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A land-based pathway to carbon neutrality in rural districts

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The land sector has a crucial role in the global pathway towards carbon neutrality, being at the same time a significant contributor to global greenhouse gases (GHG) emissions and an active removal and storage of atmospheric carbon when sustainably managed. In this paper, we develop and apply a land-based approach to assess how sustainable land management solutions can pursue the dual aim of regenerating degraded rural areas and offsetting agricultural GHG emissions, thereby contributing to the achievement of carbon neutrality in rural districts. The proposed land-based approach integrates different methodologies, including Life Cycle Assessment, literature data and IPCC methods, with the objective to determine the agriculture-related GHG emissions and the potential for mitigation through sustainable land-based solutions implemented within the same rural district. The application to a case study in the Mediterranean region, i.e., southern Apulia region (Italy) affected since 2013 by the "olive quick decline syndrome" which causal agent is identified in the bacterium *Xylella fastidiosa*, showed that sustainable land-based solutions, besides restoring the degraded farming system, can lead to a carbon neutral rural district. Land use conversions, afforestation and sustainable agricultural practices would lead to a reduction and a complete offset of the agricultural GHG emissions in the area, even producing a net carbon removal (i.e., negative emissions) up to about 384 Gg CO_2 year^{-1}. As such, this study demonstrates that sustainable land-use options are key in contributing to climate change mitigation while improving the landscape and related co-benefits.

KEYWORDS
agricultural emissions, land-based mitigation options, LCA, net-zero, Xylella fastidiosa

1 Introduction

The Paris Agreement highlights the urgency of achieving a global Net Zero target as soon as possible to limit the temperature increase to below 2 °C compared to pre-industrial levels. The European Green Deal outlines the European Union's (EU) commitment to global climate action under the Paris Agreement, aiming to make Europe the first climate-neutral continent by 2050, with an economy achieving net-zero greenhouse gas emissions. Achieving climate neutrality in the EU entails reaching net-zero greenhouse gas (GHG) emissions across all member states by reducing GHG emissions. However, since not all emissions from all sectors can be zeroed, as for the un-abatable emissions of methane from the agricultural sector, industry and waste, enhancing the EU's carbon sink of the land sector is a needed strategy to ensure achieving the climate neutral target (Mohammed et al., 2025). To this aim the recently revised (2023) LULUCF Regulation points to an EU-wide 2030 target for a net carbon removal from land-based solutions of 0.31 Gt of CO_2 eq.

This represents a reverse of the declining trend in net removals seen in recent years and a 15% increase compared to current levels in the EU's net removals, achievable through an appropriate land use and land management. A new regulatory framework at the European Union level (Reg. EU/2024/3012) for Carbon Removals and Carbon Farming (CRCF) aiming to lead towards the certification of carbon removals has also been recently approved to foster sustainable carbon farming practices, ensuring a transparent and credible governance to encourage land-based carbon removal activities and increase their deployment.

Against this backdrop, a land-based approach is proposed in this study to assess the potential of achieving carbon neutrality of rural districts, by accounting the GHG emissions of agricultural activities and estimating the potential to reduce and offset those emissions by implementing sustainable land-based options which also contribute to improving and restoring the landscape. There is a wealth of literature examining the potential to mitigate climate change through sustainable land management and land use measures at different scales, including global (Yan et al., 2024), national (de Oliveira Silva et al., 2015) or local (Kreft et al., 2023), or focusing on specific areas, such as the livestock sector (de Oliveira Silva et al., 2015; Huber et al., 2023; Kreft et al., 2023; Yan et al., 2024) or cropland management (Golub et al., 2009; Eagle and Olander, 2012; Bolinder et al., 2020). In Mediterranean and other ecologically fragile dryland regions, land degradation processes (notably erosion, soil organic matter decline and desertification risk) are widely reported as major constraints for climate mitigation and rural sustainability (Cirigliano et al., 2017; Ferreira et al., 2022). In perennial woody systems that dominate large parts of southern Europe, such as olive groves, recent syntheses and field evidence show that soil management choices (e.g., bare soil vs. groundcovers/cover crops and residue retention) are pivotal for controlling erosion, associated carbon, nutrient losses, acting therefore as restoration-oriented mitigation levers (Peñuela et al., 2026; Márquez-García et al., 2024; Chiti et al., 2024). Similar degradation pressures and restoration needs are documented across North Africa, where agroforestry/oasis systems and agroecological soil management are discussed as key strategies to address desertification, salinization and resource scarcity (Santoro, 2023; Boutagayout et al., 2025). However, only few studies assess the balance between agricultural emissions and land-based removals, although only for a specific sub-sector such as livestock (Chiriacò and Valentini, 2021) or at a wider national and EU scale (Pellerin et al., 2017). Therefore, as a further advancement in literature, this study develops and presents a more comprehensive approach that can be applied at the local rural scale, in which the potential of land-based strategies aimed at restoring degraded landscapes is assessed in terms of climate change mitigation against the overall agricultural GHG emissions of the rural area, with the final aim to reach carbon neutrality at the rural district level.

2 Methodology for carbon neutrality accounting

The proposed land-based approach integrates different methodologies that analyze GHG emissions from the agricultural sector and determine the mitigation potential of sustainable land-based options. Specifically, the proposed approach includes the following steps:

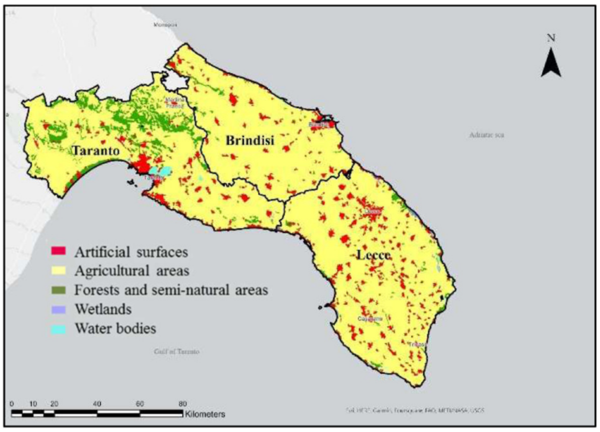

FIGURE 1
Map of land uses in the study area as reported in CLC (2018).

Step 1. Identification and stratification of a rural district into the different land-use types;
Step 2. Assessment of agricultural GHG emissions in the rural district;
Step 3. Assessment of the current carbon sink;
Step 4. Analysis of the mitigation achievable through a set of sustainable land-based practices;
Step 5. GHG balance in the rural district

2.1 Study area

A pilot area in the Mediterranean region, encompassing the provinces of Brindisi, Lecce, and Taranto of the Apulia region, Italy, was selected to apply and test the proposed land-based approach. This rural area was historically characterized by large extensions of centenary olive groves, a landmark of the landscape covering most (46%) of the total agricultural area (ISTAT, 2022). However, starting in 2013, the first symptoms of the Olive Quick Decline Syndrome (OQDS) were observed in the province of Lecce. The bacterium *Xylella fastidiosa* was identified as its causal agent (Saponari et al., 2014). As a result, today the rural landscape of southern Apulia has radically changed with all olive groves (more than 100.000 ha) hosting about 10 million dead trees. Therefore, sustainable land use and management practices are proposed to regenerate this degraded agricultural landscape and their potential to mitigate the agricultural GHG emissions in the rural district is assessed.

2.2 Land use characterization of the rural district

Figure 1 shows the land-uses distribution for the study area according to CORINE Land Cover program (CLC, 2018). The total agricultural area defined by CLC (2018) is further characterized at

TABLE 1 Characterization of the land use types in the study area as reported in ISTAT (2022) as average of the 2020–2021 period for agricultural areas and from Regione Puglia (2022) for the forest areas. Olive groves only reflect 2021 data.

Land uses	Area (ha)
Vineyards	46.478
Olive groves	190.550
Other orchards	16.185
Forage	67.230
Meadows and grasslands	*39.360*
Other annual forage crops	*27.870*
Arable lands	66.821
Vegetables (field)	24.375
Vegetables (greenhouse)	21
Total agricultural areas	414.679
Shrublands	20.702
Forests	31.954
Total forest areas	52.656

the province level (NUT3, Eurostat, 2021) in terms of main crops, using information from the latest available statistics (ISTAT, 2022) which represents the subset of lands officially managed by farmers for agricultural purposes. Similarly, also forests and semi-natural areas as defined by CLC (2018) are further detailed into forests and shrublands, based on the most updated information derived from the Apulian regional map of forest typologies (Regione Puglia, 2022).

As an output of Step 1 the most representative crops in lands managed by farmers are reported in Table 1, considering average values for two consecutive years (2020 and 2021), so as to reflect the inter-annual variability occurring especially in annual crops due to crop rotations. An exception is made for olive groves, where only the most recent available year (2021) is considered, due to the increasing trend in recent years of dead infected olive trees eradication.

2.3 Assessment of GHG emissions from agricultural activities within the rural district

In Step 2, the carbon footprint (CF) of agricultural activities in the district is assessed through a Life Cycle Assessment (LCA). The LCA was performed following the ISO 14044 "LCA - Requirements and guidelines" (ISO, 2006a), ISO 14040 standard on "LCA - Principles and procedures" (ISO, 2006b) and ISO 14067 "Greenhouse gases - Carbon footprint of products–Requirements and guidelines for quantification" (ISO, 2018).

