



WP5 | Socio-economic Analyses | Deliverable 5.1 Update

Classification of small-farm structural change species based on CSs

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¹ PU = Public

PP = Restricted to other project participants (including the Commission Services)

RE = Restricted to a group specified by the consortium (including the Commission Services)

CO = Confidential, only for members of the consortium (including the Commission Services)

List of Acronyms

Acronym	Full title	Acronym	Full Title
AP	Agronomical Practice	EU SFT	EU Sustainability Finance Taxonomy
BioL	Bio-Leasing	GWP	Global Warming Potential
CA	Conventional Agriculture	OEF	Organization Environmental Footprint
CAP	Common Agricultural Policy	OI	Open Innovation
CE	Circular Economy	PEF	Product Environmental Footprint
ChL	Chemical Leasing	PF	Production Function
CS	Case Study	RA	Regenerative Agriculture
EEP	Energy Equivalent Population	RAE	Regenerative Agriculture Economics
EG	Endogenous Growth	RV	Resistant Variety
EPR	Extended Producer's Responsibility	SEEA	System of Environmental-Economic Accounting
ET	Evapotranspiration	SO	Specific Objective
EU	European Union	WD	Weather Derivative
EU GD	EU Green Deal	WP	Work Package

Executive Summary

The large-scale enactment of *Regenerative Agriculture* (RA) practices comprises an element of vital importance for the *European Union* (EU) and its economic transformation towards the monetization of its *natural capital conservation* [1-3]. The central vehicle of the EU's RA policy is the *Green Deal* [4-5] (EU GD) and the *Sustainability Finance Taxonomy* (EU SFT) as its financial leverage, aiming at the paradigm shift of the financial and banking practices towards massive investments on environmental technologies and practices at various sectors. Specifically, the EU SFT consists of six pillars [6], where pillar 6 concerns "biodiversity and ecosystems' conservation" and is directly related to RA. SIRAM D5.1 promotes these goals via pilot economic modelling testing and the utilization of data provided by the 8 *Case Studies* (CSs) of Work Package (WP) 4.

The version 2 of the SIRAM D5.1 report titled "***Classification of small-farm structural change species based on CSs***", as part of the WP5 with title "***Socio-economic Analyses***", aims at building a *structural model* of *endogenous farm growth*. This work is an integration update of major importance between agronomic and economic variables into a single unified *Production Function* (PF) used in econometric analysis as modelling background for the next deliverables D5.2 and D5.3, as well as of any work in SIRAM aiming at the scientific substantiation of the economic potential of RA practices. The PF will be the main tool for identifying *structural change patterns* in the 8 CSs of WP4. The value-added of the SIRAM D5.1 consists in three pillars: **(1)** Benefits deriving from the SIRAM consortium synergies that increased the "knowledge stock" on how RA practices are interpreted into economic variables and the original enrichment of the scientific literature, filling the gap in a relatively uncharted field with limited to almost inexistent prior references; **(2)** The establishment and continuous enrichment of a *Regenerative Agriculture Economics* (RAE) database, beginning with data provided by the 8 CSs and its continuous maintenance by all SIRAM partners, aiming at the increase of results' accuracy and its utilization as reference hub in the post-SIRAM era; **(3)** The post-SIRAM commercial potential, as the quantitative economic framework developed can be applied in CSs with already identified potential that are outside the consortium and be further *upscaled* with measurable monetary effects and **(4)** The compatibility of the SIRAM's quantitative economic framework to the existing EU policy directions towards the EU GD, the EU SFT and the *Circular Economy* (CE) as integral element of the *Common Agricultural Policy* (CAP) all EU member-states.

In **Chapter 1** of the D5.1 we provide an overview of implemented works since the beginning of WP5 (M7), regarding the coordination of CSs, the data acquisition process and the general approach for structuring a new PF. In **Chapter 2** we present the SIRAM *Specific Objectives* (SOs) addressed by D5.1 and its high relevance to the 6 pillars of the EU SFT. **Chapter 3** describes the step-by-step process of classifying the 8 SIRAM CSs based on their examined pillars and economic data availability, which is essentially an enriched version of the M5.1 report. **Chapter 4** contains the core innovation work with the development of the *REGENA Production Function* as an original model that can depict the shift from *Conventional Agriculture* (CA) to RA or a composition of both. After a brief examination of the literature on agricultural PFs [7-13], we substantiate the differentiation of REGENA with the inclusion of *endogenous growth* approaches [14-15] as compatible to the rationale of the RA farm in regard to *knowledge accumulation* on the local ecosystem at both macroscopic and microscopic levels. This work is related to the accurate economic depiction of biophysical attributes of natural capital factors analyzed in WP1 and their interconnections; specifically beneficial *microorganisms* (T1.1), *biomasses* (T1.2) and *resistant varieties* (T1.3). *Agronomical practices* (e.g. tillage with the use of mechanical

capital) are also included in the REGENA in terms of water use intensity and *Evapotranspiration* (ET). **Chapter 5** presents the first *structural change* simulation results with the REGENA in its three basic states: (a) with CA practices' prevalence, (b) with RA practices' prevalence and (c) with a coexistence of CA and RA practices, as the most probable case of short-term transition. Not all CSs implement field experiments; hence reference values on crop outputs had to be based on external references, assumptions and simulations. **Chapter 6** provides the current state of WP5 and D5.1 and describes the evolution of the REGENA function in next deliverables (D5.2, D5.3) along with six (6) alternative versions. **Chapter 7** describes the next steps and required actions of the SIRAM consortium for the D5.1 update and upcoming WP5 deliverables (D5.2, D5.3), along with the creation and maintenance of the RAE database. **Chapter 8** makes an initial assessment of the critical academic and commercial issues regarding the post-SIRAM era. Finally, **Chapter 9** presents the list of literature and references used for the D5.1 report.

1. Introduction

The central task of D5.1 is to interpret the scientific background and data of RA into a concise and consistent economic framework for structuring a mathematical model on the individual farm's crop output, according to its adopted practices. Specifically, we set the 4 SIRAM pillars as corner stone of our analysis. We begin from the general description of each pillar's properties to identify *synergistic* or *competitive* activity that in economic science is translated as *substitutability* or *complementarity*. We further utilize data from each CS according to the examined SIRAM pillars, further enriched by 5 categories of climate and economic inputs, such as temperature, energy, water, fertilizers and labor. Data availability at this point was rather limited, as most CSs still conduct experiments; hence it was necessary for some cases to resort to external data, combined with rational assumptions that will be substituted with real data as experiments continue. These inputs were then transformed into the variables of REGENA. The REGENA was used to generate the first *structural change* simulations for each CS, comparing the output of a hypothetical CA farm to an RA farm based on CS features.

1.1 Outline of Deliverable 5.1

The D5.1 report structure is presented below:

- Chapter 1. Introduction to the methodology, data classification and structural RA model.
- Chapter 2. Scope of D5.1 and advancement of SIRAM project's objectives.
- Chapter 3. Classification of Case Studies by SIRAM pillars and economic data availability.
- Chapter 4. The REGENA Production Function for farms applying Regenerative Agriculture.
- Chapter 5. Structural change simulation with REGENA in the 8 Case Studies.
- Chapter 6. Current state of D5.1, achievements and scheduled future updates.
- Chapter 7. Conclusions, publications and next steps towards D5.2 and D5.3.
- Chapter 8. Extensions beyond SIRAM and commercialization design for the post-SIRAM era.
- Chapter 9. Literature and references used for D5.1 substantiation.

2. Scope of Deliverable 5.1

D5.1 addresses both to a number of *Specific Objectives* (SOs) of SIRAM, as well as the pillars of the EU SFT as the major financial vehicle of the EU GD, aiming at the substantiation of the environmental value of RA solutions. This can be considered a prerequisite so that financial institutions may direct

the necessary amounts of financial capital towards RA investments with measurable impact on their credit rating profiles and monetary yields. In short, the scope of D5.1 addresses both the current scientific goals of SIRAM and the conditions for the future commercial utilization of its results. The SOs directly related to D5.1 are:

SO1: The depiction of tailored approaches to address climate change, desertification, pollution and low-income issues into a concise and coherent microeconomic production function, applicable to the individual small farm in the Mediterranean area.

SO2: The ability of the production function to depict adequately the positive effect of chemicals' use reduction, their substitution by organic fertilizers, biostimulants, organic waste biomasses and the deriving restoration and regeneration of soil health via the growth of beneficial microorganisms' species and populations, as well as the use of resistant local varieties and adoption of agronomical practices, such as no-tillage and cover crops.

SO7: The ability of the production function to depict the potential of the tested RA methodologies and their positive effect to the members of the small farm household via the *endogenous increase of its knowledge capital*.

