BioINSouth

Supporting regional environmental sustainability assessment for the BIO-based sectors to improve INnovation, INdustries and INclusivity in SOUTH Europe

Deliverable 4.4

Food Security and LULUCF Methodology

Bio-based Industries Consortium

Circular Bio-based Europe Joint Undertaking

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Project title	Supporting regional environmental sustainability assessment for the bio-based sectors to improve innovation, industries and inclusivity in South Europe
Project acronym	BioINSouth
Grant agreement ID	101156363
Project start date	01/06/2024
Duration	36 months

D 4.4 Food Security and LULUCF Methodology	
Due date	31.05.2025
Delivery date	30.05.2025
Work Package	4
Author(s) responsible	UNINA
Contributor(s)	UNINA
Reviewer(s)	ASOI, ACIS, SPRING
Version	Final
Dissemination level	Public

[VERSION AND AMENDMENT HISTORY]

Version	Date (DD/MM/YYYY)	Created by/ Amended by	Review of changes
1.0	17/04/2025	Pierfrancesco Recchi Francesco Caracciolo	First draft for internal reviews

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2.0	20/05/2025	Pierfrancesco Recchi Francesco Caracciolo	Final version including revisions and improvements suggested by reviewers
Final	28/05/2025	Pierluigi Argoneto, Lara Carlet (SPRING)	Final version ready for coordinator review and submission

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Executive Summary

This deliverable presents a comprehensive methodological framework to evaluate the implications of expanding the bio-based sector in Southern Europe, with a particular focus on Land Use, Land-Use Change and Forestry (LULUCF) greenhouse gases emissions, and regional food security. Developed within the scope of the BioINSouth project, this methodology aims to provide stakeholders — including policymakers, researchers, planners, and civil society actors — with a transparent, step-by-step approach to building land-use scenarios and assessing their impacts on environmental and food-related outcomes.

The methodology responds to the growing need for integrated tools that can account for the multiple dimensions of sustainability affected by bioeconomy development. As the demand for renewable bio-based materials increases — such as for bioenergy, bioplastics, and other biomass-derived products — it becomes essential to evaluate potential trade-offs. These include increased pressure on agricultural land, changes in carbon sequestration capacity, and implications for local food production systems.

The methodological framework comprises six main phases: (1) defining a baseline and analysing historical land-use trends; (2) developing future land-use scenarios through stakeholder consultation; (3) validating scenarios via a Mini-Delphi consensus-building process; (4) estimating impacts in terms of GHG emissions using the FAO's EX-ACT tool; (5) evaluating food security indicators using a custom-built Excel-based toolkit; and (6) comparing the outcomes across scenarios to extract policy insights. This structure is designed to facilitate rigorous analysis while remaining accessible to practitioners with limited experience in environmental modelling or remote sensing.

The food security component focuses on three key indicators: Total Caloric Supply, Agricultural Land Availability Index, and Self-Sufficiency Ratio. These indicators allow users to assess whether changes in land allocation — from food production to non-food uses — are likely to affect regional resilience, import dependency, or nutritional sufficiency.

A practical application of the methodology is illustrated through a case study in one of the BioInSouth HUBs, the Campania region of Southern Italy. This case study involves the creation of three land-use scenarios — Business-as-Usual, Trend Mitigation, and Trend Reversal — each reflecting different pathways for the development of the bio-based sector. The scenarios are grounded in stakeholder input collected through a structured survey and validated through participatory workshops, capturing a diversity of perspectives across academia, public institutions, industry, and civil society.

Findings from the Campania case show that growth in the bioeconomy can be compatible with climate goals and food security, provided land use is managed carefully and inclusively. For example, the Trend Reversal scenario suggests that bio-based development can stimulate agricultural revitalization, improving both carbon sequestration and food self-sufficiency. Conversely, scenarios with uncoordinated land reallocation to bio-based uses may reduce the availability of cropland and lower the Self-Sufficiency Ratio, increasing regional dependency on food imports.

By offering a replicable structure, this deliverable provides future BioInSouth HUBs — including regional authorities and practitioners — with a valuable tool to balance climate action, economic development, and food security objectives. These are essential steps for aligning bioeconomy growth with the European Union's broader climate, food, and sustainability goals.

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1 Overview

1.1 Objective of the Work

This document provides a structured, step-by-step methodology to analyse land-use changes with a dual focus on climate impact and food security. Its purpose is to enable practitioners to develop land use change scenarios and assess their implications for Land Use, Land-Use Change and Forestry (LULUCF) emissions and food security outcomes. By following this document, users will be able to estimate greenhouse gas (GHG) emissions or removals from land use changes and evaluate how these changes affect local food production and self-sufficiency. The document is designed for professionals working in land use planning, bioeconomy development, and sustainability policy, offering them a practical framework to evaluate how the growth of bio-based sectors may influence land use dynamics and related environmental and food security outcomes. This includes government officials, project developers, researchers, and consultants involved in climate change mitigation, agricultural development, or land-use planning. Given the participatory nature of the methodology — where expert opinions shape land-use change scenarios — the guide is also useful for stakeholders engaged in bioeconomy planning, such as representatives from agriculture, forestry, and industrial bio-based sectors.

By following this methodology, users will be able to:

- Construct historically informed land use change scenarios using Earth Map and IPCC-based land use data.
- Collect expert-driven insights through structured questionnaires and validate them using a Mini-Delphi approach.
- Use FAO's EX-ACT tool to estimate carbon balance and GHG emissions under different land-use scenarios.
- Assess food security implications, focusing on agricultural land allocation, production shifts, and regional self-sufficiency.

This document is structured as an operational manual, enabling users to apply the methodology in a practical, transparent, and replicable manner. Whether for academic research, policy advisory work, or sustainability project implementation, this document provides the necessary conceptual framework and technical instructions to facilitate informed decision-making. The step-by-step instructions assume no prior expertise in specialized tools like remote sensing or GHG accounting software — each step is explained clearly so that a first-time user can implement the methodology independently.

1.2 Context and Relevance

The increasing development of the bio-based sector is reshaping global and regional land-use patterns, with significant implications for climate change mitigation, biodiversity, and food security. The shift towards bio-based solutions — including bioenergy, bioplastics, and bio-based chemicals — requires careful assessment of its potential trade-offs, particularly in terms of land availability, carbon emissions, and agricultural productivity (European Commission, 2022).

Changes in land use directly influence LULUCF emissions, a critical component of national and international climate commitments under the Paris Agreement. The LULUCF sector (which covers forests, croplands, grasslands, and other land uses) plays a dual role: it can act as a carbon source when natural or semi-natural ecosystems are degraded, or as a carbon sink when land is restored or sustainably managed. According to the Intergovernmental Panel on Climate Change (IPCC), LULUCF offers significant near-term mitigation potential while also providing essential resources like food, wood, and biodiversity.

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In fact, reducing deforestation and improving land management are among the most effective ways to cut emissions (IPCC, 2006). At the same time, modifications in cropland allocation and agricultural systems can impact food availability, regional self-sufficiency, and rural economies. Food security depends on sufficient and stable food production; drastic land use shifts can affect the availability of arable land and thus a region's capacity to feed itself. Balancing bioeconomy growth with climate and food security goals is therefore a key challenge for policymakers, planners, and sustainability analysts (Raimondo et al., 2021; Scarlat et al., 2005).

This makes integrated analysis important: understanding trade-offs and synergies between climate mitigation (via LULUCF changes) and food production is key to sustainable land management. By conducting a combined analysis, policymakers can identify strategies that reduce GHG emissions from land use (contributing to climate goals) while maintaining or even enhancing food self-sufficiency (Searchinger et al. 2019).

This document introduces a robust methodological framework to assess the potential land-use transformations driven by bio-based sector expansion. It leverages:

- Historical land use data from Earth Map (FAO) and IPCC-based classifications to understand past trends.
- Stakeholder-driven scenario building through expert consultation and Mini-Delphi validation.
- Quantitative impact assessment using FAO's EX-ACT tool to estimate changes in carbon stocks and GHG emissions.
- Food security indicators, operationalized through an Excel-based toolkit, including land allocation efficiency and regional self-sufficiency ratios, to analyse agricultural implications.

By applying this methodology, users can generate evidence-based insights to support sustainable land management policies and bioeconomy development strategies. The structured, step-by-step approach ensures that even professionals without direct experience in land use modelling can effectively conduct assessments and interpret results.

1.3 Key Concepts

1.3.1 Land Use Land Use Change and Forestry

Plants and soils store a significant amount of terrestrial ecosystems carbon, in the form of organic matter, as a product of photosynthesis. This process, known as primary production, removes carbon dioxide (CO_2) from the atmosphere and fixes it into biomolecules. Therefore, all human activities which interact with soil and vegetation impact carbon cycle. Deforestation, soil sealing, wetland drainage and ploughing are typical examples of harmful practices, while afforestation, conservative tillage and conservation of natural land improve terrestrial carbon stocks. According to IPCC, in the period 2010-2019, land use accounted for about 13-21% of global anthropogenic emissions of greenhouse gases (GHG), with carbon dioxide being the major compound in quantitative terms, followed by methane (CH_4) and nitrous oxide (N_2O) mainly due to cattle farming and crop fertilization (IPCC, 2022). Monitoring and good management of land use is therefore crucial to mitigate climate change, as well as other kind of environmental degradation.

In the context of international institutions and agreements, the term **Land Use, Land Use Change and Forestry** (**LULUCF**) refers to the whole human activities affecting land use, including agriculture, grazing, forestry and settlements. Already in 1992, the United Nations Framework Convention on Climate Change (UNFCCC) has undertaken to foster good practices for the preservation and strengthening of carbon sinks

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within terrestrial and marine ecosystems, as well as the reduction of GHG emissions not covered by the Montreal Protocol — ozone depleting substances (UN, 1992). To achieve this goal, the agreement requires the membership to monitor GHG fluxes by taking national inventories which account of both anthropogenic emissions by sources and removals by sinks. The IPCC is in charge of defining guidelines for correct calculations. National GHG inventories must be periodically updated and submitted to the Conference of the Parties (COP). As an important factor in emissions and removals, the LULUCF sector represents a specific component of GHG monitoring process and is deemed to have a significant climate mitigation potential.

In the context of the European Union, Regulation (EU) 2018/841 governs the LULUCF sector in line with the commitments of the Paris Agreement. Specifically, the LULUCF regulation precisely defines the methods for estimating GHG fluxes from agricultural, forestry and other activities and establishes the procedures for monitoring, reporting and verification to ensure data transparency and reliability (EU, 2018). This regulation is part of a broader framework of EU strategy to combat climate change, which aims to achieve climate neutrality by 2050. Following the adoption of the “Fit for 55” package, aimed at reducing EU emissions by at least 55% compared to 1990 levels by 2030, the LULUCF regulation was amended in 2023, providing for a greater contribution from the whole sector in terms of net carbon sequestration, in order to make the climate neutrality goal more concrete within the established timeline (EU, 2023).

In addition to climate change, the environmental impact of the LULUCF sector affects several ecosystem functions, such as the water cycle, biodiversity, livelihoods, and employment. This means that effective management of LULUCF must consider the complexity of local contexts in order to mitigate potential conflicts between different needs. The most effective way to address this challenge is by ensuring that LULUCF policies align with the needs and perspectives of multiple stakeholders, aiming for results that enhance synergies while minimizing trade-offs.

1.3.2 Terrestrial Carbon Pools

The primary production process is the fundamental mechanism for biomolecule formation. These biomolecules enter the trophic chain and are utilized by all heterotrophic organisms as the basic building blocks of their biomass. Consequently, the term biomass does not refer exclusively to plant matter, though it makes up the majority of Earth's biomass, but also includes microbial and animal biomass (Bar-On et al., 2018).

However, living organisms are not the only carbon reservoirs. A significant amount of organic matter is stored in the form of undecomposed dead material, humus, peat, and fossil hydrocarbons. In fact, soil represents the largest carbon stock in terrestrial ecosystems (Kayler et al., 2017). Beyond its role as a primary source of life and a regulator of climatic processes, carbon storage is essential for soil fertility and stability (Smith, 2004). For these reasons, terrestrial carbon reservoirs are among the most well-studied and recognized ecosystem services.

For the proper compilation of national GHG inventories, terrestrial carbon stocks are classified into four main carbon pools:

Aboveground biomass. This includes all living organisms at the interface between soil and atmosphere, primarily composed of living vegetation such as trees, shrubs, and grasses.

Belowground biomass. This consists of all biomass growing underground, including plant root systems and other subterranean structures (stolons, rhizomes, tubers, etc.).

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Dead material. This includes all undecomposed or partially decomposed biomass of dead organisms present above the soil surface. It encompasses deadwood and litter (i.e., leaf residues and other small non-woody organic materials).

Soil organic matter. This represents the organic component of soil, including humus, peat, microorganisms, and other living or dead organic material incorporated into the soil.

Carbon pool values vary depending on land cover, soil and climatic conditions, and, in managed lands such as agricultural and forested areas, specific management practices. In general, among terrestrial ecosystems, forests store the most carbon in each pool, followed by grasslands and, lastly, croplands. Among croplands, permanent crops tend to retain more carbon in each pool, whereas annual crops generally have lower carbon stocks. The 2006 IPCC Guidelines for National Greenhouse Gas Inventories provide technical guidance on calculating carbon stocks associated with each carbon pool for different land uses and regions of the world (IPCC,2006).

1.3.3 Global Warming Potential

Though carbon dioxide is the primary driver of climate change, other gases also contribute significantly due to their high heat-trapping capacity. **Global Warming Potential** (**GWP**) is a metric used to compare the impact of different GHGs on global warming over a specific time horizon, typically 20, 100, or 500 years. It quantifies the heat trapped by a given mass of a gas relative to the same mass of CO_2, which conventionally has a GWP of 1.

Different GHGs have varying atmospheric lifetimes and heat-trapping capacity. For example, methane has a GWP of approximately 21–34 over 100 years, while nitrous oxide has an even higher GWP of about 265–310 over the same period. This means that both CH_4 and N_2O are significantly more potent than CO_2 in relative terms, though their atmospheric concentrations are much lower.

Based on the concept of GWP, it is useful to express GHG emissions and removals in **tons of CO_2-equivalents** (**tCO_2-e**). This standardized metric, recognized by international institutions and agreements, ensures comparability across different gases and sectors. As a result, it serves as a fundamental tool for climate policies, emissions reporting, and mitigation strategies aimed at addressing global warming effectively.

GWP values are periodically reassessed based on scientific advancements. Various IPCC reports, such as the Second Assessment Report (SAR) (1995), the Fourth Assessment Report (AR4) (2007), the Fifth Assessment Report (AR5) (2013), and the Sixth Assessment Report (AR6) (2022), have provided updated GWP estimates.

1.3.4 Food Security

Food security is defined as a condition where all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life. Ensuring food security in the context of climate change and increasing demand for renewable resources has become an urgent challenge. In particular, assessing the impacts of land-use changes associated with the development of the bio-based economy requires a detailed understanding of how shifts in agricultural land allocation affect both the quantity and the nutritional quality of food produced locally and globally (FAO, 2008).

A critical component in evaluating these dynamics is the **Total Caloric Supply** (**TCS**), a key indicator that measures the total food energy available from domestic crop production. TCS serves as a fundamental benchmark for analysing the potential consequences of land-use changes under different scenarios. It

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enables policymakers and researchers to assess, within the considered production systems, the impacts on nutritional supply when agricultural land is diverted from food production to alternative uses such as bioenergy or afforestation.

Another important metric is the **Self-Sufficiency Ratio** (**SSR**), which indicates the proportion of domestic food demand that can be satisfied by domestic production. When consumption remains constant, SSR effectively reflects the relative change in caloric production compared to a baseline or Business-as-Usual (BAU) scenario. An SSR value below 100% signals a growing dependence on food imports, raising concerns about exposure to market volatility and geopolitical risks. Conversely, values above 100% suggest a production surplus, which could enable export capacity or strategic reserves — critical in building resilient food systems.

The **Agricultural Land Availability Index** (**ALAI**) also provides valuable insights into the degree of land pressure under different land use and climate mitigation scenarios. A decline in ALAI implies reduced land available for food production, often due to the expansion of non-food land uses such as afforestation or infrastructure development. This reduction can constrain future food production potential, especially in areas already facing land scarcity or degradation.

Uncoordinated expansion of land for bioenergy crops or carbon sequestration projects may inadvertently exacerbate competition for land and water resources, jeopardizing both local and global food security. These trade-offs are particularly acute in regions where malnutrition and poverty are already widespread. Smallholder farmers and rural communities — who produce a large portion of the world's food — are among the most vulnerable groups, with limited adaptive capacity to absorb ecological or market shocks. Impacts on these communities may include reduced crop yields, income loss, food price inflation, and increased social vulnerability, leading to deeper cycles of poverty and, in some cases, forced migration.

International agreements and strategic frameworks have increasingly recognized the need to balance climate action with food security. The United Nations' Sustainable Development Goals (SDGs), particularly SDG 2 ("Zero Hunger") and SDG 13 ("Climate Action"), emphasize the necessity of integrated, sustainable agricultural development. Similarly, within the European Union, the Common Agricultural Policy (CAP) and the LULUCF Regulation promote synergistic practices that reduce emissions while preserving or enhancing the productive capacity of agricultural systems.

To navigate the complex interplay between climate objectives and food security, an evidence-based approach that incorporates robust indicators such as TCS, SSR, and ALAI enables decision-makers to evaluate trade-offs and identify strategies that safeguard food availability and reduce reliance on external markets.

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2 Methodology

2.1 Methodological Framework

The methodology was derived and tailored from approaches previously developed and applied by the economist research group within the Agritech National Center and LandSupport H2020 project. The methodology combines data-driven environmental analysis with expert knowledge to build and evaluate land use change scenarios, assessing their implications on both LULUCF emissions and regional food security. As illustrated in Figure 1, the framework proceeds through a sequence of five operational phases, each supported by specific tools and clearly defined procedures: (1) baseline definition and historical land-use change analysis, (2) scenario development through expert consultation, (3) impact assessment using FAO's EX-ACT tool, (4) food security implications assessment, and (5) comparison of outcomes across scenarios. These are followed by a sixth and final phase, dedicated to the interpretation of results and formulation of policy insights, where trade-offs, synergies, and strategic options can be analysed to inform sustainable land management decisions.

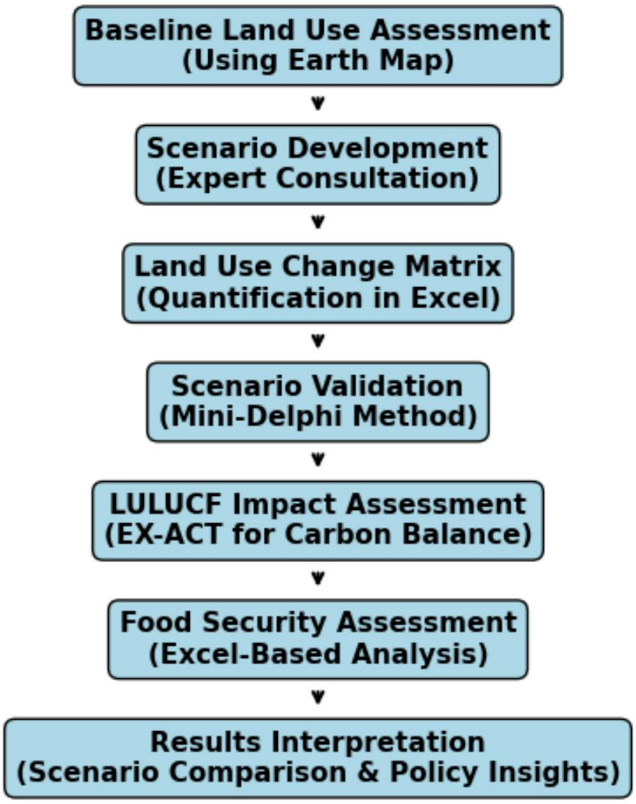

Figure 1. Methodological Framework for LULUCF and Food Security Impact.

I. Baseline Definition and Historical Land Use Change Analysis

The first phase focuses on understanding current and historical land-use dynamics. Earth Map, an open-access tool powered by Google Earth Engine and developed by FAO, can be used to extract land-use and land-cover data based on the IPCC classification (as derived from the ESA Climate Change Initiative). The user begins by selecting a region of interest and retrieving time-series land-use data.

These data are then used to construct a land-use change matrix, which quantifies the transitions between land categories (e.g., from forest to cropland, or from grassland to urban areas) over a defined reference period. This matrix serves two purposes: it provides a visual and numerical understanding of past land dynamics, and it establishes the Business-As-Usual (BAU) baseline for scenario comparison.

II. Scenario Development through Expert Consultation

The second phase involves the development of future land use scenarios, which are critical for assessing the potential impacts of bio-based sector expansion. To capture local knowledge and forward-looking insights, a group of regional experts can be engaged using a semi-structured questionnaire. The questionnaire elicits estimates on key drivers of land-use change, such as expected changes in cropland extent, forest cover, and productivity improvements.

III. Scenario Validation through Mini-Delphi

Once individual responses are collected, the initial scenario assumptions can be validated and refined through a Mini-Delphi session. This is a structured, participatory discussion in which experts evaluate the coherence and plausibility of the proposed scenarios. Through iterative feedback and consensus-building, the group finalizes a set of qualitative and quantitative land-use change scenarios, such as continued BAU, sustainable intensification, or expansive bio-based growth.

IV. Impact Assessment Using FAO's EX-ACT Tool

The fourth phase of the methodology assesses the climate impact of each scenario using the EX-ACT (Environmental Externalities Accounting Tool) developed by FAO (FAO, 2021). This Excel-based tool calculates the net greenhouse gas (GHG) fluxes associated with land-use transitions, accounting for changes in biomass and soil carbon stocks, as well as emissions from agriculture and other land-based activities.

The user inputs the land-use change data from each scenario into EX-ACT, indicating the area and type of conversion (e.g., cropland to forest, grassland to cropland), along with any relevant management practices. EX-ACT then applies default or user-defined emission factors to estimate the net GHG emissions or removals over the scenario's time horizon. The results allow for a direct comparison between the BAU and alternative development pathways, quantifying the climate mitigation potential of land-use policies.

V. Food Security Implications Assessment

Beyond climate impacts, land-use scenarios must also be evaluated in terms of their implications for food production and availability. In this phase, an Excel-based food security model has been developed to assess the impact of changes in cropland area, crop yields, and overall agricultural output on food security.

Three key indicators are calculated:

- **Total Caloric Supply** (TCS): Total kilocalories produced domestically from all crops.
- **Self-Sufficiency Ratio** (SSR): Ratio of scenario TCS to BAU TCS, reflecting the capacity to meet domestic needs.
- **Agricultural Land Availability Index** (ALAI): Total cropland in the scenario compared to the BAU, indicating shifts toward or away from food production.

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This structured assessment allows for direct comparison of food security outcomes across scenarios, offering insight into the trade-offs between food production, afforestation, and other land uses.

VI. Scenario Comparison and Policy Insights

In the final phase, the outcomes from the EX-ACT tool and food security model are compared across all scenarios. This comparison reveals the trade-offs and synergies between carbon mitigation and food availability. For example, a scenario that maximizes carbon sequestration through reforestation may reduce cropland area, potentially lowering SSR and requiring increased food imports. Conversely, an expansion of agricultural land may improve food self-sufficiency but result in higher GHG emissions.

The comparative analysis might support the formulation of policy recommendations, helping stakeholders balance climate and food goals. Key insights may include the need for sustainable intensification, protection of high-carbon ecosystems, and investments in technology and infrastructure that improve land efficiency.

However, this last phase will not be the object of the methodology, as it requires case-specific contextualization and broader stakeholder engagement beyond the scope of this methodological framework

2.2 Stakeholder Engagement and Scenario Planning

Stakeholder engagement is a central element in shaping the outcomes of scenario planning, especially when dealing with complex issues such as regional bioeconomy development. The participation of stakeholders ensures that the process is grounded in real-world insights and that the resulting scenarios reflect the priorities, challenges, and opportunities identified by those directly involved in or affected by development programs (Andersen et al. 2021).

In any scenario-building process, the involvement of stakeholders ensures that decisions are not based solely on technical expertise or top-down policies, but on a comprehensive understanding of local needs, opportunities, and constraints. Stakeholders bring to the table a variety of perspectives, from technical knowledge and scientific expertise to practical experience and insights into the social, economic, and environmental dimensions of bio-based sector (Bishop et al., 2007).

Stakeholder participation in decision-making is crucial, as it could enhance several aspects of the process, which can be summarized as follows:

Contextual relevance. Stakeholders are often the first to identify emerging trends or issues within the local context. Their insights provide a more accurate picture of the local realities and how these might evolve over time.

Scenario validity. The process of developing and testing scenarios benefits from diverse input, especially when stakeholders actively challenge assumptions and suggest alternative futures based on their lived experiences or sectoral knowledge.

Building consensus. Stakeholder involvement fosters a sense of ownership and legitimacy over the results. By engaging participants throughout the process, the final outcomes are more likely to be accepted and supported by the local communities, businesses, and institutions involved.

