The International Journal of Life Cycle Assessment
https://doi.org/10.1007/s11367-025-02559-z

CRITICAL REVIEW

The life cycle assessment of trees outside woodlands: a systematic review of methodological approaches

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Received: 23 May 2025 / Accepted: 4 October 2025
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Abstract

Purpose The purpose of this study is to understand how Life Cycle Assessment (LCA) methodology has been applied to evaluate the impacts of trees outside woodlands and where improvements are needed. This review aims to discuss the primary limitations when using LCAs to assess trees outside woodlands, particularly in comparison to existing literature on their environmental, social, and economic implications.

Methods Following the established STARR-LCA systematic review protocol, a total of 102 studies across 30 countries were identified. The selected studies used LCA frameworks to assess the impacts of five different trees outside woodland systems. Qualitative data relating to the tree system and LCA methodology were manually extracted from each study and summarised for analysis based on the four phases of an LCA: goal and scope, life cycle inventory, impact assessment, and interpretation.

Results and discussion This review showed the selected studies were primarily located in Southern Europe, South America, and Asia. Orchards were the focus of 68% of the papers, followed by 13% assessing silvopastoral systems. No papers were found on hedgerows or Miyawaki forests, which were within the scope of this review. The most common functional units were based on mass, area, and economic measures, and 29% of studies used more than one functional unit to interpret their LCA results. Environmental impacts were considered in 98% of the selected studies, whereas 13% of studies integrated an economic impact assessment, and only 5% accounted for the social implications of trees outside woodlands. Similarly, even though trees outside woodlands can increase carbon sequestration and biodiversity levels, these measures were only incorporated into 25% and 10% of the LCA studies, respectively.

Conclusions The environmental, economic, and social impacts of trees outside woodlands are dependent on the type of system and its intended purpose, climatic zone, and landscape. Process-based LCAs can be used to effectively assess the impacts of trees outside woodlands. However, the ability to holistically assess trees outside woodlands is limited by current LCA methodology, particularly when accounting for system multifunctionality or ecosystem services such as carbon sequestration and biodiversity. To address these limitations, four research recommendations have been made to improve future LCA studies. This could enhance the usefulness of LCAs in understanding sustainability trade-offs and facilitating decision-making across different tree system scenarios.

Keywords Life cycle assessment · Tree systems · Agroforestry · Orchard · Trees outside woodlands · Carbon sequestration · Multifunctionality · Systematic review

1 Introduction

Tree establishment is a widely used method for increasing carbon sequestration and reducing net greenhouse gas emissions. Globally, this is commonly achieved through planting of stands of coniferous and/or deciduous tree species in forests and woodlands, which account for around 90% of terrestrial plant biomass globally (Pan et al. 2013). However, as the global population continues to grow and become more affluent, the global demand for livestock and crop products

Communicated by Matthias Finkbeiner.

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Published online: 13 October 2025

also increases (van Dijk et al. 2021). As a result, there is a tension between the need to increase tree cover whilst increasing food production (Holl and Brancalion 2020; Meyfroidt et al. 2010). Methods to minimise this tension include altering food consumption patterns and sustainable intensification where agricultural outputs are maintained or increased whilst enhancing environmental outcomes (Pretty et al. 2018). One proposed method of sustainable intensification is the expansion of trees outside woodlands and forests, which may enable an increase in tree cover without negatively affecting food security (Waldron et al. 2017).

A forest has been defined by the FAO (2020) as having an area greater than 0.5 ha, with trees taller than 5 m and more than 10% canopy cover. Individual countries in Europe specify different minimum areas of a forest ranging from 0.1 to 1 ha (Lawson et al. 2024). In the UK, the Forestry Commission (2017) refers to trees outside forests as "trees outside woodlands" comprising trees in woodlands between 0.1 to 0.5 ha, as well as groups of trees and lone trees covering less than 0.1 ha. These trees typically occur in agricultural landscapes, parks, and urban areas (Brown and Fisher 2012). Despite the contribution of trees outside woodlands to national biomass stocks (Schnell et al. 2014), and their important landscape value, these trees have historically been overlooked and undervalued (Liu et al. 2023).

In agricultural landscapes, agroforestry is one method of establishing additional tree cover. Agroforestry has been defined as "the practice of deliberately integrating woody vegetation (trees or shrubs) with crops and/or animal systems to benefit from the resulting ecological and economic interactions'' (Burgess and Rosati 2018). Approximately 1.6 billion hectares of land globally is thought to be under agroforestry, with a greater proportion in the tropics (78%) than temperate regions (22%) (Nair et al. 2021). Agroforestry systems can be classified based on their components such as silvopastoral (trees and livestock), silvoarable or agrosilvicultural (trees and crops), and agrosilvopastoral (trees, livestock, and crops) (Nair 1993). Systems can also be described in terms of their starting point (Burgess and Rosati 2018) and whether the arrangement of trees is within or between field parcels (Lawson et al. 2016), such as shelterbelts and hedgerows. Orchards offer another method for establishing trees outside woodlands as an area of permanent woody crops "which yield fruit over several years" (Eurostat 2012). The global area of permanent crops accounted for 189 million hectares of land in 2022 (FAOSTAT 2024). There has also been interest in the establishment of Miyawaki forests – a method where trees are planted at a high density, replicating natural forest regeneration (Miyawaki 1998). This can take place on both agricultural and urban land.

Trees outside woodlands can provide private benefits to landowners and managers and public benefits to wider society. For example, agroforestry can provide ecosystem services such as improved soil health, water quality, and nutrient cycling (Smith et al. 2013), increased carbon sequestration and improved agricultural resilience against climate change (Elevitch et al. 2018; Jose 2009), and enhanced biodiversity at farm scale across temperate and tropical climates (Bhagwat et al. 2008; Torralba et al. 2016). Orchards can also provide provisioning and regulating ecosystem services, although the extent of these benefits is dependent on management practices (Demestihas et al. 2017). Urban tree planting also offers similar environmental benefits (Dobbs et al. 2011; Roy et al. 2012). For example, an improvement in physical and mental wellbeing (Turner-Skoff & Cavender 2019), among other cultural services (Dunn et al. 2021), such as improved air quality (Amini Parsa et al. 2019), and reduced noise pollution (Fletcher et al. 2022).

The economic outcomes of trees outside woodlands have not been as well-documented, especially regarding the monetisation of potential impacts (Rouquette and Holt 2017). There are also a lot of uncertainties associated with quantifying these impacts (Song et al. 2018). In agricultural settings, establishing agroforestry systems has had mixed effects on overall yield and productivity (Fahad et al. 2022; Ivezić et al. 2021; Waldron et al. 2017), depending on the context (Mukhlis et al. 2022). In urban areas, tree planting is reported to enhance property and land values, as well as aesthetic quality (Roy et al. 2012; Song et al. 2018).