In addition, in Table 1 below we assess the relation of D5.1 background works and findings to the six pillars of the EU SFT, in terms of scientific, dissemination and commercial potential:

Table 1. Relevance of D5.1 works to the pillars of the EU SFT.

EU SFT Pillar	Relevance (1-5 Scale)	Comment
Climate Change Mitigation	2	The REGENA function .v4 contains the structural elements as background for measuring climate change mitigation. The assessment of such issues is addressed by D5.2.
Climate Change Adaptation	5	The REGENA function depicts climate change adaptation, mainly via the variable of RVs and reduction of conventional pesticides.
Sustainable Water and Marine Resources	3	The REGENA function includes water use intensity as a proportional variable to tillage practices. Conservation of marine resources is outside the scope of SIRAM.
Transition to a Circular Economy	4	The REGENA function includes biomasses as a fraction of total output that enhances micro-organism species and populations and crowds-out conventional fertilizers.
Pollution Prevention and Control	3	The REGENA function can potentially include the role of nutrient surpluses (e.g. eutrophication by N, P) from excessive use of fertilizers and derived <i>Global Warming Potential</i> (GWP). The assessment of such issues is addressed by D5.2.
Biodiversity and Ecosystems	5	The REGENA function includes the growth of micro-organisms as a competitive variable to conventional fertilizers, able to depict the output of a fully RA farm.

From Table 1, we see that pillars 2 and 6 have the strongest relation to D5.1, followed by pillar 4. All SIRAM pillars deal with issues of these pillars. For instance, no-till and cover crops for mitigating soil degradation are highly related to pillar 2, the use of resistant varieties and beneficial microorganisms is highly related to pillar 6, while the crowding-out of conventional fertilizers and increase of water retention capacity is highly related to pillar 4.

On these grounds, D5.1 develops the REGENA function as an advanced economic model in order to depict patterns of *structural change* in hypothetical farms deriving from the features of SIRAM CSs. As RA begins from the microscopic level (e.g. microorganisms, organic residual biomasses), D5.1 is essentially examining the change of composition in the farm *production factors*. Of vital importance is the *endogenous growth* approach of the REGENA function for the enrichment of the *knowledge capital* of the farm household, increasing its income. Empirical studies [16-19] show that in various historical periods the driving force from the transition from *subsistence* -as the lower extreme of poverty- to *surplus* agriculture was the accumulation of knowledge on the local ecosystem and the trading synergies between neighboring farms. Contemporary examples of subsistence farms in Africa [20] demonstrated that knowledge of the local ecosystem features and diversification of crops yield promising results for the farms' growth, as well as for the active engagement and emancipation of women. This application in small-scale farms that are usually attached to local ecosystems -where in many countries women have significant responsibilities and knowledge of the local natural wealth- comprises an economic, environmental and social multiplier. A possible counterargument could be that RA practices are more dependent to geophysical phenomena, as rain-fed agriculture [21] is. However, it would be a mistake to consider agricultural practices that are geophysical-dependent as identical to RA. RA by no means should be identified as the abandonment of irrigation technology, a feature that is also incorporated in the REGENA function.

3. Case Studies groups by SIRAM profiles and data availability

The basic information of this chapter is contained in the M5.1 report. In D5.1, we include selected updates regarding (a) the classification of CSs, (b) the data preparation and (c) the simulation steps. In the next sections, we present the CS classification and data collection approach.

3.1 Classification of Case Studies by examined SIRAM Pillars

The first step of our analysis was to classify all CSs according to the examined SIRAM Pillars. SIRAM Pillars will be used in the REGENA modelling as production factors. In Table 2 below we encode the examination of SIRAM Pillars with the values 1 and 0, where **1** = SIRAM Pillar will be examined by the specific CS and **0** = SIRAM Pillar will not be examined by the CS. SIRAM Pillars are also encoded as **A** = Agronomical Practices; **B** = Biomasses; **M** = Micro-organisms; **R** = Resistant Varieties.

Table 2. Examined SIRAM Pillars by Case Study.

SIRAM Pillars	CS 1 (UCSC)	CS 2 (UCSC)	CS 3 (ENAM)	CS 4 (ARC)	CS 5 (USMBA)	CS 6 (IRTA)	CS 7 (CRRRA)	CS 8 (UC)
A Agronomical Practices	1	1	0	0	0	1	0	0
B Biomasses	1	1	0	1	0	1	1	0
M Micro-organisms	1	0	1	1	1	0	1	1
R Resistant Varieties	0	0	1	1	1	1	1	1
SIRAM Production Factors	3	2	2	3	2	3	3	2

As shown in Table 2, SIRAM CSs will examine either 2 or 3 SIRAM Pillars. A basic descriptive statistics of which SIRAM Pillars will be examined with higher frequency by CSs is presented in Table 3 below:

Table 3. Frequency of each SIRAM Pillar's examination across all CSs.

SIRAM Pillar	A	B	M	R
Examination Frequency	0.375	0.625	0.75	0.75

According to Table 3, the SIRAM Pillars examined with higher frequency are **M** = Micro-organisms and **R** = Resistant Varieties in 6 out of 8 CSs, while Pillar **A** = Agronomical Practices is the least examined one by only 3 out of 8 CSs. The next step is to identify the distribution of the number of SIRAM Pillars examined by the CSs. The results are presented below in Table 4 below:

Table 4. Number of SIRAM Pillars examined across all Case Studies.

Examined SIRAM Pillars	1	2	3	4
Number of CSs by Examined SIRAM Pillar	0	4	4	0

As Table 4 shows, 4 out of the 8 CSs (50%) will examine 2 SIRAM Pillars (irrespective of their specific combination), while 4 out of 8 CSs will examine 3 SIRAM Pillars. None of the CSs will examine only 1 Pillar or all 4 Pillars. The REGENA function includes all 4 SIRAM Pillars and any pillar not examined by a CS is substituted with the CA reference value for the CA-RA mix and fully RA scenarios.

3.2 Case Studies' Groups by SIRAM Pillars' similarity

Following Table 4, we examine the combinations of selected SIRAM Pillars in CSs. We extrapolated the similarities between CSs and classified them in two main groups consisting of secondary classes according to their specific features that are expected to affect the econometric modelling. Table 5 below presents the primary and secondary classification of CSs by examined SIRAM Pillar.

Table 5. Classification of SIRAM Case Studies in Groups and Branches by examined SIRAM Pillars.

Group	Case Studies	Branches	Case Studies	Substantiation
A	CS 1 (UCSC) CS 4 (ARC) CS 6 (IRTA) CS 7 (CRRA)	A-1	CS 4 (ARC) CS 7 (CRRA)	All CSs have 3 Pillars. CS 4 and CS 7 lack Pillar A and have Pillars B,M,R with Production Factor similarity between the CSs.
		A-2	CS 1 (UCSC)	All CSs have 3 Pillars. CS 1 lacks Pillar R, while it has Pillar A that will allow us to examine econometrically (a) the trade-off between Pillars A and R with CSs 4, 6, 7 and (b) the trade-off between Pillars M and R with CS 6.
		A-3	CS 6 (IRTA)	All CSs have 3 Pillars. CS 6 lacks Pillar M, while it has Pillar A that will allow us to examine econometrically (a) the trade-off between Pillars A and M with CS 1, 4, 6 and (b) the trade-off between Pillars R and M with CS 1.
B	CS 2 (UCSC) CS 3 (ENAM) CS 5 (USMBA) CS 8 (UC)	B-1	CS 2 (UCSC)	All CSs have only two Pillars. CS 2 has Pillars A,B while CS 3, 5 and 8 have Pillars M,R that will allow us to examine econometrically the trade-off between Pillars A,B (CS 2) and M,R (CS 3, 5, 8).
		B-2	CS 3 (ENAM) CS 5 (USMBA) CS 8 (UC)	All CSs have only two Pillars. CS 3, 5 and 8 lack Pillars A,B with Production Factor similarity between the CSs.

After classifying CSs by similarity, we are concerned with the availability of other economic data that are complementary to SIRAM Pillars and vital part of the econometric modelling. The requested data categories and variables are analytically presented in the M5.1 report.

4. The Regenerative Agriculture (REGENA) Production Function

An issue of imperative importance in the literature of *natural resource economics* is the building of structural mathematical models that depict accurately the result of the combination of *production*

factors for a desired output result. The issue is both of conceptual and empirical value, as different production function combinations may generate highly deviating output results. Although it is quite understood that a structural PF model has to consist of fundamental elements, such as species of natural resources (e.g. fuels for energy, minerals, weather and climate conditions), capital (e.g. from primitive tools to advanced automated machinery), manual and mental labor, as well as the causal topologies between them (e.g. mechanical capital endogenously depends on the transformation of raw natural resources that are subject to the *Second Law of Thermodynamics* [1,7]), the issue of how these production factors are *efficiently* combined comprises a more technical issue of econometric analysis as a quantitative framework for supporting the optimal selection of production factors.