Input data on farming and livestock activities in the study area (Table 2) were derived from existing datasets reporting information at the province level (NUT3) on the use of fertilizers and other chemicals, such as insecticides, fungicides and herbicides (ISTAT, 2022), diesel consumption for farming (MISE, 2022), electricity consumption in agriculture (Terna, 2022), and livestock heads (Anagrafe Nazionale Zootecnica, 2022).

TABLE 2 Average annual agricultural inputs (2015–2020) and reared animals in the study area.

Agricultural inputs	Production	Unit	Amount per year
N fertilizer		Mg	8.029
P_2O_5 fertilizer		Mg	3.647
K_2O fertilizer		Mg	2.999
Fungicides		Mg	2.252
Insecticides		Mg	764
Herbicides		Mg	728
Diesel for farming		Mg	51.912
Electricity (Italian energy mix)		GWh	184
Cattle and buffaloes	*Milk*	n°	38.499
	Meat	n°	7.996
	Mixed	n°	16.635
Sheep	*All*	n°	68.658
Goats	*All*	n°	26.716
Swine	*Meat*	n°	7.616
Poultry	*Eggs*	n°	471.482
Horses	*All*	n°	4.634
Mules and asses	*All*	n°	301

TABLE 3 Emission factors for field cultivation.

Inputs	Emission source	kg CO_2eq/kg input	Data source
Fertilizers	Production of fertilizer (N)	4,12	Ecoinvent (2021)
	Production of fertilizer (P_2O_5)	2,05	Ecoinvent (2021)
	Production of fertilizer (K_2O)	3,59	Ecoinvent (2021)
Plant protection products	Fungicides production	9,08	Green (1987), Silva and Kulay (2003), World Bank Group (2007)
	Insecticides production	9,89	Green (1987), Silva and Kulay (2003), World Bank Group (2007)
	Herbicides production	13,30	Green (1987), Silva and Kulay (2003), World Bank Group (2007)
Diesel	Production	0,45	Pascal et al. (2015), BP (2017), Fehrenbach (2017), ENI (2018), Oil and Gas Journal (2018)
	Burning	3,10	Nemecek et al. (2007)
Energy	Production	0,26[a]	ISPRA (2022), European Commission (2020a)

[a]kg CO_2eq kWh−1.

For mineral fertilizers and plant protection products, Table 2 reports activity data derived from provincial sales statistics expressed as multi-year averages (2015–2020) for the three provinces in the district (ISTAT, 2022). In the absence of consistent information on end-of-year stocks and cross-boundary trade flows, annual sales were used as a proxy for annual use; averaging across multiple years is intended to dampen the effect of temporary inventory changes and inter-annual market fluctuations. Residual deviations may still occur due to stockpiling and purchases outside the district, and the inter-annual variability of the 2015–2020 series can be considered an indicative uncertainty bound for these inputs.

Data analysis is carried out based on the IPCC Guidelines (IPCC, 2006; IPCC, 2019), applying emission factors (EF) specific to the Mediterranean region derived from international databases commonly used in environmental assessments, such as the Ecoinvent V3.8 Database (2021), or literature, as detailed in Table 3. The system boundaries are defined to include all GHG emissions produced alongside the agricultural activities, including raw materials and fertilizers production, their application to the soil, diesel consumption for farming activities, the energy (electricity) demand for agricultural production (excluding the food processing process), the management of livestock and their manure. The transportation of raw materials to the field is not considered, as no reliable information is available and considering that they generally account for a small share of GHG emissions in food systems. Furthermore, the study focusses on the field production phase only, since the aim is to account for a balance of removals and emissions form land sector, therefore emissions of greenhouse gases linked to the food processing phase, which may also be relevant (Mura et al., 2023a), are not accounted in this paper.

The LCA analysis can be performed at three different levels of accuracy (IPCC, 2019), ranging from the utilization of simple equations and default data (Tier 1) to the use of site-specific data and more advanced analytical methods (Tier 3). In this study we employ a hybrid Tier 1-2 approach, using more accurate national EFs (e.g., for energy production) where available. Furthermore, the CF at the rural district level was assessed not using functional units (FU) (i.e., product unit or area unit as done in Chiriacò et al., 2022) but rather assessing GHG emissions referred to the entire agricultural sector's activities. In this study, we adopt a territorial LCA perspective, where the reference system is a geographically delimited territory and the life-cycle inventory aggregates the activities occurring within the district boundary together with the upstream (cradle-to-gate) emissions embodied in the inputs consumed in the territory (Loiseau et al., 2018). This differs from product LCA, which is structured around a functional unit and is typically used to compare products or technologies (ISO, 2006a; ISO, 2006b; ISO, 2018). It also differs from farm carbon footprint studies, which usually focus on a single holding and report results per unit of product or per farm-year, whereas territorial LCA supports the assessment of a portfolio of management practices and land uses at planning scale and enables a net balance with local removals within the same spatial boundary (Loiseau et al., 2018). Finally, it differs from national greenhouse gas inventories, which follow IPCC sectoral accounting and report emissions occurring within administrative borders, generally without allocating upstream embodied emissions in external supply chains to the place of input use; the territorial LCA approach complements inventories by explicitly incorporating life-cycle supply-chain emissions associated with district-level consumption of inputs (IPCC, 2006; IPCC, 2019; Loiseau et al., 2018). This allows a direct comparison of baseline emissions (Step 2) with the current carbon sink (Step 3) and the achievable mitigation potential linked to the proposed sustainable land management practices and land use change (Step 4). The total GHG emissions assessed through the LCA are reported in CO_2-equivalents, based on Global Warming Potential (GWP) factors over a 100-year time horizon (Forster et al., 2021). These factors assign a GWP of 1 for 1 kg of CO_2, 273 for 1 kg of N_2O, and 27.9 for 1 kg of CH_4.

2.3.1 Emissions from field operations

2.3.1.1 Emissions from fertilizer use

GHG emissions from fertilizers use are linked to their production and, in the case of nitrogen fertilizers, also to their application to the soil. The annual use of fertilizers in the district was derived from the average amount of fertilizers annually sold in the three provinces (Lecce, Brindisi and Taranto) from 2015 to 2020 (ISTAT, 2022), assuming that the entire annual sold volume is used within the same year.

Emissions due to the production of fertilizers are determined by multiplying the annual amount of nitrogen, phosphorus and potassium (8.029, 3.647 and 2.999 Mg year^{-1}, respectively, Table 2) applied in agriculture by the respective emission factors (Table 3). In the case of nitrogen fertilizers, the direct and indirect emissions of N_2O from application to the soil are also assessed. Direct N2O emissions are determined based on the IPCC guidelines (IPCC, 2019 - Vol. 4, Eq. 11.1). According to the IPCC guidelines (IPCC, 2019 - Vol. 4, Eq. 11.9), indirect N_2O emissions from atmospheric deposition of nitrogen volatilized from managed soils are calculated. According to the IPCC guidelines (IPCC, 2019 - Vol. 4, Eq. 11.10), indirect N_2O emissions from leaching and runoff are calculated. For more details refer to Supplementary Material.

2.3.1.2 Emissions from the use of products for plant protection

The use of plant protection products produces GHG emissions in their production phase. The plant protection products that have been used in the district are assessed as the average of the quantities sold annually in the three provinces (Lecce, Brindisi and Taranto) from 2015 to 2020 (ISTAT, 2022), assuming that the entire amount annually sold is used in the same year. To calculate the GHG emissions the total annual quantity of fungicides, insecticides, and herbicides (2.252, 764, 728 Mg year^{-1}, respectively, Table 2) is multiplied by the respective EF (Table 3).

2.3.1.3 Emissions from diesel for farming

The use of diesel for agricultural activities is usually a relevant source of GHG emissions (Chiriacò et al., 2017; Chiriacò et al., 2019; Mura et al., 2023b). The annual amount of fuel used for agricultural activities in the district is derived from the average data of diesel sales in agriculture for the years 2020–2021 (MISE, 2022), assuming that the entire amount annually sold is used in the same year. To assess the related GHG emissions, the total annual amount of diesel used in the district (51.912 Mg year^{-1}, Table 2) is multiplied by the EFs for its production and consumption derived from the literature (Table 3).

2.3.2 Emissions from livestock

According to IPCC (2019) enteric fermentation and manure management systems are the primary contributors to GHG emissions, making the livestock sector a significant source. The Italian National Livestock Register (2022) provides the total number of animals reared in the district (642.537 heads), classified by species and productive system (Table 2).

2.3.2.1 Emissions of CH_4 linked to enteric fermentation

Significant methane emissions from enteric fermentation comes from ruminants due to their polygastric digestive system, and the level of methane emissions largely depends on the animal weight and age, the feed ingested in terms of quantity and quality according to IPCC (2019). The IPCC guidelines (IPCC, 2019 - Vol. 4, Eq. 10.19 and 10.20) are used to estimate methane emissions from enteric fermentation. Further details on this assessment are reported in Supplementary Material.

2.3.2.2 Emissions from manure management

Manure management causes CH_4, indirect and direct N_2O emissions: the former through decomposition depending on the storage treatment and type; the latter through the processes of nitrification (aerobic) and denitrification (anaerobic) (IPCC, 2019).

Since no official information was available on the grazing and manure management system in the study area, following a conservative approach, we assumed that no animals grazing occurs and that the whole manure is stored in a “solid storage” system. Therefore, the emission factors from IPCC (2019) for the “solid storage” manure management system (Tier 1), considering a low level of productivity for the study area (RICA, 2021) are used to assess the manure management emissions.