The extent to which trees outside woodlands impact different environmental and socioeconomic factors can be understood through a life cycle assessment (LCA). An LCA applies a standardised methodology to evaluate and quantify the environmental impacts of a particular product or service for its entire life cycle (i.e. cradle to grave), or up to a predetermined boundary (e.g. cradle to farm or factory gate) (ISO 2006a, 2006b). There are four principal phases in determining an LCA: establishing the goal and scope, inventory analysis, impact assessment, and interpretation (ISO 2006b). The focus of an LCA is typically on a single product, and hence the multifunctionality of trees outside woodlands are often not captured (Goglio et al. 2018; Quevedo-Cascante et al. 2023). Although the principal focus of life cycle assessment has often been on the environmental aspects, there are other life cycle-based modelling approaches such as life cycle costing (LCC) that aim to evaluate economic impacts associated with a product or service over its life cycle, (Swarr et al. 2011), and social LCA (S-LCA) frameworks that can be used to assess potential social impacts (ISO 2024; UNEP-SETAC 2009). These three life cycle methodologies – LCA, LCC, and S-LCA – are integral in achieving a more holistic evaluation of the sustainability of products, services, or systems, and can be integrated in a Life Cycle Sustainability Assessment (LCSA) architecture (Fig. 1), which thereby addresses impacts and trade-offs across all three pillars of sustainability: the environment,

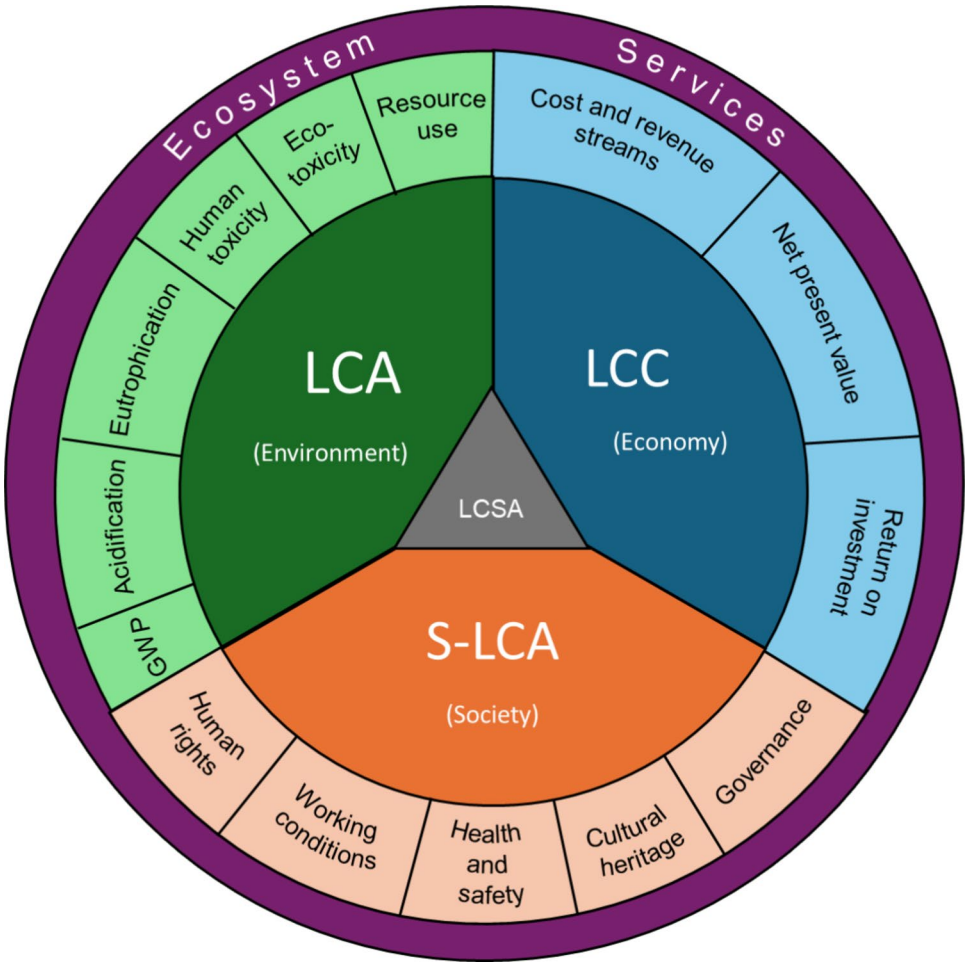


Fig. 1 The Life Cycle Sustainability Approach (LCSA) framework, demonstrating the integration of three methodologies: LCA (Life Cycle Assessment), LCC (Life Cycle Costing), and S-LCA (Social LCA), which cover the three pillars of sustainability: the environment, economy, and society. Exemplar impact categories are presented for each of the three pillars, as well as showing how ecosystem services overlap with each area. (GWP = Global Warming Potential)

economy, and society (Purvis et al. 2019). However, assessing sustainability trade-offs remains challenging due to the inherent subjectivity and uncertainties in prioritising contrasting sustainability forces, such as farm profitability, food security, and reduced GHG emissions. This is particularly relevant to the assessment of trees outside woodlands due to the diversity and complexity of ecosystem services (e.g., climate regulation, biodiversity, health and wellbeing) that are provided by both agricultural and urban tree systems (e.g., commercial orchards, Miyawaki forests, shelterbelts) (Fig. 1).

Our primary research question was to understand what the main challenges are when using standardised LCAs to assess trees outside woodlands, in comparison to existing studies on their environmental, social, and economic impacts. It is important to further understand what limitations currently exist and where LCA methodologies can be refined. This literature review builds upon previous studies in understanding the potential of LCA-based methodologies, such as the work by Goglio et al. (2018) and Quevedo-Cascante et al. (2023), by reviewing how LCA methodology has been applied to a broader range of trees outside woodlands. The main objectives are: 1) to identify and review selected LCA studies on trees outside woodlands within agricultural and peri-urban landscapes, 2) to evaluate the methodologies used and their limitations across the four LCA phases, 3) to discuss the environmental, social, and economic indicators used to assess trees outside woodlands, and 4) to provide actionable recommendations on how future LCAs can be improved to provide holistic assessments of trees outside woodlands.

2 Methods

2.1 Aim and scope of the review

The aim of this review is to understand how LCA methodology has been applied to assess the impacts of trees outside of woodlands. The scope of this review is global with all climate regions included. The types of tree outside woodlands that are within scope are agroforestry systems (agrosilvocultural, agrosilvopastoral, and silvopastoral), shelterbelts, hedgerows, and orchards planted in rural landscapes, as well

as Miyawaki forests planted in urban or peri-urban areas. Traditional woodlands and forestry plantations were not included in this review.

2.2 Identification of studies

The literature review was based on the established STARR-LCA protocol for reviewing LCA studies provided by Zumsteg et al. (2012) (Supplementary Table S1). A literature search on life cycle assessments of trees outside woodlands was conducted between May and July 2024 using SCOPUS and Web of Science. After conducting preliminary searches to identify suitable key terms, Table 1 outlines the search strings that were used to identify suitable papers. The first search string contains terms to identify papers using relevant LCA methodology, and the second search string uses terms describing the trees outside woodland systems which are relevant to this study. After screening, eligible studies were selected based on criteria listed in Table 2, based on guidelines provided by Zumsteg et al. (2012). The geographical scope of this review was global, with all life cycle impact categories being considered. Overall, a total of 659 papers were identified from two searches, from which 439 were screened for relevance based on their title, abstract and the keywords used (Fig. 2).

2.3 Data analysis

Qualitative analysis was performed on the 102 eligible papers. Only data relating to the in-scope trees outside woodland systems were extracted from each study, information regarding other activities (e.g. monoculture cropping, open pasture grazing, forestry) were not considered. From each eligible study, qualitative and descriptive data were manually extracted into categories relating to the four phases of an LCA: goal and scope, life cycle inventory, life cycle impact assessment, and interpretation (see Supplementary Table S3). These data were organised in a Microsoft Excel spreadsheet, where the results were summarised, and the key details were synthesised.

3 Results

This section is structured in four parts which cover each phase of an LCA, as outlined by ISO (2006a). The first phase is the goal and scope, which defines the system being assessed, the system boundaries, and the functional unit used. The next phase is the life cycle inventory which outlines what data have been collected relative to all the inputs and outputs of the system. The third phase is the life cycle impact assessment which measures the impacts of the system across a range of categories, while their significance is also evaluated. The final phase involves the interpretation of the LCA results, including whether any sensitivity or uncertainty analyses have been conducted.

From the literature search, only 15.5% of the 659 identified studies were relevant to this review. Of the 557 studies that were excluded, 33.4% were duplicates while the rest were studies with irrelevant functions, sectors, or methodology. As a result, a total of 102 papers were reviewed. As two papers assessed more than one tree system, this increased the total number of studies to 104. The selected studies are shown in Supplementary Table S4.