4.1 Deliverable 5.1 and REGENA Production Function Update

Following the commitment of the SIRAM Proposal, Deliverable 5.1 is updated 6 months after its first submission due date (30/11/2023) with specific new inputs in the report's chapters, as following:

- In Chapter 5, we test and present a fourth simulation on the *Conventional and Regenerative Agriculture Mix* (CA-RA Mix) with refined assumptions based on the data received by the 8 CSs, as the most probable large-scale applied scenario after the completion of SIRAM. This model utilizes the energy data provided by the CSs and transforms them into an introduction to the *REGENA Production Function* version 4 (see Chapter 6) that is planned to incorporate environmental costs in the production process that are further related to Deliverable 5.2.
- In Chapter 5, we further simulate the continuous distribution of the potential of endogenous growth due to the knowledge stock augmentation between men and women. As the results have shown that the majority of the average productivity increase of the reference farms' human capital derives from women's participation in the scientific research and application process, we present the related Gaussian distribution, assuming normality properties.

4.2 Agricultural production and Returns to Scale

An additional aspect of PFs is the general impression that they primarily concern modern industrial civilizations. This has affected not only the perception of the historical continuity of PFs but the *per se* adoption of assumptions that are considered to depict accurately the efficiency level of combined production factors. A typical example is the *Cobb-Douglas* PF [10] that is assumed to be dominated by *constant returns to scale*, which in short means a linear relationship between the increase of the amount of production factors and total output. This perception might have been an accurate view of a specific time window in humanity's economic history, however it leaves out of its analytical frame how efficiently production factors combined *before* that time window and how efficiently they will be combined *after* it, assuming that their inputs continue to increase. In short, an inclusive PF should be mathematically able to reproduce all possible *returns to scale* types across the continuous (linear) increase of production factors, even if its empirical study demonstrates only a subset. This is an issue of critical importance for RA as the starting point is considered to be the subsistence level; hence an empirical study begins from the lowest possible amount of combined production factors that may show different returns to scale across their increasing inputs.

4.3 Review of agricultural production functions

In the above context it is frequently neglected that although the current postulation of PFs concerns almost exclusively industrial output, the fundamental laws of economic production were postulated

from the study of agricultural ecosystems. For instance, the PF precursors of the widely used Cobb-Douglas PF were the Wicksteed and Wicksell PFs [10] at the late 19th century, focusing on how the production factors of early industrialized agriculture could be combined to yield the maximum result of crop output to sustain a community's population and generate surpluses. These PFs influenced the creators of the Cobb-Douglas PF that enriched it for depicting econometrically the composition of the United States (USA) economy between manual labor and mechanical capital. The general form of the Cobb-Douglas PF for a n number of inputs (production factors) is:

$$Q = f(X_1, X_2, \dots, X_n | A, a_i) = A \cdot \prod_{i=1}^n X_i^{a_i}, \quad A, X_i \in R^+; a_i \in (0,1); \sum_{i=1}^n a_i = 1 \quad (1)$$

In Eq. (1), A is considered to be an exogenous output scaling parameter, usually depicting the level of technology. The multiplicative structure of Eq. (1) suggests a minimum *complementarity* level as if even one input becomes zero ($=0$), total output becomes zero as well. In addition, the Cobb-Douglas adopts the assumption of *constant returns to scale*, as it seems from the sum of the exponents that are equal to the unit ($=1$). The exponents signify the *output elasticity*; that being the per cent (%) increase of total output per 1% of increase of input. Typically, a generalized form of Eq. (1) could assume any sum of exponents with different impact for each case. For instance, a sum $\sum a_i > 1$ would signify *increasing returns to scale*, with the graphical shape of the PF having a power behavior, while a sum $\sum a_i < 1$ would signify *diminishing returns to scale*, with the PF demonstrating a n -root behavior.

However, the Cobb-Douglas PF, although capable of describing a specific window of the total chart of production factors' combinations and total output, it is unable reproduce all possible patterns of returns to scale in a single map. In more technical terms, the main issue of Cobb-Douglas-type PFs is they are limited in a *globally monotonic behavior* of (1) growth and (2) of returns to scale. Another agricultural PF that is indicative of such behavior is the Spillman [9,13]. The first issue concerns the violation of fundamental physical laws, such as the *Second Law of Thermodynamics*, and the second concerns the accurate depiction of output elasticities across the growth path. For instance, a *logistic growth* pattern, where the system stabilizes at its *carrying capacity*, contains an exponential part at the beginning, a (small) linear part across the inflection point in the middle and a n -root part across the last growth stages that depict in the same map the sequence of all three types of returns to scale (increasing, constant, diminishing). A correction of this issue is achieved by the *Halter transcendental* PF [8,12] that can depict accurately the sequence of logistic growth but also the diminishing output across the constant increase of inputs. The general form of the Halter transcendental PF is:

$$Q = A \cdot \prod_{i=1}^n X_i^{a_i} \cdot e^{b_i \cdot X_i}, \quad A, X_i \in R^+; a_i, b_i \in R \quad (2)$$

According to Eq. (2), the 3-parameter Halter PF has exceptional flexibility as it can take any form to express accurately numerous growth patterns and returns to scale sequences. The most standard for of the Halter PF manifests for $A, a_i > 1$ and $b_i < 0$. For these parameter values the output Q generally follows a pattern of logistic growth up to a peak and the starts a slow exponential decay, suggesting that continuing to increase inputs on a constant and limited system (e.g. fertilizers on a field) will not only reduce returns to scale but the output itself. For other combinations of parameter values, the Halter PF manifests different behaviors. For instance, a parameter value $b_i = 0$ transforms the Halter PF to a Cobb-Douglas-type PF. Numerous other interesting behaviors are feasible, however as they escape from the scope of the D5.1, we will leave this technical part outside of our analysis. Finally,

an upgrade of the Halter transcendental PF that is closer to the rationale used for the REGENA PF is the de Janvry *Generalized Power* PF [11], with the following form:

$$Q = A \cdot \prod_{i=1}^n X_i^{f_i(X)} \cdot e^{g(X)}, \quad A, X_i \in R^+; a_i, b_i \in R \quad (3)$$

Essentially, Eq. (3) preserves all the flexibilities of the Halter transcendental PF, augmented by the additional flexibility to express the power and exponential parts as functions instead of parameters and single variables respectively. This property is extensively utilized in the REGENA function built in the next section as it allows to express an input as a function of another set of inputs. Combining the features of Eq. (1)-(3) we assess structural change as a *shift in natural resource use* that also affects the knowledge accumulation between the members of the farm according to the dedicated labor. As RA is founded at the bio-molecular level, what is actually examined is a fundamental change in the *composition of the farms' production factors* with the use of *local natural capital availability* and its effect on the farms' crop output. Although many approaches in the existing RAE literature identify the potential of RA for crop output [22,23] and farm income growth [24,25], including ecosystem services with proven value, such as carbon storage in natural ecosystems [26,27], the incorporation of ecosystem interactions in a microeconomic PF still remains an uncharted field. As developed in the next section, the REGENA PF includes both production factor types; biotic fitting better to CS1, CS2, CS4 and CS6 and abiotic that are more indicative of CS3, CS5, CS6, CS7 and CS8, as well as their interactions.

4.4 Structuring the REGENA Production Function

After defining that the general input-output pattern of the desired PF will be combining elements of the Cobb-Douglas, the Halter transcendental and the de Janvry Generalized Power PFs, our next task is to structure the building blocks of the PF that define the *internal* relations between the inputs. We name the derived PF as the **REGEN**erative Agriculture or **REGENA Production Function**. Essentially, the REGENA PF is a *complex endogenous growth* RA PF, where besides the output elasticities that signify the productivity of each production factor separately there are nested interactions between the production factors themselves. Hence, at a large degree they endogenize the physical properties of agro-ecosystems that affect the amount of other inputs. As shown, indicative examples are the relation between the species and population sizes of beneficial micro-organisms in the soil to the accumulation of knowledge by the farms, the amount of biomasses enhancing the growth of micro-organisms or the competition between micro-organisms and conventional fertilizers. The REGENA function is an original PF born as part of the WP5 of the SIRAM research project, aspiring to make a contribution to the RA economics literature and further evolve into more elaborate mathematical and econometric forms. The general form of the REGENA function is:

$$Q = \prod_{i=1}^n \left[X_i (X_{i0}, X_j, \dots, X_n)^{a_i} \mid i \neq j, \dots, n \right], \quad i, j, \dots, n \in N^+; X_i \in R^+; a_i \in R - [0] \quad (4)$$

Eq. (4) combines elements from Eq. (1)-(3) as it adopts the multiplicative rationale on the relation of production factors. However, it escapes from the strict assumption of constant returns to scale. Any input X_i is expressed endogenously as a function of $0 \rightarrow n-1$ inputs (which is, it is either independent or it is a partial function of up to $n-1$ variables) raised in the exponent a_i as its output elasticity. Even if the exponential decay part is missing in the general form- as it applies in the Halter or de Janvry

forms (Eq. (2)-(3))- its endogenous functional relationship with any other input may include it. In any case, we can simply assume that any variable X_i in the REGENA function follows the General Power form as shown in Eq. (3). For variables where $f_i(X) > 0$ and $e^{g(X)} = 1 \rightarrow g(X) = 0$, the variable reduces to the standard monotonic form of the Cobb-Douglas-type function.