Following the IPCC guidelines (IPCC, 2019), CH_4 emissions are assessed using Eq. 10. 22 (IPCC, 2019 - Vol. 4). Equation 10.25 (IPCC, 2019 - Vol. 4) is used to calculate direct N_2O emissions. Equations 10.26 and 10.28 (IPCC, 2019 - Vol. 4) are used to calculate indirect N_2O emissions. Furthermore, based on Equations 10.27 and 10.29 (IPCC, 2019 - Volume 4) leaching and runoff indirect N_2O emissions are determined.

The above calculations are reported in a more detailed assessment in Supplementary Material.

2.3.2.3 Emissions due to animal manure application to soil

Giving the lack of specific data on the final disposal of the stored manure in the case study area, we assumed that the whole manure produced from the livestock sector is applied to the soil as fertilizer, resulting in direct and indirect N_2O emissions. Eq. 10.34 (IPCC, 2019 - Vol. 4) is used to assess the amount of nitrogen that could be applied to soils from managed manure on an annual basis (see Supplementary Material for more information). The same methodology is used to assess indirect and direct N_2O emissions to assess emissions from fertilizer use (see Ch. 2.3.1), with the exception of emissions coming from indirect N_2O from atmospheric deposition of N volatilized from managed soils with organic nitrogen inputs. These are assessed according to Equation 11.9 (IPCC, 2019).

2.3.3 Emissions from electricity use in agriculture

The annual electricity use in agriculture was derived as the average data for the period 2015–2020 on annual electricity consumption in agriculture (184 GWh year^{-1}), retrieved from Terna (2022). GHG emissions are determined by multiplying these data by the respective EF (Table 3) according to ISPRA (2022).

TABLE 4 Forest area from Apulian regional map of forest typologies (Regione Puglia, 2022), aboveground biomass from the Apulia Region Forest Inventory (IFRP, 2023) and related increment derived from INFC 2015 (2021a).

Forest type	Area (ha)	Aboveground biomass (Mg)	% increment
Forests	31.954	2.487.535	
Mediterranean oaks	13.808	814.777	2.11
Holm oak	7.012	607.729	2.64
Temperate oaks	24	1.052	2.74
Cork oak	78	5.952	3.25
Hornbeam and Hophornbeam	45	3.435	2.20
Hygrophilous forests	58	3.506	8.22
Mediterranean pines	10.138	984.893	3.14
Other coniferous forests	157	15.294	3.49
Other deciduous broadleaved forests	117	5.771	1.95
Other evergreen broadleaved forests	511	44.770	3.25
Poplars	3	356	3.00
Shrublands	20.702		1.4[a]
Total forest lands	52.656		

[a]Data from Corona et al. (1997) in Mg CO_2 ha−1 year−1.

2.4 Assessment of the current carbon removal in the case study area

In Step 3, the current carbon sink in the district is assessed to ensure a complete GHG balance of the land sector at the rural district level, with respect to the baseline GHG emissions assessed in Step 2. In fact, land uses like forests and perennial crop systems characterized by a high carbon content, if properly managed, can be relevant carbon sinks capable of removing and storing carbon in their living biomass below- and above-ground (IPCC, 2019).

The current forest carbon sink is assessed considering the area occupied by forest as indicated in the map of Apulian forest typologies (Regione Puglia, 2022) and the aboveground biomass stock per forest type as reported by the Apulia Region Forest Inventory (IFRP, 2023) multiplied by the percentage volume increment derived as the ratio of the regional annual increment in volume over the existing volume per forest type (INFC, 2015, 2021a), as reported in Table 4. For the Mediterranean shrubs the area reported in the map of Apulian forest typologies (Regione Puglia, 2022) is directly multiplied by the annual increment of above ground living biomass (Corona et al., 1997; Costa and La Mantia, 2005).

In the case of perennial crops, their function as a carbon sink is relevant in the first 20 years, while annual growth thereafter is negligible IPCC (2019). Following a conservative approach and in the absence of information on the age of the orchards in the district, the carbon sink of these systems is therefore not included in the assessment.

Although aboveground biomass is not the only significant carbon pool, e.g., soil, belowground biomass, dead organic matter, can play an important role as carbon sinks (IPCC, 2019), giving the lack of reliable data and in view of a conservative assessment of the GHG balance it was decided not to include these pools in this assessment.

2.5 Mitigation potential of sustainable land-based practices

In Step 4, the land-based mitigation potential is evaluated by examining a set of sustainable land use and management practices that could be implemented in the rural district, assessing their effectiveness in reducing GHG emissions or enhancing carbon removals. Land-based mitigation options play a role in addressing climate change in three different ways:

a. Reducing emissions (e.g., reducing inputs);
b. Increasing carbon stocks by enhancing carbon storage in perennial woody biomass and soils;
c. Avoiding emissions through the substitution of fossil fuels with renewable resources, such as pruning residues.

Each land-based mitigation option is supported by a specific methodology for calculating its mitigation potential, which is detailed in the following sections. Table 5 provides a summary of the mitigation potential for each land-based option, expressed in Mg CO_2 equivalents (IPCC, 2019) per hectare, including reduced emissions (A) or increased carbon stocks (B) or avoided emissions from the substitution of fossil fuels (C).

2.5.1 Sustainable management of pruning residues

The pruning materials from orchards in the Mediterranean are usually burned in the field, as regulated in the study case by the Legislative Decree 24 June 2014 n. 91 art. 14 paragraph 8 letter b)

TABLE 5 Potential to mitigate emissions of a set of land use changes or land management options, classified as emissions reduction (A) or carbon stocks increase (B) or avoided emissions from the substitution of fossil fuels (C).

Mitigation option	Type of action	Mitigation potential Mg CO_2eq ha^{-1} $year^{-1}$
Energy production from pruning residues (Ch. 2.5.1)	C	1.00–5.78
On-site shredding of pruning residues (Ch. 2.5.1)	B	2.62
Cover crops in orchards (Ch. 2.5.2)	B	2.59–5.61
Conversion to organic farming (Ch. 2.5.3)	B	2.38–2.84
Conservation agriculture on annual crops (Ch. 2.5.4)	B	0.88–1.75
Reduction of synthetic nitrogen fertilizers (Ch. 2.5.5)	A	7.63[a]
Change of land use of annual crops to perennial (Ch. 2.5.6)	B	3.80
Afforestation (Ch. 2.5.7)	B	4.95–5.32

[a] kg CO_2eq per kg $N_{fertilizer}$.

(Gazzetta Ufficiale della Repubblica Italiana, 2014) and the Regional Law 10/04/2021 n. 6 (Regione Puglia, 2021). Burning biomass leads to a net carbon loss from the agricultural system and generates additional GHG emissions from the combustion process (IPCC, 2006). A more sustainable management suggests using pruning residues for energy production as a replacement for fossil fuels, or, as an alternative, to leave the shredded residues on the field, with the multiple benefits of soil fertilization, mulching, and soil organic carbon (SOC) stocks increase (Montanaro et al., 2010).

Sustainability considerations apply to both pruning-residue pathways and the mobilization of dead olive biomass. When residues are removed for bioenergy, implementation should avoid long-term depletion of soil organic matter and nutrients and minimize additional impacts from harvesting, chipping and transport through local supply chains; conversely, on-site shredding retains organic inputs within the orchard system and supports soil functions (IPCC, 2006; Montanaro et al., 2010). The use of dead olive plant material should consides site-specific constraints, including fire-risk management (De Marinis, 2021), biodiversity and soil protection, and compliance with phytosanitary and local regulatory requirements.

2.5.1.1 Energy production from pruning residues

The annual quantity of pruning residues resulting from the maintenance of perennial tree crops differs considerably across different fruit species, training systems, plant densities per hectare, prevailing climatic conditions, and geographical locations. Average data of annual biomass attainable from pruning by tree crop species (refer to Supplementary Table S2) were derived from literature studies in Mediterranean climate. The electricity generable from burning of pruning residues is calculated based on the heating power of woody biomass, which ranges from 4,300 to 4,400 kcal per kilogram of dry matter (ENEA, 2008), and using 0.001,163 kWh per kcal as conversion factor.

This option has the potential to avoid the consumption of fossil fuel and it's benefit is determined in terms of avoided GHG emissions that would have been occurred for producing the same energy amount from the national (Italy) energy mix, calculated as 0.26 kg CO_2 kW $hour^{-1}$ (ISPRA, 2022), net of the GHG emissions occurring from burning of pruning residues, calculated as 0138 kg CO_2 per MJ (Ecoinvent, 2021) where 1 kWh = 3.6 MJ.

2.5.1.2 On-site shredding of pruning residues

The average increase of SOC stock for this option is assumed being 2.62 Mg CO_2 ha^{-1} $year^{-1}$, based on literature values ranging from 2.57 to 2.67 Mg CO_2 ha^{-1} $year^{-1}$ as reported in studies for Apulia, Italy (Mohamad et al., 2016) and Andalusia, Spain (Rodríguez-Entrena et al., 2012).

2.5.2 Cover crops in orchards

Cover crops in orchards increase the stability and sustainability of the entire agroecosystem, while lowering the use of external inputs, leading to a plethora of benefits, including a larger photosynthetic surface area, SOC stocks increase (Almagro et al., 2013), a significant soil erosion decrease (Almagro et al., 2013; Novara et al., 2021), an increase in bearing capacity that can ease machine traffic (Deguine et al., 2017), preventing degradation of soil aggregate (García-Díaz et al., 2018), and improving water infiltration (Almagro et al., 2013).