3.1 Phase 1 – goal and scope

Overall, almost half (48%) of the selected studies were based in Europe, followed by South America (19%) and Asia (19%) (Fig. 3a). Oceania was the least represented continent, with only two studies based in New Zealand. The literature represented five different types of trees outside woodlands: orchards, agrosilvocultural, agrosilvopastoral, silvopastoral, and shelterbelts. Only two papers assessed more than one system, with Acosta-Alba et al. (2020) focusing on an agrosilvocultural and an agrosilvopastoral system, while Lehmann et al. (2020) studied both an agrosilvocultural and a silvopastoral system. Orchards were the most common, representing 68% of the studies selected, followed by silvopastoral systems (13%). Only one study was found for the shelterbelt system (Fig. 3b). No LCA studies were identified for other trees outside woodlands such as hedgerows and Miyawaki forests, which were within the scope of this review.

Table 1 Search terms used to identify relevant literature for this review

Search string	Search terms
1	"Life cycle assessment" OR "life cycle analysis" OR "life cycle approach" OR "life cycle method" OR "carbon footprint"
2	"Agroforest*" OR "silvoarable" OR "silvopast*" OR "agr*silvopast*" OR "alley cropping" OR "pré-verger" OR "montado" OR "dehesa" OR "shelter belt*" OR "windbreak" OR "orchard*" OR "Miyawaki forest" OR "tiny forest" OR "microforest" OR "hedgerow*" OR "tree hedge" OR "live hedge" OR "parkland"

Table 2 Selection criteria used to identify eligible studies, based on the type of article, type of life cycle assessment (LCA) methodology used, sector and system function

Criteria	Inclusion	Exclusion
Type of article	Only full-text, peer-reviewed journal articles published in English were considered	Non-journal articles, review papers and meta-analyses were excluded, as were any journal articles published in languages other than English
Type of LCA	Studies that explicitly mentioned the use of an LCA related methodology were included, covering all environmental, economic, or social LCA perspectives	Studies using non-LCA methodologies, simple carbon footprint models or input–output tools (e.g. Cool Farm Tool) were excluded
Sector	Studies focused on trees planted outside of woodland in agricultural or peri-urban landscapes (e.g. agroforestry systems, orchards) were included	Studies focused on conventional agriculture (e.g. monoculture arable), traditional woodland and forestry were excluded
Function	Studies primarily focused on food production, and where applicable, timber or wood pellets as a co-product were included	Studies primarily focused solely on non-food production activities, such as energy production were excluded

As a result of the high proportion of orchard studies, fruit trees were the most commonly assessed component across the selected studies, with a predominant focus on apple (20 studies), olive (15), and peach (11) production. Other non-timber trees include cocoa, nuts, holm oak, and cork oak. While the majority of the selected studies analysed systems containing only one tree species, there were 23 studies which assessed two or more different tree species. For agroforestry systems where non-tree components are also considered, dairy cattle, beef cattle, and pigs were the most commonly assessed, along with a variety of crops including cereals, legumes, and cover crops.

The majority of studies selected for this review were published between 2019 and 2024 (Fig. 4), which follows the general trend in LCA literature, with a large increase in publications since 2014 (Moutik et al. 2023). Environmental LCAs were conducted by almost all of the selected studies (98%), while only 13% and 5% of studies performed economic and social impact assessments, respectively. The system boundary set for the majority of studies was cradle-to-farm-gate (70%), with cradle-to-factory-gate and cradle-to-grave representing 11% and 7% of studies, respectively (Fig. 5). Despite these system boundaries being used, not all studies chose to include the impacts of tree nurseries within the cradle stage of their assessment, citing that either insufficient data was available, or that the nursery aspect had minimal impact on the overall life cycle assessment. While most studies chose to use one functional unit, there were 30 studies which selected multiple functional units. Overall, the most common functional units used were based on mass (62%), area (28%), and economic (6%) scales (Fig. 6). A handful of studies also used functional units based on energy, carbon, and nutritional measures.

3.2 Phase 2 – life cycle inventory

Multifunctionality refers to the capacity of a system to provide more than one product or service. Out of the 102 selected papers, only 25% of studies considered the multifunctionality aspect of their selected tree system. Where multifunctionality was considered, the system studied was typically orchards that were assessing other co-products, or silvopastoral systems. As most studies (75%) did not explicitly state if they used an allocation method, this suggests that they were only assessing one product and therefore did not need to allocate impacts in a multifunctional system. To assess multifunctionality, the associated inputs and emissions need to be divided between the different products or services. The most common method was to use an allocation method based on either the respective economic value (e.g. £/tonne of product) or mass (tonne of product/ha) of the products and services (ISO 2006b). In total, eleven studies used a solely economic approach,

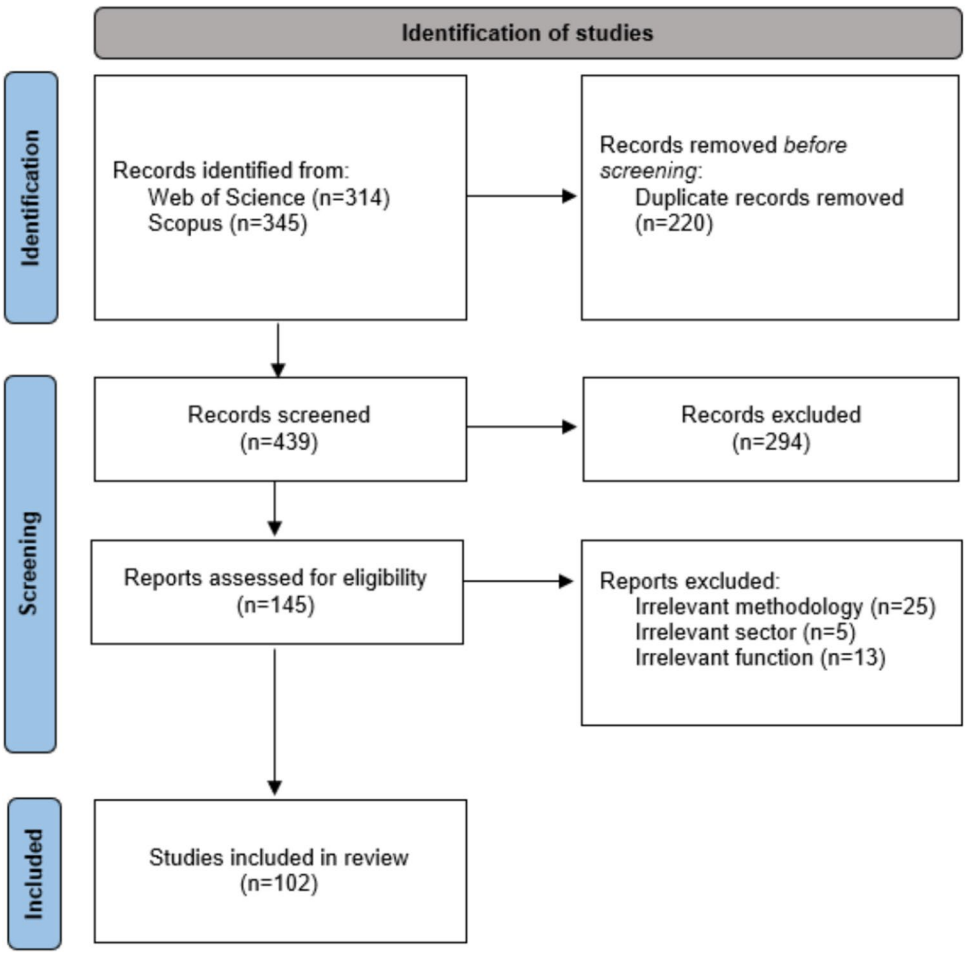
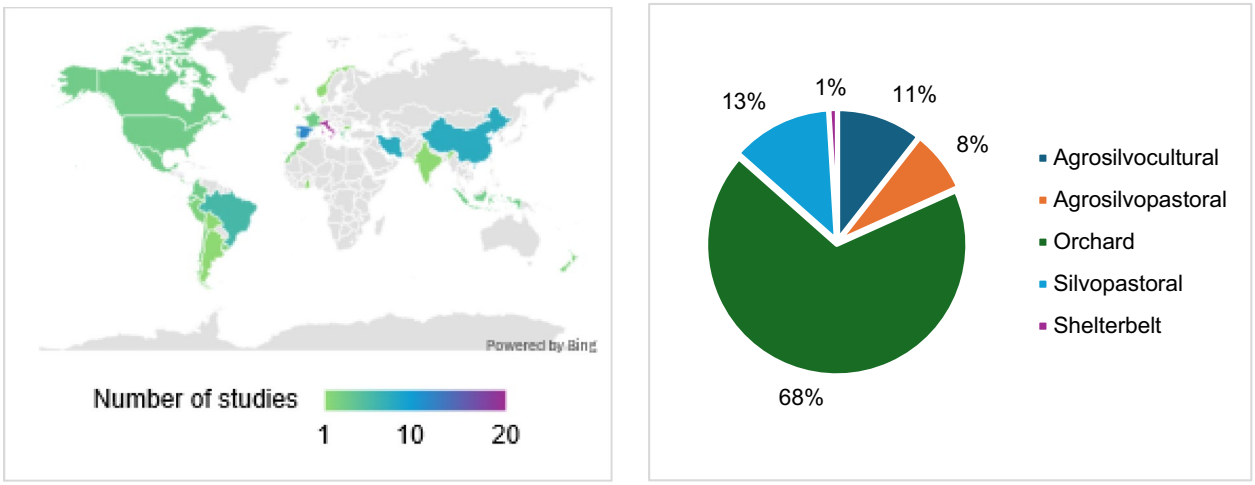


