	market	wheat	9	13282255	13282255	11455930	13632171	13112161	15331496	14181158	15431933	17903632	16428955	195
Eastern Europe	UKR	48.9730	31.3695	market	wheat	7	38924725	38924725	47610980	49648506	40176480	41933258	46622598	45689168	36830876	44922953	520
Northern Europe	GBR	53.8833	-2.6579	market	wheat	7	21250421	21250421	22659726	22742780	24540678	26261740	25945017	24645485	26113567	24501965	240
Western Europe	FRA	46.6064	2.33908	market	wheat	8	55351080	55351080	53339308	57523201	55852899	55449635	58369545	60317586	64322220	63071893	608
Oceania	AUS	-25.560	134.376	market	wheat	12	13663249	13663249	16368409	12258868	18579051	23910255	20123862	21760478	22963836	20793340	206
Russian Federation	RUS	61.6925	99.2165	market	wheat	8	41554242	41554242	34615389	32182573	34818411	34114619	36978033	30996953	34554924	47009115	456
India	IND	22.9250	79.5937	market	wheat	3	58210100	58210100	59840000	64767400	63097400	64350200	66345000	68287504	75368896	74680896	767
Pakistan	PAK	29.9734	69.4139	market	wheat	5	15144139	15144139	16895125	15740368	16789138	17492332	18056633	17604109	20290477	20469129	205
United States of America	USA	39.5015	-99.060	market	wheat	8	67782685	67782685	64054401	64667913	64943095	57024630	62464214	61616290	62076922	56076725	530
China	CPR	36.6094	103.865	market	wheat	8	105215353	105215353	104190340	101290449	104727758	111492391	111399928	112060799	110889315	110837947	1089

Figure 2: An extract of wheat producers' time series built on the FAOSTAT database.

Correspondingly, the data for buyers are imported from the `buyers_Misc_tuned_1993_2016.csv`, an extract of which is shown in Figure 3.

Area	ISO3.Code	LAT	LON	Value.PWO.1993	Value.PWO.1994	Value.PWO.1995	Value.PWO.1996	Value.PWO.1997	Value.PWO.1998	Value.PWO.1999	Value.PWO.2000	Value.PWO.2001	Value.PW
Northern America	CAN	57.74	-101.5	9365953	7506247	8429671	7895909	7128836	6941188	8600140	6910986	7369039	7
South America	BRA	-10.80	-53.05	20338635	19476994	22955588	20012259	19861796	17996728	22100477	19565955	22548317	21
Central Asia	UZB	41.74	63.203	15214574	13401296	14452689	13053681	13049387	10575470	13620884	12662886	13977340	14
Eastern Europe	POL	52.14	19.311	46080352	44999129	47428167	38050046	39316387	35228889	40238486	34437017	40980510	38
Northern Europe	GBR	53.88	-2.657	19461694	19437298	21875610	20467235	21670565	19286503	24218693	22168636	23622604	23
Western Europe	DEU	51.13	10.288	35216960	35803439	43349514	38046933	37170789	36093679	41957333	41399116	46582459	44
Oceania	NZL	-43.98	170.51	4675813	3858022	5234511	3966403	4496666	4179980	5446601	4942590	5513867	5
Russian Federation	RUS	61.69	99.216	50181291	35449319	37575293	36287649	35442551	31666225	36053466	33822785	46002568	33
India	IND	22.92	79.593	61076249	58192698	68974287	58786511	63109303	57926281	71885701	68278772	71317321	67
Pakistan	PAK	29.97	69.413	18841703	18300737	19991812	17849910	19167968	17485426	21501966	19575590	19684175	18
United States of America	USA	39.50	-99.06	34137413	34003566	35405381	33229431	31908852	31652890	35754397	32870797	31962785	27
China	CPR	36.60	103.86	117449173	109491274	123446054	108033544	109334763	96855023	117368556	103974552	111526533	102
Eastern Africa	ETH	8.653	39.551	1492654	1968811	1570615	1648421	1440219	1753631	2016932	2577648	2714862	2
Middle Africa	AGO	-12.29	17.502	573931	598637	575947	466265	649669	651913	875054	886789	928173	1
Northern Africa	EGY	26.50	29.844	13129143	14234802	16003801	11891388	14640451	11635454	13382069	14668326	14342845	16
Southern Africa	ZAF	-28.96	25.117	1328743	868087	1129747	1157020	436987	544207	626554	728116	38990	
Western Africa	NGA	9.548	7.9951	2599411	1943506	2193942	2054642	2483913	3092230	3282442	3585865	3815389	4
Central America	MEX	23.93	-102.5	4562217	4196348	3594410	4404015	4132848	4750222	5721251	5037732	6239492	5
Eastern Asia	JPN	36.01	136.88	11562567	12084683	9039903	8269338	9534055	9120814	10825449	9174652	9955253	9
Southern Asia	IRN	32.51	54.285	4782365	3815035	6112036	5868316	7870075	4692887	9938394	9257162	10792513	7
South-Eastern Asia	IDN	-0.254	114.02	6665633	7365897	9080012	7742764	7737641	6396964	8044666	8669715	8736678	10
Western Asia	IRQ	33.03	43.756	2352510	9012	1579599	3594366	6738469	5547938	6687349	6514642	4634368	5
Southern Europe	ITA	43.47	12.219	4267422	3704527	6566100	5837751	8330120	7686618	8552259	6997477	9991698	11

Figure 3: An extract of wheat buyers' time series built on the FAOSTAT database.

From the data in Figures 2 and 3, an international producer summary is computed to quantify each buyer's demand for each producer. The summary reports, in particular, the characteristics of excess production, that is, the difference between production and domestic demand. This information is collected in the table in Figure 4, where the meaning of the columns is as follows:

- `latest` is the latest recorded excess production
- `nexcesses` is the number of positive production excesses in the latest three years
- `mean` is the mean of the last three production excesses
- `cv` is the coefficient of variation, i.e., the standard deviation divided by the mean
- `mean_gt_0` is the same as mean, but the negative values are replaced with 0. This column serves to compute the next column
- `share` is given by `mean\_gt\_0/sum(mean\_gt\_0)`. It is intended to serve as a proxy for the share of the total available quantity supplied by producers on international markets.
- `Export` informs on export bans. When `False`, it means that an export ban is imposed by the producer.

