AIM-ALPHA documentation

Agricultural Land-use Partial Equilibrium Model

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Abstract

This document describes the model structure and system of equations for AIM-ALPHA v1.0. AIM-ALPHA is a one-year step sequential dynamic partial equilibrium model targeting agricultural markets and land use. It performs future projections considering 166 countries on the demand side, 400 production units on the supply side, 23 food commodities, and 5 land use categories. This model is anticipated to be applicable to research including analyses of food security issues, climate change impacts, evaluations of climate change mitigation measures, and assessments of biodiversity impacts related to land use.

Keywords: Integrated assessment model, partial equilibrium, agricultural markets, land use, climate change mitigation

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Contents

1 Introduction

1.1 About this document

This document describes the model structure and system of equations of AIM-ALPHA (the Asia-pacific Integrated Model - Agricultural Land-use Partial equilibrium model for Harmonized Analysis), a partial equilibrium model for agriculture and land use. The document is organized as follows:

1) Model Structure (Section 2)
2) System of Equations (Sections 3 and 4)
3) Data Processing (Section 5)
4) Parameter Estimation (Section 6)
5) Model Calculation Flow and Execution Method (Section 7)

1.2 Background

Future projections of agriculture and land use play an essential role in understanding global sustainability challenges. Increasing food demand, dietary shifts, and the growing use of bioenergy are intensifying pressures on land resources, while agriculture and land-use activities remain major sources of greenhouse gas (GHG) emissions and biodiversity loss. At the same time, these sectors are highly vulnerable to climate change through altered temperature and precipitation patterns that affect crop yields and food availability. Consequently, designing sustainable pathways for agriculture and land management requires an integrated understanding of the interactions among socioeconomic drivers, land-use dynamics, and environmental outcomes.

Model-based approaches provide a powerful framework for exploring such interlinked systems. A variety of global and regional models have been developed to evaluate the implications of alternative socioeconomic and climate scenarios for food security, mitigation, and ecosystem conservation. However, many existing models operate at aggregated regional scales and provide limited representation of country-specific agricultural systems, land-use competition, and trade linkages. This limits their applicability for detailed policy analysis or assessment of subnational dynamics.

To address these limitations, the AIM-ALPHA model has been developed as a high-resolution partial equilibrium model covering the agriculture and land-use sectors at national and subnational levels. The model is designed to complement the broader AIM (Asia-Pacific Integrated Model) framework by offering a detailed, bottom-up representation of agricultural markets, land-use allocation, and environmental interactions.

This formulation document provides a comprehensive description of the model structure, mathematical formulation, and computational framework of AIM-ALPHA. It aims to enhance transparency and reproducibility of the model's analytical components, facilitate linkage with other models in the AIM framework, and support further applications in global and national assessments of sustainable land-use transitions.

2 Model Structure

This section provides an overview of the AIM-ALPHA model. AIM-ALPHA is a recursive-dynamic partial equilibrium model focusing on agricultural markets and land use, operating with an annual time step. The model uses 2015 as the base year and projects up to 2100. It is formulated as a mixed complementarity problem (MCP) and handles approximately 200,000 variables.

On the spatial dimension, the demand side covers 166 countries and regions globally, while the production side consists of 400 production units. These production units are defined by overlaying the 166 demand regions with FAO's 230 major river basin boundaries. Figure 2 illustrates the geographical coverage of the demand regions and production units.

The basic model structure is shown in Figure 1. Food production is categorized into 13 primary crops, 6 livestock products, and 4 processed goods. Table 1 lists the food commodity classifications used in the model. The production functions are represented by Leontief-type functions, where each good is produced by combining cropland, feed and pasture, and raw materials as inputs. Other factors such as labor, capital, and energy are aggregated into a single production factor.

Primary crops and livestock products that require land are differentiated by production unit, whereas processed goods, which do not require land inputs, are modeled at the level of the 166 demand regions. Land use within each production unit is allocated according to a hierarchical logit function that balances total land area, and land shares are determined by relative land prices.

Food demand is driven by population and GDP, with income elasticity considered for future changes. Food prices are determined endogenously so that supply and demand are balanced in the domestic market. Within each country, the balance between production, domestic demand, and net trade (imports minus exports) is maintained. In the global market, total world imports and exports are also balanced. Furthermore, commodities that were not produced or traded in the base year are assumed to remain inactive in that country or production unit throughout the projection period.

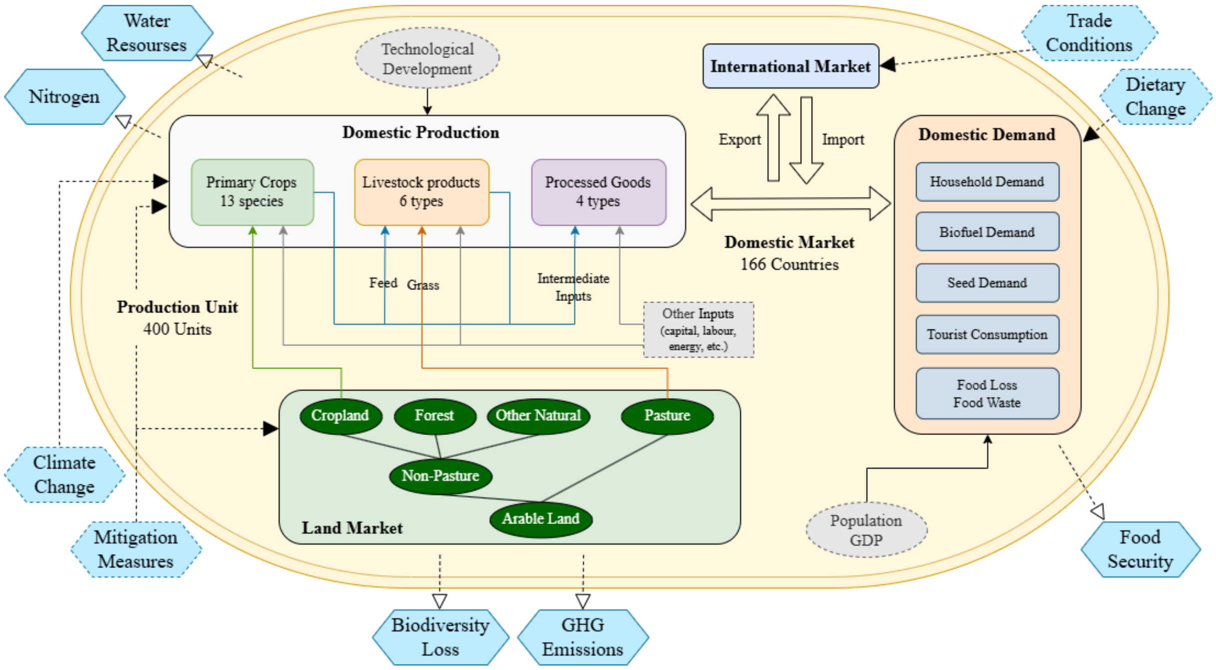

Figure 1: Overview of AIM-ALPHA

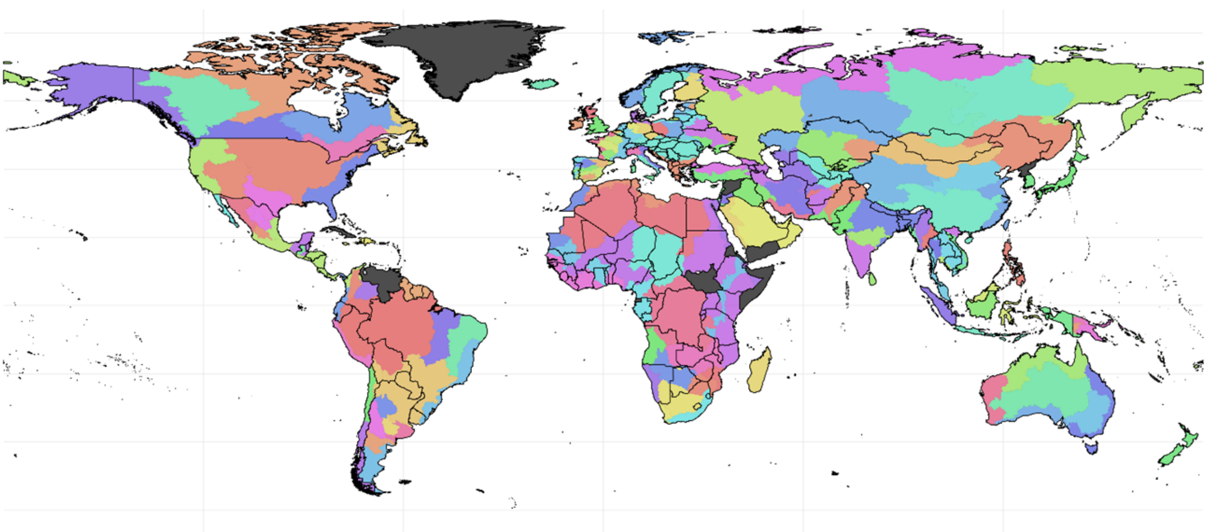

Figure 2: Geographical coverage of countries (166) and production units (400).

Table 1: Classification of food commodities

Category	**Commodity**	**Model code**
Primary crops	Wheat	`wht`
	Rice	`rce`
	Maize	`mze`
	Other cereals	`crl`
	Roots and tubers	`str`
	Sugar crops	`sgr`
	Pulses	`pls`
	Nuts	`nut`
	Oil crops	`ocr`
	Vegetables	`vgt`
	Fruits	`frt`
	Stimulant crops	`stm`
	Spices	`spc`
Livestock products	Beef	`cmt`
	Sheep and goat meat	`rmt`
	Poultry meat	`pmt`
	Other meat	`omt`
	Eggs	`egg`
	Milk	`mlk`
Processed products	Sugar products	`swt`
	Vegetable oils	`vol`
	Alcoholic beverages	`alc`
	Dairy products	`dai`

3 Variables and Parameters

This section describes the variables and parameters used in the model.

3.1 Indices

Table 2 lists the indices used in the model.

Table 2: List of indices

Index	Description	Dimension	Notes
cty	Country / region	166	
bas	River basin	400	
region	Macro region	17	Same as the regional classification in AIM-Hub
c(a)	Food commodities (production activities)	23	See Table 1
acro	Primary crops	13	
aliv	Livestock products	6	
apro	Processed products	4	
cfeed	Feed inputs	10	
cint	Intermediate inputs	8	
cbio	Biofuel crops	3	
water	Crop production technology	2	Irrigated / rainfed
cz	Climate zone	4	Tropical, temperate, arid, hyper-arid
sys	Livestock production system	2	Pasture-based, mixed farming
src	GHG emission sources	13	Enteric fermentation, manure management, rice cultivation, synthetic fertilizer application, organic fertilizer application, manure on pasture, cultivation of organic soils, crop residues, crop residue burning, grassland burning, forests, natural wildfires, deforestation
gas	Gas species	3	CO_2, CH_4, N_2O

3.2 Endogenous Variables

Table 3 lists the endogenous variables used in the model.

Table 3: List of endogenous variables

Variable	Description	Unit
QDEM	Domestic demand	1000t
QH	Household consumption demand	1000t
QF	Feed demand	1000t
QI	Intermediate input demand for processed goods	1000t
QBIO	Biofuel demand	1000t
QSEED	Seed demand	1000t
QTOUR	Tourist consumption demand	1000t
QLOSS	Food loss amount	1000t
QWASTE	Food waste amount	1000t
QOTH	Other demand	1000t
QFEED	Feed input	1000t
QINT	Raw material input	1000t
QSUP	Domestic production	1000t
QS	Production by river basin	1000t
QSWAT	Crop production by technology	1000t
QSSYS	Livestock production by system	1000t
QM	Imports	1000t
QE	Exports	1000t
NT	Net trade	1000t
PP	Producer price	$/t
PC	Consumer price	$/t
PB	Border price	$/t
PM	Import price	$/t
PE	Export price	$/t
PW	World price	$/t
YLD	Crop yield	t/ha
SYSSHARE	Livestock system share	-
QGRASS	Grass utilization	1000t
ANIMALYLD	Livestock yield per hectare	t/ha
ICL	Feed input coefficient	t/t
ANIMAL	Number of livestock	1000 head
PO	Price of other production factors	$/t
QLVEG	Vegetation area	1000ha
QLPAS	Pasture area	1000ha
QLPASN	Non-pasture grassland area	1000ha

Continued on next page

Table 3: List of endogenous variables (continued)

Variable	Description	Unit
QLCRO	Cropland area	1000ha
QLFRS	Forest area	1000ha
QLGRA	Other natural land area	1000ha
QLCROCLT	Harvested cropland area	1000ha
QLCROFAL	Fallow cropland area	1000ha
QL	Total production area	1000ha
PLPAS	Pasture land price	$/ha
PLPASN	Non-pasture land price	$/ha
PLCRO	Cropland price	$/ha
PLCROCLT	Harvested cropland price	$/ha
PL	Land price	$/ha
PENE	Energy crop land price	$/ha
GHG	GHG emissions from agriculture sector	$ktCO_2$-eq/yr
GHGLU	GHG emissions from land-use sector	$ktCO_2$-eq/yr
RR	Emission reduction rate	-
AC	Abatement cost	$/t
PCB	Carbon price on residual emissions	$/t
PPCOMP	Complementary variable for production	-
TMCOMP	Complementary variable for imports	-
PLCOMP	Complementary variable for land price	-

3.3 Exogenous Variables

Table 4 lists the exogenous variables used in the model.