Fig. 2 The systematic review process, as recommended by Zumsteg et al. (2012), to identify and select eligible studies to include in this literature review



(a) **(b)**

Fig. 3 **a** Geographical locations of the countries where the selected studies were based. **b** Types of trees outside woodland systems studied across the selected literature (total = 104)

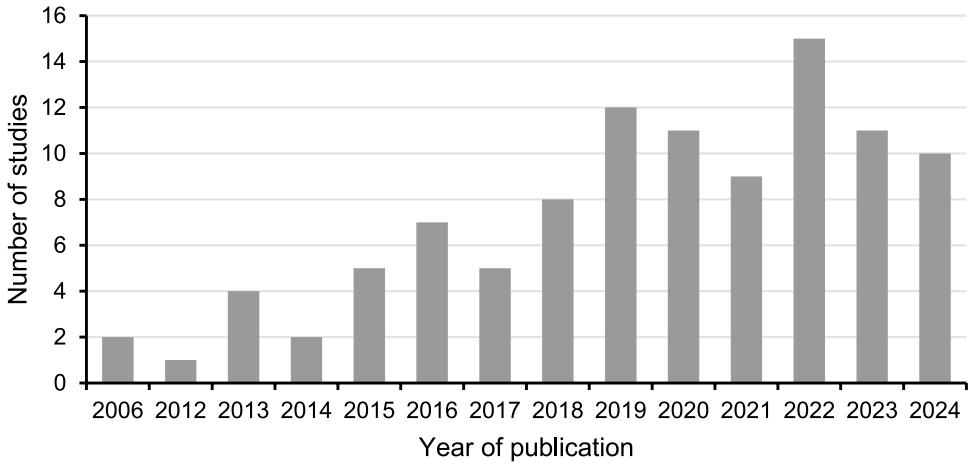


Fig. 4 The number of publications selected for this review from 2006 to 2024 ($n = 102$)

System boundary	Cradle	Farm	Post harvest facility	Factory	Packing house	Retail	Market	Plate	Grave	% of studies
Cradle-to-farm gate	■									70%
Cradle-to-factory gate	■	■	■	■						11%
Cradle-to-grave	■	■	■	■	■	■	■	■	■	7%
Cradle-to-retail gate	■	■	■	■	■	■				4%
Cradle-to-market	■	■	■	■	■	■	■			3%
Cradle-to-post harvest facility gate	■	■	■							2%
Cradle-to-packing house gate	■	■	■	■	■					1%
Cradle-to-plate	■	■	■	■	■	■	■	■		1%
Farm gate-to-farm gate		■								1%
Farm gate-to-market		■	■	■	■	■	■			1%

Fig. 5 The life cycle assessment system boundaries used across the selected studies (total = 104)

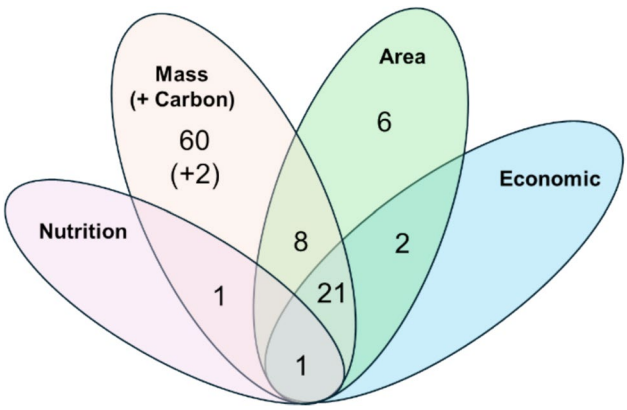


Fig. 6 Functional unit choice across the selected papers ($n = 102$), demonstrating overlap where studies have used more than one functional unit. Carbon functional units have been included within the Mass category as this also uses the mass balance approach of elemental flows

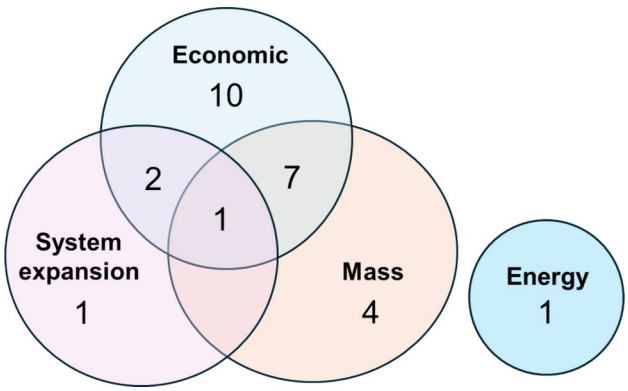


Fig. 7 Allocation method choice across the selected studies (total = 26), demonstrating overlap where studies applied more than one allocation method. This figure is based on studies that explicitly mentioned their allocation method choice, as 76 studies did not state if allocation was used

four used a solely mass-based approach, and seven studies used both economic and mass allocation methods together (Fig. 7). Aguilera et al. (2015) also used a product allocation method, where all emissions were attributed to the main product of the system rather than any co-products. By contrast, Brook et al. (2022) used energy allocation, which was based on the gross energy contained in milk and beef produced by the silvopastoral system.

An alternative approach for dividing the inputs and emissions is to use system expansion. This method considers any indirect environmental impacts of the main product or service where co-products generated by the system are assumed to displace existing products (ISO 2006b), for example replacing natural gas with wood co-products for heating purposes (Brook et al. 2022). Three studies used a system expansion approach in conjunction with an allocation method, and one study used only a system expansion method. There were also two studies examining multifunctionality that used alternative methods to avoid allocation: Costa et al. (2018) established a composite functional unit to address multifunctionality within an agrosilvopastoral system, while Paolotti et al. (2016) separated the silvopastoral system into two processes (poultry system and olive system) to be assessed individually.