	Area	latest	nexcesses	mean	cv	mean_gt_0	share	export
0	Northern America	22477104	3	19059813	0.28323777363398056	19059813	0.11736213754386345	True
1	South America	-9325003	1	-4072275	-1.5669722698000503	0	0.0	True
2	Central Asia	6887438	3	6843215	0.039676087920663024	6843215	0.042137577114331054	True
3	Eastern Europe	28926274	3	31514042	0.07113752656672857	31514042	0.19404992755002842	True
4	Northern Europe	-1128826	2	6474629	1.0386385073183344	6474629	0.039867982925303996	False
5	Western Europe	-287125	2	18203696	0.9251291056497538	18203696	0.11209053697214537	False
6	Oceania	13521897	3	15865360	0.12864504807958974	15865360	0.0976920687785819	True
7	Russian Federation	34304021	3	27008304	0.23889474881503112	27008304	0.1663055292764140 7	True
8	India	3816382	3	5232665	1.0010006373425395	5232665	0.0322205023444333	True
9	Pakistan	406308	3	1350852	0.7357512147888888	1350852	0.008317966090506923	True
10	United States of America	31372299	3	28864316	0.09444748318304165	28864316	0.1777340535555904	True
11	China	-6137455	2	1984828	4.533767661479987	1984828	0.01222171784880111	True

Figure 4: An extract of wheat buyers' time series built on the FAOSTAT database.

4.2 Buyers creation

Buyers' creation consists mainly of computing the demand directed to each producer. The initial idea for achieving this goal is as follows. We construct, for each producer, a demand schedule characterized by two parameters. The first one is the demand at the average price. The second is the price elasticity of demand. Because the price elasticity is treated as a parameter, we focus on the demand at the average price.

To establish the level of demand at the average price, the `quantity_to_be_imported` (i.e., the domestic demand minus the production) is computed. When this figure is positive, it is allocated among producers according to the share specified in the international producers summary. If some producers ban exports, the shares are rescaled to sum to 1. The corresponding variable is named `open market share rescaled`.

This idea needs some refinements because: *i)* the demand in the FAOSTAT database is yearly, while the model is organized at the monthly scale; *ii)* a buyer can also be a producer or not. If the buyer is also a producer, we have two possibilities:

1. the domestic demand is lower than production (`quantity_to_be_imported` < 0), the local demand is equal to the monthly demand, and the demand for all the foreign wheat markets is equal to 0
2. in the opposite case, the local demand is equal to the production (divided by 12), and the demand for all the foreign markets is equal to the quantity to be imported divided by 12 and multiplied by the `open market share rescaled`.

The tables in Figure 5 represent the outcome of the process for the three exemplifying cases:

a) A geographic area having production higher than the internal demand (the USA)

b) A geographic area having production lower than the internal demand (China)

c) A geographic area having no production or a production negligible compared to its demand (Northern Africa).

From the tables in Figure 5, it emerges that:

area	intercept	slope
Northern America	0.0	0.0
South America	488589.0	-3257.26
Central Asia	0.0	0.0
Eastern Europe	0.0	0.0
Northern Europe	59145.0	-394.3
Western Europe	15045.0	-100.3
Oceania	0.0	0.0
Russian Federation	0.0	0.0
India	0.0	0.0
Pakistan	0.0	0.0
United States of America	9278052.0	-61853.68
China	321576.0	-2143.84
Eastern Africa	347628.0	-2317.52
Middle Africa	110286.0	-735.24
Northern Africa	1745394.0	-11635.96
Southern Africa	93009.0	-620.06
Western Africa	434118.0	-2894.12
Central America	351135.0	-2340.9
Eastern Asia	618483.0	-4123.22
Southern Asia	466251.0	-3108.34
South-Eastern Asia	925641.0	-6170.94
Western Asia	731034.0	-4873.56
Southern Europe	216099.0	-1440.66

(a)

Area	export	domestic	open market share	open market share rescaled	demand at average price	higher demand	demand elasticity
Northern America	True	False	0.11736213754386345	0.13839197763023486	70781.0	77859.0	0.5
South America	True	False	0.0	0.0	0.0	5115.0	0.5
Central Asia	True	False	0.042137577114331054	0.04968810854539274	25413.0	27955.0	0.5
Eastern Europe	True	False	0.19404992755002842	0.22882126889189744	117032.0	128735.0	0.5
Northern Europe	False	False	0.0	0.0	0.0	0.0	0.5
Western Europe	False	False	0.0	0.0	0.0	0.0	0.5
Oceania	True	False	0.0976920687785819	0.11519727639592386	58918.0	64810.0	0.5
Russian Federation	True	False	0.16630552927641407	0.19610541840041046	100299.0	110329.0	0.5
India	True	False	0.0322205023444333	0.03799401692065462	19432.0	21375.0	0.5
Pakistan	True	False	0.008317966090506923	0.009808442494465082	5017.0	5518.0	0.5
United States of America	True	False	0.1777340535555904	0.20958179254875323	107192.0	117911.0	0.5
China	True	True	0.01222171784880111	0.014411698172267682	11169841.0	12286825.0	0.5

(b)

Area	export	domestic	open market share	open market share rescaled	demand at average price	higher demand	demand elasticity
Northern America	True	False	0.11736213754386345	0.13839197763023486	384176.0	422593.0	0.5
South America	True	False	0.0	0.0	0.0	27760.0	0.5
Central Asia	True	False	0.042137577114331054	0.04968810854539274	137934.0	151727.0	0.5
Eastern Europe	True	False	0.19404992755002842	0.22882126889189744	635207.0	698728.0	0.5
Northern Europe	False	False	0.0	0.0	0.0	0.0	0.5
Western Europe	False	False	0.0	0.0	0.0	0.0	0.5
Oceania	True	False	0.0976920687785819	0.11519727639592386	319787.0	351766.0	0.5
Russian Federation	True	False	0.16630552927641407	0.19610541840041046	544388.0	598827.0	0.5
India	True	False	0.0322205023444333	0.03799401692065462	105471.0	116018.0	0.5
Pakistan	True	False	0.008317966090506923	0.009808442494465082	27228.0	29951.0	0.5
United States of America	True	False	0.1777340535555904	0.20958179254875323	581798.0	639978.0	0.5
China	True	False	0.01222171784880111	0.014411698172267682	40007.0	44008.0	0.5

(c)

Figure 5: An example of buyers' process creation: a) US, production higher than the internal demand; b) China, production lower than the internal demand; and c) Northern Africa, no production.

- Buyers do not formulate demands for areas subject to export bans: rows with False in the export column have all zeros.
- Buyers with a production higher than domestic demand have zero demand at the average price in all international markets (see the US table). This means they are willing to buy abroad only at lower prices.
- Buyers having a production set the domestic demand according to the rules described above. This is done when `True` is found in the domestic column. Note that in the Northern Africa table, the "domestic" column is `False`.
- Buyers do not demand that producers have high domestic demand. They are not confident in their ability to find resources there. See the demands towards South America.