The potential to mitigate emissions associated to this option is obtained from studies in Mediterranean climate (Almagro et al., 2013; Márquez-García et al., 2013; Cucci et al., 2016; Vicente-Vicente et al., 2017; García-Díaz et al., 2018; Sastre et al., 2018) considering two alternative managements for the cover crop which can be (i) mowed, resulting in an average benefit of 5.61 Mg CO_2 ha^{-1} $year^{-1}$, or (ii) green manured, with an average carbon stock increase of 2.59 Mg CO_2 ha^{-1} $year^{-1}$.

2.5.3 Conversion to organic farming

According to the Regulation (EU) n. 848/2018 (European Union, 2018) "Organic production is an overall system of farm management and food production that combines best environmental practices, a high level of biodiversity, the preservation of natural resources [. . .], delivers publicly available goods that contribute to the protection of the environment and animal welfare, as well as to rural development". Converting a cropping system from conventional to organic agriculture requires a significant shift in the approach to abiotic and biotic stresses, fertilization, and agronomic management with organic fertilization that leads to a substantial increment in the organic carbon stock in soils (Costantini et al., 2020). Recent evidence also shows that organic farming systems can significantly reduce farm-level greenhouse gas emissions, as demonstrated by O'Brien et al. (2023).

The annual increase in SOC stock of cropland converted to organic farming is assumed to be 2.84 and 2.38 Mg CO_2 ha^{-1} $year^{-1}$ for perennial and annual crops, respectively, derived as the difference in the SOC stock in soils conventionally managed and organically managed, both for perennial and annual croplands in the Apulia region, as reported by the Italian NIR (2022) over a period of 20 years indicated by IPCC (2019) as the standard transition period during which variations in SOC stocks occur after a management change.

2.5.4 Conservation agriculture in annual crops

Bare and disturbed soils typically face susceptibility to erosion (Palese et al., 2014) and reduced fertility due to mineralization of organic matter and nitrogen, with the latter being lost through leaching and volatilization (Castro et al., 2008). Therefore, adopting sustainable farming practices is crucial to minimize soil disturbance, preserve soil fertility, and maintain chemical-physical and microbiological characteristics. Conservation agriculture practices for annual crops are founded on three main principles, as outlined by FAO (2022): (i) to minimize the disturbance of soil through minimum or no/zero tillage; (ii) maintaining the soil covered with organic matter through cover crops; and (iii) crops rotation.

No and Minimum-tillage practices contribute in decreasing soil erosion, preserving soil structure, and increasing earthworm populations that consequently enhance soil fertility, aeration, water infiltration, and plant nutrient intake (FAO, 2012). Reducing tillage intensity also helps avoid carbon losses due to SOC mineralization (Freibauer et al., 2004; FAO, 2012; Santilocchi et al., 2012; Chiriacò and Valentini, 2021) and decreases fuel consumption during farming operations (FAO, 2012). Following the second and third principles, introducing cover crops and crops rotation may lead to multiple benefits: absorption of nitrogen (Kaye and Quemada, 2017) which is lost in bare fallow due to volatilization and leaching; fixation of atmospheric nitrogen for of leguminous cover crops (Abdalla et al., 2019; Kaye and Quemada, 2017); prevention of soil erosion (Kaye and Quemada, 2017; Tribouillois et al., 2018) and SOC mineralization in the soil surface avoiding direct exposure to sun radiation. Furthermore, cover crops enhance crop system's biodiversity (Page et al., 2020) and can result in a change in albedo which has the potential to cool the soil surface (Poeplau and Don, 2015; Tribouillois et al., 2018). Recent syntheses also confirm that increasing biomass inputs through cover crops enhances farmland carbon sequestration and contributes to mitigation of agricultural GHG emissions (Li et al., 2023).

Without comprehensive studies on the potential to remove carbon from the conservation agriculture, the effect of its principles is derived separately from existing literature, resulting in 0.88 and 1.29 for minimum tillage and no-tillage, respectively (Lal, 2008; González-Sánchez et al., 2012; Francaviglia et al., 2017); 1.75 for cover crops (Kaye and Quemada, 2017; Abdalla et al., 2019) and 1.43 for crops rotation (West and Post, 2002; Morari et al., 2006; Francaviglia et al., 2017).

2.5.5 Reduction of synthetic nitrogen fertilizers

One of the main aims of the EU Farm to Fork Strategy and the Green Deal is to reduce the use of agricultural chemical fertilizers European Commission, 2020a. Several studies in literature have found that reducing nitrogen fertilization to a limited extent compared to business-as-usual practices does not negatively impact production in terms of quantity or quality (Cassman et al., 2002; Niles et al., 2019), while this contributes in reducing N_2O emissions. The reduced N_2O emissions for each N fertilizer reduction is assessed using the methods described in chapter 2.3.1 resulting in 7.63 Mg CO_2eq Mg N^{-1} $year^{-1}$.

2.5.6 Land-use change from annual to perennial crops

The transition from annual to perennial cropping systems increases carbon stocks in fields by promoting carbon storage in both woody biomass and soil, with significant effects that can persist for at least 20 years (IPCC, 2019). An average carbon removal of 2.2 Mg CO_2 ha^{-1} $year^{-1}$ is derived by studies on the main species of Mediterranean orchards (Morari et al., 2006; Liguori et al., 2009; Marvinney et al., 2014; Correia et al., 2016; Scandellari et al., 2016; IPCC, 2019; ISMEA, 2020) taking into account the woody biomass annual increments net of biomass removed with pruning (for further details see Supplementary Table S3). Given the limited availability of reliable data and adopting a conservative approach, our analysis does not account for the carbon sequestration potential of below-ground biomass.

Freibauer et al. (2004) report that European soils shifting from croplands to woodlands can sink carbon at a rate of 0.3 to 0.6 Mg C ha^{-1} $year^{-1}$ over a period of at least 20 years (IPCC, 2019). Consequently, an average increment in SOC of 1.6 Mg CO_2 ha^{-1} $year^{-1}$ has been considered.

Thus, the overall mitigation potential of land use change from annual to perennial crops, taking into account both aboveground biomass and soil, averages 3.80 Mg CO_2 ha^{-1} $year^{-1}$.

2.5.7 Afforestation

Following IPCC definitions, afforestation refers to the conversion to forest land of areas that have not been forested for a long period (commonly ≥50 years), whereas reforestation refers to the re-establishment of forest on land that was forested recently (IPCC, 2006). For this study, afforestation and reforestation are used as synonyms and are considered to be applicable to land which is currently without woody vegetation (e.g., pastures, arable land, uncultivated land, etc.) and exceptionally to dead olive groves, assuming that dead olive trees are replaced by forest trees. Mediterranean forest species considered suitable for the study area are selected among the most currently widespread (INFC 2015, 2021a), which include holm oak (*Quercus ilex*), Mediterranean oaks (*Quercus amplifolia*, *Q. virgiliana*), temperate oaks (*Quercus trojana*, *Q. coccifefra*, *Q. ithabruensis*) and Mediterranean pines (*Pinus pinea*, *Pinus pinaster*, *Pinus halepensis*). To evaluate the mitigation potential of afforestation, data on the average annual increment of aboveground tree biomass are derived from the INFC 2015 (2021a), resulting in 4.95 Mg CO_2 ha^{-1} $year^{-1}$ for holm oak, 5.32 Mg CO_2 ha^{-1} $year^{-1}$ for Mediterranean oaks, 4.95 Mg CO_2 ha^{-1} $year^{-1}$ for Temperate oaks, 5.32 Mg CO_2 ha^{-1} $year^{-1}$ for Mediterranean pines.

TABLE 6 Results of the LCA analysis representing the GHG emissions linked to the whole agricultural sector in the pilot area and the current carbon sink.

Impact categories	Mg CO_2eq year^{-1}	Share
Emissions from field operations	311.199	52%
Fertilizers use	89.052	15%
Plant protection products use	37.683	6%
Fuel for farming	184.287	31%
Emissions from livestock	239.644	40%
Emissions of CH4 from enteric fermentation	186.151	31%
Emissions from manure management	53.494	9%
CH_4 emissions	10.825	2%
N_2O emissions - Direct	16.734	3%
N_2O emissions - Indirect - volatilization, leaching and runoff	6.506	1%
N_2O Emissions due to animal manure application to soil	19.429	3%
Emissions from electricity consumptions	47.879	8%
Total GHG emissions	600.388	
Current carbon sink	−149.158	−25%

2.5.8 Energy production from dead olive trees' biomass

Since 2013, more than 10 million olive trees died in the district due to the *Xylella f.* pandemic. The majority of the dead wood is still currently in the fields, exposed to natural decay and to wildfire (De Marinis, 2021). Recovering the dead tree biomass available in olive groves with the aim of producing bioenergy represents a sustainable option allowing to produce energy in place of fossil fuel while preventing the release of GHG emissions from decomposition or accidental fires.

Olive groves in the region were mainly centenarian and as such were considered mature trees (>20 years old) we assumed the carbon content in the aboveground biomass to be equal to the maximum carbon stock in olive groves, which is 9.1 Mg C ha^{-1} according to IPCC (2019, Vol. 4 Tab 5.3) or 20.22 Mg dry matter (dm) per hectare, considering 0.45 kg C kg dm^{-1} (IPCC, 2006). The electricity generable (101.135 kWh ha^{-1}) and the consequent avoided GHG emissions are determined using the same methods described in Ch. 2.5.1. And results in 23.09 Mg CO_2eq ha^{-1}.