Building each separate input, we begin from scientific and technological knowledge (A) that the farm accumulates along with the shift to RA practices. Although all of the three above models depict (A) as an exogenous coefficient that multiplies linearly total output as the technical level upgrades, the REGENA function depicts it as an endogenous variable depending on the knowledge accumulation on *Micro-organisms* (M_S) and *Biomasses* (B_S) species that combine with *full complementarity* as:

$$A = A_0 \cdot e^{m \cdot M_S + b \cdot B_S}, \quad A_0, M_S, B_S \in R^+; m, b \in R \quad (5)$$

According to Eq. (5), the physical meaning of this form is that as long as the species of populations of micro-organisms grow, statistically new and more available samples of them arrive so that the total knowledge on the micro-ecosystem becomes increasingly representative of the full RA potential of the farm at rate (m). Respectively, organic biomasses have a similar effect, as their amount increases and farmers can classify, separate and utilize them with higher precision for the soil's fertilization. Knowledge accumulation on biomasses increases at a rate (b). Eq. (5) comprises also a multiplier of manual *Labor* (L_M) as every additional hour dedicated in the farm is increasingly efficient due to the (exponential) accumulation of knowledge. Hence, the total labor (mental and manual) in the farm is:

$$L_T = A^\alpha \cdot L_M^\lambda = (A_0 \cdot e^{m \cdot M + b \cdot B})^\alpha \cdot L_M^\lambda, \quad A_0, L_T, L_M, M, B, \alpha, \lambda \in R^+; m, b \in R \quad (6)$$

Eq. (6) suggests that manual labor L_M is an independent variable as it only concerns standard works that any unskilled worker can perform. Any special skill, knowledge and technique that is beneficial for the better care of the soil is included in the mental labor variable A_0 that is further augmented by the knowledge stock on micro-organisms and biomasses. The output elasticity (λ) of manual labor, as well as (α) of knowledge, are the typical exponents found in all multiplicative production functions.

Although Eq. (5) suggests an exponential growth without a limit, practically is limited by the values of M and B , which are maximized according to the agro-ecosystem's carrying capacity when a full shift towards RA practices is achieved. In contrast, the use of conventional *Fertilizers* (F) is competitive to the use of biomasses and the growth of micro-organism populations as:

$$M_F = M_0 \cdot e^{-\varphi \cdot F}, \quad M_0, F \in R^+; \varphi \in R \quad (7)$$

Eq. (7) suggests the competitive relationship between micro-organisms and conventional fertilizers (F) by a rate (φ) that expresses the intensity of micro-organisms crowding-out from the use of each unit of conventional fertilizer. Biophysically, coefficient (φ) could express the intensity of (negative) response of micro-organisms due to toxicity etc.. It is expected that different micro-organisms have different response towards conventional fertilizers; hence this coefficient is essentially a *weighted average* of a "basket" of selected micro-organisms. In turn, as mentioned, conventional fertilizers (F) are also competitive to the use of organic biomasses B as:

$$B = B_Q \cdot (1 - h \cdot F), \quad B_0, F, h \in R^+ \quad (8)$$

Eq. (8) suggests that the total amount of biomass B as organic fertilizer depends on a base amount (B_Q), reduced by the amount of conventional fertilizer F that is further multiplied by a coefficient of substitution (h). This coefficient is practically the amount of conventional fertilizer that is required to substitute one unit of biomass for an *equivalent* result. Hence, for $h < 1$ the conventional fertilizer is more efficient than the biomass, for $h = 1$ both are *qualitatively* equivalent, while for $h > 1$ biomass is more efficient. Respectively, the base amount B_Q is considered to be a fraction of total output (Q) as:

$$B_Q = q \cdot Q, \quad B_Q, Q \in R^+; q \in (0,1) \quad (9)$$

Eq. (9) suggests that the (thermodynamic) losses abstracted from total output that are assessed as inadequate for consumption along with any other material losses across harvesting can be reused as biomasses. Closing the loop of relationships between micro-organisms, biomasses and conventional fertilizers we model the population of micro-organisms as:

$$M = \frac{M_0 \cdot e^{-\varphi \cdot F}}{(1 + M_0 \cdot e^{-\gamma \cdot B})}, \quad M_0, F, B, \gamma \in R^+; \varphi \in R \quad (10)$$

Eq. (10) suggests that micro-organisms' diversity and populations grow proportionally to the amount of biomasses fertilizing the soil. The coefficient (γ) depicts the metabolic ability of micro-organisms and also depends on their "basket". A higher value of (γ) signifies higher metabolism and population growth, reaching the maximum population more quickly. The maximum population (M_0) is further dominated by the *Sprengel-Liebig Law of the Minimum* [28], suggesting that an organism's biomass is constrained by the growth factor (e.g. nutrient C, N, P, S) in *minimum relative availability*. Relative availability is further defined as the ratio between the minimum necessary amount of a nutrient that is *exactly* (i.e. with complete complementarity and no substitutability), combined with a set of other nutrients to form one unit of biomass, in relation to its environmental availability [1,7]. For instance, a typical necessary ratio of carbon, nitrogen and phosphorus nutrients $C/N/P = 41/7/1$ with natural availability of phosphorus at only 0.5 units, will allow the utilization of only 20.5 units of carbon and 3.5 units of nitrogen to preserve this ratio. Any excess amounts will remain unutilized by the system at the risk of them being transferred via water flows to wetlands and groundwater aquifers, causing eutrophication and pollution. By the above, we model M_0 to be the system's *limiting factor* as:

$$M_0 = \text{Max}\{M[(C_1 / R_1); (C_2 / R_2); \dots; (C_n / R_n)]\}, \quad C \leq R, C, R_{1 \rightarrow m} \in R^+ \quad (11)$$

Eq. (11) depicts the law of the minimum as a *Consumption to Reserves* (C/R) ratio, which is widely used in natural resource economics and is equivalent to the standard formulation. Completing the modelling of population size of micro-organisms, we postulate the general condition of total output (Q) in relation to the state of adopting full RA practices or any deviation from them as:

$$\text{Max}(Q): \left\{ \left[M_0^{a_n} \cdot \prod_{i=1}^{n-1} X_{i|M_0}^{a_i} \mid M = M_0 \right]; \left[\prod_{i=1}^n [X_i (X_{i0}, X_j, \dots, X_n)^{a_i}] \mid M < M_0 \right] \right\} \quad (12)$$

Eq. (12) essentially suggests that if full RA practices are adopted, the system's growth will depend on the micro-organisms' maximum population (M_0) and the amount of each other input used to reach that level. Any further input (e.g. fertilizers) will either reduce M_0 or will not have any further effect on total output growth. Hence, three deriving conditions are: (a) the full RA farm follows a pattern of logistic growth that is usually observed in natural ecosystems, which is physically backed from the

fact that full RA farms utilize almost completely the properties of the local natural ecosystem; **(b)** in essence, the full RA farm's limiting factor is the population of micro-organisms. In contrast, for any lower micro-organisms' population size, total output will continue to accept the further increase of the inputs and their functional relationships. A third important feature of Eq. (12) is **(c)** that the total output of mixed RA-CA or full CA *is not necessarily lower* than of the full RA farm's output. Indeed, it is possible (even theoretically) that the maximum total output with full CA practices via combining inputs in a very different way from RA may be higher. However, such a practice is *not sustainable in the long-term*, as the soil will need to enter a phase of fallow after an intense period of conventional fertilizers and pesticides use. In addition to the above, the REGENA function allows any intermediate RA-CA mix, where the *trade-off between output size and long-term sustainability* is a vital research issue of SIRAM WP5 that will be investigated partially in the D5.1 update (M24) and D5.2 (M30).

