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Synergic use of existing environmental certification schemes can support impact neutrality goals and future claims

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Abstract

The balance between detrimental and beneficial impacts is often overlooked in agricultural sustainability assessments. The recently developed TREEIN (TREE for Environmental Impact Neutrality) model addresses this gap by promoting the integrated use of fragmented environmental management and certification schemes. Although designed to support the integrated use of those schemes, TREEIN has not yet been tested empirically. This study makes a step forward by applying TREEIN in a real-world case of support to the environmental sustainability claims of a winegrowing company in Tuscany, Italy. The farm's natural capital was assessed in terms of carbon sequestration potential, taken as priority target ecosystem service, and an organisational life cycle assessment (O-LCA) was developed. Following TREEIN, the company was for the first time certified with 'Forest Stewardship Council' and 'Equalitas' standards. Those ensure transparency and robustness in quantifying ecosystem services and life cycle impacts, respectively. Farm's forest ecosystems were found to roughly absorb the double of company's total greenhouse gas emissions. Integrating these data into the O-LCA framework enabled the creation of a long-term mitigation plan to compensate the GHG impact of the organization activities, confirming TREEIN as an effective and replicable model to guide companies achieving environmental impact neutrality.

Keywords

Agriculture; ecosystem service; environmental certification; environmental footprint; life cycle sustainability; grape; natural capital accounting; sustainability protocol

1 Introduction

Human activities are increasingly threatening dynamic equilibrium of ecosystem's functioning through the overexploitation of natural resources. This includes, among others, rising greenhouse gas (GHG) emissions and disruption to the water cycle (Berger et al., 2025; Millward-Hopkins et al., 2025; Rockström et al., 2023). Agriculture plays a significant role in this context, accounting for over 20% of global GHG emissions and consuming 70% of freshwater resources (FAO, 2021), thereby raising concerns about environmental sustainability (Rosa et al., 2020). In response, sustainability targets have become a core economic focus for prompting corporations to disclose their environmental performance (Ciccullo et al., 2018). However, there is a lack of standardised impact accounting frameworks to balance environmental costs and benefits associated with interventions of improvements towards sustainability.

The EU has responded with initiatives, such as the Green Deal and the Climate Law (Fetting, 2020), which promote tools like Life Cycle Assessment (LCA) for quantifying environmental impacts of production processes (Schutzbach et al., 2022). However, a focus solely on negative externalities can overlook potential environmental benefits raising from Ecosystem Services (ES) management, particularly in agriculture (Stoeckl et al., 2025; Xue & Bakshi, 2022). A deeper investigation on these issues is offered in a literature review included in the Supplementary Material 1 (SM1, section 1).

The 'TREe Model for Environmental Impact Neutrality' (TREEIN) was recently built to offer a holistic framework based on the so-called "mitigation hierarchy", which serves to balance positive against negative environmental impacts through improved management and ecosystem service enhancement (Varavallo et al., 2024). The model proposes to combine standardized LCA principles, which quantify detrimental impacts on human and ecosystem health throughout the life cycle of the production system (Hauschild et al., 2017), with certification-based protocols that account for the beneficial impact provided by increased ES. This integration allows to enhance the model's operational applicability and provides data-driven insights for implementing certified sustainable agricultural practices.

Sustainability certification schemes and environmental labels, such as the ones in the ISO 14000's family, have become ubiquitous tools for agricultural governance (Stabile et al., 2020; Taoumi & Lahrech, 2023). However, their adoption does not inherently guarantee verifiable reductions in environmental impacts. While certain sectors achieve direct greenhouse gas (GHG) mitigations (Schmidt & Weidema, 2026) others merely satisfy institutional compliance criteria without realizing tangible environmental improvements (Velaoras et al., 2025). This decoupled effect often stems from the structural design of the schemes themselves; for instance, Harvey et al. (2025) found that the adoption of the Forest Stewardship Council (FSC) certification does not necessarily lead to measurable reductions in GHG emissions, largely because FSC standards do not explicitly require the implementation of carbon-focused management practices such as Reduced-Impact Logging for Carbon. As a result, certified operations may formally comply with certification requirements while still failing to maximize their climate change mitigation potential. More broadly, a key limitation of many environmental certification schemes is their narrow assessment framework and predominantly compliance-based approach:

64 by focusing on the verification of predefined requirements rather than on performance outcomes, these
65 schemes often lack mechanisms for continuous monitoring and adaptive management, thereby limiting
66 opportunities for iterative operational improvement and long-term environmental optimization (Khairani et al.,
67 2026).

68 Addressing this gap requires integrated methodological frameworks to be put in place that relate a baseline
69 footprint accounting with actionable, long-term operational management and improvements. The TREEIN
70 methodology embraces this concept and was originally introduced to assess carbon emissions versus removals
71 in viticulture; however, its initial application remained limited to establishing a static baseline balance
72 (Varavallo et al., 2024). The present study shortens the distance between theoretical modelling and practical
73 governance by executing all stages of the TREEIN framework, making it operational for the first time for an
74 agricultural enterprise in Tuscany, Italy. By moving beyond passive compliance logic, this full-scale
75 implementation could guide concrete, certified environmental interventions and embed a continuous
76 sustainability management process into the core business model of the company. In doing so, this paper
77 customizes TREEIN for the specific sector of viticulture and makes it a robust, replicable methodological
78 reference for driving agricultural enterprises toward verifiable environmental impact neutrality directions.

2 Materials and methods

2.1 Case study

The agricultural company taken as a case study in this paper is named Arillo in Terrabianca (hereafter AriTer), and it is constituted by farms located in three different Municipalities in Tuscany (Italy). The core business of the company is wine production, but extra-virgin olive oil (evoo) is also marketed. At regional scale, the climate where the farms are located is typically Mediterranean, with rainy and cold winters, and dry and hot summers. Precipitation is concentrated in both autumn and spring, averaging 700 mm annually. The most productive farm is the one located in the municipality of Massa Marittima (hereafter Site C), with more than 600 hectolitres of wine and around 4,000 litres of extra-virgin olive oil (evoo) produced in 2022 (Figure 1). Site A (in the municipality of Radda in Chianti), which is mostly constituted by forest properties (not yet productive at the time this study was conducted), follows with around 500 hectolitres of wine, while Site B in the municipality of Pienza is the smallest one in terms of productive area, with only agricultural commodities delivered: ~750 kg olives (milled outside the farm, and the produced evoo transported to Site C), and ~30 tonnes of grape in 2022, which is usually sold as such in close markets. It is worth noting that the highest land use diversity of Site C is reflected in the production of several agricultural commodities that mainly serve as inputs for internal uses, mostly cereals, ~10 tons (data from 2022 retrieved from the organization).

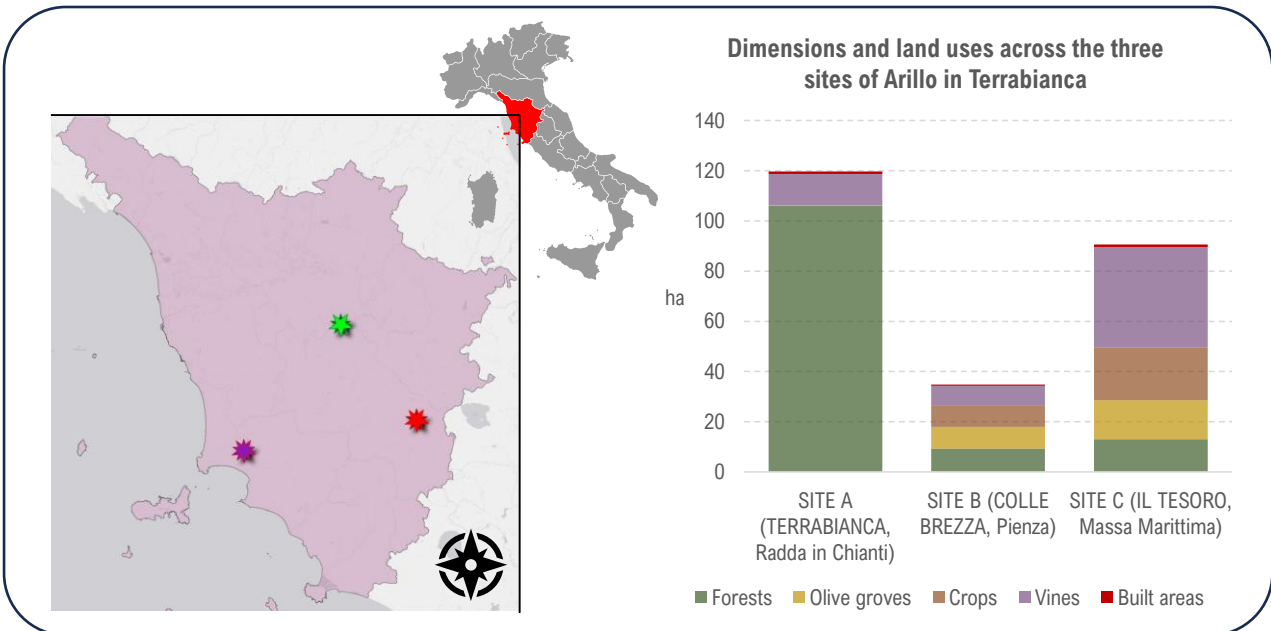


Figure 1 Characteristics and location of the three farms owned by Arillo in Terrabianca (company in Tuscany, Italy): Terrabianca (green star), Colle Brezza (red star), and Il Tesoro (purple star).

2.2 Implementation of the TREEIN model

Figure 2 shows the methodological phases carried out according to the stepwise TREEIN model (Varavallo et al., 2024). The use of certification systems is not mandatory, but highly recommended to ensure data quality, methodological transparency and results robustness. TREEIN essentially suggests following two distinct pathways of assessment: i) to assess the environmental footprint (through LCA-based approaches), and ii) to assess benefits associated with ecosystem service assessments (ESA). The further steps of implementation, results and dissemination of the model foresee the integration of the outcomes from the two assessment pathways.