3 Results

3.1 Agricultural greenhouse gas emissions and current forest carbon sink

In the studied rural district, GHG emissions from the livestock and agricultural system account for a total CF of 600.388 Mg CO_2eq year^{-1} (Table 6), related to a total of 414.679 ha of agricultural land (Table 1) and 642.537 heads of livestock (Ch. 2.3.2). Out of these, 471.482 heads are laying hens, while ruminants (cattle and buffaloes, sheep and goats) account for 158.504 heads (Table 2). Although poultry accounts for the largest share of livestock heads, the overall emissions profile is primarily driven by ruminants, despite their lower numbers, due to the high global warming potential of methane emitted through enteric fermentation (IPCC, 2019). Field operations are the primary contributors to GHG emissions in the area with 311.199 Mg CO_2eq year^{-1}, accounting for about 52% of all agricultural and livestock emissions. Among these, fuel for farming emerges as the most significant hot spot, representing about 31% of the emissions from agricultural and livestock activities in the district. The livestock sector, accounting for 40% (241.310 Mg CO_2eq year^{-1}) of the livestock and agricultural emissions in the district, even though it is not as significant in terms of number of animals reared as in other regions of Italy (Anagrafe Nazionale Zootecnica, 2022). The principal source of greenhouse gas emissions coming from livestock are linked to the methane resulting from enteric fermentation, accounting for 31% of the whole livestock and agricultural emissions in the district. The manure management, on the other hand, generates approximately 9% of the total emissions. Lastly, the electricity consumption in agriculture represent about 8% of the whole emissions from livestock and agricultural activities in the district, releasing 47.879 Mg CO_2eq year^{-1}.

Contrarywise, forests and shrublands within the district act as a carbon sink, with annual removals of 120.175 and 28.983 Mg CO_2eq year^{-1}, respectively. Together, these land covers account for a total removal of 149.158 Mg CO_2eq year^{-1} across 52.656 ha.

3.2 Potential of sustainable land use and land management to mitigate GHG emissions

Each land-based mitigation option was evaluated for its potential application across the entire district or in specific portions of it, under three different applicability scenarios. While

TABLE 7 **Mitigation potential in the rural district under three scenarios of application (options marked with the same letter, i.e., [a] and [b], are alternative to each other).**

Mitigation options	Extent of application in the realistic (A), technical (B), policy-driven (C) scenarios	Mitigation potential (Mg CO_2eq $year^{-1}$)		
		Realistic (A)	Technical (B)	Policy-driven (C)
Energy production from pruning residues [a]	A: 43% of the vineyard and other orchards (26.945 ha out of 62.663 ha) B: 50% of the vineyard and other orchards (39.164 ha out of 62.663 ha) C: 75% of the vineyard and other orchards (46.997 ha out of 62.663 ha)	77.489	112.629	135.155
Shredding of pruning residues on site [a]	A: 43% of the vineyard and other orchards (26.945 ha out of 62.663 ha) B: 50% of the vineyard and other orchards (39.164 ha out of 62.663 ha) C: 50% of the vineyard and other orchards (31.331 ha out of 62.663 ha)	70.596	102.610	82.088
Cover crops in orchards, mowed [b]	A: 18% vineyard and other orchards (11.279 ha out of 62.663 ha) B: 50% vineyard and other orchards (39.164 ha out of 62.663 ha) C: 75% vineyard and other orchards (46.997 ha out of 62.663 ha)	63.328	219.890	263.868
Cover crops in orchards, green manured [b]	A: 18% vineyard and other orchards (11.279 ha out of 62.663 ha) B: 50% vineyard and other orchards (39.164 ha out of 62.663 ha) C: 75% vineyard and other orchards (46.997 ha out of 62.663 ha)	29.207	101.414	121.697
Conversion to organic farming	A: 22% of vineyard and other orchards (13.786 ha out of 62.663 ha) and 22% of arable lands, vegetables (field), and other annual forage crops (26.125 ha out of 119.066 ha) B: 37.5% of vineyard and other orchards (23.499 ha out of 62.663 ha) and 37.5% of arable lands, vegetables (field), and other annual forage crops (44.650 ha out of 119.066 ha) C: 25% of vineyard and other orchards (15.666 ha out of 62.663 ha) and 25% of arable lands, vegetables (field), and other annual forage crops (29.767 ha out of 119.066 ha)	101.494	173.001	115.334
Conservation agriculture in annual crops Minimum tillage	A: 5% of arable lands, vegetables (field), and other annual forage crops (5.953 out of 119.066 ha) B: 13% of arable lands, vegetables (field), and other annual forage crops (15.627 out of 119.066 ha) C: 11% of arable lands, vegetables (field), and other annual forage crops (13.097 out of 119.066 ha)	5.239	13.758	11.526
No-tillage	A: 5% of arable lands, vegetables (field), and other annual forage crops (5.953 out of 119.066 ha) B: 13% of arable lands, vegetables (field), and other annual forage crops (15.627 out of 119.066 ha) C: 11% of arable lands, vegetables (field), and other annual forage crops (13.097 out of 119.066 ha)	7.677	20.158	16.888
Cover crop	A: 10% of arable lands, vegetables (field), and other annual forage crops (11.907 out of 119.066 ha) B: 13% of arable lands, vegetables (field), and other annual forage crops (15.627 out of 119.066 ha) C: 21.5% of arable lands, vegetables (field), and other annual forage crops (25.599 out of 119.066 ha)	20.860	27.389	44.849
Crop rotation	A: 10% of arable lands, vegetables (field), and other annual forage crops (11.907 out of 119.066 ha) B: 13% of arable lands, vegetables (field), and other annual forage crops (15.627 out of 119.066 ha) C: 21.5% of arable lands, vegetables (field), and other annual forage crops (25.599 out of 119.066 ha)	17.026	22.355	36.606
Reduction of nitrogen fertilizers	A: 15% reduction in N fertilizers utilized in the district (1.204 Mg out of 8.029 Mg) B: 15% reduction in N fertilizers utilized in the district (1.204 Mg out of 8.029 Mg) C: 20% reduction in N fertilizers utilized in the district (1.606 Mg out of 8.029 Mg)	9.194	9.194	12.259
Land-use change from annual to perennial crops	A: 5% of forage, arable lands, and vegetables (field) (7.921 out of 158.426 ha) B: 10% of forage, arable lands, and vegetables (field) (15.843 out of 158.426 ha) C: 10% of forage, arable lands, and vegetables (field) (15.843 out of 158.426 ha)	30.101	60.202	60.202

(*Continued*)

TABLE 7 Continued

Mitigation options	Extent of application in the realistic (A), technical (B), policy-driven (C) scenarios	Mitigation potential (Mg CO_2eq year^{-1})		
		Realistic (A)	Technical (B)	Policy-driven (C)
Afforestation	A: 5% of olive groves (dead trees), meadows and grassland (11.496 ha out of 229.910) B: 15% of olive groves (dead trees), meadows and grassland (34.487 ha out of 229.910) C: 10% of olive groves (dead trees), meadows and grassland (22.991 ha out of 229.910)	59.010	177.031	118.021
Total		**350.404–391.418**	**707.112–835.607**	**619.469–814.707**

some of the proposed measures may already be partially implemented in the study area, their potential contribution was excluded from the current GHG balance due to insufficient data on the extent of their implementation. Furthermore, we assume that those options which could be already in place in part of the study area are currently applied only on a limited extent of the study area, not representing the majority of agricultural practices and therefore well below the average management conditions (e.g., the agricultural land in the district is certified as organic farming only for the 22% - ORAB, 2021).

The first scenario, the "Realistic scenario" considers the effective applicability under real-world conditions. This assessment is based on factors such as activity type, costs, technical and administrative feasibility, implementation timelines, and required investments. To operationalize this scenario, we relied on data describing the average adoption rate of each practice at the national level considering national statistics and, where not available, we referred to peer-reviewed literature for comparable contexts.

The second scenario, the "Technical scenario" considers the purely technical feasibility of each option, assessed in terms of availability of suitable land for each sustainable option. To some extent, this represents a theoretical maximum potential, assuming full use of all physically suitable land allocated across the different mitigation options, and without accounting for socio-economic, regulatory, or behavioral constraints.

The third scenario, the "Policy-driven scenario" is based on the targets set by the main existing policies at the European level. It is grounded on the analysis of the key current policy frameworks and their quantified objectives relevant to land-based mitigation options, specifically for the agricultural sector (Di Lallo et al., 2024).

Next paragraphs and Table 7 outline the extent of applicability considered for each option under the three scenarios within the study area. The mitigation potential of the proposed sustainable land use and management practices is estimated to range between 350.404 and 391.418 Mg CO_2eq year^{-1} under the Realistic scenario, between 707.112 and 835.607 Mg CO_2 year^{-1} under the "Technical scenario," and between 619.469 and 814.707 Mg CO_2eq year^{-1} under the "Policy-driven scenario."

The study also assesses the climate change mitigation potential associated with the single-use exploitation of standing dead woody biomass from olive groves in the study area (see Section 2.5.8). We found that bioenergy production from dead olive tree biomass could avoid fossil fuel-related emissions amounting to 4.053.120 Mg CO_2eq. However, since this option represents a non-recurring mitigation measure, it was not included in the final district GHG balance.

3.2.1 Realistic scenario

Pruning residues are assumed to be sustainably managed on 43% of land occupied by "Vineyards" and "Other orchards" (26.945 ha of the total 62.663 ha, Table 1) based on Calatrava and Franco (2011) as a conservative benchmark, although European evidence in recent literature show even higher rates (Gómez et al., 2021; Payen et al., 2023). The resulting mitigation potential is 77.489 Mg CO_2eq year^{-1} for bioenergy use and 70.596 Mg CO_2 year^{-1} for on-site mulching. Pruning residues from olive trees were not considered since due to the effects of the OQDS most of the olive groves in the district area are dead and as such do not produce annual pruning biomass.