Table 4: List of exogenous variables

Variable	Description	Data Source
QHBASE	Household consumption demand in the base year	FAOSTAT
QBIOBASE	Biofuel demand in the base year	FAOSTAT
QSEEDBASE	Seed demand in the base year	FAOSTAT
QTOURBASE	Tourist consumption demand in the base year	FAOSTAT
QLOSSBASE	Food loss in the base year	FAOSTAT
QOTHBASE	Other demand in the base year	FAOSTAT
QSUPPRE	Domestic production in the previous year	FAOSTAT
QSPRE	Production by river basin in the previous year	GAEZ v4
QENE	Demand for dedicated energy crops	AIM-Hub

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Table 4: List of exogenous variables (continued)

Variable	Description	Data Source
QST	Change in stock	FAOSTAT
QRES	Residual of international trade balance	FAOSTAT
LOSSRATE	Food loss rate	FAOSTAT
WASTERATE	Food waste rate	FAO (2011)
GDPPC	GDP per capita	SSP 3.0
GDPPCBASE	GDP per capita in the base year	World Bank
POP	Population	SSP 3.0
POPBASE	Population in the base year	World Bank
MMJ	Market margin	GTAP 10
PSE	Producer Support Estimate (PSE)	GTAP 10
CSE	Consumer Support Estimate (CSE)	GTAP 10
CSEBASE	CSE in the base year	GTAP 10
TM	Import tariff rate	GTAP 10
MMM	Import margin rate	GTAP 10
TE	Export tariff rate	GTAP 10
MME	Export margin rate	GTAP 10
YLDBASE	Crop yield in the base year	FAOSTAT, GAEZ v4
YLDGR	Yield change rate due to technological progress	IMPACT
YLDCHAN	Yield change rate due to climate change impacts	GAEZ v4
CROPINTENSITY	Cropping intensity	MAPSPAM
GRASSYLD	Grass yield	GAEZ v4
ANIMALPRODRATE	Slaughtering / milking rate	FAOSTAT
FEEDEFFICIENCY	Feed conversion efficiency	Herrero & Acosta et al. (2018)
FEEDSHARE	Share of concentrate feed	Herrero & Acosta et al. (2018)
GRAINSHARE	Share of grain feed	FAOSTAT
ANIMALWEIGHT	Livestock body weight	FAOSTAT
ANIMALRES	Number of non-productive livestock	FAOSTAT
QLRES	Pasture area not used for livestock production	FAOSTAT, LUH2
POBASE	Price of other production factors in the base year	FAOSTAT, GTAP 10
QLTOT	Total land area	LUH2
QLVEGN	Non-vegetated land area	LUH2
QLAFR	Afforested area	AIM-PLUM
PLFRS	Forest land price	LUH2, GTAP 10
PLGRA	Price of other natural land	LUH2, GTAP 10
PLCROFAL	Fallow land price	LUH2, GTAP 10
EF	GHG emission factor in agriculture sector	FAOSTAT
EFLU	GHG emission factor in land-use sector	FAOSTAT
PRCCAR	Carbon price	AIM-Hub

Continued on next page

Table 4: List of exogenous variables (continued)

Variable	Description	Data Source
MRP	Maximum reduction potential of abatement technologies	Harmsen et al. (2019)

3.4 Parameters

Table 5 lists the parameters used in the model.

Table 5: List of parameters

Parameter	Description	Notes
elhg	Income elasticity of consumption	Estimated from the food demand model
elhp	Price elasticity of consumption	Estimated by regression based on Muhammad et al. (2011)
ica	Intermediate input coefficient	
elop	Elasticity of other production factors	
δ	Coefficient parameter of the logit function	
ρ	Exponent parameter of the logit function	For land use, adopted from GCAM; for production systems, estimated by regression based on Herrero Acosta et al. (2018)
res	Residual parameter	
watshare	Share of primary-crop production technologies	
czshare	Climate zone share	
grassusagerate	Grass (pasture) utilization rate	
pintcoef	Price coefficient for intermediate inputs	
pfeedcoef	Price coefficient for feed inputs	
pbres	Residual between consumer price and border price	
pmres	Residual between import price and world price	
peres	Residual between export price and world price	
exr	Exchange rate	
σ	Elasticity of adoption of abatement technologies	Estimated by regression based on Harmsen et al. (2019)

4 System of Equations

This section presents the mathematical formulation of the model and its explanation. In the following, **endogenous variables** are denoted by uppercase letters, **exogenous variables** by uppercase letters with an overline, and **parameters** by lowercase or Greek letters.

4.1 Demand Block

This block describes the equations related to demand determination. In the demand block, food demand is determined by factors such as prices, population, and GDP.

Total Demand

$$\begin{aligned} QDEM_{c,cty} = {} & QH_{c,cty} + QF_{c,cty} + QI_{c,cty} + QBIO_{c,cty} \\ & + QSEED_{c,cty} + QTOUR_{c,cty} + QLOSS_{c,cty} + QWASTE_{c,cty} + QOTH_{c,cty} \end{aligned} \tag{QDEMEQ}$$

Household Consumption Demand

$$\begin{aligned} QH_{c,cty} = {} & \overline{QHBASE}_{c,cty} \cdot \left(\frac{\overline{GDPPC}_{cty}}{\overline{GDPPCBASE}_{cty}} \right)^{elhg_{c,cty}} \\ & \cdot \prod_{cc} \left(\frac{\left(1 - \overline{CSE}_{cc,cty}\right) \cdot PC_{cc,cty}}{\left(1 - \overline{CSEBASE}_{cc,cty}\right) \cdot \overline{PCBASE}_{cc,cty}} \right)^{elhp_{c,cc,cty}} \cdot \frac{\overline{POP}_{cty}}{\overline{POPBASE}_{cty}} \end{aligned} \tag{QHEQ}$$

Feed Demand

$$QF_{cfeed,cty} = \sum_{bas} \sum_{aliv} QFEED_{aliv,cfeed,cty} \tag{QFEEDEQ}$$

Intermediate Input Demand for Processing

$$QI_{cint,cty} = \sum_{apro} QINT_{apro,cint,bas,cty} \tag{QINTEQ}$$

Biofuel Demand

$$QBIO_{c,cty} = \overline{QBIOBASE}_{c,cty} \cdot \prod_{cc} \left(\frac{(1 - \overline{CSE}_{cc,cty}) \cdot PC_{cc,cty}}{(1 - \overline{CSEBASE}_{cc,cty}) \cdot \overline{PCBASE}_{cc,cty}} \right)^{elhp_{c,cc,cty}} \tag{QBIOEQ}$$

Seed Demand

$$QSEED_{c,cty} = \overline{QSEEDBASE}_{c,cty} \cdot \frac{\overline{POP}_{cty}}{\overline{POPBASE}_{cty}} \cdot \prod_{cc} \left(\frac{(1 - \overline{CSE}_{cc,cty}) \cdot PC_{cc,cty}}{(1 - \overline{CSEBASE}_{cc,cty}) \cdot \overline{PCBASE}_{cc,cty}} \right)^{elhp_{c,cc,cty}} \tag{QSEEDEQ}$$

Tourist Consumption Demand

$$QTOUR_{c,cty} = \overline{QTOURBASE}_{c,cty} \cdot \prod_{cc} \left(\frac{(1 - \overline{CSE}_{cc,cty}) \cdot PC_{cc,cty}}{(1 - \overline{CSEBASE}_{cc,cty}) \cdot \overline{PCBASE}_{cc,cty}} \right)^{elhp_{c,cc,cty}} \tag{QTOUREQ}$$

Loss and Waste

$$QLOSS_{c,cty} = QDEM_{c,cty} \cdot \overline{LOSSRATE}_{c,cty} \tag{QLOSSEQ}$$

$$QWASTE_{c,cty} = QH_{c,cty} \cdot \overline{WASTERATE}_{c,cty} \tag{QWASTEEQ}$$

Other Demand

$$QOTH_{c,cty} = \overline{QOTHBASE}_{c,cty} \cdot \prod_{cc} \left(\frac{(1 - \overline{CSE}_{cc,cty}) \cdot PC_{cc,cty}}{(1 - \overline{CSEBASE}_{cc,cty}) \cdot \overline{PCBASE}_{cc,cty}} \right)^{elhp_{c,cc,cty}} \tag{QOTHEQ}$$

4.2 Production Block

The production block describes the equations determining the production quantities of each food commodity, the input of intermediate goods and production factors, and the producer prices. Primary crops are differentiated by production technologies (irrigated and rainfed), while livestock products are distinguished by climate zones and production systems (pasture-based or mixed). Yield improvements due to technological progress and climate impacts are considered for crops, and productivity changes in livestock are captured through feed requirements and feed share. For energy crops, production quantities by year and macro-region are given exogenously from AIM-Hub, and allocated to production units according to price and yield.

4.2.1 Crop Production

The livestock production block describes equations for determining livestock output, production systems, feed requirements, and associated prices. Livestock products are distinguished by climate zones and production systems (pasture-based or mixed). Feed use and production efficiency depend on feed composition, feed efficiency, and animal productivity.

Domestic Production

$$QSUP_{a,cty} = \sum_{bas} QS_{a,bas,cty} \tag{QSUPEQ}$$

Crop Production by Technology

$$QSWAT_{acro,bas,cty,water} = QS_{acro,bas,cty} \cdot watshare_{acro,bas,cty,water} \tag{CROWATEREQ}$$

Producer Price of Crops

$$\begin{aligned} PP_{acro,cty} = \Big(& PL_{acro,bas,cty} \cdot \sum_{water} \frac{watshare_{acro,bas,cty,water}}{YLD_{acro,bas,cty,water} \cdot \overline{CROPINTENSITY}_{acro,bas,cty,water}} \\ &+ PO_{acro,bas,cty}\Big) / \left(1 + PPCOMP_{acro,bas,cty}\right) \end{aligned} \tag{PPCROEQ}$$

Land Input for Crop Production

$$QL_{acro,bas,cty} = QS_{acro,bas,cty} \cdot \sum_{water} \frac{watshare_{acro,bas,cty,water}}{YLD_{acro,bas,cty,water} \cdot \overline{CROPINTENSITY}_{acro,bas,cty,water}} \tag{QLCROINPUTEQ}$$

Crop Yield

$$\begin{aligned} YLD_{acro,bas,cty,water} = {} & \overline{YLDBASE}_{acro,bas,cty,water} \cdot \overline{YLDGR}_{acro,bas,cty,water} \\ & \cdot \overline{YLDCHAN}_{acro,bas,cty,water} \end{aligned} \tag{YLDEQ}$$

Other Production Factor Price

$$PO_{acro,bas,cty} = \overline{POBASE}_{acro,bas,cty} \cdot \left(\frac{QS_{acro,bas,cty}}{\overline{QSPRE}_{acro,bas,cty}}\right)^{elop_{acro,cty}} \tag{POCROEQ}$$

4.2.2 Livestock Production

The livestock production block describes equations for determining livestock output, production systems, feed requirements, and associated prices. Livestock products are distinguished by climate zones and production systems (pasture-based or mixed). Feed use and production efficiency depend on feed composition, feed efficiency, and animal productivity.

