Evaluation of policies for enhancing sustainable wheat production in Italy

Work Package 2: Model development

Task report I23

Global and Italian models integration

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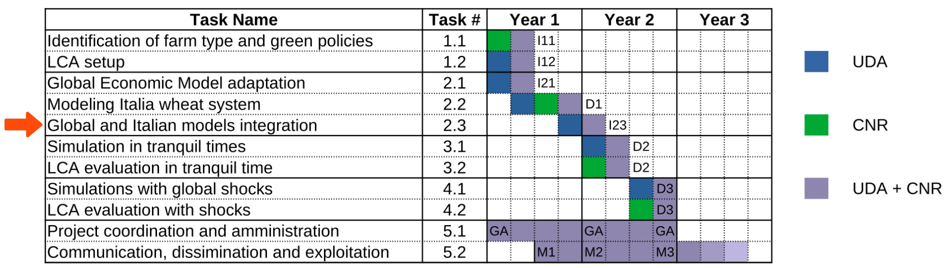

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Global and Italian models integration

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Executive Summary

This report presents the results of Task 2.3 of the ECOWHEATALY project, which focuses on the integration between the Global Economic Model (GEM) and the Italian wheat production module developed in the previous tasks of the project. The objective of this integration is to embed heterogeneous farm-level production decisions within a dynamically evolving international wheat market environment characterized by endogenous price formation, inventory management, and trade reallocation.

The integrated modelling framework combines two distinct temporal layers. The first layer represents the global wheat market and operates at a monthly time scale, simulating price formation, trade flows, and inventory dynamics across international agents. The second layer represents the Italian agricultural sector and operates at an annual time scale, where approximately 130,000 heterogeneous farms determine their production and input decisions based on observed market conditions.

Farm behaviour is modeled through microeconomic optimization problems in which farmers choose input intensities to maximize profits while accounting for environmental impacts through heterogeneous environmental awareness parameters. Production decisions are based on the annual average of observed prices, reflecting adaptive expectations and delayed supply responses commonly observed in agricultural production systems.

The integration between the two modules is achieved through a sequential coupling mechanism in which the global market determines price signals that influence farm decisions, while national production enters the international system through inventory updates at harvest time. This structure preserves market-clearing dynamics while avoiding numerical instability and circular dependencies between price formation and production decisions.

The resulting system enables the analysis of how global shocks—such as export bans, production disruptions, demand shifts, or transport cost increases—propagate through international markets and affect domestic production decisions. At the same time, the framework allows the environmental consequences of production adjustments to be evaluated through farm-level environmental indicators.

The integrated model is implemented using the `repast4py` agent-based modelling platform with MPI-based parallelization. The architecture distributes farm agents across computing ranks while maintaining centralized price formation in the global market module, ensuring computational efficiency and scalability.

Overall, Task 2.3 provides the core integration of the ECOWHEATALY modelling framework, linking international commodity market dynamics, heterogeneous farm behaviour, and environmental impact assessment within a unified computational system.

1 Introduction and Scope

The integration between the Global Economic Model (GEM) and the Italian wheat production module developed within the ECOWHEATALY framework situates this project at the intersection of commodity market dynamics, agricultural supply response theory, and agent-based computational economics. The objective of this integration is to embed heterogeneous microeconomic production decisions within a dynamically evolving international wheat market characterized by endogenous price formation and inventory adjustment.

Commodity markets have long been analyzed as dynamic systems in which prices adjust over time in response to imbalances between supply and demand. Classical contributions such as Samuelson (1947) formalized price adjustment as a dynamic process, while early agricultural models emphasized the importance of biological lags in production decisions. The cobweb theorem, originally formulated by Ezekiel (1938), demonstrated that delayed supply responses may generate cyclical or damped price fluctuations depending on relative elasticities. Subsequent empirical work by Nerlove (1958) introduced adaptive expectations to explain farmers' responses to past prices rather than contemporaneous signals.

Modern analyses of commodity markets further emphasize the stabilizing role of storage and inventory smoothing. Competitive storage models developed by Deaton and Laroque (1992) and Deaton and Laroque (1996), as well as the comprehensive treatment by Wright and Williams (1991), show how stock accumulation and release mechanisms buffer price volatility and transmit shocks across time. The inventory-based interface implemented in the present framework draws conceptually on this tradition, though without imposing rational-expectations arbitrage conditions.

From a methodological perspective, the model belongs to the class of hybrid systems combining aggregate market mechanisms with decentralized agent behavior. Agent-based computational economics has highlighted the importance of modeling heterogeneous agents interacting through price-mediated coordination processes (Tesfatsion, 2006). Similarly, Kirman (2010) argues that macroeconomic outcomes cannot be understood without explicitly accounting for heterogeneity and interaction among agents. The ECOWHEATALY integration adopts this perspective by coupling a centralized multi-market trade system with a distributed farm-level optimization module.