Continuing with the description of inputs in the REGENA function, we may continue with the aspect of the crop's resistance ability towards abiotic stresses, such as heat shocks and droughts. Weather conditions are included as production factors in the measurement of crop output. Although with the progress of technical means, the dependence of agriculture from hydrometeorological phenomena is highly mitigated, optimal combinations of weather conditions maximize crop output or reduce the cost of any production level. In general, the central weather variable is temperature (T), modeled in the REGENA function as a stochastic process following the *Normal Distribution* $T(\mu, \sigma)$; with μ as the mean value and σ depicting standard deviation. However, irrespective of the exact pattern that the time-series of temperature follow, to measure a RV's resistance against external weather conditions from an RA perspective we are required to structure a function of the RV's response towards a range of temperature values. We may depict the map of a variety's *internal productivity* (H) across a range of temperatures with a general mathematical form as:

$$H^\delta = \left[\varepsilon \cdot T \cdot \left(1 - \frac{\eta}{\varepsilon} \cdot T \right) - c \right]^\delta, \quad H, T, \varepsilon, \eta, c \in R^+; \delta \in R \quad (13)$$

Eq. (13) is essentially the continuous and symmetrical quadratic map, where the parameters' values determine the *range* of the map's positive values, as well as its global *maximum* value. For simplicity, we may consider at this point $c=0$, so that the initial value of the map is for $T=0$. Its physical meaning is that for any deviation from an optimal temperature, the system will perform less than maximum. In our case, this concerns crop output that is highest at a specific temperature, while it is reduced for any deviation from it, higher or lower. The significance of the quadratic map in regard to the process of temperature time-series in an area is to show how temperature values are distributed in relation to the map's points indicating crop *intrinsic productivity*. For instance, as the maximum point of the quadratic map is for $T=\varepsilon/2\cdot\eta$ [1,7], setting a reference optimal temperature at 25°C and beginning from a reference value of a crop with neutral resistance ability at $\varepsilon=1$, the quadratic map yields by default a value of $\eta=0.02$ for a ε/η ratio equal to 50°C. Hence, the physical meaning of the quadratic map is that the crop will be able to survive within a range of 0-50°C and with maximum productivity at 25°C. This specific ratio can be preserved for infinite combinations of parameters ε and η values. For example, even if both combinations $\varepsilon_1/\eta_1=1/0.02$, $\varepsilon_2/\eta_2=2.5/0.05$ preserve this ratio, the second combination suggests higher crop intrinsic productivity, as for any temperature T it is able to yield a higher output. Respectively, the exponent (δ) is a smoothing *resistance* or *homeostasis* coefficient. The above approach is quite representative of the arid and semi-arid conditions of many countries in

the Mediterranean (in SIRAM represented by CS3-CS5, CS7) and is directly related to the application of *Weather Derivatives* (WDs) [29] as financial instruments for managing operational risks deriving from weather variability. Essentially, planting RVs in heat-stressed areas comprises a form of future cost savings from the avoidance of the need to pay the premiums of these instruments. Such aspects are part of RA ecological finance engineering schemes that will be developed in D5.3.

The next main category of the REGENA function variables concerns environmental-intensive inputs. These inputs are further grouped into energy-intensive and water-intensive. Although at this phase the REGENA function will not deal with the measurement of environmental impacts as a cost for the farm that affects its decisions toward one or another combination of inputs (closer to CA or RA), we include the structural elements that will allow future updates and next deliverables to address such issues in a monetized manner. The group of energy-intensive resources is modeled as:

$$E = (k \cdot E_K) \cdot K_0 \cdot (F^s \cdot (1 - \pi) \cdot P^p), \quad E, E_K, K_0, F, P, k, \varepsilon, s, p \in R^+; \pi \in [0,1] \quad (14)$$

Eq. (14) measures the *energy use* (E) of a farm as a function of *mechanical capital* (K), *conventional* (petrochemical) *fertilizers* (F) and *conventional pesticides* (P). Respectively, the endogenous variables and parameters concern the *energy used by each unit of mechanical capital* (E_K) as weighted average of the energy mix, augmented by parameter (k) signifying the CO2 emissions intensity as a weighted emissions' energy mix average. The crucial variable here is the base use of mechanical capital K_0 . In economic literature, mechanical capital concerns any material tool or machinery used to leverage the value of manual labor. For this particular case we may consider that K_0 is the minimum amount of machinery (e.g. vehicles, monitoring systems, tools) in a fully RA farm. This base machinery stock increases with the increase of fertilizers and pesticides that are assumed to be utilized via machinery (e.g. spraying from a tractor). Parameters s and p signify how efficiently fertilizers and pesticides are utilized via the use of machinery. Practically, at the endogenous level, exponents s and p function as *input elasticities*, where contrarily to the *output elasticities* of Eq. (1)-(4) their desired value is as low as possible. The physical meaning of this combination is how well the mechanical capital is able to operate as a *multi-purpose* production factor. For instance, a tractor may have attached systems for spraying both fertilizers and pesticides, without the need of using separate vehicles. Hence, across the combined increase of fertilizers and pesticides, the use of mechanical capital will increase at a monotonically diminishing rate. Finally, coefficient (π) depicts the variety's *pest resistance* ability, in analogy to its heat stress resistance via coefficient (δ) in Eq. (13), suggesting the degree at which the crop requires less chemical pesticides from the standard (for $\pi=0$) to cope with biotic stresses.

The formulation of energy-intensive endogenous production factors in Eq. (14) provides a flexibility of modelling them into both their overall energetic efficiency (e.g. how productive is each fuel and CO2 emission unit) or their *Global Warming Potential* (GWP) and by building blocks (e.g. how well machinery, fertilizers and pesticides combine per unit output). A similar rationale is adopted for the category of environmental-intensive inputs regarding water use, as shown in Eq. (15) below:

$$W = W_0 \cdot e^{wK - z \cdot B} \mid K = K_0 \cdot F^s \cdot (1 - \pi) \cdot P^p, \quad W, W_0, K, K_0, B, w, z \in R^+; \pi \in [0,1] \quad (15)$$

Eq. (15) suggests that *water use* (W) is a function of a minimum required amount W_0 for a specific RV with properties described in Eq. (13)-(14), increasing exponentially with use of mechanical capital (K) for tillage (as factor of reduced water capture by the soil and increased ET) at an intensity rate (w). In

contrast, the need for additional water is reduced by the amount of biomass (B), fertilizing the soil at an intensity rate (z) and enhancing its water capture ability.

Describing the endogenous (nonlinear) cross-relations between production factors with Eq. (5)-(15), the building blocks of the REGENA Production Function are structured. Its overall form according to the principles followed for PFs by Eq. (1)-(4) is:

$$Q = \left(A^\alpha \cdot L_M^\lambda \right) \cdot B^\beta \cdot M^\rho \cdot H^\delta \cdot E^\nu \cdot W^\xi, \quad A, L_M, B, M, H, E, W, \alpha, \lambda, \beta, \rho, \delta, \nu, \xi \in R^+ \quad (16)$$

The above structure of the REGENA function is inclusive of all challenges addressed by SIRAM CSs and generally RA as part of the EU GD and EU SFT. Indicatively, we mention **CS1** with the challenge to increase carbon and nitrogen contents in the soil; **CS2** with the challenge of increasing farmers' income, water efficiency and reduce the use of conventional fertilizers; **CS3** planting and testing RVs; **CS4** with the challenge of coping with the shortage of fertilizers and increasing the share of organic agriculture and bio-pest control; **CS5** challenged with enhancing soil fertility and bio-pest control; **C6** coping with nitrate pollution from the excessive amounts of conventional fertilizers and reduction of soil quality, along with the increase of water use efficiency and carbon sequestration increase); **CS7** challenged with enhancement of the contribution of bio-pests, increasing water use efficiency and reducing conventional fertilizers and finally **CS8** enhancing the share of bio-pests and testing RVs. In the next chapter we present preliminary results based on the application of the REGENA to simulate structural change patterns in the 8 CSs.

As a conclusion of this chapter we address the following question: *Should the REGENA function take the crop output or crop value modelling path?* Each option incorporates benefits and costs. Although the value approach would be more accurate as it can include the cost of CO2 atmospheric emissions, fuel and water resources depletion, this work will be part of D5.2 after finalizing the REGENA version (see Chapters 6 and 7). Specifically, the crop output modelling path embodies a possibility of farm growth even with the full adoption of CA practices. However, as mentioned this is not indicative of the full environmental cost. However, this approach compensates with the ability to present more accurately that CA practices are *long-term unsustainable* with the need of periodic disruption of the crop output to put the soil into fallow state. In contrast, within the EU GD and EU SFT contexts the value modelling path is more realistic as it accounts for the reduction of the farm's net revenue due to excessive environmental costs contained in Eq. (14)-(15) (that from a mathematical standpoint may be explained as the exponential decay part of the transcendental PF dynamics of Eq. (2)-(3)). In the current REGENA version, we deal exclusively with outputs and assume coupling between output and value, which means that the pattern of the output's growth is reflected to the one of the value (with or without a linear or a nonlinear combination) and that any excessive increase of inputs will lead to reduced output.