Livestock Production by System

$$QSSYS_{aliv,bas,cty,cz,sys} = QS_{aliv,bas,cty} \cdot czshare_{aliv,bas,cty,cz} \cdot SYSSHARE_{aliv,bas,cty,cz,sys} \tag{LIVSYSEQ}$$

Livestock System Share Function

$$SYSSHARE_{aliv,bas,cty,cz,sys} = \frac{1}{1 + \delta^{sys}_{aliv,cz,sys} \cdot \overline{GDPPC}_{cty}^{\rho^{sys}_{aliv,sys}}} + res_{aliv,bas,cty,cz,sys} \tag{SYSSHAREEQ}$$

Producer Price of Livestock

$$\begin{aligned} PP_{aliv,cty} = \Big(& PL_{aliv,bas,cty} / ANIMALYLD_{aliv,bas,cty} \\ & + pfeedcoef_{aliv,cty} \cdot \sum_{cfeed} (1 - \overline{CSE}_{cfeed,cty}) \cdot PC_{cfeed,cty} \\ & \cdot \sum_{cz,sys} \left(czshare_{aliv,bas,cty,cz} \cdot SYSSHARE_{aliv,bas,cty,cz,sys} \cdot ICL_{aliv,cfeed,bas,cty,cz,sys} \right) \\ & + PO_{aliv,bas,cty} \Big) / (1 + PPCOMP_{aliv,bas,cty}) \end{aligned} \tag{PPLIVEQ}$$

Grass Input Calculation

$$\begin{aligned} Qgrass_{aliv,bas,cty} = & \frac{QS_{aliv,bas,cty}}{\overline{ANIMALPRODRATE}_{aliv,cty}} \\ & \cdot \sum_{cz,sys} \Big(czshare_{aliv,bas,cty,cz} \cdot SYSSHARE_{aliv,bas,cty,cz,sys} \\ & \cdot \overline{FEEDEFFICIENCY}_{aliv,bas,cty,cz,sys} \cdot (1 - \overline{FEEDSHARE}_{aliv,bas,cty,cz,sys}) \Big) \end{aligned} \tag{QGRASSINPUTEQ}$$

Available Grassland Area

$$\begin{aligned} Qgrass_{aliv,bas,cty} = & \left(QL_{aliv,bas,cty} - \overline{QLRES}_{aliv,bas,cty} \right) \\ & \cdot \overline{GRASSYLD}_{bas,cty} \cdot grassusagerate_{bas,cty} \end{aligned} \tag{QLLIVINPUTEQ}$$

Livestock Yield

$$ANIMALYLD_{aliv,bas,cty} = \frac{QS_{aliv,bas,cty}}{QL_{aliv,bas,cty} - \overline{QLRES}_{aliv,bas,cty}} \tag{ANIMALYLDEQ}$$

Feed Input Calculation

$$\begin{aligned} QFEED_{aliv,cfeed,bas,cty} = & \frac{QS_{aliv,bas,cty}}{\overline{ANIMALPRODRATE}_{aliv,cty}} \\ & \cdot \sum_{cz,sys} \big(czshare_{aliv,bas,cty,cz} \cdot SYSSHARE_{aliv,bas,cty,cz,sys} \\ & \cdot ICL_{aliv,cfeed,bas,cty,cz,sys} \big) \end{aligned} \tag{QFEEDINPUTEQ}$$

Feed Input Coefficient

$$\begin{aligned} ICL_{aliv,cfeed,bas,cty,cz,sys} = & \overline{FEEDEFFICIENCY}_{aliv,bas,cty,cz,sys} \\ & \cdot \overline{FEEDSHARE}_{aliv,bas,cty,cz,sys} \cdot \overline{GRAINSHARE}_{aliv,cfeed,bas,cty,cz,sys} \end{aligned} \tag{ICLEQ}$$

Other Production Factor Price (Livestock)

$$PO_{aliv,bas,cty} = \overline{POBASE}_{aliv,bas,cty} \cdot \left(\frac{QS_{aliv,bas,cty}}{\overline{QSPRE}_{aliv,bas,cty}} \right)^{elop_{aliv,cty}} \tag{POLIVEQ}$$

Livestock Production Quantity

$$\begin{aligned} QS_{aliv,bas,cty} = & \overline{ANIMALWEIGHT}_{aliv,cty} \cdot (ANIMAL_{aliv,bas,cty} - \overline{ANIMALRES}_{aliv,bas,cty}) \\ & \cdot \overline{ANIMALPRODRATE}_{aliv,cty} \end{aligned} \tag{ANIMALEQ}$$

4.2.3 Processed Goods produciton

This section describes the production equations for processed agricultural products. Processed products are produced using intermediate inputs and other production factors.

Producer Price of Processed Products

$$\begin{aligned} PP_{apro,cty} = & pintcoef_{apro,cty} \cdot \sum_{cint} \Big((1 - \overline{CSE}_{cint,cty}) \cdot PC_{cint,cty} \cdot ica_{apro,cint,cty} \Big) \\ & + PO_{apro,cty} \end{aligned} \tag{PPPROEQ}$$

Intermediate Input Demand for Processed Products

$$QINT_{apro,cint,cty} = QSUP_{apro,cty} \cdot ica_{apro,cint,cty} \tag{QINTINPUTEQ}$$

Other Production Factor Price (Processed Products)

$$PO_{apro,cty} = \overline{POBASE}_{apro,cty} \cdot \left(\frac{QSUP_{apro,cty}}{\overline{QSUPRE}_{apro,cty}} \right)^{elop_{apro,cty}} \tag{POPROEQ}$$

4.2.4 Energy Crop Production

Energy crop production is determined from regional totals provided exogenously by the AIM-Hub model.

Regional Energy Crop Supply Balance

$$\overline{QENE}_{region} = \sum_{bas,cty \in region} QS_{\mathrm{ecr},bas,cty} \tag{QSENEEQ}$$

Land Input for Energy Crops

$$QL_{\mathrm{ecr},bas,cty} = \frac{QS_{\mathrm{ecr},bas,cty}}{YLD_{\mathrm{ecr},bas,cty}} \tag{QLENEINPUTEQ}$$

Land Price for Energy Crops

$$PL_{\mathrm{ecr},bas,cty} = PENE_{region} \tag{PLENEEQ}$$

4.3 Land Use Block

The land-use block allocates available land among different uses through a Logit function. Prices for non-human-used land (forest, other natural land, and fallow land) are fixed at their baseline values. A constraint is imposed to ensure that total agricultural land does not exceed the physically available land area due to slope and soil limitations. Afforestation areas are given exogenously from AIM-PLUM results.

Vegetation Area

$$QLVEG_{bas,cty} = \overline{QLTOT}_{bas,cty} - \overline{QLVEGN}_{bas,cty} - \overline{QLAFR}_{bas,cty} \tag{QLVEGEQ}$$

Pasture Area Allocation

$$QLPAS_{bas,cty} = QLVEG_{bas,cty} \cdot \frac{\delta_{pas,bas,cty} \cdot PLPAS_{bas,cty}^{\rho_{pas,bas,cty}}}{\delta_{pas,bas,cty} \cdot PLPAS_{bas,cty}^{\rho_{pas,bas,cty}} + \delta_{pasn,bas,cty} \cdot PLPASN_{bas,cty}^{\rho_{pasn,bas,cty}}} \tag{QLPASEQ}$$

Non-pasture Grassland Area

$$QLPASN_{bas,cty} = QLVEG_{bas,cty} \cdot \frac{\delta_{pasn,bas,cty} \cdot PLPASN_{bas,cty}^{\rho_{pasn,bas,cty}}}{\delta_{pas,bas,cty} \cdot PLPAS_{bas,cty}^{\rho_{pas,bas,cty}} + \delta_{pasn,bas,cty} \cdot PLPASN_{bas,cty}^{\rho_{pasn,bas,cty}}} \tag{QLPASNEQ}$$

Cropland Area

$$QLCRO_{bas,cty} = QLPASN_{bas,cty} \cdot \frac{\delta_{cro,bas,cty} \cdot PLCRO_{bas,cty}^{\rho_{cro,bas,cty}}}{\delta_{cro,bas,cty} \cdot PLCRO_{bas,cty}^{\rho_{cro,bas,cty}} + \delta_{frs,bas,cty} \cdot \overline{PLFRS}_{bas,cty}^{\rho_{frs,bas,cty}} + \delta_{gra,bas,cty} \cdot \overline{PLGRA}_{bas,cty}^{\rho_{gra,bas,cty}}} \tag{QLCROEQ}$$

Forest Area

$$QLFRS_{bas,cty} = QLPASN_{bas,cty} \cdot \frac{\delta_{frs,bas,cty} \cdot PLFRS_{bas,cty}^{\rho_{frs,bas,cty}}}{\delta_{cro,bas,cty} \cdot PLCRO_{bas,cty}^{\rho_{cro,bas,cty}} + \delta_{frs,bas,cty} \cdot \overline{PLFRS}_{bas,cty}^{\rho_{frs,bas,cty}} + \delta_{gra,bas,cty} \cdot \overline{PLGRA}_{bas,cty}^{\rho_{gra,bas,cty}}} \tag{QLFRSEQ}$$

Other Natural Land

$$QLGRA_{bas,cty} = QLPASN_{bas,cty} \cdot \frac{\delta_{gra,bas,cty} \cdot PLGRA_{bas,cty}^{\rho_{gra,bas,cty}}}{\delta_{cro,bas,cty} \cdot PLCRO_{bas,cty}^{\rho_{cro,bas,cty}} + \delta_{frs,bas,cty} \cdot \overline{PLFRS}_{bas,cty}^{\rho_{frs,bas,cty}} + \delta_{gra,bas,cty} \cdot \overline{PLGRA}_{bas,cty}^{\rho_{gra,bas,cty}}} \tag{QLGRAEQ}$$

Harvested Cropland Area

$$QLCROCLT_{bas,cty} = QLCRO_{bas,cty} \cdot \frac{\delta_{croclt,bas,cty} \cdot PLCROCLT_{bas,cty}^{\rho_{croclt,bas,cty}}}{\delta_{croclt,bas,cty} \cdot PLCROCLT_{bas,cty}^{\rho_{croclt,bas,cty}} + \delta_{crofal,bas,cty} \cdot \overline{PLCROFAL}_{bas,cty}^{\rho_{crofal,bas,cty}}} \tag{QLCROCLTEQ}$$

Fallow Cropland Area

$$
\begin{aligned}
QLCROFAL_{bas,cty} &= QLCRO_{bas,cty} \\
&\cdot \frac{\delta_{crofal,bas,cty} \cdot \overline{PLCROFAL}_{bas,cty}^{\rho_{crofal,bas,cty}}}{\delta_{croclt,bas,cty} \cdot PLCROCLT_{bas,cty}^{\rho_{croclt,bas,cty}} + \delta_{crofal,bas,cty} \cdot \overline{PLCROFAL}_{bas,cty}^{\rho_{crofal,bas,cty}}}
\end{aligned}
\tag{QLCROFALEQ}
$$

Cropland Allocation

$$
QL_{acro,bas,cty} = QLCROCLT_{bas,cty} \cdot \frac{\delta_{acro,bas,cty} \cdot PL_{acro,bas,cty}^{\rho_{acro,bas,cty}}}{\sum_{acro} \delta_{acro,bas,cty} \cdot PL_{acro,bas,cty}^{\rho_{acro,bas,cty}}} \tag{QLCRODISTEQ}
$$

Pasture Allocation

$$
QL_{aliv,bas,cty} = QLPAS_{bas,cty} \cdot \frac{\delta_{aliv,bas,cty} \cdot PL_{aliv,bas,cty}^{\rho_{aliv,bas,cty}}}{\sum_{aliv} \delta_{aliv,bas,cty} \cdot PL_{aliv,bas,cty}^{\rho_{aliv,bas,cty}}} \tag{QLLIVDISTEQ}
$$

Land Prices

$$
PLCROCLT_{bas,cty} \cdot QLCROCLT_{bas,cty} = \sum_{acro} PL_{acro,bas,cty} \cdot QL_{acro,bas,cty} \tag{PLCROCLTEQ}
$$

$$
\begin{aligned}
PLCRO_{bas,cty} \cdot QLCRO_{bas,cty} = \big(&PLCROCLT_{bas,cty} \cdot QLCROCLT_{bas,cty} \\
&+ \overline{PLCROFAL}_{bas,cty} \cdot QLCROFAL_{bas,cty}\big) \\
&/(1 + PLCOMP_{bas,cty})
\end{aligned}
\tag{PLCROEQ}
$$

$$
\begin{aligned}
PLPASN_{bas,cty} \cdot QLPASN_{bas,cty} = &PLCRO_{bas,cty} \cdot QLCRO_{bas,cty} \\
&+ \overline{PLFRS}_{bas,cty} \cdot QLFRS_{bas,cty} \\
&+ \overline{PLGRA}_{bas,cty} \cdot QLGRA_{bas,cty}
\end{aligned}
\tag{PLPASNEQ}
$$

$$
PLPAS_{bas,cty} \cdot QLPAS_{bas,cty} = \frac{\sum_{aliv} PL_{aliv,bas,cty} \cdot QL_{aliv,bas,cty}}{1 + PLCOMP_{bas,cty}} \tag{PLPASEQ}
$$

Agricultural Land Constraint

$$
\overline{QLLIM}_{cty} \geq QLCRO_{bas,cty} + QLPAS_{bas,cty} \;\perp\; PLCOMP_{bas,cty} \geq 0 \tag{QLLIMEQ}
$$

4.4 Market Block

This subsection describes the equations in the market block, where consistency between food demand and supply is ensured. Trade of food commodities is represented as a complementarity problem. When the import price is higher than the border price, the import quantity becomes zero. Once the import price decreases to equal the border price, imports begin. Similarly, when the border price is higher than the export price, exports become zero, and once the export price rises to match the border price, exports take place.