Introducing cover crops in the orchards' inter-rows in 11.279 ha out of the total 62.663 ha classified as "Vineyards" and "Other orchards" (Table 1) was assumed to be implemented on 18% of the area, based on what is reported in for Mediterranean countries by Kathage et al. (2022). This option can potentially mitigate 63.328 Mg CO_2 year^{-1} when cover crops are mowed or 29.207 Mg CO_2 year^{-1} when green manured. Olive groves were not included as explained in the previous paragraph.

For conversion to organic farming, the current regional share of certified organic agriculture in Apulia (22% of total agricultural area; ORAB, 2021) is adopted as reference for the district-wide assumption. Accordingly, 13.786 ha out of 62.663 ha of "Vineyards" and "Other orchards" and 26.195 ha out of 119.066 ha of "Arable lands, Vegetables (Field), and Other annual forage crops" (see Table 1) are considered under organic management. The overall mitigation potential associated with this conversion amounts to 101.494 Mg CO_2 year^{-1}. Applying conservation agriculture principles to the 30% of "Arable lands, Vegetables (Field), and Other annual forage crops" (Table 1), corresponding to 35.720 ha out of 119.066 ha, results in a mitigation potential of 50.802 Mg CO_2 year^{-1}. This share is conservatively defined considering that about 90% of tillable land in Italy is still under conventional tillage (Eurostat, 2025). Accordingly, minimum tillage and no-tillage are each assumed at 5% of the area (5.954 ha out of 119.066 ha), while cover crops and crop rotation practices are each applied to 10% of the area (11.907 ha out of 119.066 ha).

Reducing the annual use of synthetic nitrogen fertilizers by 15% in the district (i.e. 1.204 Mg out of 8.029 Mg of N applied annually, as reported in Table 2) can potentially mitigate 9.194 Mg CO_2 year^{-1}. This extent is conservatively assumed as an expert judgment under this scenario, since no robust literature benchmarks were identified.

Converting to perennial woody systems the 5% of land currently classified as "Forage," "Arable lands," and "Vegetables (Field)," corresponding to 7.921 ha out of 158.426 ha (Table 1), could generate a carbon sink of 30.101 Mg CO_2 year^{-1}. This conservative share reflects the slow adjustment dynamics and long investment horizons typical of perennial systems (Seyoum-Tegegn and Chan, 2013; Martinez-Nuñez et al., 2024). Forests currently cover only 10% of the study area, as Apulia is among the Italian regions with the lowest forestland share (INFC, 2015, 2021b). Under a realistic scenario, afforestation is applied to 5% of "Meadows and grasslands" and dead "Olive groves" area, corresponding to 11.496 ha out of 229.910 ha (Table 1), reflecting a conservative implementation level based on evidence that landholders are generally less willing to convert productive agricultural land at scale (Schirmer and Bull, 2014). The available area is equally allocated to the four forest categories considered appropriate for the study area due to their current widespread presence, i.e., holm oak, Mediterranean oaks, temperate oaks and Mediterranean pines, considered appropriate for the study area under this scenario due to their current widespread presence (see 2.5.7). The resulting mitigation potential amounts to 59.010 Mg CO_2 year^{-1}.

The overall mitigation potential under this scenario ranges from 350.404 to 391.418 Mg CO_2eq year^{-1}.

3.2.2 Technical scenario

Pruning residues are considered to be sustainably managed on the 62.5% of the orchards area (i.e., 39. 164 ha out of the total area reported as "Vineyard" and "Other orchards" in Table 1) resulting in a total mitigation potential of 112.629 Mg CO_2 year^{-1}. As an alternative, the mitigation potential from the on-site shredding of pruning residues is estimated in 102.610 Mg CO_2 year^{-1}. Pruning residues from olive trees were not considered as explained in Ch. 3.2.1.

Introducing cover crops in the inter-rows of 39. 164 ha, i.e. 62.5% of the "Vineyards" and "Other orchards" (as reported in Table 1) can potentially mitigate 219.890 Mg CO_2 year^{-1} if mowed or 101.414 Mg CO_2 year^{-1} if green manured. Olive groves were not included as explained in Ch. 3.2.1.

When the conversion to organic farming is assumed to occur on 37.5% of "Vineyards" and "Other Orchards," "Other annual forage crops," "Arable lands" and "Vegetables (Field)" (i.e., 68.148 ha out of 181.729 ha, as shown in Table 1), 1.5 times the Green Deal objective of achieving 'at least 25% of the EU's agricultural land under organic farming by 2030 (European Commission, 2021), the achievable mitigation potential is assessed in 173.001 Mg CO_2 year^{-1}.

By applying conservation agriculture principles to the 52.5% of land occupied by "Other annual forage crops," "Arable lands," and "Vegetables (Field)" (i.e. 62.510 ha as shown in Table 1), a mitigation potential of 83.660 Mg CO_2 year^{-1} can be achieved.

Reducing the annual use of synthetic nitrogen fertilizers by 15% in the district can lead to a reduction in GHG emissions equal to 9.194 Mg CO_2eq year^{-1}.

Planting new orchards on the 10% (15.843 ha) of the land currently occupied by "Forage," "Arable lands," and "Vegetables (Field)" (Table 1) could result in a carbon sink of 60.202 Mg CO_2 year^{-1}.

In this scenario, afforestation is applied to 34.487 ha, corresponding to 15% of the area currently classified as "Meadows and grasslands" and dead "Olive groves" (Table 1), adopting the same species composition and allocation shares described in Ch. 3.2.1. This land-use change results in a mitigation potential of 177.031 Mg CO_2 year^{-1}.The overall mitigation potential under this scenario ranges from 707.112 to 835.607 Mg CO_2eq year^{-1}.

3.2.3 Policy-driven scenario

In this scenario, energy production from pruning residues is assumed to be implemented on the entire share of "Vineyards" and "Other orchards" remaining available after excluding the 25% that will be allocated to organic farming, i.e. 46.997 ha out of 62.663 ha. This assumption is guided by the RED III target of reaching at least a 42.5% share of renewable energy by 2030 (European Union, 2023). Using the methodologies described in Ch. 2.5.1 and deriving the district's electricity sources and demand by Terna (2022), this supply can only cover about 14% of the district's average annual total electricity demand, well below the renewable-energy benchmark implied by that target. Resulting in a mitigation potential of 135.155 Mg CO_2eq year^{-1}.

Shredding of pruning residues is assumed to be implemented on 50% of the area classified as "Vineyards" and "Other orchards" (i.e. 31.331 ha out of 62.663 ha, as shown in Table 1), resulting in a mitigation potential of 82.088 Mg CO_2 year^{-1}. In the absence of a specific quantitative policy target directly supporting a wider district-scale allocation for this option, the extent adopted under the policy-driven scenario was set conservatively and framed under the Farm to Fork objective of reducing nutrient losses by at least 50% by 2030, given that on-site shredding returns organic matter and associated nutrients to the soil and supports nutrient retention within the orchard system (Rodrigues et al., 2012; Cirigliano et al., 2017; Petersson et al., 2024). Pruning residues from olive trees were not considered as explained in Ch. 3.2.1.

Introducing cover crops in the inter-rows of 46.997 ha out of 62.663 ha, i.e. 75% of the area classified as "Vineyards" and "Other orchards" in Table 1, can potentially mitigate 263.868 Mg CO_2 year^{-1} if mowed or 121.697 Mg CO_2 year^{-1} if green manured. Meta-analyses on cover crops report average reductions in nitrate leaching of approximately 50% in irrigated systems and 56%–69% in both irrigated and non-irrigated systems (Quemada et al., 2013; Thapa et al., 2018; Nouri et al., 2022). This is aligned with the Farm to Fork target of reducing nutrient losses by at least 50%, if cover crops are introduced on the total available land. However, we considered introduction of cover crops on 75% instead of 100% of the area classified as "Vineyards" and "Other orchards" since the 25% is already allocated to organic farming where potentially cover crops are already included. Olive groves were not included as explained in Ch. 3.2.1.

As mentioned, conversion to organic farming is assumed on 25% of "Vineyards" and "Other orchards," "Other annual forage crops," "Arable lands" and "Vegetables (Field)" (i.e. 45.432 ha out of 181.728 ha, as reported in Table 1), in line with the Green Deal objective of achieving at least 25% of the EU's agricultural land under organic farming by 2030 (European Commission, 2021), the achievable mitigation potential is assessed at 115.334 Mg CO_2 year^{-1}.

Applying minimum tillage and no-tillage each on 13.097 ha, for a total of 26.194 ha, out of 119.066 ha, i.e. 11% + 11% (22%) of the area classified as "Arable lands," "Vegetables (Field)" and "Other annual forage crops" in Table 1, can potentially mitigate 11.526 and 16.888 Mg CO_2 year^{-1}, respectively. The share of 22% remains aligned with the average EU share of conservation tillage, which in Italy is only 10% (Eurostat, 2025).