We did not supply an explanation for the last three columns of the tables. The following aims to accomplish this task. We assume that demand curves are linear. Because demand directed to various producers can vary greatly in magnitude, we begin with the concept of elasticity. In particular, we require that all demands have the same elasticity when lowering the price from the average price. Denote p_a the average price, and p_l a price lower than the average. Moreover, d_a denotes the demand at the average price and d_l the demand when the price is p_l. Note that while $p_a > p_l$, $d_a < d_l$. We define *elasticity* η as the ratio between the price and the percentage change in quantity:

$$\eta = \frac{-\frac{p_l - p_a}{p_a}}{\frac{d_l - d_a}{d_a}}$$

The minus sign in the numerator ensures that the entire ratio is positive. First, we solve by p_l as follows:

$$-\eta \frac{d_l - d_a}{d_a} = \frac{p_l - p_a}{p_a}$$

$$-\eta \frac{d_l - d_a}{d_a} = \frac{p_l}{p_a} - 1$$

$$\left(-\eta \frac{d_l - d_a}{d_a}\right) + 1 = \frac{p_l}{p_a}$$

$$p_l = p_a \left(1 - \eta \frac{d_l - d_a}{d_a}\right)$$

Then, we compute the slope and the intercept of the demand function. The slope is:

$$b = \frac{d_a - d_l}{p_a - p_l}$$

while the intercept is

$$\bar{d} = d_a + b p_a$$

Therefore, the demand function becomes:

$$d = \bar{d} - bp$$

Let us clarify the use of this algebra with a numerical example. Suppose a country wants to meet a demand of 10,000 units at the average price for a larger producer and a demand of 1,000 units at the average price for a smaller producer. Suppose, furthermore, that the country has $\eta = 0.5$ and $p_a = 100$. We must choose a percentage increase in demand, for example, 10% (any other value yields the same demand function). The computation of p_l is the same in both cases:

$$p_l = p_a \left(1 - \eta \frac{d_l - d_a}{d_a}\right) = 100(1 - 0.5 \times 0.1) = 100 \times 0.95 = 95$$

In the case of the larger producer, the slope is:

$$b = \frac{1000}{100 - 95} = \frac{1000}{5} = 200$$

In the case of the smaller producer, the slope is:

$$b = \frac{100}{100 - 95} = \frac{100}{5} = 20$$

The intercepts are:

$$\bar{d} = 10000 + 200 \times 100 = 30000$$

and

$$\bar{d} = 1000 + 20 \times 100 = 3000$$

Therefore, the demand function for the large producer is

$$d = 30000 - 200p$$

while that for the smaller producer is

$$d = 3000 - 20p$$

We can now understand the last three columns of the tables: `demand at average price` is d_a, `higher demand` is p_l, and `elasticity` is η. Using these variables, together with the average price p_a, we can recover the parametric demand function.

4.3 Producers markets

Producers organize markets and collect the demand directed to them. The market opens each month. As an example, the tables in Figure 6 show: (a) the demands received by the United States from the various buyers; (b) the aggregate demand directed to the US at several different prices; and (c) the quantities sold to each demanding country at the equilibrium price.

area	intercept	slope
Northern America	0.0	0.0
South America	488589.0	-3257.26
Central Asia	0.0	0.0
Eastern Europe	0.0	0.0
Northern Europe	59145.0	-394.3
Western Europe	15045.0	-100.3
Oceania	0.0	0.0
Russian Federation	0.0	0.0
India	0.0	0.0
Pakistan	0.0	0.0
United States of America	9278052.0	-61853.68
China	321576.0	-2143.84
Eastern Africa	347628.0	-2317.52
Middle Africa	110286.0	-735.24
Northern Africa	1745394.0	-11635.96
Southern Africa	93009.0	-620.06
Western Africa	434118.0	-2894.12
Central America	351135.0	-2340.9
Eastern Asia	618483.0	-4123.22
Southern Asia	466251.0	-3108.34
South-Eastern Asia	925641.0	-6170.94
Western Asia	731034.0	-4873.56
Southern Europe	216099.0	-1440.66

(a)

	quantity
50	10800990
60	9720891
70	8640793
80	7560692
90	6480594
100	5400495
110	4320396
120	3240298
130	2160197
140	1080099
150	0

(b)

area	quantity
Northern America	0
South America	172107
Central Asia	0
Eastern Europe	0
Northern Europe	20834
Western Europe	5300
Oceania	0
Russian Federation	0
India	0
Pakistan	0
United States of America	3268225
China	113276
Eastern Africa	122453
Middle Africa	38849
Northern Africa	614821
Southern Africa	32763
Western Africa	152920
Central America	123688
Eastern Asia	217863
Southern Asia	164238
South-Eastern Asia	326060
Western Asia	257509
Southern Europe	76122

(c)

Figure 6: Example of market organization by a main wheat producer worldwide: a) demands received by the United States from the various buyers, b) aggregate demand function for the US, c) quantities sold to each demanding country.

More specifically, the individual demands are aggregated to compute the US aggregate demand function. Since aggregate demand is the sum of linear functions, it is linear. Given the US monthly supply (5,707,045 tons), it is then possible to compute the equilibrium price (in this case, 97.162 \$).

Once the equilibrium price is determined, the quantities sold to each demanding country can be derived. Subsequently, buyers can aggregate the quantities purchased across markets at their corresponding prices. They can also determine their total expenditure and adjust their demand strategies accordingly.

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4.4 Transportation costs

The international transport of grains is typically conducted by ship. However, we assume that land transport between two nearby areas is more convenient.

First, we identify the centroids and the nearest port for each geographical area (subregion or country). We then use the distance between centroids to compute land transportation costs, and the sea route length between the corresponding ports to compute maritime shipping costs. The centroids and ports of each production area are reported in Table 2, and the centroids and ports of each buying area are reported in Table 3.

Table 2: The centroids and ports of each wheat production sub-region or country.