The primary objectives of the integration are fourfold. First, to ensure temporal consistency between monthly international market clearing and annual farm production cycles. Second, to preserve physical mass balance through explicit stock accounting identities. Third, to allow exogenous shocks to propagate coherently across international markets and domestic production decisions. Fourth, to evaluate environmental consequences of production responses under global price volatility.

The resulting framework therefore bridges classical commodity theory, modern storage dynamics, and agent-based heterogeneity within a unified computational environment. By combining delayed production adjustment, inventory buffering, and environmental decision parameters, the integrated model provides a structurally consistent platform for analyzing the joint economic and sustainability implications of global wheat market shocks.

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2 Integrated Economic Architecture

The integration between the Global Economic Model (GEM) and the Italian farm module is built upon three structural pillars:

- delayed production adjustment,
- inventory-based price stabilization,
- sequential numerical coupling.

Each pillar draws on established economic theory while serving a precise functional role in the integrated system.

2.1 Delayed Production Adjustment and Adaptive Expectations

Agricultural production is inherently characterized by biological lags that separate price observation from output realization. Classical models of agricultural dynamics demonstrate that delayed supply response may generate cyclical price paths (Ezekiel, 1938). The stability of such systems depends critically on the relative slopes of supply and demand curves.

Biological production lag. In agricultural settings, production decisions must be taken prior to harvest, and output cannot be instantaneously adjusted in response to price movements. This structural delay introduces a slow adjustment mechanism into the system. The integrated framework reflects this constraint by allowing farms to revise input decisions only once per year, at harvest month t_h.

Adaptive expectations. Empirical research by Nerlove (1958) shows that farmers typically base expectations on past observed prices rather than perfect foresight. Consistent with this evidence, Italian farms use the twelve-month moving average price:

$$\bar{p}_{t_h}^{IT} = \frac{1}{12} \sum_{s=t_h-12}^{t_h-1} p_s^{IT}. \tag{1}$$

This averaging mechanism dampens high-frequency volatility and prevents production from reacting excessively to short-lived price spikes.

Stability implications. In the classical cobweb framework, naïve expectations may produce divergent cycles. However, smoothing the price signal and introducing annual adjustment reduces effective responsiveness, shifting the system toward damped convergence rather than explosive oscillation.

2.2 Inventory Dynamics and Commodity Market Stabilization

The second structural pillar of the integration concerns inventory management. The system incorporates explicit stock accounting:

$$S_{a,t+1} = S_{a,t} - Q_{a,t}^{sell}, \tag{2}$$

together with the proportional release rule:

$$\bar{Q}^{supply}_{a,t} = \frac{S_{a,t}}{m_{a,t}}. \tag{3}$$

where $m_{a,t}$ denotes the number of months remaining until the gathering at time t.

The economic implications of this design can be understood through storage theory. Competitive storage theory shows that inventories smooth intertemporal price variation by transferring supply across periods (Deaton and Laroque, 1992, 1996; Wright and Williams, 1991). High stocks increase effective supply and moderate prices; low stocks restrict supply and amplify price signals.

Although the present model does not include forward-looking arbitrage by storage agents, the proportional release mechanism reproduces the stabilizing effect of buffer stocks.

In addition, the inventory rule introduces endogenous negative feedback, whose buffering mechanism limits price overshooting and smooths shock transmission.

- High stock $\Rightarrow$ larger monthly supply $\Rightarrow$ lower prices;
- Low stock $\Rightarrow$ constrained supply $\Rightarrow$ higher prices.

Finally, stock non-negativity constraints ensure physical feasibility and prevent artificial supply creation. The inventory mechanism, therefore, serves both economic and accounting purposes.

2.3 Sequential Coupling and Numerical Consistency

The third structural pillar concerns the numerical integration between modules. Many multi-market models rely on simultaneous equilibrium solvers (Judd, 1998; Miranda and Fackler, 2002), which compute prices and quantities through fixed-point iteration.

The ECOWHEATALY framework instead adopts a sequential coupling:

$$\text{GEM}_t \to \text{Italy}_{t_h} \to \text{GEM}_{t+1}.$$

In this framework, production enters the global system only at harvest through stock augmentation:

$$S^{+}_{IT,t_h} = S^{-}_{IT,t_h} + Y^{proxy}_{IT,t_h}. \tag{4}$$

This resembles block Gauss–Seidel iteration in numerical analysis, where system components are updated sequentially rather than solved simultaneously.

