Supplementary materials

Parameters and variables considered in the AGRITALIM model

The model maximizes the operating income of the various farms, considering elements of market (outputs and input prices), production function (yields and input quantities), agricultural policy, and depreciation costs (Table A1).

Table A1. Main components of the objective function: parameters (market, production function, policy) and variables.

Components	Market	Production function	Policy	Variables
Gross Saleable Production - crops	prices	yields		hectares of crops
Gross Saleable Production - animals	prices	yields		number of animals
CAP coupled payments			payments	hectares of crops, number of animals
CAP decoupled payments			payments	
Complementary activities	total revenues			
Variables costs - crops	prices	quantities		hectares of crops
Variables costs - animals	average costs			number of animals
External labour	prices			hours of labour
Feed purchased	prices			quantity of feed
Pumped water	prices			quantity of water pumping
Depreciation rates observed	costs			
Depreciation rates - tree crops	costs			additional area of tree crops
Depreciation rates - animals	costs			additional area of stables and facilities

Model variables include crop hectares, number of animals, hours of labour, quantities of feed, water pumped from wells, additional areas of tree crops, and additional areas of stables and structures.

The costs related to the additional depreciable capital (tree area, stables, and animal facilities) are annualized in the objective function as depreciation costs. The latter are obtained by dividing the replacement value of those depreciable capitals by the years of their technical duration indicated by the FADN. For tree crops, it is assumed that the variation of the surface involves investments both in the planting of orchards and in harvesting machinery. The variation in the size of herds and flocks is associated with investments in stables and farming facilities.

The model is subject to different types of constraints (Table A2) concerning land, labour, and water availability, tree crops area (including the additional area), stables and facilities area (including the additional area), animal

nutrition (in terms of ratio between reused crops and animals), and ratios between categories of animals (productive and not).

Table A2. Structure of the constraints: left-hand and right-hand sides, involved variables.

Types	Matrix coefficients	Availabilities	Variables
Land		farm land	hectares of crops
Labour	manual and mechanical labour needs	family labour, permanent employment temporary employment, external labour	crops (hectares), animals (number), external labour (hours)
Water	water needs	WUA, natural, artificial, pumped waters	crops (hectares), quantity of water pumping
Tree crops		tree crop area	tree crops (hectares), additional area of tree crops
Stables and facilities	area per animal	area of stables and facilities	animals (number), additional area of stables and facilities
Feeding	feed needs	feed produced on the farm	crops (hectares), animals (number), purchased feed (quantity)
Productive and non-productive animals	ratio		productive and non-productive animals (number)

In other words, the mathematical model maximizes operating income by choosing productive activities (hectares of crops and number of animals), and is constrained by the resources availability (land, labour, water, feeds). As for labour and water, the model allows additional variables (hours of labour, quantity of groundwater pumped). Other variables of the model concern the possibility of purchasing external feeds and an additional area of fixed capital. As for the feed, in fact, the model considers that the animals are fed both with crops produced on the farm and with feeds purchased on the market.

As for livestock nutrition, an advance was made in implementing the model to endogenize the quantification of nutrient requirements and supply to dairy cattle, according to the nutritional system established by the French National Research Institute for Agriculture, Food and the Environment (INRA, 2019). The pre-existing feed constraint was replaced with the nutritional constraint specified in the following equation:

$$\sum_{ja} nr_{n,ja,nutr} * XA_{n,ja} \leq \sum_{j} XC_{j,n} * yc_j * nc_{j,nutr} + \sum_{f} XF_n * nc_{f,nutr} \quad \forall\, n, nutr$$

The nutritional constraint acts at farm level to balance each nutritional parameter (*nutr*: capacity of intake, metabolizable energy and protein). Here, $nr_{n,ja,nutr}$ represents animals'(ja) requirements for each nutritional parameter, varying among farms (n) based on milk yield and herd composition. Overall requirements have to be primarily satisfied with supply from crops (j) grown on-farm, based on the extension of the different crops ($XC_{j,n}$), crop yield (yc_j) and nutritional content of the corresponding feedstuff ($nc_{j,nutr}$). Possible shortages

can be integrated through feed purchase (XF_n), choosing the best combination among a set of market-available feedstuffs with different nutritional content ($nc_{f,nutr}$).