Area	ISO3	lat	lon	port name	port lat	port lon	inland km
Northern America	CAN	57.75	-101.57	Vancouver	49.28	-123.12	1696
South America	ARG	-35.22	-65.15	Buenos Aires	-34.60	-58.38	621
Central Asia	KAZ	48.19	67.28	Novorossiysk	44.72	37.77	2279
Eastern Europe	UKR	48.97	31.37	Odesa	46.48	30.73	281
Northern Europe	GBR	53.88	-2.66	Felixstowe	51.95	1.31	342
Western Europe	FRA	46.61	2.34	Rouen	49.44	1.09	328
Oceania	AUS	-25.56	134.38	Port Adelaide	-34.93	138.60	1118
Russian Federation	RUS	61.69	99.22	Novorossiysk	44.72	37.77	4302
India	IND	22.93	79.59	Mumbai	18.95	72.84	829
Pakistan	PAK	29.97	69.41	Karachi	24.86	67.01	616
United States of America	USA	39.50	-99.06	New Orleans	29.95	-90.07	1341
Italy	ITA	43.47	12.22	Genoa	44.41	8.93	283

Table 3: The centroids and ports of each wheat production sub-region or country.

Area	ISO3	lat	lon	port name	port lat	port lon	inland km
Northern America	CAN	57.75	-101.57	Vancouver	49.28	-123.12	1696
South America	BRA	-10.81	-53.05	Santos	-23.96	-46.33	1626
Central Asia	UZB	41.75	63.20	Karachi (gateway)	24.86	67.01	1910
Eastern Europe	POL	52.15	19.31	Gdansk	54.35	18.65	249
Northern Europe	GBR	53.88	-2.66	Felixstowe	51.95	1.31	342
Western Europe	NLD	52.30	5.51	Rotterdam	51.95	4.14	101
Oceania	AUS	-25.56	134.38	Port Adelaide	-34.93	138.60	1118
Russian Federation	RUS	61.69	99.22	Novorossiysk	44.72	37.77	4302
India	IND	22.93	79.59	Mumbai	18.95	72.84	829
Pakistan	PAK	29.97	69.41	Karachi	24.86	67.01	616
United States of America	USA	39.50	-99.06	New Orleans	29.95	-90.07	1341
Italy	ITA	43.47	12.22	Genoa	44.41	8.93	283
Eastern Africa	KEN	0.60	37.79	Mombasa	-4.05	39.67	557
Middle Africa	AGO	-12.29	17.50	Luanda	-8.84	13.23	604
Northern Africa	EGY	26.51	29.84	Alexandria	31.20	29.92	522
Southern Africa	ZAF	-28.96	25.12	Durban	-29.87	31.05	583
Western Africa	NGA	9.55	8.00	Lagos	6.45	3.40	612
Central America	MEX	23.94	-102.58	Veracruz	19.20	-96.14	848
Eastern Asia	KOR	36.43	127.82	Busan	35.10	129.04	184
Southern Asia	BGD	23.84	90.27	Chattogram	22.33	91.80	230
South-eastern Asia	IDN	-0.25	114.02	Jakarta	-6.10	106.88	1025
Western Asia	TUR	38.99	35.39	Mersin	36.80	34.63	253
Southern Europe	ESP	40.35	-3.62	Valencia	39.45	-0.32	298
China	CHN	36.61	103.87	Shanghai	31.23	121.47	1728

On the other hand, an example involving Central America and Central Asia, as well as Italy and the US, for exchanges between producers and buyers is reported in Table 4 and Table 5, respectively. These tables have three types of entries:

- two port names for transport by sea. If the source or destination is landlocked, the gateway qualifier is added.

- two centroids ISO3 codes for transport by land
- or the word domestic if the ISO3 codes of the source and destination are the same. Even in this case, the transport is by land

Table 4: Global wheat trade: source-destination ports for Central America and Central Asia.

producer_area	Central America	Central Asia
Central Asia	Novorossiysk (gateway) → Veracruz	KAZ (Kazakhstan) → UZB (Uzbekistan)
Eastern Europe	Odesa → Veracruz	Odesa → Karachi (gateway)
India	Mumbai → Veracruz	Mumbai → Karachi (gateway)
Italy	Genoa → Veracruz	Genoa → Karachi (gateway)
Northern America	Vancouver → Veracruz	Vancouver → Karachi (gateway)
Northern Europe	Felixstowe → Veracruz	Felixstowe → Karachi (gateway)
Oceania	Port Adelaide → Veracruz	Port Adelaide → Karachi (gateway)
Pakistan	Karachi → Veracruz	Karachi → Karachi (gateway)
Russian Federation	Novorossiysk → Veracruz	Novorossiysk → Karachi (gateway)
South America	Buenos Aires → Veracruz	Buenos Aires → Karachi (gateway)
United States of America	USA → MEX (Mexico)	New Orleans → Karachi (gateway)
Western Europe	Rouen → Veracruz	Rouen → Karachi (gateway)

Table 5: TGlobal wheat trade: source-destination ports for Italy and the US.

producer_area	Italy	United States of America
Central Asia	Novorossiysk → Genoa	Novorossiysk (gateway) → New Orleans
Eastern Europe	Odesa → Genoa	Odesa → New Orleans
India	Mumbai → Genoa	Mumbai → New Orleans
Italy	Domestic	Genoa → New Orleans
Northern America	Vancouver → Genoa	CAN (Canada) → USA
Northern Europe	Felixstowe → Genoa	Felixstowe → New Orleans
Oceania	Port Adelaide → Genoa	Port Adelaide → New Orleans
Pakistan	Karachi → Genoa	Karachi → New Orleans
Russian Federation	Novorossiysk → Genoa	Novorossiysk → New Orleans
South America	Buenos Aires → Genoa	Buenos Aires → New Orleans
United States of America	New Orleans → Genoa	Domestic
Western Europe	Rouen → Genoa	Rouen → New Orleans

In addition, the previous tables' contents are visualized in the map of Figure 7.