5. Simulating structural change with REGENA

In this chapter we present the primary simulation results of the REGENA function for each CS, based on the available data and rational assumptions on benchmark values for critical variables, according to the literature. In section 5.1 we present visually the three main patterns of the REGENA function; (a) for full CA, (b) for full RA and (c) for a CA-RA composition. Specifically, for the CA-RA mix, in the updated version we performed a fourth scenario (d) based on assumptions on the reduction of the production values to energetic costs, as a smooth introduction to the REGENA version 4 (see Chapter

6) that will be further examined in D5.2 for three (3) selected CSs in combination to environmental life-cycle assessments and product labeling. Furthermore, in section 5.2 we discuss the issue of OI as the main mechanism for farmers to accumulate knowledge and its distinction from other forms of knowledge regarding CA. In section 5.3 we present a first assessment on the how the benefits from knowledge accumulation are allocated between men and women, as a special issue of D5.1.

5.1 REGENA crop output patterns in the Case Studies

In this section we present the simulation results of three “hypothetical farms” that represent the features of each SIRAM CS. The simulation was based either from the direct utilization of available field data or the simulated upscaling of each CS performing pot or laboratory experiments.

The adopted approach consists in the following elements. We primarily defined the conditions of a “global” fully CA farm, which is a standard farm that is assumed for simplicity to apply as benchmark for each CS, irrespective of the different climate conditions (by Koppen-Geiger classifications) met in each CS site. This reference CA farm is common for all CSs and shows the REGENA dynamics as well; however with the variables regarding SIRAM pillars taking the minimum positive values. The CA farm is considered to depict the maximum crop output irrespective of its environmental sustainability. To reveal the REGENA dynamics for the CA farm, we increase each input shown by Eq. (4)-(15) *except for the four SIRAM pillars* that are considered to remain at a minimum value. We then normalize the CA farm’s outputs so that its maximum value is (=1). We further simulate with the REGENA function the case of composite CA-RA practices by CS, now allowing the four SIRAM pillars to *grow along with all other production factors*. Finally, we simulate the fully RA farm where we allow the four SIRAM pillars to grow at the expense of their competitive production factors, setting the condition that the system will stop growing as soon as it meets its carrying capacity (the limiting factor). The production factors are also normalized as a weighted average *Inputs Basket Index* (IPI) with a range $IPI \in [0, 300]$.

Figure 3 presents the REGENA simulation results for each of the 8 CSs for the three initial scenarios, as well as the new scenario (d) on an energetic approach of REGENA that was applied for the CA-RA mix as the dominant scenario in all CSs and the most probable for a hypothetical commercial pilot applying the SIRAM results. An issue of major importance is the diversity of examined SIRAM pillars, as presented in Table 2. As none of the CSs examines all four SIRAM pillars but only specific pillars combined as subsets by two or three, there are potentially significant issues of underestimation for the CA-RA mix standard, updated and RA scenarios. Specifically, as there is strong relation between Biomasses and Micro-organisms, for CSs that examined only one of the two pillars, we assumed a neutral effect for the other (e.g. in CS2 examining the effect of Biomasses but not Micro-organisms, the increase of Biomasses leaves unaffected the growth of the latter, contrary to Eq. (10), although it crowds-out conventional fertilizers). In any case though, the revealed common pattern for each CS is that every scenario has a range (wider or shorter) where it is *dominant*, suggesting *succession* from CA to CA-RA mix and eventually RA. Specifically, in every CS, we may identify that at an initial stage output with CA prevails against the other two scenarios. At a mid-stage the CA-RA mix will become dominant, while for a very high IBI index, the fully RA scenario prevails.

A possible argument against the above approach could be: *Why not choosing every single time the CA scenario at the maximum output that utilizes a lower amount of inputs and maintain this level of land use in perpetuity?* The answer is that even if with full RA the maximum output level stays below the one with mixed or CA practices, as it is based on ecosystem functions, metabolizing primary solar

energy inputs to secondary in the form of biochemical bonds [7], it will perpetually stabilize around the carrying capacity M_0 (where in the REGENA function is also the system's limiting factor), without the need of periodical disruptions for putting the soil into fallow.

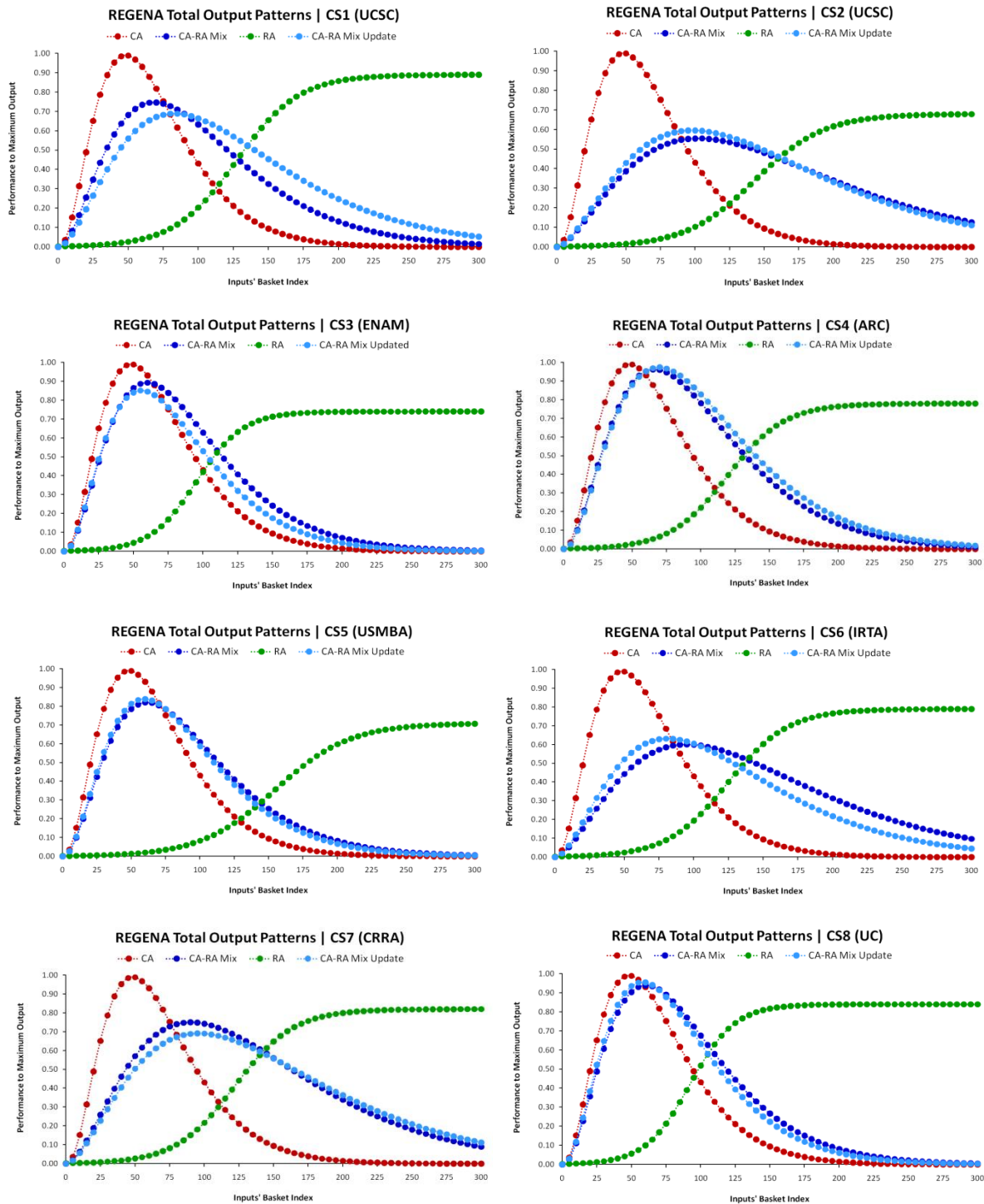


Figure 3. Simulation results of the REGENA function on the eight SIRAM CSs for three crop output patterns: **(a)** Exclusively CA practices, **(b)** Mixed CA-RA practices and **(c)** Exclusively RA practices.

In regard to the above sustainability issues, Figure 3 presents schematically the relation between CA and RA cumulative output in time. In addition, as we have partially accounted for the *environmental costs* of each scenario in terms of PEF/OEF or/and GWP that are in compliance to the rationale of the emerging *System of Environmental-Economic Accounting* (SEEA) at corporate and national levels, the

CA-RA mix demonstrates small deviations from the initial estimations. Specifically, while the main pattern is preserved (even the CA-RA mix will eventually become unsustainable in the long term as we keep adding non-RA production factors, such as chemical fertilizers, pesticides and mechanical capital that eventually overwhelm the RA constituents) it demonstrates higher stability and gradual behavior than the CA scenario.