Domestic Trade Balance

$$NT_{c,cty} = QSUP_{c,cty} - QDEM_{c,cty} - \overline{QST}_{c,cty} \tag{NTEQ}$$

$$NT_{c,cty} = QE_{c,cty} - QM_{c,cty} \tag{QEQMEQ}$$

International Trade Balance

$$\sum_{cty} NT_{c,cty} - \overline{QRES}_c = 0 \tag{NT0EQ}$$

Import and Export Conditions

$$PM_{c,cty} \geq PB_{c,cty} \quad \perp \quad QM_{c,cty} \geq 0 \tag{PBPMEQ}$$

$$PB_{c,cty} \geq PE_{c,cty} \quad \perp \quad QE_{c,cty} \geq 0 \tag{PBPEEQ}$$

4.5 GHG Emission Block

This subsection describes the equations in the GHG emission block. GHG emissions are calculated based on the production quantities of each food commodity. When carbon prices are considered, the amount of mitigation technology adoption and its cost are computed from the MAC (Marginal Abatement Cost) curve. Emissions from the land-use sector are calculated according to each land area.

GHG Emissions

$$GHG_{a,src,gas,cty} = QSUP_{a,cty} \cdot \overline{EF}_{a,src,gas,cty} \cdot (1 - RR_{a,src,gas,cty}) \tag{GHGEQ}$$

Land-Use Emissions

$$\begin{aligned} GHGLU_{src,gas,bas,cty} = {} & \overline{EF\_LU}_{src,gas,cty} \cdot QLFRS_{bas,cty} + \overline{EF\_LU}_{src,gas,cty} \cdot QLGRA_{bas,cty} \\ & + \overline{EF\_LU}_{src,gas,cty} \cdot QLCRO_{bas,cty} + \overline{EF\_LU}_{src,gas,cty} \cdot QLPAS_{bas,cty} \end{aligned} \tag{GHGLUEQ}$$

Emission Reduction Rate

$$RR_{a,src,gas,cty} = \overline{MRP}_{src,gas,cty} \cdot \left(1 - \left[1/(1 + \overline{PRCCAR}_{cty})\right]^{\sigma_{src,gas,cty}}\right) \tag{RREQ}$$

Abatement Cost

$$AC_{a,cty} = \sum_{src,gas} \overline{EF}_{a,src,gas,cty} \cdot \left[\frac{\sigma_{src,gas,cty}}{(\sigma_{src,gas,cty} - 1)} \cdot \overline{MRP}_{src,gas,cty} \cdot \left(1 - (1 - RR_{a,src,gas,cty}/\overline{MRP}_{src,gas,cty})^{(1-1/\sigma_{src,gas,cty})}\right) - RR_{a,src,gas,cty} \right] \tag{ACEQ}$$

Carbon Cost on Remaining Emissions

$$PCB_{a,cty} = \sum_{src,gas} \overline{PRCCAR}_{cty} \cdot \overline{EF}_{a,src,gas,cty} \cdot (1 - RR_{a,src,gas,cty}) \tag{PCBEQ}$$

4.6 Complementarity Conditions

This subsection describes the complementarity conditions introduced to avoid numerical errors in the Logit function when production quantities in specific production units become zero. If the production of a unit becomes zero, its land-use area would also become zero, leading to instability. Therefore, a minimum positive value is imposed to ensure that production quantities do not fall to zero.

Minimum Production Share for Trade

$$\frac{QSUP_{c,cty}}{QM_{c,cty}} \geq 0.01 \quad \perp \quad TMCOMP_{c,cty} \geq 0 \tag{DEPQMEQ}$$

Minimum Production Share for Supply

$$\frac{QS_{a,bas,cty}}{QSUP_{a,cty}} \geq 0.01 \quad \perp \quad PPCOMP_{a,bas,cty} \geq 0 \tag{QSBOUEQ}$$

5 Data and Preprocessing

This section explains the calibration and processing of data used in the model. Exogenous variables and parameters were estimated using multiple datasets, adjusted to obtain equilibrium in the base year, and parameters were estimated by regression analysis.

5.1 Data Sources

Table 6 lists the datasets used in the model.

Table 6: List of data sources

Data Source	Dataset Name	URL
FAOSTAT	Food Balances	`https://www.fao.org/faostat/en/#data/FBS`
FAOSTAT	Production	`https://www.fao.org/faostat/en/#data/QCL`
FAOSTAT	Trade	`https://www.fao.org/faostat/en/#data/TCL`
FAOSTAT	Producer Prices	`https://www.fao.org/faostat/en/#data/PP`
FAOSTAT	Land Use	`https://www.fao.org/faostat/en/#data/RL`
FAOSTAT	Emissions	`https://www.fao.org/faostat/en/#data/GCE`
AQUASTAT	Major hydrological basins of the world	`https://data.apps.fao.org/catalog//iso/7707086d-af3c-41cc-8aa5-323d8609b2d1`
FAO and IIASA	GAEZ v4	`https://gaez.fao.org/`
IIASA	SSP 3.0	`https://data.ece.iiasa.ac.at/ssp/#/about`
GTAP	GTAP 10	`https://jgea.org/ojs/index.php/jgea/article/view/77`

Continued on next page

Table 6: List of data sources (continued)

Data Source	Dataset Name	URL
IFPRI	MAPSPAM	https://doi.org/10.7910/DVN/SWPENT
World Bank	World Bank Open Data	https://data.worldbank.org/
EDGAR	EDGAR v8.0	https://edgar.jrc.ec.europa.eu/dataset_ghg80
Herrero Acosta et al. (2018)	Livestock production systems	https://doi.org/10.4225/08/5aa068b33fe06
Muhammad et al. (2011)	International Evidence on Food Consumption Patterns	http://199.135.94.241/publications/pub-details/?pubid=47581
T. P. Robinson et al. (2018)	Global distribution of ruminant livestock production systems V5	https://doi.org/10.7910/DVN/WPDSZE
Harmsen et al. (2019)	CH_4 and N_2O MAC curves	https://doi.org/10.1016/j.envsci.2019.05.013
Hurtt et al. (2019)	Land Use Harmonization 2	https://luh.umd.edu/index.shtml

5.2 Calibration and processing of data

5.2.1 Adjustment of demand-side data

First, the adjustment of demand-side data was conducted. In the model, if a country–commodity pair has missing data for the base year 2015, it is assumed that consumption does not occur thereafter. Therefore, for country–commodity pairs without 2015 data in the Food Balance Sheets (FBS), the average value of subsequent years was used as the 2015 consumption level.

$$QH_{(c,cty,2015)} = \frac{\sum_{yr} QH^{FAO}_{(c,cty,yr)}}{N_{yr}} \quad \text{for } QH_{(c,cty,2015)} = \text{NA} \tag{5.1}$$

where QH^{FAO} is household consumption data from FAO, and N_{yr} is the number of years for which data exist.

In the FBS data, household consumption includes the amount of food wasted at the household level. To distinguish this, waste rates by seven commodities and seven regions were obtained from FAO (2011). Using these coefficients, household consumption and food waste were estimated as follows:

$$QWASTE_{(c,cty)} = QH^{FAO}_{(c,cty)} \times WASTERATE_{(c,cty)} \tag{5.2}$$
$$QH_{(c,cty)} = QH^{FAO}_{(c,cty)} \times (1 - WASTERATE_{(c,cty)}) \tag{5.3}$$

For model simplification, the commodities used as livestock feed, processing materials, and biofuel inputs were limited. Wheat, rice, maize, other cereals, roots and tubers, sugar crops, pulses, oil crops, and vegetables were used as livestock feed. Wheat, rice, maize, other cereals, and fruits were used as raw materials for alcoholic beverages. Sugar crops were used as inputs for sugars, oil crops for vegetable oils, and maize, sugar crops, and vegetable oils for biofuels. Feed demand, intermediate input demand, and biofuel demand for other commodities were set to zero.

$$QF_{(c \notin c_{feed},cty)} = 0 \tag{5.4}$$
$$QBIO_{(c \notin c_{bio},cty)} = 0 \tag{5.5}$$
$$QI_{(c \notin c_{int},cty)} = 0 \tag{5.6}$$

As a result of these adjustments, the total domestic demand changed. If the sum of all demand components was less than the total demand from the data, the residual was added as “other demand”:

$$\begin{aligned} QOTH_{(c,cty)} = QDEM_{(c,cty)} - &\big(QH_{(c,cty)} + QF_{(c,cty)} + QI_{(c,cty)} + QSEED_{(c,cty)} + \\ &QTOUR_{(c,cty)} + QLOSS_{(c,cty)} + QWASTE_{(c,cty)}\big) \end{aligned} \tag{5.7}$$

5.2.2 Adjustment of crop production data

Next, the adjustment of crop production data was conducted. From the FBS data, the production quantities of primary crops for each country were obtained. These were disaggregated into production units and production technologies using the GAEZ data as follows:

$$QSWAT_{(acro,bas,cty,water)} = QSUP^{FAO}_{(acro,cty)} \times \frac{QS^{GAEZ}_{(acro,bas,cty,water)}}{\sum_{(bas,water)} QS^{GAEZ}_{(acro,bas,cty,water)}} \tag{5.8}$$

where $QSUP^{FAO}$ denotes production quantity data from FAO, and QS^{GAEZ} represents production data from GAEZ.

From the LUH2 dataset, the cultivated land area for each production unit was obtained. Using the FAOSTAT data on national land use, these cultivated lands were divided into harvested and fallow lands as follows:

$$QLCROCLT_{(bas,cty)} = QLCRO^{LUH2}_{(bas,cty)} \times \frac{QLCROCLT^{FAO}_{cty}}{QLCROCLT^{FAO}_{cty} + QLCROFAL^{FAO}_{cty}} \tag{5.9}$$

$$QLCROFAL_{(bas,cty)} = QLCRO^{LUH2}_{(bas,cty)} \times \frac{QLCROFAL^{FAO}_{cty}}{QLCROCLT^{FAO}_{cty} + QLCROFAL^{FAO}_{cty}} \tag{5.10}$$

where $QLCRO^{LUH2}$ denotes cultivated area data from LUH2, $QLCROCLT^{FAO}$ is harvested land area data from FAO, and $QLCROFAL^{FAO}$ is fallow land area data from FAO.

Furthermore, the harvested land was disaggregated by crop type and production technology using GAEZ data as follows:

$$QLWAT_{(acro,bas,cty,water)} = QLCROCLT_{(bas,cty)} \times \frac{QL^{GAEZ}_{(acro,bas,cty,water)}}{\sum_{(acro,water)} QL^{GAEZ}_{(acro,bas,cty,water)}} \tag{5.11}$$

where $QLWAT$ is the cropland area by crop type and production technology, and QL^{GAEZ} is the crop-specific land area from GAEZ.

From the MAPSPAM dataset, harvested and physical area data were obtained for each crop, production unit, and production technology. Using these data, the cropping intensity was estimated as follows:

$$CROPINTESNSITY_{(acro,bas,cty,water)} = \frac{QLHARVESTED^{MAPSPAM}_{(acro,bas,cty,water)}}{QLPHYSICAL^{MAPSPAM}_{(acro,bas,cty,water)}} \tag{5.12}$$

where $QLHARVESTED^{MAPSPAM}$ is the harvested area data from MAPSPAM, and $QLPHYSICAL^{MAPSPAM}$ is the physical area data from MAPSPAM.

Crop yields were calculated using the obtained production quantities, harvested areas, and cropping intensities as follows:

$$YLD_{(acro,bas,cty,water)} = \frac{QSWAT_{(acro,bas,cty,water)}}{QLWAT_{(acro,bas,cty,water)} \times CROPINTSNSITY_{(acro,bas,cty,water)}} \tag{5.13}$$

5.2.3 Adjustment of livestock production data

Next, the adjustment of livestock production data was conducted. From FAO data, the numbers of livestock animals and slaughtered (or milked) animals were obtained. Using these, the production rate was calculated. A minimum threshold of 0.3 was set for the production rate; if it fell below this value, it was assumed that a portion of livestock was not involved in production activities.

$$ANIMALPRODRATE_{(aliv,cty)} = \frac{ANIMAL^{FAO}_{(aliv,cty)}}{ANIMALSTOCK^{FAO}_{(aliv,cty)}} \tag{5.14}$$

$$ANIMALRES_{(aliv,cty)} = ANIMALSTOCK^{FAO}_{(aliv,cty)} - \frac{ANIMAL^{FAO}_{(aliv,cty)}}{0.3} \quad (\text{if } ANIMALPRODRATE_{(ali} \tag{5.15}$$

where $ANIMAL^{FAO}$ is the number of slaughtered (or milked) animals from FAO, and $ANIMALSTOCK^{FAO}$ is the total livestock population.

When non-productive livestock exist, the corresponding unused pasture area was estimated as:

$$QLPASRES_{(aliv,cty)} = QLPAS^{LUH2}_{(aliv,cty)} \times \frac{ANIMALRES_{(aliv,cty)}}{ANIMALSTOCK^{FAO}_{(aliv,cty)}} \tag{5.16}$$

where $QLPASRES$ denotes the unused pasture area, and $QLPAS^{LUH2}$ is the pasture area from LUH2.