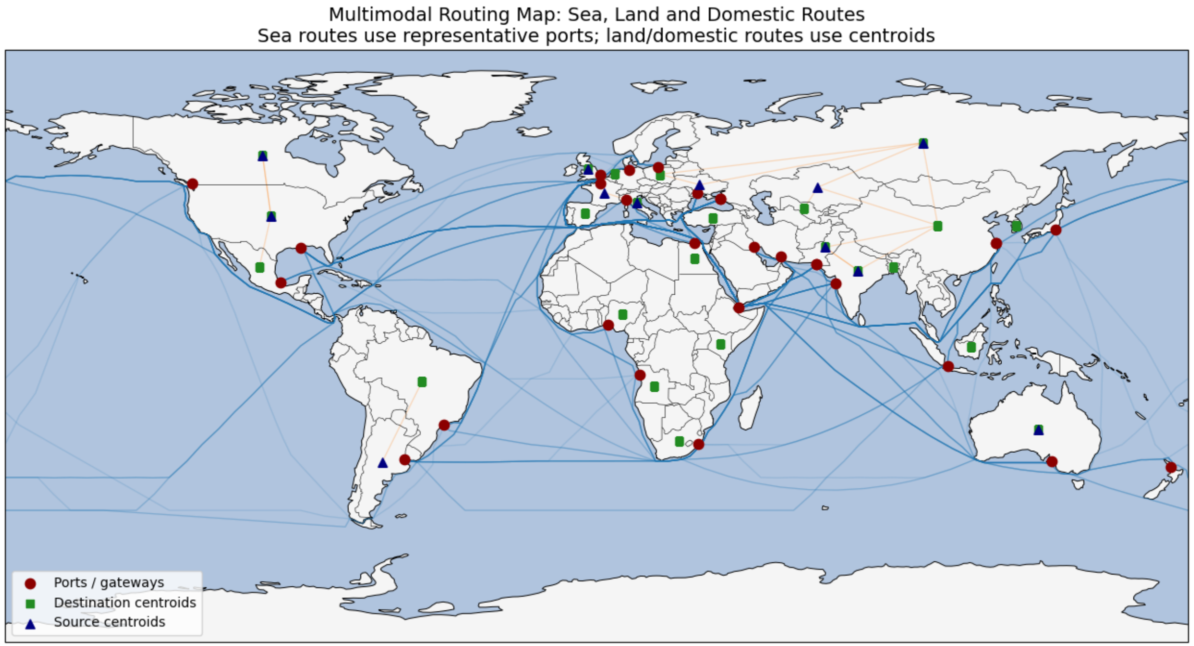

Figure 7: Map of the source-destination routes for exchanges between each producer and each buyer of wheat.

Deuss et al. [2022] and Korinek and Sourdin [2009] provide data on grain transport costs. For simplicity, we assume a linear relationship between transportation costs and distance:

$$\text{Cost} = v \times d$$

where v is the unit cost per ton and d is the distance in kilometers between the source and the destination. According to the literature, v is approximately 0.001 for sea routes, whereas it is higher for land routes, at around 0.05.

4.5 Buyer-side dynamic reallocation of demand across producers

At each simulation step, each buyer b observes the equilibrium outcomes in the set of international producer markets and updates its buying strategy by reallocating a fraction of its planned monthly demand from relatively expensive suppliers to relatively cheap suppliers. The procedure is implemented as a deterministic adjustment of the buyer's bilateral demand targets, using delivered (i.e., transport-inclusive) prices as the ranking criterion.

Observed prices and quantities. Let $\mathcal{P}$ denote the set of international producers. For each producer $p \in \mathcal{P}$, buyer b observes the equilibrium market price p_p^* and the exchanged quantity q_{bp} obtained in the producer market. The buyer also computes the delivered price

$$\tilde{p}_{bp} \;=\; p_p^* \;+\; \tau_{bp}, \tag{5}$$

where τ_{bp} is the transport cost from producer p to buyer b. Producers are then ranked in increasing order of delivered prices $\tilde{p}_{bp}$.

Baseline monthly demand targets. The buyer maintains a vector of bilateral monthly demand targets $\{D_{bp}\}_{p\in\mathcal{P}}$, which the model stores as the variable `demand at average price`. The buyer's total planned monthly demand is

$$D_b \;=\; \sum_{p\in\mathcal{P}} D_{bp}. \tag{6}$$

Price dispersion and fraction of demand to reallocate. The model measures cross-supplier price dispersion through the delivered price range:

$$R_b \;=\; \max_{p\in\mathcal{P}} \tilde{p}_{bp} \;-\; \min_{p\in\mathcal{P}} \tilde{p}_{bp}. \tag{7}$$

The share of demand to be reallocated is an increasing logistic function of R_b:

$$\alpha_b(R_b) \;=\; \frac{0.05}{1 + \exp[-0.748\,(R_b - 8.0)]}. \tag{8}$$

The corresponding quantity to be moved is

$$\Delta_b \;=\; \text{round}(\alpha_b(R_b)\, D_b)\,. \tag{9}$$

Hence, when delivered prices across producers are similar (R_b small), α_b is close to zero and reallocation is negligible; when price dispersion increases, the buyer shifts a larger fraction of planned demand toward cheaper sources.

Reallocation toward cheaper producers. Let $(p_{(1)}, p_{(2)}, \dots)$ denote producers sorted by increasing delivered price $\tilde{p}_{bp}$. Starting from the cheapest producers, the algorithm increases bilateral targets until the cumulative increase reaches Δ_b. For producer $p_{(k)}$, define an incremental addition

$$\delta^{+}_{bp_{(k)}} = \begin{cases} \text{round}\big(0.1\, D_{bp_{(k)}}\big), & \text{if } D_{bp_{(k)}} > 0, \\ \text{round}\big(0.01\, S_{p_{(k)}}\big), & \text{if } D_{bp_{(k)}} = 0, \end{cases} \tag{10}$$

where S_p denotes the producer's monthly supply (stored as `monthly_supply`). The buyer updates

$$D_{bp_{(k)}} \leftarrow D_{bp_{(k)}} + \delta^{+}_{bp_{(k)}} \tag{11}$$

iterating over $k = 1, 2, \dots$ until the cumulative added quantity reaches Δ_b. If the last increment overshoots the target, it is corrected by subtracting the excess so that the total added quantity equals exactly Δ_b.

Reduction from expensive producers. After the upward adjustments, producers are sorted in descending order of delivered price (most expensive first). The algorithm reduces bilateral targets until the cumulative reduction reaches Δ_b. For producer $p_{(k)}$ in this expensive-first ranking, the decrement is

$$\delta^{-}_{bp_{(k)}} = \begin{cases} \text{round}\big(1.0\, D_{bp_{(k)}}\big), & \text{if } D_{bp_{(k)}} > 0, \\ 0, & \text{if } D_{bp_{(k)}} = 0, \end{cases} \tag{12}$$

so that, whenever positive, the algorithm attempts to remove the full planned quantity from the most expensive producers first. Bilateral targets are updated as

$$D_{bp_{(k)}} \leftarrow D_{bp_{(k)}} - \delta^{-}_{bp_{(k)}} \tag{13}$$

until the cumulative reduction reaches Δ_b, with an analogous correction in the last step to match exactly Δ_b. This ensures the reallocation is quantity-preserving at the buyer level:

$$\sum_{p \in \mathcal{P}} D_{bp} \quad \text{remains equal to} \quad D_b. \tag{14}$$

Updating auxiliary demand levels. Finally, the buyer updates an auxiliary "higher demand" level used elsewhere in the model as

$$D^{H}_{bp} = \text{round}(1.1\, D_{bp}), \tag{15}$$

and sets $D_{bp} = D^{H}_{bp} = 0$ for producers for which the update would be degenerate under the rounding rule used in the implementation.[1]

The pseudo code of the just described buyers demand reallocation process is reported in algorithm 1 and 1.