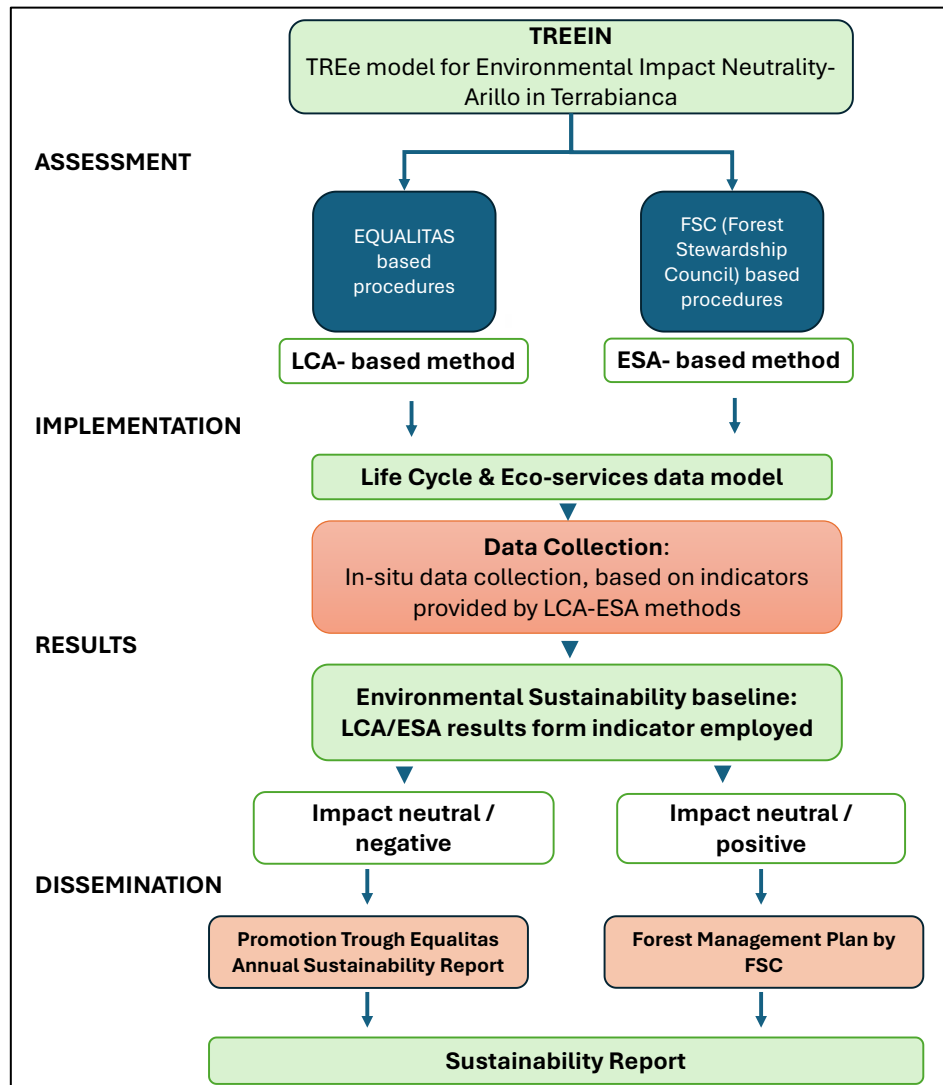


Figure 2 Flowchart of the methodological approach following the TREEIN model (Varavallo et al., 2024). LCA = life cycle assessment; ESA = ecosystem service assessment.

Concerning the environmental footprint analysis, the methodological procedure in this paper was aligned with the internationally recognised ISO standards for product-LCA (ISO, 2006a, 2006b), which describe the principles and application for LCA. Those standards constitute the basis for the ISO Technical Specification

116 (TS) for Organisational Life Cycle Assessment (O-LCA), i.e., ISO/TS 14072:2014 (ISO, 2014), which guided
117 the AriTer's life cycle model development and the identification of its input/output relationships with upstream
118 suppliers and downstream distributors for the main products, i.e., wine and evoo. From the O-LCA model,
119 several environmental impact indicators were calculated, among which carbon and water footprints (see
120 Section 2.3.1). These were further certified under the Equalitas scheme to enhance the robustness and
121 comparability of the negative environmental impact evaluation and monitoring.
122 In parallel, an ESA was performed in accordance with the FSC certification pathway for the forest's natural
123 capital, considering the potential for carbon uptake. (Section 2.6).

124 **2.3 Framework of the O-LCA**

125 Similarly to the product-LCA (ISO, 2006a, 2006b), the O-LCA methodological framework follows four
126 methodological phases: i) goal and scope definition, where the system boundaries for the analysis and the
127 reporting unit (replacing the so-called functional unit in LCA) are defined; ii) the life cycle inventory (LCI)
128 analysis, where physical input and output data are collected, classified and aggregated; iii) the life cycle impact
129 assessment (LCIA), which is used to quantify the potential environmental impacts of the organisation; and iv)
130 the life cycle interpretation, for report and critical review of the LCA results, including considerations of the
131 study limitations and results uncertainty, the relationship between the LCA phases, and the conditions for the
132 use of value choices and optional elements. Additional information concerning the LCA methodological
133 framework applied in this study is provided in SM1, Section S2.

134 **2.3.1 Definition of the scope and creation of the model**

135 According to the O-LCA framework setup for this study, the reporting unit of the model is the overall “Set of
136 agricultural activities in the three farms of Arillo in Terrabianca conducted over one representative year”, which
137 is the 2022 (year of data reference). Figure 3 shows the input and output flows, relationships and activities
138 underlying the O-LCA model of AriTer. Beside the LCI and LCIA performed for the reporting unit, thus
139 encompassing the whole set of activities of AriTer, a focus on the marketed products (wine and evoo) was
140 dedicated in the analysis defining specific functional units (FUs), i.e., “the 75 cl bottle of wine sold in the
141 market” and “the extra virgin olive oil bottled in one typical metal can of 1 L sold in the market”. Such further
142 definition was performed to enhance the results comparability, since most of the literature studies on wine
143 and/or evoo production LCAs use those FUs (Guerra et al., 2024; Marques et al., 2025; Rapa & Ciano, 2022)
144 As a consequence, with regard to the structure of the LCI model, the life cycle activities were divided, for both
145 wine and evoo, into three distinct macro-phases: “Upstream” (processes *from cradle-to field gate*); “Core”
146 (processes *from field gate-to farm gate*); and “Downstream” (processes *from farm gate-to cradle*) (Figure 3).
147 This subdivision and inventory framework aligned to the product category rules (PCRs) for wine and evoo,
148 and it was performed to allowing consistent comparisons of the results of this study with the existing literature
149 market products with competing environmental labels based on ISO 14025:2006 certification schemes.

Specifically, for the supply-chain of wine, the PCRs for goods falling under the UN CPC 2421 classification (“Wine of fresh grapes, whether or not flavoured; grape must”) were followed (EPD-International, 2024). Those PCRs were recently developed under the EPD® International System, as well as the PCRs of the other main products of the company, i.e., “olives” and “extra virgin olive oil”, the supply-chain model of which was adapted to the currently available PCRs for goods falling under the UN CPC 21537 classification (“Olive oil, crude, including virgin olive oil and its fractions”) (EPD-International, 2024).

The Upstream phase (Phase 1) captured cradle-to-gate agricultural activities for grape and olive cultivation, including raw material extraction, resource inputs (fertilizers and fuels), and field transport. The Core phase encompassed processing operations (Phase 2: winemaking and oil extraction/filtration) alongside bottling and packaging (Phase 3). Finally, the Downstream phase (Phase 4) addressed post-gate product distribution to wholesale and retail channels, as well as end-of-life packaging waste management, including recycling, recovery, and disposal.

To accomplish the need to adapt the calculation of the Carbon and Water Footprints of the wine supply-chain to the requirements of the Equalitas standard, the distribution of the life cycle activities in those cases was slightly modified, as explained in the SM1 (Section S3).

To create the LCI model, primary data collected from the company were supplemented by secondary data found in literature, which were further manipulated and entered within datasets defined specifically to represent the AriTer’s life cycle activities (those sketched in Figure 3). The process datasets were developed using OpenLCA v2.1, which is an open access LCA software tool with which the environmental impacts of the organisation and its production systems were then calculated. Impacts were calculated by applying pre-calculated characterisation factors related to the indicators recommended mainly by the *Environmental Footprint (EF) 3.1* method (ELPCA, 2026), with some integrations from other LCIA methods (further details on the assumptions made to select the characterisation factors are included in the SM1, S2.1). The impact category indicators selected for this study are listed below and additionally described in the SM1 (Table S1):

- Radiative forcing as Global Warming Potential (GWP), or Carbon Footprint;
- Stratospheric ozone depletion potential (ODP);
- Photochemical ozone creation potential (POCP);
- Particulate matter formation potential (PMFP);
- Acidification potential (AP);
- Eutrophication potential (EP);
- Comparative toxic unit for humans (CTUh);
- Comparative toxic unit for ecosystems (CTUe);
- Water consumption potential (WCP);
- Water deprivation potential for users (WSF);
- Abiotic resource depletion, fossil fuels (ADP-fossil);
- Abiotic resource depletion (ADP-ultimate reserves);
- Equivalent agricultural land occupation potential (ALOP).