Risk identification. Stakeholders are uniquely positioned to identify potential risks that might be overlooked in purely technical assessments. These include issues related to land use, economic sustainability, or even social and political barriers that could hinder the implementation of bioeconomy growth plans.

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To ensure that stakeholders' contribution to scenario construction is well-balanced and effective, it is important that the stakeholder group includes members from multiple sectors, such as academia, government, enterprise, and civil society, following the principle of the quadruple helix (Carayannis & Campbell, 2009). Each stakeholder brings their own expertise, which is crucial for developing well-rounded and viable solutions.

While non-technical stakeholders provide valuable realism and pragmatism, their lack of specific preparation may lead to assumptions that are not entirely rational, potentially compromising the process. Conversely, technical experts, despite their rigorous approach, might overlook practical constraints, overestimating the role of purely rational elements. Striking the right balance in stakeholder representation is therefore essential. Ensuring inclusivity while maintaining competence and methodological rigour allows for a more effective and comprehensive decision-making process.

The stakeholder engagement process proposed in this document is designed to be iterative, with information collected in stages, scenarios refined over time, and feedback loops ensuring that final outcomes align with shared priorities. The process is structured into the following steps:

1. **Questionnaire design and distribution.** The first step in stakeholder engagement is the creation of a detailed questionnaire that captures key information needed to inform scenario development. This survey serves as the foundation for understanding stakeholder views on land-use changes, bioeconomy development, and associated environmental and social factors. Stakeholders are invited to provide responses that reflect their perspectives on existing conditions, potential future scenarios, and areas of concern.
2. **Scenario building.** Based on the data collected through the questionnaires, a set of potential bioeconomy growth scenarios is constructed. These scenarios explore different paths of bio-based development, including land-use changes, technological advancements, and the connection within new bio-based production systems. This phase aims to explore the possible implications of these various aspects, including trade-offs and challenges.
3. **Scenario discussion.** After the initial scenarios are developed, they are presented to stakeholders in workshops or feedback sessions. The purpose of these sessions is to gather feedback, refine the scenarios, and ensure that they reflect the collective priorities of stakeholders. The validation process allows stakeholders to review, discuss, and suggest changes to the scenarios. This approach is crucial for ensuring that the scenarios are not only technically sound but also socially acceptable and relevant.
4. **Feedback and refinement.** The scenario validation process is iterative, meaning that stakeholders are invited to revisit the scenarios multiple times, providing feedback at each stage. This ensures that the final set of scenarios is thoroughly vetted and supported by the stakeholders, making it a more reliable basis for policy and decision-making.

The proposed process is conceptually analogous to the Delphi method (Helmer, 1968), focusing on iterative feedback and consensus-building. However, it is a more streamlined approach designed to be accessible without requiring the specialized socioeconomic expertise typically needed for a full Delphi process. While the Delphi method involves anonymous rounds of feedback among a large group of experts, this approach maintains the core logic of iterative engagement and collective decision-making, but in a format that is more adaptable and easier to implement, making it suitable for diverse stakeholders and contexts.

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2.2.1 Structure of the Questionnaire

The questionnaire is designed to gather the necessary information to develop a well-rounded understanding of stakeholders' views on the relationship between bio-based sector growth and LULUCF, along with its environmental and food security implications.

The key areas of focus in the questionnaire include:

1. **Land use.** The most fundamental data required for scenario building pertains to land use. Stakeholders are asked to provide input on how different types of land are currently used and how they could potentially be repurposed for bioeconomy-related activities, such as biomass production, bioenergy, and bioproduct manufacturing. The questionnaire specifically addresses which types of land are suitable for bio-based production systems and which are unlikely to undergo significant changes. In particular, stakeholders are encouraged to consider possible transitions between different land-use categories. In other words, to collect meaningful information, it is not only necessary to determine whether a given land use will increase or decrease, but also to specify at the expense of which other land uses or in favour of which alternatives. Notably, only non-urban surfaces (such as agricultural, forested, or pasture lands) can be allocated to biomass production, while urban land should be considered practically irreversible due to infrastructure and zoning constraints.
2. **Management and inputs.** A second important aspect of scenario building concerns understanding how land-based production systems are managed. Accordingly, the survey includes questions about the use of by-products, the employment of inputs (such as fertilizers, pesticides and fuels), and the broader management practices that influence bio-based production. Stakeholders are also asked to evaluate the sustainability of bio-based related management practices and provide recommendations for improvement.
3. **Food security.** Given the close relationship between the bio-based sector and food production, the questionnaire examines stakeholders' views on the interplay between the bioeconomy and food security. This helps identify potential conflicts or synergies between different land uses, such as the competition between bioenergy crops and food crops. Additionally, the questions explore broader implications for food security, such as indirect land-use changes caused by the displacement of land-based production in different regions of the world.
4. **Environmental and social implications.** The questionnaire also gathers stakeholders' perspectives on the environmental and social implications of bioeconomy expansion. This includes the potential impacts on natural areas and, generally, ecosystem services. Furthermore, stakeholders are asked to identify any barriers or constraints to bioeconomy development, including regulatory, economic, or social factors that could inhibit the transition to a more sustainable bio-based economy.

Aiming for clarity, efficiency, and ease of use, the questionnaire allows respondents to participate without excessive effort while facilitating an easy interpretation of the results. To achieve this, it primarily consists of closed-ended questions to streamline responses but also includes a few open-ended ones for those who wish to elaborate on their opinions or explore specific aspects in more depth.

The questionnaire mainly gathers qualitative information but integrates some quantitative elements where necessary. Rather than obtaining precise numerical values, quantitative questions aim to establish an order of magnitude for key phenomena. An example of qualitative question is: "*Do you believe that the development of bio-based supply chains could lead to changes in cropping systems? (Yes, No, Don't know)*". An example of quantitative question is: "*What share of total cereal by-products will be used in the bio-based sector? (Less than 5%, 5-10%, More than 10%)*".

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Since the survey's main focus is on land-use changes, which are inherently exclusive — meaning an increase in one category necessarily implies a decrease in another — logical consistency between questions is essential (Bryman, 2016). The structure must ensure that no question contradicts previous ones, maintaining coherence throughout. In cases where different conditions apply based on prior answers, clear instructions guide respondents on how to proceed (e.g., "If you answered yes to the previous question, also answer this one…"). To ensure reliable responses, no question is mandatory, and a "Don't know" option is always available, preventing respondents from guessing answers without proper knowledge and thus reducing the risk of distorted results.

To ensure that stakeholders can provide well-informed responses, it is essential to give them relevant context about the region's land-use history and current trends (Andersen et al. 2021). Before completing the survey, stakeholders will receive an introduction to the territorial context, including information on past land-use changes and key drivers of change. This background information can be drawn from various sources, such as historical land-use data and reports from regional planning authorities, which will be described in the following chapters.

By providing this context, stakeholders will be better equipped to make informed decisions about potential land-use transitions and the broader implications of bioeconomy development. They will also be able to contribute more effectively to scenario-building discussions and assess the trade-offs between different bioeconomy pathways.

The questionnaire can be administered either through an online platform, which facilitates automatic branching and data processing, or in person during meetings. The survey developed for the Campania region case study is available in the appendix.

2.2.2 Scenario Building

The construction of scenarios for this project follows a structured approach, drawing on both historical land-use data and future projections. Based on input from stakeholders, several growth scenarios for the regional bioeconomy sector are expected to be developed. These scenarios may include changes in land use, forestry, agricultural systems, and the use of organic by-products, as well as production inputs.

The scenario-building process is designed to facilitate a comparative analysis between a baseline scenario and alternative scenarios related to bio-based sector growth. The baseline scenario represents a Business-as-Usual trajectory, assuming no major policy or market-driven interventions. In contrast, growth scenarios explore the potential effects of specific actions aimed at enhancing bio-based supply chains at the regional level. This comparative approach is essential for assessing the implications of different development paths, particularly in terms of GHG emissions, removals, and food security (van Notten et al., 2003).

A critical element in scenario construction is the analysis of historical land-use changes. This is conducted using a land-use matrix, where rows and columns represent the same land-use categories, and each entry indicates the proportion of land that transitioned from one category to another over a reference period. By examining historical trends, it is possible to estimate future land-use changes under BAU conditions, applying either linear or non-linear projections depending on expected technological advancements, policy interventions, and economic drivers.

The second step in scenario building involves synthesizing the information collected from stakeholders. Their responses provide insights into perceptions of land-use changes, the feasibility of bioeconomy expansion, and potential trade-offs. In particular, qualitative data may help identify the types of expected changes, while quantitative data may help define their magnitude. Moreover, stakeholder responses may

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contribute to outlining plausible trajectories of change, taking into account both enabling factors and constraints.

Initially, it is important to assess whether stakeholder opinions converge toward one or more preferred solutions. These should be prioritized based on the consistency of responses. If no clear consensus emerges, all alternative solutions remain under consideration and may be re-evaluated in subsequent rounds, where stakeholders have the opportunity to exclude the less convincing options as the process progresses.

The draft scenarios are then presented to stakeholders in participatory sessions for further refinement following a Mini-Delphi structure (Linstone & Turoff, 1975). These discussions provide an opportunity to validate assumptions, assess the plausibility of different land-use changes, and ensure that the scenarios align with regional priorities. Stakeholder feedback plays a crucial role in refining scenario narratives and adjusting input parameters where necessary. An example of the PowerPoint used to present scenarios resulting from the survey is provided in the appendix.

2.2.3 Scenario Validation

The scenario validation process is a crucial phase of stakeholder engagement, ensuring that the developed land-use change scenarios accurately reflect the collective vision of the actors involved. This process is structured around iterative feedback loops conducted through dedicated validation meetings. Initially, stakeholders are presented with the survey results and the scenarios derived from them, including the BAU scenario and alternative growth scenarios for the bio-based sector.

During these sessions, stakeholders are asked to assess the plausibility of each scenario and to express their level of agreement with key assumptions, such as the impact of the bio-based sector on agricultural land use, the potential recovery of abandoned lands, and the integration of agricultural by-products into bio-based value chains. This assessment is typically performed using structured rating scales, allowing for a quantitative comparison of stakeholder opinions (Linstone & Turoff, 1975).

If significant divergence emerges in stakeholder views, multiple iterations of discussions may be carried out. In cases where a convergence of opinions is not initially achieved, all scenario alternatives remain under consideration, and further refinements are made based on stakeholder input. The process continues until a sufficient level of consensus is reached, ensuring that the final scenarios are both technically robust and widely accepted. This iterative approach strengthens the credibility of the scenarios and enhances their relevance for policy development and decision-making in the bio-based sector.

2.3 LULUCF Assessment: the FAO EX-ACT

The Environmental Externalities Accounting Tool (EX-ACT) is an open license system developed by the FAO, designed to assess the potential impact of specific human activities on carbon stocks and GHG emissions. This tool performs carbon balance by comparing a baseline scenario, typically reflecting a “Business-as-Usual” situation, with a scenario where specific actions are implemented in order to achieve targeted objectives, such as climate change mitigation projects or sustainable development programs and policies (FAO, 2021). EX-ACT is a land-use-based tool and accounts for major drivers of GHG emissions and sequestration, including land-use change and land management. Standard carbon stocks and emissions associated with different land use in each ecoregion are derived from the IPCC guidelines for national GHG inventories. The carbon balance is calculated as the difference in carbon stocks and emissions between the baseline and the target scenarios, with results expressed as tCO_2-e per unit of

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land per year. This allows decision makers or project designers to prioritize activities and choose the solutions that best suits their purposes, offering significant climate and economic benefits.

This tool is versatile, applicable to a wide range of development initiatives across the whole LULUCF sector, including livestock, fishery, aquaculture, settlements and other land uses. It is user-friendly and requires relatively little data input, which can be sourced from a set of external platforms such as FAOSTAT and Earth Map.

EX-ACT can be used for both ex-ante analysis — as in this case — as well as for monitoring and ex-post evaluation of interventions impacts over a maximum duration of 20 years, which is divided into an implementation phase and a capitalization phase, respectively corresponding to the periods during which actions are realized and their effects take hold. Though EX-ACT is typically employed for project-level analysis, it can be easily up-scaled to program or sector levels and can also be utilized for policy analysis. The tool's cost-effectiveness and ability to deliver valuable insights into LULUCF and other activities make it a powerful asset for decision-makers in a wide array of development sectors.

The FAO provides access to EX-ACT in two formats: an Excel-based applet and an online, web-based application, both available at https://exact.apps.fao.org/ after registration. These formats enhance accessibility and flexibility, allowing users to choose the platform that best suits their needs. According to the scope of BioINSouth, the Excel-based format will serve as the reference tool for these guidelines, as it ensures platform stability and makes users completely independent from external providers. However, users may also choose to use the web-based application.

In line with FAO's Terms of Use, the tool may be freely included in BioINSouth toolkits when accompanied by appropriate guidance. Users must strictly adhere to the non-commercial use requirement, which cannot be waived under any circumstances (Terms of Use, sections 10.I and 10.IV). These provisions explicitly prohibit any modification to the tool's structure, formulas, text, or any other integral component. Furthermore, it is not permitted to publicly suggest or imply that the inclusion or use of EX-ACT constitutes FAO sponsorship, endorsement, or involvement (Terms of Use, section 9.IV).

2.3.1 Dynamics of Change

Before illustrating the functionalities of EX-ACT, it is important to introduce the concept of change dynamics, which help define how specific land-use transitions influence the carbon balance over time. Understanding these dynamics is essential for analysing the impact of different actions within the scenarios under consideration. Since each type of change follows a distinct pattern over time, selecting the appropriate dynamic is crucial for accurate assessments. In particular, users can choose among three possible change paths:

Immediate. This applies when an activity causes a sudden shift in carbon stocks (Figure 2a). In this case, the impact of the change reaches 100% of its potential by the end of the analysis period. For example, if a forested area is cleared all at once for agricultural expansion, the impact on carbon emissions is immediate, and this dynamic should be used in calculations.

Exponential. This applies when the rate of change is initially rapid but slows down over time (Figure 2b). Here, the impact of the change reaches 78% of its potential by the end of the analysis period. This might occur when afforestation projects begin with a high tree planting rate, which gradually declines as available land becomes scarcer.

Linear. This describes gradual changes occurring at a constant rate (Figure 2c). In this case, the impact of the change reaches 50% of its potential by the end of the analysis period. An example would be the steady conversion of grassland into cropland over several years, where emissions and carbon sequestration evolve progressively.

These dynamics not only describe land-use transitions but can also be applied to model the adoption rate of new land management practices. Thus, selecting the appropriate dynamic is required for every action investigated in the analysis. If no specific dynamic is chosen, the linear path will be applied by default.

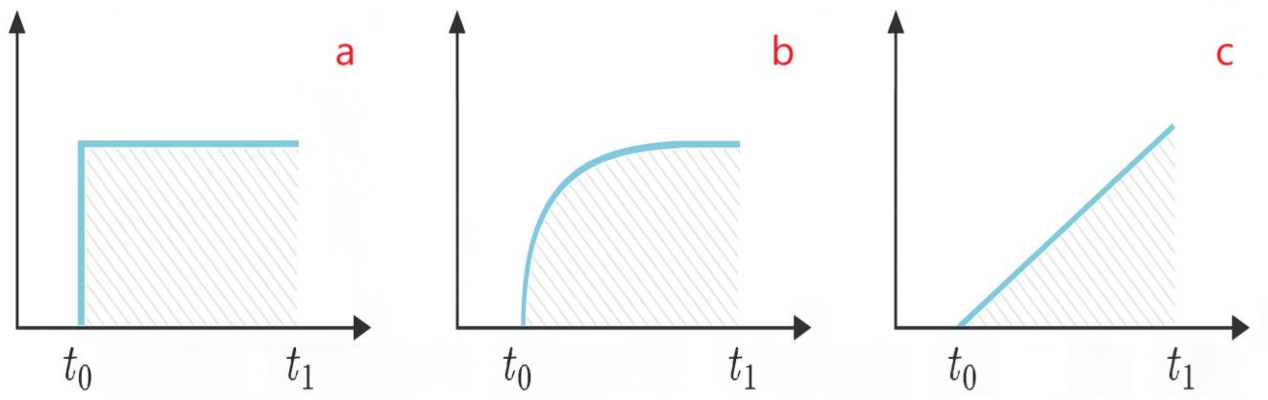

Figure 2. Graphical depiction of different change dynamics: (a) immediate response, (b) exponential growth, and linear progression (c). Adapted from EX-ACT Guidelines (FAO, 2021).

2.3.2 Structure of the Tool

EX-ACT is land use-based, meaning that the basic information required to populate the tool includes the extent of each land use type at the start and the end of the analysis period, for both the BAU and target scenarios, expressed in hectares. Additional information may concern land management aspects such as the use of fire, logging intensity, biomass removal, fertilization, and fuel consumption in agriculture, forestry, and other activities. Standard carbon stocks and GHG emissions associated with each land use type or activity follow Tier 1 of the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. However, if more detailed information is available at the regional or local scale, it is recommended to redefine the standard values at Tier 2 or even Tier 3 (IPCC, 2019).

The latest release of the EX-ACT Excel-based applet is version 9.4.2, which requires enabling macros for full functionality. In this version, the tool is organized into a system of spreadsheets divided into 10 sections. All of them, except the first and last, correspond to a specific component of the carbon balance and are further structured into several subsections. Based on the general goal of the BioINSouth project, which focuses on the development of the bio-based sector, as well as the various regional contexts and scenarios investigated, some of these sections can be omitted. The following paragraphs will provide detailed information about each section and how to input data to perform the analysis.

2.3.2.1 Description Section

The first section of EX-ACT is dedicated to the configuration of basic analysis parameters, such as intervention or project duration and the identification of ecoregion and soil characteristics, which are crucial for accurate calculations. Indeed, climate and soil type strongly influence the inherent capacity of ecosystems for carbon storage and sequestration, as they are key determinants for primary production and the rate of organic matter mineralization. By setting these parameters, the user will activate site-specific emission factors and carbon stock values for use in subsequent calculations.

This section is structured into the following subsections:

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I. Project Description

In this module, the user can specify the project's name and additional information for reporting purposes (Figure 3a). While not mandatory, it is helpful for identifying the project, especially if multiple projects are being carried out.

II. Project Site and Duration

In this module, the user must define the location characteristics of the target area (continent, country, climate, moisture, soil type) to determine specific reference carbon stocks and GHG emission factors (Figure 3b). It includes a help tab that guides the user in defining key parameters by providing general global classifications (Figure 3c). However, it is recommended to input more precise information from external sources, if available. This module is mandatory, as its information is essential for the calculation.

III. Global Warming Potential

In this module, the user can define the reference global warming potential (Figure 3d). If no action is taken, the model will adopt the IPCC Fifth Assessment Report (2013) values by default. If the Tier 2 option is selected, the user must manually enter coefficients.

IV. Reference Soil Organic Carbon Stock

This module is automatically defined based on previous choices. However, it is recommended to input more precise information from external sources, if available. In this case, the user must manually specify this parameter in the Tier 2 entry (Figure 3e).

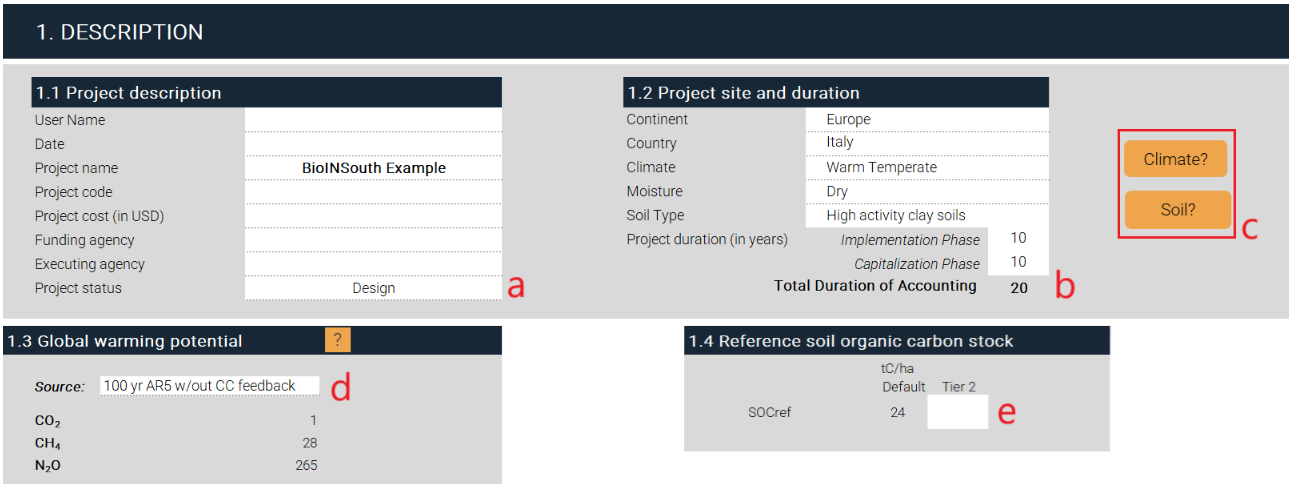

Figure 3. Illustrative excerpt from the "Description" section of the EX-ACT spreadsheet: (a) project description, (b) site and duration, (c) help tab for defining soil and climate, (d) global warming potential, and (e) reference value for soil carbon stock.

2.3.2.2 Land-Use Change

This section of EX-ACT focuses on land-use change (LUC), defined as the process of converting land from one use to another. Common examples of LUC include agricultural expansion, urbanization, deforestation, and afforestation. To distinguish what can be strictly considered as LUC from other types of changes,

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which are addressed in other sections, the tool defines a set of nine different land-use types, summarized as follows:

Forest land. A minimum area of 0.5 ha, covered by multiple tree species of varying ages, arranged unevenly, with a minimum density of 10-30% (depending on the vegetation type), and a potential minimum height of 2-5 meters at maturity (also depending on the vegetation type).

Forest plantation. Monoculture of tree species, consisting of trees of the same age and arranged in a regular spatial pattern. Typically used for afforestation or reforestation purposes.

Annual cropland. Plantations of species that complete their production cycle within a single growing season. These are typically annual herbaceous species, but also include non-woody perennial species, if they are completely harvested within a single season, and they need to be seeded annually. This category includes cereal crops, legumes, fruity and leafy vegetable plantations.

Perennial cropland (agroforestry). Plantations of species that occupy the same field for several growing seasons. These are typically perennial woody species that retain the same root system throughout the entire production cycle. This category includes fruit and berry plantations, nut crops, vineyards, and olive groves.

Flooded rice. Lowland rice plantations permanently or seasonally flooded. This type of land use differs significantly from non-flooded rice in terms of carbon stocks and GHG emission factors. Non-flooded rice is considered an annual cropland.

Annual fallow. Agricultural land temporarily set aside from production or other types of unused land covered by spontaneous herbaceous vegetation.

Grassland. Land permanently covered by perennial grasses, which may be used for grazing or fodder production.

Degraded land. Land where the native vegetation has been significantly altered, resulting in severely reduced biomass and soil organic carbon levels.

Other lands. All types of land not included in the previous categories, such as settlements and infrastructure, generally characterized by low carbon stocks and are, for the sake of simplicity, considered as having null values within the model.

Some of these categories are further subdivided to provide a more detailed representation of local variations. For example, within the forest land category, the user has to select from different forest types (e.g. temperate continental forest, subtropical dry forests, rainforest, mangroves, etc.), while in the annual and perennial cropland categories, the user can choose among a set of several crop type or even specific crops (e.g. wheat, maize, root crops, tubers, rice, olive trees, orchards, hedgerows, etc.). This two-level classification makes the difference between land use and land cover. If more detailed data is available on the forest or crop types in the area of interest, it is possible to define the associated carbon stock values and GHG emission factors at Tier 2.

Each data entry line in this section represents a single type of land use or land cover transition. If multiple types of transitions affect the initial or final land use or land cover, the user must fill in as many lines as there are different types of transitions.

This section is structured into the following subsections:

I. Deforestation

This module is dedicated to deforestation, defined as the transformation of land originally covered by forest into any other type of land use, including agroforestry. The minimum information to be provided in

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this module includes the type of forest to be removed (Figure 4a), the final land-use type (Figure 4b), and the forested area at the beginning and end of the analysis period, for both the BAU and target scenario (Figure 4c). Additional information should include the amount of harvested wood products and any use of fire. If no action is taken in this regard, no wood removal or fire use will be considered by default. If any final land use is perennial cropland, the specific crop type should be specified; otherwise, default values for carbon stock and emission factor will be applied.

II. Afforestation and Reforestation.

This module is dedicated to afforestation and reforestation, which are defined as the transformation of land originally used for any purpose, including agroforestry, into forest. The main difference between afforestation and reforestation is that the former refers to areas that have never been covered by forests, while the latter applies to areas that have been previously deforested. The minimum information required in this module includes the type of forest to be established, the initial land-use type, and the forested area at the end of the analysis period, for both the BAU and target scenario. Additional information should specify whether fire will be used to clear the area before afforestation or reforestation. If no action is taken in this regard, fire use will not be considered by default. If the initial land use is perennial cropland, the specific crop type should be specified; otherwise, default values for carbon stock and emission factor will be applied.