Country-level livestock production data from the FBS were disaggregated into production units, climate zones, and production systems using the dataset from Herrero Acosta et al. (2018). Similarly, LUH2 pasture area data were disaggregated by livestock type, climate zone, and production system.

$$QSSYS_{(aliv,bas,cty,cz,sys)} = QSUP^{FAO}_{(aliv,cty)} \times \frac{QS^{HERRERO}_{(aliv,bas,cty,cz,sys)}}{\sum_{(bas,cz,sys)} QS^{HERRERO}_{(aliv,bas,cty,cz,sys)}} \tag{5.17}$$

$$QLSYS_{(aliv,bas,cty,cz,sys)} = \left(QLPAS^{LUH2}_{(cty,bas)} - QLPASRES_{(aliv,cty)}\right) \times \frac{QGRASS^{HERRERO}_{(aliv,bas,cty,cz,sys)}}{\sum_{(aliv,cz,sys)} QGRASS^{HERRERO}_{(aliv,bas,cty,cz,sys)}} \tag{5.18}$$

where $QS^{HERRERO}$ denotes production data and $QGRASS^{HERRERO}$ represents pasture use data from Herrero Acosta et al. (2018).

Next, the feed efficiency and concentrate feed share were estimated as follows:

$$FEEDEFFICIENCY_{(aliv,bas,cty,cz,sys)} = \frac{QF^{HERRERO}_{(aliv,bas,cty,cz,sys)} + QGRASS^{HERRERO}_{(aliv,bas,cty,cz,sys)}}{QS^{HERRERO}_{(aliv,bas,cty,cz,sys)}} \tag{5.19}$$

$$FEEDSHARE_{(aliv,bas,cty,cz,sys)} = \frac{QF^{HERRERO}_{(aliv,bas,cty,cz,sys)}}{QF^{HERRERO}_{(aliv,bas,cty,cz,sys)} + QGRASS^{HERRERO}_{(aliv,bas,cty,cz,sys)}} \tag{5.20}$$

where $QF^{HERRERO}$ is the amount of concentrate feed from Herrero Acosta et al. (2018).

Using these values and the FBS feed demand data, the quantities of pasture and concentrate feed use were estimated. The amount of concentrate feed input was adjusted with a correction coefficient to ensure consistency with the FBS data. Consequently, the feed efficiency and concentrate feed share were also adjusted. If the estimated pasture use exceeded the available supply, it was replaced with the available amount.

$$QFEEDSYS^{temp}_{(aliv,cfeed,bas,cty,cz,sys)} = \frac{QSSYS_{(aliv,bas,cty,cz,sys)}}{ANIMALPRODRATE_{(aliv,cty)}} \times FEEDEFFICIENCY_{(aliv,bas,cty,cz,sys)} \tag{5.21}$$

$$qfcoef_{(cfeed,cty)} = \frac{QF^{FAO}_{(cfeed,cty)}}{\sum_{(aliv,bas,cz,sys)} QFEEDSYS^{temp}_{(aliv,cfeed,bas,cty,cz,sys)}} \tag{5.22}$$

$$QFEEDSYS_{(aliv,cfeed,bas,cty,cz,sys)} = QFEEDSYS^{temp}_{(aliv,cfeed,bas,cty,cz,sys)} \times qfcoef_{(cfeed,cty)} \tag{5.23}$$

$$QGRASSSYS_{(aliv,bas,cty,cz,sys)} = \frac{QSSYS_{(aliv,bas,cty,cz,sys)}}{ANIMALPRODRATE_{(aliv,cty)}} \times FEEDEFFICIENCY_{(aliv,bas,cty,cz,sys)} \tag{5.24}$$

If the estimated pasture demand exceeded the available supply, it was replaced with the available amount:

$$QGRASSSYS_{(aliv,bas,cty,cz,sys)} = QLSYS_{(aliv,bas,cty,cz,sys)} \times GRASSYLD_{(bas,cty)} \quad \text{if } QLSYS_{(aliv,bas,cty,cz,sys)} \times G \tag{5.25}$$

where:

- $QFEEDSYS^{temp}$: estimated feed demand by production system,
- QF^{FAO}: feed demand data from FAO,
- $qfcoef$: adjustment coefficient for consistency with FAO feed demand,
- $QFEEDSYS$: adjusted feed demand consistent with FAO data,
- $QGRASSSYS$: pasture demand by production system.

5.2.4 Adjustment of food trade

Next, the adjustment of food trade data was conducted. In order to express trade through complementary conditions, the net import and net export quantities were derived as follows:

$$QM_{(c,cty)} = QM^{FAO}_{(c,cty)} - QE^{FAO}_{(c,cty)} \quad (\text{if } QM^{FAO}_{(c,cty)} > QE^{FAO}_{(c,cty)}) \tag{5.26}$$

$$QE_{(c,cty)} = QE^{FAO}_{(c,cty)} - QM^{FAO}_{(c,cty)} \quad (\text{if } QE^{FAO}_{(c,cty)} > QM^{FAO}_{(c,cty)}) \tag{5.27}$$

where QM^{FAO} denotes the import quantity data from FAO, and QE^{FAO} denotes the export quantity data from FAO.

In the FBS dataset, global trade is not balanced; that is, the total export quantity and total import quantity of the world do not match. Therefore, the global discrepancy between total exports and imports was treated as a residual. This residual can be interpreted as trade with countries or regions outside the model scope, as well as losses occurring during international food transport.

$$QRES_c = \sum_{cty} QM_{(c,cty)} - \sum_{cty} QE_{(c,cty)} \tag{5.28}$$

5.2.5 Estimation of land constraints

Next, the estimation method for land areas unsuitable for agricultural use due to soil and topographical constraints is described. From the GAEZ dataset, area data for 57 agro-ecological zone (AEZ) classes, classified according to climate, soil, and topographical conditions, were obtained. Among these, land classes with strong constraints were selected and considered unsuitable for agricultural use. The area of such constrained land was calculated as follows:

$$QLLIM_{(bas,cty)} = QLTOT^{LUH2}_{(bas,cty)} \times \frac{\sum_{aezlim} QL^{GAEZ}_{(aezlim,bas,cty)}}{\sum_{aez} QL^{GAEZ}_{(aez,bas,cty)}} \tag{5.29}$$

where:

- $QLTOT^{LUH2}$: total land area from LUH2,
- QL^{GAEZ}: area data by AEZ class from GAEZ,
- aez: the set of 57 AEZ classes,
- $aezlim \in aez$: AEZ classes with severe land-use constraints.

5.2.6 Adjustment of price data

From the FAO dataset, producer prices, import prices, and export prices for each country and commodity were obtained. Since the price data contained many outliers and missing values, appropriate preprocessing was conducted.

First, outlier values were treated as missing when the producer price was greater than ten times or less than one-tenth of the country-level median.

$$PP_{(c,cty)} \leftarrow \text{NA} \quad \text{if } \left(PP_{(c,cty)} > 10{\times}\text{median}_{cty}(PP_{(c,cty)}) \cup PP_{(c,cty)} < 0.1{\times}\text{median}_{cty}(PP_{(c,cty)})\right) \tag{5.30}$$

Next, missing values were complemented. A world average price was calculated from the available country-level producer prices, weighted by production quantities. A country-specific correction coefficient was then derived based on the deviation of each country's prices from the world average. This coefficient was used to impute the missing prices. The same procedure was applied for import and export prices.

$$PP_{ave,c} = \frac{\sum_{cty} PP_{(c,cty)} \times QSUP_{(c,cty)}}{\sum_{cty} QSUP_{(c,cty)}} \tag{5.31}$$

$$PP_{coef,cty} = \frac{\sum_{c} PP_{(c,cty)}}{PP_{ave,c}} \tag{5.32}$$

$$PP_{(c,cty)} = PP_{ave,c} \times PP_{coef,cty} \tag{5.33}$$

where PP_{ave} denotes the global average producer price, and PP_{coef} denotes the country-specific adjustment coefficient.

Next, using the GTAP10 dataset, exogenous variables related to prices were estimated. The Producer Support Estimate (PSE) represents the monetary transfers from consumers and taxpayers to producers resulting from agricultural policies. In this study, the PSE is expressed as the proportionate impact of subsidies and taxes on producer prices. Similarly, the Consumer Support Estimate (CSE) represents the transfers from or to consumers, expressed as the proportionate impact of subsidies and taxes on consumer prices.

$$PSE_{(i,cty)} = \frac{OSEP^{GTAP}_{(i,cty)} + \sum_{i} ISEP^{GTAP}_{(i,ii,cty)} - \sum_{endw} FTRV^{GTAP}_{(i,endw,cty)} + \sum_{endw} FBEP^{GTAP}_{(i,endw,cty)}}{VOA^{GTAP}_{(i,cty)}} \tag{5.34}$$

$$CSE_{(i,cty)} = \frac{VDPM^{GTAP}_{(i,cty)} - VDPA^{GTAP}_{(i,cty)}}{VDPM^{GTAP}_{(i,cty)}} \tag{5.35}$$

where:

- $OSEP^{GTAP}$: subsidies/taxes on production,
- $ISEP^{GTAP}$: subsidies/taxes on intermediate inputs,
- $FTRV^{GTAP}$: taxes on factor inputs,
- $FBEP^{GTAP}$: subsidies on factor inputs,
- VOA^{GTAP}: production value,
- $VDPM^{GTAP}, VDPA^{GTAP}$: household consumption at market and consumer prices, respectively.

To link producer (farm-gate) prices with consumer (market) prices, the market margin ratio MMJ was estimated. Intermediate inputs and factor inputs corresponding to market margins were identified from the GTAP input–output tables, and their total was divided by the production value to obtain the ratio. Similarly, trade-related costs MMM and MME were estimated from GTAP data, using the difference between import values at CIF prices and export values at FOB prices.

$$MMJ_{(i,cty)} = \frac{\sum_{immj} VDFA^{GTAP}_{(i,immj,cty)} + \sum_{immj} VIFA^{GTAP}_{(i,immj,cty)} + \sum_{immj} EVFA \ldots}{\Big(\sum_{ii} VDF^{A,GTAP}_{(i,ii,cty)} + \sum_{ii} VIF^{A,GTAP}_{(i,ii,cty)} + \sum_{endw} EVF^{A,GTAP}_{(i,endw,cty)} - (\sum_{immj} VDF^{A,GTAP}_{(i,immj,cty)} + \sum_{immj} V \ldots} \tag{5.36}$$

$$MMM_{(i,ccty)} = \frac{\sum_{cty} VIWS^{GTAP}_{(i,cty,ccty)} - \sum_{cty} VXWD^{GTAP}_{(i,cty,ccty)}}{\sum_{cty} VXWD^{GTAP}_{(i,cty,ccty)}} \tag{5.37}$$

$$MME_{(i,cty)} = \frac{\sum_{ccty} VIWS^{GTAP}_{(i,cty,ccty)} - \sum_{ccty} VXWD^{GTAP}_{(i,cty,ccty)}}{\sum_{ccty} VXWD^{GTAP}_{(i,cty,ccty)}} \tag{5.38}$$

where:

- $VDFA^{GTAP}, VIFA^{GTAP}, EVFA^{GTAP}$: intermediate and factor input values at consumer prices,
- $VIWS^{GTAP}, VXWD^{GTAP}$: import (CIF) and export (FOB) values,
- $immj \in (i \cup endw)$: goods and factors corresponding to market margins.

The import tariff (TM) and export tariff (TE) were then calculated. The import tariff rate was obtained as the ratio of import value at domestic prices to that at international prices, and the export tariff rate as the ratio of export value at international prices to that at domestic prices.

$$TM_{(i,ccty)} = \frac{\sum_{cty} VIMS^{GTAP}_{(i,cty,ccty)}}{\sum_{cty} VIWS^{GTAP}_{(i,cty,ccty)}} \tag{5.39}$$

$$TE_{(i,cty)} = \frac{\sum_{ccty} VXWD^{GTAP}_{(i,cty,ccty)}}{\sum_{ccty} VXMD^{GTAP}_{(i,cty,ccty)}} \tag{5.40}$$

where:

- $VIMS^{GTAP}$: import value at domestic (market) prices,
- $VXMD^{GTAP}$: export value at domestic (market) prices.