187 In order to investigate aspects of GHG emissions responsibilities, for the Carbon Footprint assessment this
188 study was further informed by the GHG Protocol Corporate Accounting and Reporting Standard (Ranganathan
189 et al., 2004), which classifies a company's GHG emission into three 'Scopes'. In particular, Scope 1 were
190 considered as direct emissions of GHGs, i.e., emissions that came from sources owned or controlled by the
191 organization (e.g., heat generation from heating, as a result of natural gas combustion in the company's boilers;
192 emissions due to internal transportation and use of agricultural machinery; emissions related to fertilizer use,
193 etc.); Scope 2 were instead considered indirect emissions of GHGs of the first type, released from upstream
194 production sources of the electricity consumed by AriTer; finally, Scope 3 were indirect emissions of GHGs
195 of the second type, which included both upstream and downstream emissions from the system's processes and
196 were the result of the organization's core activities. However, those emissions originated from sources that
197 were not owned or controlled by the organization.

198 **2.3.2 Data collection and elaboration**

199 'Primary' data used for building the LCI model referred to the year 2022 and were collected in the period May-
200 2023-Sep 2023 through a questionnaire provided to the company and filled in with invoice data and
201 observation-based estimates. The overall quality of the primary data and its coverage is considered *high*, since
202 the company was able to complete all the pre-filled forms on life cycle activities and provide comments and
203 guidance useful for quantitatively estimating any unknown information. Only a small fraction of data (also
204 called 'secondary' data) were collected from the literature, while estimates based on observation by technical
205 experts on the farm (to generate so-called 'tertiary' data) were mostly geared towards clarifying doubts or
206 deciding how to allocate data provided in aggregated form (e.g., how to allocate diesel consumption between
207 viticulture and olive groves management). Further information is included in the SM1, Section 2.2.
208 To construct the life cycle network of the energy (such as electricity and diesel fuel) and material (e.g., water,
209 chemicals, glass, cardboard, ...) flows consumed by the company, average technology datasets were selected
210 from comprehensive and reliable databases nowadays available, such as ecoinvent v3.9.1 (Wernet et al., 2016)
211 and Agribalyse v3.1 (Cornelus et al., 2024). The full list of primary, secondary and tertiary data is provided in
212 spreadsheet format with comments and references to the original sources as SM2 to this paper.

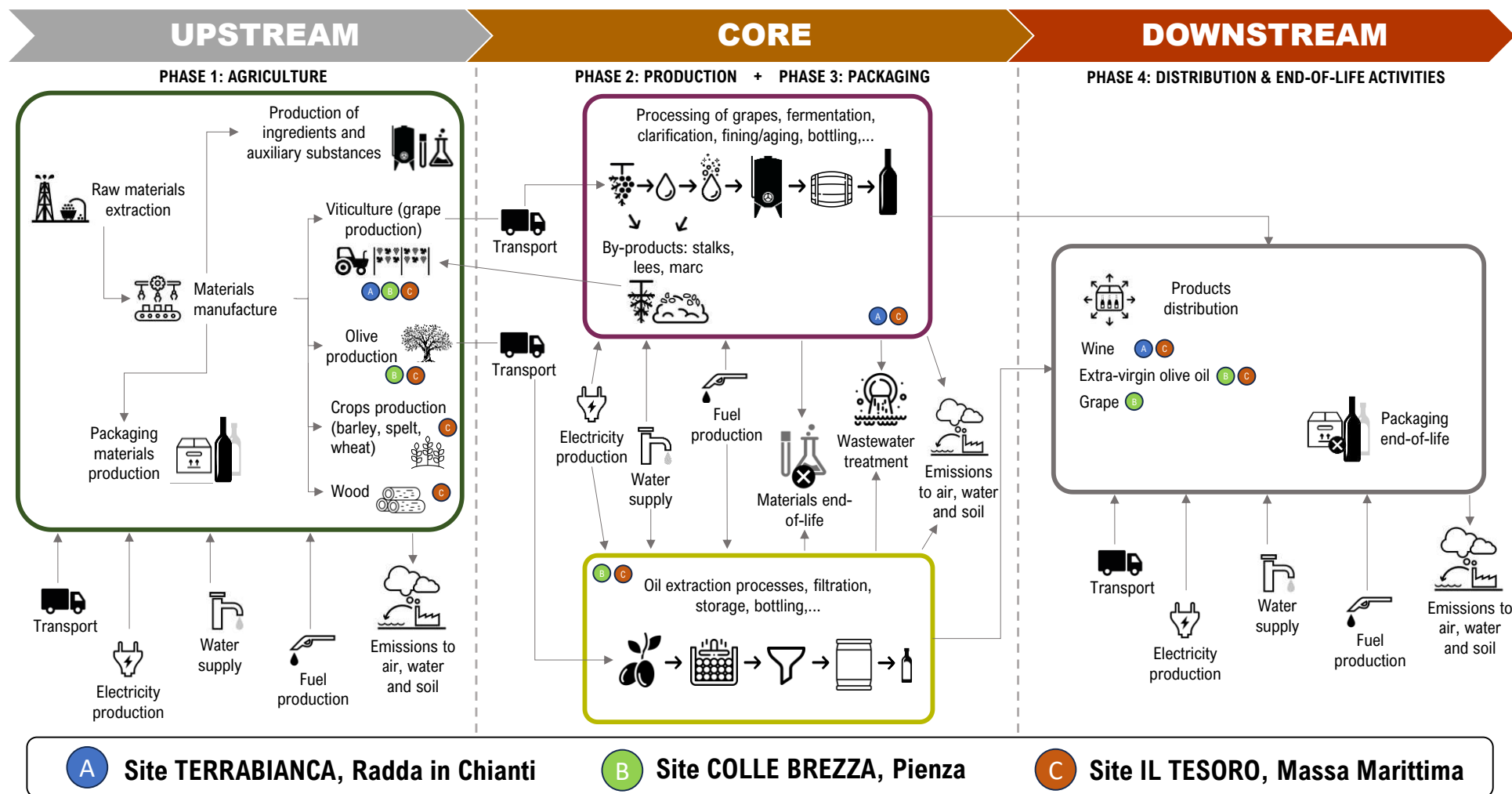


Figure 3 Life cycle diagram of Arillo in Terrabianca's production activities and product supply-chains across its three sites in Tuscany, Italy.

215 **2.4 Approach to account for ecosystem services**

216 According to TREEIN, the impact assessment of AriTer's operations also implied valuing the managed Natural
217 Capital and its potential, in terms of ecosystem services, to eventually investigate the balance between positive
218 and negative impacts generated by the company's wine and olive oil production.

219 Forests of AriTer are distributed across the three estate areas owned by the company and located in Pienza,
220 Massa Marittima, and Radda in Chianti. As shown in Figure 1 the total surface of Arillo's forests is around 130
221 hectares (105 ha in Radda in Chianti). The analysis of natural capital potential started from the results of on-
222 field surveys and related elaborations included in the Forest Management Plan (FMP) drawn up for the
223 company in accordance with Regional Law 39/00, and adapted to the FSC certification protocol commissioned
224 by AriTer (Saponeri et al., 2024).

225 More specifically, 108 sampling activities were conducted in Radda in Chianti, 10 ones in Pienza, and 7 ones
226 in Massa Marittima. For each sampling plot, a complete trestle was performed and the heights of some trees
227 belonging to the most representative diameter classes were measured. Additionally, incremental cores were
228 collected using a Pressler drill to determine the age of the stand and the increment. The collected data,
229 appropriately processed, enabled to determine the following dendrometric characteristics: number of trees
230 and/or number of stumps and/or number of rootstocks; basimetric area; wood provision (Saponeri et al., 2024).
231 Those instrumental dendrometric surveys were integrated with additional surveys, particularly on soils, to
232 determine the organic carbon stock in quantitative terms. The carbon stock calculation was done adopting 2019
233 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2019) and carbon
234 stocks were calculated using IPCC formulas (IPCC, 2019) employing field data relating to the forests under
235 study.

236 The snapshot of the current state conditions allowed for the development of scenarios on growth and variation
237 of the carbon stock based on different possible management choices made by the company, with a time horizon
238 of 10 years. In particular, an interventions plan was made for the sustainable management of the AriTer's forest
239 land, which included a variety of management interventions such as selective logging, thinning and clearing,
240 phytosanitary cutting and cultivation treatments (Saponeri et al., 2024). From this plan, an economic estimation
241 of the improvement in ecosystem services other than just carbon storage increase could also be performed.
242 This complemented the physical assessment of carbon stock and uptake. In particular, the total economic value
243 of carbon storage, healthy soil, thriving biodiversity, and recreation was estimated as the equivalent of the total
244 monetary investment foreseen by AriTer to perform all the interventions planned in the FSC management plan.

245 **3 Results and Discussion**

246 **3.1 Assessment and interpretation of negative impacts**

247 **3.1.1 Life cycle inventory indicators: a synthesis**

248 A set of selected indicators of resource/product consumption and waste release, disaggregated by major life
249 cycle activity and site of production, are reported in Table 1. As it can be observed, the highest scores (with
250 relative contributions in between 55% and 99%) concern Site C in Massa Marittima (the biggest one both in
251 terms of production and land occupation). Nevertheless, Site A shows a relevant contribution in terms of
252 electricity consumption, especially for the operations of wine making and packaging. This is well reflected in
253 terms of performance when looking at the energy use per bottle of wine produced. In contrast, Site A performs
254 better in terms of water consumption and fossil fuel use during the on-field operations, while Site B presents
255 a relatively high consumption of chemicals.

Table 1 Selected indicators from the life cycle inventory exercise, with scores distributed by production site.