Elimination of intra-period circularity. Because farm output does not affect prices within the same month in which decisions are taken, the model avoids circular dependencies between price and quantity in a single time step. This enhances numerical stability and prevents convergence failures.

Commodity aggregation consistency. The durum-to-soft conversion factor,

$$Y^{proxy}_{IT,t_h} = Y^{durum}_{IT,t_h}\left(1 + \frac{1}{\kappa}\right), \tag{5}$$

ensures compatibility between the Italian module and the GEM commodity definition while preserving dimensional coherence.

3 Formal Representation of the Integrated System

The integrated GEM–Italy framework can be interpreted as a hybrid dynamic system combining: i) a fast monthly market adjustment layer, ii) a slow annual production adjustment layer, iii) a coupling operator linking micro-level production to macro-level stocks.

This section formalizes these components and situates the model within the literature on dynamic economic systems and heterogeneous-agent modeling.

The model has a hybrid time-scale structure because it operates on two distinct time scales:

- Monthly evolution of prices, trade flows, and inventories;
- Annual adjustment of farm-level input decisions.

Let time be indexed monthly by $t = 1, 2, \dots, T$. The global state vector is:

$$\mathcal{S}_t = (\mathbf{P}_t, \mathbf{S}_t, \mathbf{Q}_t, \mathbf{D}_t),$$

where prices, inventories, trade flows, and demand schedules evolve according to:

$$\mathcal{S}_{t+1} = \Phi(\mathcal{S}_t, \epsilon_t).$$

This representation places the GEM within the class of nonlinear **discrete-time dynamical systems** (Gandolfo, 2009).

The Italian farm module introduces a slower adjustment process, updating decisions only at harvest months t_h. Such slow-fast or multi-scale structures are common in economic systems, where production lags interact with faster price dynamics (Strogatz, 1994). The separation of time scales enhances tractability and reduces instability relative to fully simultaneous adjustment mechanisms.

Unlike classical cobweb models in which supply reacts directly to last-period price (Ezekiel, 1938), the present system incorporates price smoothing and inventory buffering, reducing the likelihood of divergent oscillations.

3.1 Heterogeneous Farm-Level Optimization

The Italian farm population consists of approximately 130,000 heterogeneous agents indexed by $i \in \mathcal{F}_{IT}$.

The farm state vector is:

$$\mathcal{X}_{i,t} = (A_i, \theta_i, x_{i,t}, y_{i,t}),$$

where A_i denotes cultivated area, θ_i denotes environmental awareness, $x_{i,t}$ is the vector of input intensities, and $y_{i,t}$ is yield per hectare.

Microeconomic foundation. At harvest, farms solve:

$$x_{i,t_h} = \arg\max_x \left[\pi_i(x, \bar{p}^{IT}_{t_h}) - \theta_i DALY_i(x)\right].$$

This formulation introduces heterogeneous objective functions consistent with agent-based computational economics (Tesfatsion, 2006). Unlike representative-agent models, aggregate supply emerges from the distribution of farm characteristics rather than from a single optimizing entity.

As emphasized by Kirman (2010), macroeconomic behavior cannot generally be reduced to representative-agent dynamics when heterogeneity matters. In the present framework, variation in θ_i, farm size, and productivity parameters generates non-linear aggregate responses to price shocks.

3.2 Coupling Operator and Stock Integration

Aggregate durum wheat production is:

$$Y_{IT,t_h}^{durum} = \sum_{i \in \mathcal{F}_{IT}} y_{i,t_h} A_i.$$

The coupling between farm output and the global market occurs through stock augmentation:

$$S_{IT,t_h}^{+} = S_{IT,t_h}^{-} + Y_{IT,t_h}^{proxy},$$

with:

$$Y_{IT,t_h}^{proxy} = Y_{IT,t_h}^{durum} \left(1 + \frac{1}{\kappa}\right).$$

The integration can be interpreted as a block-structured system in which micro-level production feeds into macro-level stock dynamics. Such block decomposition resembles numerical partitioning methods commonly used in large-scale computational economics (Judd, 1998; Miranda and Fackler, 2002).

Furthermore, let us define a coupling operator Ψ such that:

$$\Psi(Y^{durum}) = Y^{durum} \left(1 + \frac{1}{\kappa}\right)$$

Then the integrated state transition can be written as:

$$\mathcal{S}_{t+1} = \Phi(\mathcal{S}_t + \mathbf{e}_{IT} \Psi(Y_{IT,t_h}^{durum}), \epsilon_t)$$

where $\mathbf{e}_{IT}$ updates only the Italian stock component.

This operator-based representation clarifies the separation between market dynamics and production updates.