III. Other Land-Use Changes

This module covers all non-forestry land-use changes, including those occurring within cropland, pasture, and settlements. The minimum information required in this module includes the initial and final land-use types (Figure 4d and 4e), as well as the corresponding area at the end of the analysis period, for both the BAU and target scenario (Figure 4f). Additional information should specify whether fire will be used to clear the area before conversion. If no action is taken in this regard, fire use will not be considered by default. Further details about cropping and grazing systems will be provided in the "Cropland Management" and "Grassland and Livestock" sections.

Figure 4. Illustrative excerpt from the "Deforestation" and "Other Land-Use Changes" modules in the "Land-Use Change" section of the EX-ACT spreadsheet: (a) forest type removed, (b) final land-use, (c) forest area at the start and end of the analysis period for both the BAU ("Without") and target ("With") scenarios, (d) initial non-forest land use, (e) final non-forest land use, and (f) non-forest area affected by LUC.

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2.3.2.3 Cropland Management

This section of EX-ACT is dedicated to cropping systems, defined as the set of actions, techniques, and technologies adopted to conduct agricultural production. In particular, this term refers to a wide range of elements, including crop choice, planting pattern, irrigation, inputs, and crop rotations. Regarding the estimation of GHG emissions and the mitigation potential linked to cropland management, three aspects are crucial: soil tillage, input of organic materials, and residue management.

Soil tillage refers to the mechanical manipulation of soil to prepare it for planting, control weeds, incorporate fertilizers, or manage water runoff. It involves breaking up, turning, or mixing the soil using tools like ploughs, rippers, harrows, or rototillers. These actions strongly influence agricultural land's ability to store carbon, as well as GHG emissions generated by the necessary tractive power, use of fertilizers, and degradation of soil organic matter. Minimal soil disturbance typically results in higher carbon stocks and lower GHG emissions. In this regard, soil tillage can be classified into the following types, which should be specified to refine calculation:

Full tillage. This involves deep ploughing and harrowing to create a fine seedbed, improving seed-to-soil contact, soil consistency, and water infiltration, but increasing the risk of soil erosion, organic matter loss, and degradation of soil structure over time.

Reduced tillage. This minimizes soil disturbance with shallow breaking or once-off ploughing. It preserves organic matter and soil structure while reducing erosion, though it may require alternative weed management strategies.

No tillage. No land breaking is performed. Seeds are directly sown into undisturbed soil, enhancing soil health, moisture retention, and microbial activity while preventing erosion. However, it often relies on herbicides for weed control.

Input of organic materials such as compost, manure, and other bio-based fertilizers into the soil enhances its fertility and carbon stock, resulting in a higher climate mitigation potential for the cropping system. Accounting for this kind of input is important to perform an accurate carbon balance. Accordingly, the user should choose among low, medium, and high organic input, with or without the use of manure.

Finally, residue management should also be specified, as it can contribute to soil carbon stock. In particular, the conservation of cropping residues increases soil organic matter, which again leads to a higher climate mitigation potential of cropland. As a consequence, the user can choose among burning, exporting, or retaining cropping residues.

Each data entry line in this section represents a single set of cropland management practices. If multiple sets of practices apply to the same initial or final land use or land cover, the user must fill in as many lines as there are different sets.

All other agriculture-related activities, as well as non-organic inputs, including fossil fuels, mineral fertilizers, and pesticides, are covered in the “Inputs and Investments” section.

In order to account for the characteristics and technical needs of different cropping systems, this section is structured into the following subsections:

I. Annual Cropping Systems

The first part of this module focuses on annual cropping systems that either come from other land uses or are converted into other land uses. Land surfaces in this section are automatically populated based on the information provided in the “Land-Use Change” module, ensuring a consistent distinction between each type of transition: annual crops following deforestation, conversion of annual crops to forest land, annual crops from non-forest land uses, and conversion of annual crops to non-forest land uses. Since

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this information is directly linked to an expected change in land use, it is not mandatory but important to fill these fields for a more accurate calculation. The minimum information required in this module includes tillage type (Figure 5a), input of organic materials (Figure 5b), and residue management (Figure 5c). Additional information should specify the crop type (grains, beans, tubers, etc.) and yield. If no action is taken in this regard, the calculation will use default standard values. If the land management options provided by the tool do not meet the user's needs, it is possible to redefine the values at Tier 2 when local-specific information is available.

The second part of this module focuses on annual cropping systems that remain unchanged. Since this information is not directly related to land-use change, it is only required if there are expected changes in land management, such as changes in crop type or other practices covered in this module. The minimum information required includes tillage type, input of organic materials, residue management (Figure 6a), and the area treated with specific management practices at the start and end of the analysis period, for both the BAU and target scenario (Figure 6b). Since this submodule refers to surfaces not undergoing land-use change, the total area must remain the same for both the start situation, BAU, and target scenario. Additional information should specify the crop type (grains, beans, tubers, etc.) and yield. If no action is taken in this regard, the calculation will use default standard values. If the land management options provided by the tool do not meet the user's needs, it is possible to redefine the values at Tier 2 when local-specific information is available.

II. Perennial Cropping Systems

This module is analogous to annual cropping systems in both rationale and structure. The main difference is that the tool offers options tailored to the characteristics of perennial cropping systems. Specifically, the user can choose from different crop types (orchard, olives, vines, etc.), and residue management practices (burning or not).

III. Flooded Rice Systems

This module is analogous to annual cropping systems in both rationale and structure. The main difference is that the tool offers options tailored to the characteristics of flooded rice systems, as described in the 'Land-use changes' module. Specifically, the user can choose from different water regimes during the growing season (irrigated, rainfed, permanently flooded, single drainage, etc.), water management before the growing season (duration of pre-season dry period), and residue management practices (straw burning, composting, green manure, etc.), as shown in Figure 7.

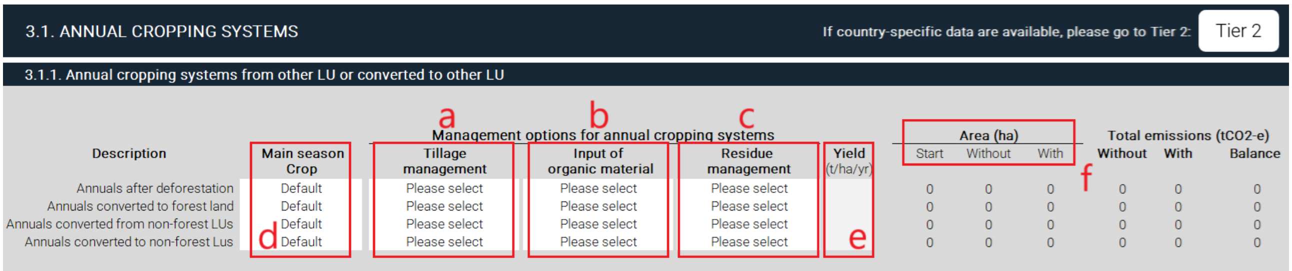

Figure 5. Illustrative excerpt from the "Annual Cropping Systems" section of the EX-ACT spreadsheet. This module accounts for annual cropping systems from other land use or converted to other land use. It includes information on: (a) tillage management, (b) input of organic material, (c) residue management, (d) main season crop, and (e) crop yield (for reporting purpose only). The surface fields (f) are automatically populated based on information provided in the "Land-Use Change" section.

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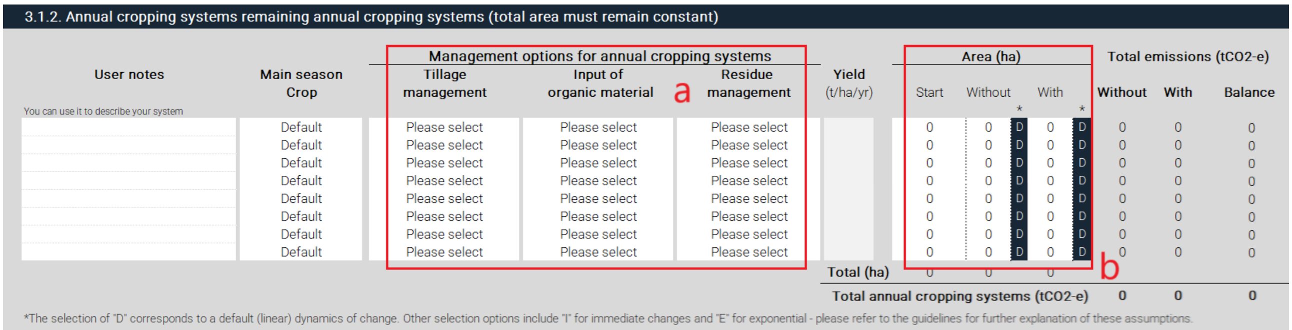

Figure 6. Illustrative excerpt from the "Annual Cropping Systems" section of the EX-ACT spreadsheet. This module accounts for annual cropping systems that remain unchanged. It includes information on: (a) management options, and (b) cropland area under each combination of management practices at the start and end of the analysis period for both the BAU ("Without") and target ("With") scenarios.

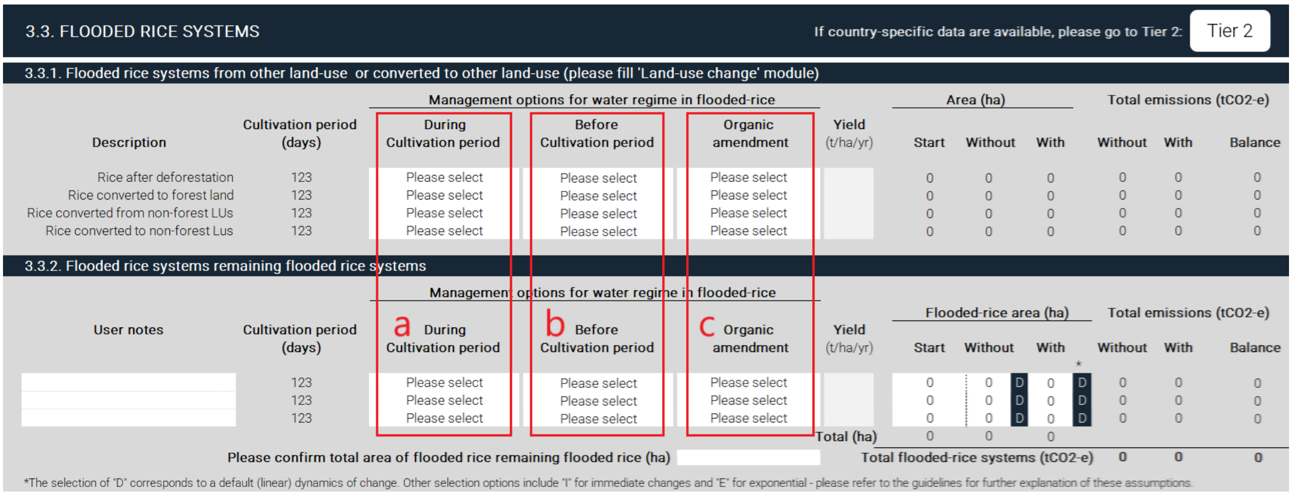

Figure 7. Illustrative excerpt from the "Annual Cropping Systems" section of the EX-ACT spreadsheet. This module accounts for flooded rice systems. It includes information on: (a) water regime during the growing season, (b) water regime before sowing, and (c) rice-specific residue management practices.

2.3.2.4 Grassland and Livestock

This section of EX-ACT focuses on grassland and livestock management, which involve essential actions for maintaining ecosystem productivity, biodiversity, and soil health while reducing GHG emissions.

Grassland management impacts carbon storage and sequestration by influencing plant growth, root systems, and soil carbon content. Sustainable practices like rotational grazing, controlled burning, reseeding, and fertilization promote resilient ecosystems, enhancing grasslands' potential as a significant terrestrial carbon sink. In contrast, overgrazing and poor management can quickly lead to grassland degradation.

According to the FAO, in 2017 the livestock sector accounted for approximately 14.5% of global human-induced GHG emissions, primarily methane (CH_4) from enteric fermentation and nitrous oxide (N_2O) from manure (FAO, 2017). This makes livestock management another crucial pillar of climate mitigation measures. Improved feeding strategies, optimized grazing patterns, and better manure management can lower GHG emissions. In particular, by improving cattle productivity, it is possible to reduce the total number of livestock while maintaining the same production level, with a clear advantage in terms of emissions.

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Each data entry line in this section represents a single combination of factors. If multiple combinations apply to the same initial or final situation in terms of grassland degradation or cattle type, the user must fill in as many lines as there are different combinations.

This section is structured into the following subsections:

I. Grassland Management

The first part of this module focuses on grassland that either comes from other land uses or is converted into other land uses. Land surfaces in this section are automatically populated based on the information provided in the “Land-Use Change” module, ensuring a consistent distinction between each type of transition: grassland following deforestation, conversion of grassland to forest land, grassland from non-forest land uses, and conversion of grassland to non-forest land uses. Since this information is directly linked to an expected change in land use, it is not mandatory but important to fill these fields for a more accurate calculation. The minimum information required in this module includes grassland degradation linked to management practices (high intensity grazing, improved management with or without inputs, etc.) and possible occurrence of controlled fire, specifying its frequency on annual base (Figure 8a and 8b). Additional information should specify yield, for reporting purposes only.

The second part of this module focuses on grassland remaining as such. Since this information is not directly related to land-use change, it is only required if there are expected changes in terms of grassland management practices. The minimum information required includes grassland degradation level and area treated with different management practices at the start and end of the analysis period, for both the BAU and target scenario, and possible occurrence of fire. Additional information should specify yield, for reporting purposes only. Since this submodule refers to surfaces not undergoing land-use change, the total area must remain the same for both the start situation, BAU, and target scenario.

II. Livestock and Manure Management

This module covers all emissions directly linked to livestock activities. The minimum information required includes the type of livestock category or species (beef cattle, dairy sheep, broiler chickens, ostriches, etc.), livestock productivity level (high, medium, or low), and the total number of heads at the beginning and end of the analysis period, for both BAU and target scenario (Figure 8c, 8d and 8e). If a specific livestock type is not included in the list, users may redefine emission factors at Tier 2 when specific data is available.

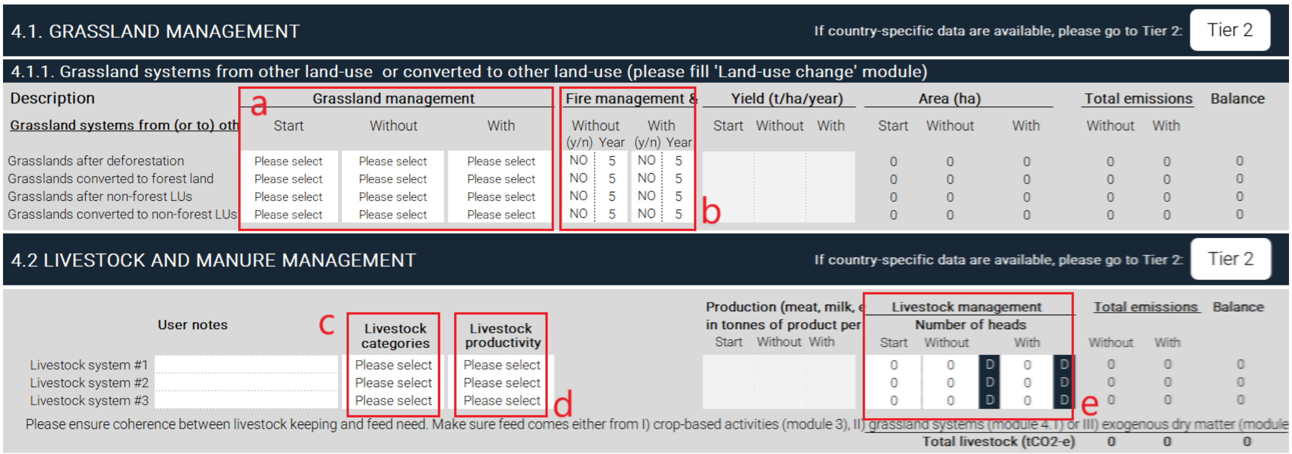

Figure 8. Illustrative excerpt from the “Grassland Management” section, including: (a) grassland degradation linked to management practices, (b) fire management and periodicity, (c) livestock category, (d) livestock productivity, and (e) number of heads at the start and end of the analysis period.

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2.3.2.5 Forest Management

This section of EX-ACT is dedicated to forest management, which involves planning and implementing practices to maintain forest health, productivity, and biodiversity. It impacts carbon storage and sequestration by influencing tree growth, soil carbon levels, and overall ecosystem stability. Sustainable practices, such as controlling invasive pests, optimizing forest stand density, selective logging and wildfire prevention, enhance carbon sequestration by fostering resilient ecosystems that absorb CO_2 efficiently. Well-managed forests act as carbon sinks, offering a significant climate mitigation potential by capturing carbon over long periods. Balancing conservation with responsible resource use ensures forests remain effective in absorbing and storing carbon. Conversely, poor management can reduce forests ability to store carbon resulting in forest degradation, herein expressed as percentage of biomass loss.

The minimum information to be provided in this module includes the type of forest that will be managed, the forest degradation level at the beginning and end of the analysis period, for both the BAU and target scenario, and the total managed forest area. Additional information should include the possible occurrence of wildfire, in which case it should be specified the fire periodicity, expressed as the average interval of years between consecutive fire events, and the fire impact, expressed as the average percentage of forested area impacted by fire for both BAU and target scenario.

Each data entry line in this section should represent a distinct combination of forest type, management, and resulting degradation level. If multiple management approaches apply to the same forest type or lead to different degradation outcomes, a separate line should be completed for each unique combination. This principle, which also applies to other land management modules described in the previous paragraphs, is here illustrated with a simple practical example shown in Figure 9. In this example, we consider 100 hectares of subtropical dry forest, half of which is moderately degraded due to poor management, while the other half remains nearly intact. Assuming that the implementation of improved management practices across the entire area leads to full forest recovery by the end of the simulation, the result in terms of carbon sequestration is strongly positive (–13,072 tCO_2eq). By adjusting the parameters, more complex scenarios can be effectively represented. The only limitation is the total number of lines, which is restricted to eight in the current version of the tool.

5.1 FOREST DEGRADATION & MANAGEMENT — If country-specific data are available, please go to Tier 2: Tier 2

Type of forest vegetation that will be managed	Forest degradation level			Fire occurrence		Fire periodicity		Fire impact (% burnt)		Forested area (ha)					Total emissions		Balance
	Start	Without	With	Without (y/n)	With (y/n)	Without Year	With Year	Without	With	Start	Without	*	With	*	Without	With	
Subtropical dry forest	Very low	Very low	None	NO	NO	1	1	1,0%	1,0%	50	50	D	50	D	0	-2.614	-2.614 ▼
Subtropical dry forest	Moderate	Moderate	None	NO	NO	1	1	1,0%	1,0%	50	50	D	50	D	0	-10.458	-10.458 ▼
Please select	Please select	Please select	Please select	NO	NO	1	1	1,0%	1,0%	0	0	D	0	D	0	0	0
Please select	Please select	Please select	Please select	NO	NO	1	1	1,0%	1,0%	0	0	D	0	D	0	0	0
Please select	Please select	Please select	Please select	NO	NO	1	1	1,0%	1,0%	0	0	D	0	D	0	0	0
Please select	Please select	Please select	Please select	NO	NO	1	1	1,0%	1,0%	0	0	D	0	D	0	0	0
Please select	Please select	Please select	Please select	NO	NO	1	1	1,0%	1,0%	0	0	D	0	D	0	0	0
Please select	Please select	Please select	Please select	NO	NO	1	1	1,0%	1,0%	0	0	D	0	D	0	0	0
Total forest degradation and management (tCO2-e)															0	-13.072	-13.072 ▼

*The selection of "D" corresponds to a default (linear) dynamics of change. Other selection options include "I" for immediate changes and "E" for exponential - please refer to the guidelines for further explanation of these assumptions.

Figure 9. Example of land recovery in the "Forest Management" section. At the beginning of the simulation, 100 hectares of "Subtropical dry forest" are evenly split between "Very low" and "Moderate" degradation level, while at the end, the entire area is fully recovered (degradation level set to "None"). No occurrence of fire was assumed.

2.3.2.6 Inland Wetlands

This section of EX-ACT focuses on land use and management practices within inland wetlands, defined as areas where water saturates the soil or covers the land seasonally or permanently, located away from coastal regions. These wetlands play a vital role in water purification, flood control, and biodiversity

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support. The soils in inland wetlands are typically organic, rich in decomposed plant material, contributing significantly to nutrient cycling and carbon storage.

Although inland wetlands are typically associated with natural or semi-natural ecosystems such as marshes, swamps, and floodplains, various land uses can coexist on or around them, including agriculture, forestry, and grazing. However, carbon stocks and emission factors related to these activities on such land differ significantly from those on mineral soils.

Accordingly, this section consists of multiple submodules that account for both land-use changes and land management practices, as described in previous chapters. The main difference from other sections is that each submodule includes an additional calculation block accounting for land drainage and rewetting (**Figure 10**). Specifically, the information required includes the area under drainage at the initial stage and at the end of the analysis period, for both BAU and target scenario. Rewetted areas are automatically calculated by difference. Additional data should include the proportion of ditches, expressed as a percentage of total surface area, and the occurrence of fires before or after drainage.

Other submodules addressing additional activities on inland wetlands, such as peat extraction and inland water body management, are beyond the scope of this document.

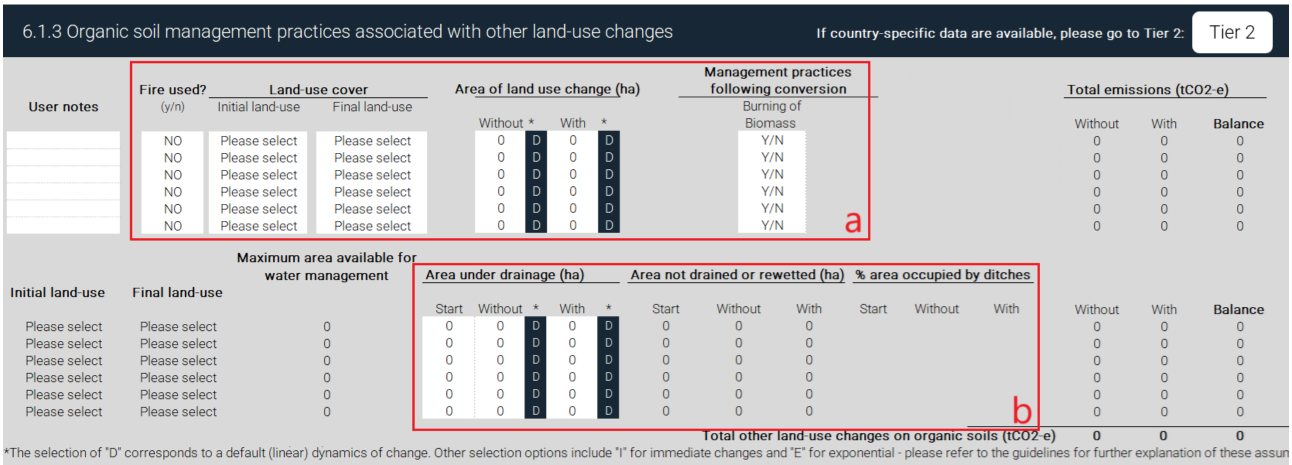

Figure 10. Illustrative excerpt from the "Inland Wetland" section of the EX-ACT spreadsheet. It includes information on: (a) land use change on organic soil and additional parameters (e.g. use of fire), (b) drainage and rewetting of land at the beginning and end of the analysis period for both the BAU ("Without") and target ("With") scenarios.

2.3.2.7 Coastal Wetlands

This section of EX-ACT is dedicated to coastal wetlands, typically characterized by salty or brackish water, located along shorelines or estuaries. These wetlands play a crucial role in coastline protection, biodiversity, water filtration, and carbon storage. Unlike inland wetlands, the unique salinity conditions shape the ecosystems, resulting in characteristic formations such as mangroves, tidal marshes, and seagrass meadows, which strongly limit other potential land uses. Accordingly, the only possible land use conversion is excavation and drainage to create surfaces for construction or agriculture, though such actions are highly detrimental to the environment.

This section is structured into three submodules dedicated to extraction (**Figure 11a**), drainage (**Figure 11b**), rewetting and revegetation (**Figure 11c**). The minimum information required includes the area affected by each action at the beginning and end of the analysis period, for both BAU and target scenario. Additional information may include biomass restoration, expressed as a percentage of the standard level.

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The last submodule, dedicated to coastal water body management, is beyond the scope of this document.