Indicator, by life cycle activity	Unit	Total (annual)	Site A	Site B	Site C
Electricity consumption	kWh	139,652	49.60%	3.20%	47.10%
on field (outdoor) activities		29,389	15,041	4,534	9,814
process (indoor) activities		110,263	54,277	0	55,986
Fossil fuel consumption	l	42,122	33.00%	7.30%	59.70%
on field (outdoor) activities		30,920	2,686	3,080	25,154
process (indoor) activities		11,202	11,202	0	0
Freshwater consumption (direct)	m³	8,717	35.40%	4.90%	59.70%
on field (outdoor) activities		5,141	34	425	4,682
process (indoor) activities		3,576	3050	0	526
Use of chemicals	t	256.4	3.80%	39.40%	56.80%
on field (outdoor) activities		255.3	9.5	101	144.8
process (indoor) activities		1.1	0.3	0	0.8
Waste production	t	704.2	0.40%	0.00%	99.60%
for recycling		2.7	0.9	0	1.8
not for recycling		701.5	2.1	0.1	699.4
Outputs, for sale (market products)					
Grape, at farm gate	t	203.6	33.50%	14.40%	52.00%
Wine (bulk), at winery gate	l	113,172	43.50%	-	56.50%
Bottles of wine	nr	131,429	35.20%	-	64.80%
Olives, at farm gate	t	27.3	-	2.80%	97.20%
Extra-virgin olive oil, bottled	l	3,995	-	1.40%	98.60%
Key Performance Indicators <i>(the lower, the better...)</i>		Organisation scale	<i>specific for Site A</i>	<i>specific for Site B</i>	<i>specific for Site C</i>
Use of electrical energy*	kWh/bottle	0.8	1.17	-	0.66
Water embodied in 1l of wine ^λ	l _{water} /l _{wine}	77	62.6	-	81.5
Use of fossil fuels**	l/ha	271	214.9	123.2	328.3
Use of freshwater for irrigation**	m³/ha	45.1	2.7	17	61.1
Use of chemicals**	t/ha	2.2	0.8	4	1.9

* only the electricity consumptions in process (indoor) activities for wine making and packaging have been considered

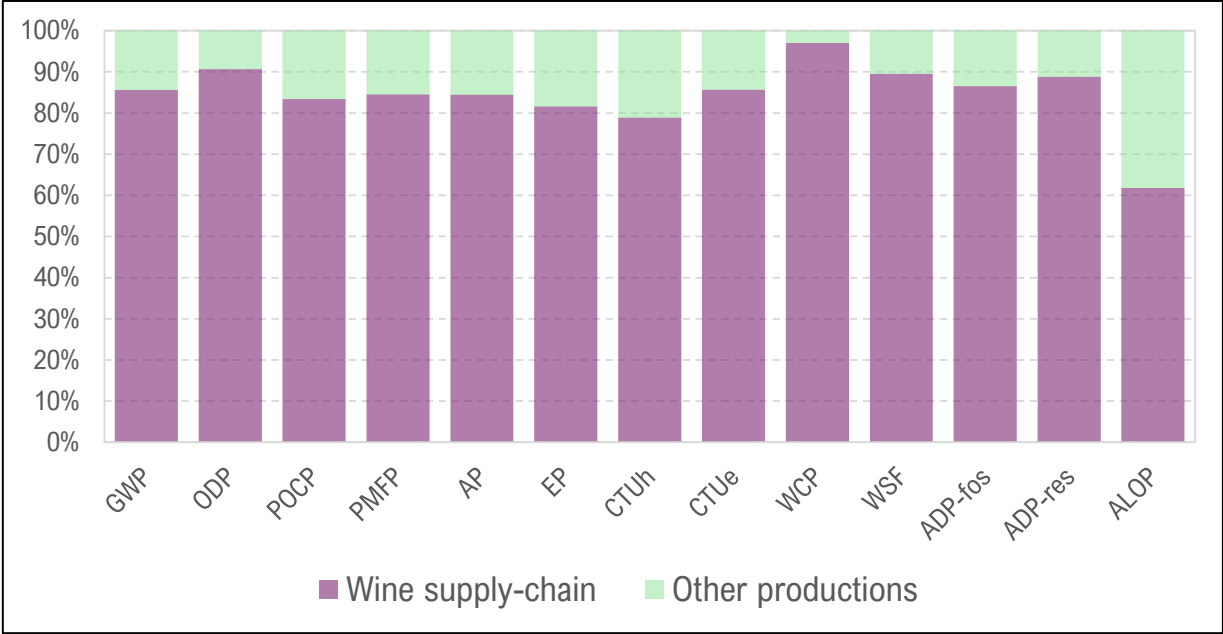
^λthis value includes all the direct and indirect consumptions of water

** only the fossil fuel consumptions and use of freshwater and chemicals on field (for outdoor activities) have been considered, accounting for the productive agricultural land use (olive groves, crops and vines): Site A = 12.5 ha; Site B = 25 ha; Site C = 76.6 ha

257 3.1.2 Environmental footprint and hotspots of the company and its products

258 First, the extent of the environmental footprint associated with all the activities of the company was estimated
 259 according to the impact category indicators listed in Section 2.3.1 and described in Table S1 of the SM1. The
 260 wine supply-chain determines most of the company's impact in absolute terms, with values in between 62%
 261 to 97% of contribution to the total score for each indicator when calculated on an annual basis and considering

262 the three sites together (Figure 4). This is not surprising for two reasons: AriTer produces a relatively small
 263 amount of evoo, mainly in one out of three sites, and most of the activities are dedicated to grape and wine
 264 production; in addition, there is no use of synthetic chemicals (the company is certified as “organic”) or water
 265 resources for irrigation in the olive groves, which further reduces the environmental load for this production
 266 line.
 267



268
 269 **Figure 4** Relative contribution of the wine supply-chain to the overall environmental impact of AriTer; GWP = Global
 270 Warming Potential, ODP = stratospheric ozone depletion potential, POCP = photochemical ozone creation potential,
 271 PMFP = particulate matter formation potential, AP = acidification potential, EP = eutrophication potential, CTUh =
 272 comparative toxic unit for humans, CTUe = comparative toxic unit for ecosystems, WCP = water consumption
 273 potential, WSF = water scarcity footprint, ADP-fos = abiotic resource depletion, fossil fuels, ADP-res = abiotic resource
 274 depletion, ALOP = equivalent agricultural land occupation.

275
 276 Figure 5 shows the contribution of each life cycle stage to some environmental impact scores for categories
 277 that are considered “key” for the interpretation of the environmental footprint related to the use of fuels (GWP,
 278 PMFP, AP, CTUh), water (WSF) and chemicals (AP, EP, CTUe).
 279 From an initial overview of these results, it is worth noting that the farm stage (Phase 1) and the operations of
 280 bottling and packaging (Phase 3) represent the two phases where most of the environmental footprint is
 281 concentrated, with values around 71% and 19%, respectively, considering the average distribution of all the
 282 analysed indicators. While the contribution to the environmental footprint distributed in the other phases
 283 averages around 6% and 4% for the winery/milling activities (Phase 2) and the product distribution and end-
 284 of-life of the packaging waste (Phase 4), respectively.
 285

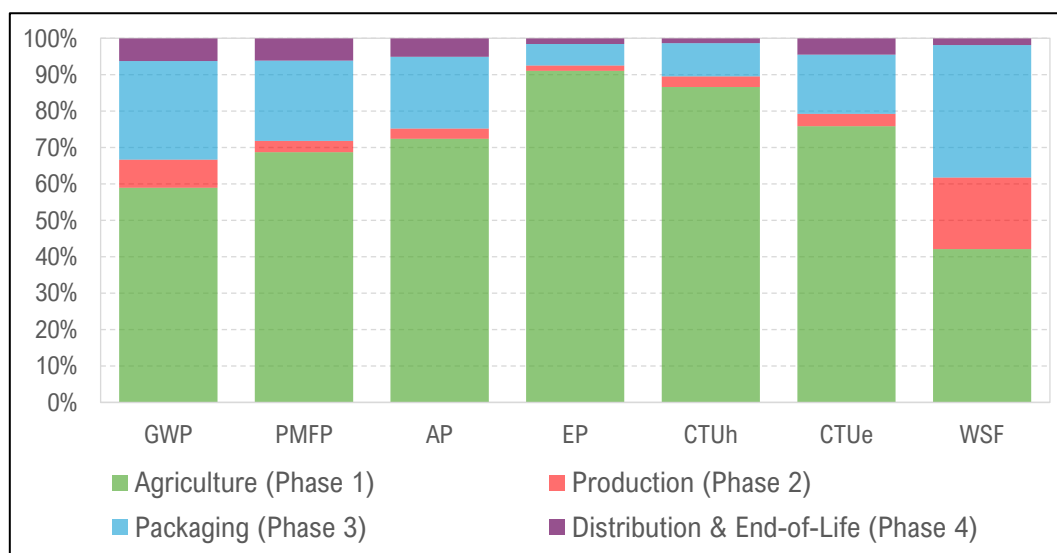


Figure 5 Relative importance of selected indicators when looking at each phase of the wine life cycle. Phases from 1 to 3 include the activities with greater/direct management/decision-making control or responsibility by the company. GWP = global Warming Potential, PMFP = particulate matter formation potential, AP = acidification potential, EP = eutrophication potential, CTUh = comparative toxic unit for humans, CTUe = comparative toxic unit for ecosystems, WSF = water scarcity footprint.

Nevertheless, a relevant portion of the impact occurs outside the company's territorial boundaries, and it is to be attributed to the effect of environmental stressors (i.e., resource extractions, land uses, release of pollutants) recorded in the background operations. It should be noted in fact that the impact may spatially and temporally occur far from the sites of production, as it is for the case of GHG emissions and the responsibility that AriTer may have for them.

The baseline carbon footprint of the company for the year 2022 amounts to approximately 450 t CO₂-eq. and is estimated considering the whole life cycle of the company from cradle to grave. As illustrated in Figure 6, the distribution of Scope 1, Scope 2 and Scope 3 GHGs across the production sites and phases of AriTer reflects the impact responsibility for the carbon footprint, and highlights where carbon mitigation and management plan should be put in place.