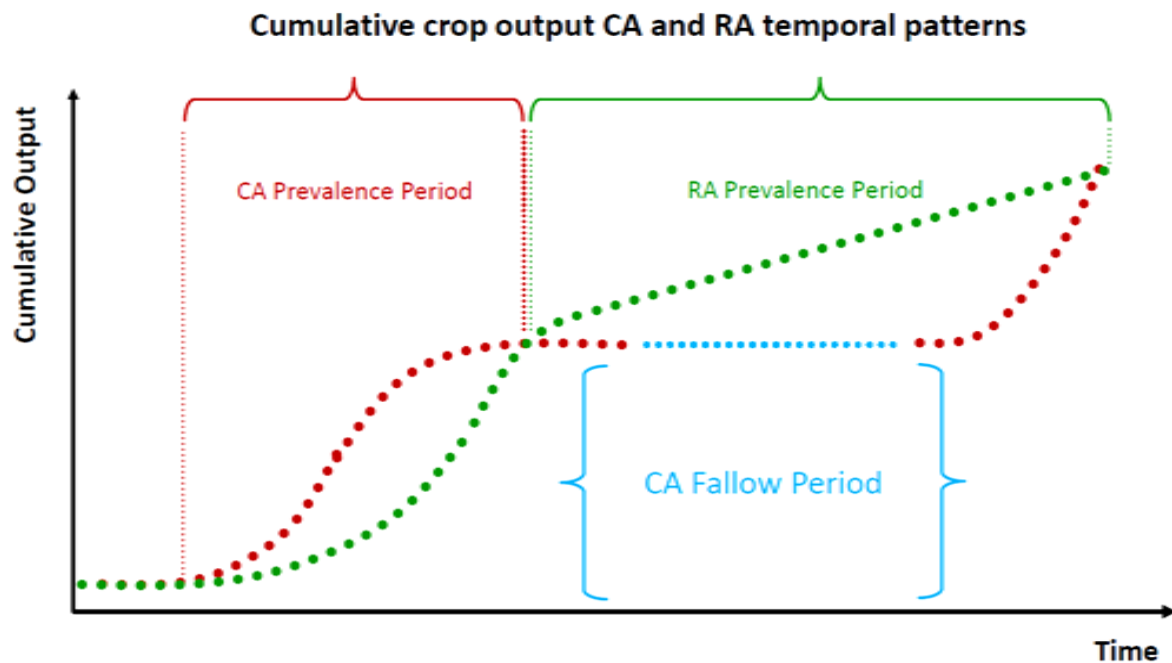


Figure 4. Schematic depiction of CA and RA sequences in perpetual time. Is it a *rabbit-turtle dilemma*?

Figure 4 suggests that even when optimal production factor combinations are selected for maximum output in the case of full CA or mixed CA-RA practices, fallow periods will follow to replenish the soil, putting a temporary cap on cumulative output until the next CA cycle is able to begin. In contrast, RA utilizes ecosystems' functions and can be a continuous practice without the need for fallow periods. Assuming that RA follows a logistic growth pattern, maximizing output at carrying capacity (limiting factor), it generates a constant output in perpetuity at its maximum level. These outputs are added year after year, so eventually the cumulative RA output surpasses CA output although its yield occurs more gradually at a slower growth rate. Hence, although in the short-term a fully RA farm may yield less, in perpetuity it is expected to yield more. Although the presented sequence in Figure 4 is purely theoretical, we may assume a number of factors that have an impact on both the growth rate and the intermediate fallow periods for CA, able to change the structure between the two approaches. Such an issue includes a more complex analysis, including the *substitutability* of soils, as well as their physical availability for establishing periodical shifts from one practice to another. Such issues are beyond the scope of our current work, however will be discussed in next deliverables.

5.2 Knowledge accumulation via Open Innovation

A major issue in the endogenous growth literature concerns the type of knowledge accumulation. As a complex nonlinear endogenous growth function, the REGENA develops a similar discussion that fits best to the EU's RA challenge. How is knowledge accumulated, as described in Eq. (5)? What factor triggers and maintains the process of small RA farms accessing scientific knowledge that cannot be of empirical nature on the microscopic ecosystem of micro-organisms and classification of biomasses

to optimize their species and population sizes? Why the optimal use of conventional fertilizers from the farmers cannot be considered as knowledge accumulation? It is of crucial importance to denote that knowledge accumulation from the observation and classification of agro-ecosystems' natural capital is a process observed across the whole duration of the agricultural civilization, where farmers incorporated it as a crucial part of their property [30]. However, the sharing of knowledge between communal farms for enhancing crop output and protection against various natural and social risks was a common practice, especially during the Western European Middle Ages. Today, the model of knowledge diffusion that has the features fitting endogenous growth and RA is *Open Innovation* (OI) [31,32] as a form of free-access outsourced knowledge that is incorporated to the firm's (for SIRAM the farm's) internal works. This model establishes the conditions for a *positive sum game* for both the external innovator and the farmer.

The OI-type endogenous growth part suggests that for any composition containing CA and RA in the REGENA, even the optimal utilization of conventional fertilizers limits the farmer only to the *Use* of the *exogenously developed* production factor (even if the farmer receives special training for it) that incorporates industrial R&D inputs (e.g. patents) from the developer and manufacturer. Hence, the farmer has no fundamental knowledge (in the sense of basic or applied scientific research) on the fertilizer's manufacturing stages and *Product Environmental Footprint* (PEF). Essentially, the farmer makes use of a *final product from the perspective of the industry and an intermediate product from his perspective* to grow his own final product (the crop). He does not know or even needs to know anything else on the fertilizer other than the instructions how to use it, putting an upper limit to the farmer's knowledge potential and a minimum level of environmental impacts on which he/she holds no direct control. Business models such as *Chemical Leasing* (ChL) attempt to partially resolve this issue, including the *Extended Producer's Responsibility* (EPR) principle, where the manufacturer is obliged by law to offer a minimum level of knowledge to the farmer on the optimal use of fertilizers. However, even these schemes deviate significantly for the potential offered by endogenous growth and OI. On the contrary, the RA part embodies R&D from the very foundations of the crop's growth. The farmer has actual free access (OI) to the information of the crop's growth via observations and scientific orientation (e.g. such as the designed WP6 training activities) from the very beginning of the crop's process and accessing all of its functional levels; from the nutrient-bounding organisms at the micro-ecosystem scale to the manifestation of their macro-ecosystemic benefits. Extensions of such type of knowledge accumulation patterns concern the value added of BioL instruments across synergies between small farms forming local conglomerates that will be examined in D5.3.

5.3 Allocation of knowledge stock augmentation between men and women

In this section we particularly focus on the simulated allocation of knowledge accumulation, as it is described by Eq. (5) between men and women working in the model farm. As the accumulation of knowledge occurs in the form of OI, it essentially comprises a *public good*. We define a public good as *a good that its use from one consumer does not exclude the use by any other consumer*. Hence, although both sexes benefit from the OI-type knowledge diffusion, we perform an initial assessment on how the OI benefits are allocated between the working hours of men and women as an effect to the L_T variable of the REGENA function.

In Table 6, we present the data by each CS on the estimated annual working hours per individual and how these working hours are allocated between the sexes. The maximum initial equality of working

hours was observed in CS 8 (UC), followed by CS 7 (CRRA) with an allocation of 51.6% for men and 48.4% for women.

Table 6. Simulated working hour benefits of endogenous knowledge accumulation in the farm by sex.

Productivity growth	CS 1 (UCSC)	CS 2 (UCSC)	CS 3 (ENAM)	CS 4 (ARC)	CS 5 (USMBA)	CS 6 (IRTA)	CS 7 (CRRA)	CS 8 (UC)
Annual work hours Men	1,728.0	1,536.0	1,968.0	1,783.0	1,968.0	1,920.0	192.0	1,020.0
Annual work hours Women	0.0	0.0	0.0	200.0	0.0	640.0	180.0	1,020.0
Productivity ↑ (%) Men	0.23	0.12	0.19	0.26	0.19	0.21	0.25	0.50
Productivity ↑ (%) Women	1.00	1.00	1.00	0.87	1.00	0.63	0.31	0.50

Specifically, Eq. (5) of the REGENA function was applied for each CS, assuming that men keep their existing OI knowledge level from their existing working hours, but share their current manual labor with women by 50%. As OI is considered to be a public good, women receive all the benefits of the accumulated knowledge capital as a “copy” (without respective loss from men), while synergies (as labor economies of scale) can achieve an increase in total and by-sex productivity. In the majority of cases where the initial working hours of women where zero, their productivity increase is by default 100% (=1.0), while for other CSs with non-zero working hours it increases from 31% to 87%. For CS 8, productivity increases are equally shared as initial conditions remain unchanged.