Finally, coefficients for decomposing producer prices by input factor were estimated. Each agricultural commodity is produced using land, feed, raw materials, and other production factors. Using the GTAP input–output tables, the cost share of each factor in the producer price was estimated. By multiplying the producer price by these shares, the base-year prices of each factor were obtained.

$$LND_{(i,cty)} = \frac{\sum_{ilnd} VDF^{A,GTAP}_{(i,ilnd,cty)} + \sum_{ilnd} VIF^{A,GTAP}_{(i,ilnd,cty)} + \sum_{ilnd} EVF^{A,GTAP}_{(i,ilnd,ct}}{\Big(\sum_{ii} VDF^{A,GTAP}_{(i,ii,cty)} + \sum_{ii} VIF^{A,GTAP}_{(i,ii,cty)} + \sum_{endw} EVF^{A,GTAP}_{(i,endw,cty)} - (\sum_{immj} VDF^{A,GTAP}_{(i,immj,cty)} + \sum_{immj} VIF} \tag{5.41}$$

$$FED_{(i,cty)} = \frac{\sum_{ifed} VDF^{A,GTAP}_{(i,ifed,cty)} + \sum_{ifed} VIF^{A,GTAP}_{(i,ifed,cty)} + \sum_{ifed} EVF^{A,GTAP}_{(i,ifed,c}}{\Big(\sum_{ii} VDF^{A,GTAP}_{(i,ii,cty)} + \sum_{ii} VIF^{A,GTAP}_{(i,ii,cty)} + \sum_{endw} EVF^{A,GTAP}_{(i,endw,cty)} - (\sum_{immj} VDF^{A,GTAP}_{(i,immj,cty)} + \sum_{immj} VIF} \tag{5.42}$$

$$IMD_{(i,cty)} = \frac{\sum_{iimd} VDF^{A,GTAP}_{(i,iimd,cty)} + \sum_{iimd} VIF^{A,GTAP}_{(i,iimd,cty)} + \sum_{iimd} EVF^{A,GTAP}_{(i,iimd,c}}{\Big(\sum_{ii} VDF^{A,GTAP}_{(i,ii,cty)} + \sum_{ii} VIF^{A,GTAP}_{(i,ii,cty)} + \sum_{endw} EVF^{A,GTAP}_{(i,endw,cty)} - (\sum_{immj} VDF^{A,GTAP}_{(i,immj,cty)} + \sum_{immj} VIF} \tag{5.43}$$

$$OFC_{(i,cty)} = 1 - (LND_{(i,cty)} + FED_{(i,cty)} + IMD_{(i,cty)}) \tag{5.44}$$

where:

- LND: share of land cost in the producer price,
- FED: share of feed cost in the producer price,
- IMD: share of raw material cost in the producer price,
- OFC: share of other production factors in the producer price,
- $ilnd, ifed, iimd \in (i \cup endw)$: goods and factors corresponding to land, feed, and raw materials,

- The denominator represents the total value of domestic and imported intermediate inputs and factor inputs, excluding those corresponding to market margin sectors.

6 Parameter Estimation

6.1 Parameter estimation through regression analysis

This section presents the results of regression analyses used to estimate the parameters of the model. In the following equations, variables with an overline represent the dependent and independent variables used in the regressions.

Since price elasticities in the model were assumed to vary with per-capita GDP, the following regression equation was estimated:

$$\overline{elhp}_{(c,cty)} = \alpha_c^{pe} + \beta_c^{pe} \cdot \log(\overline{GDPPC}_{cty}) \tag{6.1}$$

For livestock products, it was assumed that production systems change with economic development. Thus, the parameters determining the production share were estimated using logistic regression analysis. In this estimation, dummy variables were introduced to represent climatic zones.

$$\log\left(\frac{\overline{SYSSHARE}_{(aliv,bas,cty,cz,sys)}}{1-\overline{SYSSHARE}_{(aliv,bas,cty,cz,sys)}}\right) = \delta_{(aliv,cz,sys)}^{sys} + \rho_{(aliv,sys)}^{sys} \cdot \log(\overline{GDPPC}_{cty}) \tag{6.2}$$

It was further assumed that feed requirements and the share of concentrate feed also change with the level of economic development. Regression analyses were conducted using the following equations:

$$\log\left(\overline{FEEDEFFICIENCY}_{(aliv,bas,cty,cz,sys)}\right) = \alpha_{(aliv,cz,sys)}^{fe} + \beta_{(aliv,cz,sys)}^{fe} \cdot \log(\overline{GDPPC}_{cty}) \tag{6.3}$$

$$\log\left(\frac{\overline{FEEDSHARE}_{(aliv,bas,cty,cz,sys)}}{1-\overline{FEEDSHARE}_{(aliv,bas,cty,cz,sys)}}\right) = \delta_{(aliv,cz,sys)}^{fs} + \rho_{(aliv,sys)}^{fs} \cdot \log(\overline{GDPPC}_{cty}) \tag{6.4}$$

Following Harmsen et al. (2019), the elasticity parameter σ related to the adoption of emission-reduction technologies was estimated using the following regression equation:

$$\log\left(1 - \frac{\overline{RR}_{(src,gas,cty)}}{\overline{MRP}_{(src,gas,cty)}}\right) = \sigma_{(src,gas,cty)} \cdot \log(\overline{PRCCAR}_{cty} + 1) \tag{6.5}$$

6.2 Results of parameter estimation

This section presents the results of the regression analyses conducted to estimate the model parameters. Variables with an overline in the equations represent the data used in the regressions.

6.2.1 Relationship between price elasticity and per-capita GDP

Figure **??** illustrates the relationship between per-capita GDP and price elasticity. Table 7 shows the estimated parameters and the coefficient of determination (R^2).

Since the model assumes that price elasticity varies with per-capita GDP, the following regression equation was estimated:

$$\overline{elhp}_{(c,cty)} = \alpha_c^{pe} + \beta_c^{pe} \cdot \log(\overline{GDPPC}_{cty}) \tag{6.6}$$

For all commodities, the estimated elasticities increased with higher levels of per-capita GDP. For most commodities, high coefficients of determination ($R^2 \approx 0.8$) were obtained. However, for commodities such as sugars, eggs, and spices, R^2 values were lower, around 0.5 or 0.3. The p-values for all regressions were below 0.001, indicating statistically significant relationships between the variables. Furthermore, the 95% confidence intervals for β^{pe} did not include zero, confirming the statistical significance of the estimated coefficients.

Table 7: Estimated parameters of price elasticity from regression analysis (values in parentheses denote 95% confidence intervals)

Commodity	α_{pe}	β_{pe}	β_{pe} (95% CI)		R^2	p-value
			lower	upper		
wht rce mze crl	-1.28	0.11	0.10	0.12	0.79	<0.001
str pls nut ocr vgt frt	-0.99	0.066	0.061	0.071	0.81	<0.001
sgr swt egg	-2.83	0.22	0.18	0.25	0.48	<0.001
vol	-1.18	0.10	0.090	0.105	0.80	<0.001
stm spc alc	-2.80	0.22	0.17	0.27	0.33	<0.001
cmt rmt omt pmt	-1.04	0.059	0.054	0.064	0.76	<0.001
mlk dai	-1.08	0.061	0.056	0.066	0.76	<0.001

6.2.2 Relationship between livestock production system share and per-capita GDP

Figure **??** illustrates the relationship between per-capita GDP and the proportion of pasture-based production by livestock type and climatic zone. Table 8 presents the estimated parameters.

The following regression model was estimated:

$$\log\left(\frac{\overline{SYSSHARE}_{(aliv,bas,cty,cz,sys)}}{1-\overline{SYSSHARE}_{(aliv,bas,cty,cz,sys)}}\right) = \delta^{sys}_{(aliv,cz,sys)} + \rho^{sys}_{(aliv,sys)} \cdot \log(\overline{GDPPC}_{cty}) \tag{6.7}$$

As per-capita GDP increases, the share of pasture-based production decreases for all livestock products. Adjusted coefficients of determination were moderate (0.2–0.3), and all p-values were below 0.001, indicating statistically significant relationships. The 95% confidence intervals for ρ^{sys} did not include zero, confirming the significance of the coefficients.

Table 8: Estimated parameters for pasture-based production share (95% confidence intervals in parentheses)

Commodity	ρ_{sys}	δ_{sys} by climate zone				R^2	p-value
		Arid	Temperate	Humid	HyperArid		
cmt	"-0.51 (-0.69 – -0.33)"	3.87	3.07	2.86	5.88	0.24	<0.001
mlk	"-0.54 (-0.72 – -0.36)"	4.15	3.36	3.03	6.06	0.24	<0.001
rmt	"-0.34 (-0.53 – -0.15)"	3.05	1.66	1.46	3.38	0.15	<0.001

6.2.3 Relationship between feed efficiency and per-capita GDP

Figure **??** shows the relationship between per-capita GDP and feed efficiency by livestock type, climate zone, and production system. Table 9 presents the estimated regression parameters.

The regression model used is expressed as:

$$\log(\overline{FEEDEFFICIENCY}_{(aliv,bas,cty,cz,sys)}) = ^{fe}_{(aliv,cz,sys)} + ^{fe}_{(aliv,sys)} \cdot \log(\overline{GDPPC}_{cty}) \tag{6.8}$$

Higher per-capita GDP is associated with lower feed requirements. For ruminants, the adjusted R^2 ranged from 0.66 to 0.97, indicating high explanatory power, while for poultry and other livestock it was relatively low (0.22 and 0.05, respectively). The coefficients ^{fe} were smaller for ruminants, suggesting stronger efficiency improvements with economic development. All p-values were below 0.001, and the 95% confidence intervals for ^{fe} did not include zero, confirming statistical significance.

Table 9: Estimated parameters of feed efficiency (95% confidence intervals in parentheses)

Commodity	System	$_{fe}$	$_{fe}$ by climate zone					R^2	p-value
			Arid	Temperate	Humid	HyperArid	Total		
cmt	LG	"-0.46 (-0.52 – -0.41)"	8.52	7.60	8.03	8.76		0.96	<0.001
cmt	MX	"-0.52 (-0.57 – -0.48)"	8.86	7.97	8.44	8.70		0.96	<0.001
mlk	LG	"-0.37 (-0.41 – -0.33)"	4.43	3.68	3.99	4.48		0.71	<0.001
mlk	MX	"-0.38 (-0.41 – -0.34)"	4.36	3.62	3.92	3.99		0.66	<0.001
rmt	LG	"-0.27 (-0.32 – -0.21)"	6.46	6.23	6.39	6.21		0.97	<0.001
rmt	MX	"-0.33 (-0.38 – -0.28)"	7.01	6.76	6.96	5.61		0.97	<0.001
pmt	Total	"-0.14 (-0.17 – -0.12)"					2.03	0.22	<0.001
omt	Total	"-0.087 (-0.13 – -0.044)"					2.82	0.05	<0.001

6.2.4 Relationship between concentrate feed share and per-capita GDP

Figure **??** shows the relationship between per-capita GDP and the share of concentrate feed by livestock type, climatic zone, and production system. Table 10 reports the estimated regression parameters. Poultry and other livestock are excluded from the analysis because they do not consume pasture.

The following regression model was estimated:

$$\log\left(\frac{\overline{FEEDSHARE}_{(aliv,bas,cty,cz,sys)}}{1-\overline{FEEDSHARE}_{(aliv,bas,cty,cz,sys)}}\right) = \delta^{fs}_{(aliv,cz,sys)} +^{fs}_{(aliv,sys)} \cdot \log(\overline{GDPPC}_{cty}) \tag{6.9}$$

The results indicate that higher per-capita GDP is associated with a higher share of concentrate feed and a lower share of pasture. Adjusted coefficients of determination range from 0.74 to 0.90, indicating a relatively high explanatory power. All p-values are below 0.001, suggesting statistically significant relationships between the variables. Furthermore, the 95% confidence intervals for ^{fs} do not include zero, which confirms the statistical significance of the estimated coefficients.

Table 10: Estimated parameters of concentrate feed share (95% confidence intervals in parentheses)

Commodity	System	$_{fs}$	δ_{fs} by climate zone				R^2	p-value
			Arid	Temperate	Humid	HyperArid		
cmt	LG	"0.95 (0.74 – 1.16)"	-13.24	-11.94	-13.09	-11.49	0.76	<0.001
cmt	MX	"1.04 (0.88 – 1.21)"	-13.51	-12.21	-13.29	-11.89	0.74	<0.001
mlk	LG	"0.77 (0.65 – 0.89)"	-10.62	-9.39	-9.95	-9.58	0.79	<0.001
mlk	MX	"0.70 (0.61 – 0.78)"	-9.11	-8.05	-8.59	-8.06	0.78	<0.001
rmt	LG	"0.42 (0.36 – 0.48)"	-6.22	-5.98	-6.09	-6.34	0.90	<0.001
rmt	MX	"0.52 (0.46 – 0.57)"	-6.89	-6.69	-6.81	-6.56	0.88	<0.001

7 Model Calculation Flow and Execution

7.1 Model Calculation Flow

Figure **??** shows the processing flow of the AgLU model. The model begins with the processing of the original data sources, including extraction of necessary information, aggregation of gridded datasets, and conversion of data formats. Next, the processed data are adjusted through parameter estimation via regression analysis, data calibration to ensure equilibrium in the base year, and coefficient calibration for model consistency.