In short, results from the carbon footprint analysis reveal that around 70% of AriTer's greenhouse gas emissions are of *indirect* type, particularly of Scope 3 (~58%). Thus, while most of the carbon footprint performance can be attributed to external factors, the company has relatively low opportunities for improvement: it owns the potential control to reduce its emissions in processes that contribute for less than 1/3 to the overall life cycle impact load (e.g., activities of Phase 1 in the three sites). Most of the GHG emissions are of Scope 2 (~12% of the total) and Scope 3 (~58% of the total), which means that the direct GHGs release within the territorial boundaries of the company (under its control) does not overcome 140 t CO₂-eq. per year, mostly due to diesel combustion and manure direct emission as confirmed by the literature (Agnusdei et al., 2024; Bosco et al., 2011; Schmidt Rivera et al., 2017).

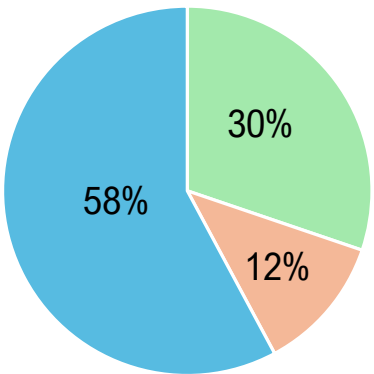
Most of the carbon emission load is to be attributed to the wine supply-chain (~86%), while the production of extra-virgin olive oil would contribute to around 12%. The remaining portion (around 10 t CO₂-eq.) is

314 essentially due to the agricultural and silvicultural activities conducted in the site of Massa Marittima, which
315 do not concern olive groves and vines management.

316 Focusing on the FU scale of the AriTer's products and considering a "from cradle to gate" system boundary,
317 the impact of AriTer's wine is slightly higher than the average value observed in recent comparable literature.
318 While the carbon footprint per bottle of AriTer's wine is around 2.1 kg CO₂-eq. per 0.75 L, D'Ammaro et al.
319 (2021) estimate the carbon footprint of wine ranging between 0.9 and 1.9 kg CO₂-eq. for the same FU.
320 However, when the FU of single site is considered, Site A in Radda in Chianti results in ~1.4 kg CO₂-eq, and
321 the carbon footprint per bottle delivered from Site C in Massa Marittima is ~2.8 kg CO₂-eq. When looking at
322 the extra-virgin olive oil's supply-chain, the carbon footprint of AriTer's products is also higher than
323 comparative values for central Italy, since it shows scores of around 13 kg CO₂-eq. per litre of product against
324 literature values ranging between 4.4 and 10.1 kg CO₂-eq. (Pattara et al., 2012).

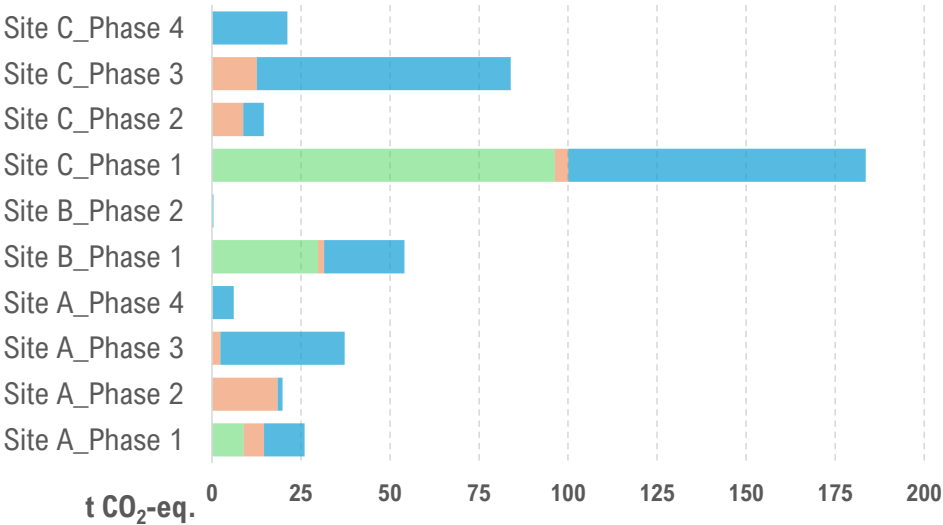
325 To objectively validate these observations at the product scale, a detailed and specific comparison of the tools,
326 indicators and data used in those, and other literature studies should be carried out, since the methodological
327 differences can be a factor of wide variability for the sensitivity of models and results in LCA. For example,
328 when compared with impact scores from recent Environmental Product Declaration (EPD) studies based on a
329 similar methodological framework followed in the present study – despite the two products are not perfectly
330 comparable in terms of market and type –, it is observed that the carbon footprint of AriTer's wine is very
331 similar to that estimated for the prosecco wine of Bortolomiol company (Neri & Pulsinelli, 2021). While as far
332 as extra virgin olive oil is concerned, the company Monini declares a carbon footprint around 34% lower than
333 that estimated for AriTer's evoo (Massari & Canzanelli, 2023). Such a difference is mainly due to the
334 conservative assumption of allocating 25% of the total resource consumption to the evoo supply-chain, which
335 is likely a too generous estimation that largely influences the final impact score (in the model, around 60% of
336 the carbon footprint of AriTer's evoo is due to the use of diesel).

Categories of GHG emissions
total Carbon Footprint = 447 t CO₂-eq.



■ SCOPE 1
■ SCOPE 2
■ SCOPE 3

Distribution of the carbon footprint



Gravity analysis

Site A_Phase 1 - Agricultural and agroforestry activities	Diesel consumption	50%
	Electricity consumption	22%
	Use of infrastructure materials, steel/iron	8%
	Emissions, from the use of manure	7%
	Other inputs (with contrib. <3%)	13%
Site A_Phase 2 - Operations for the production of wine and other products/services	Electricity consumption	92%
	Use of materials, for wine making	4%
	Other inputs (with contrib. <3%)	4%
Site A_Phase 3 - Products packaging operations	Primary packaging	89%
	Electricity consumption	6%
	Secondary packaging	4%
Site A_Phase 4 - Products distribution and end-of-life operations of materials packaging	Transport of wine, lorry 16-32t	59%
	Transport of wine, container ship	30%
	Waste treatment processes	11%
Site B_Phase 1 - Agricultural and agroforestry activities	Emissions, from the use of manure	40%
	Diesel consumption	28%
	Use of infrastructure materials, steel/iron	24%
	Electricity consumption	3%
	Other inputs (with contrib. <3%)	5%
Site B_Phase 2 - Products packaging, distribution and hypothetical end-of-life	Transport of grape, lorry 7.5-16t	42%
	Production of aluminium cans, for evoo	30%
	Treatment of hazardous waste, incineration	13%
	Extra virgin olive oil production, at mill	8%
	Treatment of MSW, incineration	4%
	Transport of evoo, light commercial vehicle	3%
Site C_Phase 1 - Agricultural and agroforestry activities	Diesel consumption	68%
	Emissions, from the use of manure	16%
	Use of infrastructure materials, steel/iron	8%
	Other inputs (with contrib. <3%)	7%
Site C_Phase 2 - Operations for the production of wine and other products/services	Electricity consumption	61%
	Extra virgin olive oil production, at mill	17%
	Use of materials, for wine making	9%
	Other inputs (with contrib. <3%)	13%
Site C_Phase 3 - Products packaging operations	Primary packaging	83%
	Electricity consumption	15%
	Secondary packaging	2%
Site C_Phase 4 - Products distribution and end-of-life operations of materials packaging	Transport of wine, container ship	50%
	Transport of wine, lorry 16-32t	42%
	Transport of grape, lorry 7.5-16t	6%
	Waste treatment processes	3%

Figure 6 (A) Overview of the distribution of Scope 1, Scope 2 and Scope 3 GHG emissions associated with AriTer’s activities and its life cycle stages (the three production sites have been aggregated for simplicity). (B) Gravity analysis is shown for processes contributing more than 3% to the carbon footprint in each phase.

340 Finally, the environmental footprint analysis (Table 2) highlights that the agricultural activities in Massa
341 Marittima (Phase 1, Site C) generate the highest potential impacts among all the life cycle activities of the
342 companies in its three sites, with contributions that range between ~27% and ~65% to the total impact in each
343 environmental impact category. This is mainly due to relatively high rates of diesel consumption, which reflects
344 inefficient uses of this resource. A reason for this is associated with the adverse meteorological conditions in
345 the reference year of the analysis, which brought the company to increase the number of treatments and
346 operations by tractor on the field. Such a reason may also justify the relatively high consumptions of irrigation
347 water observed in Site C, represented by more than 60 m³ of water use per hectare (around 4 times more than
348 in Pienza, Site B, and around 22 times more than in Radda in Chianti, Site A). Other relevant hotspots of the
349 life cycle of AriTer are associated with the consumption of electricity (the least efficient phase being the
350 production of wine in Site A) and by the upstream production of glass used for the bottles (this being a common
351 issue observed in any life cycle of wine).

352 A water footprint analysis was conducted in parallel to the carbon footprint one to provide the company with
353 quantitative environmental impact figures in compliance with the requirements of the Equalitas certification
354 scheme for the wine supply-chain of organisation. The analysis of water footprint indicators, with regard to
355 the ecotoxicity indicator, do not reveal specific critical issues related to the use of plant protection products to
356 protect vines against fungal and insect attack. The actual magnitude of water footprint impacts is hardly
357 measurable in absolute terms without any previous reference. Nevertheless, a comparison with literature values
358 from published sustainability reports of Equalitas certified companies highlights that Arillo in Terrabianca
359 generally places below the average for most of the impact indicators and life cycle phases (references and data
360 provided in Table S4 in the SM1).

361
362

Table 2 Environmental footprint of the company at the baseline year 2022; distribution of the impact scores across sites and main life cycle stage. Blue shade means lower contribution to overall impact, red shade higher share of impacts.