3.3 Phase 3 – life cycle impact assessment

3.3.1 Environmental impacts

In total, 81 out of 104 studies analysed more than one impact category. Most studies used midpoint indicators which focus on singular environmental issues such as climate change, eutrophication, and acidification. The most common impact that was assessed was climate change (Fig. 8), also referred to as global warming potential in some studies. Across the studies selected, 97 measured climate change, 67 measured eutrophication and 64 measured acidification (Table 3). Other common midpoint indicators analysed included ecotoxicity, human toxicity, resource depletion, and photochemical oxidant creation (POC), photochemical oxidation (PO), or photochemical ozone formation (POF). There were 10 studies which chose to use an endpoint methodology, which demonstrates the aggregation of midpoint indicators at a higher level. Across the studies that used this methodology, the three endpoint indicators of human health, ecosystems, and resources were considered almost equally (Table 4).

In addition, 34 studies assessed other environmental effects which are not covered by the standard LCA impact categories. In total, 25 studies assessed the impact of their selected tree system on carbon sequestration, 10 studies evaluated biodiversity, and two studies (Aguilera et al. 2015; Costa et al. 2018) also investigated the effects on soil health.

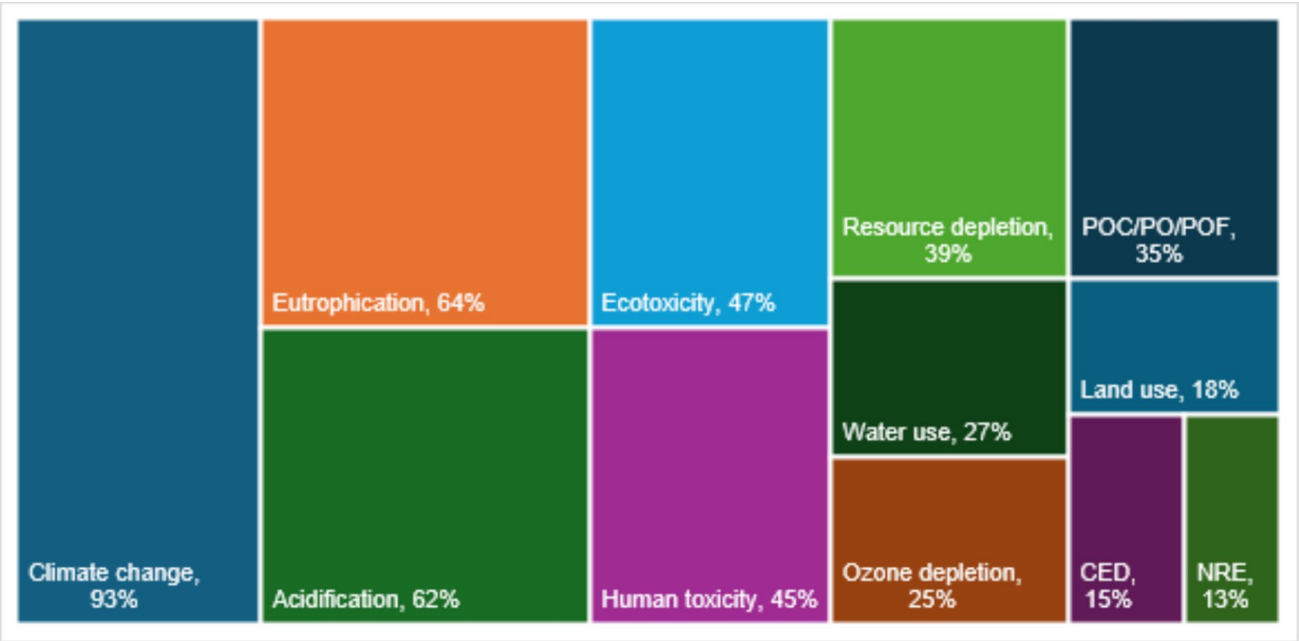


Fig. 8 The relative proportion of the selected studies (total = 104) that assessed each midpoint impact category in their environmental LCA. (POC/PO/POF = Photochemical Oxidant Creation/Photochemical Oxidation/Photochemical Ozone Formation; CED = Cumulative Energy Demand; NRE = Non-renewable Energy)

Table 3 Frequency of midpoint impact categories analysed for each type of tree system across the selected studies (total = 104)

Impact category [a]	Orchard	Silvopastoral	ASC [b]	ASP [c]	Shelterbelt	Total
Climate change	67	10	11	8	1	**97**
Eutrophication	52	2	8	5	0	**67**
Acidification	49	2	8	5	0	**64**
Ecotoxicity	40	0	4	5	0	**49**
Human toxicity	40	2	2	3	0	**47**
Resource depletion	31	2	4	4	0	**41**
POC/PO/POF	29	0	3	4	0	**36**
Water use	23	0	2	3	0	**28**
Ozone depletion	23	0	1	2	0	**26**
Land use	16	1	1	1	0	**19**
CED	14	0	1	1	0	**16**
NRE	11	1	0	1	0	**13**

[a] *POC/PO/POF* Photochemical Oxidant Creation/Photochemical Oxidation/Photochemical Ozone Formation, *CED* Cumulative Energy Demand, *NRE* Non-renewable Energy. [b] Agrosilvocultural. [c] Agrosilvopastoral

Table 4 Frequency of endpoint impact categories for each tree system across the selected studies (total = 104)

Impact category	Orchard	Silvopastoral	ASC [a]	ASP [b]	Shelterbelt	Total
Ecosystems	7	2	1	0	0	**10**
Human health	7	2	1	0	0	**10**
Resources	7	2	0	0	0	**9**

[a] Agrosilvocultural. [b] Agrosilvopastoral

3.3.2 Economic impacts

In the selected studies that assessed the economic and social impacts of their respective tree system, additional impact categories and externalities were considered. For the 13 studies that conducted an economic assessment, the most common approach used by 62% of these studies was the Life Cycle Costing (LCC) method, where a margin is determined from the estimated revenues minus the costs of a product or service throughout its lifetime. Several studies then actualised these cash flows to their net present value (NPV) to understand the system's projected profitability (De Gennaro et al. 2012; De Luca et al. 2018; Sottile et al. 2020). Tziolas et al. (2022) also used the Activity-Based Costing (ABC) method to classify value-added and non-value-added activities within the value chain.

3.3.3 Social impacts

In total, five studies looked at the social impacts of trees outside woodlands, of which two studies had only conducted an S-LCA and had not considered any environmental impact categories (Rivera-Huerta et al. 2019; Safeie-Noghlbari et al. 2024). These two studies used the methodological framework proposed by UNEP-SETAC (2009) for conducting an S-LCA. As a result, both studies assessed impact categories such as human rights, working conditions, and socio-economic repercussions, which were all split into further subcategories to enable a more detailed assessment. Safeie-Noghlbari et al. (2024) also reported on the cultural heritage and community development, while Rivera-Huerta et al. (2019) also considered the impact on governance.

The other three studies performed a social impact assessment alongside an environmental LCA and economic analysis, all using different approaches. De Luca et al. (2018) also used the UNEP-SETAC guidelines in conjunction with other methods to conduct a social LCA of an olive orchard, focusing on social health, job opportunities, and contribution to national welfare. Costa et al. (2018) conducted a socio-eco-efficiency (SEE) analysis which integrates economic and social metrics into an environmental LCA. Different stakeholder groups (e.g. employees, local and national communities, and future generations) were considered within the social impact assessment for off-farm activities regarding the manufacturing of inputs, as well as on-farm activities. Rocchi et al. (2019) instead selected social criteria relating to labour safety, animal welfare, and landscape to compare the sustainability of a silvopastoral poultry system to conventional and free-range poultry systems using a multicriteria analysis approach.