Introducing cover crops and crop rotation each on 25.599 ha, for a total of 51.198 ha, out of 119.066 ha, i.e. 21.5% + 21.5% (43%) of the area "Arable lands," "Vegetables (Field)" and "Other annual forage crops" area (Table 1), can potentially mitigate 44.849 and 36.606 Mg CO_2 year^{-1}, respectively. The potential of cover crops of reducing nutrient loss by at least 50% in accordance with Quemada et al. (2013), Thapa et al. (2018), and Nouri et al. (2022), as previously explained, is aligned with the Farm to Fork target of reducing nutrient losses by at least 50%. Crop rotation is instead mandatory to be eligible for CAP payment according to the Good Agricultural and Environmental Conditions (CAP 2023–2027). However, we considered introduction of cover crops and crop rotation each on 21.5% instead of 100% of the area classified "Arable lands," "Vegetables (Field)" and "Other annual forage crops" since 22% has been already allocated to minimum and no tillage, 25% is already allocated to organic farming where potentially cover crops and crop rotation are already included, and 10% is considered for land use change from annual to perennial croplands.

Reducing the annual use of synthetic nitrogen fertilizers by 20% in the district (i.e. 1.606 Mg out of 8.029 Mg of N applied annually, as reported in Table 2) can potentially mitigate 12.259 Mg CO_2eq year^{-1}. The share adopted under this scenario is in line with the Farm to Fork objective of reducing fertilizer use by at least 20% by 2030 (European Commission, 2020a).

Planting new orchards on 10% of the land currently occupied by "Forage," "Arable lands," and "Vegetables (Field)" (i.e. 15.843 ha out of 158.426 ha, as shown in Table 1) could result in a carbon sink of 60.202 Mg CO_2eq year^{-1}. In the absence of policy targets directly linked to the conversion of annual cropland into perennial woody systems, this extent was assumed using the 10% benchmark of the EU Biodiversity Strategy for 2030 as a proxy reference for increasing structural diversity and woody permanence in the agricultural landscape.

Afforestation is applied to 22.991 ha, corresponding to 10% of the area currently classified as dead "Olive groves" and "Meadows and grasslands" (Table 1), adopting the same species composition described in Ch. 3.2.1. This land-use change results in a mitigation potential of 118.021 Mg CO_2eq year^{-1}. This extent was assumed using the 10% benchmark of the EU Biodiversity Strategy for 2030 (European Commission, 2020b).

The overall mitigation potential under this scenario ranges from 619.469 to 814.707 Mg CO_2eq year^{-1}.

3.3 GHG balance in the rural district

A combined analysis (Step 5) of the current agricultural GHG emissions (Step 2) and carbon sink (Step 3) against the total mitigation potential (Step 4) achievable in the study area is reported in Figure 2.

Against the total GHG emissions of about 600.388 Mg CO_2eq year^{-1} from the entire agricultural sector of the rural district, the mitigation potential ranges from about 350.404 Mg CO_2eq year^{-1} to about 835.607 Mg CO_2eq year^{-1} dependent on the scenario considered and on the application of different mitigation options alternative to each other (e.g., pruning residues used for energy production vs. their shredding on site, and cover corps in orchards mowed vs. green manured) – see also Table 5.

These results show that the emissions of greenhouse gases arising from agriculture can be completely offset by implementing the proposed land-based mitigation options, resulting in a final balance ranging from 249.984 Mg CO_2eq year^{-1} to −235.219 Mg CO_2eq year^{-1}, thus allowing to reach the carbon neutrality target in the land sector in different scenarios of application. When the current carbon sink of existing forests, equal to 149.158 Mg CO_2 year^{-1}, is also taken into account, the land sector in the district shows an even greater potential to become a net carbon sink (excluding the Realistic scenario) significantly contributing to climate change mitigation by producing negative emissions in the range between 168.239 and 384.377 Mg CO_2eq year^{-1}, that could be potentially used also by other sectors to offsets other un-abatable GHG emissions (e.g., waste, industrial processes) to pursue the global climate targets.

4 Discussion and perspectives

The findings presented in Figure 2 demonstrate that the rural district can reach carbon neutrality by offsetting or reducing agricultural GHG emissions through the implementation of land-based sustainable options. The approach proposed, although starting from a case study in south Italy, indicates potential pathways applicable at the district level across Europe and beyond to regenerate degraded rural areas while achieving carbon neutrality in the agricultural and land sector.

Results show that the proposed sustainable farming and land-based practices if simultaneously implemented in the rural district allow to offset completely or reduce agricultural GHG emissions in two out of three scenarios, even turning the system into a net carbon sink, especially when the current carbon sink from the forest sector is included, thus producing negative emissions significantly contributing to achieve the targets on mitigation of climate change linked to EU policies.

The mitigation potential reported under the three scenarios should be interpreted as the outcome of the simultaneous implementation of all land-based options at the assumed extents (Table 7), under an explicit non-overlap constraint designed to prevent double counting. In particular, "sustainable management of pruning residues" is implemented through one of two mutually

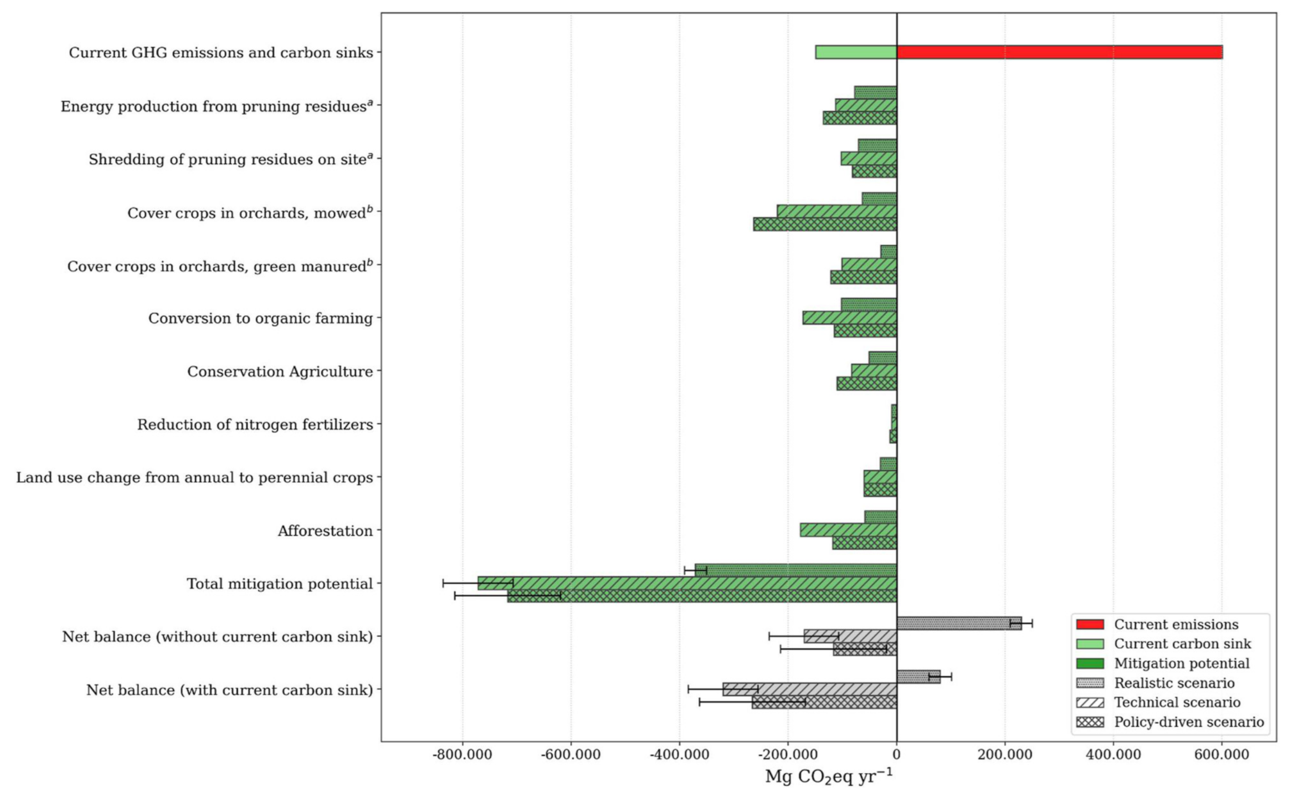

FIGURE 2
Combined results of emissions from agriculture sector (in red), current carbon sink (in light green) and mitigation potential attainable from sustainable land-based options (in dark green) under the Realistic, Technical and Policy-driven scenarios. The resulting GHG balance is reported in gray. Bars represent the range attainable for mutually exclusive implementation of alternative options (marked with the same superscript, i.e., [a] and [b]) in the total mitigation potential and in the net balance. Negative values represent sinks and positive values represent emissions.

exclusive alternatives (energy production or on-site shredding), and "cover crops in orchards" through one of two mutually exclusive alternatives (mowed or green manured); the selected residue-management option and the selected orchard cover-crop option can be applied concurrently on the same "Vineyard and Other orchards" area. Consistency of the land allocation is ensured by verifying that the sum of the areas assigned to non-overlapping measures does not exceed the total eligible land. Accordingly, the maximum orchard share simultaneously supporting pruning-residue management and orchard cover crops is set to 43% in the Realistic scenario (26.945 ha out of 62.663 ha), 62.5% in the Technical scenario (39.164 ha out of 62.663 ha), and 75% in the Policy-driven scenario (46.997 ha out of 62.663 ha). Cover crops is also proposed as a principle of conservation agriculture. However, "conservation agriculture" is proposed only on annual crops, therefore it does not overlap with the practice "cover crops in orchards." Instead, the reachable carbon stock in soil linked to the "conversion to organic farming" could be achieved with different methods including cover crops, both mowed or green manured, as well as the on-site shredding of pruning residues. Therefore, to prevent double counting, organic farming is treated as non-overlapping with the other options within the same land-use class and allocated to a distinct share of land in each scenario. Accordingly, in "Vineyards" and "Other orchards" (62.663 ha), organic farming is allocated to 22% in the Realistic scenario (13.786 ha), 37.5% in the Technical scenario (23.499 ha), and 25% in the Policy-driven scenario (15.666 ha), which are additional to the land already dedicated, as previously described, to "sustainable management of pruning residues" and "cover crops in orchards" (i.e., 43% in Realistic scenario; 62.5% in Technical scenario; and 75% in Policy-driven scenario). The same non-overlap logic is applied to annual crops ("Arable lands," "Vegetables (Field)," and "Other annual forage crops"; 119.066 ha): organic farming is allocated to 22% (26.195 ha) in the Realistic scenario, 37.5% (44.650 ha) in the Technical scenario, and 25% (29.767 ha) in the Policy-driven scenario, while the "application of the principles of conservation agriculture" are allocated on a total of 30% (35.720 ha), 52.5% (62.510 ha), and 65% (77.393 ha) in the three scenarios, respectively.