Using these prepared data, the model then performs future scenario calculations. For each year, equilibrium solutions are iteratively computed based on the base-year data, the results of the previous year, and the scenario assumptions. The aggregated annual results provide the final outputs for each scenario. Additionally, model results are converted into the submission templates of AgMIP (Agricultural Model Intercomparison and Improvement Project) and IAMC (Integrated Assessment Modeling Consortium) to facilitate data exchange and comparison.

7.2 Programs within the Model

This section provides an overview of the major programs used in the AgLU model. Each component plays a specific role in data processing, parameter calibration, and scenario simulation.

`0_csv_to_gdx.R`

Converts datasets in `csv` or `xlsx` format into `gdx` format. This script processes raw datasets such as FAOSTAT and MAC Curve sources.

`0_grid_data.R`

Aggregates gridded datasets by country and production unit, and exports the results in `gdx` format. It processes geospatial data from sources such as GAEZ, Livestock System, and LUH2.

`1_data_import.gms`

Integrates and reformats the `gdx`-formatted datasets into structures compatible with the model's computation framework. It performs country code conversions, consolidates data into AgLU's food and land-use classifications, and includes submodules that output historical data in AgMIP and IAMC template formats.

`1-5_regression.gms`

Performs parameter regression analyses based on the original datasets to estimate elasticities and adjustment coefficients.

`2_basetear.gms`

Adjusts baseline datasets to ensure equilibrium consistency in the base year.

`3_equilibrium.gms`

Solves for annual equilibrium states for future years, using base-year data and previous results as inputs.

`4_combine_gdx.gms`

Aggregates annual simulation outputs and compiles them into scenario-level result files.

`5_scenario_combine.gms`

Combines outputs from all scenarios to produce the comprehensive simulation dataset.

`Visualization.R`

Generates graphical outputs and visualization figures from the simulation results.

7.3 Execution Method

The AgLU model can be executed by running the shell script `AgLU/shell/execution.sh` on either Cygwin or Ubuntu environments. Model configurations are defined in `AgLU/shell/model_setting.sh`. As summarized in Table 11, the configurable items include the selection of executable programs, scenario settings, and computational environment settings.

Table 11: Model configuration parameters in `model_setting.sh`

Setting item	Description	Default
Model switches		
`data_download`	Executes a script to download data from submodules when the repository is first cloned. Once downloaded, this can be turned off.	on
`data_import`	Executes `1_data_import.gms` and `1-5_regression.gms`.	on
`baseyear_run`	Executes `2_baseyear.gms`.	on
`model_run`	Executes `3_equilibirium.gms`.	on
`combine_gdx`	Executes `4_combine_gdx.gms`.	on
`scenario_combine`	Executes `5_scenario_combine.gms`.	on
`Visualization`	Executes `Visualization.R`.	on
`data_update`	Executes `0_csv_to_gdx.R`. If no data update is needed, this may be turned off.	off
`grid_data`	Executes `0_grid_data.R`. If no data update is needed, this may be turned off. If executed, the folder `L/ModelData/AgLU/grid` must be copied to `AgLU/data`.	off
`Scenario_compare`	Enables comparison across scenarios in plots.	off
`Model_compare`	Enables comparison across models in plots.	off
`historical_check`	Compares simulated and historical data in plots.	off
`aggregate`	Performs aggregation of results into 17-region, 10-region, and 5-region groupings.	on
`AGMIP`	Outputs results in AGMIP and IAMC_Template formats.	on
Scenario settings		
`socioeconomic_setting`	Specifies the socioeconomic scenario. A file with the scenario name should exist in `AgLU/setting/socioeconomic`.	SSP2_BaU
`climate_setting`	Specifies the climate scenario. A file with the scenario name should exist in `AgLU/setting/climate`.	NoCC
`runlist`	Allows individual scenario specification without using the socioeconomic–climate matrix. Scenario names are defined as combined strings (e.g., `SSP2_BaU-NoCC`). If this item is specified, the two settings above are ignored.	–
`start_year`	Starting year of simulation.	2015
`target_year`	Ending year of simulation.	2100
Execution environment		
`run_single`	Runs the model for one scenario at a time.	on
`run_paralell`	Runs scenarios in parallel.	off
`iteration_number`	Number of iterations per year. Larger values improve convergence but increase computation time.	0
`NCPU`	Maximum number of CPUs used for parallel computation.	8
`mem_check`	Performs memory usage checks (Windows only).	off
`mem_threshold`	Memory usage threshold (%) at which parallel computation pauses when `mem_check` is enabled.	80

7.4 Execution Environment Requirements

The model can be executed under either Cygwin or Ubuntu with the following dependencies installed:

- **Cygwin** (required packages: `zip`, `unzip`)
- **Ubuntu**
- **R 4.3.2** (required libraries: `tidyverse`, `gdxrrw`, `openxlsx`, `readxl`, `ggplot2`, `furrr`, `ggpmisc`, `patchwork`, `sf`, `raster`, `ncdf4`, `exactextractr`, `rmapshaper`, `grDevices`)
- **GAMS 38**

- **GitHub**

8 Update History

2025-10-25 | R. Totake v1.0

Initial release of AIM-ALPHA documentation.