3.4 Phase 4 – interpretation

In total, 79% of studies conducted a contribution analysis, which identifies the impact hotspots across environmental impact categories and life cycle stages. For the two papers that assessed more than one system (Acosta-Alba et al. 2020; Lehmann et al. 2020), a contribution analysis was performed for each system studied. For all the trees outside woodlands studied throughout the selected literature, the key environmental impact hotspots were from in-field emissions. Fertiliser inputs were highlighted as being the principal contributor to various environmental impacts categories including climate change, acidification, and eutrophication. Nitrous oxide emissions from soil and manure management were also noted as a hotspot for in-field emissions, alongside machinery use. In addition, agrosilvopastoral and silvopastoral studies reported enteric methane from livestock to be the main source of greenhouse gas emissions. Important environmental hotspots attributed to off-farm operations primarily included the manufacturing of inputs (e.g. inorganic fertilisers, and pesticides), as well as imported feed production and transportation, although these environmental hotspots were not described as significant contributors overall.

For the interpretation phase of an LCA, sensitivity and uncertainty analyses are recommended (ISO 2006b). While sensitivity analysis aims to identify which input variables have the most significant impact on the outputs of the LCA, the objective of an uncertainty analysis is to quantify the probability of different possible outcomes. Across all the studies selected, 26% performed a sensitivity analysis and 11% performed an uncertainty analysis. Conducting a sensitivity analysis is useful as it indicates how input variables can affect output variables. For example, Aguilera et al. (2015) found that changing temporal boundaries from 100 to 20 years had a large effect on the global warming potential of organic olive production, while the effect was lower for conventional olive production. Different impact assessment methods and allocation choices can also impact the results of an LCA. Six studies conducted a sensitivity analysis to determine if different life cycle impact assessment methods lead to different results, while four studies conducted a sensitivity analysis on different allocation methods, including product, mass, and economic allocations.

Monte Carlo simulation is a common method for performing uncertainty analysis in an LCA. In total, six studies used the Monte Carlo method to understand the certainty and validity of the data used. In addition, Brook et al. (2022) and Milà i Canals et al. (2006) both performed error propagation to understand the uncertainty of the emission factors used. To reduce uncertainty in an LCA, Brito de Figueirêdo et al. (2016) reported that site-specific rather than global generic emission factors should be used where possible. However, many of the studies in this review used default emission factors and equations.

4 Discussion

Previous reviews have discussed how LCA frameworks can be applied to agricultural cropping systems (Goglio et al. 2018) and agroforestry systems (Quevedo-Cascante et al. 2023). This review builds upon such studies by increasing the scope to include a wider variety of trees outside woodlands, thereby aiming to understand the effectiveness of current LCA frameworks. This has provided insight into how LCA methodology is applied across different contexts, allowing for the evaluation of methodological choices so that specific recommendations could be made for future research. While previous studies have focused primarily on the application of LCAs to assess environmental outcomes, this review also aimed to understand the extent to which LCA methods are used to evaluate the economic and social impacts of trees outside woodlands.

4.1 LCA methodology

The LCA studies were dominated by orchard systems. Only one study was conducted on a shelterbelt system, and no studies were found for hedgerows and Miyawaki forests. This may be a result of hedgerows and Miyawaki systems not being directly associated with the output of a physical product. This remains to be a significant knowledge gap, which may hinder the informed adoption and implementation of trees outside woodlands (Staley et al. 2023), especially for newly introduced systems like Miyawaki forests (Qi et al. 2024).

Across the selected literature, the studies were predominately based in Southern Europe and South America (Fig. 3a). This may be partly due to this being the primary location of orchard and agroforestry systems, with both systems being more common in Southern than Northern Europe (Eurostat 2019; Rubio-Delgado et al. 2023). Similarly, it is estimated that 78% of global agroforestry systems are located in tropical regions, such as parts of South America (Nair et al. 2021). While studies were conducted across other areas, it would be beneficial for additional studies to develop datasets which address a wider range of geographies and climate zones.

Functional unit choice is dependent on the goal and scope of the LCA (ISO 2006b). However, it was recognised by multiple studies that this choice can impact the interpretation of the results, particularly when comparing between different products or services. In total, there were 30 studies which chose to use more than one functional unit. A mass based functional unit can be more appropriate for quantifying the

eco-efficiency of a product, but when assessing land use efficiency or production intensity, an area based functional unit can be more useful (Pérez et al. 2024). In practice, planners may need to consider both per unit product and per unit area metrics. The use of a per unit product metric can be particularly useful from a processor or retailer perspective, whereas the output per unit area of land can be pertinent when considering spatial impacts.

Some trees outside woodlands, such as agroforestry systems, can be used to provide multiple products and services, such as crop production, livestock grazing, and timber production. This can make it challenging to choose the appropriate functional units. Acosta-Alba et al. (2020) used three functional units (mass, area, and economic based) in order to address the various functions of a coffee agroforestry system. However, other studies which considered multifunctionality used alternative approaches, including allocation methods primarily based on mass and economic values, as well as system expansion methods. While there is no standardised approach for understanding multifunctional systems, different methods may have a significant impact on the results of an LCA and thus, it is also recommended for a sensitivity analysis to be conducted (Guinée et al. 2021).

4.2 Environmental impacts

Trees outside woodlands have various effects on the natural environment and provision of ecosystem services (Demestihas et al. 2017; Köthke et al. 2022), and the impact assessment for each study varies depends on factors such as tree system type and design, management practices, system boundaries, inventory data used, timescale, and allocation methods. Around 75% of studies assessed multiple environmental impact categories, either at a midpoint (Table 3) or endpoint level (Table 4), while 23% of studies only considered the climate change impact category. Climate change was the most assessed impact category, which is not surprising given the global effort to reduce GHG emissions and achieve net zero targets, especially for commercial agri-food systems looking to reduce their climate impact. As the papers selected for this review were dominated by commercial orchard studies, this may have amplified the imbalance in environmental impact representativeness.

Similarly, the prevalence of eutrophication and acidification impact assessments in the selected studies was also expected, since these impact categories are directly linked with core agronomic operations of tree system management, including fertiliser use, irrigation, and soil management. However, the land use, cumulative energy demand (CED), and non-renewable energy (NRE) categories were assessed to a lesser extent, which is interesting given that land and energy use have been noted as environmental impact hotspots for orchards (Alaphilippe et al. 2016; Castillo-González et al. 2024; Marvinney and Kendall 2021) and agroforestry systems (Caicedo-Vargas et al. 2022; Pérez-Neira et al. 2020). Therefore, omitting land use change and energy use assessment in an LCA could conceal important sustainability trade-offs and impact potential decisions guided by such assessments.

While these studies provide useful insights about trees outside woodlands, in most circumstances it is beneficial to assess a wide range of impact categories to ensure that positive impacts related to one factor are not undermined by a major negative environmental impact relating to another factor (Quevedo-Cascante et al. 2023). For example, impacts such as carbon sequestration and biodiversity change were rarely calculated in the same framework as the other environmental impact categories, despite the literature highlighting how trees outside woodlands can affect them. There are difficulties in capturing these impacts effectively within an LCA framework, as discussed below.

4.2.1 Carbon sequestration and storage

One of the motivations for increasing tree planting is climate change mitigation by increasing carbon sequestration and storage (Brancalion and Holl 2020). Carbon sequestration refers to trees removing atmospheric carbon dioxide through photosynthesis and storing it within above- and below-ground biomass, such as the leaves, branches, trunk, or roots (Sedjo and Sohngen 2012). In an LCA, carbon sequestration and the effect on climate change can be considered in the life cycle inventory phase. The primary focus of many LCAs is on the carbon sequestration related to a single product. By contrast, many tree outside woodland systems produce multiple products and allocating carbon sequestration and stocks between the main product and other co-products can be difficult (Plassmann and Norton 2017).