7.1 MANAGEMENT OF COASTAL WETLANDS (mangroves, tidal marsh and seagrass meadow) If country-specific data are available, please go to Tier 2: Tier 2

7.1.1. Extraction and excavation (port construction, construction of aquaculture or salt production) a

Type of vegetation	Area (ha)	% excavated		Area excavated (ha)		Maximum area available for drainage			Total emissions (tCO2-e)		Balance
	Start	Without	With	Without	With	Start	Without	With	Without	With	
Please select	0	0%	0%	0	0	0	0	0	0	0	0
Please select	0	0%	0%	0	0	0	0	0	0	0	0
Please select	0	0%	0%	0	0	0	0	0	0	0	0
Please select	0	0%	0%	0	0	0	0	0	0	0	0
Total for extraction and excavation (tCO2-e)									0	0	0

7.1.2 Drainage b — If country-specific data are available, please go to Tier 2: Tier 2

Please specify area in the "Extraction and Excavation" module above.

Type of vegetation	Maximum area available for drainage			% drained					Area drained (ha)			Total emissions (tCO2-e)		Balance
	Start	Without	With	Start	Without	*	With	*	Start	Without	With	Without	With	
Please select	0	0	0	0%	0%	D	0%	D	0	0		0	0	0
Please select	0	0	0	0%	0%	D	0%	D	0	0		0	0	0
Please select	0	0	0	0%	0%	D	0%	D	0	0		0	0	0
Please select	0	0	0	0%	0%	D	0%	D	0	0		0	0	0
Total for drainage (tCO2-e)												0	0	0

7.1.3 Rewetting & revegetation c — If country-specific data are available, please go to Tier 2: Tier 2

Type of vegetation	Area rewetted (ha)				Percentage of nominal biomass restored		Total emissions (tCO2-e)		Balance
	Without	*	With	*	Without	With	Without	With	
Please select	0	D	0	D	0%	0%	0	0	0
Please select	0	D	0	D	0%	0%	0	0	0
Please select	0	D	0	D	0%	0%	0	0	0
Please select	0	D	0	D	0%	0%	0	0	0
Total for rewetting & revegetation (tCO2-e)							0	0	0

*The selection of "D" corresponds to a default (linear) dynamics of change. Other selection options include "I" for immediate changes and "E" for exponential - please refer to the guidelines for further explanation of these assumptions.

Figure 11. Illustrative excerpt from the "Coastland Wetland" section of the EX-ACT spreadsheet. It is composed of the following modules: (a) "Extraction and Excavation", (b) "Drainage", and (c) "Rewetting & Revegetation". For each of these submodules the user has to provide related area at the beginning and end of the of the analysis period for both the BAU ("Without") and target ("With") scenarios.

2.3.2.8 Input and Investments

This section of EX-ACT focuses on the GHG emissions related to all inputs and actions not covered in the previous sections, such as mineral fertilization, fuel consumption, and the construction of plants and facilities. The calculations account for emissions generated by the production, storage, and transport of inputs, as well as those related to the construction and operation of plants. For this reason, it is important to specify the country in the "Description" section, in order to obtain at least country-specific emission factors. Additionally, emission factors can be redefined at Tier 2 when local-specific information is available.

Data requirements refer to aggregate-level information rather than field-level data (for example, the total regional amount of gasoline per year, rather than the unitary consumption per activity).

This section is structured into the following subsections (the "Building and Infrastructure" section is omitted here for the purpose of this document):

I. Agricultural Inputs

This module assesses emissions resulting from mineral fertilization and pest control. The data requirements involve specifying the total amount of fertilizer or pesticide used per year at the start and end of the analysis period, for both BAU and target scenario (Figure 12). The module accounts for six categories of input: lime, synthetic fertilizers, N-fertilizers for irrigated rice, other organic N-fertilizers, pesticides, and animal feed. The units are input-dependent: some are expressed in tonnes of product per year, while others are expressed in tonnes of active ingredient per year.

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9.1 INPUTS (liming, fertilizers, pesticides) — If country-specific data are available, please go to Tier 2: Tier 2

Fertilizers	Amount applied per year (in tonne)					Total emissions at field level (tCO2-e)				Emissions from production, transportation, storage and transfer (tCO2-e)		Total emissions (tCO2-e)		
						CO2 emissions		N2O emissions						
	Start	Without	*	With	*	Without	With	Without	With	Without	With	Without	With	Balance
Lime application														
Limestone (tonnes per year)	0,00	0,00	D	0,00	D	0	0	-	-	0	0	0	0	0
Dolomite (tonne per year)	0,00	0,00	D	0,00	D	0	0	-	-	0	0	0	0	0
Not-specified (tonnes per year)	0,00	0,00	D	0,00	D	0	0	-	-	0	0	0	0	0
Synthetic fertilizers														
Urea (tonnes of Urea per year)	0,00	0,00	D	0,00	D	0	0	0	0	0	0	0	0	0
Phosphorus (tonnes of P2O5 per year)	0,00	0,00	D	0,00	D	-	-	-	-	0	0	0	0	0
Potassium (tonnes of K2O per year)	0,00	0,00	D	0,00	D	-	-	-	-	0	0	0	0	0
N-fertilizers on irrigated rice														
N-fertilizer in continuously irrigated rice (tonn	0,00	0,00	D	0,00	D	-	-	0	0	0	0	0	0	0
N-fertilizer in wet and dry irrigated rice (tonnes	0,00	0,00	D	0,00	D	-	-	0	0	0	0	0	0	0
Organic N-fertilizers														
Sewage (tonnes of N per year)	0,00	0,00	D	0,00	D	-	-	0	0	-	-	0	0	0
Compost (tonnes of N per year)	0,00	0,00	D	0,00	D	-	-	0	0	-	-	0	0	0
Rendering waste, brewery waste, guano (tonn	0,00	0,00	D	0,00	D	-	-	0	0	-	-	0	0	0
Pesticides														
Fungicides (tonnes of active ingredient)	0,00	0,00	D	0,00	D	-	-	-	-	0	0	0	0	0
Herbicides (tonnes of active ingredient)	0,00	0,00	D	0,00	D	-	-	-	-	0	0	0	0	0
Insecticides (tonnes of active ingredient)	0,00	0,00	D	0,00	D	-	-	-	-	0	0	0	0	0
Animal feed (in tonnes per year)														
User defined (Tier 2)	0,00	0,00	D	0,00	D							0	0	0
											Total inputs (tCO2-e)	**0**	**0**	**0**

Figure 12. Illustrative excerpt from the "Agricultural Inputs" module in the "Inputs and Investments" section.

II. Energy consumption

This module focuses on energy use in target activities and is divided into three submodules: electricity, liquid or gaseous fuels, and solid sources of energy (Figure 13). Electricity is expressed in megawatt-hours per year, with a default 10% electricity loss applied, which can be modified at Tier 2. Liquid or gaseous fuels are expressed in cubic meters (m³) per year. The user may choose from various fuel types (gasoline, diesel, LPG, ethanol) for stationary, mobile, or off-road (tractors) use — excluding that for irrigation, accounted in the next submodule. Solid energy sources such as wood, peat, and charcoal are expressed in tonnes of dry matter per year.

9.2. ENERGY CONSUMPTION (electricity, fuel...) except for irrigation, i.e. see next section — If country-specific data are available, please go to Tier 2: Tier 2

Description and unit to report	Quantity consumed per year					Total emissions (tCO2-e)		Balance
Electricity (MWh per year)	Start	Without	*	With	*	Without	With	
Country of origin of electricity								
Please select	0,00	0,00	D	0,00	D	0	0	0
User defined (Tier 2)	0,00	0,00	D	0,00	D	0	0	0
Liquid or gaseous (in m3 per year)								
Please select	0,00	0,00	D	0,00	D	0	0	0
Please select	0,00	0,00	D	0,00	D	0	0	0
Please select	0,00	0,00	D	0,00	D	0	0	0
User defined (Tier 2)	0,00	0,00	D	0,00	D	0	0	0
Solid (in tonnes of dry matter per year)								
Wood	0,00	0,00	D	0,00	D	0	0	0
Peat	0,00	0,00	D	0,00	D	0	0	0
Charcoal	0,00	0,00	D	0,00	D	0	0	0
Peat (from peatlands)	0,00	0,00	D	0,00	D	0	0	0
User defined (Tier 2)	0,00	0,00	D	0,00	D	0	0	0
					Total energy (tCO2-e)	**0**	**0**	**0**

Figure 13. Illustrative excerpt from the "Energy Consumption" module in the "Inputs and Investments" section.

III. Irrigation

This module covers GHG emissions generated by the construction and operation of irrigation systems and is divided into two submodules.

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The first submodule accounts for emissions from the construction of new irrigation plants (Figure 14a). The information required includes the type of irrigation system (surface irrigation with or without runoff recovery systems, sprinkler irrigation, drip irrigation, etc.) and the area covered by the intervention for both BAU and target scenario.

The second submodule covers emissions from the operational phase of irrigation plants (Figure 14b). Here, the user should specify the total irrigated area at the beginning and end of the analysis period, for both BAU and target scenario, the source of energy for pumping, irrigation water requirements of the crop (expressed in millimetres per year), and the water source depth (expressed in metres).

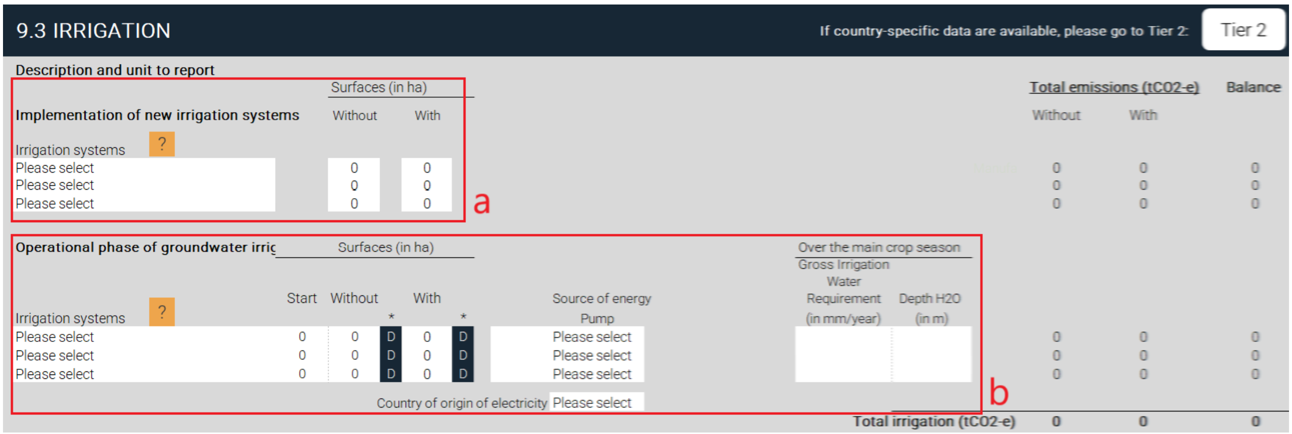

Figure 14. Illustrative excerpt from the "Irrigation" module in the "Inputs and Investments" section of the EX-ACT spreadsheet. It is composed of the following submodules: (a) "Implementation of New Irrigation Plants", and (b) "Operational Phase of Irrigation Plants Drainage".

2.3.2.9 Results Section

The main output of the data processing is the carbon balance, accompanied by charts and tables that provide a detailed explanation of the results. The first part of this section presents a summary report, highlighting the carbon balance, defined as mitigation potential, expressed in tonnes of CO_2 equivalent. Supporting this balance, a series of illustrative charts offer additional insights into the overall GHG flow, specifically: the carbon balance by activity category, the share of each GHG in the total balance, the annual balance, and the year-by-year cumulative balance. It's important to note that negative carbon balance values indicate that the target scenario has a higher mitigation potential than the BAU scenario. Additionally, green in the charts and partial results represents a carbon sink, while red denotes a net source of emissions.

The second part of this section focuses on detailed results. Specifically, tables break down the carbon balance by individual components, categorized by activity (e.g., deforestation, annual cropland management, grassland management, etc.), and by the share of each GHG. A key element in this section is the land-use change matrix, which provides a detailed representation of how land use shifts from one category to another over the analysis period.

The detailed results are further divided between mineral soils and organic soils (i.e., those under the "Inland Wetlands" and "Coastal Wetlands" sections) to account for differences in management practices and carbon storage capacity between these soil types.

An overview of the report layout for the results is shown in Figure 15.

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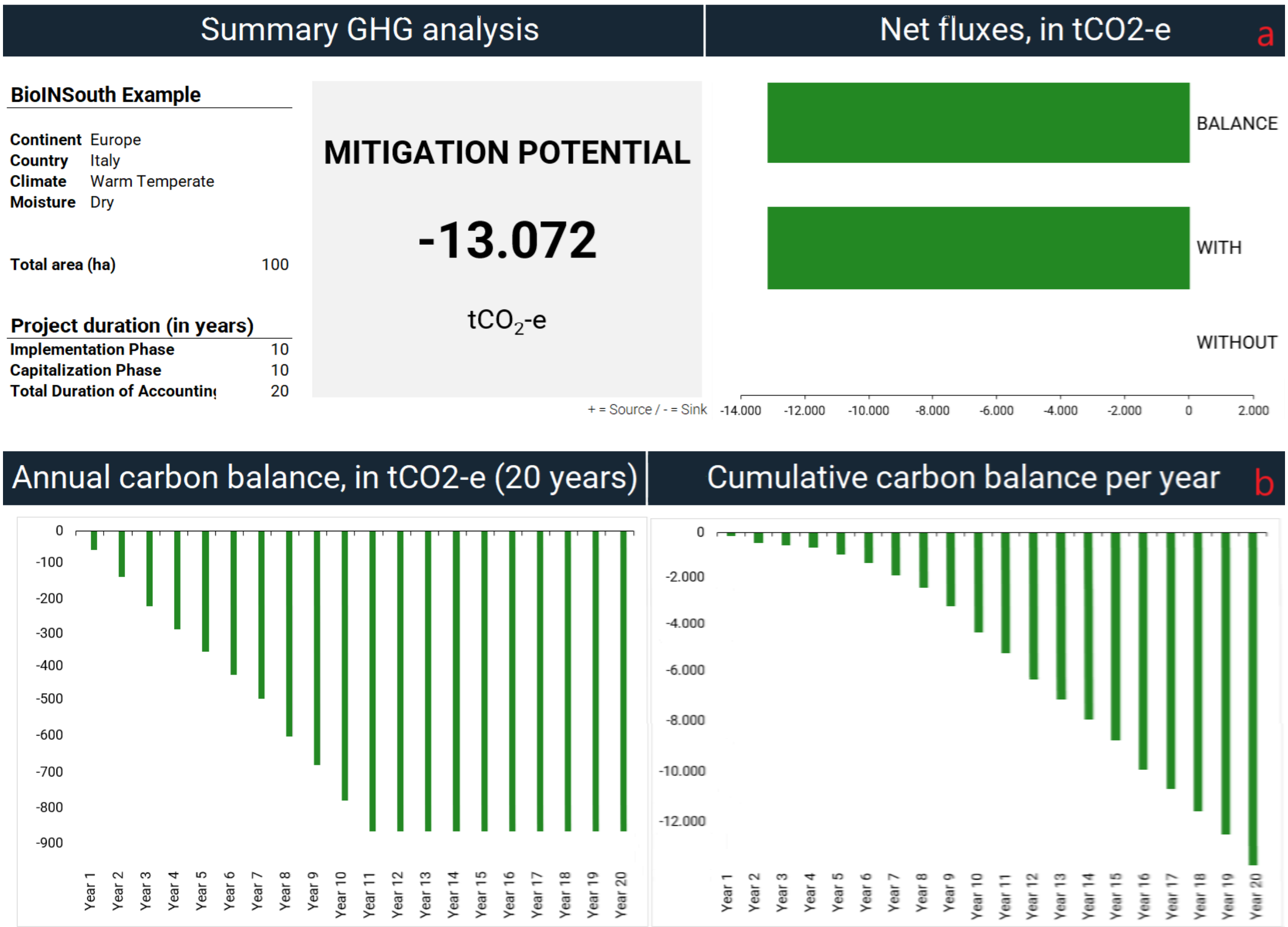

C

PROJECT COMPONENTS		GROSS FLUXES (In tCO2-e over the whole period analysis) WITHOUT	WITH	BALANCE	SHARE PER GHG OF THE BALANCE (In tCO2-e over the whole period analysis) CO2 BIOMASS	CO2 SOIL	N_2O	CH_4	ALL NON-AFOLU EMISSIONS*	AVERAGE ANNUAL EMISSIONS (In tCO2-e/yr) WITHOUT	WITH	BALANCE
Land use changes	Deforestation	0	0	0	0	0	0	0		0	0	0
	Afforestation	0	0	0	0	0	0	0		0	0	0
	Other land-use	0	0	0	0	0	0	0		0	0	0
Cropland	Annual	0	0	0	0	0	0	0		0	0	0
	Perennial	0	0	0	0	0	0	0		0	0	0
	Flooded rice	0	0	0	0	0	0	0		0	0	0
Grasslands & Livestock	Grasslands	0	0	0	0	0	0	0		0	0	0
	Livestock	0	0	0			0	0		0	0	0
	Forest mngt.	0	-13.072	-13.072	-13.072	0	0	0		0	-654	-654
	Inland wetlands	0	0	0	0	0	0	0		0	0	0
	Coastal wetlands	0	0	0	0	0	0	0		0	0	0
	Fisheries and aquaculture	0	0	0	0	0	0	0	0	0	0	0
	Inputs & Invest.	0	0	0		0	0		0	0	0	0
Total emissions, tCO2-e		**0**	**-13.072**	**-13.072**	**-13.072**	**0**	**0**	**0**	**0**	**0**	**-654**	**-654**
Total emissions, tCO2-e/ha		**0,0**	**-130,7**	**-130,7**	**-130,7**	**0,0**	**0,0**	**0,0**	**0,0**			
Total emissions, tCO2-e/ha/		**0,0**	**-6,5**	**-6,5**	**-6,5**	**0,0**	**0,0**	**0,0**	**0,0**			

+ = Source / - = Sink

Figure 15. Report layout showing the main features of the “Results” section. It includes: (a) numerical and graphical summary of the results, (b) the carbon balance over the years, and (c) the carbon balance by individual components.

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2.4 Food security assessment

2.4.1 Analytical Approach

Assessing the impacts of land-use changes on food security requires a detailed understanding of how shifts in agricultural land allocation influence the quantity and nutritional quality of food produced locally. This paragraph outlines the methodological approach applied to quantify and evaluate these impacts, integrating geospatial data, agricultural yield statistics, and nutritional parameters.

For the scope of the analysis, the following approach assumes constant crop yields across scenarios, meaning that all differences in food production outcomes are attributed exclusively to changes in land-use allocation. Since increases of the productivity can be considered independent by the development of the bio-based sector, involving in the same way both the reference scenario and alternative land-use configurations.

The methodology includes the following interconnected steps:

Step 1: Data Collection

The first step regards the identification of the baseline agricultural area (hectares) dedicated to each arable crop. This step establishes the spatial extent of current agricultural production systems. Regional statistics or SAR/LUCAS data accessible through Earth Map can be used (see paragraph 2.5.1.3); Similarly, National/Regional average yields for each crop need to be collected. Yields can be collected by national/regional official statistics or can be obtained from the FAO's FAOSTAT database (see paragraph 2.5.2.1). Yield, assumed constant across all scenarios, are essential for accurately estimating total agricultural output. Moreover, to standardize the comparison across multiple crops, total crop production needs to be expressed in kilocalories (kcal), a universally accepted measure of food energy. For this reason, data on caloric content of each crop need to be collected (see paragraph 2.5.2.2).

Step 2: Calculation of Indicators for Scenario Valuation

To standardize the comparison across multiple crops, total crop production is expressed in kilocalories (kcal). For each crop, we apply the following formula:

$$\text{Caloric Supply}_{i,j} = \text{Area}_{i,j} \times \text{Yield}_i \times \text{Caloric Value}_i$$

Where:

$\text{Area}_{i,j}$ is the area allocated to crop i in a given j-th scenario (ha);

Yield_i is the average yield at regional/national level for the i-th crop (kg/ha);

Caloric Value_i is the caloric content per kilogram (kcal/kg).

Once calculated the caloric content for each crop for the j-th scenario, by summing all crop-level caloric supplies we can obtain the Total Caloric Supply associated to the specific j-th scenario:

$$\text{Total Caloric Supply}_j = \sum_{i=1}^{n} \text{Caloric Supply}_{i,j}$$

Total Caloric Supply (TCS) thus measures the total food energy available from domestic crop production. This is the primary output of the above procedure and serves as the baseline for all further comparisons.

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Table 1. Caloric Supply Calculation (Scenario j).

Crop	Area (ha)	Yield (kg/ha)	Caloric Value (kcal/kg)	Caloric Supply (Million kcal)
Common Wheat	40,000	3,692	3,340	493,251
Maize	10,000	10,731	3,560	382,024
Barley	25,000	4,113	3,320	341,379
Pulses	10,000	2,006	3,410	68,405
Total	85,000	—	—	**1,285,356**

Moreover, the self-sufficiency ratio (SSR) will be calculated as follows:

$$SSR_j = \frac{TCS_j}{TCS_{BAU}} ' SSR_{BAU}$$

By assuming domestic consumption remains constant across scenarios, SSR simplifies to the relative change in caloric production between scenario and BAU. Negative SSR values indicate increasing reliance on imports; Positive values indicate decreasing reliance on imports or relative surplus comparing to the BAU scenario.

Table 2. Example of SSR comparison across scenarios.

Scenario	Total Caloric Supply (Million kcal)	SSR (%) (Assuming SSR_BAU = 100)
BAU	1,285,356	100
Negative	964,114	-25.0%
Positive	1,428,672	+11.1%

Moreover, Agricultural Land Availability Index (ALAI) will be calculated, reflecting the total area available for food production relative to BAU. Given constant yields, it acts as a proxy for potential food output.

$$ALAI_j = \frac{Total\ Arable\ Land_j}{Total\ Arable\ Land_{BAU}} ' 100$$

ALAI helps highlight scenarios that involve reallocation of land to non-food uses (e.g., bioenergy, afforestation) with possible consequences for food availability.

Table 3. Example of ALAI comparison across scenarios.

Scenario	Arable Land (ha)	ALAI (%)
BAU	85,000	100
Negative	76,500	82.4
Positive	93,500	114.1

2.4.2 Excel-Based Food Security Toolkit

To operationalize the proposed methodology, an Excel-based Food Security Toolkit has been developed within the framework of the BioInSouth project. This toolkit offers stakeholders, policymakers, and

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planners a robust analytical framework to quantitatively assess the implications of land-use changes on regional food security.

Specifically designed to examine how alternative land-use scenarios — particularly the reallocation between food and non-food uses — impact key food security indicators, the toolkit enables the calculation of the following core metrics: Total Caloric Supply (TCS), Agricultural Land Availability Index (ALAI), and Self-Sufficiency Ratio (SSR).

The toolkit supports the integration of scenario-specific assumptions derived from stakeholder consultations and expert validation. These inputs may include detailed information on land availability, crop yields, and the caloric content of different crops. Users interact with a structured, user-friendly Excel interface that consolidates essential datasets. Required inputs include:

Area (ha): Land area allocated to each crop under the defined scenario;

Yield (kg/ha): National or regional average yield (assumed constant across scenarios);

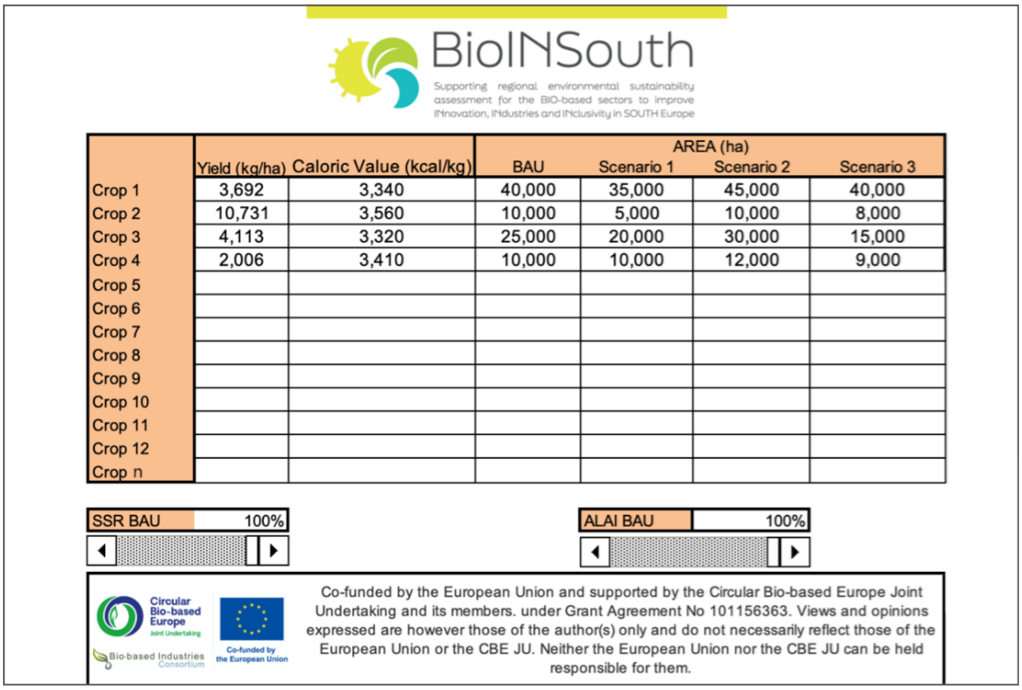
Caloric Value (kcal/kg): Nutritional content of the selected crops.