Environmental impact category	Impact characterisation indicator	Unit	Site A - Radda in Chianti				Site B - Pienza		Site C - Massa Marittima				Total
			Phase 1	Phase 2	Phase 3	Phase 4	Phase 1	Phase 2	Phase 1	Phase 2	Phase 3	Phase 4	
Carbon Footprint	Radiative forcing as Global Warming Potential (GWP)	t CO ₂ eq.	5.8%	4.4%	8.3%	4.7%	12.1%	0.1%	41.1%	3.3%	18.8%	1.4%	447
Ozone depletion	Stratospheric ozone depletion potential (ODP)	g CFC-11 eq.	15.5%	5.0%	9.8%	1.4%	7.8%	0.1%	29.6%	4.3%	21.8%	4.6%	10
Photochemical ozone formation	Photochemical ozone creation potential (POCP)	kg NMVOC eq.	6.9%	2.1%	6.2%	1.7%	9.2%	0.0%	49.4%	2.9%	13.5%	8.1%	2841
Fine particulate matter formation	Particulate matter formation potential (PMFP)	kg PM _{2.5} eq.	5.4%	1.8%	7.0%	1.0%	16.3%	0.0%	47.0%	1.3%	15.1%	5.1%	1120
Acidification	Acidification potential (AP)	kg SO ₂ eq.	4.8%	1.6%	6.2%	0.8%	21.5%	0.0%	46.1%	1.2%	13.5%	4.2%	4241
Freshwater eutrophication	Eutrophication potential (EP)	kg PO ₄ ³⁻ eq.	4.5%	0.8%	1.9%	0.3%	32.4%	0.0%	54.2%	0.6%	4.0%	1.3%	2309
Human toxicity	Comparative toxic unit for humans (CTUh), carcinogenic	CTUh	10.4%	1.6%	3.2%	0.5%	26.2%	0.1%	48.3%	1.4%	6.7%	1.7%	0.0006
	Comparative toxic unit for humans (CTUh), non-carcinogenic	CTUh	11.5%	1.8%	2.8%	0.3%	9.7%	0.0%	65.5%	1.2%	6.3%	1.0%	0.0160
Freshwater ecotoxicity	Comparative toxic unit for ecosystems (CTUe)	CTUe	11.9%	1.7%	5.2%	1.0%	19.2%	0.1%	44.8%	1.8%	11.1%	3.4%	4207209
Water use	Water consumption potential (WCP)	L	2.0%	19.8%	11.8%	0.1%	5.3%	0.0%	45.9%	6.5%	8.3%	0.4%	12138
Water scarcity	Water deprivation potential for users (WSF)	m ³ eq.	7.5%	11.7%	10.7%	0.4%	7.8%	0.1%	26.9%	7.9%	25.7%	1.4%	93838
Fossil resource use	Abiotic resource depletion, fossil fuels (ADP-fossil)	GJ	6.0%	5.9%	10.1%	1.5%	7.4%	0.1%	36.6%	4.3%	22.9%	5.3%	5243
Minerals and metals resource use	Abiotic resource depletion (ADP-ultimate reserves)	g Sb eq.	8.5%	7.4%	6.8%	0.5%	11.0%	0.0%	42.6%	4.4%	17.0%	1.7%	2742
Land use (agricultural)	Equivalent agricultural land occupation potential (ALOP)	m ² a crop eq.	3.1%	1.3%	12.6%	0.3%	7.1%	0.0%	51.8%	1.4%	21.8%	0.7%	58692

Legend:

SITE A_PHASE 1 - AGRICULTURAL ACTIVITIES (GRAPE PRODUCTION)
SITE A_PHASE 2 - OPERATIONS FOR THE PRODUCTION OF WINE
SITE A_PHASE 3 - WINE PACKAGING OPERATIONS
SITE A_PHASE 4 - WINE DISTRIBUTION AND END-OF-LIFE OPERATIONS OF MATERIALS PACKAGING
SITE B_PHASE 1 - AGRICULTURAL ACTIVITIES (GRAPE AND OLIVES PRODUCTION)

SITE B_PHASE 2 - EXTRA-VIRGIN OLIVE OIL PRODUCTION, PACKAGING, DISTRIBUTION AND END-OF-LIFE
SITE C_PHASE 1 - AGRICULTURAL AND AGROFORESTRY ACTIVITIES (GRAPE, OLIVES, WOOD AND CROPS)
SITE C_PHASE 2 - OPERATIONS FOR THE PRODUCTION OF WINE AND EXTRA-VIRGIN OLIVE OIL
SITE C_PHASE 3 - PRODUCTS (WINE AND EXTRA-VIRGIN OLIVE OIL) PACKAGING OPERATIONS
SITE C_PHASE 4 - PRODUCTS DISTRIBUTION AND END-OF-LIFE OPERATIONS OF MATERIALS PACKAGING

363

3.1.3 Scenario analysis

This section presents the preliminary evaluation of possible scenarios for environmental management and performance improvement of the overall AriTer's life cycle. More specifically, Figure 7 compares the environmental impact scores of the “business-as-usual” scenario (i.e., O-LCA results reported in Table 2) with those estimated for a “realistic future scenario”. These are practical changes that can be hypothetically implemented directly by the organisation's management according to future company sustainability planning. Ultimately, the potential impact scores associated with the construction, in Site C, of an artificial lake of 30,000 m³ of water capacity is also estimated in order to enrich information about the actual environmental impact of the future scenario. To estimate the impact of this latter, data from a recent literature study (Asadollahfardi et al., 2023) were used and adapted to the O-LCA model of AriTer (see also Table S6 in the SM1).

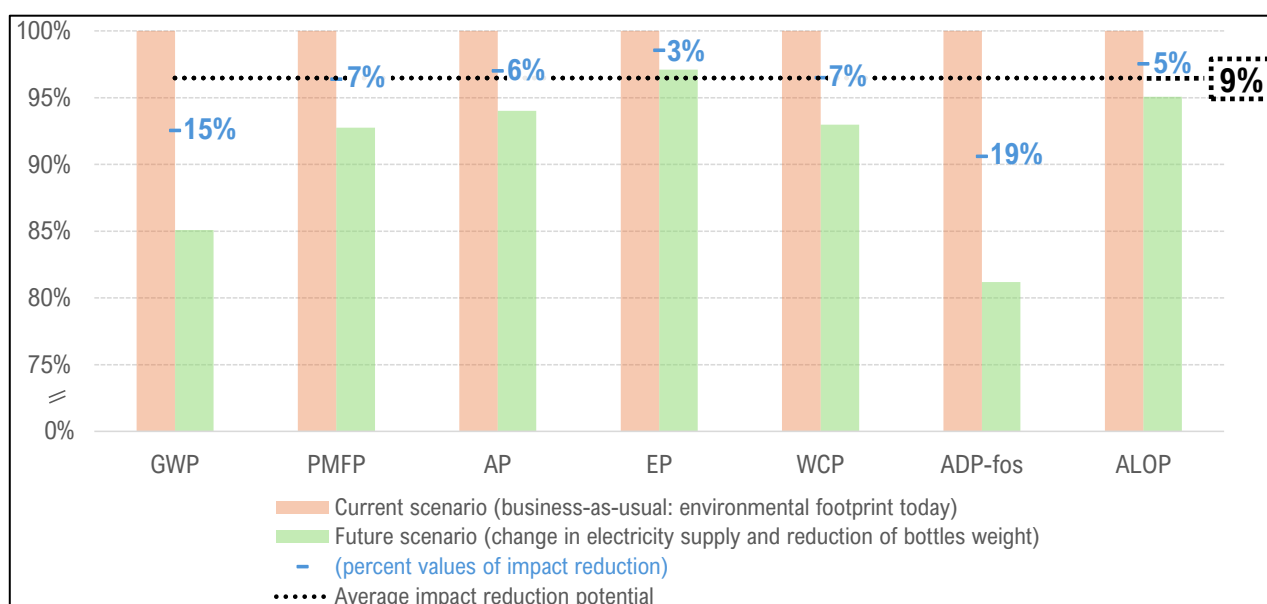


Figure 7 Comparison of the future with the current scenario of environmental footprint for selected impact category indicators; reduction impact scores are reported in %. GWP = global Warming Potential, PMFP = particulate matter formation potential, AP = acidification potential, EP = eutrophication potential, WCP = water consumption potential, ADP-fos = abiotic resource depletion, fossil fuels, ALOP = equivalent agricultural land occupation potential.

Figure 7 shows that the AriTer system has the long-term capacity to reduce its current carbon footprint by around 15%, which would correspond to an amount of almost 70 t CO₂-eq. avoided (~38% of which to be attributed to the reduction in bottle weight and the remaining ~62% to the use of PV electricity). As detailed in the complementary avoided impacts matrix (Table 3), the impact reduction among all these environmental footprint indicators may reach even high scores, such as in the case of Phase 2 in Site A (more than 70% of potential reduction of the indicators of global warming and fossil resource scarcity). On average across the sites and phases, however, the environmental footprint reduction potential is around 9% (Figure 7).

388

389 **Table 3** Matrix of avoided impact scores obtained after applying the impact mitigation measures in the prospective
 390 scenario of the O-LCA model (= difference between the impact scores outlined in Figure 7); red shade means lower
 391 contribution to reduce the environmental impact; green shade means higher contribution.