Overall, only 25 studies considered carbon sequestration or carbon stocks in their LCA. Of these studies, the number assessing carbon sequestration within the different agroforestry systems was slightly higher (15), compared to those focusing on orchards (10). This could be due to agroforestry systems being seen as a potentially more effective strategy for increasing carbon sequestration (Nair et al. 2009). Some studies accounted for carbon sequestration in above-ground biomass only (Brook et al. 2022; Doddabasawa et al. 2020; Rana et al. 2019; Rivera et al. 2024; Zhu et al. 2018), while others only focused on soil carbon sequestration (Aguilera et al. 2015; De Feudis et al. 2022; Eldesouky et al. 2018; Escribano et al. 2022; Fernández-Lobato et al. 2021; Horrillo et al. 2021; Parra-Paitan and Verburg 2022; Pergola et al. 2017, 2022; Utomo et al. 2016). There were also studies which accounted for both above and below-ground biomass accumulation, as well as soil carbon sequestration (Brito de Figueirêdo et al. 2016; Crous-Duran et al. 2019;

Martinelli et al. 2019; Müller Carneiro et al. 2019; O'Brien et al. 2023; Reyes-Palomo et al. 2022, 2023; Rudd et al. 2021).

While current methods for estimating carbon sequestration and storage can be used with a reasonable degree of accuracy, these methods may not be highly applicable to all studies (Goglio et al. 2015). Some studies chose not include carbon sequestration in their assessment due to a lack of standardised methodology and reliable data (Brook et al. 2022; Costa et al. 2018; Vinyes et al. 2015). To overcome some of these challenges, a framework has been proposed by Leinonen (2022) to account for carbon in LCAs by quantifying the flows of both fossil and biogenic carbon according to the mass balance principle, thereby accounting for all inputs and outputs of the system. This framework has been applied to forestry and agricultural product LCAs in Finland, demonstrating the ability to account for carbon stock changes in living biomass, organic matter, and soil organic carbon (SOC) over a period of less than 100 years (Lehtilä et al. 2025), which could therefore also be applied to LCAs of trees outside woodlands.

There is also the issue of acknowledging the permanence of carbon in trees outside woodlands, which remains an area of uncertainty. Carbon permanence refers to removing carbon from atmosphere and guaranteeing its storage over a long period of time (Ruseva et al. 2020). It has been suggested that permanence should be measured over 200 years (DESNZ 2024), or thousands of years (Jørgensen and Hauschild 2013) as opposed to the 100-year period that is frequently used. Newly sequestered carbon may only be stored temporarily, so for the above-ground biomass of trees, using wood products in construction or industry presents a long-term carbon storage method (Amiri et al. 2020; Eriksson et al. 2012). However, SOC estimation methods need further refining to increase data reliability for use in LCAs (Nayak et al. 2019), and there is still a need for additional research on how to more accurately account for carbon sequestration and its permanence within an LCA.

4.2.2 Biodiversity

Orchards can be useful for biodiversity conservation and providing other ecosystem services, however this is dependent on management practices such as the type of tillage and use of pesticides and cover crops (Katayama et al. 2019; Montanaro et al. 2017). For agroforestry systems, a meta-analysis by Torralba et al. (2016) reported a positive effect of agroforestry on the biodiversity of tree-only systems. The impact of agroforestry on biodiversity could result from the capacity to act as wildlife corridors and to provide habitat niches for additional species (Jose 2009). Agroforestry systems can also improve soil health and increase soil microbial diversity (Udawatta et al. 2019).

Overall, only 10 studies considered the effect of trees outside woodlands on biodiversity. It was most often considered at an endpoint level, as part of the ecosystem quality impact category (Heidarisoltanabadi and Elhami 2023; Ingrao et al. 2015; Ordikhani et al. 2021; Paolotti et al. 2016; Smith and Lal 2022; Zamani et al. 2024). Other studies used the Potentially Disappeared Fraction of Species (PDF) indicator within an LCA to measure the effects of land use change on biodiversity loss (Parra-Paitan and Verburg 2022), or alternative life cycle thinking methods such as AgBalance to measure biodiversity (Costa et al. 2018). Finally, two studies assessed biodiversity independently of their LCA: Recanati et al. (2018) used the Simpson and Shannon biodiversity indices to estimate plant diversity, while Rocchi et al. (2019) used a combination of genetic diversity, naturalness, and biodiversity indices.

Biodiversity was not assessed in the majority of the selected studies, and it has been acknowledged that this is a research gap and further methodological improvements are needed to integrate biodiversity effectively into LCA frameworks (Crenna et al. 2020; Rugani et al. 2019). Recommendations to reduce uncertainties in LCA outputs regarding biodiversity include improving data collection, refining inventory databases and LCA frameworks, as well as using uncertainty analysis methods (Bromwich et al. 2025). Alejandre et al. (2019) proposed an original framework that extended the current ReCiPe 2016 methodology (Huijbregts et al. 2017) to include an additional 11 ecosystem service categories, thereby providing more holistic coverage. Studies outside of this review have also presented new characterisation factors which are sensitive to different land management practices to assess biodiversity at midpoint level in an LCA (Knudsen et al. 2017; Koellner et al. 2013). In addition, Lindner et al. (2019) proposed a novel framework to quantify biodiversity impacts within an LCA for different land use classes. However, there still is no method which is capable of fully accounting for all biodiversity dimensions (Damiani et al. 2023).

4.3 Economic impacts

Trees outside woodlands have the potential to provide a variety of economic benefits (Rouquette and Holt 2017). However, it has been acknowledged that these systems can incur high establishment and maintenance costs, which means they may not be a financially viable option for farmers and landowners (Rois-Díaz et al. 2018; Roman et al. 2021).

Only 13 of the papers selected for this review conducted an economic assessment, of which nine studies focused on orchards and four assessed agroforestry systems. The results of any economic assessments are dependent on factors including the type of tree system, management practices, the products being assessed, and the assumptions made. Despite

this variation, agroforestry and orchard systems employing more sustainable practices often had higher investment costs than their conventional counterparts (Costa et al. 2018; De Gennaro et al. 2012; De Luca et al. 2018; Sottile et al. 2020). However, it is challenging to draw conclusions about the economic impacts of trees outside woodlands throughout their lifetime due to the lack of papers that completed an economic assessment. Data quality has been mentioned as a limitation of applying a Life Cycle Costing (LCC) model (De Gennaro et al. 2012), and economic sensitivity analyses have demonstrated the extent to which results can be influenced by input data quality and methodological choices (De Luca et al. 2018). In addition, integrating LCC approaches with environmental LCAs can pose challenges, especially when calculating the monetary value of different environment impacts (Rodrigues and da Silva 2024). While ISO 14008 (ISO 2019) may be helpful for calculating such external costs, it is not specific to LCA methodology. Nevertheless, it is important that assessments consider the economic implications of trees outside woodlands, as this provides a more balanced approach and can identify potential sustainability trade-offs.

4.4 Social impacts

A social life cycle assessment (S-LCA) aims to understand the social impacts of a product or service throughout its life cycle. Evidence on the social impacts of trees outside woodlands in the literature is sparse. However, it is thought that they can provide a range of social and cultural services such as physical and mental health benefits, improved community cohesion, as well as work and business opportunities (Mukhlis et al. 2022; Rouquette & Holt 2017).

Across the selected literature, only five papers considered the social impacts of their selected tree system: three studied agroforestry systems and two focused on orchards. Social impacts are often overlooked in favour of understanding the environmental implications (Safeie-Noghlbari et al. 2024). A systematic review by Guglielmetti Mugion et al. (2025) found that social impacts are not often considered in the agri-food sector, primarily due to a lack of data, as well as no standardised guidelines for selecting stakeholder groups, indicators, and impact categories. Furthermore, while S-LCAs have the potential to handle multifunctional systems, current methods still present difficulties (Tragnone et al. 2022) which may therefore prevent S-LCAs being applied to trees outside woodlands that are inherently multifunctional. While methodologies differed between the selected studies, social impact assessments should be included to provide a more holistic perspective on the sustainability of trees outside woodlands, especially when combined with environmental and economic assessments. Such considerations can be important when policymakers and actors within agricultural value chains make strategic decisions (Voglhuber-Slavinsky et al. 2022).