3.3 System-Level Feedback Structure

The complete feedback loop can be summarized as:

- Exogenous shock ϵ_t affects global prices $\mathbf{P}_t$;
- Smoothed price $\bar{p}_{t_h}^{IT}$ affects farm decisions;
- Farm production modifies inventories;
- Inventory changes influence future price formation.

Formally:

$$\epsilon_t \to \mathbf{P}_t \to \bar{p}_{t_h}^{IT} \to \mathcal{G} \to Y_{IT,t_h}^{durum} \to S_{IT,t_h} \to \mathbf{P}_{t+1}.$$

From a systems perspective, the integrated model can be viewed as a delayed feedback control system. Inventory acts as a buffer state variable, while annual production decisions introduce inertia. Such feedback structures typically generate bounded trajectories under moderate shocks (Gandolfo, 2009).

Because farm decisions are based exclusively on information available up to $t_h - 1$, the model satisfies informational consistency and avoids forward-looking circularity. This property strengthens both economic plausibility and numerical stability.

4 Computational Implementation and Parallelization

The integrated GEM–Italy framework combines centralized market clearing with distributed farm-level optimization. From a computational perspective, the architecture rests on four principles:

- centralized global price formation,
- distributed heterogeneous-agent computation,
- minimal and structured inter-rank communication,
- deterministic execution with scalability guarantees.

These principles reflect established practices in agent-based computational economics and high-performance simulation.

4.1 Centralized Market Layer and Distributed Agent Layer

The model is implemented in `repast4py`, a Python-based agent-based modeling framework built on MPI. The parallel structure follows a master–worker topology:

- **rank 0 (master):** executes the Global Economic Model (GEM), including monthly market clearing, inventory updates, and shock implementation;
- **ranks 1 to $R - 1$ (workers):** host distributed Italian farm agents and execute annual production decisions.

Agent-based modeling emphasizes decentralized decision-making by heterogeneous agents interacting through markets (Tesfatsion, 2006). However, large-scale ABMs often face computational bottlenecks when agent populations are large. Parallel agent distribution across computing ranks has therefore become standard practice in high-performance ABM environments (North et al., 2013; Collier and North, 2013).

The architecture of our model separates macro-level coordination (prices and trade flows) from micro-level optimization (farm decisions). This block separation reflects modular system design principles common in large-scale economic simulation (see Figure 1).

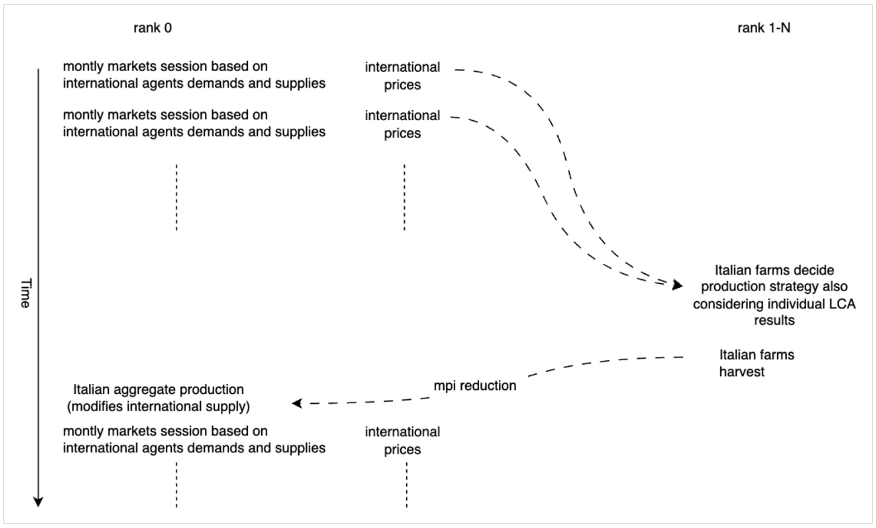

Figure 1: Parallel execution structure of the integrated model.

4.2 Data Partitioning and Load Balancing

The Italian farm population comprises approximately $N_f \approx 130{,}000$ agents. Let $R_w = R - 1$ denote worker ranks. Each worker rank stores approximately $\frac{N_f}{R_w}$ farms.

The computational structure relies on three design choices: 1) static partitioning of farm agents, 2) localized memory ownership, and 3) aggregation-only communication.

Farm-to-rank assignment is fixed prior to execution. Static partitioning avoids dynamic migration overhead and ensures predictable memory usage. This design is consistent with large-scale distributed agent simulation practices (North et al., 2013).

Each worker rank stores only local farm states (A_i, θ_i, input vectors, yield outcomes). Global objects such as price vectors and trade matrices remain exclusively on rank 0. This minimizes memory duplication.