Appendix A: Production Units

Figure A1: Production units in Africa

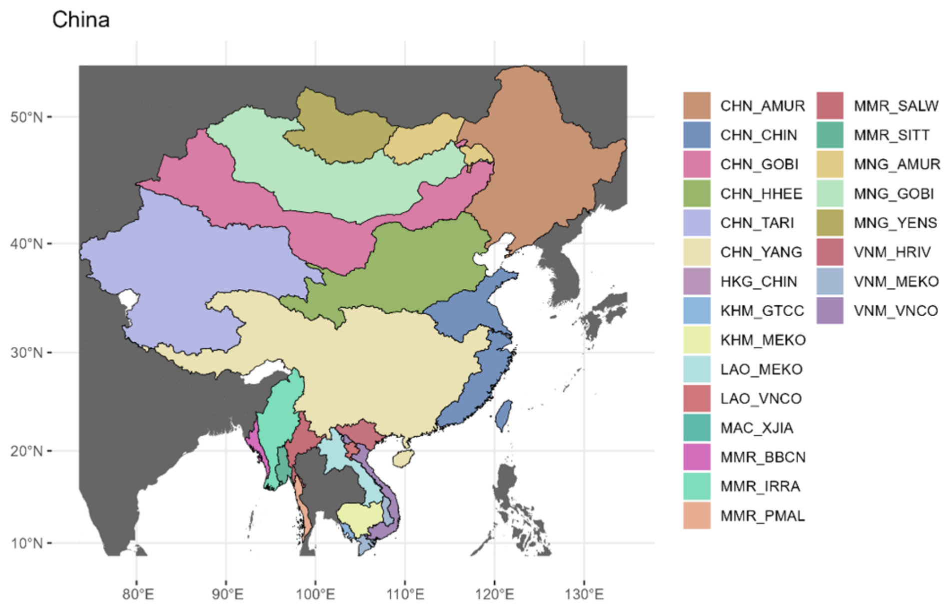

Figure A2: Production units in the China region

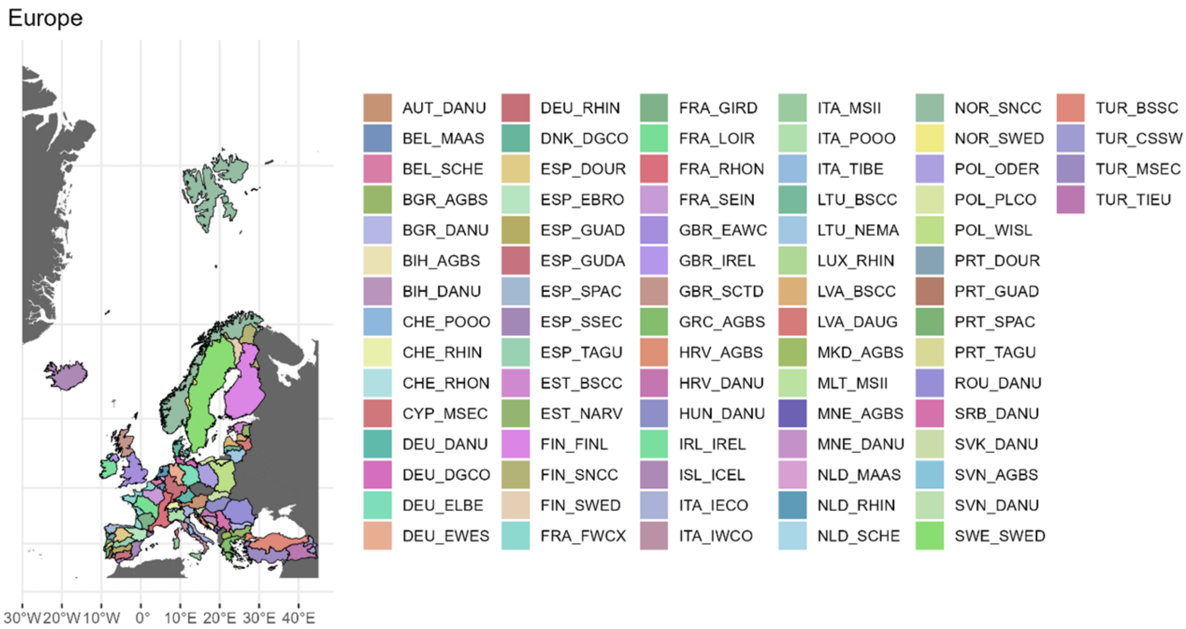

Figure A3: Production units in Europe

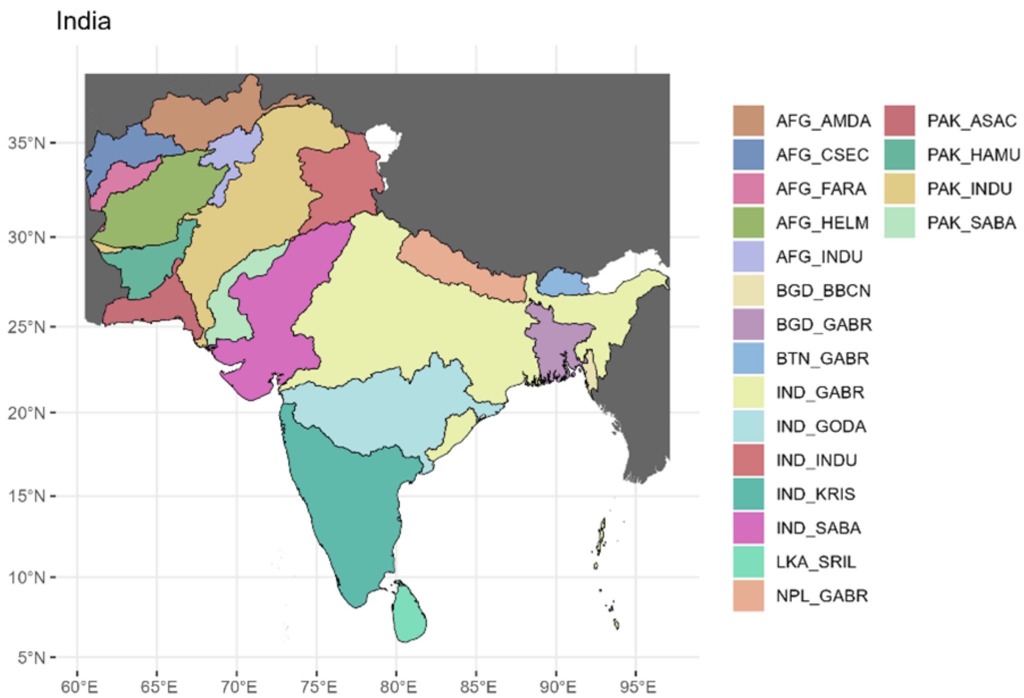

Figure A4: Production units in the India region

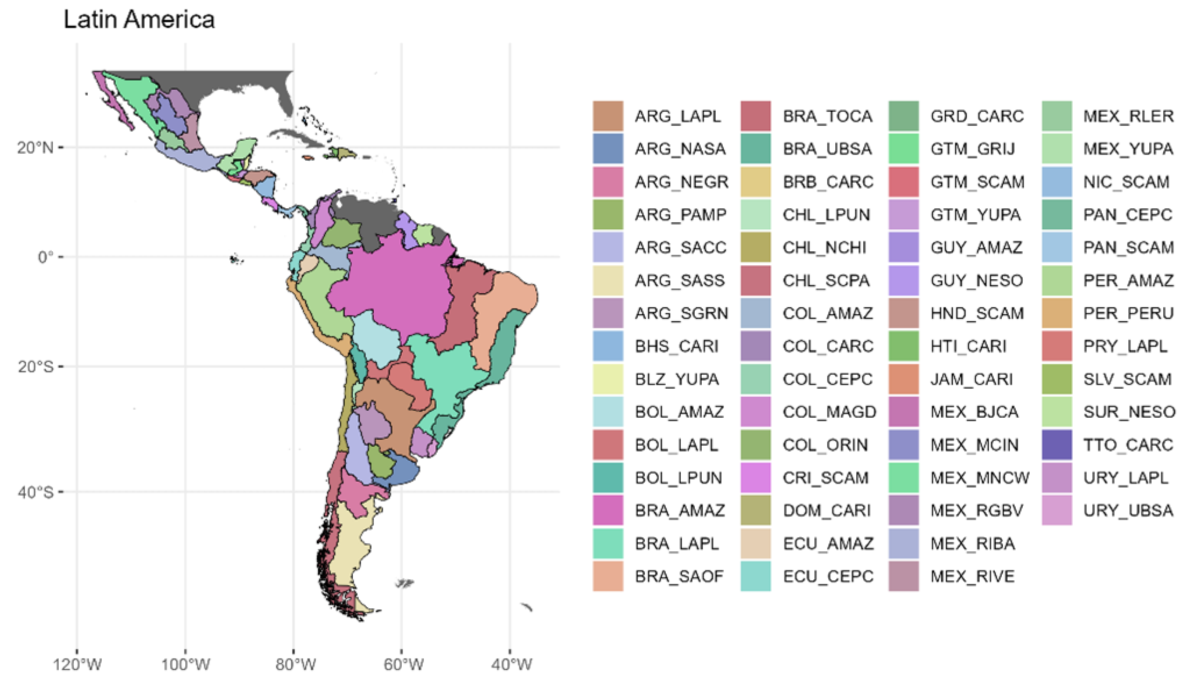

Figure A5: Production units in Latin America

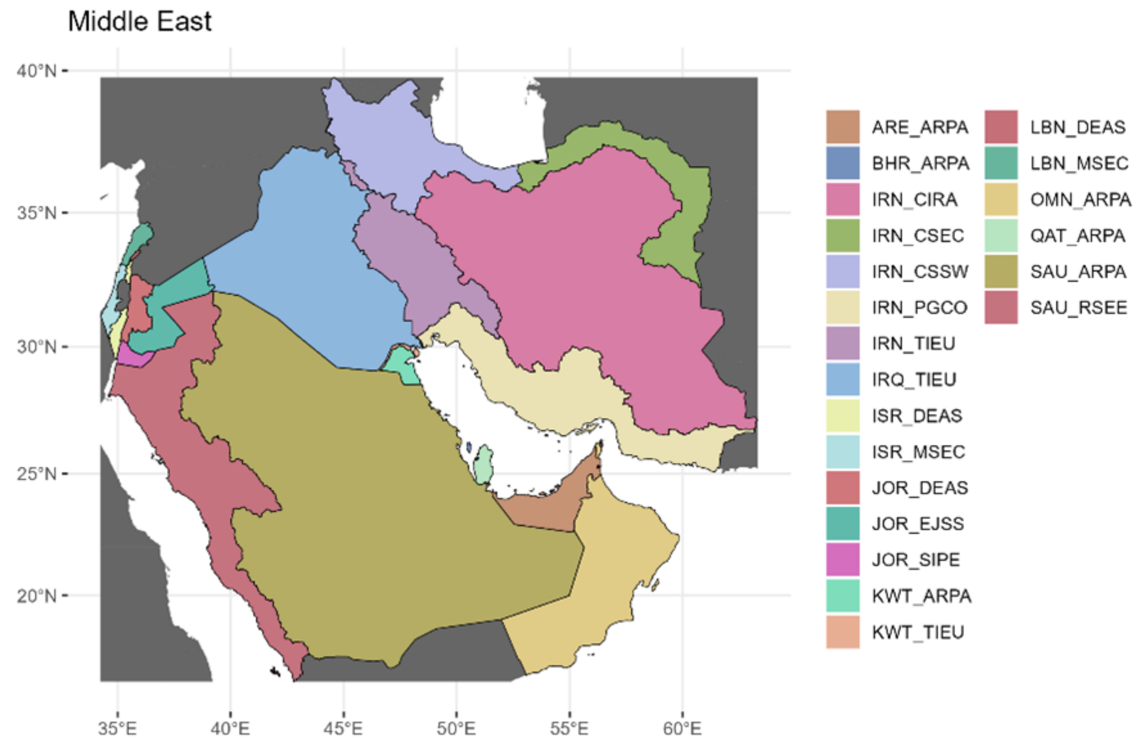

Figure A6: Production units in the Middle East

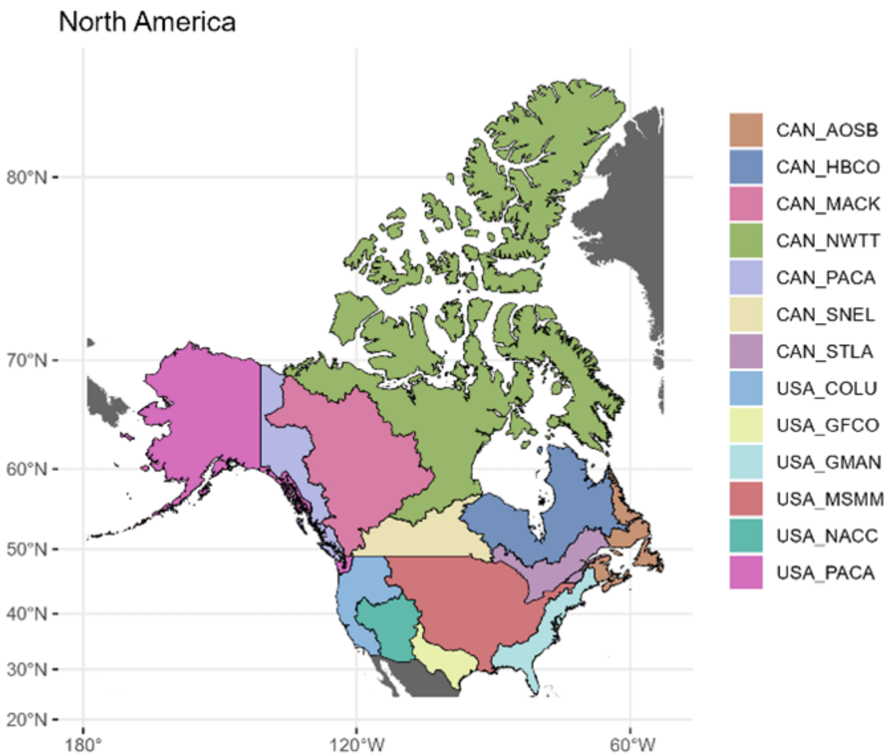

Figure A7: Production units in North America

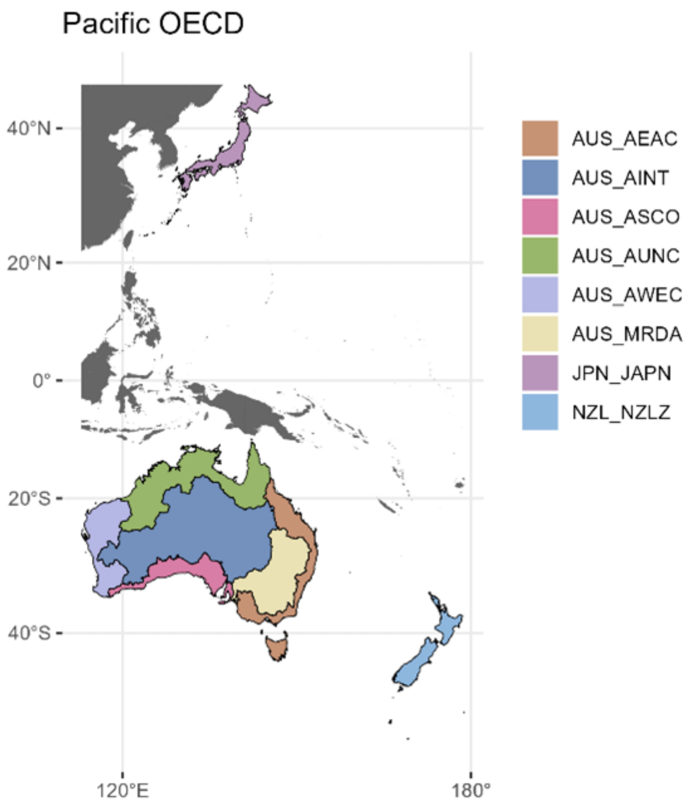

Figure A8: Production units in the Pacific OECD region

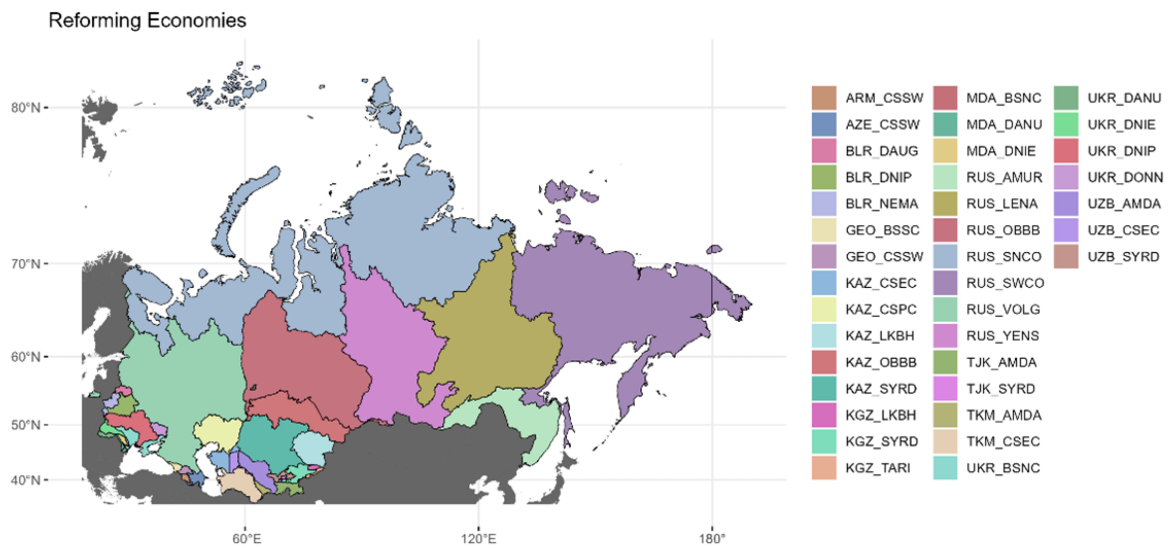

Figure A9: Production units in the former Soviet Union

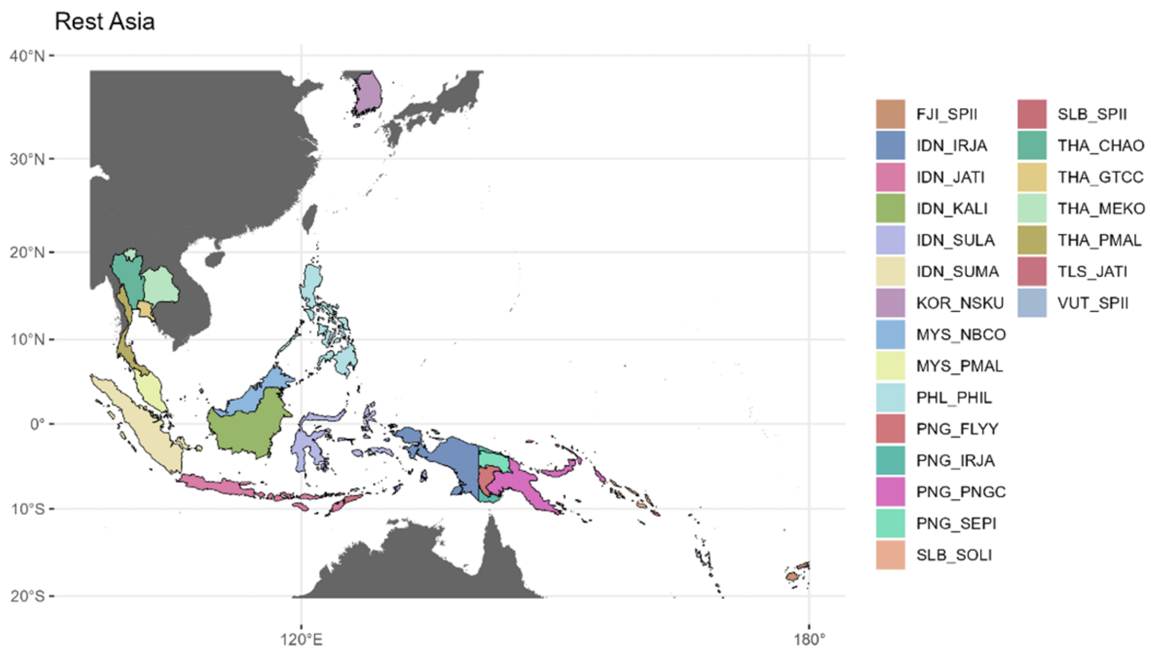

Figure A10: Production units in other Asian regions