Phases by site of Arillo in Terrabianca's life cycle	GWP	PMFP	AP	EP	WCP	ADP-fos	ALOP
Site A_Phase 1 - Agricultural and agroforestry activities	-17.3%	-4.6%	-5.4%	-3.4%	-26.4%	-22.0%	-6.5%
Site A_Phase 2 - Operations for the production of wine and other products/services	-72.4%	-44.6%	-57.4%	-34.6%	-8.5%	-76.7%	-50.4%
Site A_Phase 3 - Products packaging operations	-27.0%	-24.4%	-25.2%	-19.0%	-7.8%	-27.4%	-8.6%
Site A_Phase 4 - Products distribution and end-of-life operations of materials packaging	-0.1%	0.0%	0.0%	-0.1%	-0.3%	0.0%	-0.1%
Site B_Phase 1 - Agricultural and agroforestry activities	-2.5%	-0.5%	-0.3%	-0.2%	-3.0%	-5.3%	-0.8%
Site B_Phase 2 - Products packaging, distribution and hypothetical end-of-life	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Site C_Phase 1 - Agricultural and agroforestry activities	-1.6%	-0.3%	-0.3%	-0.2%	-0.7%	-2.3%	-0.3%
Site C_Phase 2 - Operations for the production of wine and other products/services	-47.6%	-29.0%	-38.4%	-23.3%	-12.5%	-49.9%	-22.1%
Site C_Phase 3 - Products packaging operations	-32.0%	-25.8%	-27.1%	-22.5%	-31.3%	-33.1%	-11.5%
Site C_Phase 4 - Products distribution and end-of-life operations of materials packaging	0.0%	0.0%	0.0%	0.0%	-0.1%	0.0%	0.0%

392

393

394 It should be noted that these results are not time-dependent and do not incorporate feasibility or cost-benefit
 395 analyses, as the implementation of mitigation measures can range from immediate to gradual. Nevertheless,
 396 the analysis offers preliminary estimates regarding the scale of environmental footprint reductions achievable
 397 by Arillo in Terrabianca. Concerning the water footprint, implementing an artificial lake at Site C for irrigation
 398 would help mitigate the company's impact on freshwater depletion. However, beside avoiding well-water
 399 extraction, an artificial lake can generate environmental trade-offs that shall be take into account. For example,
 400 literature indicates that the construction of a lake with a 5 million m³ capacity may be responsible for the
 401 emission of more than 100 kt CO₂-eq. and 650 t SO₂-eq., among others (Asadollahfardi et al., 2023). Using
 402 these literature figures, a linear calculation was applied to estimate the impacts of a possible reservoir
 403 implemented at Site C with an equivalent 0.6% capacity. Table 3 details these findings, derived by applying
 404 the ratio 30,000/5,000,000 to the values in Table S7 (SM1). Assuming a minimum 100-year lifespan, the
 405 resulting annual carbon footprint for the lake is approximately 6 t CO₂- eq.

406 3.2 Assessment and interpretation of positive impacts

407 3.2.1 Estimation of the carbon stock, annual uptake and emissions balance

408 Table 4 details timber provision (biomass), projected growth, and planned harvests for AriTer, categorized by
 409 forest type and expressed in tons of carbon and CO₂ equivalent. The properties contain a timber volume of

approximately 12,300 m³. Although certain areas peak above 300 m³ha⁻¹, the average provision is assessed at 97 m³ha⁻¹. Total stored carbon, including canopy and root systems, is estimated at 7,200 tons, which are approximately 26,316 t CO₂ equivalent stored in AriTer's forest ecosystems. Considering the observed biomass growth of about 3.8%, for the 127 hectares of forest cover of AriTer this means approximately 989 t CO₂-eq. sequestered per year). Results therefore reveal a favourable forest profile with medium to high timber provision, suggesting strong soil fertility and good ecosystem conditions. Nevertheless, only five soil samples from the AriTer Site B forests were collected (Saponeri et al., 2024), which is certainly a not comprehensive and representative set of samples for the entire company. However, it can give an overview of the state of the art: the average soil organic carbon (SOC) value is 1.30 %. By upscaling this data to the entire surface of Site A, the carbon stock conserved in the managed forest soil of the company would reach around 19,000 t CO₂-eq.

Table 4 Summary of the forest surveys for the AriTer's natural capital. Different forest types, extensions, wood provisions, and current and future growth are reported.

Forest types	Surface (ha)	Current wood provision (m ³)	Current growth (m ³ /ha/year)	Annual growth (m ³ /year)	Growth in the next decade (m ³)	Harvest volume in 10 years (m ³)
Acidophilous chestnut grove	13	1,558	52	68	675	-710
Sub-Mediterranean acidophilous Turkey oak woodland with heathers	49	5,144	66	180	1,804	-1,595
Mesoxerophilous Turkey oak woodland	4	193	7	16	161	0
Typical holm oak woodland with <i>Viburnum tinus</i>	8	439	6	16	155	-90
Mesophilous hop hornbeam woodland on siliceous substrates	12	1,988	36	44	438	-738
Hill pinewood of stone pine and downy oak with blackthorn shrubs	5	436	8	19	195	0
Neutro-acidocline black pine woodland	1	140	4	3	29	-56
Acidophilous downy oak and Turkey oak woodland	29	1,948	30	58	583	-529
Mesophilous downy oak and Turkey oak woodland	5	275	4	10	98	-30
Robinia woodland	1	194	14	8	84	-58
Total	127	12,314	227	422	4,222	-3,806
Stock of carbon (t C)		7,177		270	2,698	-2,432
Equivalent stock of carbon (t CO ₂ eq)		26,316		989	9,893	-8,918

The TREEIN based analysis carried out in this paper demonstrates with quantitative evidence how a company owning natural capital can pursue a process to reach environmental impact neutrality with an in-setting approach.

Focusing on GHG emissions released at organizational scale, data concerning the analysis of carbon stock and annual uptake of AriTer can be integrated and compared with the carbon footprint results of the present study. The integration of life cycle and ES assessments within the TREEIN model enables a comprehensive evaluation of environmental impacts and management opportunities. Focusing on climate change mitigation, the analysis shows that, excluding soil organic carbon, AriTer's natural capital has an annual carbon

sequestration capacity approximately twice as large as the company's total life cycle greenhouse gas emissions, including both direct and indirect emissions ($\approx 450 \text{ t CO}_2\text{-eq. yr}^{-1}$). However, some considerations are necessary. While theoretically the forest maintains a constant growth rate of 422 m^3 per year, the average age of the forest canopy ranges between 20 and 50 years. If sustainable silvicultural interventions planned the FMP (Saponeri et al., 2024) are carried out, a punctual harvest of wood biomass will lead to an exponential increase in growth from the first year, with a recovery of lost biomass and a further increase in the short term. Collalti et al. (2018) examined the response of a forest stand to management interventions of varying intensity, comparing carbon sequestration dynamics over time among unmanaged stands, heavily thinned stands, and lightly thinned stands managed under sustainable practices. According to these observations, AriTer would fall under the "light thinning" case or, if no management is applied, under the "unthinned" profile. However, once maturity is reached, as mentioned, the growth rate would tend to level off. It is worth noting that a significant portion of the carbon in forests is stored in the soils. It is expected that a careful management of AriTer's forests as planned in the FMP will lead to a gradual accumulation of carbon in the soils as well.

3.2.2 Valuation of AriTer's natural capital

Estimated FMP intervention costs (cutting, preparation, and removal) amount to $\sim 5,000 \text{ € ha}^{-1}$. Given a 30% harvest rate and a standing timber value of 13.50 € m^{-3} , the resulting return of $\sim 500 \text{ € ha}^{-1}$ may create a net negative economic impact. Consequently, total 10-year expenditures are projected at 550,000 €, with only 55,000 € in timber revenue, and these interventions are considered beneficial for improving compensatory ecosystem services, both internally (company in-setting) and externally (third-party off-setting). The carbon stock of over 26,300 t CO_2 eq. will be maintained throughout the FMP, as removals remain below the expected biomass increase. Beyond the tenth year, the shift toward high-stand forest management is expected to further enhance biomass accumulation. The estimated value using a price of CO_2 equal to 77 €/t (<https://www.sendeco2.com/it/prezzi-co2>; last access: August 31, 2026) would be around 2 M€ for the current stock, which will be maintained unchanged over the 10-year term of the plan. This value represents a theoretical estimate derived from carbon market prices. Given the volatility of carbon markets and the absence of eligibility conditions for carbon credit generation in the assessed forests, the estimated value should be interpreted as a theoretical indicator rather than a realizable market value. Nevertheless, it offers a useful proxy for the economic importance of this natural asset and for the investments required to maintain and enhance its ecosystem functions. For the remaining FSC-certified ES related to soil conservation, biodiversity, water regulation, and cultural heritage, no established markets currently exist. Their value can therefore be estimated indirectly through the costs associated with the management and conservation actions necessary to sustain or improve their provision.

3.3 Environmental sustainability interpretation

3.3.1 Pathways to achieve impact neutrality

The results of this study indicate that, under current conditions, annual GHG emissions generated throughout the production life cycle are approximately balanced by the carbon sequestration capacity of the company's natural capital. This balance is achieved without the implementation of additional mitigation measures aimed at reducing life cycle impacts and without specific management interventions designed to enhance carbon stocks or increase annual carbon uptake. Consequently, any future actions targeting either emissions reduction or the enhancement of natural carbon sequestration would be expected to further improve this baseline condition.

Nevertheless, the current situation should not be interpreted as carbon neutrality. Although a balance between emissions and removals is observed, the system does not satisfy the principle of additionality, which represents a fundamental requirement for credible carbon neutrality claims (Huber et al., 2024). Achieving carbon neutrality would require the implementation of tangible, measurable, and verifiable actions beyond the existing baseline, including both measures to avoid or reduce GHG emissions across the production system and interventions aimed at increasing the annual carbon sequestration capacity of the managed ecosystems. Only through demonstrable improvements on both fronts can a genuine carbon neutrality pathway be established.

The operational value of the TREEIN framework in this paper extends beyond carbon accounting by providing the evidence base required for third-party verification and certification processes. By integrating greenhouse gas emissions, water-related impacts, and natural capital indicators within a unified assessment framework, the approach supported the attainment of both FSC certification for ES and Equalitas certification, demonstrating its applicability as a tool for standardized environmental performance assessment and compliance.