4.5 Limitations

Our review adopted a broader scope to investigate state-of-the-art LCA frameworks and highlight their effectiveness in holistically assessing the sustainability of trees outside woodland systems. In doing so, we found a key limitation of this review to be the significant imbalance in LCA studies applied to different trees outside woodlands. Current scientific and grey literature demonstrates a clear bias towards the assessment of commercial tree systems, such as orchards and agroforestry systems (Fig. 3b). While this may have hindered our ability to make general conclusions about the application of LCA frameworks across different systems, we present a balanced discussion to reflect on the strengths and weaknesses of current LCA methodology, as well as to recommend specific actions that can help to enhance the robustness and applicability of LCAs to all trees outside woodlands.

This review also acknowledges another key limitation around the possibility that some relevant publications were missed. However, the specific inclusion criteria used here inspire confidence in that literature has been identified and captured effectively, since most relevant studies are published in English and provided through resources the authors could access through their affiliated institutions. To further minimise risks of under-representation in our study sample, the search terms for identifying LCA studies were kept broad. We performed a post-hoc analysis by adding LCC or S-LCA in the search strings, which did not result in any relevant additional studies. A range of the most common terms used for different trees outside woodland systems were included in the search strings for this review, but relevant studies may have been missed if authors used different keywords. In addition, there is also the risk of potential bias during the selection and screening process of this review. However, this was mitigated to an extent by using defined inclusion criteria, adhering to screening validation principles within the authoring team and in collaboration with independent researchers, and following the guidelines established by Zumsteg et al. (2012).

5 Can future LCAs provide a holistic assessment of trees outside woodlands?

Evidence in literature suggests that current, standardised LCA frameworks can provide useful insights into the potential environmental, economic, and social impacts of trees outside woodlands. However, there are significant methodological limitations that need to be addressed through future

research. This would improve our understanding around the potential benefits and broader implications of these systems, especially considering carbon sequestration potential and provision of ecosystem services. We therefore present four strategic recommendations below that provide a roadmap towards enhancing future LCA research on trees outside woodlands:

5.1 Prioritise research on the mechanisms underpinning the multifunctionality of trees outside woodlands for interpretation within an LCA context

Our review of existing literature on LCAs of trees outside woodlands demonstrates a fundamental need for further research into the underlying biological processes which underpin the multifunctionality of these systems. It is also important to evaluate these systems from a cradle-to-grave perspective where possible, as while the majority of impacts can occur at a farm or field level, downstream processes should also be considered (Sinden 2009). This review demonstrates that orchard studies dominate the existing literature, and research should focus on understanding the inherent complexities of agroforestry systems, as well as Miyawaki forests, and other urban and peri-urban tree systems. Future research should aim to generate new insights and useful data about the carbon dynamics, nitrogen flows, and biomass accumulation over time. This information can then be applied to future case studies to provide a more holistic LCSA perspective.

5.2 Co-design a data collection protocol for life cycle inventory development with different stakeholders

The availability and quality of data is of paramount importance for the development of more balanced and accurate LCSAs. While detailed life cycle inventories (LCI) have been developed for trees outside woodlands, significant data gaps remain regarding critical processes and socioeconomic impacts. Therefore, studies rely heavily on assumptions and coarse resolution data (both temporal and spatial). As a result, these studies are often deemed incomplete or inaccurate, and thereby not adequate for decision or policymaking. Establishing a protocol for collecting environmental, economic, and social data is a key step for enhancing the modelling capacity of material flows of trees outside woodlands. This will also improve the robustness and transferability of these LCSA frameworks, particularly in cases of economic and social impact assessments that are currently dependent on geographic and cultural variabilities. For example, Saavedra-Rubio et al. (2022) has published step-by-step guidelines for collecting LCI data, and data collection templates have been developed for the agri-food (Turner et al. 2020) and forestry sectors (Cardellini et al. 2018) which could be repurposed for trees outside woodlands. Furthermore, it is important that the data collection protocol is co-designed with tree system managers, LCA practitioners and inter-disciplinary research teams to ensure its completeness and usefulness for both theoretical research and practical application.

5.3 Account for system-related spatiotemporal variabilities across all pillars of sustainability

Unlike annual production systems, the products and services provided by trees outside woodlands develop over time and current LCA methods have difficulty with modelling temporal heterogeneity. Developing a dynamic life cycle inventory can be challenging but including spatial and temporal dimensions within the inventory can improve the accuracy of the results (Lueddeckens et al. 2020). There is no standardised methodology available for creating a dynamic LCA, but a variety of experimental approaches have been developed (VanderWilde and Newell 2021). This further illustrates the need for more diverse case studies to apply these methods which account for spatiotemporal uncertainties across environmental, economic, and social aspects. This would allow new insights to be gained which would inform policymakers and guide future decision making around tree planting strategies. This requires also improving existing LCC and S-LCA methodologies as well as their integration in an LCSA framework (Larsen et al. 2022).

5.4 Develop integrated and prospective LCSA frameworks to holistically assess trees outside woodlands

A common theme from the selected studies in our review is that while standardised LCA frameworks can provide some useful insights about the effects of trees outside woodlands, they lack the ability to analyse more complex sustainability impacts. This is particularly the case for LCA frameworks developed in most commercial software, which are often inflexible and do not allow integration with other sustainability assessment frameworks. We recommend that LCSA practitioners and researchers use integrated approaches to enable a more complete and balanced assessment of trees outside woodlands. We have identified the following analytical approaches that could improve the usefulness of the results generated by LCSAs on trees outside woodlands:

- Soil biogeochemical modelling – For instance, integrating the denitrification-decomposition (DNDC) model in an LCA would capture the biogeochemical flows within trees outside woodlands. This could provide a better

understanding of short and long-term SOC dynamics, as well as greenhouse gas emissions.

- Climate change scenario modelling—For example, utilising the representative concentration pathways (RCPs) climate change effects can be modelled to the year 2100 (van Vuuren et al. 2011). This would enable a better understanding of how trees outside woodlands may be affected in the future, and how the environmental, economic, and social impacts may change under different climate scenarios.
- Spatial modelling – Integrating a geographic information system (GIS) into an LCA framework could help to address current issues with spatial resolution. This would also provide useful insights as the sustainability impacts of trees outside woodlands could be spatially analysed.
- Agent-based modelling – Developing a dynamic LCA model that can evaluate the complexity and multifunctionality of trees outside woodlands by focusing on different system components and their interactions. This would allow for a better understanding of what factors influence these systems and their respective impacts.

6 Conclusions

This review identified 102 papers that conducted an LCA on trees outside woodlands. Of these papers, 68% focused on orchards, suggesting that there is a research gap regarding LCA of other trees outside woodlands methods, such as agroforestry, hedgerows, and Miyawaki forests.

The environmental impacts were the primary focus of the studies selected in this review, with only 13 and 5 studies conducting economic and social impact assessments, respectively. This demonstrates that useful insights could be gained from completing more economic and social analyses, which could inform policymakers and guiding future decision making around the most effective methods of achieving a range of aims through tree planting strategies.

In conclusion, while frameworks have been proposed for holistic LCAs of trees outside woodlands, that address economic, social, and environmental aspects, there is a need to demonstrate their usefulness in practice.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11367-025-02559-z.

Author contributions All authors were responsible for the conception, design, and editing of this work. EW was responsible for data collection, analysis and interpretation. The first draft of the manuscript was written by EW, and all authors contributed to subsequent revisions of the work. All the authors have read and approved the final manuscript.

Funding This research has been funded by the UK Government's Shared Outcomes Fund as part of the Trees Outside Woodland programme.

Data availability The data generated from the study are available in the Supplementary Material.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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2025-12
Springer
https://doi.org/10.1007/s11367-025-02559-z
Webb E, Burgess PJ, Pexas G, McKnight CJ. (2025) The life cycle assessment of trees outside woodlands: a systematic review of methodological approaches. The International Journal of Life Cycle Assessment, Volume 30, December 2025, pp. 2725-2744

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