Both yield and caloric data are embedded in the toolkit for user convenience.

Users can define a Business-As-Usual scenario along with up to three alternative land-use scenarios, ranging from negative to positive outcomes. These are built by adjusting cropland allocation assumptions between food and bio-based sectors, with flexibility to tailor parameters based on regional characteristics and stakeholder feedback.

Upon entering the inputs, the toolkit automatically computes the food security indicators (TCS, ALAI, SSR) for each scenario, providing immediate quantitative insights. Furthermore, it generates three illustrative graphs (Figure 17) to enable rapid visual comparison, facilitating intuitive interpretation and effective communication of results to a broad range of stakeholders.

The Excel-based design ensures accessibility and ease of use, making the toolkit suitable for both technical and non-technical users.



	Yield (kg/ha)	Caloric Value (kcal/kg)	AREA (ha) BAU	Scenario 1	Scenario 2	Scenario 3
Crop 1	3,692	3,340	40,000	35,000	45,000	40,000
Crop 2	10,731	3,560	10,000	5,000	10,000	8,000
Crop 3	4,113	3,320	25,000	20,000	30,000	15,000
Crop 4	2,006	3,410	10,000	10,000	12,000	9,000
Crop 5						
Crop 6						
Crop 7						
Crop 8						
Crop 9						
Crop 10						
Crop 11						
Crop 12						
Crop n						

Figure 16. Data input interface of the Excel-based toolkit.

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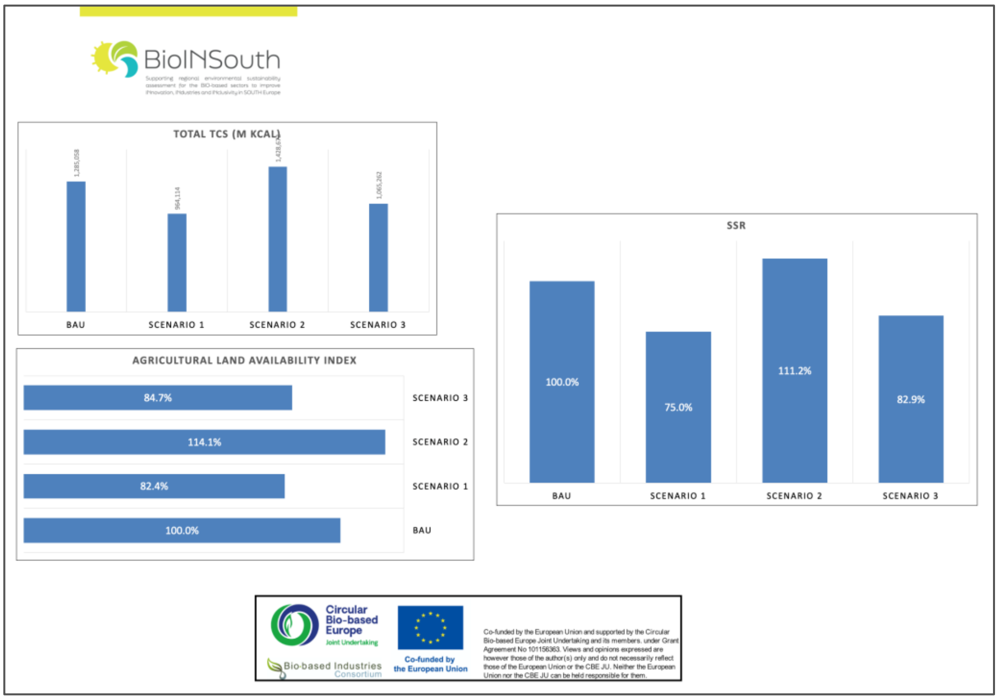

Figure 17. Graphs summarizing food security indicators across the scenarios.

2.5 Data sourcing

2.5.1 Earth Map

Earth Map is a web-based application developed by the FAO which allows free access to Earth Observation (EO) big data, provided by several national and international agencies such as ESA, USGS, WWF and IPCC. It was designed to assist a wide range of stakeholders, such as public institutions, scholars, and private entities in monitoring land in an easy, integrated, and multi-temporal way. Geographic information is divided into 18 thematic categories, including climate, soil, biodiversity, land-use and satellite imagery, covering more than 100 parameters.

Earth Map has a user-friendly graphical interface and does not require specific expertise in geodata management or high computing power. Users can select their area of interest, visualize the desired parameter and process it to generate on-the-fly statistics, including map comparisons. The outputs from Earth Map queries can be thematic maps, graphs, and tables, which can be exported as GeoTIFF, PNG, and CSV files.

In the absence of local-specific information for conducting the analysis, Earth Map can provide critical support at several levels of the current framework, particularly concerning land-use maps, land-use transition matrices, and the definition of climate, soil types, forest cover, and crop composition. Each of these variables will be explained step by step in the following paragraphs.

Before illustrating how to obtain input data, here's a brief explanation of the preliminary steps. Earth Map can be accessed through any internet browser or downloaded as a stand-alone application at https://earthmap.org/. Users can log in as guests or register with an email address or Google account. Guest users have full access to information but cannot save projects.

Once logged in, users need to select their area of interest (AOI) by typing the country name or scrolling through the search bar at the top left of the platform interface (**Figure 18a**). Users can further refine their search by selecting a subnational level (region, province, or district) from the dropdown menu below. If the AOI doesn't match an existing administrative boundary, users can draw a custom area by clicking on the map or upload a boundary shapefile by clicking the "+" symbol next to the search bar (Figure 18b).

After selecting the AOI, users can explore information through the layer panel (Figure 18c) on the left side of the screen. Once a layer is chosen, a legend box will appear in the top-right corner (Figure 18d). This legend box allows users to select the data date and view a full explanation of the symbols.

Finally, the analysis panel on the right side of the screen enables users to process data, generate statistics, and download results. To do this, the layer of interest must be selected again from the dropdown menu at the top of the analysis panel (Figure 18e). Then, users can choose the desired options and run the calculations.

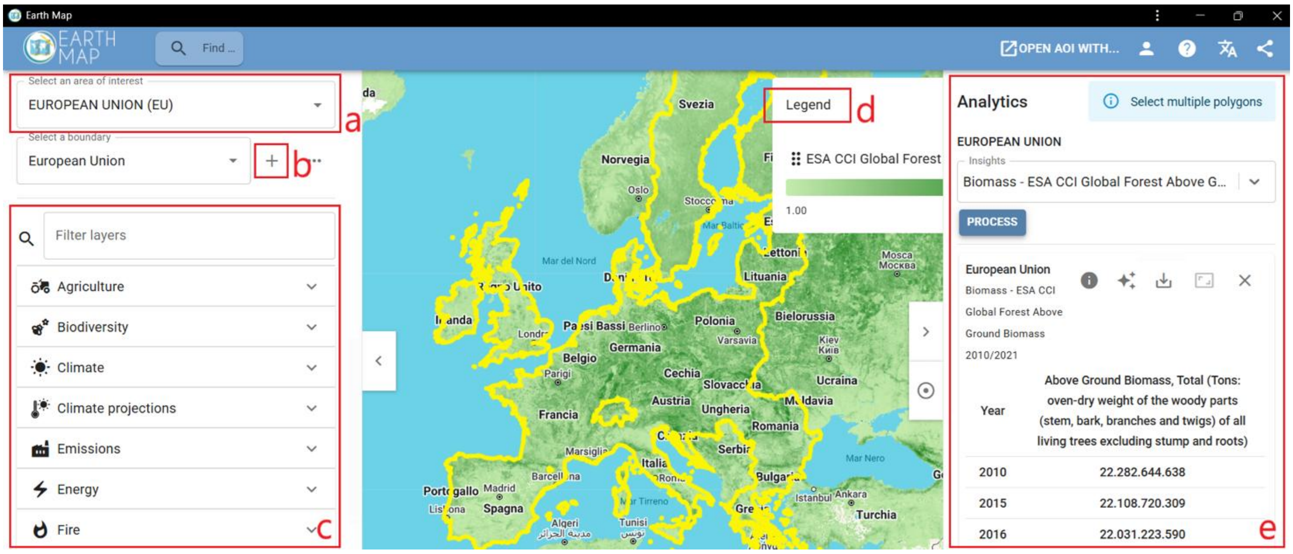

Figure 18. General view of the Earth Map screen: area of interest search bar (a), area of interest customization options (b), layer panel (c), legend box (d), and analysis panel (e).

2.5.1.1 Land-Use Data

Earth Map provides access to a wide range of land-use databases, which can be selected from the layer panel. In this example, we refer to the IPCC Land Use Classification based on ESA-CCI categories, as shown in Figure 19a. This represents the most generalized classification, making it suitable for aggregate reporting, such as the regional-level analysis proposed in this document. At this level, land-use types are grouped into six main classes: forest, cropland, settlements, grassland, wetland, and other land.

For local-level reporting, more detailed layers should be used, such as CGLS-LC100 or CORINE Land Cover. Regardless of the level of detail, it is essential that the data is standardized according to the IPCC classification to ensure compatibility with the tools presented in this document.

The key land use statistic required for our analysis is the **land-use transition matrix**. In this matrix, rows and columns represent the same land-use categories, and each entry shows the proportion of land that transitioned from one category to another during the reference period. To generate this matrix, select the desired layer from the dropdown menu at the top of the analysis panel and click the "PROCESS" button (Figure 19b). Then, click "SHOW CHANGE MATRIX" (Figure 19c) to open a window displaying the matrix and a summary of changes (Figure 20a), presented in both absolute area and percentage. Users can set the reference period by clicking the clock icon in the top-right corner (**Figure 20b**). Finally, data can be exported as a CSV file using the “EXPORT CSV” button (**Figure 20c**).

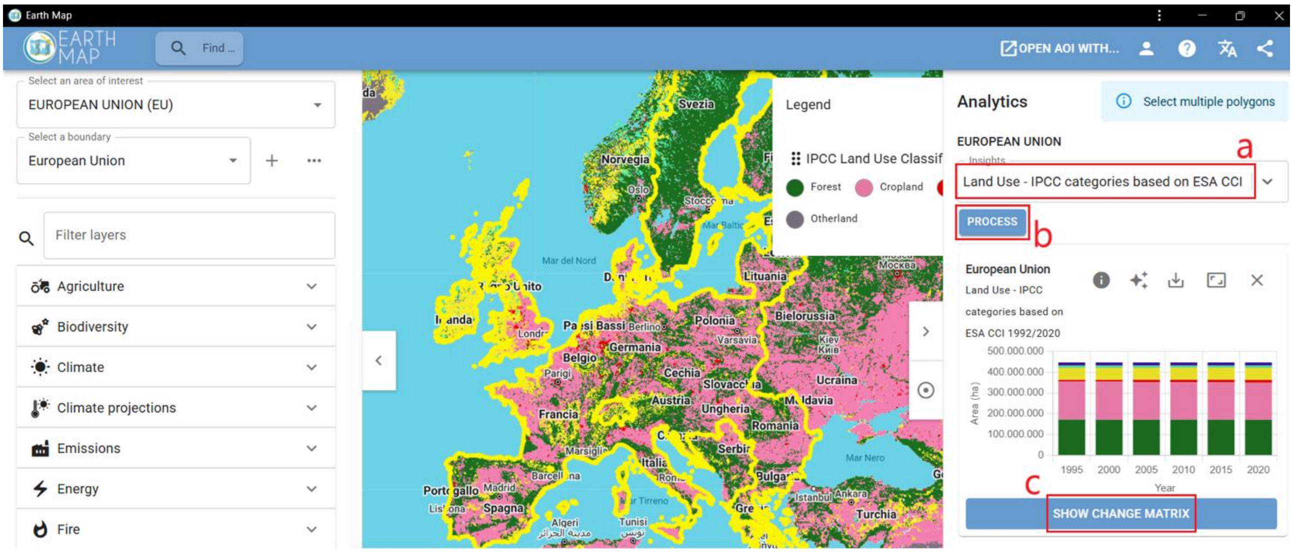

Figure 19. Visualization and analysis of land-use data on Earth Map: layer selection within the analysis box (a), start data processing button (b), and land-use change matrix generation button (c).

Change matrix for 1992-2022 (ha)

EXPLAIN | 1992 - 2022 (b) | EXPORT CSV (c)

1992 \ 2022	Forest	Grassland	Cropland	Wetland (a)	Settlement	Otherland	Water Bodies/No Data	Total
Forest	160.631.661	2.596.603	6.408.047	1.259.186	548.276	86.691	522.252	172.052.716
Grassland	1.330.133	54.555.218	792.144	54.044	559.535	47.149	38.437	57.376.660
Cropland	7.121.635	569.218	172.146.269	6.536	4.754.988	8.603	122.083	184.729.332
Wetland	1.480.523	100.147	18.924	8.532.521	27.632	851	35.126	10.195.724
Settlement	-	-	-	-	6.481.726	-	-	6.481.726
Otherland	15.788	17.323	16.955	34	393.299	2.293.551	9.392	2.746.342
Water Bodies/No Data	285.390	25.884	72.706	38.735	44.681	21.250	13.179.354	13.668.000
Total	170.865.130	57.864.393	179.455.045	9.891.056	12.810.137	2.458.095	13.906.644	

Figure 20. Example of a land-use change matrix generated using Earth Map: summary of change (a), analysis period setting options (b), and results export button (c).

2.5.1.2 Environmental Data

The present analysis requires basic information on key environmental parameters, namely climate, moisture regime, and soil type. These factors are essential in determining land capability for carbon sequestration and storage, setting site-specific carbon stocks and emission factors.

Insights on climatic parameters can be sourced from the IPCC Climatic Zones layer (**Figure 21**), which provides data on both climate and moisture regime, in accordance with the requirements of EX-ACT, as outlined in paragraph 2.3.2.1.

Analysis at local level may rely on more detailed environmental parameters including elevation, mean annual temperature, mean annual precipitation and potential evapotranspiration. These parameters are also available on Earth Map.

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Soil type can refer to the IPCC Soil Classes — HWSD 2.0 layer (**Figure 22**). In this case as well, soils are already categorized according to the requirements of EX-ACT, as outlined in paragraph 2.3.2.1. If the AOI rests on organic soils, it is necessary to specify the reference soil organic carbon stock in the specific module, as described in paragraph 2.3.2.1. This parameter can be found in the Global Soil Organic Carbon layer.

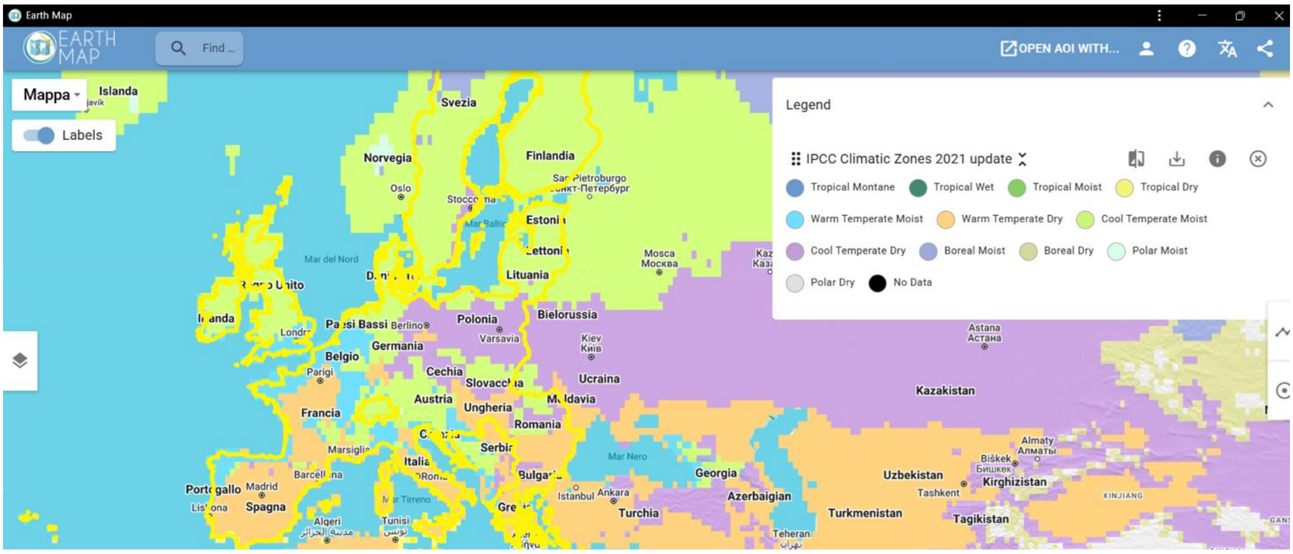

Figure 21. Climatic zones according to the IPCC classification.

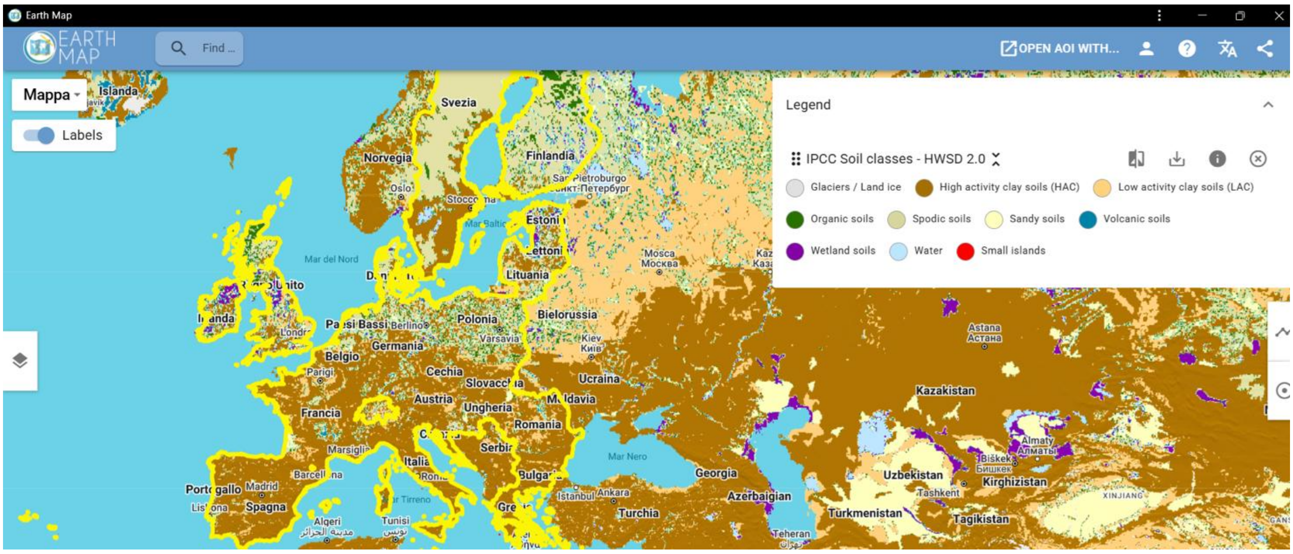

Figure 22. Soil types according to the IPCC — HWSD 2.0 classification.

2.5.1.3 Cropland Composition

To accurately assess the impacts on food security, it is essential to determine both the current and projected extent of agricultural land use at a detailed spatial scale. For this purpose, crop mapping data from the European Union (EU), based on the SAR/LUCAS survey (Synthetic Aperture Radar/Land Use and Coverage Area Frame Survey), are used and made accessible through the FAO Earth Map tool (**Figure 23**).

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The SAR/LUCAS data provide high-resolution information that enables precise quantification of agricultural areas dedicated to individual crops across specific regions/provinces of EU member states. Earth Map offers a spatial analysis framework to access these geospatial layers, supporting the calculation of area-based statistics and facilitating comparisons of land use dynamics under different scenarios.

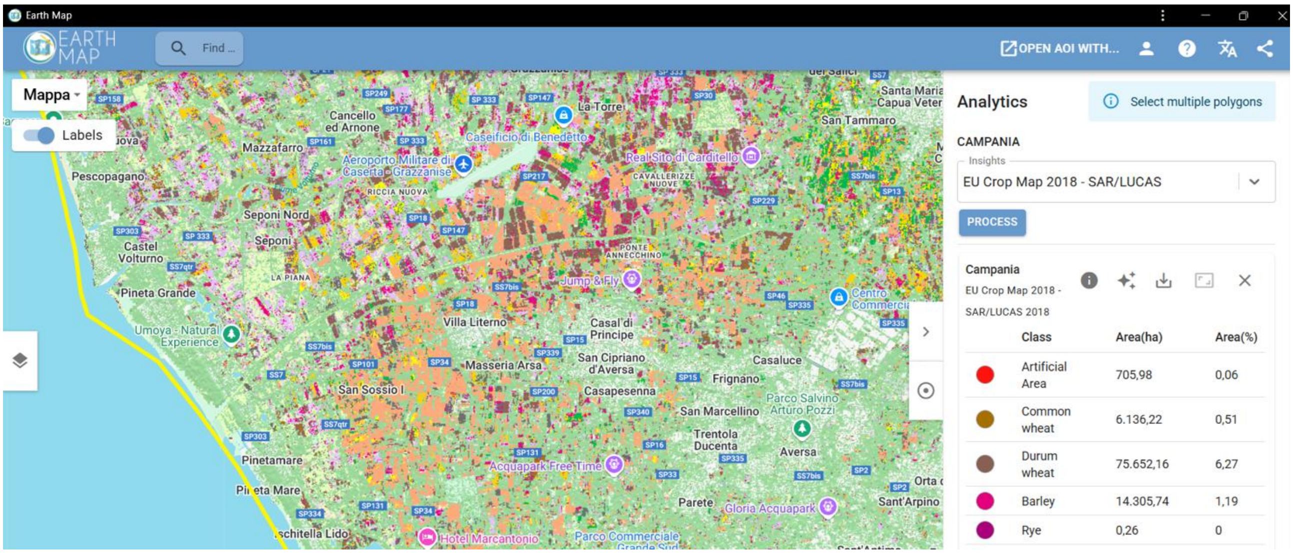

Figure 23. SAR/LUCAS crop map and area estimates visualized in EarthMap.

2.5.2 FAO Databases

2.5.2.1 Yield data

To estimate food availability and its potential contribution to food security, it is necessary to combine land use data with information on crop yields. National-level crop production statistics are retrieved from FAOSTAT, the Food and Agriculture Organization’s comprehensive database on agricultural outputs. FAOSTAT provides time-series data on the harvested area, yield, and total production for a wide range of crops at the country level (FAO, 2023), as shown in **Figure 24**. These figures enable the calculation of average yields (in kg per hectare) for each crop, which are then used to estimate the total agricultural output corresponding to the areas identified in the spatial analysis. This yield data serves as a fundamental input for further conversion into caloric values.

2.5.2.2 Caloric Content

To translate crop production into a standardized measure of food energy, we rely on the FAO Food Composition Tables[1]. These tables provide detailed information on the caloric content per 100 grams of edible portion for a wide variety of crops and food items (FAO, 1953). By applying these caloric coefficients to the production volumes obtained from FAOSTAT, we can estimate the total caloric output associated with each crop. This step allows the conversion of physical agricultural production into a common energy unit (kilocalories), which is essential for quantifying food availability and assessing the nutritional implications of land use change scenarios.