Uniform distribution of farms ensures approximately equal computational load per rank. Because farm-level optimization is the dominant computational cost, parallel efficiency improves nearly linearly with the number of worker ranks until communication latency becomes binding.

4.3 Communication Structure and Complexity

Communication occurs exclusively at harvest months and involves scalar aggregation. The communication pattern includes: i) broadcast of annual average price, ii) reduction of aggregate production, iii) optional reduction of environmental indicators.

More in detail, at harvest month t_h, rank 0 computes:

$$\bar{p}_{t_h}^{IT} = \frac{1}{12} \sum_{s=t_h-12}^{t_h-1} p_s^{IT},$$

and distributes this scalar using `MPI_Bcast`. Communication complexity scales as $O(\log R)$.

Cuncurrently, each worker rank computes local production:

$$Y_{IT,t_h}^{durum}(r) = \sum_{i \in \mathcal{F}_{IT}^{(r)}} y_{i,t_h} A_i.$$

Global production is obtained via `MPI_Reduce`. Note that communication cost remains negligible relative to local computation because only scalar values are transmitted.

High-performance agent-based platforms emphasize minimizing communication volume to maintain scalability (Collier and North, 2013). The ECOWHEATALY design adheres to this principle by restricting inter-rank exchange to low-dimensional aggregates.

4.4 Determinism, Numerical Consistency, and Reproducibility

Large-scale simulations must ensure reproducibility across parallel executions. The integrated architecture guarantees determinism through:

- fixed farm-to-rank assignment,
- deterministic random seed initialization per rank,
- absence of asynchronous messaging,
- explicit synchronization at harvest.

Sequential execution discipline. Monthly GEM sessions occur exclusively on rank 0, eliminating race conditions in price formation. Farm-level updates occur simultaneously across worker ranks but do not interact until aggregation.

Relation to computational economics practice. Numerical economic models often rely on deterministic block updates to ensure convergence and replicability (Judd, 1998). By avoiding simultaneous cross-rank dependencies, the model preserves strict execution ordering.

Scalability bounds. Let C_f denote cost per farm optimization and C_m cost per monthly market session. Annual computational complexity is:

$$12C_m + \frac{N_f}{R_w} C_f.$$

Communication cost scales logarithmically with R. Thus, computational workload dominates communication overhead for realistic cluster sizes.

5 Stability, Shock Transmission, and Environmental Implications

The integrated GEM-Italy framework generates a closed-loop dynamic system that links global shocks, price formation, production adjustment, and environmental outcomes. Its behavior is governed by three interrelated mechanisms: (i) inventory-mediated price stabilization, (ii) delayed supply responses with adaptive expectations, and (iii) heterogeneous environmental internalization at the farm level. Together, these mechanisms produce bounded dynamic trajectories under moderate shocks, gradual convergence toward new equilibria, and economically interpretable propagation delays.

This section analyzes the system?s dynamic properties and situates them within the broader literature on commodity market stability and environmental economics.

5.1 Dynamic Stability and Inventory-Mediated Adjustment

To preserve dynamic stability, we use the stock accounting identity of Equation 6 because it ensures physical conservation of mass and constrains feasible trajectories.

$$S_{IT,t+1} = S_{IT,t} + \delta_{t,t_h} Y^{proxy}_{IT,t_h} - Q^{sell}_{IT,t}, \tag{6}$$

Furthermore, the non-negativity conditions,

$$S_{a,t} \geq 0, \qquad Q^{sell}_{a,t} \leq S_{a,t},$$

prevent artificial stock creation and guarantee boundedness.

As demonstrated in Section 2.2, when stocks are high, effective supply expands and prices moderate; when stocks are low, supply contracts and prices increase. This endogenous negative feedback reduces the amplitude of shocks (Deaton and Laroque, 1992; Wright and Williams, 1991).

Although the present model does not explicitly include forward-looking storage arbitrage, the presence of inventory prevents instantaneous quantity-price feedback loops that could otherwise produce explosive divergence.

Recall also that in our model, production adjustment occurs only at annual harvest months, introducing a structural lag between price signals and output realization. These mechanisms reduce effective responsiveness and shift the system toward damped adjustment.

In addition, following Nerlove (1958), adaptive expectations reduce volatility transmission by anchoring decisions in observed historical data. The annual averaging operator acts as a low-pass filter, mitigating high-frequency shocks before they affect production.

The dynamic chain can be summarized as:

$$\epsilon_t \to \mathbf{P}_t \to \bar{p}^{IT}_{t_h} \to Y^{durum}_{IT,t_h} \to S_{IT,t_h} \to \mathbf{P}_{t+1}.$$

The delay structure inherently limits the speed of adjustment and reduces oscillatory amplification.