Consistent with the Mitigation Hierarchy principles underpinning the TREEIN framework, the combined adoption of the Equalitas standard for the progressive reduction of the carbon footprint, the implementation of the FMP interventions, and the certification of AriTer's forest ecosystem services under the FSC scheme (Boubacar & Sissoko, 2025) can strengthen the company's environmental credentials. In this context, the ES generated and maintained through active management may be interpreted as a form of environmental compensation that complements the damage-oriented perspective of LCA, enabling a more comprehensive evaluation of environmental performance that accounts for both impacts and positive contributions.

The results of the prospective scenarios, indicate that replacing grid electricity with electricity generated from an on-site photovoltaic system and reducing bottle weight by 25% could decrease the overall carbon footprint by approximately 15%. In addition to climate change mitigation benefits, these measures would generate positive co-benefits across the other environmental indicators considered, reducing impact scores by an average of 8% across the remaining six categories. Further improvements could be achieved by addressing

another relevant hotspot identified by the O-LCA, namely diesel consumption associated with agricultural operations.

By applying the social cost of carbon (SCC), environmental impacts can be expressed in monetary terms and compared with the value of ecosystem services generated through natural capital enhancement. Under this framework, impact neutrality may be theoretically achieved when the monetary value of environmental damages is balanced by an equivalent value of additional ecosystem services generated through targeted management interventions. For example, if an activity generates environmental damages valued at €100,000, and an investment of €10,000 in sustainable forest management produces an additional €100,000 in ecosystem services value, the resulting environmental balance could be considered neutral from a natural capital accounting perspective.

Alternatively, environmental impacts may be compensated through financial transfers to third parties capable of generating equivalent environmental benefits, provided that the resources are effectively used to implement actions that enhance ecosystem service provision. In practice, such mechanisms resemble offsetting approaches, whereby compensation payments support interventions that increase carbon sequestration and other ecosystem services.

In the case of AriTer, two potential pathways can be envisaged. The first is an insetting approach, whereby the company directly invests in the sustainable management of its own natural capital assets. Based on the FMP, net investments of approximately €500,000, after accounting for revenues from timber sales, could generate ES whose estimated value exceeds the environmental impacts associated with the company's operations. Indeed, the environmental damages attributable to the production system, estimated at approximately €1.43 million over a ten-year period using a conservative SCC of 300 €/t CO₂⁻¹ (Dong et al., 2024; Molocchi & Mela, 2024; Tol, 2023), together with the required management investments, remain lower than the total value of the ES expected to be generated through the planned FMP interventions (approximately 2 M €, plus the value associated with the investment itself, i.e., 500,000 €; see Section 3.2.2). Under this scenario, the company could potentially achieve a net positive environmental balance.

A second pathway involves the transfer or commercialization of the surplus ES and associated carbon benefits generated through the implemented interventions. In this case, external actors could contribute financially by purchasing certified ES credits and/or carbon credits, estimated at approximately 250,000 €, thereby supporting the maintenance of an overall impact-neutral balance.

Nevertheless, the practical implementation of such insetting and offsetting mechanisms requires the development of robust accounting protocols, valuation methodologies, and certification frameworks. In particular, clear rules are needed to govern the application of social cost metrics, demonstrate additionality, avoid double counting, and ensure the credibility and permanence of the environmental benefits generated.

3.3.2 Limitations and methodological challenges

Beyond carbon and water footprint indicators, a broader set of environmental footprint metrics was quantified (Table 2). These results provide a valuable baseline for future internal benchmarking, enabling comparisons

535 between subsequent reporting years and the baseline year, as well as for external benchmarking against values
536 reported in the scientific literature. Nevertheless, such comparisons should be interpreted with caution, taking
537 into account differences in system boundaries, data quality, allocation procedures, and methodological
538 assumptions that may affect the comparability of environmental performance results.

539 In this regard, addressing uncertainty is a fundamental aspect of LCA studies. While the present analysis was
540 conducted using the best available data and established inventory compilation procedures, certain limitations
541 remain due to data uncertainty and methodological choices. In particular, some allocation factors were derived
542 through consultation with company managers and therefore involve a degree of expert judgement. This may
543 have influenced the estimated environmental impacts of evoo production, potentially resulting in an
544 overestimation of the diesel use associated with olive grove management and harvesting activities.

545 The environmental impacts associated with pollutant GHG emissions resulting from the application of organic
546 fertilizers and plant protection products may be subject to uncertainty and potential overestimation. In
547 particular, emissions data were derived from a French organic viticulture system reported by Cornelus et al.,
548 2024 and subsequently adapted to AriTer's agricultural management practices. While this approach enabled
549 the completion of the inventory, the transferred data were not validated against site-specific measurements,
550 introducing an additional source of uncertainty into the assessment. Similarly, the estimation of water
551 consumption remains one of the weaker components of the analysis and should be considered a priority area
552 for future methodological refinement.

553 The reliability of impact estimates for ecotoxicity and eutrophication categories could be further improved
554 through the revision of emissions inventories, and the adoption of characterization approaches better suited to
555 local-scale assessments. Such approaches should account for site-specific soil physicochemical properties and
556 for the interactions between chemical emissions and environmental receptors, including soil invertebrates as
557 well as surface and groundwater ecosystems, as demonstrated in previous sustainability assessment
558 frameworks (Lamastra et al., 2014). In this context, the AriTer O-LCA model could be enhanced by
559 incorporating methods specifically designed to quantify the effects of chemical emissions on soil and water-
560 related ecosystem services, including erosion control, groundwater recharge, physicochemical and mechanical
561 filtration, and biotic production. Models such as LANCA® (Bos et al., 2016) represent promising tools for
562 capturing these dimensions and improving the environmental relevance of the assessment.

563 Further methodological developments could also include the systematic monitoring of biodiversity through the
564 adoption of suitable ecological indicators and bioindicator species. In particular, the Aquatic Biodiversity Index
565 (IBA-bf) and the Soil Biodiversity Index (IBS-bf), recommended within the Equalitas framework, could
566 provide valuable information on the ecological status of the farm and its evolution over time. The integration
567 of such indicators would facilitate the evaluation of potential relationships between the use of organic
568 insecticides and fungicides and changes in the abundance and diversity of macroinvertebrate communities
569 inhabiting farm soils and adjacent aquatic ecosystems.

570 It is important to note that several initiatives aimed at strengthening biodiversity conservation and ecological
571 monitoring have already been incorporated into the FMP. The implementation of these measures is expected
572 to improve both environmental performance and the robustness of future sustainability assessments, thereby

573 supporting a more comprehensive evaluation of the interactions between agricultural practices, natural capital,
574 and ecosystem service provision.

575 4 Conclusion

576 This paper demonstrates for the first time how adopting sustainability certification schemes throughout the
577 TREEIN approach can have positive environmental impacts on the agricultural sector. To this end, results from
578 applying TREEIN are shown and discussed for a typical small to medium-size agricultural company (called
579 ‘Arillo in Terrabianca’) in Tuscany, Italy. The assessment establishes a 2022 “Year Zero” baseline compliant
580 with the procedures of the ISO 14072 and Equalitas standards. By synthesizing environmental footprint data
581 with carbon sequestration potential in forests and soils, the study provides a quantitative framework for
582 achieving carbon neutrality —and potentially carbon-positive status — in accordance with EU Green Deal
583 targets. The Organizational LCA thus serves as a foundational tool for both internal decision-making and
584 external sustainability communication, supporting the company’s transition toward a more environmentally
585 responsible and climate-resilient agricultural model

586 The ultimate goal was to guide Arillo in Terrabianca toward achieving carbon neutrality, or even a carbon-
587 positive status, through the development and implementation of a carbon management plan. Regardless of the
588 certification eventually pursued, such a status can only be claimed after careful monitoring, footprint
589 mitigation, and carbon stock verification, which takes a few years. Moreover, the novelty of the research lies
590 in its active improvement of the organisation’s environmental profile while complying with the requirements
591 of the certification schemes adopted.

592 Future steps include continuous monitoring of the environmental performances, reassessment of soil and
593 ecosystem benefits from organic management, and incorporating climate change projections to understand
594 future impacts on water use and agricultural production. To ensure transparent communication and avoid
595 greenwashing, it will be crucial to regularly update primary data, recalculate indicators, and compare results
596 against the 2022 baseline. Carbon stock inventories must also be revised in line with forest management
597 interventions, which will need to be effectively implemented to achieve conservation goals, helping define the
598 actual progress toward climate objectives.

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606 **Ethics approvals**

607 No ethical approval was needed, as no sensitive data was requested from the participants during the survey.
608 Only anonymised data for the LCA modelling was collected from the organisation under study.

609 **Consent to participate**

610 Informed consent was obtained from all participants involved in the study.

611 **Data Availability**

612 For any information regarding the O-LCA model, the authors declare that the data supporting the findings of
613 this study are available within the paper and its supplementary information files. While data from the forest
614 management plan regarding plants and soil sampling data, which are in Italian language, are available upon
615 request.

616 **Author contributions statement**

617 All authors contributed to the study conception and design. Material preparation, data collection and analysis
618 were performed by Benedetto Rugani, Niccolò Renzi, Marco Allocco, Cinzia Saponeri, Marta Cimini,
619 Gianluca Boffa. The first draft of the manuscript was written by Benedetto RUGANI and Niccolò RENZI, and
620 all authors commented and contributed to the improvement of subsequent versions of the manuscript. All
621 authors read and approved the final manuscript.

622 **Supplementary Material (SM)**

623 SM1: S1. Details on the development of the O-LCA model / S2. Application of the Equalitas procedure

624 SM2: Spreadsheet file with the full life cycle inventory (LCI) table

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