[1] Specifically, the analysis in this document uses the FAO Food Composition Tables, accessible at https://www.fao.org/4/x9892e/X9892e05.htm

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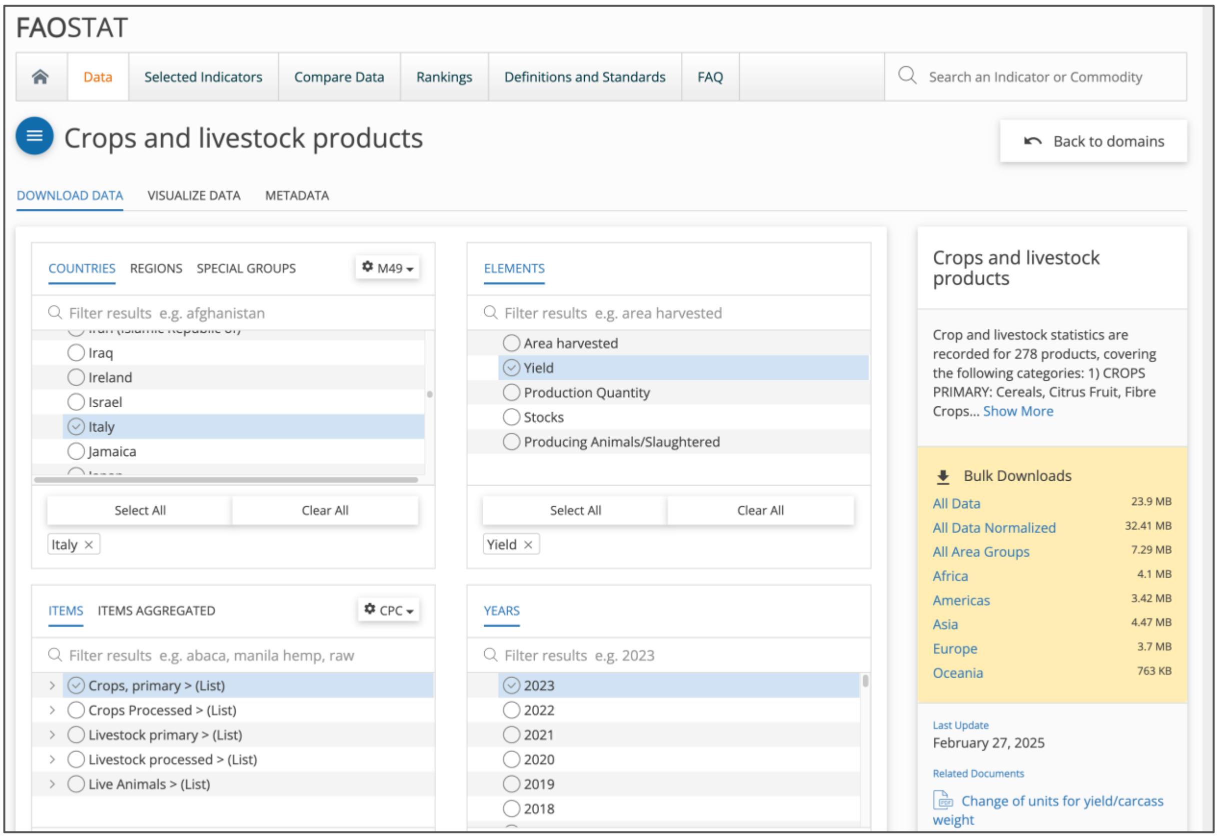

Figure 24. FAOSTAT user interface for accessing crop and livestock product statistics.

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3 Case study

3.1 The Campania Region

Campania is a region located in southern Italy, encompassing a diverse territory that extends from the Tyrrhenian Sea along its coastline to the Apennine Mountain range inland. The region covers approximately 13,590 km² and presents a wide range of geomorphological features, from fertile plains — most notably the Campanian Plain — to hills and mountainous areas such as the Matese and the Cilento ranges. Major rivers include the Volturno, the longest river in southern Italy, and the Sele, both of which play a crucial role in supporting the region's agricultural and natural ecosystems. The coastal strip includes important gulfs such as Naples, Salerno, and Policastro.

Campania has a population of approximately 5.6 million people, making it the second most populous region in Italy. The population is heavily concentrated in the metropolitan area of Naples, the regional capital, which is also among the most densely populated urban zones in Europe. This strong urbanization, paired with ongoing socio-economic disparities between coastal and inland areas, poses significant challenges to balanced territorial development and resource management (ISTAT, 2023).

The region benefits from a Mediterranean climate, with hot, dry summers and mild, wet winters, conditions that support a wide variety of agricultural productions. Campania is historically renowned for its fertile volcanic soils, particularly in areas around Mount Vesuvius, and for the high-quality production of fruit, vegetables, wine, and dairy products. Agriculture continues to play an important economic and cultural role, particularly in rural and peri-urban areas, despite increasing pressure from urban sprawl and land abandonment in marginal zones (Regione Campania, 2022).

Campania's territorial and economic context is particularly relevant for exploring strategies related to sustainable development and bioeconomy transitions. The region is currently engaged in several initiatives aimed at promoting circular economy models, enhancing rural value chains, and increasing the resilience of local food systems. In the 2021–2027 Regional Development Plan, Campania identifies innovation in the bioeconomy and green technologies as key priorities for achieving climate neutrality, rural revitalization, and social cohesion (Regione Campania, 2021). These strategic objectives are aligned with the European Green Deal and national goals for sustainable growth, placing particular emphasis on the role of agri-food systems, biomass valorisation, and integrated land-use planning.

The coexistence of areas affected by structural decline and land abandonment with areas under intense productive or demographic pressure makes Campania a significant testing ground for policies aimed at balancing environmental, economic, and food security goals. Its territorial heterogeneity — coupled with its socio-economic contrasts — highlights the need for context-specific, multi-level approaches to land use planning and resource governance. In this light, Campania represents a compelling case for evaluating the impacts and opportunities of bio-based transitions at regional scale.

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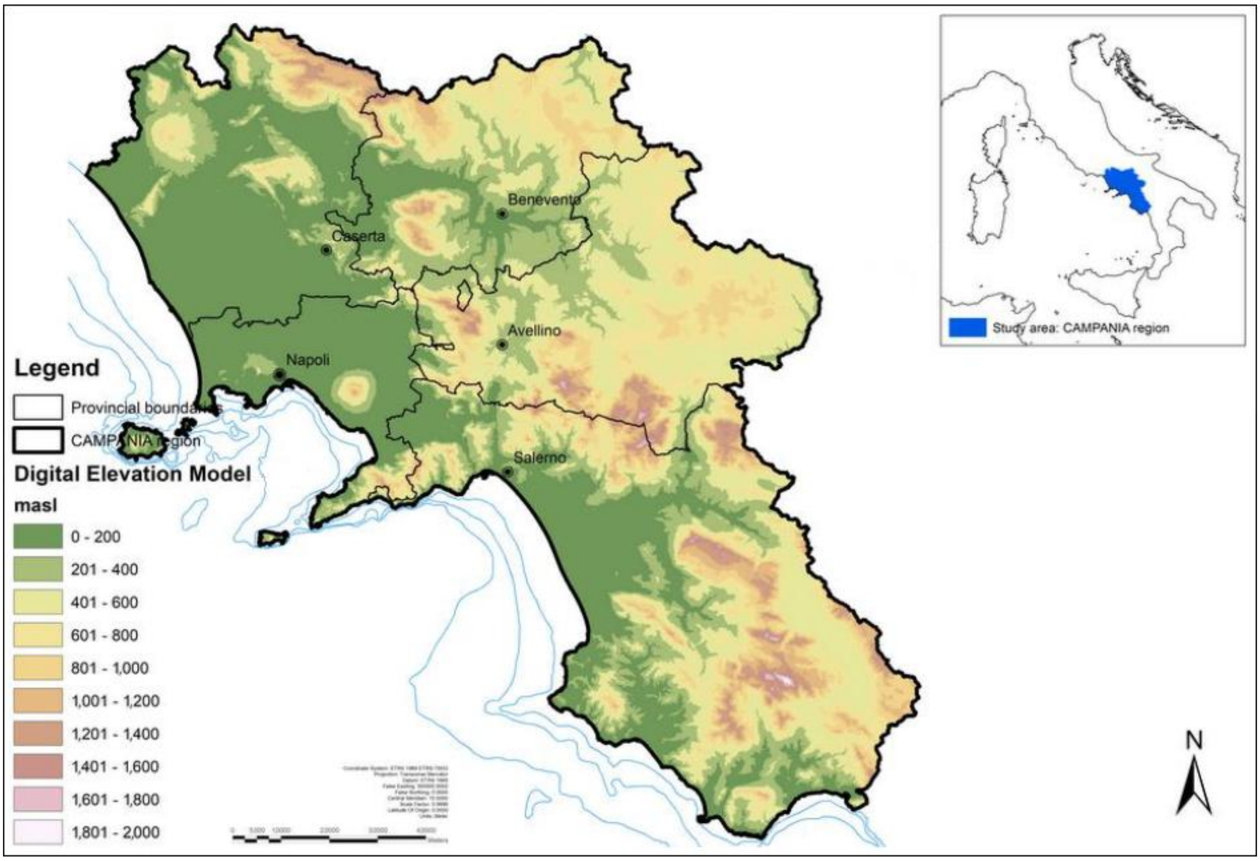

Figure 25. The Campania region in southern Italy. Adapted from Cervelli et al. (2023).

3.2 Future Development of the Bio-Based Sector in Campania

Understanding stakeholders' perspectives was a key step in outlining future development of the bio-based sector in Campania. The number of participants in the survey was relatively small, with responses from various sectors, including a majority from universities and research institutions, as well as from the private sector, the public sector and NGO. Despite the limited sample size, the responses provide valuable insights into the perceived role of the bio-based sector in Campania's development, particularly regarding land use, agricultural practices, forestry management, and food security.

A clear majority of respondents believe the bio-based sector will serve as a driving force for regional economic growth over the next decade. They also anticipate this growth will influence territorial dynamics, particularly in agriculture, a sector that has experienced continuous decline for over two decades. This decline is currently offset by urban expansion on one hand and spontaneous reforestation of abandoned farmland on the other. Most respondents expect the bio-based sector to counterbalance this trend. While some believe it may only slow the reduction of agricultural land, others are more optimistic, predicting a reversal that could lead to the recovery of uncultivated or pasture land for productive use.

The majority of respondents foresee significant changes in agricultural practices driven by the rise of bio-based industries. These changes are expected to include a shift toward high-yield biomass crops (e.g., for biodiesel production) and the adoption of more sustainable practices, such as reducing chemical inputs and fossil fuel reliance. The expected magnitude of these changes could affect up to 20% of the region's agricultural land. Respondents strongly agree that agricultural and agro-industrial by-products will play a central role in supporting the bio-based sector. Many predict that a substantial portion of these by-

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products — potentially over 25% — could be reclaimed and repurposed, transforming what would otherwise be waste into valuable secondary resources.

In contrast, the survey reveals greater uncertainty regarding the impact on forestry. A significant number of respondents either did not express an opinion or were evenly split on whether the bio-based sector would affect forest management. Among those who foresee an impact, the perception remains predominantly positive. They anticipate improvements in forest management practices, emphasizing better utilization of forest residues, increased maintenance, and more rational resource planning to enhance both primary products and by-products. Estimates of the land area potentially affected range from 5% to, at most, 10% of the region's forested land.

Food security emerged as a less divisive topic. Most respondents believe the bio-based sector will not pose a major threat to food production, either regionally or globally. The prevailing sentiment is that the sector will integrate alongside current cropping systems rather than compete with it. However, a minority voiced concerns about potential trade-offs, particularly the risk of replacing food crops with industrial biomass crops. This concern reflects broader debates on balancing industrial and food production within a bioeconomy framework.

When asked about potential barriers to the development of the bio-based sector in Campania, respondents identified several critical challenges. The most commonly cited obstacles include a lack of information about sector opportunities and doubts about the economic sustainability of emerging bio-based supply chains. Respondents emphasized that overcoming these barriers will require targeted policies and strategic investments. Key recommendations include strengthening innovation, research, education, and public awareness, alongside financial incentives to support farmers and businesses transitioning to bio-based production. Suggestions also pointed to the need for better sector planning and coordination to ensure that growth is both economically viable and environmentally sustainable.

In summary, although the survey's limited size prevents definitive conclusions, it reveals clear trends and shared perspectives among stakeholders. The bio-based sector is widely viewed as a promising avenue for Campania's economic and environmental revitalization, particularly within agriculture. However, realizing this potential will require addressing knowledge gaps, economic challenges, and ensuring a balanced approach that supports both industrial production and food security.

Based on these survey results, three land-use scenarios were developed to provide an example the potential implications of bio-based value chain expansion in Campania:

Business-as-Usual (BAU). This scenario assumes a continuation of current land-use trends, with no significant influence from bio-based sector development. Agricultural land continues to decline, forest areas expand due to land abandonment, while settlements grow steadily.

Trend Mitigation (TM). The growth of bio-based value chains contributes to slowing the reduction of agricultural land. As a result, forest expansion is moderated, and pasture areas slightly decline. Urban development continues unabated, mirroring the BAU trajectory, as bio-based growth is not expected to affect urbanization dynamics.

Trend Reversal (TR). The development of bio-based supply chains leads to a net increase in agricultural land, reaching 1% compared to 2020 levels within a decade. This curbs forest expansion and reduces pasture areas. As with TM scenario, urban land use follows the same growth pattern as in the BAU case.

These scenarios were presented and discussed during a workshop held in Naples on March 18th 2025, as part of the participatory phase involving stakeholders in decision-making. Following a Mini-Delphi structure (Linstone & Turoff, 1975), the workshop served to both validate the proposed methodology and gather additional insights on its practical application. The discussion confirmed a generally positive reception of the scenario framework and its underlying assumptions. Participants agreed that the

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scenarios effectively reflect potential land-use trajectories under different bioeconomy development paths.

However, the dialogue also brought critical reflections, mainly regarding the pertinence of land-use classification and the assumption that bio-based value chain development does not influence urbanization dynamics. In particular, stakeholders emphasized that land-use classifications must be tailored to the local context to capture meaningful distinctions in biomass potential and associated carbon stock changes. Properly differentiating between land categories is essential for estimating impacts on the LULUCF sector and for supporting informed decision-making.

Finally, participants stressed the importance of broad stakeholder engagement throughout the process: while the current sample provided a valuable first step, achieving robust and widely accepted results will require a significantly larger and more diverse group of stakeholders. That said, for the purpose of testing the proposed methodology, this initial workshop was deemed sufficient. The high degree of consensus reached during the meeting supported the decision not to schedule additional rounds of discussion.

In conclusion, this first validation meeting successfully tested the methodological approach and confirmed its relevance for guiding scenario development in the context of regional bioeconomy planning. The insights gathered not only refined the current set of scenarios but also laid the groundwork for future iterations involving broader participation and more detailed modelling.

3.2.1 Historical Land-Use Dynamics and the Business-as-Usual Scenario

The development of the Business-as-Usual (BAU) scenario was based on a linear projection of past land-use trends. As a preliminary step, these trends were assessed through the Earth Map platform and referred to the IPCC Land Use Classification derived from ESA-CCI categories. The analysis focused on the period 2000-2020 and relied on the land-use change matrix (Table 4), which was generated following the procedure outlined in paragraph 2.5.1.1. As previously explained, this matrix shows transitions between land-use categories over time, indicating the proportion of land that shifted from one category to another during the reference period.

The observed changes in Campania's land use over the 20-year period are summarized in Table 5 and reveal clear trends. Settlements expanded significantly (+52.58%), followed by a moderate increase in forested areas (+2.83%). In contrast, agricultural land declined by 4.91%, while pastures remained relatively stable (+0.28%). These changes are expressed as net variations in the total surface of each category. This means that local-level shifts in the opposite direction (e.g., from forest to cropland or pasture) may still have occurred but were offset at the aggregate scale. Settlements expansion, however, is largely irreversible and tends to permanently remove land from productive ecosystems.

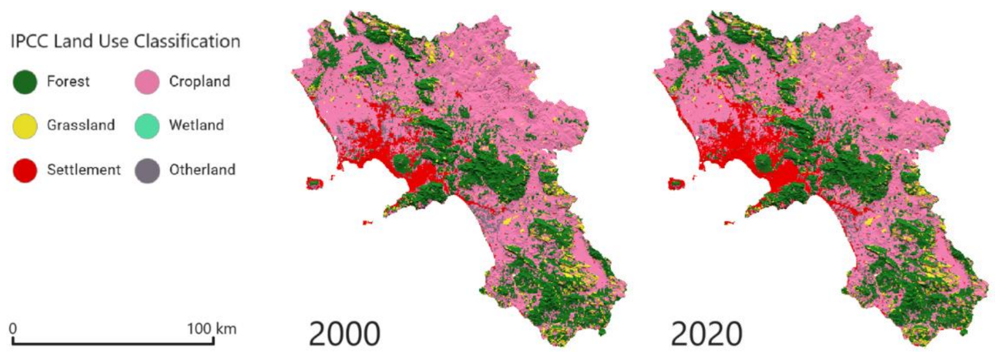

Figure 26. Land-use maps for the years 2000 and 2020 in Campania, based on the IPCC Land Use Classification derived from ESA-CCI categories.

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Table 4. Land-use change matrix expressed in hectares for 2000-2020 in Campania.

	Forest	Grassland	Cropland	Wetland	Settlement	Otherland	Water Bodies	Total 2000
Forest	387.204	1.492	6.707	-	2.220	144	-	**397.767**
Grassland	1.121	74.273	-	-	163	-	-	**75.557**
Cropland	20.519	6	705.736	-	22.972	-	-	**749.233**
Wetland	13	-	-	32	-	-	-	**45**
Settlement	-	-	-	-	87.709	-	-	**87.709**
Otherland	122	-	-	-	20.376	26.054	-	**46.552**
Water Bodies	34	-	-	-	385	-	11.049	**11.468**
Total 2020	**409.013**	**75.771**	**712.443**	**32**	**133.825**	**26.198**	**11.049**	

Table 5. Summary of land-use change by category for 2000-2020 in Campania.

	Total area 2000 (ha)	Total area 2020 (ha)	Change in area (ha)	Change in area (%)
Forest	397.767	409.013	+11.246	**+2,83%**
Grassland	75.557	75.771	+214	**+0,28%**
Cropland	749.233	712.443	-36.790	**-4,91%**
Wetland	45	32	-13	**-28,89%**
Settlement	87.709	133.825	+46.116	**+52,58%**
Otherland	46.552	26.198	-20.354	**-43,72%**
Water Bodies	11.468	11.049	-419	**-3,65%**

Overall, these trends reflect a steady decline in agricultural activity, which, as it contracts, gives way either to urban sprawl or to spontaneous forest regrowth on abandoned land. According to the latest Italian report on land take (ISPRA, 2024), Campania is in fact the third Italian region in terms of total land consumption (over 10% of the regional surface) and ranks fourth for absolute increase in land consumption between 2022 and 2023, with 643 hectares converted.

Once the historical change rates were identified through the transition matrix, a linear projection method was applied. The total observed change for each land-use category over the 2000-2020 period was divided by 20 to estimate an average annual rate of change. These annual rates were then projected forward over a 10-year period to generate the BAU scenario. This linear method is intentionally simple and designed primarily to test the proposed scenario-building methodology. While more complex and non-linear models could be applied (e.g., incorporating policy drivers, economic constraints, or biophysical thresholds), such approaches go beyond the scope of this first phase of the BioINSouth project.

Similarly, the selection of the reference period was based on a balance between relevance and representativeness. A shorter period might have failed to capture slower, long-term dynamics such as forest expansion, which has become a well-established trend across Europe and other regions of the world in response to agricultural decline (Keenan et al., 2015; European Commission, 2023). Conversely, extending the period further back could introduce distortions due to outdated development models, policies, or technologies, no longer reflective of present-day territorial dynamics.

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To ensure compatibility with the carbon balance assessment, conducted in the following phase using the EX-ACT tool, land-use categories were harmonized. In this context, the “Settlements” category was aggregated under “Other land”, which includes all non-vegetated areas (e.g., rocks, bare soils, glaciers) and is treated, for simplicity, as having negligible carbon storage capacity. Additionally, the “Wetlands” category was excluded from the analysis due to its marginal presence in Campania, with only a few dozen hectares out of the total regional area. Similarly, inland water bodies were omitted, as they remained largely stable over the reference period and fall outside the core focus of this study.

As a result, Table 6 summarizes the projected changes for each land-use category in 2035, assuming current trends continue at the same pace. This projection does not aim to predict the future with precision, but rather to illustrate how historical dynamics can inform scenario design and support methodological development for future land-use planning.

Table 6. Share of land use by category under the Business-as-Usual scenario in 2035.

	Area 2020 [ha]	Area 2020 [%]	Area BAU 2035 [ha]	Area BAU 2035 [%]
Forest	409,013	30.14	417,124	30.73
Grassland	75,771	5.58	75,931	5.59
Cropland	712,443	52.49	684,851	50.46
Other land	160,023	11.79	179,344	13.21
Total area	1,357,250	100.00	1,357,250	100.00

3.2.2 Trend Mitigation Scenario

The Trend Mitigation (TM) scenario builds directly on the methodological structure established in the BAU scenario but assumes the implementation of partial mitigation measures capable of slowing, though not reversing, current land-use trajectories. In this case, the reduction of agricultural land continues, but at half the annual rate estimated under BAU assumptions. Consequently, forest expansion — mainly driven by agricultural abandonment — is also projected to proceed at a reduced pace, mirroring the diminished contraction of farmland.

As no significant correlation was found between the development of bio-based value chains and changes in urban expansion dynamics, the “Other land” category (which includes settlements) was assumed to follow the same growth rate as in the BAU scenario. Accordingly, the class that absorbs the remaining balance of land-use changes is grassland, which declines proportionally to accommodate the reduced but ongoing transitions toward forest and non-vegetated surfaces. This assumption is consistent with stakeholder insights collected during the survey phase.

All other parameters and conventions applied in the BAU scenario — such as land-use category harmonization for carbon assessment purposes and the exclusion of marginal land types (wetlands and inland waters) — remain valid and are maintained here. The results of the TM scenario are summarized in Table 7, providing an intermediate outlook on future land-use configurations that balances observed trends with the potential impact of mitigation efforts.

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Table 7. Share of land use by category under the Trend Mitigation scenario in 2035.

	Area 2020 [ha]	Area 2020 [%]	Area TM 2035 [ha]	Area TM 2035 [%]
Forest	409,013	30.14	413,230	30.45
Grassland	75,771	5.58	66,029	4.86
Cropland	712,443	52.49	698,647	51.48
Other land	160,023	11.79	179,344	13.21
Total area	1,357,250	100.00	1,357,250	100.00

3.2.3 Trend Reversal Scenario

The Trend Reversal (TR) scenario projects land-use changes under the assumption of a moderate recovery in agricultural land, reversing the decline observed in previous decades. Specifically, cropland is assumed to increase by 1% compared to 2020 levels, reflecting a potential revitalization of farming activities. This shift is supported by the anticipated development of bio-based value chains, which could stimulate demand for agricultural products and promote the use of land for bioenergy and other renewable biomaterials.

As a result of the recovery in agricultural land, forest expansion continues but at a significantly slower pace compared to the BAU scenario. Forested areas are projected to grow at a rate reduced to one-quarter of that in BAU, reflecting a more limited process of spontaneous regrowth due to the reduced abandonment of agricultural lands. While this slowdown might suggest a future stabilization of forest growth, the trend is unlikely to halt entirely, as forest expansion has already become a long-term, established trend across Europe, fueled by agricultural decline and land abandonment.

As in the TM scenario, the “Other land” category — which includes settlements — is assumed to grow at the same pace as in BAU, since no clear relationship has been established between urban expansion and the bioeconomy. Accordingly, the remaining balance of land-use transitions is absorbed by grassland, which is projected to decline. This contraction is consistent with stakeholder feedback gathered during the survey phase, which identified pastureland as the most likely category to undergo shifts toward cropland or natural succession, due to its marginal role in regional land-use dynamics.

All other assumptions applied in the BAU and TM scenarios — including the harmonization of land-use classes for carbon balance analysis and the exclusion of marginal land types (wetlands and inland waters) — are maintained here. The results of the TR scenario are summarized in Table 8 and provide a contrasting yet plausible vision of future land-use configurations under active trend reversal policies.

Table 8. Share of land use by category under the Trend Reversal scenario in 2035.

	Area 2020 [ha]	Area 2020 [%]	Area TR 2035 [ha]	Area TR 2035 [%]
Forest	409,013	30.14	411,049	30.29
Grassland	75,771	5.58	47,290	3.48
Cropland	712,443	52.49	719,567	53.02
Other land	160,023	11.79	179,344	13.21
Total area	1,357,250	100.00	1,357,250	100.00

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3.3 Possible Impact of the Bio-Based Sector on LULUCF

To estimate the carbon balance of the developed scenarios, the fundamental input consists of the expected land-use changes in each scenario. This includes not only the total surface area allocated to each land-use class at the beginning and end of the analysis period, but also the specific transitions between land-use categories. In other words, it is not sufficient to know the aggregated final surface area of each class; it is also necessary to understand how much of this area is derived from transformations from other classes, and how much remains unchanged during the reference period. For instance, if the land-use class "Cropland" gains 100 hectares by the end of the analysis, it is essential to determine whether this gain comes entirely from a 100-hectare loss in the "Forest" class or from a mix, such as 50 hectares from "Forest" and 50 from "Grassland". Table 9 provides an overview of the land-use distribution at the beginning and end of the simulation for each scenario, along with the corresponding net gains or losses.

Table 9. Land use distribution and net change by category for each scenario [ha].

	Area 2020	BAU 2035	TM 2035	TR 2035	BAU gain	TM gain	TR gain
Forest	409,013	417,124	413,230	411,049	+ 8,111	+ 4,217	+ 2,036
Grassland	75,771	75,931	66,029	47,290	+ 160	– 9,742	– 28,481
Cropland	712,443	684,851	698,647	719,567	– 27,592	– 13,796	+ 7,124
Other land	160,023	179,344	179,344	179,344	+ 19,321	+ 19,321	+ 19,321
Total area	1,357,250	1,357,250	1,357,250	1,357,250	0	0	0

Since the most recent land-use data available refer to the year 2020, this year has been adopted as the starting point of the simulation. Although the actual implementation of the scenarios is envisioned to start in 2025 — consistent with the ten-year horizon proposed to stakeholders in the questionnaire — the 2020-2025 interval is included as a projected, transitional phase common to all scenarios. Therefore, the analysis covers a total period of 20 years: 5 years for the pre-implementation phase (2020-2025), 10 years for the main implementation phase (2025-2035), and an additional 5 years (2035-2040) for capitalization, acknowledging that the effects of the actions undertaken are likely to extend beyond the active implementation period. Given the nature of the envisioned land-use transitions, all changes are assumed to follow a linear path of change over time (see paragraph 2.3.1). These and other parameters adopted in the analysis are shown in Figure 27.