5.2 Environmental Internalization and Heterogeneous Response

The farm-level objective function incorporates an environmental awareness parameter:

$$x_{i,t_h} = \arg\max_x \left[\pi_i(x, \bar{p}^{IT}_{t_h}) - \theta_i DALY_i(x) \right].$$

In this configuration, the parameter θ_i acts as an internalized shadow price of environmental damage. In classical welfare economics, Pigouvian taxation corrects externalities by internalizing social costs (Pigou, 1920). Here, instead of imposing an external tax, heterogeneity in θ_i reflects voluntary or policy-induced internalization of environmental damages.

Recent literature emphasizes that agents may differ in pro-social or environmental preferences (Bénabou and Tirole, 2010). Heterogeneous environmental awareness generates nonlinear aggregate supply responses, since farms with high θ_i respond less aggressively to price increases. Thus, under positive price shocks, it is assumed that:

- farms with low θ_i intensify input use strongly,
- farms with high θ_i moderate their response.

such that the distribution of environmental awareness shapes the environmental consequences of global price volatility.

5.3 Shock Transmission and System-Level Resilience

By linking storage dynamics, delayed supply adjustment, and environmental internalization, the model provides a structurally coherent representation of how global instability interacts with sustainability outcomes.

Exogenous shocks ϵ_t may include export bans, production disruptions, transport cost increases, or demand shifts.

Shock propagation follows three layers:

1. immediate price adjustment at the monthly scale,
2. delayed production response at the annual scale,
3. environmental impact through input intensity choices.

In the short run, prices adjust rapidly due to inventory constraints and decentralized trade reallocation. At the next harvest, farms adjust their input decisions based on the smoothed price signal, and production correspondingly increases or decreases. In the long run, however, inventory accumulation following production expansion exerts downward pressure on prices, leading to a gradual convergence toward a new equilibrium.

This integrated framework enables an assessment of market resilience to supply shocks, the persistence of price volatility, the environmental costs of commodity price spikes, and the effectiveness of policies that influence θ_i.

6 Conclusions

This report presented the integration between the Global Economic Model and the Italian wheat production module developed within the ECOWHEATALY project. The objective of Task 2.3 was to create a coherent modelling framework capable of linking global wheat market dynamics with farm-level production behaviour and environmental impact assessment.

The integrated system combines two complementary modelling perspectives. At the global level, the model represents the international wheat market as a dynamic system in which prices, inventories, and trade flows evolve monthly in response to supply and demand conditions. At the national level, the Italian production module models heterogeneous farms that adjust input use and production decisions on an annual basis according to observed market signals.

The interaction between these two layers is governed by a sequential coupling mechanism that ensures numerical consistency and preserves the physical accounting of production and inventories. Price signals generated by the global market influence farm-level decisions through adaptive expectations based on smoothed price observations, while aggregate national production enters the international market through inventory updates at harvest time.

The modelling framework also incorporates heterogeneous environmental awareness parameters that allow environmental impacts to influence production decisions. This feature enables the model to capture how sustainability-oriented policies or behavioural changes may affect the environmental consequences of agricultural production.

From a computational perspective, the integrated model is implemented using a parallel agent-based architecture based on repast4py and MPI. The international market module operates centrally, while farm agents are distributed across worker processes. This structure ensures scalability while keeping communication costs low and preserving deterministic execution.

The integration achieved in Task 2.3 represents a key step in the development of the ECOWHEATALY modelling framework. By connecting international market dynamics, heterogeneous farm behaviour, and environmental impact indicators, the model provides a comprehensive platform for analysing the economic and environmental consequences of global shocks and agricultural policies affecting wheat production.

The integrated system will be used in the subsequent stages of the project to perform scenario simulations evaluating how global market instability, environmental policies, and technological changes influence both market outcomes and sustainability indicators in the Italian wheat sector.

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Appendix

A Model Initialization and Execution Scheduling

The initialization function defines the structural, temporal, and computational foundations of the integrated simulation. Its role is to establish the execution schedule, instantiate agents across MPI ranks, configure stochastic processes, and initialize data logging structures.

The initialization phase can be conceptually decomposed into four components:

- execution scheduling,
- parallel environment configuration,
- agent instantiation and distribution,
- logging and reproducibility setup.

Execution scheduling. The simulation relies on the `repast4py` scheduling engine, which executes events at fixed temporal intervals. Monthly international market sessions are scheduled with period 1, while Italian production events occur every 12 months, beginning at month 6 (harvest timing). Priority ordering ensures deterministic execution sequencing within each monthly tick.