[1] In the code, the condition `tmp_new_dem == round(tmp_new_dem*1.1)` is used as a guard to prevent unstable updates driven purely by integer rounding at very small quantities.

Interpretation. This mechanism implements a cost-minimization heuristic consistent with trade diversion: when delivered price dispersion across producers is large, the buyer reallocates a larger fraction of its planned demand from high-cost to low-cost sources. Because the rule is based on delivered prices $\tilde{p}_{bp}$, geographic frictions directly shape reallocation patterns. At the same time, the quantity-preserving design ensures that the buyer's total planned monthly demand remains fixed, so that the rule governs the *composition* of imports rather than the aggregate scale of consumption.

Algorithm 1: Dynamic reallocation of buyer demand across producers (delivered-price rule)

Input: Buyer b; set of producers $\mathcal{P}$; current demand targets $\{D_{bp}\}_{p\in\mathcal{P}}$ (`demand at average price`); monthly supplies $\{S_p\}_{p\in\mathcal{P}}$ (`monthly_supply`); transport costs $\{\tau_{bp}\}_{p\in\mathcal{P}}$; observed equilibrium prices $\{p_p^*\}_{p\in\mathcal{P}}$.
Output: Updated demand targets $\{D_{bp}\}_{p\in\mathcal{P}}$ and auxiliary levels $\{D_{bp}^H\}_{p\in\mathcal{P}}$ (`higher demand`).

Collect delivered prices and exchanged quantities.
foreach $p \in \mathcal{P}$ **do**
  $\tilde{p}_{bp} \leftarrow p_p^* + \tau_{bp}$ `// price_plus_transport`
  Observe q_{bp} from market clearing `// exchanged_quantities`

Compute price dispersion and the quantity to reallocate.
$D_b \leftarrow \sum_{p\in\mathcal{P}} D_{bp}$ `// Total planned monthly demand`
$R_b \leftarrow \max_{p\in\mathcal{P}} \tilde{p}_{bp} - \min_{p\in\mathcal{P}} \tilde{p}_{bp}$
$\alpha_b \leftarrow \dfrac{0.05}{1+\exp[-0.748\,(R_b - 8.0)]}$
$\Delta_b \leftarrow \mathrm{round}(\alpha_b\, D_b)$ `// Quantity to move`
if $\Delta_b = 0$ **then**
  foreach $p \in \mathcal{P}$ **do**
    $D_{bp}^H \leftarrow \mathrm{round}(1.1\, D_{bp})$
  return

(continues in Algorithm 2)

5 Implications of the Modifications for Scenario and Shock Analysis

The structural modifications introduced in the ECOWHEATALY GEM have important implications for the design, interpretation, and robustness of scenario and shock analysis at the global level.

First, the adoption of the revised FAOSTAT Food Balance Sheets methodology over 2010–2023 ensures that baseline simulations are constructed on a harmonized and internally consistent accounting framework. By incorporating the updated *Residuals* component and revised geographic coding, the model avoids structural breaks and measurement inconsistencies that could otherwise distort counterfactual comparisons. This is particularly relevant when simulating medium-term policy transitions or evaluating shock persistence over multiple years, as it guarantees that deviations from baseline trajectories are attributable to modeled interventions rather than to inconsistencies in underlying data definitions.

Second, the explicit treatment of Italy as an autonomous geographic entity enhances the model's ability to assess country-specific exposure to global disturbances. In the previous CMS-Wheat configuration, Italy's behavior was embedded within a macro-area, limiting the granularity of national-level impact analysis. In the ECOWHEATALY GEM, Italy's production, demand, and trade balances are represented explicitly within the global market environment. This allows shock transmission mechanisms—such as export bans, supply contractions in major exporting regions, or transport disruptions—to be traced directly to their effects on Italian market outcomes while preserving the global price formation mechanism.

Third, the revised procedure for constructing international producers' summaries and for allocating buyer demand improves the transparency of market participation under stress scenarios. Because supply availability is now explicitly linked to recent excess production and export policy indicators, global supply contractions can be simulated in a data-driven and reproducible manner. Similarly, the rescaling of open-market supply shares under export bans provides a clear mechanical representation of trade diversion effects, ensuring that global reallocation patterns emerge consistently when some markets close.

Fourth, the parameterization of bilateral demand curves through common elasticities at the average price enhances the coherence of comparative statics across heterogeneous trade relationships. This design ensures that large and small trading flows respond proportionally to price changes while maintaining computational tractability. As a result, simulated price shocks propagate through the system in a controlled and analytically interpretable manner, facilitating sensitivity analysis and elasticity-based robustness checks.

Fifth, the refined transport module—based on explicit centroids, representative ports, gateway ports for landlocked regions, and differentiated land/sea cost coefficients—improves the realism of spatial shock transmission. In scenarios involving logistical disruptions, trade frictions, or energy-price-driven transport cost increases, the model can represent heterogeneous geographic exposure. This allows the evaluation of how distance-based trade costs interact with export restrictions and supply contractions in shaping equilibrium price adjustments and trade reallocation.

Finally, the building of the model in Python and its modular architecture enhances computational reproducibility and scalability for systematic experimentation. Scenario analysis in ECOWHEATALY is designed to involve repeated simulations under alternative policy regimes and exogenous shocks. The current architecture facilitates batch execution, structured sensitivity analysis, and the comparison of tranquil and crisis regimes under a unified computational environment.

Overall, the modifications introduced in the ECOWHEATALY GEM strengthen the model's capacity to perform structured scenario analysis, to simulate global supply and policy shocks in a transparent manner, and to provide a consistent global price environment within which country-specific outcomes can be evaluated.

6 Conclusions

This report presented the work carried out in Task 2.1 of the ECOWHEATALY project, which focused on the adaptation of the Global Economic Model used to simulate the dynamics of the international wheat market. The objective of this task was to prepare a modelling framework capable of linking global market dynamics with the farm-level and environmental components developed in the earlier stages of the project.

The model builds upon the CMS-Wheat model previously developed by members of the research team. This agent-based computational model represents the global wheat system as a network of interacting countries that simultaneously act as producers, consumers, and traders of wheat. By simulating market interactions across multiple regions and incorporating transportation costs between geographically located agents, the model is able to reproduce the spatial structure of international wheat trade.