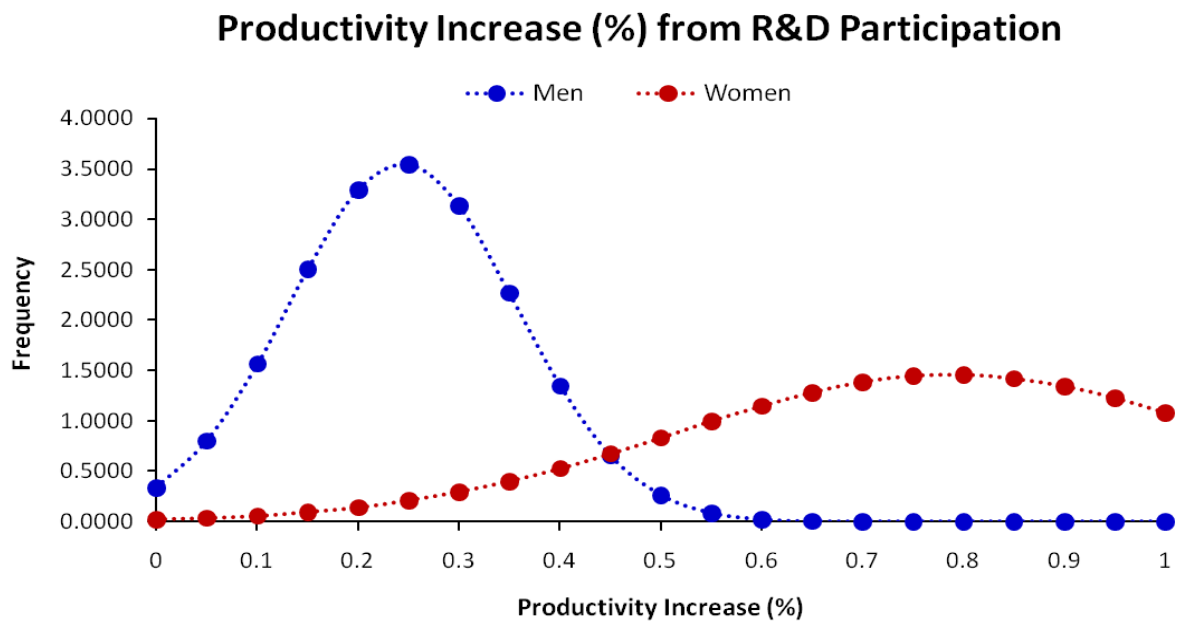


Figure 5. Continuous (Gaussian) distribution models of per cent (%) productivity increases for men and women after sharing knowledge and manual labor.

As expected, Figure 5 demonstrates a higher per cent (%) productivity increase in women, as men were already utilizing a higher fraction of their potential. In addition to the overall shaping of small independent farms in agrarian societies (~10ka BC - 1,800 AC), evidence show that the allocation of works between men and women in the farm household optimized output for the creation of food surpluses that allowed demographic increase [33]. Besides these historical evidences, this pattern is observed even in contemporary subsistence farms. Specifically, the transition from the dependence on CA methods or external food aid to endogenous growth with the utilization of biomass energy as

foundation, activated productivity increases and free time that was in turn dedicated to knowledge accumulation of local ecosystems' properties [20], resulting to output diversification and growth.

6. Current State of D5.1 and WP5

According to the above, the state of development of WP5 can be considered as *Ahead of Schedule* as D5.1 has been implemented with an achievement of additional goals besides the ones planned. The 1st level classification of CSs has been implemented since M5.1, while the 2nd level classification was implemented across the econometric modelling and simulations (see Section 5.1). Any issues of lack of optimal data to best fit REGENA, such as lower ranges of time series in crop outputs, are mainly due to the necessary time lag of experiments by WP4 CSs to yield measured results. In addition, as some CSs perform pot experiments, others lab experiments and others field experiments, the first two categories had to be upscaled via simulations. These issues were partially compensated in the D5.1 update at M24, with an elaboration of the REGENA Production Function.

For D5.1 specifically, the current version of the REGENA Production Function does not incorporate all environmental costs across the crowding-out of RA in favor of CA (e.g. excess N, P amounts that are not absorbed by biomass and comprise a pollutant for surface and groundwater resources), although in the update we include initial assessments of embodied carbon footprints for machinery, petrochemical fertilizers and pesticides. This selection was made on purpose, as D5.1 is concerned with building a flexible model of the farm's *production structure*. The *production cost* issues with monetization will be examined in D5.2, with the introduction of *full cost accounting* by incorporating the value of ecosystem services and PEF assessments, in compliance to the SEEA [1] approach.

Specifically on the REGENA Production Function, currently at its version 1 with a first attempt to test version 4, we have already identified five (5) alternative versions to be tested for higher accuracy. In brief, these versions are:

- **Version 2:** A REGENA structure closer to the Halter and de Janvry transcendental forms for each variable except for the knowledge accumulation.
- **Version 3:** A REGENA structure with a lower number of variables, compensated by a higher degree of nesting (as composite functions of the form $f(g(x))$).
- **Version 4:** A REGENA structure incorporating environmental costs in the production process that are directly related to D5.2.
- **Version 5:** A REGENA structure able to model the upscaling of farms that adopt OI practices to local or regional farm conglomerates that adopt protected IP practices, where R&D and knowledge accumulation provides its holders with competitive advantages and excluding all competitors that are not part of the conglomerate.
- **Version 6:** A discrete time dynamic version of REGENA, where the intrinsic growth rate of micro-organisms is the critical parameter towards stability or instability of crop output.

7. Conclusions and next steps

With the objectives of D5.1 update achieved and the progress of WP5 considered above satisfactory, the next scheduled steps are the following:

- During the whole period December 2023 - June 2024, all SIRAM partners will contribute to the creation and maintenance of a *Regenerative Agriculture Economics* (RAE) database that will be operational in the post-SIRAM era.
- The WP5 Leader will collaborate with the responsible partners for the related deliverables to be completed (D2.4 | M32; D3.2 | M36; D3.4 | M36; D4.2-4.3 | M36) in order to enrich the RAE database.
- The CSs will provide the latest available data that are necessary for D5.2 by mid-June, so that the analysis is more accurate and the REGENA function more enriched.
- During June 2024, the WP5 Leader will complete the M5.2 version 1 report (M25).
- Publication of a paper to an open access peer-reviewed journal with the findings of Chapters 3, 4 and 5 as main body of text is planned by the end of 2024.
- Dissemination of the REGENA Production Function by WP6 and inclusion of the model to the training workshops.
- Dissemination of the REGENA Production Function to the supporters of SIRAM who provided recommendation letters, as well as new identified stakeholders and supporters.

8. Extensions beyond SIRAM

From the collaboration with the partners of the SIRAM consortium and the integration of agronomic and economic methods, we have already identified commercial breakthrough extensions for which our current work is the foundation. In this chapter we focus exclusively on economic utilizations that are a results' exploitation target during the post-SIRAM era, as for now they are beyond the scope of our current research objectives and can only be discussed.

The corner stone of our post-SIRAM targets concerns the effect of adopting RA practices on crop production across the increase of the analytical scale. Specifically, as the *micro-economic* structural change concerns the farm's production factors' shift towards the utilization of local ecosystem and biodiversity capital, at a first level, we may investigate its effect on *meso-economic* farm organization and synergistic clustering. Given the change in information flow assumed in the REGENA function and the shift from OI to protected *Intellectual Property* (IP) across the formation of RA clusters, do the latter tend to the formation of trading alliances and conglomerates for achieving *economies of scale* to substitute imports, or they operate completely competitively? In turn, how can RA clusters affect *macro-economic* topodynamics in the global agritrade web? In general, as it is expected that the ability of RA farms to form conglomerates signifies their higher potential to substitute imports and enhance crop and food security, we may state the following indicative, however non-exhaustive, post-SIRAM issues to be investigated:

- What is the projection of the global demand for RA products?
- What is the total potential of RA in the EU in terms of output and value?
- What is the potential of RA to substitute *intermediate* agricultural imports to maintain the high content of proteins in the final good (e.g. legumes instead of soy-based cattle feed)?
- How can the establishment of RA practices affect structurally the EU CAP and the allocation of agricultural products between its country-members?

- What is the RA-derived IP value for private investors and their critical investment variables (e.g. Return on Investment periods, risk coefficients, use of weather derivatives)?
- Does the enhancement of RA practices from the single farm lead to a fragmentation of the global agritrade web towards regionalization and localization? What mechanisms are behind this process?
- Does the fragmentation of the global agritrade web and the disruption of traditional trade relationships increases respectively geopolitical risks?

As mentioned, the above issues are only indicative and WP5 of SIRAM will set the foundations via the next deliverables (D5.2, D5.3) and their updates (D5.1, D5.2) along with the collaboration with stakeholders and project supporters for continuing the research towards this direction.

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