Specifically:

- International market clearing precedes logging.
- Harvest checks occur before farm-level optimization.
- Farm optimization precedes stock update.
- LCA indicators are computed after production aggregation.
- Buyer strategy adaptation occurs at the end of the tick.

This strict priority ordering guarantees temporal coherence between market evolution and production updates.

Parallel environment configuration. The initialization receives an MPI communicator and configures:

- rank identity,
- total number of processes,
- inter-rank communication structure.

Random seeds are deterministically generated and assigned per rank. This ensures:

- reproducibility across runs,
- independence of stochastic draws across ranks,
- invariance of results to execution ordering.

Such deterministic seeding is essential for scientific replicability in parallel simulations.

Agent instantiation by rank. The model distinguishes between:

- rank 0 (international layer),
- ranks 1–$R-1$ (Italian farm layer).

On rank 0, the following agents are created:

- the Policy Maker agent,
- international producer agents,
- international buyer agents.

International production and demand data are loaded from external CSV files. Surplus production statistics are computed to initialize supply conditions and export shares.

On worker ranks, Italian farm agents are instantiated using two data sources:

- Real farms derived from RICA microdata;
- Artificial farms generated via province-specific statistical distributions (acreage, age, gender).

Artificial farms are generated to ensure that the aggregate farm population reproduces provincial-level structural characteristics observed in ISTAT census data.

In addition, farm attributes such as age, wheat acreage, and total farm acreage are generated using parametric distributions whose parameters are province–altimetry specific. Truncation rules enforce realistic bounds (e.g., non-negative acreage, age constraints). This procedure ensures structural heterogeneity while preserving empirical consistency.

Ghost agents and cross-rank synchronization. Worker ranks request a ghost instance of the Policy Maker agent to ensure cross-rank consistency of policy signals. The `request_agents` mechanism maintains shared state across distributed processes without duplicating full agent logic.

This ghosting mechanism allows for centralized policy control, decentralized farm decision execution, and minimal communication overhead.

Logging and data structures. The initialization phase creates structured output files for:

- international prices,
- producer stocks,
- quantities sold,
- farm-level production and environmental data,
- aggregated Italian indicators.

Reduction-based logging ensures that farm-level quantities computed across ranks are correctly aggregated before being written to disk. Furthermore, at the end of initialization, the Italian production module is executed once to replace historical FAOSTAT production with model-generated production. This guarantees consistency between initial stock conditions and endogenous production.

As a matter of fact, the initialization function performs more than a technical setup; it establishes a temporal ordering of economic processes, a parallel decomposition of the economic system, an empirical calibration of heterogeneous farms, and a deterministic reproducibility guarantee. Thus, this structured initialization ensures that the integrated model begins from a coherent economic state while maintaining scalability and computational robustness.

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B Performances

We report here the performance of the software when run on a 16-core laptop. The three panels of Figure 2 show the laptop resource-usage monitoring window when launching simulations with 5, 9, and 13 ranks. The corresponding execution times are 9:08, 5:21, and 4:08 minutes, respectively.

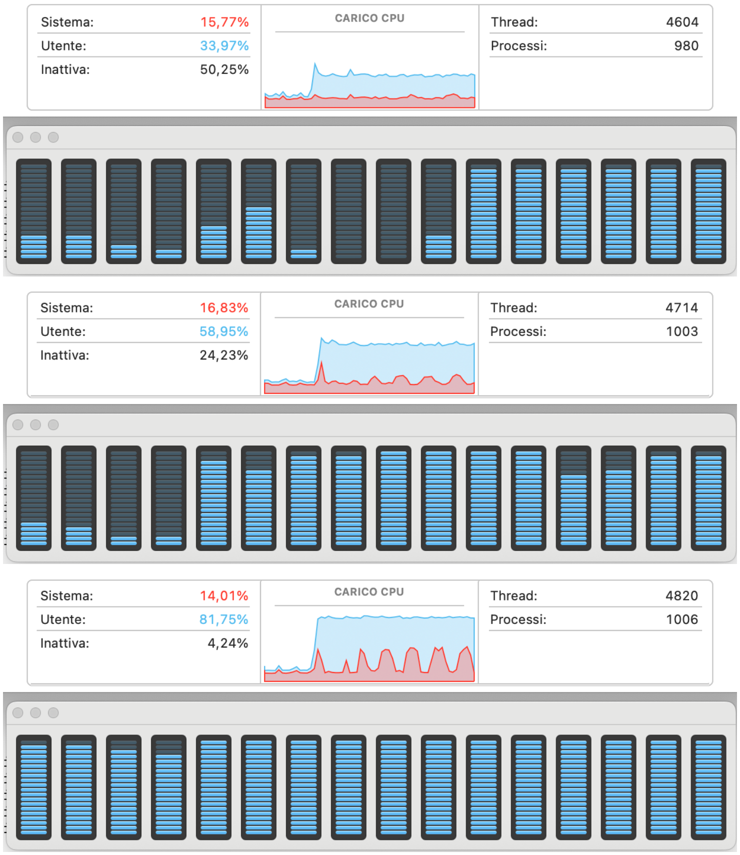

Figure 2: Resource-usage monitoring window when launching simulations with 5 (upper panel), 9 (middle panel), and 13 (lower panel) ranks.