The adaptation carried out in this task allows the model to be connected with the empirical data infrastructure developed within the ECOWHEATALY project. In particular, the model is designed to incorporate detailed information on wheat production practices derived from the RICA-based database described in Task 1.1. Moreover, the model structure is compatible with the environmental impact indicators produced by the Life Cycle Assessment framework developed in Task 1.2.

This integration between global market dynamics, farm-level production behaviour and environmental assessment represents a key methodological advancement of the project. It creates the conditions for analysing how changes in agricultural policies, market conditions or environmental constraints may affect both economic outcomes and environmental impacts within the wheat production system.

The modelling framework developed in Task 2.1 will be employed in the subsequent phases of the ECOWHEATALY project to simulate alternative policy scenarios and to evaluate their potential effects on wheat production, international trade, and environmental sustainability.

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Appendix

A International Producer Agent: Implementation Notes

This appendix documents the implementation of the `InternationalProducer` agent, which represents a geographic wheat-producing area participating in monthly international market sessions. Each producer is characterized by an annual harvest schedule, an annual production level, an evolving inventory stock, and a local market-clearing routine that determines a monthly equilibrium export price given demand schedules received from international buyers.

A.1 Agent role and state variables

The `InternationalProducer` agent (agent `TYPE = 3`) is instantiated from a parameter row `my_params` containing geographic and production descriptors. The main state variables are:

- **Geographic identifiers:** `area_name`, `latitude`, `longitude`. These fields label the market and support distance-based transport cost computations in other modules.
- **Harvest timing:** `gatherMonth` $\in \{1, \ldots, 12\}$ specifies the harvest month for the producer area.
- **Annual production:** `production` (e.g., FAOSTAT-based annual production in the initialization dataset).
- **Inventory stock:** `stock` evolves monthly and is initialized as a fraction of annual production proportional to the months elapsed since the last harvest. This ensures the producer begins the simulation with a strictly positive export capacity even before the first harvest event.
- **Domestic demand and exportable supply:** `domestic_demand` and `supply` are assigned at initialization by matching producers and buyers within the same area, thereby setting the initial export surplus.
- **Demand aggregation grid:** `aggregate_demand` is a discrete price grid centered on an `initial_price`, with step size `pstep` and a symmetric number of steps. This grid is used to compute an aggregate demand schedule and locate a clearing price.
- **Market outcomes:** `equilibrium\_price`, `sold\_quantity`, and `exchanged\_quantities` store the monthly equilibrium price and the resulting bilateral allocations to buyers.

A.2 Inventory logic and harvest event

The producer's monthly export capacity is derived from the current inventory level and the remaining months until the next harvest. At simulation month t (mapped into $\{1, \ldots, 12\}$), the algorithm computes:

1. the number of months left until harvest, `months_left`;

2. monthly exportable supply as an inventory-smoothing rule:

$$Q_{a,t}^{supply} \approx \text{round}\left(\frac{S_{a,t}}{\texttt{months\_left}}\right),$$

which ensures that stock is released gradually rather than immediately.

A harvest event is triggered when the current month equals `gatherMonth`. For non-Italian producer areas, harvest increases inventory by the annual production level:

$$S_{a,t}^{+} = S_{a,t}^{-} + Y_a.$$

The Italian harvest is handled by the Italian module and integration layer; therefore the producer's internal harvest routine excludes Italy.

A.3 Monthly market session and equilibrium price computation

Each month, the producer executes a market session that determines its equilibrium export price and allocates traded quantities to buyers.

Buyer demand queries and reconstruction of linear demand. The producer queries each international buyer for demand information specific to this producer area through a demand-query interface. For each buyer b, the producer receives quantities such as demand at a reference (average) price and a higher-demand quantity, together with a demand elasticity parameter. Using these values, the producer reconstructs a buyer-specific *linear inverse demand schedule* in direct form:

$$D_b(p) = \alpha_b + \beta_b p,$$

where (α_b, β_b) are computed to match the reported quantities at the reference price and at a lower implied price derived from the elasticity parameter. If the buyer reports non-positive quantities, the buyer's demand is treated as zero for that session.

Aggregate demand schedule. After reconstructing buyer-specific linear demand functions, the producer aggregates demands over all buyers on a discrete price grid:

$$D(p) = \sum_b \max\{0,\, \alpha_b + \beta_b p\}.$$

This yields the producer's `aggregate_demand` schedule.

Market clearing on a discrete price grid. Given the monthly supply $Q_{a,t}^{supply}$, the producer locates the interval on the price grid where aggregate demand crosses supply. The code computes an approximate clearing price through interpolation between adjacent grid points:

$$p_{a,t}^{*} \approx \text{interp}\Big(D(p),\, Q_{a,t}^{supply}\Big),$$

and stores it in `equilibrium_price`. This approach yields a robust, computationally light market-clearing procedure appropriate for repeated execution across many producer areas.

Allocation of bilateral quantities and stock update. Once the price is determined, the producer computes each buyer's traded quantity by evaluating its buyer-specific demand at the equilibrium price:

$$q_{b,a,t} = \max\{0, \alpha_b + \beta_b p^*_{a,t}\}.$$

These bilateral flows are stored in `exchanged_quantities`. The producer then computes total sold quantity and updates inventory:

$$Q^{sell}_{a,t} = \sum_b q_{b,a,t}, \qquad S_{a,t+1} = S_{a,t} - Q^{sell}_{a,t}.$$

A.4 Interpretation and relevance for integration

The `InternationalProducer` class implements a decentralized market mechanism in which each producer acts as a local market that clears against the demand schedules of multiple buyers. The key integration-relevant features are:

- **Inventory-mediated supply release,** consistent with stock-smoothing logic used in the integration layer.
- **Monthly equilibrium price formation,** which generates the Italian price history used for annual farm decisions.
- **Explicit bilateral allocation,** enabling detailed tracking of trade quantities and the propagation of shocks through demand reallocation.

Overall, this implementation provides a computationally efficient approximation to multi-market price formation while preserving a transparent mapping from buyer demand primitives to realized prices and traded quantities.

B International Buyer Agent: Implementation Notes

This appendix documents the implementation of the `InternationalBuyer` agent, which represents a geographic wheat-importing area participating in decentralized international market sessions. Each buyer interacts simultaneously with multiple producer markets and dynamically adjusts its allocation of demand in response to relative price signals.

B.1 Agent Role and State Variables

The `InternationalBuyer` agent (agent `TYPE = 2`) is characterized by:

- **Geographic identifier:** `area_name`
- **Domestic demand requirement**
- **Transport cost matrix** linking buyer to producer areas
- **Demand function parameters** for each producer market
- **Observed purchase quantities**

For each producer a, the buyer maintains a demand schedule expressed at a reference (average) price and at a higher quantity level. These values are used by producers to reconstruct linear demand functions during market clearing.