The scientific basis and methods utilized to assess potential of mitigating GHG emissions of proposed sustainable practices are rather robust, relying on well recognized LCA and IPCC methodologies. Nevertheless, the accuracy in accounting both removals and GHG emissions in the proposed land-based approach can be further enhanced reaching Tier 2 or 3 (IPCC, 2019) by adopting as much as possible site-specific emission factors, data and country-specific models for calculation. A further improvement could be reached by assessing the climatic and environmental suitability of each land-based practice proposed in a specific geographic context.

It is noteworthy that the agricultural sector's GHG emissions in the district, assessed with an LCA analysis, are reported as total emissions per entire district. Therefore, the total agricultural activities' carbon footprint of at the rural district level is assessed with a "territorial LCA" (Loiseau et al., 2018), which, as in Chiriacò and Valentini (2021), provides information on the whole GHG emissions produced in a given geographic area by a specific rural system with its characteristics. This measurement cannot be directly compared to other results from studies that evaluate the CF of agricultural production usually measured as GHG emissions per functional unit, such as per area (Kulak et al., 2013; Chiriacò et al., 2017; 2019) or per product (Kulak et al., 2013; Kendall et al., 2015; Chiriacò et al., 2019) but rather it provides a clear assessment of the real role in climate change of the rural district.

A relevant assumption in this approach is that the land-based options here proposed are considered new for the district. However, it is possible that some of these practices are already applied in the study area, albeit on a limited scale since sustainable land use and management practices are generally still sparsely implemented and do not represent the majority. For example, according to ORAB (2021) the land certified as organic reaches today about 22% of the land destined to agriculture in the study area. Despite it seems already in line with the target in the Green Deal of reaching 25% of organic farming in the EU (European Commission, 2019), there is still room for increasing this share in the study area. Therefore, we considered all the options as additional to the average current management, but with a limited extent of implementation as defined in Table 7.

The set of land-based options was identified based on the most common practices proposed in literature as promising solutions to increase climate change mitigation in the land sector (IPCC, 2019). However, it does not represent an exhaustive list and other mitigation options could be included in the future, such as the use of biochar as a byproduct of energy production from pruning residues. This practice not only leads to a SOC stock increase, but also shows various correlated positive impacts on the improvement of the soil chemical-physical fertility, improving its structure, increasing bearing and water retention capacity thanks to greater porosity, enhancing biodiversity in terms of microflora and microfauna (Mukherjee and Lal, 2013).

Proximity is also a crucial aspect of the proposed land-based approach. Most of the existing carbon offsetting mechanisms acts on a global scale, where the offset through carbon sequestration typically occurs in areas geographically far away from the source of emissions. Instead, the land-based approach we propose allows to achieve carbon neutrality through an increase in carbon sinks or reduction of emissions near the source of the GHG emissions due to livestock and agricultural activities. It not only contributes to efforts in mitigating climate change globally but in the meantime enhances local agro-ecosystems and their services (Foley et al., 2011; Allen and Hof, 2019). For example, it promotes the improvement of biodiversity, protection of water, soil and air quality, and increases the landscape and aesthetic values, potentially resulting in positive returns for rural tourism.

However, achieving carbon neutrality requires the simultaneous application of many land-based mitigation solutions, at the farm level many changes are required in agricultural practices, a reorganization at the district level and a systematic adaptation process. As such, the implementation of such practices can face limitations due to various factors, such as the need for substantial economic investments (e.g., proper agricultural machinery for grass management, creation of new wood-based power plants, land use changes, etc.), increased production and management costs (e.g., costs related to management of pruning materials), technical skills of entrepreneurs and local farmers, missing information and education. More broadly, sustainability-transition research highlights that overcoming these barriers typically requires "whole economy and society" enabling conditions, i.e., coherent policy mixes spanning multiple domains (e.g., skills and education, energy infrastructure, buildings/housing and transport) and coordinated participation of public authorities, private actors and civil society, rather than isolated sectoral instruments (Markard et al., 2012; Rogge and Reichardt, 2016; Kivimaa and Kern, 2016; Kern et al., 2019). Evidence on demand-side mitigation likewise shows that deep emission reductions depend on complementary packages of behavioral, infrastructural and technological measures across end-use sectors, supported by coordinated policy action (IPCC, 2022).

A comprehensive assessment of the potential socio-economic and environmental trade-offs and a detailed cost-benefit analysis could help stakeholders understand the potential benefits and profitability of the implementation of these land-based mitigation options.

The widespread implementation of a land-based approach for GHG offsetting requires strong advocacy at various institutional and socio-economic levels. For example, regulatory and planning mechanisms implemented at the local level (e.g., regional, municipal, etc.) can help to create carbon neutral rural districts, aligning to the recently approved EU Carbon Removals and Carbon Farming Certification Framework established by Regulation (EU) 2024/3012 (European Union, 2024) that fosters the recognition of incentives to farmers who implement sustainable and carbon farming practices, also through voluntary carbon mechanisms. Furthermore, incentives and subsides for sustainable farming systems contributing to climate change mitigation may be fostered by national governments and under the EU Common Agricultural Policy (CAP).

It is important to stress that the "net carbon sink" outcome identified in this study emerges from a territorial accounting framework in which emissions and removals are balanced within the same rural district and over a 100-year GWP time horizon. This approach is conceptually aligned with net-zero accounting at system level, but it does not automatically imply the generation of durable Carbon Dioxide Removals (CDR) in the sense adopted in international climate governance. Durable CDR generally requires demonstrable additionality, long-term storage permanence, monitoring, reporting and verification provisions, and safeguards against reversal (IPCC, 2022). The negative balance estimated in this study reflects the combined effect of avoided emissions and enhanced biogenic sequestration under specific land-use scenarios. Clarifying this distinction helps avoid overinterpretation of territorial mitigation potentials and situates the results within the appropriate scientific and policy context.

5 Conclusion

At rural district level, GHG agricultural emissions can be reduced and completely offset through land-based mitigation options that implement sustainable use and management of land in proximity of the emissions source. This study demonstrates how different land-based mitigation options can completely offset agricultural GHG emissions and even create a net carbon sink system.

The approach here presented contributes not only to global mitigation targets for climate change but also improves the entire agro-ecosystem by rethinking the land management and land use with the aim to restore degraded rural areas as for dead olive groves in the Apulia region (south Italy) due to the pathogen *Xylella fastidiosa*. Beyond climate mitigation, the assessed options may contribute to improving soil quality, enhancing biodiversity, restoring ecological functionality in abandoned or degraded agricultural areas, and increasing the overall resilience of rural systems. These outcomes are particularly relevant in districts where agricultural decline and landscape degradation are closely interconnected. This approach could provide multiple co-benefits for local rural communities, institutions, and citizens as positive environmental outcomes, territorial image, and quality of life, encouraging the sustainable use of resources and making rural systems and farmers important driving forces to mitigate and adapt to climate change. This approach could be further exploited and used as basis for creating local voluntary carbon markets as an opportunity (Fang et al., 2023) to generate an additional income for farmers from the implementation of carbon framing practices, in line with the recent EU regulation, and for exploring a possible carbon neutral certification of local agri-food chain thus providing added values to food commodities.

This proposed land-based approach provides a robust framework to support decision-making processes for policymakers, farmers, and other stakeholders. By facilitating the identification of optimal strategies for sustainable land management at the rural district level, this approach offers a replicable model that can be effectively applied across Europe and in other regions globally. However, its application outside Mediterranean districts requires context-specific parameterization, because mitigation potentials and feasible uptake levels are sensitive to climate, soils, land systems and farm structure. In practice, replication should therefore be treated as an adaptive exercise where emission factors need to be updated with regionally appropriate sources, and the suitability and implementability of each option are re-screened against local regulatory and socio-economic constraints before computing the district GHG balance. Accordingly, the method is replicable as a framework whereas the resulting mitigation potentials remain inherently region-dependent.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

GP: Investigation, Methodology, Conceptualization, Validation, Visualization, Formal Analysis, Writing – original draft, Data curation. RV: Supervision, Conceptualization, Validation, Writing – review and editing. ME: Writing – original draft, Methodology, Formal Analysis. RL: Writing – review and editing. GS: Writing – review and editing. MC: Investigation, Writing – original draft, Writing – review and editing, Validation, Funding acquisition, Data curation, Methodology, Conceptualization.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

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Supplementary material

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