Hereafter, the details returned by the run script when invoked on 5 ranks are reported.

```
(repast4py3.13) ecowheataly_repast4py_model % ./run 5

Not all provinces,altimetry in Rica are in census, Please check
{"Valle d'Aosta / Vallée d'Aoste,Montagna", 'Gorizia,Pianura',
 'La Spezia,Collina'}
Valle d'Aosta / Vallée d'Aoste,Montagna 1 farms removed from RICA
Gorizia,Pianura 1 farms removed from RICA
La Spezia,Collina 1 farms removed from RICA
rank 1 n real farm 531 n artificial farm 33341 total 33872
rank 2 n real farm 314 n artificial farm 33558 total 33872
rank 3 n real farm 529 n artificial farm 33343 total 33872
rank 4 n real farm 469 n artificial farm 33402 total 33871
total number of real farms 1843
total number of artificial farms 133644
total number of farms 135487
Cleaning output directory
starting simulation Sab 21 Feb 2026 11:42:30 CET
simulation finished Sab 21 Feb 2026 11:51:38 CET
```

Hereafter, the details returned by the run script when invoked on 9 ranks are reported.

```
(repast4py3.13) ecowheataly_repast4py_model % ./run 9

Not all provinces,altimetry in Rica are in census, Please check
{'Gorizia,Pianura', "Valle d'Aosta / Vallée d'Aoste,Montagna",
 'La Spezia,Collina'}
Gorizia,Pianura 1 farms removed from RICA
Valle d'Aosta / Vallée d'Aoste,Montagna 1 farms removed from RICA
La Spezia,Collina 1 farms removed from RICA
rank 1 n real farm 229 n artificial farm 16707 total 16936
rank 2 n real farm 302 n artificial farm 16634 total 16936
rank 3 n real farm 151 n artificial farm 16785 total 16936
rank 4 n real farm 163 n artificial farm 16773 total 16936
rank 5 n real farm 289 n artificial farm 16647 total 16936
rank 6 n real farm 240 n artificial farm 16696 total 16936
rank 7 n real farm 244 n artificial farm 16692 total 16936
rank 8 n real farm 225 n artificial farm 16710 total 16935
total number of real farms 1843
total number of artificial farms 133644
total number of farms 135487
Cleaning output directory
starting simulation Sab 21 Feb 2026 11:28:04 CET
simulation finished Sab 21 Feb 2026 11:33:25 CET
```

Hereafter, the details returned by the run script when invoked on 13 ranks are reported.

```
(repast4py3.13) ecowheataly_repast4py_model % ./run 13

Not all provinces,altimetry in Rica are in census, Please check
{'Gorizia,Pianura', 'La Spezia,Collina',
```

```
 "Valle d’Aosta / Vallée d’Aoste,Montagna"}
Gorizia,Pianura 1 farms removed from RICA
La Spezia,Collina 1 farms removed from RICA
Valle d’Aosta / Vallée d’Aoste,Montagna 1 farms removed from RICA
rank 1 n real farm 207 n artificial farm 11084 total 11291
rank 2 n real farm 56 n artificial farm 11235 total 11291
rank 3 n real farm 268 n artificial farm 11023 total 11291
rank 4 n real farm 99 n artificial farm 11192 total 11291
rank 5 n real farm 108 n artificial farm 11183 total 11291
rank 6 n real farm 107 n artificial farm 11184 total 11291
rank 7 n real farm 87 n artificial farm 11204 total 11291
rank 8 n real farm 227 n artificial farm 11063 total 11290
rank 9 n real farm 215 n artificial farm 11075 total 11290
rank 10 n real farm 180 n artificial farm 11110 total 11290
rank 11 n real farm 140 n artificial farm 11150 total 11290
rank 12 n real farm 149 n artificial farm 11141 total 11290
total number of real farms 1843
total number of artificial farms 133644
total number of farms 135487
Cleaning output directory
starting simulation Sab 21 Feb 2026 11:20:07 CET
simulation finished Sab 21 Feb 2026 11:24:15 CET
```