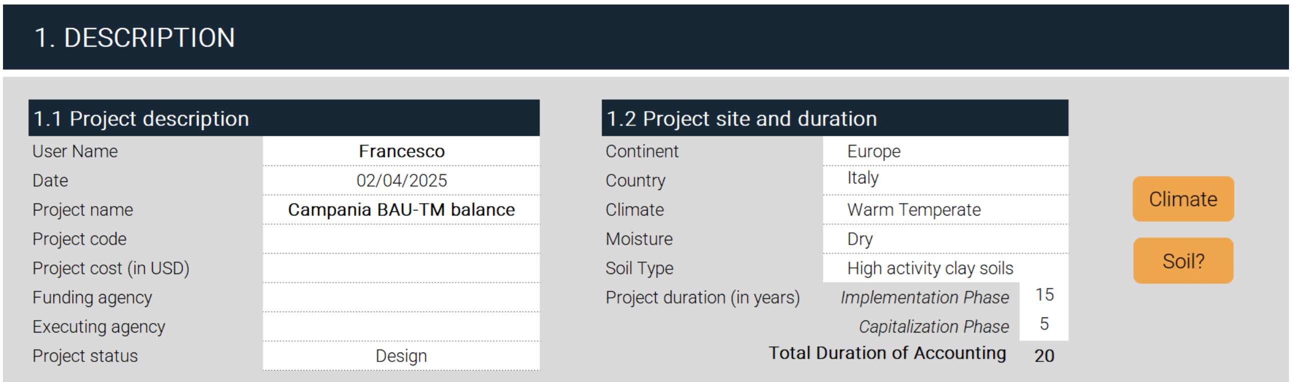

Figure 27. Overview of EX-ACT basic parameters adopted in this analysis.

Following the structure of EX-ACT, the carbon balance calculation proceeds by filling out the required fields module by module. It is computed as a differential between a baseline — in this case, the BAU

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scenario — and one or more alternatives — namely, the TM and TR scenarios. Given the objectives of this document, a detailed step-by-step explanation is provided for the comparison between the BAU and TM scenarios. As for the TR scenario, only the resulting outcomes are presented and discussed.

Afforestation Module

Since both scenarios involve an overall increase in forested area, the first step is to complete the "Afforestation" module within the "Land-Use Change" section. The forest type selected from the drop-down menu is "Subtropical dry forest" (**Figure 28a**). The initial land use is set to "Annual cropland" (**Figure 28b**), which is a subcategory within the broader IPCC "Cropland" class, as derived from ESA-CCI data. This choice represents a methodological simplification: at this scale, it is not feasible to predict the variety and extent of potential crop-to-crop transitions, given the large number of possible combinations. While a more granular differentiation might be appropriate in smaller areas dominated by a limited set of crops, such detailed predictions would be speculative and unwarranted in this context. However, a slightly more refined approach could distinguish between annual and permanent cropping systems, using default values for carbon stock and emission factors.

Next, the reforested area is entered for each scenario: the BAU value is entered in the "Without" column, and the TM value in the "With" column, as shown in **Figure 28c**. These values are derived from the net gain in the "Forest" category in **Table 9**. In this case, a red-coloured result (**Figure 28d**) indicates that afforestation contributes less to the mitigation potential in the TM scenario than in the BAU scenario. This is expected, as the BAU scenario assumes a higher increase in forest area, and forests typically act as significant carbon sinks.

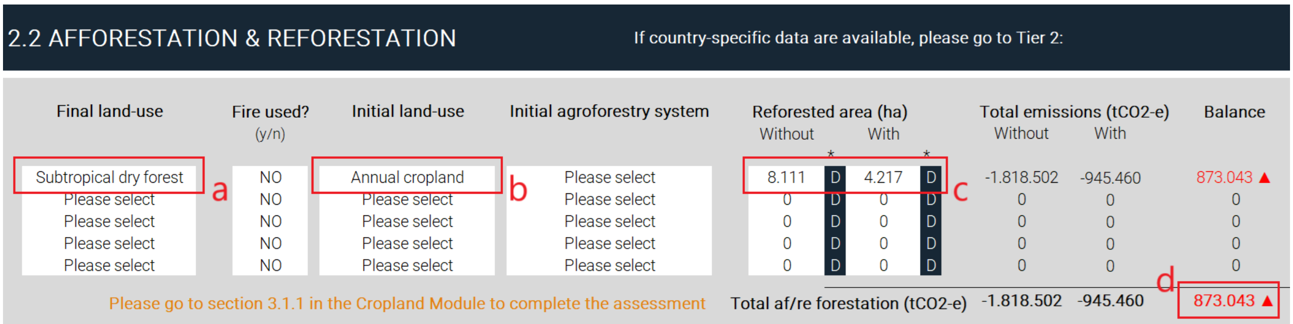

Figure 28. Detailed configuration of the "Afforestation" module according to scenario assumptions: growing forest type (a), initial land use (b), reforested area for both the BAU ("Without") and TM ("With") scenarios (c), and partial results (d).

Other Land-Use Change Module

The next module addresses all land-use changes not related to forestry. The first transformation considered is urban expansion, which is assumed to continue at the same pace across all scenarios and primarily affects cropland, consistent with historical trends (see change matrix, paragraph 3.2.1). Therefore, for simplification, urban expansion is assumed to be identical in both BAU and TM and is entirely at the expense of cropland. While such a symmetrical change does not influence the net carbon balance (since it cancels out), it is still valuable to include it to ensure surface area consistency across classes. This helps later calculations, especially those concerning food security. Thus, a row is added indicating a land-use change from "Annual cropland" to "Other land", with the corresponding values for BAU and TM taken from **Table 9** (**Figure 29a**).

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A second relevant transformation in the TM scenario is the expansion of cropland into grasslands. Due to the rise of bio-based value chains, the decline in cropland is mitigated (see paragraph 3.2.2), and this mitigation is offset by a reduction in grassland area. This is recorded as a transition from "Grassland" to "Annual cropland," with values from Table 9: 0 ha in BAU and +9,742 ha in TM (Figure 29b).

A third minor land-use change occurs only in the BAU scenario, where a slight increase in grassland is observed, coming at the expense of cropland. This is captured by a row indicating a change from "Annual cropland" to "Grassland," with +160 ha for BAU and 0 for TM (Figure 29c).

2.3 OTHER LAND-USE CHANGES — If country-specific data are available, please go to Tier 2:

User notes	Fire used? (y/n)	Initial land-use	Final land-use	Area of land use change (ha) Without *		Area of land use change (ha) With *			Total emissions (tCO2-e) Without	Total emissions (tCO2-e) With	Balance
	NO	Annual cropland	Other land (non-vegetated)	19.321	D	19.321	D	a	77.928	77.928	0
	NO	Please select	Please select	0	D	0	D		0	0	0
	NO	Grassland	Annual cropland	0	D	9.742	D	b	0	63.118	63.118 ▲
	NO	Please select	Please select	0	D	0	D		0	0	0
	NO	Annual cropland	Grassland	160	D	0	D	c	-1.037	0	1.037 ▲
Please go to the Cropland and Grassland modules to complete the assessment			Total non forest land-use change (tCO2-e)						76.891	141.046	64.155 ▲

Figure 29. Detailed configuration of the "Other Land-Use Changes" module based on scenario assumptions. The first row (a) represents settlement expansion on agricultural land, which occurs at the same rate in both scenarios; the second row (b) shows agricultural shift onto grassland (as in the TM scenario); and the third row (c) indicates grassland expansion on agricultural land (as in the BAU scenario).

Cropland Management Section

After defining all land-use changes, the focus shifts to land management. Given the simplified classification mentioned above, cropland is here represented entirely by the "Annual cropland" category. Crop-specific differentiation is omitted, and default values are used (Figure 30a).

The first relevant submodule addresses annual cropping systems involved in land-use transitions. This section is partly auto-filled based on LUC inputs. Stakeholder feedback collected through questionnaires suggests that the growth of the bio-based sector is expected to encourage more sustainable farming practices, with reduced inputs and enhanced soil carbon stocks. Thus, for cropland converted to other land uses, a conventional management profile is assumed, which includes a combination of "Full tillage," "Low C input," and "Retained," respectively concerning tillage practices, organic material input, and residue management (Figure 30b). Conversely, for cropland resulting from land-use conversion, a more sustainable profile is selected: "Reduced tillage," "Medium C input," and "Exported," the latter reflecting the use of residues in bio-based industries (Figure 30c).

3.1.1. Annual cropping systems from other LU or converted to other LU

Description	a Main Crop	Management options for annual cropping systems: Tillage management	Input of organic material	Residue management		Yield (t/ha/yr)	Area (ha): Start	Without	With	Total emissions (tCO2-e): Without	With	Balance
Annuals converted to forest land	Default	Full tillage	Low C input	Retained	b		8.111	0	3.894	19.048	34.289	15.241 ▲
Annuals after deforestation	Default	Please select	Please select	Please select			0	0	0	0	0	0
Annuals converted from non-forest	Default	Reduced tillage	Medium C input	Exported	c		0	0	9.742	0	4.072	4.072 ▲
Annuals converted to non-forest Lus	Default	Full tillage	Low C input	Retained			19.481	0	160	45.749	46.375	626 ▲

Figure 30. Detailed configuration of the annual cropping systems converted from or to other use under the "Cropland Management" module, based on scenario assumptions: crop selection, here set as "Default" (a); combination of crop management settings representing conventional practices; and combination of crop management settings oriented towards bio-based practices (c).

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A specific note concerns cropland that remains unchanged. Stakeholders suggested that management improvements could affect up to 20% of the total agricultural area. The smallest total cropland area between the two scenarios (Table 9) is taken as the reference. This area is divided into 80% that remains unchanged under conventional practices, and 20% that shifts to sustainable practices. The first row records the area not subject to changes, using the conventional profile (“Full tillage”, “Low C input”, “Retained”), kept identical in both scenarios (80% of the total surface), as shown in Figure 31a. Though not strictly necessary for the carbon balance, this entry ensures internal consistency and supports later food security assessments. The next two rows distinguish the remaining 20% of cropland area: in BAU, it keeps following conventional practices, while in TM, it adopts the sustainable bio-based profile (Figure 31b). This reflects a scenario where BAU maintains current agricultural practices, whereas TM introduces a partial transition.

3.1.2. Annual cropping systems remaining annual cropping systems (total area must remain constant)

User notes	Management options for annual cropping systems					Area (ha)			Total emissions (tCO2-e)		
You can use it to describe your system	Main season Crop	Tillage management	Input of organic material	Residue management	Yield (t/ha/yr)	Start	Without *	With *	Without	With	Balance
	Default	Full tillage	Low C input	Retained		547.881	547.881 D	547.881 D	3.639.128	3.639.128	0
	Default	Please select	Please select	Please select		0	0 D	0 D	0	0	0
	Default	Please select	Please select	Please select		0	0 D	0 D	0	0	0
	Default	Full tillage	Low C input	Retained		136.970	136.970 D	0 D	909.780	341.168	-568.613 ▼
	Default	Reduced tillage	Medium C input	Exported		0	0 D	136.970 D	0	60.505	60.505 ▲
	Default	Please select	Please select	Please select		0	0 D	0 D	0	0	0
					Total (ha)	684.851	684.851	684.851			
					Total annual cropping systems (tCO2-e)				4.613.706	4.125.537	-488.169 ▼

Figure 31. Detailed configuration of the annual cropping systems remaining unchanged under the “Cropland Management” module, based on scenario assumptions: combination of crop management settings representing conventional practices (a); and combination of crop management settings oriented towards bio-based practices, applied to 20% of total agricultural surface in the TM scenario (b).

Grassland and Livestock Section

No assumptions were made regarding pasture management. Considering the absence of degradation indicators for grasslands in Campania, the “Grassland” category is uniformly classified as “Non-degraded”, and fire usage is set to “No” across all relevant submodules. To maintain area consistency, one row is filled in the submodule for grassland that remains unchanged, based on the smallest grassland area between the two scenarios (Figure 32).

The livestock submodule is left blank, as animal husbandry was not addressed in the scenario design. However, users may expand on this aspect in other applications if needed.

Forest Management Section

Following the same logic applied to cropland management, the analysis also considers potential improvements in forest management practices. Stakeholder feedback suggests that the growth of the bio-based sector is likely to promote more sustainable forest management approaches. These may involve better maintenance, more efficient use of forest residues, and more rational resource planning aimed at enhancing both primary outputs and by-products.

Based on these assumptions, it was estimated that 5% of the total forest area (calculated as the area at the beginning of the simulation period, i.e. 2020) could be managed under improved conditions. Accordingly, in the “Forest Management” section of EX-ACT, two entries were made: the first representing 95% of the forest area, which remains under a “Low” degradation level (Figure 33a); and the second for

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the remaining 5%, reflecting enhanced management, assigned to the "Very Low" degradation level (Figure 33b).

4.1.1. Grassland systems from other land-use or converted to other land-use (please fill 'Land-use change' module)

Description	Grassland management			Fire manag				Yield (t/ha/year)			Area (ha)			Total emissions		Balance
Grassland systems from (or	Start	Without	With	Without (y/n)	Year	With (y/n)	Year	Start	Without	With	Start	Without	With	Without	With	
Grasslands after deforestation											0	0	0	0	0	0
Grasslands converted to forest											0	0	0	0	0	0
Grasslands after non-forest LU		Non-degraded		NO	5						0	160	0	0	0	0
Grasslands converted to non-f	Non-degraded	Non-degraded		NO	5						9.742	9.742	0	0	0	0

4.1.2. Grassland systems remaining grassland systems (total area must remain constant)

User notes	Grassland management			Fire manag				Yield (t/ha/year)			Area (ha)			Total emissions		Balance
	Start	Without	With	Without (y/n)	Year	With (y/n)	Year	Start	Without	With	Start	Without *	With	Without	With	
	Non-degraded	Non-degraded	Non-degraded	NO	5	NO	5				66.029	66029 D	66029 D	0	0	0
	Please select	Please select	Please select	NO	5	NO	5				0	0 D	0 D	0	0	0
	Please select	Please select	Please select	NO	5	NO	5				0	0 D	0 D	0	0	0
	Please select	Please select	Please select	NO	5	NO	5				0	0 D	0 D	0	0	0
Please consider if livestock feed derives from grassland systems (e.g. natural pastures) of should be included as crop-base…												Total grassland systems (tCO2-e)		0	0	0

Figure 32. Detailed configuration of the "Grassland Management" module, according to scenario assumptions.

5.1 FOREST DEGRADATION & MANAGEMENT If country-specific data are available, please go to Tier 2:

Type of forest vegetation that will be managed	Forest degradation level			Fire occurrence		Fire periodicity		Fire impact		Forested area (ha)			Total emissions		Balance	
	Start	Without	With	Without (y/n)	With (y/n)	Without Year	With Year	Without	With	Start	Without *	With *	Without	With		
Subtropical dry forest	Low	Low	Low	NO	NO	1	1	1,0%	1,0%	388.563	388.563 D	388.563 D	0	0	0	a
Please select	Please select	Please select	Please select	NO	NO	1	1	1,0%	1,0%	0	0 D	0 D	0	0	0	
Subtropical dry forest	Low	Low	Very low	NO	NO	1	1	1,0%	1,0%	20.450	20.450 D	20.450 D	0	-1.069.322	-1.069.322 ▼	b
Please select	Please select	Please select	Please select	NO	NO	1	1	1,0%	1,0%	0	0 D	0 D	0	0	0	
Please select	Please select	Please select	Please select	NO	NO	1	1	1,0%	1,0%	0	0 D	0 D	0	0	0	
Please select	Please select	Please select	Please select	NO	NO	1	1	1,0%	1,0%	0	0 D	0 D	0	0	0	
													0	-1.069.322	-1.069.322 ▼	

Figure 33. Detailed configuration of the "Forest Management" module, based on scenario assumptions: proportion of forest area remaining under a low degradation level (a), and proportion of forest area shifting to a very low degradation level in the TM scenario (b).

Inputs and Investments Section

Despite convergence in stakeholder opinions pointing to reduced use of inputs such as fuels, chemical fertilizers, and pesticide, these are not included in the analysis. This is due to the complexity of quantifying regional-scale input use, given their multiple applications beyond land-based activities (e.g., transport or heating). Moreover, EX-ACT's "Inputs and Investments" module requires aggregate product quantities rather than changes or differences. Nevertheless, users may consider addressing this in their applications if relevant.

The following sections present the results of the comparative analysis between the BAU scenario and the two alternative pathways: TM, resulting from trend mitigation, and TR, resulting from trend reversal connected with different development of the bio-based sector. For each comparison, the analysis focuses on the carbon balance — expressed as mitigation potential in tonnes of CO_2 equivalent — followed by a breakdown of key contributing components.

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The results are discussed both quantitatively and qualitatively, highlighting the influence of land-use change and land management practices on overall GHG emissions and removals. Particular attention is paid to the role of sustainable land management in shaping the final outcome. Each scenario is assessed in relation to the BAU scenario, which provides a reference trajectory based on historical trends, as described in paragraph 2.3.

3.3.1 Scenario Comparison: BAU vs. TM

The comparison between the BAU scenario and the TM scenario results in a climate mitigation potential of –620,293 tCO_2eq over the analysis period, as shown in Figure 34a. This negative value indicates that, under the assumptions adopted, the TM scenario would lead to a more favourable carbon balance than BAU, representing a lower level in GHG emissions.

Despite this result, both the "With" and "Without" bars (representing the TM and BAU scenarios, respectively) appear in red in the summary chart (Figure 34b), indicating that both scenarios are net sources of emissions when compared to the initial reference condition. This outcome can be attributed largely to the assumed land-use trajectories, which maintain historical trends characterized by significant land consumption driven primarily by urban expansion.

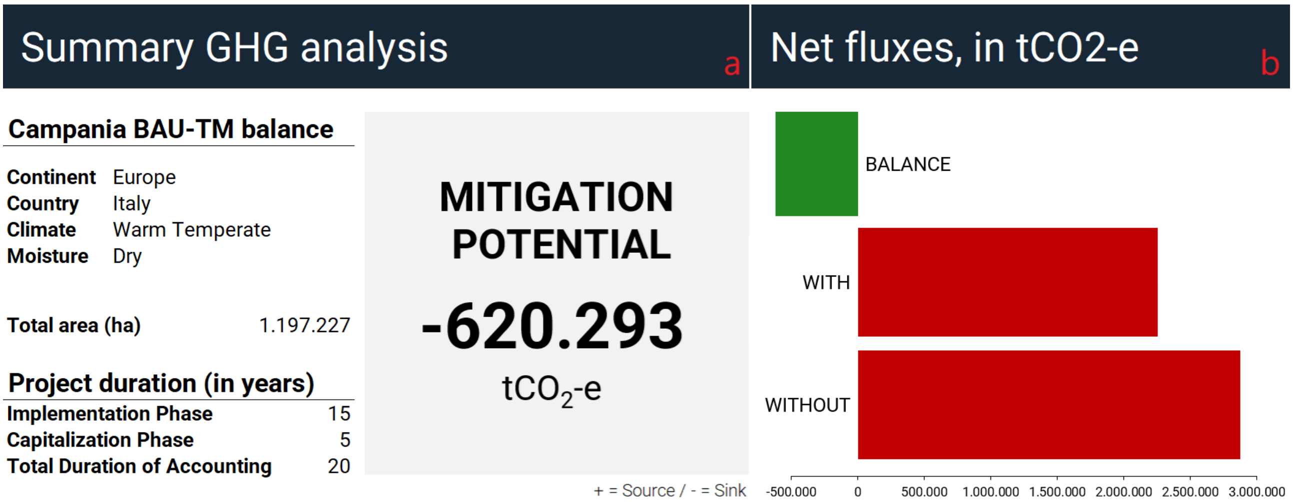

Figure 34. Carbon balance report for the TM scenario: summary of GHG fluxes (a), and charts of net GHG fluxes for each scenario (b).

In the TM scenario, the rate of forest expansion is slightly lower than in BAU, while grassland contracts more markedly (Figure 35). This dynamic reflects the increased competitiveness of agricultural land associated with bioeconomy growth: as abandonment declines, fewer areas are available for spontaneous afforestation, and the shift of croplands occurs largely at the expense of grassland. Since forests and pastures generally store more carbon and entail lower disturbance — due to the absence of tillage and permanent vegetation cover — their loss translates into a less favourable impact on the LULUCF sector (Figure 36a).

If only land-use change were considered, the TM scenario would exhibit a higher carbon cost than BAU. However, this effect is largely compensated by the improvements in land management. In particular, in the "Annual cropland" component, the TM scenario results in lower emissions than BAU (Figure 36b), despite the overall greater extent of cropland. This is attributable to improved agricultural practices, which enhance soil organic carbon and reduce N_2O emissions through more sustainable input use and residue management. These practices, although implemented on a relatively small share of total land, have a considerable impact on the overall balance.

Even more significant is the contribution of improved forest management. Under the TM scenario, assuming only 5% of forest areas are subject to enhanced silvicultural practices, the net gain amounts to −1,069,322 tCO_2eq (Figure 36c). This single element enhances forest as a net carbon sink, demonstrating the substantial mitigation potential of targeted interventions, even at modest scales.

In conclusion, although the TM scenario involves land-use dynamics that are less favourable in terms of carbon sequestration, the adoption of improved land management practices not only compensates for the associated emissions but ultimately outweighs them. The scenario therefore emerges as a more effective mitigation strategy than BAU, underscoring the central role of land management in shaping climate outcomes.

WITHOUT PROJECT a	Forest	Annual	Grassland	Other land	Total area (ha)
Forest	409.013	0	0	0	409.013
Annual cropland	8.111	684.851	160	19.321	712.443
Grassland	0	0	75.771	0	75.771
Other land	0	0	0	0	0
Total area without project	417.124	684.851	75.931	19.321	1.197.227

WITH PROJECT b	Forest	Annual	Grassland	Other land	Total area (ha)
Forest	409.013	0	0	0	409.013
Annual cropland	4.217	688.905	0	19.321	712.443
Grassland	0	9.742	66.029	0	75.771
Other land	0	0	0	0	0
Total area with project (ha)	413.230	698.647	66.029	19.321	1.197.227

Figure 35. Land-use change matrices for the BAU (a) and the TM (b) scenarios. Note: Total area excludes "Other land" remaining unchanged, as this category is only considered in relation to land-use change.

GROSS FLUXES | **SHARE PER GHG OF THE BALANCE**

PROJECT COMPONENTS		WITHOUT	WITH	BALANCE	CO2 BIOMASS	CO2 SOIL	N_2O	CH_4	ALL NON-AFOLU EMISSIONS*	
Land use changes	Deforestation	0	0	0	0	0	0	0		
	Afforestation	-1.818.502	-945.460	873.043	821.642	51.401	0	0		a
	Other land-use	76.891	141.046	64.155	-66.551	130.706	0	0		
Cropland	Perennial	0	0	0	0	0	0	0		
	Annual	4.613.706	4.125.537	-488.169	0	-216.469	-271.700	0		b
Grasslands & Livestock	Grasslands	0	0	0	0	0	0	0		
	Livestock	0	0	0			0	0		
	Forest mngt.	0	-1.069.322	-1.069.322	-1.069.322	0	0	0		c
	Inputs & Invest.	0	0	0	0	0	0	0	0	
Total emissions, tCO2-e		**2.872.095**	**2.251.801**	**-620.293**	**-314.232**	**-34.362**	**-271.700**	**0**	**0**	
Total emissions, tCO2-e/ha		**2,4**	**1,9**	**-0,5**	**-0,3**	**0,0**	**-0,2**	**0,0**	**0,0**	
Total emissions, tCO2-e/ha/yr		**0,1**	**0,1**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	

+ = Source / - = Sink

Figure 36. Component-wise carbon balance between BAU and TM scenarios, including emissions and removals from land-use changes (a), cropland management (b), and forest management (c).

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3.3.2 Scenario Comparison: BAU vs. TR

The comparison between the BAU and the TR scenario results in a mitigation potential of +6,471 tCO_2eq over the analysis period (Figure 37a). This value, though marginally positive, is close to neutrality and indicates that the two scenarios would yield comparable climate outcomes, at least in terms of net carbon balance. The relatively small difference is particularly notable considering that it applies to the entire regional scale of analysis.

As in the TM scenario, both the “With” and “Without” bars in the summary chart appear in red (Figure 37b), confirming that both BAU and TR scenarios would represent net GHG sources relative to the initial reference condition. This again stems from the underlying land-use trajectories, which follow historical patterns characterized by substantial land take, primarily for urban development.