B.2 Demand Query Interface

During a market session, producers call the buyer method:

```
answerDemandQueryFromProducer(area)
```

which returns:

- demand at average price,
- higher demand quantity,
- demand elasticity,
- monthly supply information.

These values allow the producer to infer a local linear demand curve.

Thus, the buyer does not set price directly; instead, it communicates primitives from which demand schedules are reconstructed.

B.3 Dynamic Allocation Adjustment Mechanism

After observing realized trade quantities and equilibrium prices across producer markets, the buyer updates its demand allocation.

The adjustment mechanism operates as follows:

1. Compute the price range across producer markets (including transport costs).
2. Determine a percentage of total demand to reallocate using a logistic function of price dispersion.
3. Shift demand from higher-cost producers to lower-cost producers.
4. Update demand schedules accordingly.

The logistic function ensures smooth behavioral adjustment:

$$\phi = \frac{\bar{\phi}}{1 + \exp\left(-\gamma(\Delta p - \bar{p})\right)}$$

where Δp is the observed price range and ϕ determines the share of demand reallocated.

This mechanism produces adaptive but gradual demand reallocation rather than instantaneous switching.

B.4 Interpretation and relevance for integration

The `InternationalBuyer` implements:

- price-responsive reallocation across competing suppliers,
- bounded rationality through gradual adjustment,
- transport-cost-inclusive purchasing decisions,
- decentralized reaction to global price signals.

The adjustment mechanism introduces cross-market coupling: a shock in one producer market affects relative prices, which induces demand reallocation and, in turn, influences market clearing in other markets.

Algorithm 2: Dynamic reallocation of buyer demand across producers (delivered-price rule)

(Continued from Algorithm 1)

Step 1: add demand to cheap producers.
Sort $\mathcal{P}$ by increasing $\tilde{p}_{bp}$ (cheapest first)
$A \leftarrow 0$ `// Cumulative added quantity`
$k \leftarrow 1$
while $A \leq \Delta_b$ ***and*** $k \leq |\mathcal{P}|$ **do**
  $p \leftarrow p_{(k)}$
  if $D_{bp} > 0$ **then**
    $\delta^+ \leftarrow \text{round}(0.1\, D_{bp})$
  else
    $\delta^+ \leftarrow \text{round}(0.01\, S_p)$
  $D_{bp} \leftarrow D_{bp} + \delta^+$
  $A \leftarrow A + \delta^+$
  $k \leftarrow k + 1$
if $A > \Delta_b$ **then**
  Let $p \leftarrow p_{(k-1)}$ `// Last updated producer`
  $D_{bp} \leftarrow D_{bp} - (A - \Delta_b)$ `// Remove overshoot`
  $A \leftarrow \Delta_b$

Step 2: remove demand from expensive producers.
Sort $\mathcal{P}$ by decreasing $\tilde{p}_{bp}$ (most expensive first)
$R \leftarrow 0$ `// Cumulative removed quantity`
$k \leftarrow 1$
while $R \leq \Delta_b$ ***and*** $k \leq |\mathcal{P}|$ **do**
  $p \leftarrow p_{(k)}$
  if $D_{bp} > 0$ **then**
    $\delta^- \leftarrow \text{round}(1.0\, D_{bp})$ `// Attempt full removal`
    $D_{bp} \leftarrow D_{bp} - \delta^-$
    $R \leftarrow R + \delta^-$
  $k \leftarrow k + 1$
if $R > \Delta_b$ **then**
  Let $p \leftarrow p_{(k-1)}$ `// Last updated producer`
  $D_{bp} \leftarrow D_{bp} + (R - \Delta_b)$ `// Add back excess removal`
  $R \leftarrow \Delta_b$

Finalize auxiliary demand level and rounding guard.
foreach $p \in \mathcal{P}$ **do**
  $D^H_{bp} \leftarrow \text{round}(1.1\, D_{bp})$
  if $D_{bp} = D^H_{bp}$ **then**
    $D_{bp} \leftarrow 0; \quad D^H_{bp} \leftarrow 0$ `// Guard against rounding degeneracy`

Algorithm 3: International Producer Monthly Market Session

Input: Current stock $S_{a,t}$, harvest month g_a, price grid $\mathcal{P}$
Output: Equilibrium price $p^*_{a,t}$, updated stock $S_{a,t+1}$

$current\_month \leftarrow (t \bmod 12) + 1$;
if $current\_month \leq g_a$ **then**
  $months\_left \leftarrow g_a - current\_month + 1$;
else
  $months\_left \leftarrow 12 - (current\_month - g_a) + 1$;
$supply \leftarrow \text{round}\left(\frac{S_{a,t}}{months\_left}\right)$;
foreach *buyer* b **do**
  Retrieve $(d_b^{avg}, d_b^{high}, \varepsilon_b)$;
  if $d_b^{avg} > 0$ ***and*** $d_b^{high} > 0$ **then**
    Compute linear demand parameters (α_b, β_b);
  else
    $\alpha_b \leftarrow 0$;
    $\beta_b \leftarrow 0$;
foreach *price* $p \in \mathcal{P}$ **do**
  $D(p) \leftarrow \sum_b \max\{0, \alpha_b + \beta_b p\}$;
Find adjacent grid points where $D(p)$ crosses $supply$;
Interpolate to obtain equilibrium price $p^*_{a,t}$;
foreach *buyer* b **do**
  $q_{b,a,t} \leftarrow \max\{0, \alpha_b + \beta_b p^*_{a,t}\}$;
$Q^{sell}_{a,t} \leftarrow \sum_b q_{b,a,t}$;
$S_{a,t+1} \leftarrow S_{a,t} - Q^{sell}_{a,t}$;

Algorithm 4: International Buyer Demand Reallocation Mechanism

Input: Observed prices p_a, transport costs c_a, total demand D
Output: Updated demand allocation across producers

foreach *producer* a **do**
  Compute effective price $p_a^{eff} = p_a + c_a$;
Compute price range $\Delta p = \max_a p_a^{eff} - \min_a p_a^{eff}$;
Compute reallocation share:

$$\phi = \frac{\bar{\phi}}{1 + \exp(-\gamma(\Delta p - \bar{p}))}$$

$Q^{move} \leftarrow \phi \cdot D$;
Sort producers by p_a^{eff} (ascending);
Add quantities to cheapest producers until Q^{move} allocated;
Sort producers by p_a^{eff} (descending);
Remove quantities from most expensive producers until Q^{move} removed;
Update demand schedules;