Mathematical representation and calibration of the AGRITALIM model

The model is structured as follows:

1. Objective function

$\max Z = \text{GPS} + \text{CAP} + \text{RCA} - \text{VC} - \text{QC} - \text{EXL} - \text{FP} - \text{PW} - \text{DRO} - \text{DRNI}$

Operating income = Z

Gross Saleable Production = $\text{GSP} = pc * yc * XC + pm * ym * XA + revnm * XA$

CAP payments = $\text{CAP} = dp + cpc * XC + cpa * XA$

Revenues from Complementary Activities = RCA

Variable Costs = $\text{VC} = pfp * qfp * XC + acc * XC + aca * XA$

Quadratic Costs = $\text{QC} = \frac{1}{2} XC' \, Q \, XC + \frac{1}{2} XA' \, Q \, XA$

External Labour = $\text{EXL} = ph * XH$

Feed Purchased = $\text{FP} = pf * XF$

Pumped Water = $\text{PW} = pw * XW$

Depreciation Rates Observed = DRO

Depreciation Rates New Investments = $\text{DRNI} = drtc * ADTC + drsf * ADSF$

Variables

XC = hectares of crops

XA = number of animals

XH = hours of labour

XF = quantity of feed

XW = quantity of water pumped

ADTC = additional area of tree crops

ADSF = additional area of stables and facilities

Market

pc = prices of crops

pm = prices of milk

pfp = prices of factors of production (fertilizers, pesticides)

ph = prices of external labour

pf = prices of feed purchased

pw = prices of water pumped

drtc = depreciation rates of new investments (tree crops)

drsf = depreciation rates of new investments (animals)

Production function

yc = yields of crops

ym = yields of milk

qfp = quantities of factors of production (fertilizers, pesticides)

Common Agricultural Policy payments

dp = decoupled payments

cpc = coupled payments for crops

cpa = coupled payments for animals

Revenues and average costs

revnm = revenues from other animal products, no milk (meat, eggs, honey,…)

acc = average costs for crops (per hectare)

aca = average costs for animals (per number)

2. Constraints

$$\sum_{j} XC_{j,n} \leq ald_n \quad \forall\, n$$

$$\sum_{j} ml_{j,n} * XC_{j,n} + \sum_{ja} ml_{ja,n} * XA_{ja,n} \leq alb_n \quad \forall\, n$$

$$\sum_{j} mw_{j,n} * XC_{j,n} \leq awt_n \quad \forall\, n$$

$$\sum_{jt} XC_{jt,n} \leq atc_n + ADTC_n \quad \forall\, n$$

$$\sum_{ja} msf_n * XA_{ja,n} \leq asf_n + ADSF_n \quad \forall\, n$$

$$\sum_{ja} nr_{n,ja,nutr} * XA_{n,ja} \leq \sum_{j} XC_{j,n} * yc_j * nc_{j,nutr} + \sum_{f} XF_n * nc_{f,nutr} \quad \forall\, n, nutr$$

$$\sum_{jan} rc_n * XA_{jan,n} \geq \sum_{jap} XC_{jap,n} \quad \forall\, n$$

Sets shown in the mathematical representation

j = types of crops

n = farms

ja = types of animals

jt = tree crops

jan = types of animals non-productive

jap = types of animals productive

nutr = nutrients in animal feeding

Other sets (not shown in the mathematical representation): geographical area [NUTS 2 and NUTS 3], altimetric level, types of cultivation (field, vegetable garden, greenhouse), following crops, main vegetable product, animal production, time

Matrix coefficients

ml = labour (manual and mechanical) needs for each crop and animal

mw = water needs for each irrigated crop

msf = square meter of stables and facilities per animal

nr = nutrient requirements for each animal

nc = nutrient content in each produced or purchased feed

rc = ratio between productive and non-productive animals

Availabilities

ald = land availability per farm

alb = labour availability per farm

awt = water availability per each source (e.g., water users' association, well,…) and farm

atc = tree crops area per farm

asf = total square meters of stables and facilities

The calibration is performed with the Positive Mathematical Programming (PMP) approach, which perfectly calibrates the model to baseline (in this study, year 2021) and avoids adding ad-hoc constraints and over-specialized responses of the model in the simulation phase. In general, a PMP model can be built and calibrated using a very simplified farms' database, based only on production levels (e.g., land use and quantities produced) and the main economic information related to production processes (e.g., output prices and variable costs). In fact, even in the presence of few data, a PMP model guarantees the reconstruction of the structure of variable costs, of the substitutability relationships between processes as well as of farm productions, used to carry out ex-ante analyses (Paris and Howitt, 1998; de Frahan et al. 2007; Heckelei et al, 2012). However, more data and information used to specify objective function and constraints, as in the case of the AGRITALIM model, determine a more robust model in the simulation phase.