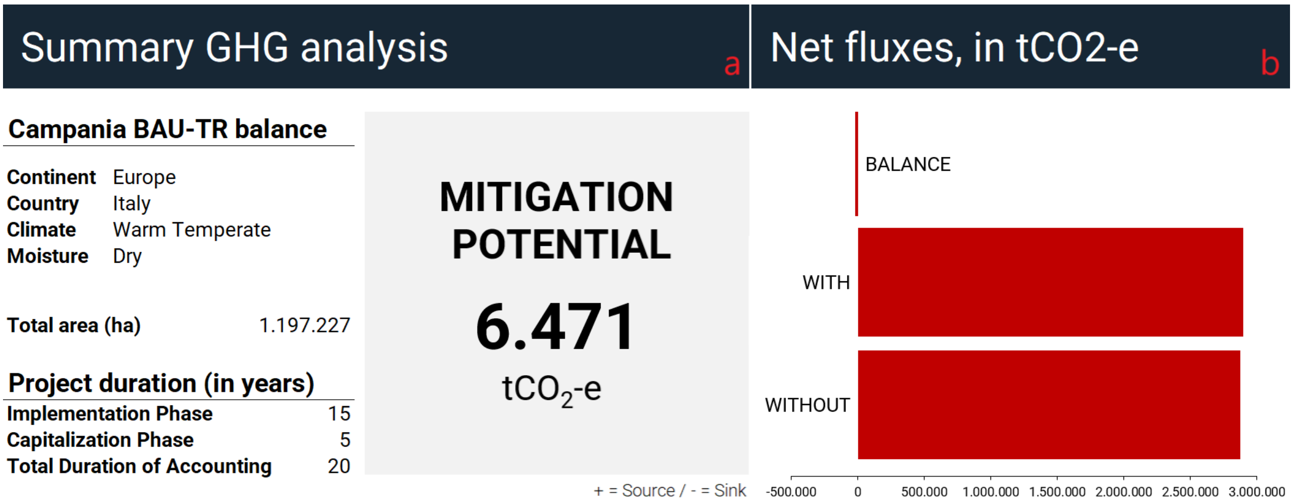

Figure 37. Carbon balance report for the TR scenario: summary of GHG fluxes (a), and charts of net GHG fluxes for each scenario (b).

In the TR scenario, forest expansion slows even further compared to BAU, while the contraction of grassland is significantly more pronounced (Figure 38). This is a consequence of the scenario’s assumption of increased cropland areas, which grow not only as a compensation for urbanization but also through the recovery of abandoned land and the conversion of grassland. Given that forests and pastures tend to sequester and store more carbon than croplands, this shift contributes negatively to the overall carbon balance (Figure 39a).

Nevertheless, as observed in the TM scenario, land management improvements play a critical compensatory role. In the cropland component, the TR scenario yields lower emissions under improved practices (Figure 39b), despite the increased extent of cropland. This reduction results mainly from higher soil organic carbon stocks and decreased N_2O emissions, achieved through more environmentally conscious farming approaches, as resulted from stakeholder opinions. The same applies to the forest management component (Figure 39c), which follows an identical assumption as in TM: enhanced silvicultural practices applied to 5% of the forest area. As in TM, this intervention alone enhances forest as a net carbon sink.

Therefore, even though the land-use changes in TR are less favourable in terms of carbon storage, the implementation of sustainable land management strategies offsets much of the associated impact. This again highlights the considerable mitigation potential embedded in improved management, especially when applied to extensive land categories such as forests and croplands.

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WITHOUT PROJECT a	Forest	Annual	Grassland	Other land	Total area (ha)
Forest	409.013	0	0	0	409.013
Annual cropland	8.111	684.851	160	19.321	712.443
Grassland	0	0	75.771	0	75.771
Other land	0	0	0	0	0
Total area without project	417.124	684.851	75.931	19.321	1.197.227
WITH PROJECT b	**Forest**	**Annual**	**Grassland**	**Other land**	**Total area (ha)**
Forest	409.013	0	0	0	409.013
Annual cropland	2.036	691.086	0	19.321	712.443
Grassland	0	28.481	47.290	0	75.771
Other land	0	0	0	0	0
Total area with project (ha)	411.049	719.567	47.290	19.321	1.197.227

Figure 38. Land-use change matrices for the BAU (a) and the TR (b) scenarios. Note: Total area excludes "Other land" remaining unchanged, as this category is only considered in relation to land-use change.

GROSS FLUXES					SHARE PER GHG OF THE BALANCE					
PROJECT COMPONENTS		WITHOUT	WITH	BALANCE	CO2 BIOMASS	CO2 SOIL	N_2O	CH_4	ALL NON-AFOLU EMISSIONS*	
Land use changes	Deforestation	0	0	0	0	0	0	0		
	Afforestation	-1.818.502	-456.475	1.362.027	1.281.837	80.190	0	0		a
	Other land-use	76.891	262.456	185.565	-192.496	378.061	0	0		a
Cropland	Perennial	0	0	0	0	0	0	0		
	Annual	4.613.706	4.141.906	-471.799	0	-204.078	-267.722	0		b
Grasslands & Livestock	Grasslands	0	0	0	0	0	0	0		
	Livestock	0	0	0			0	0		
	Forest mngt.	0	-1.069.322	-1.069.322	-1.069.322	0	0	0		c
	Inputs & Invest.	0	0	0	0	0	0	0	0	
Total emissions, tCO2-e		**2.872.095**	**2.878.565**	**6.471**	**20.019**	**254.174**	**-267.722**	**0**	**0**	
Total emissions, tCO2-e/ha		**2,4**	**2,4**	**0,0**	**0,0**	**0,2**	**-0,2**	**0,0**	**0,0**	
Total emissions, tCO2-e/ha/yr		**0,1**	**0,1**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	

+ = Source / - = Sink

Figure 39. Component-wise carbon balance between BAU and TR scenarios, including emissions and removals from land-use changes (a), cropland management (b), and forest management (c).

3.4 Possible Impact of the Bio-Based Sector on Food Security

The fourth phase of the methodology aims to estimate the impact of each scenario on food security using the Excel-based Food Security Toolkit specifically developed within the BioInSouth project. The toolkit evaluates the implications of alternative land-use trajectories on regional food production in the Campania region, particularly considering the expansion of the bio-based sector. The analysis quantitatively assesses how changes in agricultural land availability and allocation — especially shifts from food to non-food uses — affect the caloric output of the agri-food system and regional food self-sufficiency.

It is important to underline that the three hypothetical scenarios analysed (Negative, Intermediate, and Positive) represent the range of diverse and nuanced opinions articulated by multiple stakeholders through an extensive participatory engagement process. These stakeholders included regional agricultural producers, policymakers, academic experts, representatives of the bio-based sector, and other relevant social and economic actors. Their perspectives were collected systematically and

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deliberated upon, ensuring comprehensive representation and balanced consideration of various interests and concerns. The initial stakeholder inputs were rigorously assessed, discussed, and refined during subsequent validation phases, particularly through the structured Mini-Delphi method, which ensured clarity, consensus, and reliability in shaping the final scenario assumptions, subsequently validated through an expert consultation round. Thus, these scenarios illustrate the spectrum from worst-case to best-case possibilities, serving primarily as examples of how such an analysis can be operationally conducted. Consequently, the results should be contextualized within this framework, recognizing that even the negative scenario does not pose a severe risk to food security.

To launch and initialize the Food Security Toolkit, it is necessary first to input the specific data as shown in Figure 40. This data represents the basic information required for conducting scenario analyses within the toolkit. To this aim, the toolkit includes a dedicated sheet named "Yield Data", sourced from FAOSTAT, containing national average yield values for European countries (EU-27) as of 2023 (Figure 41). Additionally, caloric content per unit crop is provided within another specialized sheet titled "Caloric Value", which covers caloric information for the primary food items included in the analysis (Figure 42).

	Yield (kg/ha)	Caloric Value (kcal/kg)	AREA (ha) BAU	Scenario 1	Scenario 2	Scenario 3
Barley	4,113	3,320	80,722	72,535	79,087	85,791
Broad beans a	2,006	3,410	82,358	82,358	82,358	82,358
Maize (corn)	10,731	3,560	28,538	28,538	28,538	28,538
Oats	2,256	3,850	942	942	942	942
Sunflower see	2,510	3,080	10,598	9,523	10,383	11,264
Tomatoes	60,768	170	20,193	20,193	20,193	20,193
Wheat	3,692	3,340	461,501	414,694	452,152	490,482

Figure 40. Data inputs required for calculating food security indicators, as provided in the Food Security Toolkit.

Domain	Area Code (M4	Area	Elemen	Item	Year	Unit	Value
Crops and livestock products	380	Italy	Yield	Barley	2023	kg/ha	4112.7
Crops and livestock products	380	Italy	Yield	Broad beans and horse beans, dry	2023	kg/ha	2005.8
Crops and livestock products	380	Italy	Yield	Maize (corn)	2023	kg/ha	10730.7
Crops and livestock products	380	Italy	Yield	Oats	2023	kg/ha	2255.7
Crops and livestock products	380	Italy	Yield	Sunflower seed	2023	kg/ha	2509.6
Crops and livestock products	380	Italy	Yield	Tomatoes	2023	kg/ha	60768.2
Crops and livestock products	380	Italy	Yield	Wheat	2023	kg/ha	3691.7

Figure 41. Dataset reporting average yield for the selected crop, extracted from the "Yield Data" sheet of the Food Security Toolkit.

Source : https://www.fao.org/4/x9892e/X9892e05.htm — **Food composition in terms of the retail weight ("as purchased") in 100 grams**

ITEM	CALORIES	PROTEIN	FAT	ITEM	CALORIES	PROTEIN	FAT
	kcal	Grams	Grams		kcal	Grams	Grams
CEREALS AND PRODUCTS				ROOTS, TUBERS AND PRODUCTS			
WHEAT	334	12,2	2,3	POTATOES	67	1,6	0,1
FLOUR OF WHEAT	364	10,9	1,1	FLOUR OF POTATOES	349	8,5	0,4
BRAN OF WHEAT	213	12,1	3,1	POTATOES FROZEN	73	1,2	0
MACARONI	367	11	1,1	POTATO STARCH	362	0,5	0,3
GERM OF WHEAT	382	29,1	10,7	POTATO TAPIOCA	362	0,5	0,3
BREAD	249	8,2	1,2	SWEET POTATOES	92	0,7	0,2

Figure 42. Excerpt from the "Caloric Value" sheet of the Food Security Toolkit.

Regarding crop distribution by area, sources like SAR/LUCAS through Earth Map can be used. This dataset provides relative distributions of cropland under annual cultivation, classified by crop type. Using this relative share, it is possible to proportionally apply these distributions to the total cropland figures calculated in the LULUCF framework.

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Specifically, the Business-As-Usual scenario in the toolkit corresponds directly to the BAU scenario utilized in the LULUCF calculations. Alternative scenarios can similarly follow the LULUCF methodology, with variations applied across the entire spectrum of crop production areas. In implementing these scenarios, it is important to note that individual crop categories may experience differentiated impacts, reflecting distinct susceptibilities to changes driven by the growth of the bio-based sector.

For the current case study and associated scenario analyses, we explicitly assume that the expansion of the bio-based sector will not significantly impact the cultivation and production areas of maize, tomatoes, beans, and oats, preserving these crop categories at their initial baseline values throughout the simulation.

The toolkit allows customization of baseline (Business-As-Usual, BAU) values for both the Agricultural Land Availability Index and the Self-Sufficiency Ratio. Specifically, in the case of the Campania region, the BAU scenario has been initialized by setting the ALAI at 96%. This value results from a linear projection of cropland trends observed over the past 20 years as previously discussed. For the SSR, in absence of specific and detailed data on current or projected future values, a neutral equilibrium condition of 100% was assumed. This assumption serves as a reference point for comparative analysis across the various scenarios.

Empirically, the toolkit employs a comparative scenario-based approach, contrasting a Business-as-Usual reference trajectory with the three stakeholder-derived scenarios. The BAU scenario provides a baseline, reflecting continued observed trends without significant policy or market-driven changes, featuring a 4% reduction in cropland availability relative to the theoretical maximum (ALAI = 96%). In this baseline, the Total Caloric Supply is estimated at 8,744,821 million kcal, and the Self-Sufficiency Ratio is assumed at equilibrium (100%).

According to stakeholder insights validated via the mini-Delphi method, the three scenarios are defined as follows:

FS Scenario 1: Negative Development Trajectory

Cropland: following the **Trend Mitigation** scenario +2% relative to BAU.

Land Conversion: -10% of cropland reallocated to non-food bio-based uses.

Indicators: TCS = 8,047,585 million kcal; ALAI = 88.1%; SSR = 92.0%.

Overall, the scenario 1 illustrates a decline in food security indicators, though the resulting SSR indicates only a moderate increase in external dependency.

FS Scenario 2: Intermediate Development Trajectory

Cropland: +3% compared to BAU.

Land Conversion: -5% allocated to bio-based uses.

Indicators: TCS = 8,605,553 million kcal; ALAI = 94.4%; SSR = 98.4%.

Representing a balanced approach, this scenario maintains near-complete food self-sufficiency, highlighting its acceptability in transitional policy contexts.

FS Scenario 3: Positive Development Trajectory

Cropland: following the **Trend Reversal** scenario +4% relative to BAU.

Land Conversion: No reallocation; all agricultural land dedicated to food crops.

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Indicators: TCS = 9,176,528 million kcal; ALAI = 100.9%; SSR = 104.9%.

This scenario demonstrates strengthened regional resilience and surplus food production capacity, positively reinforcing food security.

	BAU	Scenario 1	Scenario 2	Scenario 3
Total TCS (M kcal)	8,744,821	8,047,585	8,605,553	9,176,528
Agricultural Land Availability Index	96.0%	88.1%	94.4%	100.9%
SSR	100.0%	92.0%	98.4%	104.9%

Figure 43. Food security indicators for the three scenarios.

The Food Security Toolkit automatically generates three intuitive graphs summarizing the key food security indicators analysed under each scenario. These graphs include:

Total Caloric Supply: Displayed as a vertical bar chart, representing the total food energy produced in each scenario, measured in millions of kilocalories (M kcal);

Agricultural Land Availability Index: Presented as a horizontal bar chart, illustrating the percentage of agricultural land available relative to a theoretical maximum (set at 100%), highlighting how land availability changes under each scenario compared to the BAU scenario;

Self-Sufficiency Ratio: Shown as a vertical bar chart, providing a clear comparison of the food energy produced versus the dietary energy required within the region under different scenarios, with values expressed as percentages.

These visual outputs facilitate quick comparative assessments, effectively supporting decision-makers in interpreting scenario impacts on regional food security.

The scenario outcomes underscore the utility of quantitative tools such as TCS, ALAI, and SSR in evaluating land-use strategies. Scenario 1 serves as a cautionary example of how relatively modest reallocations could moderately impact food security, yet remain manageable. Scenario 2 represents a pragmatic middle path that aligns bioeconomy growth with minimal risk to food sovereignty, while Scenario 3 illustrates potential strategies for enhancing regional food self-sufficiency through targeted land-use measures.

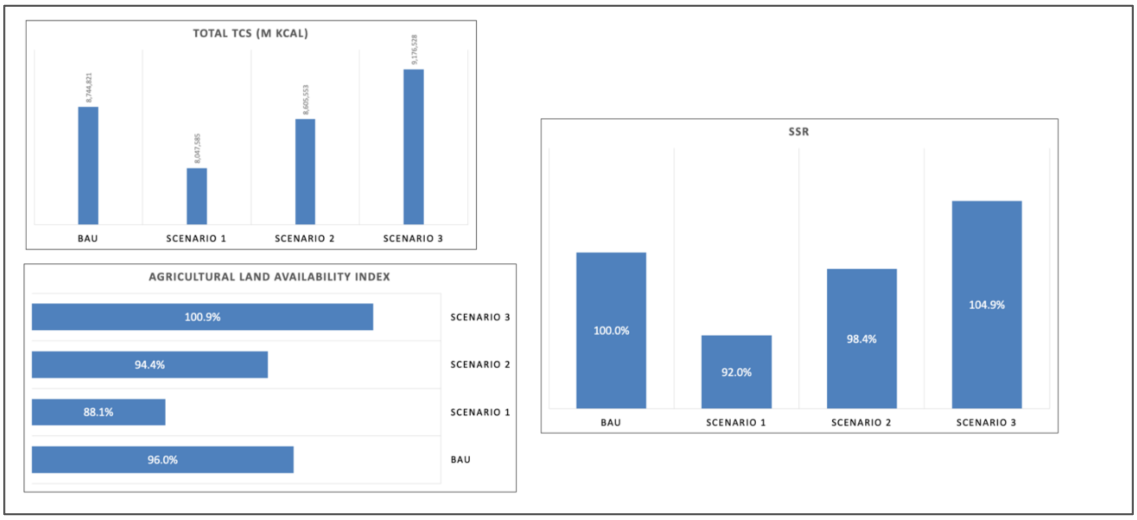

Figure 44. Graphs summarizing food security indicators generated for the Campania case study.

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3.5 General Assessment and Comparative Insights

The comparative assessment of the described land-use scenarios underscores the inherent trade-offs between environmental and food production priorities. On the one hand, potential land-use changes driven by the expansion of bio-based sectors could jeopardize long-term sustainability by altering carbon dynamics and, in some cases, increasing pressure on agricultural land. On the other hand, such shifts may enhance short-term food or bio-resource production, revealing a tension between climate mitigation objectives and the growing demand for food supply.

From a climate perspective, the TM scenario balances afforestation with agricultural land availability while minimizing the negative effects of land conversion, resulting in a substantial carbon sequestration potential. However, this trajectory can also limit the availability of land for food production, which may negatively affect regional food security — as illustrated in the TM-based FS Scenario 1. In this case, a 10% reallocation of cropland to non-food uses leads to a reduction in agricultural output and food self-sufficiency.

Conversely, the TR-based FS Scenario 3 prioritizes food production, maximizing caloric output and improving self-sufficiency, but contributes little to climate mitigation, with carbon outcomes broadly comparable to the BAU scenario. This juxtaposition highlights the delicate balance between land-use choices and carbon outcomes: expanding cropland may support food security but reduce carbon sequestration potential by limiting higher carbon-absorbing ecosystems, and vice versa.

In this context, FS Scenario 2 emerges as a balanced path, involving a modest decrease in agricultural land availability while still preserving carbon sinks and mitigating the negative impacts of land conversion. This scenario reflects a trade-off strategy where agricultural production is maintained at near-BAU levels, while improved land management practices help preserve or even enhance carbon stocks, despite notable shifts in land allocation.

The key takeaway is the critical role of land management practices in offsetting the potential negative impacts of land-use change. Even when structural transformations (e.g., cropland expansion or conversion to bio-based uses) appear unfavourable for carbon sequestration, the adoption of sustainable land management can significantly compensate for such effects. In this regard, improved agricultural practices — such as reducing soil tillage, increasing the use of bio-based fertilizers, and avoiding the burning of crop residues — can simultaneously improve yields and reduce emissions, helping bridge the gap between food security and climate mitigation goals.

The comparison underscores a crucial insight: land management improvements can substantially influence climate outcomes, even in the presence of unfavourable land-use trends. From a practical perspective, this suggests that targeted interventions in management practices — especially when supported by appropriate policies and active stakeholder engagement — can deliver tangible benefits even in contexts where broader structural transformations are difficult to govern.

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4 Conclusions

This document has set out a comprehensive, replicable methodology for assessing the implications of bio-based sector growth on land use, climate mitigation, and food security. By integrating geospatial data, expert knowledge, participatory planning, and analytical tools such as the FAO's EX-ACT and the Excel-based Food Security Toolkit, the proposed approach enables stakeholders to simulate land use change scenarios and understand the trade-offs between carbon emissions/removals and agricultural productivity.

By combining quantitative modelling with participatory scenario design, the methodology offers a powerful framework for integrating climate and food system objectives into territorial development strategies. It allows planners and decision-makers to evaluate the synergies and tensions between competing land uses and to identify pathways for sustainable growth of the bioeconomy. Notably, the approach emphasizes stakeholder engagement throughout the process, ensuring that outputs reflect local priorities and real-world feasibility.

The methodology was tested through a case study in the Campania region. This case study serves as an illustrative example to demonstrate the operational features of the methodology and to support its dissemination for informative and educational purposes. It provides a concrete application of the approach, highlighting how stakeholder input, historical land use trends, and scenario modelling can be effectively combined to generate policy-relevant insights.

The resulting scenarios – Business-as-Usual, Trend Mitigation, and Trend Reversal – demonstrated how moderate shifts in land allocation and management can lead to substantially different outcomes for LULUCF emissions and food self-sufficiency. These insights validate the relevance and applicability of the methodology to regional planning and policy development in Southern Europe.

Despite its strengths, the methodology also presents some limitations that should be acknowledged:

While scenarios are built on stakeholder knowledge and historical data, their projections necessarily simplify complex socio-economic and environmental dynamics. Assumptions such as constant crop yields and linear land-use trends, while useful for comparability, may overlook nonlinear feedbacks and future shocks (e.g., climate events, market volatility).

The case study involved a relatively small and potentially unbalanced sample of stakeholders, with overrepresentation from academia. Broader and more diversified engagement — including farmers, civil society, and marginalized groups — is essential to fully capture the range of local perspectives and potential conflicts.

The methodology assumes that the growth of the bio-based sector does not affect urban expansion, which may not hold true in areas experiencing bio-industry clustering or rural-urban migration induced by land-use changes.

Another important limitation concerns the representation of agricultural land use within scenario building. For modelling purposes, all agricultural areas are assumed to be annual cropland. While this simplification enables a clearer application of the methodology, it does not account for permanent crops or more complex land-use categories. Disaggregating agricultural land into detailed typologies would require handling a much larger number of land-use transitions, each with specific implications and assumptions. Addressing this level of complexity would necessitate advanced modelling techniques and substantial geospatial expertise, which go beyond the scope and ambition of the current approach.

Similarly, the food security analysis relies on crop composition data derived from the SAR/LUCAS survey, which only covers arable land and excludes permanent crops. Moreover, the food security component assumes constant productivity, excluding possible yield increases or technological innovations that could

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influence future food availability. This assumption, while methodologically convenient, may underestimate the adaptive capacity of agricultural systems.

Finally, the EX-ACT model operates under Tier 1 IPCC default parameters unless regional data is provided. This limits the precision of carbon accounting in areas with highly variable or unique ecological characteristics unless users have the capacity to input Tier 2 or 3 data.

These approximations are considered acceptable at the current regional scale. However, more granular analyses could be conducted at smaller territorial levels — for example, in areas with a few dominant crops — allowing for refined data selection and more detailed investigations. In this sense, the methodology could be applied to targeted value chains or project areas, in line with the scalable nature of EX-ACT, which is designed to support assessments from the project level up to broader policy applications.

The current methodology focuses on land use, climate, and caloric food output. Broader sustainability indicators — such as life cycle assessment (LCA), biodiversity — are not currently integrated in this methodology but are critical for comprehensive assessments of bioeconomy impacts. However, we are confident that these components will be successfully addressed by other activities already underway within the BioINSouth project. Therefore, the combined use of these complementary outputs is both feasible and advisable to achieve a more holistic evaluation framework.

Despite these limitations, we believe the proposed methodology may represent a valuable tool for evidence-based scenario analysis and planning. Its structured approach, grounded in both empirical data and participatory insight, provides a flexible framework that can support diverse regional contexts across Southern Europe. In particular, for regions facing structural agricultural decline, land abandonment, and the need for climate-resilient development — such as many areas in Southern Italy, Spain, Portugal, and Greece — the methodology offers a means to explore how bio-based growth can be aligned with sustainability and food security objectives.

As the BioINSouth project advances, further applications and refinements of the methodology will help enhance its robustness, accessibility, and strategic relevance for guiding the ecological and economic transformation of Southern Europe's bio-based sectors.

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BioINSouth Info Box

The BioINSouth project aims to support decision-makers to incorporate considerations of ecological limits into their regional bioeconomy strategies and roadmaps relevant to circular bio-based activities. We aim to develop guidelines and digital tools, considering the safe and sustainable by design (SSbD) assessment framework, to support the adoption of innovative methodologies to assess environmental impacts in multiple industrial bio-based systems, increasing regional competitiveness and innovation capacity, and contributing to the EU fair & green transition.

Find out more:

Website: https://www.bioinsouth.eu/
LinkedIn: https://www.linkedin.com/company/104361906/
YouTube: https://www.youtube.com/@BioINSouth
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This document was published as "D4.4 Food Security and LULUCF Methodology", and as part of the project "BioINSouth: Supporting regional environmental sustainability assessment for the BIO-based sectors to improve INnovation, INdustries and INclusivity in SOUTH Europe" (Grant Agreement No. 101156363), co-funded by the European Union and supported by the Circular Bio-based Europe Joint Undertaking and its members. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CBE JU. Neither the European Union nor the CBE JU can be held responsible for them.

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